

US EPA ARCHIVE DOCUMENT

HYDROGEOLOGIC INVESTIGATION REPORT

SPARTA AQUIFER VULNERABILITY ASSESSMENT AT THE FORMER SHUMAKER NAVAL AMMUNITION DEPOT EAST CAMDEN, ARKANSAS



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EAST CAMDEN, ARKANSAS**



By:

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U.S. EPA Region 6

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1. INTRODUCTION

A. *Overview*

This report describes the U.S. Environmental Protection Agency (EPA) groundwater contamination vulnerability assessment for the Sparta aquifer located at the former Shumaker Naval Ammunition Depot (NAD) in south-central Arkansas. New information is presented about the vulnerability of the Sparta aquifer to contamination based on a geological and hydrogeological investigation conducted during 2007-2008. The investigation involved exploratory drilling, core sampling, logging, and groundwater and surface water sampling including special isotopic analysis. This report also discusses the origin of perchlorate detected at Locust Bayou.

This investigation was undertaken because of concerns about potential impacts to the Sparta aquifer from past military operations and current industrial activities, and because of detections of perchlorate contamination in drinking water at the nearby community of Locust Bayou. The area's main drinking water supplies come from groundwater within the Sparta aquifer and the overlying shallow alluvial aquifer. Any contamination impacting the Sparta aquifer or the alluvial aquifer by organic and inorganic contaminants above health based levels could pose a public health hazard and result in greater water treatment costs and limit the future utility of groundwater.

Shumaker is about 75 miles south of Little Rock, Arkansas, near the City of Camden. The study area boundary (fig. 1) is the same as the Shumaker NAD boundary, except for the southern side, which extends southward to include residences near state highway 278 (Locust Bayou community). The investigation covered approximately 73,000 acres including the former Shumaker NAD, the City of East Camden, the Locust Bayou area, an industrial complex known as Highland Industrial Park, and timber production lands.

Site access includes state roads 203, 205, 274, 278, and Calhoun County road 95, which are all paved roads. Other roads are logging roads and other unimproved roads on timber company lands. A minor number of gravel roads are maintained by county

governments. A number of small communities surround the Shumaker area including East Camden, Harmony Grove, Eagle Mills, Bearden, and Woodberry.

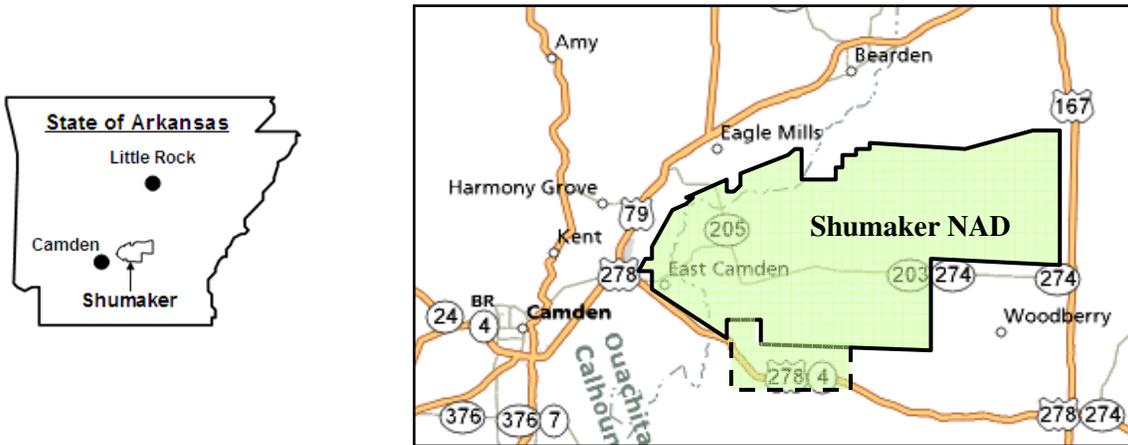


Figure 1: Location of Shumaker NAD and Study Boundary
Boundary of investigation includes area within solid black line, and dashed line south of Shumaker NAD (Locust Bayou community).

The area of investigation encompasses numerous industrial facilities operated by defense contractors, including facilities regulated by the Resource Conservation and Recovery Act (RCRA). These facilities utilize many of the buildings, ammunition magazines, and other structures that were previously part of Shumaker but are now privately owned. Shumaker NAD operated from 1944-1961 and was used for the manufacture, testing, distribution, destruction, and storage of ordnance and naval rockets.

B. Water Resources

There are 4 public water systems near Shumaker that utilize groundwater as their primary water source. These include: Bearden Waterworks and the Harmony Grove Water Association in Ouachita County; and the Locust Bayou Water Association and Shumaker Public Service Company in Calhoun County (EPA, 2008a). These utilities obtain their water supplies from the Sparta aquifer.

The most significant of these water supply companies is the Shumaker Public Service Company located at Highland Industrial Park (fig. 2). The company’s 2007 annual report, prepared for the Arkansas Public Service Commission (2008), reports that the annual average domestic water demand is 18,731,000 gallons per month, serving a

community of 5,000. The Shumaker Public Service Company obtains groundwater from 6 Sparta aquifer wells consisting of 2-18 inch wells and 4-12 inch wells averaging 180-250 feet deep. Pumping rates are 500 gallons per minute (GPM) each. Water treatment consists of aeration, chemical treatment, pre and post chlorination, sand filtration, and sedimentation. Three samples of water are submitted to the Health Department each month and there have been no health based violations, and no monitoring, reporting, or other violations in the last 10 years (EPA, 2008a).

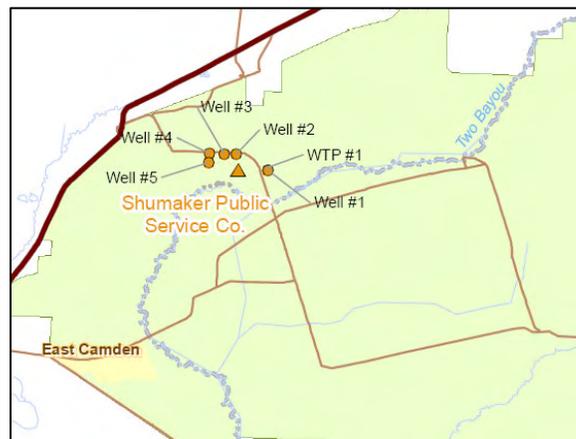


Figure 2: Location of Most (5 of 6) Shumaker Public Service Company Wells

Privately owned domestic water supplies are obtained by individual homeowners from water wells in the shallow gravel aquifer or the Sparta aquifer. Most private domestic supplies are probably from the shallow Quaternary sediments because the sediments contain a basal gravel layer (gravel aquifer) capable of producing useable quantities of groundwater. The gravel aquifer is relatively shallow, thus reducing drilling and production costs. Some residences at Locust Bayou are known to utilize water from private domestic wells. There are approximately 40 residential properties at Locust Bayou, and of these, approximately 14 use private wells as their main drinking water source and do not have access to a municipal drinking water supply (ATSDR, 2007). A number of additional residences along county roads in the vicinity of Locust Bayou may also utilize private wells. During 2005, EPA and ADEQ collected water samples from Locust Bayou residences utilizing water from private domestic wells, and detected perchlorate concentrations up to 2.2 $\mu\text{g}/\text{l}$. Assuming the state-wide average of 3 people

per household and 14 residences, approximately 42 people living at Locust Bayou may have potentially been exposed to perchlorate contamination.

C. Shumaker History

Shumaker NAD existed from 1944 to 1961 for the manufacture, testing, distribution, destruction, and storage of ordnance and naval rockets (U.S. Army Corps of Engineers, 2003a). Defense related industrial activity still takes place today, but Shumaker no longer exists as a military installation and there is no land within the study area owned by the Navy. Local residents reported during fieldwork that the area was primarily used for farming prior to the existence of Shumaker, beginning in 1944. Shumaker NAD was operational during periods of WWII through the Korean War, with employment levels varying between 20,000 in 1945, to 3,900 in 1951. In 1956, the Navy announced plans to close Shumaker, and the property was sold to private owners from 1959 to 1961. These owners included International Paper, and Brown Engineering (which became Highland Resources and was later renamed Highland Industrial Park). Shumaker finally closed in 1961 (U.S. Army Corps of Engineers, 2003b).

Currently, the eastern two-thirds of the former Shumaker site is heavily forested and used for timber production and hunting. The western one-third contains numerous industrial facilities which are operated by, or have been operated by, defense contractors. Some of these defense contractors include Lockheed-Martin, Loral Vaught Systems, Aerojet, BEI Defense Systems, Tracor Aerospace, Hughes Missiles Systems, National Testing Service, Olin Industries, Camden Ordnance, Hitech Incorporated, Armtec Defense Products, and Austin Powder.

2. PURPOSE OF INVESTIGATION

A. Background

When this study began, there was no significant information indicating whether the Sparta aquifer had been impacted by contamination, or whether it was likely for the Sparta aquifer to become impacted. A number of organizations including the EPA, the Arkansas Department of Environmental Quality (ADEQ), the Army Corps of Engineers, and industrial facilities have been collecting and evaluating shallow groundwater contamination data and conducting other types of site evaluations at Shumaker for years, but have not collected much information on the Sparta aquifer until now. Industrial facilities routinely conduct site specific groundwater investigations and corrective actions as required by RCRA permits, but these investigations are typically for shallow groundwater and not the Sparta aquifer.

In 2005, EPA and ADEQ agreed that a groundwater study of the entire Shumaker footprint was needed to evaluate Sparta aquifer vulnerability and to establish a groundwater monitoring system. Groundwater investigations at RCRA regulated facilities were fairly detailed on a site-specific basis, but covered only about 3% of the entire Shumaker footprint, based on an estimated comparison of facility areas to total Shumaker area. Conversely, regional groundwater studies conducted by government agencies (e.g., the U.S. Geological Survey, Arkansas Geological Survey, etc.) covered such large geographic areas that their large scales lack sufficient detail for making decisions about Shumaker. Other previous studies at Shumaker were conducted by the Army Corps of Engineers and involved the investigation of unexploded ordnance and possible sources of contamination at certain areas including the former rocket test range, fuse test range, rocket burn area, TNT burn area, a buried drum area, and some possible ordnance disposal wells.

Understanding the vulnerability of the Sparta aquifer to contamination depends, in part, on having sufficient information about the subsurface framework. Shumaker is so large that it is not practical or economically feasible to place monitoring wells in all

unassessed areas. The geological framework then becomes critical to developing an assessment of which areas are most and least vulnerable to contamination. Determining the presence of thick clay, specifically clay of the Cook Mountain Formation, can reduce concerns about where contamination may have impacted the Sparta aquifer because of clay's ability to limit downward groundwater flow. The likelihood of impacts to the Sparta aquifer would conceptually be less in areas where the Sparta aquifer was covered by thick clays of the Cook Mountain Formation (fig. 3). Prior to this study, the extent of the Cook Mountain Formation at Shumaker was a significant site uncertainty, and its extent was unable to be assessed by using either site-specific facility data or by much larger regional studies.

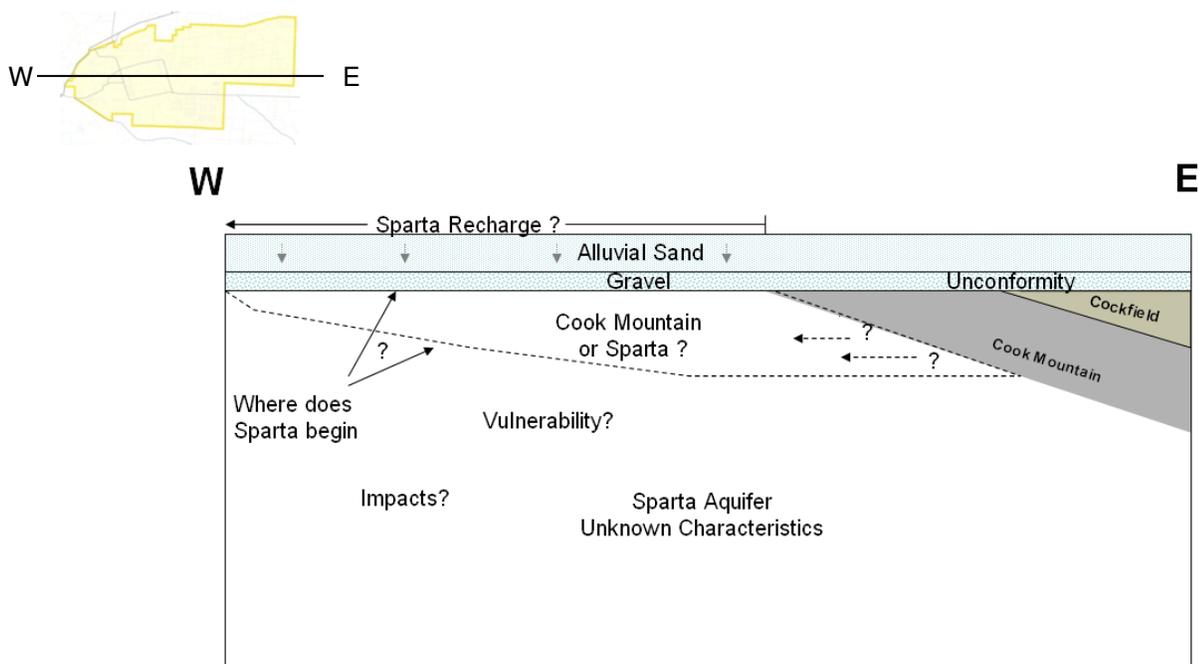


Figure 3: Generalized Geologic Diagram

Diagram depicts geologic uncertainties prior to study. They include (i) the western extent of Cook Mountain Formation, (ii) geologic characteristics of Sparta aquifer, and (iii) elevation of Sparta aquifer surface. Unconformity refers to missing strata (not deposited) between Claiborne Formations and younger Quaternary sediments.

Also in 2005, EPA and ADEQ performed routine sampling of drinking water at Locust Bayou to evaluate the human health environmental indicator referred to as CA-725. This evaluation, required by the Government Performance and Results Act (GPRA) of 1993, is a procedure for determining whether potential human health exposures to

contamination at RCRA facilities could be reasonably expected to be under control. For the Locust Bayou area sampling, a total of 6 water samples were collected, and 5 of those were found to contain low concentrations (0.5- 2.2 µg/l) of a contaminant known as perchlorate. Perchlorate (ClO_4^-) is used in explosives and rocket propellants including mortars, grenades, flares, and solid rocket fuel. Perchlorate is also known to occur naturally in limited numbers of geologic deposits used as feedstock for certain fertilizer products. Perchlorate is readily soluble in water and may cause human health impacts involving the thyroid gland. One of the goals of the current investigation is to determine the source of perchlorate in water at Locust Bayou.

Another unknown involved the possibility of contamination of water in streams and lakes. If streams contain contamination, contamination could rapidly spread across and outward from Shumaker and downward through permeable sediments into the Sparta aquifer. A surface water sampling program was needed to collect samples from all major streams, lakes, and ponds at Shumaker. A particularly important element of stream water sampling is that it makes a good reconnaissance tool for covering large areas because individual sampling points can represent large-scale drainage basin runoff.

B. Goals

Investigation goals were centered on completing four interrelated project tasks which were supported by two phases of fieldwork and sampling conducted during 2007-2008. During this period, EPA conducted hydrogeologic field investigations and made observations about Sparta aquifer vulnerability. Investigations for the vulnerability assessment are mainly discussed under Goals 1-3. These involved collecting geological information, installing wells, determining flow directions, and collecting and analyzing samples of groundwater and surface water. During this period, EPA also performed a focused investigation at Locust Bayou and vicinity to evaluate possible sources of perchlorate contamination. The most likely sources of perchlorate at Locust Bayou are described under results for Goal 4.

Project Goals:

- Goal 1: Evaluate the vulnerability of the Sparta aquifer with respect to: (i) the presence of confining clay overlying the Sparta aquifer, and (ii) by making observations about the occurrence of clay and sand within the Sparta aquifer.
- Goal 2: Examine the vulnerability of the Sparta aquifer by: (i) installing permanent groundwater monitoring wells, (ii) by monitoring for impacts to the aquifer, and (iii) by examining groundwater flow directions.
- Goal 3: Examine aquifer vulnerability by conducting surface water sampling including streams, lakes, and ponds over the extent of Shumaker, and the Locust Bayou area.
- Goal 4: Determine the source of perchlorate detected in groundwater monitoring wells and drinking water at Locust Bayou.

Completing these 4 goals benefits regulatory agencies and industries by providing subsurface information leading to more consistent data interpretations from individual facility investigations, and from other investigations at individual areas of concern located at isolated sites across Shumaker. This study benefits the public by providing current information on groundwater contamination and provides a groundwater monitoring system to provide a level of protection for drinking water supplies.

C. Project Planning

Project planning took place during 2005-2006 and included a project proposal and project scoping meetings. Field sampling and laboratory analysis were addressed in two Quality Assurance (QA) Project Plans developed under the Uniform Federal Policy for Quality Assurance Project Plans (UFP), (EPA 2007a and 2007b). A QA Project Plan is a formal document describing in comprehensive detail the necessary quality assurance, quality control, and other technical activities that must be implemented to ensure that the results of the work performed will satisfy the stated performance criteria. Nationally, the

UFP was developed as a joint initiative between the EPA, the Department of Defense (DOD), and the Department of Energy (DOE), to consistently implement quality system requirements. The QA Project Plans for this study present the overall project description, project organization, staff responsibilities, and QA objectives associated with each phase of sampling. The two plans comply with all QA requirements and underwent peer-review.

Plans for addressing study Goals 1 and 2 are included in the QA Project Plan dated January 31, 2007 (EPA 2007a). During this first phase of study, the QA Project Plan specifies that 10 Sparta aquifer monitoring wells and 10 alluvial aquifer monitoring wells will be installed and sampled, and that geological information (core samples and logs) will be obtained during the drilling. Plans for study Goals 3 and 4 are contained in the QA Project Plan dated December 18, 2007 (EPA 2007b). This plan states that EPA will collect additional groundwater samples from all 20 EPA groundwater monitoring wells, collect water level data, conduct reconnaissance level surface water sampling, and conduct specialized sampling for perchlorate isotopes.

3. GOAL 1: GEOLOGIC INVESTIGATION

(Evaluate the vulnerability of the Sparta aquifer with respect to: (i) the presence of confining clay overlying the Sparta aquifer, and (ii) by making observations about the occurrence of clay and sand within the Sparta aquifer.)

A. *Geologic Setting*

The purpose of Section A is to briefly introduce the geologic history, depositional environments, and stratigraphy needed to understand the basis for the geologic investigation and related complexities under Goal 1. Information in this section was compiled from published sources.

Shumaker NAD lies within the Gulf Coastal Plain physiographic province. This province is characterized by low relief and heavily timbered lands and hills characteristic of many parts of the southern United States. The Gulf Coastal Plain physiographic province extends from the Florida Panhandle to southern Texas, and geologically includes sedimentary rock and loose sediments deposited through cyclic marine and nonmarine depositional events. These events took place during a geologic time known as the Tertiary Period. The Tertiary Period occurred from 2 to 65 million years ago, and is subdivided into individual time units (series) based on geological events that occurred during the earth's history at those times. The deposition of sediments most relevant to this study occurred within the Eocene and Holocene series resulting in the Sparta Formation and the Cook Mountain Formation (both Eocene Series), and the overlying Holocene Series alluvial deposits (Table 1).

Eocene sediments are divided into separate geologic units called the Wilcox, Claiborne, and Jackson Groups. The Wilcox is the oldest group and contains sediments from continental depositional environments including fluvial, lacustrine, lagoonal, and deltaic environments which produced complexly interbedded sands, slits, clays, and lignite (Hosman, 1988). Claiborne sediments were deposited during alternating marine and nonmarine depositional cycles which produced distinctive lithologies; thereby allowing Claiborne sediments to be differentiated into individual Formations. Sediments

in the Claiborne Group, whether deposited under subaerial or submarine conditions or both, are composed of near shore deposits (Albin, 1964). These formations are called the Carrizo, Cane River, Sparta, Cook Mountain, and Cockfield Formations. The Eocene Period ended with deposition of the Jackson Group which is composed of marine sediments.

Era	System	Series	Group	Formation Or Subdivision	Approximate Number Years Ago	
Cenozoic	Quaternary	Holocene		Alluvium	11,000	
		Pleistocene		Terrace Deposits	500,000 to 2,000,000	
	Tertiary	Eocene	Jackson			58,000,000
			Claiborne		Cockfield Formation	
					Cook Mountain Formation	
					Sparta Sand	
					Cane River Formation	
				Carrizo Sand		
		Wilcox				
		Paleocene	Midway		Porters Creek Clay Clayton Formation	65,000,000
Mesozoic	Cretaceous	Gulf		Arkadelphia Marl	135,000,000	

Table 1: Generalized Geologic Column

Column shows sediments relevant to this investigation in yellow. They are the Eocene Sparta, Cook Mountain, and Cockfield Formations, and Pleistocene-Holocene terrace and alluvial deposits. Table modified from Albin, 1964.

The geology and hydrogeology of the three county areas surrounding Shumaker, including the counties of Bradley, Calhoun, and Ouachita, were described by Albin (1964). He reported that rocks of these counties were deposited in the shallow Mississippi embayment part of the Coastal Plain physiographic province as the sea alternately advanced and retreated over the land. During early and mid-Eocene time, including the time when the Sparta Formation was deposited, the main depositional environment was deltaic deposition of sand, silt, clay, and lignite. During late Eocene, which may have included deposition of the Cook Mountain Formation, moderately deep-water clay and marl were deposited. These sediments are reported to dip to the east and southeast at approximately 25-50 feet per mile towards the axis of the Mississippi Embayment (Payne, 1968, and Albin, 1964).

Additional detailed information on depositional environments is necessary to help understand the differences between Sparta and Cook Mountain deposits. The following descriptions illustrate that the Sparta Formation was deposited in a near-shore marine/non marine environment, but a range of specific near-shore environments may exist as noted by the author's referenced below.

The Sparta Formation is described by Albin (1964) as having been deposited as the beach of an advancing sea. Shallow-water clay and back beach lignitic clay and lignite, indicate that the shoreline fluctuated in the Calhoun and Ouachita County area. Another perspective, however, is provided by Payne (1968), who reported on the percentage of sand within the Sparta Formation.

Payne reports that based on sand percentage (total thickness of sand divided by total formation thickness), the Sparta could be divided into two areas having different depositional environments. One area covers Louisiana, Mississippi, southern Arkansas, and eastern Texas, and the other area extends from Grimes to Webb Counties, Texas. For the area including southern Arkansas, the distribution of sand represents a system of braided stream channels and interlacing lakes, swamps, and marshes as would be developed on a large deltaic-fluvial plain; the delta represents an ancestral Mississippi River system that existed during Claiborne deposition. Payne reported that areas which contain at least 50% sand represent areas of channel "flow-ways" similar to channel development along areas of present courses of the Ouachita and Mississippi Rivers, and areas containing less than 50% sand represent interchannel swamp, marsh, and lake areas where finer detritus and vegetation accumulated. For the Shumaker area, Payne's regional mapping indicates that approximately the eastern half of Shumaker contains from 30 to 50% sand, with a maximum sand unit thickness of 150 feet. Regional data are not presented for the western half of Shumaker, which is indicated as being a Sparta outcrop area.

Literature contains only limited descriptions of the Cook Mountain Formation but it is briefly described in several articles on regional and local geology and hydrogeology, including Albin (1964), Fitzpatrick, et. al. (1990), and Joseph (2000). According to

Fitzpatrick, the Cook Mountain Formation ranges between 100 and 150 feet thick and is composed chiefly of carbonaceous clay, with some lignite and lenticular beds of sand less than a few feet thick. He reports that the formation is a significant confining bed covering the Sparta aquifer in east-central Arkansas. Similarly, Joseph (2000) reports that the Cook Mountain Formation occurs as a massive clay serving as an upper confining unit to the Sparta aquifer. The article by Albin (1964) reports that the Cook Mountain Formation occurs as a moderately deep water marine clay in most of the Mississippi embayment. However, an exception occurs in Bradley, Calhoun, and Ouachita Counties where the formation consists of near-shore shallow-water dark-grey to dark-brown silty clay. Albin states that the thickness of the Cook Mountain Formation is approximately 150 feet, and includes silt, sand, and lignite clay deposited in a back-beach environment.

Lying above the Cook Mountain Formation is the Cockfield Formation. The Cockfield Formation consists of sands, slits, and clays deposited primarily under subaerial conditions Albin (1964). The Cockfield Formation is less significant than the Cook Mountain Formation in limiting vulnerability of the Sparta aquifer, because the Cockfield occurs only over approximately the eastern 1/5 of Shumaker and does not underlie industrialized areas to the west.

The youngest sediments at Shumaker are Quaternary (Pleistocene) terrace deposits and Holocene alluvium. Quaternary deposits unconformably overly the Claiborne Group, and the Jackson Group is absent at Shumaker. Terrace deposits occur as a relatively thin (approximately 45 feet) blanket of sediments covering both the Cook Mountain and Sparta Formations. These deposits consist mainly of gravel, sand, silt, and clay which coarsen downward. Where the Cook Mountain Formation is absent, Quaternary sediments (terrace deposits) rest directly on the Sparta Formation. Gravel at the bottom of the Quaternary sediments forms an aquifer capable of producing significant quantities of groundwater. The gravel layer averages about 10-20 feet thick and is the most transmissive shallow aquifer in the Shumaker area. Holocene alluvium occurs as deposits along stream channels.

B. Subsurface Investigation

The geologic investigation filled important data gaps with new information previously unavailable from either regional geologic studies or local industrial facility reports. The geologic investigation included collecting subsurface information about the stratigraphy and sediments comprising the Sparta Formation, Cook Mountain Formation, and Quaternary deposits. The investigation determined whether the Sparta Formation is overlain by Quaternary sediments or the Cook Mountain Formation, or both, and also provided information on sand and clay sequences occurring within the Sparta aquifer itself.

From February through April 2007, EPA drilled 7 exploratory stratigraphic test holes at selected locations across Shumaker (fig. 4). Test hole locations were chosen to address the geologic unknowns previously described, and they were chosen as locations for Sparta aquifer monitoring wells. Monitoring wells served multiple purposes including monitoring the Sparta near the Shumaker Public Service Company wells, monitoring the Sparta near known contaminated areas and industrial areas, monitoring groundwater at Locust Bayou, and providing data on groundwater flow directions.

Drilling depths ranged from 200-300 feet per location and approximately 1800 feet of sediment core were collected and examined from the 7 locations. Coring began at the contact of the terrace deposits and the Sparta aquifer, and continued to approximately 300 feet per location. The percentage of core recovery, lithology, and related geological characteristics was recorded in field notes. The depth of 300 feet was determined to be adequate based on published information on regional geologic structure. Field information is available in TechLaw, Inc. (2007, 2008).

C. Extent of the Cook Mountain Formation

The most important geological factor affecting the vulnerability of the Sparta aquifer to contamination is the presence or absence of the Cook Mountain Formation. Where the Cook Mountain Formation is present in relative thickness, it provides a

significant layer of clay over the Sparta aquifer, restricting downward groundwater movement, and thus decreases Sparta aquifer vulnerability. The formation was identified as discussed below.

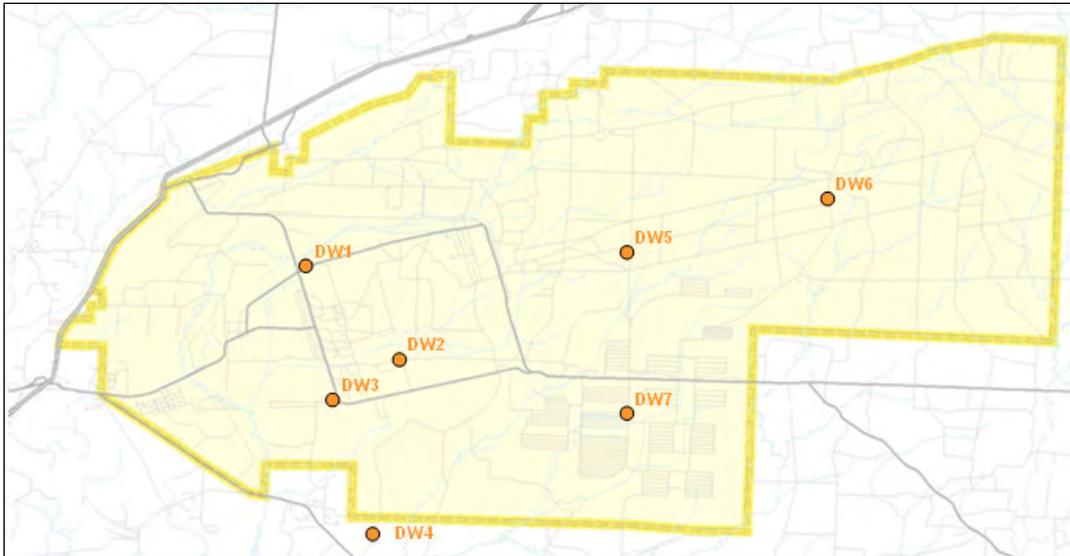


Figure 4: Exploratory Test Holes DW1 - DW7

Because the depositional environments were similar during the time the Sparta and Cook Mountain Formations were deposited, their respective lithologies are also similar and make them difficult to differentiate based strictly on sediments. However, the amounts of sand each formation contains, and their stratigraphic sequences of sand and clay, were found to be different based on core samples. Cores from each stratigraphic test hole were examined for stratigraphy, lithology, texture, uniformity, bedding, laminations, fractures, sedimentary particles, core recovery, and other related information. The most distinguishing characteristic of the Cook Mountain Formation was found to be its overall stratigraphic composition which is thick massive clay interspersed with thin beds of sand, thin layers of siltstone, sand and clay laminations, and minor amounts of coal. Sparta stratigraphy is significantly different, and exhibits much thicker deposits of sand and thinner layers of clay. Comparing cores to depositional environments also assisted in differentiating formations. Albin (1964) reported the Cook Mountain Formation consists of silt, sand, and lignite clay, deposited in a near-shore back-beach environment. The sediments described above are consistent

with this type of system. The Sparta, by comparison, was deposited in more of a beach front environment and thus contains thicker sand units along with thinner clays associated with other lower energy fluvial-deltaic processes.

Drilling indicates the eastern part of Shumaker, near the eastern end of the former rocket test range, was found to contain 108 feet of dense clay. At location DW6, coring began at approximately 36.6 feet below ground surface (bgs), continued through the Cook Mountain Formation to the Sparta aquifer contact at approximately 144 feet bgs, and advanced deeper into the Sparta aquifer to a depth of 203 feet bgs. The transition between formations is shown in core sample photographs A-D (fig. 5). No sediments representing the Cockfield Formation were identified. Published maps by Albin (1964) indicate the Cockfield probably overlies the Cook Mountain Formation further to the east than DW6. If so, the Cockfield would provide an additional layer of protection over the Sparta, although no industries exist east of DW6.



A. Core sample from DW6. Core transitions from Quaternary sediment (brown iron stained sediment at 36.6') to Cook Mountain Formation.

B. Core sample from Cook Mountain Formation. Clay appears generally uniform in bulk composition and density. Sand and coal laminations were encountered in some samples.

C. Core showing transitions from Cook Mountain to Sparta aquifer. Formation contact is approximately 144'. At 144', sand content begins to increase forming broken core wedges consisting of sand and clay.

D. Core from Sparta aquifer. Material consists of wedges and laminations of sand and clay.

Figure 5: Core Sample Photographs A-D

The Cook Mountain Formation provides a significant protective layer over the Sparta aquifer where it exists. Cores indicate the Cook Mountain Formation probably pinches out in a westerly direction between DW5 and DW6, and is absent over approximately 40,000 of the 73,000 acre study area. Where the Cook Mountain Formation is absent, the Sparta aquifer occurs beneath approximately 30-40 feet of Quaternary terrace deposits and alluvium including the shallow gravel aquifer.

D. Sedimentary Particle Analysis

The drilling program provided an opportunity to closely examine material making up the Cook Mountain and Sparta Formations by microscopically comparing sediments and mineral compositions from each formation. The intention of this comparison was to see whether sediment and mineral characteristics could be used to help differentiate between Cook Mountain and Sparta sediments.

The analysis involved performing evaluations of discrete sediment samples taken from cores in 5 foot intervals. Samples were examined for mineral types and composition, grain size and shape including the degree of roundness and sphericity, and vertical and interwell consistency and variability. The analysis shows that sand within the Sparta is about 95% quartz [SiO₂]. Most quartz grains are rounded, but overall shapes range from being well rounded to subangular. Quartz grains become rounded when they contact and abrade against each other during transport. The degree of roundness and sphericity indicates the amount of energy in the transport process and the nature and type of the depositional environment. Besides quartz, sand grains also include small percentages of biotite, muscovite, reworked coal, opaque minerals, and possibly trace amounts of glauconite (fig. 6). This finding is consistent with Payne (1968) who reported that Sparta sand is composed almost entirely of rounded to subrounded, fine to medium quartz grains and is generally well sorted. The analysis indicated that there is not any significant difference in mineral composition between the Sparta and Cook Mountain Formations, and that sediments alone cannot be used to differentiate these Formations. This is probably due to the fact that the alternating marine and non-marine depositional environments were similar for each Formation as previously noted.

Therefore, the most reliable way to identify these Formations is by making careful observations on sequences, cycles, and thicknesses of sand and clay.

Based on findings about the area's geological framework alone, impacts to the Sparta aquifer would be most likely to occur in areas where overlying regional confining clay is absent, where the aquifer is close to the surface, and where existing contamination is present in the overlying alluvial aquifer. This is mainly the case for saturated sands near the top of the Sparta aquifer. As depth increases, however, geologic, hydrologic and chemical data indicate that vulnerability decreases as will be pointed out in subsequent sections.

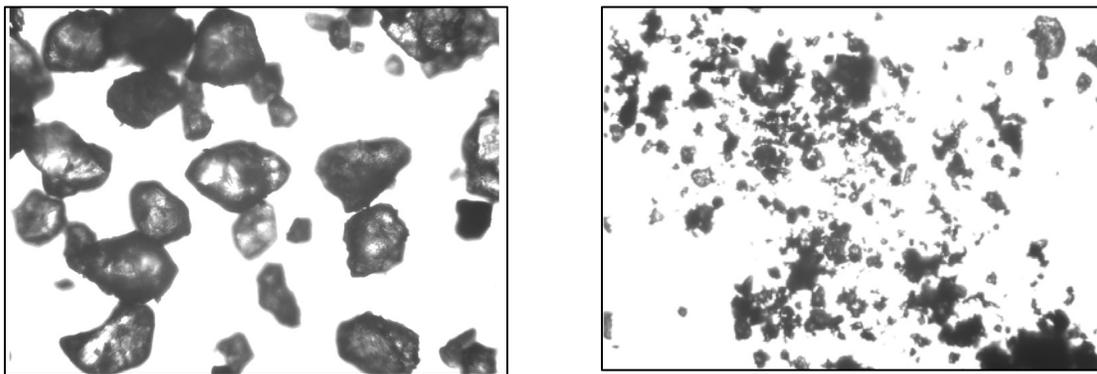


Figure 6: Photomicrographs of Sand and Clay within the Sparta Aquifer

Samples from well DW2 at depths of 282 feet bgs (left) and 157 feet bgs (right). View on left shows well rounded to rounded quartz grains indicative of high-energy depositional environment typical of near shore marine sediments. View on right, taken under same magnification, shows clay fraction of Sparta with cohesive clay-sized particles.

E. Deeper Sparta Sands

Geologic vulnerability was also assessed by examining the occurrence and sequences of clay, fine sand, and rock (sandstone) deeper within the Sparta aquifer. Sparta core samples indicate that Sparta stratigraphy is complex and consists mainly of discontinuous layers of saturated fine sand and clay in thicknesses ranging from tens of feet to only a fraction of an inch. Vertically, there is frequent alternation between sand and clay strata, and individual sand and clay units do not appear continuous between test

holes. The occurrence of discontinuous sand and clay strata in various thicknesses is consistent with the types of deposits occurring in a fluvial-deltaic depositional system. Sand and clay also occur as laminations, seams, and lenses, with deposits of organic matter, lignitic clay and sand, and lignite seams typically less than 1 foot thick.

Almost all of the Sparta sediments, like most sediments on the Gulf Coastal Plain, were found to consist of loose sediments. A few thin layers of rock (sandstone) were found, but only in thicknesses of several inches and which probably have no more effect on groundwater flow than layers of clay. When sediments are changed to rock, it occurs through a process known as lithification, involving the compaction and cementation of sediments. Compaction reduces pore space within a body of sediments, and cementation is a chemical process by which particles are held together by cements such as calcium carbonate. The ability of the Sparta to produce large quantities of water and function as a regional aquifer, is a reflection of an overall lack of compaction and cementation associated with the Sparta deposition.

Each core interval percent recovery was estimated for every 10 feet of core. Percent recovery is the amount of core actually obtained divided by the total possible core length (10 foot core barrel length). Percent recovery ranged from 100% in sediments consisting of mostly clay, to 0% in sediments which was practically all sand. A recovery of 0% was frequently encountered in deeper sections of the Sparta, because thicknesses of saturated, loose, fine sand would wash out of the core barrel as the barrel was withdrawn from the ground. Where sand was not recoverable by core, its presence was verified by geophysical logging which increased confidence in the ability of core recovery to indicate the relative amounts of sand and clay.

F. Summary of Findings

In summary, the geological risk to deeper sands of the Sparta aquifer is mainly associated with stratigraphy, including the presence/absence of clay within the formation, continuity of clay strata, thickness of clay, and the interconnection of saturated fine sands. Interconnected fine sands occur relatively close to the surface at industrial sites as the Sparta aquifer becomes closer to the surface in a westerly direction. Based on

analyses of core sample material and percent recovery, the likelihood of downward contaminant migration into deeper saturated fine sands of the Sparta aquifer (i.e., beyond the first 100' of the aquifer), is greatest at EPA well location DW1, followed by DW2, DW4, DW3, and DW7. At each of these locations, saturated fine sands alternate with clay layers, and the percentages of fine sand layers in the first 100' are approximately 55% (DW1), 49% (DW2), 51% (DW4), 51% (DW3), 35% (DW5), and 28% (DW7). The position of sand layers in DW2, being at the top of the section, seem to increase the likelihood of downward migration at DW2. Estimations were not made for DW6 where the Sparta is overlain by Cook Mountain.

4. GOAL 2: SPARTA AQUIFER MONITORING

(Examine the vulnerability of the Sparta aquifer by: (i) installing permanent groundwater monitoring wells, (ii) by monitoring for impacts to the aquifer, and (iii) by examining groundwater flow directions.)

A. Procedures Summary

The second major component of the vulnerability assessment was performing groundwater monitoring. EPA installed a total of 10 wells in the Sparta aquifer. These wells were constructed from the 7 exploratory test holes used for Goal 1, plus 3 additional monitoring wells with deeper screens to help understand vertical flow (fig 7). Well construction information and field sampling procedures are described in detail in field activity reports by Tech Law Inc. (2007 and 2008). Quality assurance criteria are contained in the two QA Project Plans previously mentioned in Section II. C (EPA 2007a and 2007b).

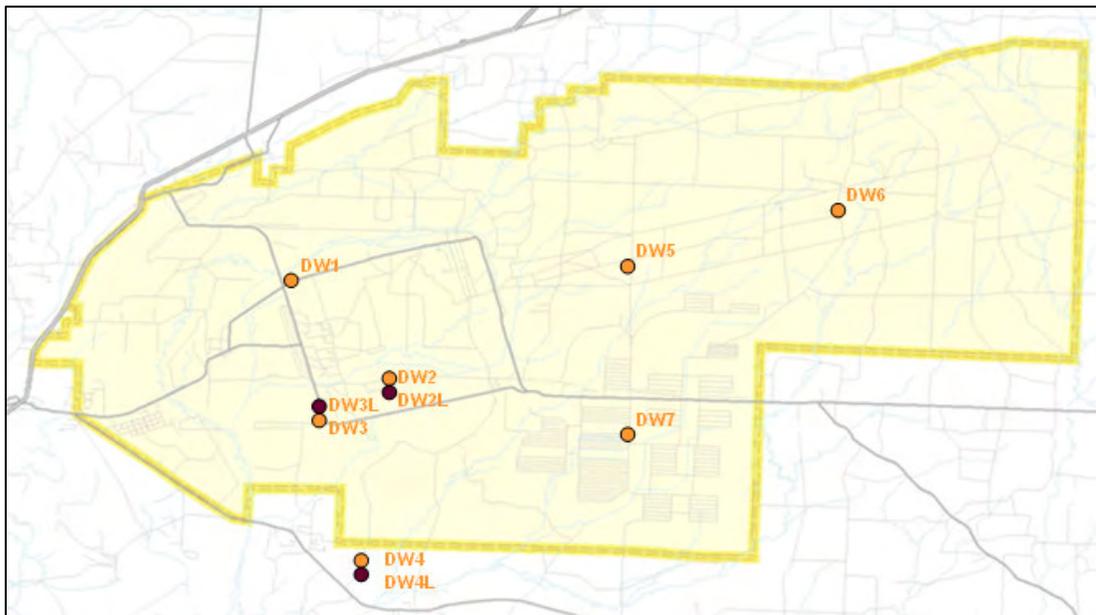


Figure 7: Location Of The 10 Sparta Aquifer Monitoring Wells

Wells DW2L, DW3L, and DW4L are screened lower in the Sparta than adjacent wells.

Aquifer vulnerability was assessed by performing monitoring and determining flow directions and gradients. Monitoring was conducted for volatile organic compounds (VOCs), semi-volatile organic compounds (SVOCs), explosives, perchlorate, and RCRA

metals. Analytes are listed in EPA 2007a and 2007b. There were two groundwater sampling events: (1) March-April 2007, and (2) January 2008. Analytical results were compared to EPA Regional Screening Levels (RSLs). EPA uses screening levels when a site is initially investigated to determine if potentially significant levels of contamination are present to warrant further investigation. Screening levels represent relatively protective environmental concentrations. The significance of detections to vulnerability is discussed under Key Observations and Uncertainties (Section 7).

B. Analytical Results Summary

In 2007, arsenic, lead, and bis(2-ethylhexyl)phthalate exceeded RSLs for tap water. Table 2 contains a summary of detections versus RSLs. Samples from wells DW-1, DW-2, DW-2L, DW-2LD, DW-3L, DW-4 and DW-4L exceed RSLs for arsenic with a maximum concentration of 18.30 ug/l. Samples denoted with a “D” are QA duplicate samples. Samples from DW-2, DW-2L, DW-2LD, DW-4, DW-4L exceeded RSLs for lead with a maximum concentration of 65.9 ug/l. Samples collected from DW-1, DW-2LD, DW-3, DW-4L, and DW-6 exceeded RSLs for bis(2-ethylhexyl)phthalate with a maximum concentration of 9.20 ug/l. Perchlorate was not detected in any of the Sparta aquifer samples. The complete results are in Tech Law (2007 and 2008).

Contaminant	Frequency of Detection	Screening Concentration (RSL)	Well ID	Concentration (ug/l)
Arsenic	7/9	0.045	DW1	10.50J
			DW2	9.80J
			DW2L	18.30J
			DW2LD	16.50J
			DW3L	4.00J
			DW4	11.40J
			DW4L	5.50J
Lead	11/12	15.0	DW2	43.40
			DW2L	65.9
			DW2LD	56.7
			DW4	20.50
			DW4L	18.80
bis(2-ethylhexyl)phthalate	8/12	4.80	DW1	9.20J
			DW2LD	8.60J
			DW3	8.30J
			DW4L	5.20J
			DW6	7.20J

Table 2: Screening Levels vs. Sample Concentrations 2007
Laboratory qualifier “J” stands for estimated results. RSL for lead is the treatment technology action level.

In 2008, samples were collected and analyzed for the identical analytical suite as in 2007 (Table 3). Arsenic and lead exceeded their constituent-specific RSLs. The sample collected from deep well DW3L showed an arsenic concentration of 17 µg/l. The samples collected from deep well DW2L exceeding the RSL for lead with a maximum concentration of 20 µg/l.

Contaminant	Frequency of Detection	Screening Concentration (RSL)	Well	Concentration (µg/l)
Arsenic	1/12	0.045	DW3	17.0
Lead	2/12	15.0	DW2L	18.0
			DW2L	20.0

Table 3: Screening Levels vs. Sample Concentrations 2008

C. Sparta Aquifer Flow Directions

Measurement data was collected for both horizontal and vertical groundwater flow directions. Water levels were measured on two separate occasions, on May 9, 2007, and then approximately 1-year later on May 19, 2008. To reduce any temporal effects on measurements, all water levels were measured within a 24-hour period on each of the two occasions. Wells DW1, DW2L, DW3L, DW4L, DW5, DW6, and DW7 were used to determine horizontal flow directions. Vertical gradients were determined by using well clusters. These clusters are: (1) DW2, DW2L, and SW9; (2) DW3, DW3L, and SW8; and (3) DW4, DW4L, and SW5. Wells SW9, SW8, and SW5 are shallow alluvial wells installed as part of alluvial aquifer monitoring discussed under Goal 4. Water level measurements for 2007 and 2008 are listed below in Table 4.

Well	May 9, 2007	May 19, 2008
DW1	110.42'	111.23'
DW2	138.68'	138.60'
DW2L	114.67'	115.12'
DW3	132.88'	132.16'
DW3L	110.13'	110.48'
DW4	119.23'	119.49'
DW4L	97.56'	98.02'
DW5	190.53'	190.19'
DW6	210.51'	210.71'
DW7	179.70'	179.94'

Table 4: Water Level Measurements (mean sea level)

For both years, the highest water levels measured were in the eastern part of the study area at well DW6. From that location, water levels were found to decrease in all wells towards the west and southwest. The lowest water level measured was in well DW4L located approximately 12 miles from DW6. Horizontal Sparta flow directions are provided in figure 8. Based on the gradients in figure 8, the total change in Sparta hydraulic head across Shumaker is approximately 145' (over 15 miles), as measured from an approximate 230' contour line on the east, to an approximate 85' line on the west. This results in an average approximate groundwater gradient of 9.6' per mile, or 0.18%.

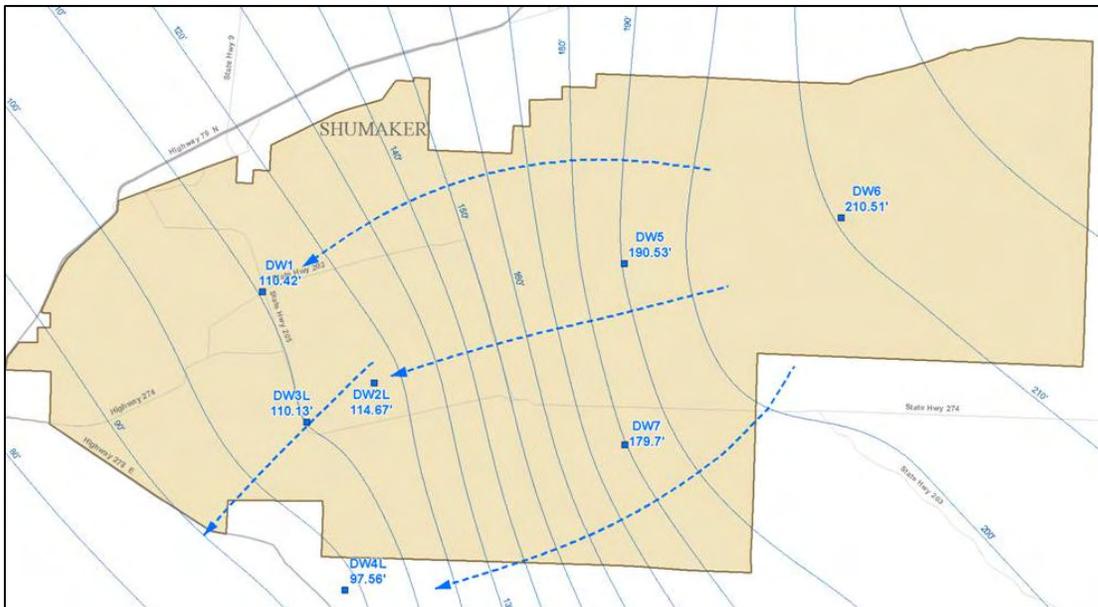


Figure 8: Groundwater Flow Direction In Sparta Aquifer 2008

Wells DW2L, DW3L, and DW4L were used for developing figure 8, rather than wells DW2, DW3, and DW4. Wells DW2L, DW3L, and DW4L have well screen depths more consistent with the remaining Sparta wells (i.e., wells DW1, DW5, DW6, and DW7). A comparison of well screen depths and water levels by aquifer is provided in Table 5.

Figure 8 only presents flow directions for 2008, because 2007 water levels and flow directions are practically the same. Contoured data are most accurate where contours are nearest well locations/control points that constrain contour lines. As one moves away from well locations and reduced data control, more careful interpretation of flow direction is needed because contour lines are not constrained by actual measurement data. This is particularly important near the outside edge of the Shumaker NAD

boundary and even further around the perimeter of flow direction maps. Flow gradients appear more uniform and consistent in the central part of Shumaker than the outer part, and this is probably a function of the spacing of wells.

EPA data from well clusters indicate a substantial downward groundwater flow gradient. The downward gradient exists from the alluvial aquifer to the upper sands of the Sparta aquifer, and then again from the upper Sparta sands to where the lower Sparta wells are screened. Water level elevations decrease in each successive deeper aquifer from a high of 143.38 ft msl to a low of 98.02 ft msl (Table 5).

Well Cluster	Water Level (ft msl)	Screen Interval (ft msl)	Aquifer	Gradient Magnitude (unitless)
SW8	135.97	122.78-112.78	Alluvial	0.16 (SW8 to DW3) 0.26 (DW3 to DW3L)
DW3	132.16	99.56-89.56	Sparta	
DW3L	110.48	21.36-1.36	Sparta	
SW5	123.22	111.50-101.50	Alluvial	0.10 (SW5 to DW4) 0.30 (DW4 to DW4L)
DW4	119.49	75.86-65.86	Sparta	
DW4L	98.02	10.89- (-9.11)	Sparta	
SW9	143.38	134.52-124.52	Alluvial	0.16 (SW9 to DW2) 0.28 (DW2 to DW2L)
DW2	138.60	104.82-94.82	Sparta	
DW2L	115.12	25.96-5.96	Sparta	

Table 5: Water Level Data For Well Clusters, 2008
Magnitude is change in water level divided by change in well screen midpoint (dh/dl). More data on alluvial water levels is contained in Table 8.

The alluvial water levels appear distinct from upper Sparta water levels, which are about 4 feet lower than the alluvial levels. As depth increases, separation in water levels also increases and the difference between the upper Sparta and lower Sparta levels averages about 22 feet. Water levels in the upper Sparta more closely resemble alluvial water levels than lower Sparta water levels, suggesting increased vulnerability in the upper Sparta aquifer. **Separation between upper and lower Sparta levels does not mean the lower Sparta cannot become contaminated, but it is less likely.** If

contamination were to find a pathway downward, it would probably move quickly to impact deeper sections of the Sparta.

5. GOAL 3: SURFACE WATER INVESTIGATION

(Examine aquifer vulnerability by conducting surface water sampling including streams, lakes, and ponds over the extent of Shumaker, and the Locust Bayou area.)

A. Streams and Lakes

Considering the possibility of interaction between surface water and groundwater in the Shumaker vicinity, EPA conducted surface water sampling and analysis to determine whether surface water contains contamination that may impact the Sparta aquifer. The natural down-cutting action of streams of the Shumaker drainage network has caused a dissection of terrace deposits overlying the Sparta aquifer. The presence of terrace deposits incised by streams, and the occurrence of relatively high and fluctuating water table levels, increases the possibility of surface water and groundwater interaction. Topographic data from U.S. Geological Survey quadrangle maps indicates stream level elevations are close to water table elevations.

There are approximately 172 miles of stream courses at Shumaker. Most streams are probably intermittent and flow only after significant rainfall events. Other streams obtain water from groundwater seepage (i.e., baseflow), and land surface runoff. The area's larger streams are Two Bayou, Locust Bayou, and Caney Creek, which are all probably perennial streams. These and other relatively large streams connect with numerous smaller creeks and tributaries forming a dendritic drainage pattern. This pattern suggests that stream courses are controlled by slope, as opposed to other factors such as geologic structure, and that sediments have a relatively uniform resistance to erosion. Stream channel dimensions are highly variable and range from small tributaries which are approximately 10-15 feet wide and several feet deep, to large streams which are up to 30-40 feet wide and possibly 5 or more feet deep at high water stage.

The direction of stream flow is generally northeast to southwest (fig. 9). A few streams have different flow directions including Taylor Creek, located at the eastern end of Shumaker which flows to the south, and an unnamed stream just north of Taylor Creek

which flows to the southeast. Other exceptions to southwest flow occur at Two Bayou and in channelized drainage (flowing to the south) near the western end of Shumaker.

Surface water also occurs in 4 relatively large (5-10 acre) lakes/ponds, and also within a small number of man-made channels constructed near former and present operating industrial areas. The most significant lakes/ponds are Covington Pond, North Pond, Middle Pond, and South Pond. Water from streams and lakes/ponds were sampled as described below.

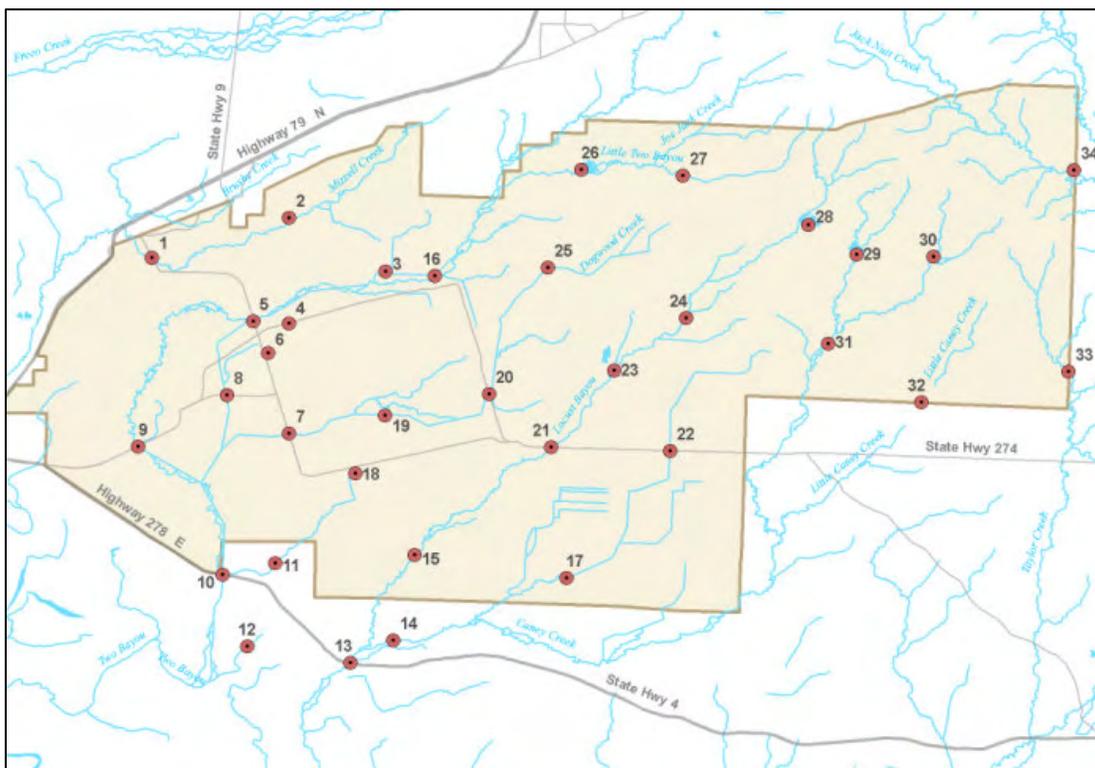


Figure 9: Surface Water Sampling Locations

All locations were streams except for locations 26, 28, 29, and 30 which were lakes.

B. Sampling Results

During February 2008, EPA conducted reconnaissance surface water sampling and analysis for perchlorate, explosives, and metals. QA plans and procedures were established in the QA Project Plan dated December 18, 2007 (EPA 2007b). Detailed analytical information is presented in the field activity report by Tech Law 2008.

EPA collected surface water from a total of 34 locations, as shown in figure 9. Locations were determined by selecting sampling points which captured surface water runoff representing as much of the Shumaker land area as possible. As part of the planning process, a field reconnaissance trip was made prior to sampling to plan and inspect each possible location. The purpose was to check for water availability, site accessibility, and locations of stream courses relative to industrial areas and potential land-based sources of contamination. Prior to collecting samples, global positioning system (GPS) coordinate data, pH, and water flow characteristics were collected and recorded at each sampling site.

RSLs were not exceeded in surface water samples. Detections still occurred for metals (arsenic, barium, cadmium, chromium, lead, and selenium), explosives (2-nitrotoluene and 3-nitrotoluene), and perchlorate, although these were below screening levels. The full list of detections and other field observations by location is available in Tech Law (2008). Although results for explosives are reported, difficulties with laboratory analyses for explosives indicate a level of uncertainty for those results. Perchlorate was detected at many surface water sampling locations at concentrations ranging from less than 1.0 $\mu\text{g/l}$ to 5.2 $\mu\text{g/l}$. The origins of perchlorate are discussed in the next Section under Goal 4, and uncertainties about explosives are discussed in the chapter on Key Observations and Uncertainties.

6. GOAL 4: PERCHLORATE AT LOCUST BAYOU

(Determine the source of perchlorate detected in groundwater monitoring wells and drinking water at Locust Bayou.)

A. Background

Locust Bayou and vicinity consists of a small community located several miles southeast of East Camden extending along State Highway 278 and various county roads (fig. 10). Perchlorate was initially detected in residential tap water samples in 2005, and since then has been detected in follow up sampling and in monitoring wells used for this study. To accomplish Goal 4, EPA performed monitoring of groundwater in the Pleistocene terrace deposit gravel, considered the presence and location of known existing perchlorate sources, evaluated groundwater velocity relative to perchlorate releases, tested for perchlorate in surface water, and conducted fingerprinting of perchlorate by using chlorine and oxygen isotopes.



Figure 10: Locust Bayou and Vicinity

EPA targeted the gravel aquifer because residential wells at Locust Bayou are probably screened in that aquifer. The gravel aquifer is capable of producing large quantities of groundwater and is relatively shallow, thus reducing drilling and pumping costs, making the aquifer an economical water source. The gravel is about 5-20 feet thick and is significant because it is the most transmissive water bearing zone above the Sparta. It can transport relatively large amounts of groundwater fairly rapidly, and provide a pathway for perchlorate to spread out and contact the top of the Sparta aquifer. The size of the area selected for monitoring the gravel aquifer encompasses approximately 16,000 acres (25 square miles) including the area between Locust Bayou and highway 274 to the north (fig 11). The area includes land both within and outside the Shumaker NAD footprint.

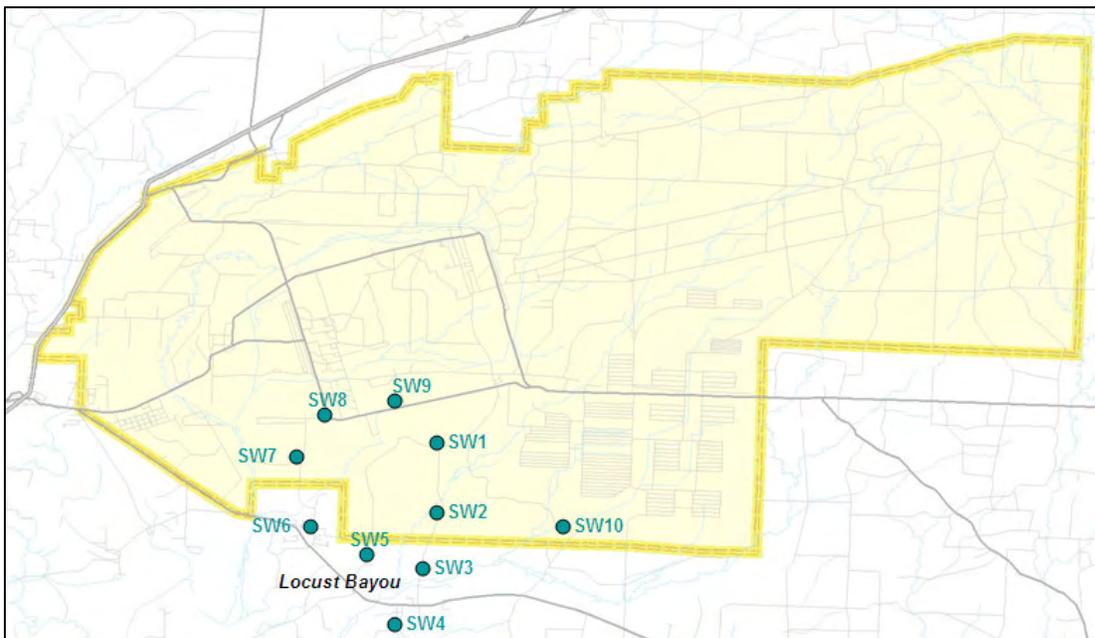


Figure 11: Location of Gravel Aquifer Monitoring Wells

Because fundamental groundwater information needed to be collected, EPA believed it was best to place gravel aquifer monitoring wells over a wide area to collect fundamental information on flow direction and perchlorate concentrations. EPA installed 10 monitoring wells (SW1 – SW10) which range from 26 to 55 feet deep. Individual well locations were determined by considering site characteristics including the locations of existing industrial areas, site accessibility, topography, possible

groundwater discharge areas, and monitoring well distribution. Although perchlorate was the main constituent of interest, sampling was also conducted for VOCs, SVOCs, explosives, and metals. The purpose for these constituents was to help determine whether perchlorate was occurring by itself, or was occurring as one of a number of contaminants in a chemically complex plume. Analytical results, except for perchlorate, were compared to RSLs. Perchlorate results are discussed separately in Section D below. Field procedures are described in detail in field activity reports by Tech Law (2007 and 2008). Quality assurance criteria are contained in the two QA Project Plans previously mentioned in Section II. C (EPA 2007a and 2007b).

B. Monitoring Results

In 2007, RSLs were exceeded for arsenic, lead, and bis(2-ethylhexyl)phthalate. Samples from wells SW-1, SW-1D, SW-5, SW-6, SW-7, SW-8 and SW-10 showed arsenic concentrations exceeding the RSL with a maximum concentration of 29.60 ug/l. Lead concentrations exceeded the RSL with a maximum concentration of 65.90 ug/l, and were found in samples from wells SW-5, SW-6, SW-7 and SW-10. Samples collected from wells SW-1, SW-2, SW-5, SW-7 and SW-10 exceeded the RSL for bis(2-ethylhexyl)phthalate with a maximum concentration of 72.00 ug/l. Table 6 provides a summary of exceedances from the 2007 shallow groundwater samples. The full set of analytical results may be found in Tech Law (2007 and 2008).

In 2008, samples were collected and analyzed for the identical analytical suite as in 2007 (Table 7). Arsenic and lead exceeded their constituent-specific RSLs. Samples collected from shallow wells SW2, SW7, and SW8 showed arsenic concentrations exceeding the RSL with a maximum concentration of 29 µg/l at well SW7. Samples collected from shallow wells SW2, SW4, SW7, SW8, and SW9 showed lead concentrations exceeding the RSL with a maximum concentration of 41 µg/l at shallow well SW7. Table 7 provides a summary of RSL exceedances for 2008 sampling results.

Contaminant	Frequency of Detection	Screening Concentration (RSL)	Well ID	Concentration (µg/l)
Arsenic	7/12	0.045	SW1	2.30J
			SW1D	3.20J
			SW5	7.0J
			SW6	29.60
			SW7	12.10J
			SW8	4.30J
Lead	11/12	15.0	SW5	18.60
			SW6	48.90E
			SW7	24.20E
			SW10	22.6
bis(2-ethylhexyl)phthalate	8/9	4.80	SW1	72.07
			SW2	5.71J
			SW5	6.70J
			SW7	4.90J
			SW10	6.60J

Table 6: Screening Levels vs. Sample Concentrations, 2007

Laboratory qualifier “J” stands for estimated result “E” means results did not meet serial dilution acceptance criteria.

Contaminant	Frequency of Detection	Screening Concentration	Lab ID/Well	Concentration (µg/l)
Arsenic	3/10	0.045	SW2	16
			SW7	29
			SW8	21
Lead	5/10	15.0	SW2	29
			SW4	21
			SW7	41
			SW8	37.7J
			SW9	22

Table 7: Screening Levels vs. Sample Concentrations, 2008.

Laboratory qualifier “J” stands for estimated result.

C. Flow Directions

Water level measurements were collected within a 24 hour period on May 9, 2007 and then on May 19, 2008. Water levels are similar for each year as indicated on Table 8. The highest water levels were measured east and north of Locust Bayou at wells SW 9 and SW10. From SW10, the approximate flow direction is to the west-southwest, and flow from SW9 is towards the south. The lowest water level measured was at SW4 located just south of highway 278.

Well	May 9, 2007	May 19, 2008
SW1	135.08'	133.84'
SW2	134.28'	133.53'
SW3	126.29'	125.28'
SW4	117.99'	117.17'
SW5	123.67'	123.22'
SW6	122.30'	121.84'
SW7	129.37'	128.82'
SW8	133.49'	135.97'
SW9	143.47'	143.38'
SW10	158.04'	158.40'

Table 8: Water Level Elevations for Alluvial Wells 2007 and 2008.

Groundwater flow directions are shown on Figure 12. Because water levels, contoured gradients, and flow directions are nearly the same for 2007 and 2008, only the 2008 mapped data are presented. Similar to data for the Sparta aquifer, care must be used when interpreting contoured data. Contours should only be considered reliable in areas where there are actual data points, as is the case for the area within and north of Locust Bayou between highways 278 and 274. Where contours extend beyond this area, additional care must be used in making interpretations about flow directions and gradients.

The approximate total change in head from SW8 to SW6 is 14.13 ft over 2.2 miles, which gives an approximate hydraulic gradient of 0.0012. A notable feature is a flattened gradient just south of SW1 and extending to near SW2. This anomalous feature is probably the result of SW1 being screened lower than the other alluvial wells. SW1 was screened lower because it was the first well installed during the alluvial aquifer drilling program, and consistency on screen elevations had not yet been developed. If SW1 had been screened higher, the gradient would probably be more uniform showing a more consistent south-southwest flow direction.

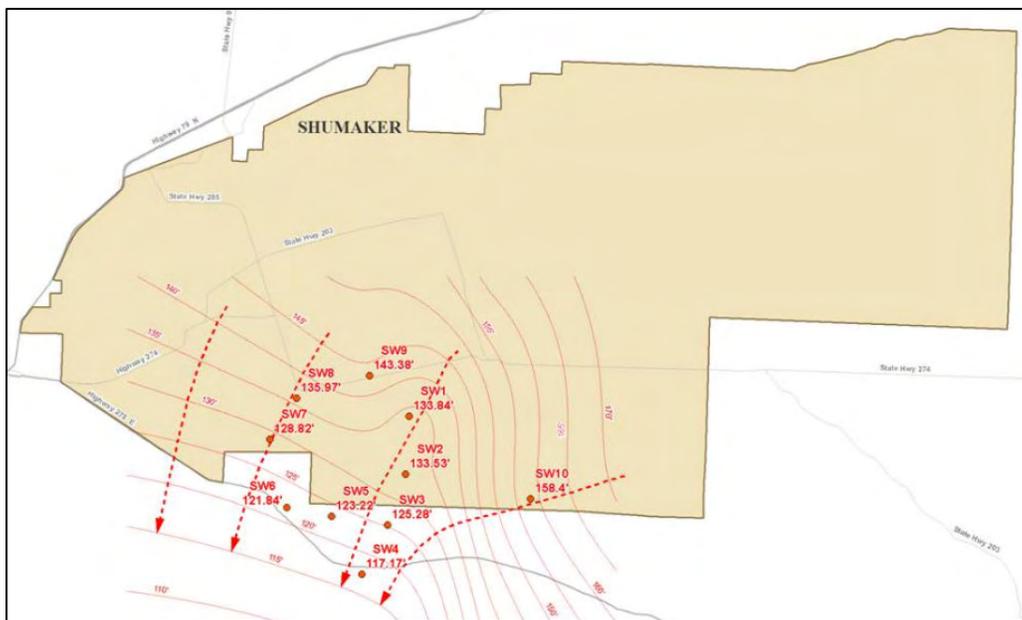


Figure 12: Groundwater Flow Directions in Alluvial Aquifer Near Locust Bayou

D. Perchlorate Fingerprinting

i. Introduction

The determination of the source of perchlorate required using a special analytical technique, fingerprinting, which can differentiate between types of natural and man-made perchlorate. Perchlorate fingerprinting relies on an analysis of chlorine and oxygen stable isotopes. Perchlorate occurs as a natural and man-made chemical consisting of one chlorine atom bonded to four oxygen atoms. An isotope is one of two or more atoms whose nuclei have the same number of protons, but different number of neutrons. A stable isotope is a non-radioactive isotope that does not decay. The rationale for using stable isotope analysis is that it would provide isotopic signatures which would significantly narrow down the field of possible sources.

Man-made perchlorate, also referred to as synthetic and anthropogenic, is commonly used as an oxidizer in explosives, road flares, fireworks, rocket motors, and other uses (EPA, 2008). Man-made perchlorate is also found in some hypochlorite products and disinfectants (Massachusetts DEQ, 2006). EPA (2008b) reports that about 90% of all domestically produced perchlorate is used by the defense and aerospace industries in the form of ammonium perchlorate. The most well known natural

perchlorate is associated with nitrate ore deposits from the Atacama Desert of Chile. These ore deposits are used to make fertilizer which has long been imported into the U.S. and is still imported today. One metric ton of imported fertilizer could yield as much as 40 to 340 million gallons of water with 6 $\mu\text{g/l}$ of perchlorate (Böhlke, 2005). Perchlorate may also occur naturally in other areas such as arid areas of the western U.S., and possibly in west Texas where perchlorate has been detected in groundwater over wide areas.

Both natural and synthetic perchlorate are possible at Locust Bayou, and were both given careful consideration during this investigation. Since Shumaker was used for the manufacture, testing, distribution, destruction, and storage of naval rockets, it was reasonable to consider that historical operations might have been a source of perchlorate in groundwater. Existing perchlorate contamination at nearby industries was also considered as possible sources. The most well known perchlorate plume in the Shumaker area is at the Aerojet facility north of Locust Bayou. Aerojet purchased the facility from Atlantic Research in 2003, which had existing perchlorate groundwater contamination. Imported fertilizer was also considered a possible source since Shumaker was used for farming prior to the existence of Shumaker, and perchlorate has the ability to persist in groundwater for decades. Household bleach was also considered. An analysis of the perchlorate content of 4 household bleach products was shown to contain from 89 to 8000 $\mu\text{g/l}$ (Massachusetts DEQ, 2006). Still other possible sources were thought to be road flares and fireworks. The stable isotope analysis provided a means to confidently rule out many of these possibilities and provide positive identification of source types.

ii. Field Sampling

Field sampling had to be carefully designed to ensure that enough perchlorate was collected for analysis. Each sample had to contain 10 mg of perchlorate. The laboratory analysis was performed by the Environmental Isotope Geochemistry Laboratory at the University of Illinois at Chicago. Field sampling took place from May 19, 2008 through May 24, 2008.

Perchlorate was identified in 8 of 10 alluvial monitoring wells with concentrations ranging from 0.57 $\mu\text{g/l}$ to non-detect (fig 13). Because it was difficult to collect 10 mg perchlorate per sample from water containing low concentrations, the two wells showing the highest concentrations were chosen for isotopic sampling (i.e., wells SW5 and SW7). Well SW5 contained 0.57 $\mu\text{g/l}$ perchlorate, and well SW7 contained 0.25 $\mu\text{g/l}$ perchlorate. For comparison purposes, a third well was also chosen for isotopic analysis, which was located at the Aerojet facility a few miles to the north.

Sampling was completed by concentrating perchlorate in a highly perchlorate-selective bifunctional ion exchange resin (Purolite A-53E), in columns designed for low perchlorate concentrations. Pumping through the ion exchange columns at well SW5 took 42 hours at a rate of 8 liters/minute, and pumping at well SW7 took 55 hours at a rate of 12 liters/minute. Water pressure was set not to exceed 30 pounds per square inch to allow the proper residence time in the filter. A filter (with 5-15 micron sand/sediment filter insert) was used between the pump and ion-exchange column to reduce the sand/sediment particulates in the groundwater entering the ion-exchange column. The sampling team observed the sampling 24 hours a day. No additional QC samples were required. At the laboratory, perchlorate was converted to a form that could be isotopically analyzed using a gas-source isotope ratio mass spectrometer.

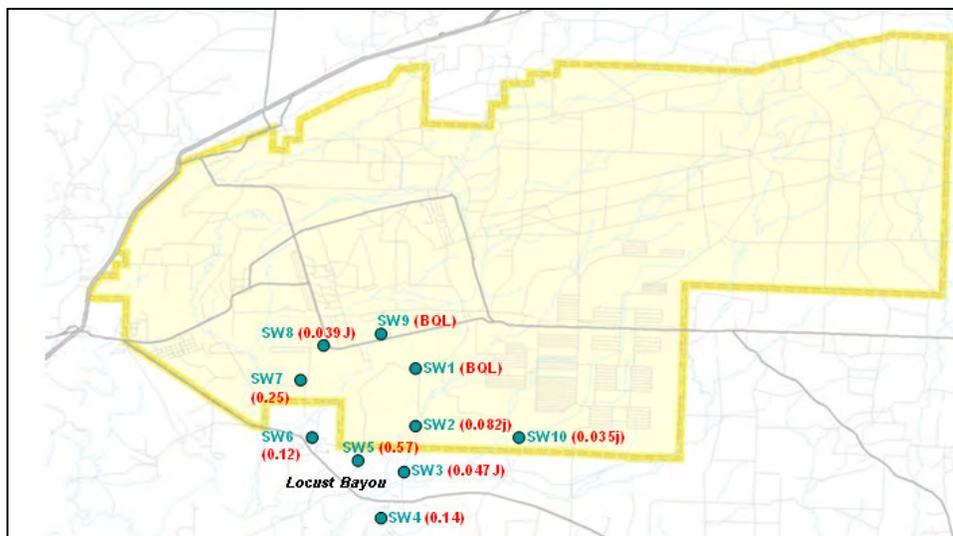


Figure 13: Perchlorate Detections In Monitoring Wells Near Locust Bayou

The sample collected from Aerojet was collected from a known perchlorate source area (Building 52) where perchlorate had been released into groundwater during previous operations by Atlantic Research (1983-1985). This sample did not require ion exchange columns and extended pumping times because the concentration was sufficiently high to provide 10 mg perchlorate by direct sampling. The well sampled was Aerojet monitoring well 25s, identified as AJ-01 for this study. Five gallons of water were collected from well AJ-01 and sent to the University of Illinois for analysis.

iii. Isotopic Results

This section begins by explaining how isotopic results are reported. Analyses are reported by comparing isotopic ratios for $\delta^{37}\text{Cl}$, $\delta^{18}\text{O}$, $\Delta^{17}\text{O}$ and by comparing those ratios to specific reference standards. The ratios are determined from the following relationships:

Chlorine Isotope Ratio Analysis

$$\delta^{37}\text{Cl} (\text{‰}) = [({}^{37}\text{Cl}/{}^{35}\text{Cl})_{\text{sample}}/({}^{37}\text{Cl}/{}^{35}\text{Cl})_{\text{smoc}} - 1] \times 1000$$

Oxygen Isotope Ratio Analysis

$$\delta^{18}\text{O} (\text{‰}) = [({}^{18}\text{O}/{}^{16}\text{O})_{\text{sample}}/({}^{18}\text{O}/{}^{16}\text{O})_{\text{vsmow}} - 1] \times 1000$$

$$\Delta^{17}\text{O} (\text{‰}) = [(1 + \delta^{17}\text{O}/1000)/(1 + \delta^{18}\text{O}/1000)^{0.525}] - 1] \times 1000$$

*smoc is standard mean ocean chloride; vsmow is Vienna standard mean ocean water.

Isotopic ranges for natural and synthetic perchlorate are reported by Böhlke, et. al., (2005) and Sturchio et. al., (2006). Samples from the Atacama Desert and derivative fertilizer products have $\delta^{37}\text{Cl}$ values range from -14.5 to -11.8 ‰. The range of $\delta^{37}\text{Cl}$ for synthetic perchlorate is -3.1 to +1.6 ‰. The $\delta^{18}\text{O}$ range is -9.3 to -4.2 ‰ for natural perchlorate, and the synthetic range is -24.8 to -12.5 ‰. The range of $\Delta^{17}\text{O}$ for synthetic perchlorate is 0.0 ± 0.1 ‰, and +8.93 to +9.57 ‰ for natural perchlorate. Sturchio et.al, (2006) reports the most diagnostic isotopic characteristic of natural perchlorate is its positive $\Delta^{17}\text{O}$ value compared to synthetic perchlorate. An example plot of isotopic ranges can be viewed graphically in figure 14, using values for δ^{37} and $\delta^{18}\text{O}$, to illustrate how data from natural and man-made perchlorate may group. Although EPA data fall

reasonably close to this idealized graph, actual data results, however, should fall close to the numerical ranges indicated above.

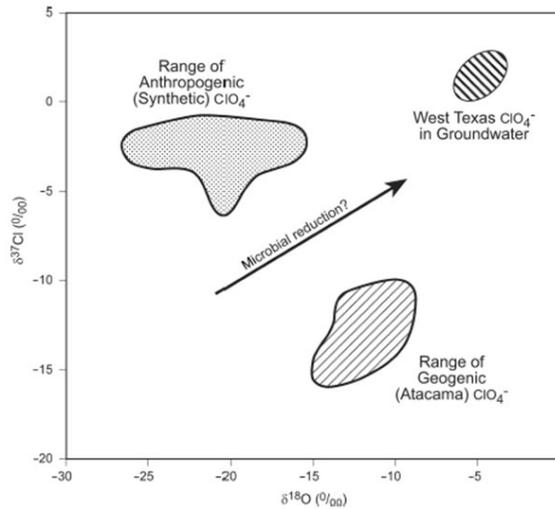


Figure 14: Idealized Graph Showing Natural and Man-Made Perchlorate Data.
 From Motzer, 2006

Results for the 2 samples from Locust Bayou and sample from Aerojet are presented in Table 9. Results indicate the 3 groundwater samples are isotopically distinct and fall within ranges for synthetic perchlorate (sample AJ01) and natural perchlorate (sample SW5), and include a possible mixture of the two types showing microbial reduction (SW7). Sample SW7 appears to contain a 2:1 mixture of AJ01 and SW5 where the mixture experienced a minor extent of biodegradation after being mixed.

Sample ID	$\Delta^{18}\text{O}$	$\Delta^{17}\text{O}$	$\Delta^{37}\text{Cl}$
AJ01	-15.8	0.0	0.8
SW5	-1.5	8.0	-10.6
SW7	-2.7	2.7	0.5

Table 9: Fingerprinting results for Locust Bayou and Aerojet

E. Most Likely Sources of Perchlorate

Multiple lines of evidence, along with uncertainties, were evaluated to determine the most likely sources of perchlorate. Major indications of perchlorate sources are the following: stable chlorine and oxygen isotopes, groundwater flow directions, geologic

conditions, travel time estimations, land use, facility operations, history of perchlorate releases, perchlorate age constraints, and the respective locations of existing facility perchlorate contamination. **The most significant uncertainties involve possible perchlorate contributions from past naval operations, and differentiating perchlorate between individual existing industrial facilities.**

i. Imported Chilean Nitrate Fertilizer

Chilean nitrate fertilizer was the primary nitrate fertilizer used in the U.S. during the early 1900s. This fertilizer is still imported today and 68,000 metric tons are used in the U.S. annually. No historical records were identified that indicate how much imported nitrate fertilizer may have been used at Shumaker in the past, but the analysis of stable chlorine and oxygen isotopes clearly indicates imported Chilean nitrate fertilizer is a source of naturally occurring perchlorate in groundwater at Locust Bayou. It is also reported that before Shumaker existed, the area was used primarily for farming.

Different populations of perchlorate concentration data may possibly be used to differentiate between natural and man-made perchlorate at Shumaker. There appear to be two populations of data based on concentration levels. These two data populations appear most evident in surface water results, where concentrations of $<0.1 \mu\text{g/l}$ were found in areas without any indication of past or present industrial activity. These concentrations appear to represent surface or near surface perchlorate contamination indicative of the land application of Chilean nitrate fertilizer. As streams pass near certain industrial areas, perchlorate concentrations increase indicating perchlorate loading of stream water with synthetic perchlorate. Although more research would be required to determine specific relationships, there may be similar indications in groundwater. For example, concentrations of fertilizer based perchlorate may only be a fraction of a part per billion, whereas synthetic concentrations or mixtures of synthetic and fertilizer based perchlorate, may generally be higher.

ii. Synthetic Perchlorate

Stable chlorine and oxygen isotopes indicate synthetic perchlorate is occurring as a mixture with perchlorate from Chilean nitrate fertilizer. However, synthetic

perchlorate, and perchlorate from Chilean nitrate fertilizer, may also occur separately. Perchlorate from Chilean nitrate fertilizer was detected, in fact, without synthetic perchlorate in well SW5.

There are two likely possibilities for how synthetic perchlorate is being transported to the Locust Bayou vicinity. The first possibility is through the gravel aquifer. Geologic information, obtained by drilling during this investigation and from published information previously discussed, indicates the gravel aquifer is a continuous blanket beneath the entire Shumaker area including the Locust Bayou area. The gravel provides a physical pathway for transport from upgradient sources.

A second possible transport mechanism is through surface water. Surface water sampling data indicates perchlorate loading is occurring where streams pass near industrialized areas associated with the aerospace industry. Perchlorate loading is occurring in Dogwood Creek as it passes from Section 5 into Section 6 (Township 13 Range 15) where perchlorate increases from 0.027 $\mu\text{g/l}$ to 5.2 $\mu\text{g/l}$. The stream segment in Dogwood Creek is near the perchlorate groundwater plume at Aerojet. Increases are also seen in Two Bayou from Section 10 to Section 24 (Township 13 Range 16) where perchlorate increases from 0.026 $\mu\text{g/l}$ to 1.3 $\mu\text{g/l}$. The increase in Two Bayou is near a sewage treatment plant outfall owned by Highland Industrial Park, and perchlorate was discovered near the outfall in 2007. **Up to 0.944 mg/l perchlorate has been detected in a stream just south of the outfall. Perchlorate is believed to have been transported to the sewage plant through a pipeline extending approximately 2 miles west from a building with a basement pump at the Aerojet facility.** Since this release was discovered, Aerojet has ceased discharge from the building sump.

Since a perchlorate plume exists at Aerojet, and the Locust Bayou vicinity and other residences are downgradient, it is reasonable to consider the existing perchlorate plume at Aerojet a possible source. It should be noted, however, that any other perchlorate releases from other past or present facilities or units in the vicinity,

should they be identified as having released perchlorate to groundwater in significant quantities and concentrations, could just as well be considered potential sources.

For the Aerojet area, Building 52 was used for washing out rocket motor casings from 1983 to 1985 (Atlantic Research Corporation, 2001), and was investigated for the 2001 RCRA facility investigation report. Based on perchlorate concentration maps, Building 52 is the primary source area for the plume at Aerojet, with concentrations in shallow groundwater reaching several thousand parts per million (mg/l). Groundwater near Building 52 is currently undergoing remediation, and concentrations have decreased according to site personnel.

In order to evaluate whether contaminated groundwater could reach the Locust Bayou vicinity since the 1983-1985 time frame, a basic travel time estimate was made for seepage velocity in the alluvial gravel layer based on a form of Darcy's law:

$$V = \frac{K \Delta h}{n \Delta x}$$

Where: K = hydraulic conductivity
 N = porosity
 $\frac{\Delta h}{\Delta x}$ = gradient

Using a hydraulic gradient of 0.0012, and text book values for gravel hydraulic conductivity (0.1 cm/s), and a porosity (0.25), the groundwater seepage velocity in the gravel layer is 1.36 ft/day (496.5 ft/yr). **Based on this rough estimate, there is enough time for the front of the perchlorate plume to have extended approximately 13,405 feet since the release at Building 52 occurred.** Other factors affecting the southward extent of perchlorate contamination are transport of perchlorate through surface water, and any perchlorate that may have been released from source areas located further south than Building 52, thus potentially resulting in contamination still further to the south.

Atlantic Research (2001) reported travel times for shallow sands and clays overlying the gravel layer as being 21 to 49 ft/yr, and reported other velocities as being

29 to 68 ft/yr to 14 to 28 ft/yr for intermediate and deeper sediments. However, Atlantic Research noted that the actual rate of water movement may be higher through zones of coarser aquifer matrix, and indicated a generally westward flow.

iii. Other Possible Sources and Uncertainties

Although fingerprinting can differentiate between plumes of perchlorate from Chilean nitrate fertilizer and synthetic perchlorate, the technique cannot tell the difference between individual sources of synthetic perchlorate, and it cannot determine the difference between old and new synthetic perchlorate. Therefore, other sources of information were used to try and further evaluate the scope of these possibilities.

The history of potassium and ammonium perchlorate for use in solid rocket propellant was described by J.C. Schumacher (1999) in a paper from the American Institute of Aeronautics and Astronautics. Schumacher presents a timeline for domestic perchlorate production and describes the evolution of production facilities and companies, including contracting agreements with the U.S. Navy. The timeline suggests it is unlikely for perchlorate to have been used in naval solid rocket motors during the time Shumaker was in operation by the Navy, but does not completely rule out the possibility either.

During WWII, the Western Electrochemical Company (WECCO) was the preeminent company which designed, constructed, and operated perchlorate plants from 1940 until its merger with American Potash and Chemical Company in 1955. In 1942, WECCO designed and constructed a small pilot plant to produce experimental quantities of potassium and ammonium perchlorate for the Air Corps Jet Propulsion Research Project in Los Angeles, California, known as the GALCIT Project No 1 (after the Guggenheim Aeronautics Laboratory at the California Institute of Technology). The GALCIT project is described as the prelude to the formation of the Aerojet Engineering Corporation and large-scale commercial development of composite solid rocket motors. The paper reports that the first application of solid rocket motors was for military aircraft Jet-Assisted-Take-Off (JATO) devices. In 1945, WECCO modified and operated a new perchlorate plant in Henderson, Nevada, and then began to produce perchlorate for the

U.S. Navy in 1953 at a capacity of 50 tons/day. A timeline of critical dates relative to Shumaker and the history of early perchlorate production in the U.S. is given below:

- 1942: WEECO GALCIT Project No 1 (small scale perchlorate production)
- 1944: Shumaker ammunition depot operations begin
- 1945: WEECO starts plant in Henderson, Nevada
- 1953: WEECO contracts with U.S. Navy to produce perchlorate
- 1954: Shumaker Rocket Test Range Completed
- 1956: U.S. Navy announces plans to close Shumaker NAD
- 1959-1961: Shumaker property sold
- 1961: Shumaker ammunition depot closes

Additional recent timeline information follows (from U.S. Army Corps of Engineers, 2003b)

- 1961: Brown Engineering formed, later named Highland Resources/Industrial Park (HIP)
- Mid 1960s: Dozens of private businesses operated in HIP, many ordnance related businesses
- 1987: 37 companies, 4700 employees at businesses located at HIP
- Early 1990s: downturn caused a number of defense contractors to relocate from HIP
- 2003: 40 companies operate at HIP

In terms of early perchlorate production history, of particular interest is the time from 1953 until 1961. This is when the U.S. Navy was known to have utilized perchlorate, although perchlorate may not necessarily have been used in naval rockets at Shumaker during this period. An indication of perchlorate not having been used is the non-detect sampling results for groundwater and surface water from the rocket test range. There were a few low-level perchlorate detections in surface water outside the rocket test range near the eastern end of Shumaker, but these concentrations are very low (under 0.1 µg/l) and are probably due to Chilean nitrate fertilizer.

The article by Schumacher indicates perchlorate manufacturing processes used today are similar to those used in the past, because WEECO and its successor companies were instrumental in modern plant design. Because of plant engineering and production similarities, it is difficult to differentiate between multiple sources of aerospace industry perchlorate. Sturchio (2009, personal communication), reported that the isotopic

signatures of synthetic (aerospace) perchlorate produced in the past would probably have the same isotopic signatures of recently produced perchlorate, and different sources of modern aerospace perchlorate are difficult to determine as well. At Shumaker, there are a number of aerospace industry facilities besides the Aerojet facility. **However, the types of operations that take place at Aerojet, and which took place when the facility was owned by Atlantic Research, are to develop and produce solid rocket motors, automotive air bags, and perhaps other products that utilize ammonium perchlorate.** The other aerospace facilities are believed to function mainly as assemblers of rocket and missile components, some utilizing perchlorate containing components from Aerojet.

7. KEY OBSERVATIONS AND UNCERTAINTIES

The following observations about Sparta vulnerability are presented under project Goals 1-3. No single observation by itself is conclusive about vulnerability. All observations should be considered collectively because they are all related in a complex 3-dimensional subsurface environment. Observations about the source of perchlorate at Locust Bayou are presented under Goal 4.

***GOAL 1:** Evaluate the vulnerability of the Sparta aquifer with respect to: (i) the presence of confining clay overlying the Sparta aquifer, and (ii) by making observations about the occurrence of clay and sand within the Sparta aquifer.*

Key Observations

- **Where the Cook Mountain Formation is relatively thick, it provides substantial protection to the Sparta aquifer. Where the Cook Mountain Formation is absent, the Sparta aquifer is closer to the surface and has more exposure to possible contamination.**
- **Clay within the Sparta aquifer provides protection from movement of contamination to lower strata.**
- **Where contamination exists in the gravel aquifer, contamination would spread relatively quickly and affect upper sand units of the Sparta aquifer.**
- **Where contamination exists in surface water, contamination would spread relatively quickly and affect the gravel aquifer.**

The two main geological factors affecting vulnerability are: (a) the presence/absence of the Cook Mountain Formation, and (b) the amount of clay and alternating sequences of clay and fine sand within the Sparta aquifer. Clay also exists in the overlying Quaternary sediment, but is not as extensive or protective as thick clays of the Cook Mountain Formation. The importance of the Cook Mountain Formation is that it can be a protective clay layer preventing contamination from reaching the top of the Sparta aquifer. Core sample examination and regional geologic studies indicate the Cook

Mountain Formation is thickest at the eastern end of Shumaker and thins to the west. The Cook Mountain Formation was not identified in core samples taken near the industrial areas west of well DW5.

Within the Sparta aquifer, clay and alternating sequences of clay and fine sand provide protection limiting the migration of dissolved contamination (e.g., perchlorate) downward through the strata. Sandy units positioned at the top of the Sparta aquifer are much more vulnerable to contamination than deeper sands.

Uncertainties

- Sparta stratigraphy between monitoring wells must be extrapolated from what would normally be expected in geologic deposits in a fluvial-deltaic system, and by using observations made from cores taken from each well.
- The precise western limit of the Cook Mountain Formation is approximate. Core samples indicate it probably pinches out between DW5 and DW6.

The Sparta geologic deposits at Shumaker appear highly variable, both laterally and vertically, and strata cannot be correlated between EPA wells. While the geology between wells is not exactly known, reasonable predictions can be made from an understanding of sediments laid down in a fluvial deltaic depositional environment, and an understanding of the site-specific variations in wells.

***GOAL 2:** Examine the vulnerability of the Sparta aquifer by: (i) installing permanent groundwater monitoring wells, (ii) by monitoring for impacts to the aquifer, and (iii) by examining groundwater flow directions.*

Key Observations

- **Arsenic and lead were detected in the Sparta aquifer above Regional Screening Levels. Perchlorate was not detected in Sparta monitoring wells.**
- **A downward groundwater flow gradient exists, but actual flow to strata lower than the uppermost saturated sands may be only minor. The Shumaker area may not be a significant recharge area for lower strata of the Sparta aquifer.**
- **No influences are seen on Sparta monitoring wells from high-capacity public water supply production wells.**

Detections of arsenic and lead occurred near presently operating industrial facilities and just north of highway 278 at Locust Bayou. No detections above screening levels occurred in wells to the east where the Cook Mountain overlies the Sparta. The origin of these metals is questionable and is discussed further in the uncertainties section below.

Chemical evidence indicates downward flow may be only minor and that low concentrations of perchlorate may not penetrate very deeply. Perchlorate was detected in the gravel aquifer well SW5 at Locust Bayou (0.57 $\mu\text{g/l}$), but was not detected in adjacent clustered wells DW4 or the deeper DW4L. Well DW4 is screened about 35 feet below SW5 and the amount of clay (72% percent core recovery) above the DW4 well screen is probably a factor limiting downward migration. Alternatively, much higher concentrations of perchlorate in shallow groundwater appear more likely to migrate downward into deeper strata. Historical data at the Aerojet facility (Atlantic Research, 2001) shows perchlorate at Building 52 in alluvial groundwater exceeding 100,000 $\mu\text{g/l}$. At this location, perchlorate was detected just below the top of the Sparta aquifer 13.0 $\mu\text{g/l}$. The ability of highly concentrated perchlorate (brine solution) to migrate deeper may result from site specific geological factors, or chemical effects of highly concentrated perchlorate on clay strata.

Uncertainties

- The natural occurrence of arsenic and lead in the Sparta aquifer at Shumaker is unknown. Arsenic and lead may be due to either natural or industrial sources. More data are needed to determine the source.
- Detections of bis(2-ethylhexyl)phthalate may be from well construction material or laboratory contaminants.
- Results for explosives are problematic because of laboratory error. Confirmatory sampling is needed.

The presence of arsenic and lead may simply result from geologic deposits characteristically containing these metals at elevated concentrations. Additional investigation would be necessary to make that determination.

Laboratory results for explosives (2-nitrotoluene, 3-nitrotoluene, 4-nitrotoluene, and nitrobenzene) are not conclusive. Two laboratory analyses were conducted for explosives. The original analysis did not yield any detections, but had low recoveries which resulted in estimated results. The re-extraction and re-analysis for explosives yielded detections below the reporting limit, but were analyzed 1 day outside of the holding time. Therefore, results are not reliable at the present time and additional sampling should be conducted to verify results. Sampling could be conducted in only those wells which had explosives detections, rather than re-sampling all wells at Shumaker.

***GOAL 3:** Examine aquifer vulnerability by conducting surface water sampling including streams, lakes, and ponds over the extent of Shumaker, and the Locust Bayou area.*

Key Observations

- **There are many detections of perchlorate which appear to result from two types of sources: nitrate fertilizer and synthetic perchlorate.**
- **Relatively high concentrations of perchlorate may be moving downstream in surface water near Two Bayou and Dogwood Creek.**
- **Analytical results show no exceedences of RSLs. Arsenic, barium, cadmium, chromium, lead, and selenium were detected, but were below RSLs.**

Perchlorate was detected at many surface water sampling locations at concentrations ranging from less than 1.0 µg/l to 5.2 µg/l. There appear to be two populations of analytical data which can be roughly divided by fertilizer and synthetic source type. Groundwater/surface interaction, including mixing with synthetic perchlorate along parts of Two Bayou and Dogwood Creek, may affect shallow alluvial

groundwater. Data does not indicate, however, that surface water contamination increases the vulnerability of deeper sections of the Sparta aquifer.

Uncertainties

- Low concentrations of perchlorate cannot be readily verified.
- Results for explosives are problematic because of laboratory error. Confirmatory sampling is needed.
- No information is available on the possible contribution of metals to surface water from soils.

There are two reasons why it is unlikely that the source of low concentration perchlorate in surface water can be positively verified with current technology. First, surface water contains interferences that affect isotopic analysis (Sturchio, personal communication, 2009). Secondly, even if interferences did not exist, 10 mg of perchlorate are required for analysis, which would be extremely difficult to obtain from water containing only a fraction of one part per billion.

Surface water may be receiving some or all metals from surrounding soil horizons. A soil sampling and analysis program, and/or geologic formation sampling, would be needed to develop analytical data sets to fill this information gap. Surface water sampling did not indicate sources of metals such as waste disposal units or types of spills. Metals in surface water are fairly evenly distributed across Shumaker indicating soil is a possible source.

GOAL 4: Determine the source of perchlorate detected in groundwater monitoring wells and drinking water at Locust Bayou.

Key Observations

- **Isotopic analysis indicates perchlorate at Loucst Bayou and vicinity is from both Chilean nitrate fertilizer and from synthetic perchlorate. The vast majority of synthetic perchlorate is used by the aerospace industry.**
- **A mixture of synthetic and fertilizer based perchlorate was identified in well SW7, located upgradient of residences near county road 95.**
- **Synthetic perchlorate is probably being transported through the gravel aquifer from an upgradient source to the north, and possibly through surface water.**
- **Relatively high concentrations of perchlorate have been present in the alluvial aquifer at the Aerojet facility north of Locust Bayou.**

There are two distinctive types of perchlorate in groundwater at Locust Bayou and vicinity as determined from the analysis of chlorine and oxygen isotopes. These types may be mixed, or may occur separately, as was noted in one sample. The transport pathway is probably mainly through the gravel aquifer, with additional contamination from surface water transport. Perchlorate in surface water may infiltrate the gravel aquifer.

Uncertainties

- It cannot be completely ruled out that more than one aerospace industry source, or past Navy operations, contributed to perchlorate contamination.
- Seasonal changes in groundwater flow directions may exist.
- Relationship between southward flow direction in gravel aquifer, to west/south-west flow in shallower zones (above gravel) at Aerojet.

Even with the current state-of-the-art science, isotopic analysis still cannot differentiate between specific synthetic perchlorate aerospace sources. There are multiple aerospace industry facilities at Shumaker, but only one, Aerojet, is known to be associated with significant perchlorate releases that occurred during previous operations

by Atlantic Research. While it cannot be ruled out that past Naval rockets contained perchlorate, it was not detected in the former rocket test range.

8. CONCLUSIONS

The vulnerability of the Sparta aquifer to contamination across Shumaker varies by location and depth. Sparta vulnerability is greatest in the western half of Shumaker where Sparta sand contacts the gravel aquifer. Sparta vulnerability decreases with depth because of clay within the Sparta and possible limitations to the downward movement of groundwater. The least likely part of the Sparta to become contaminated from surface use is the eastern half of Shumaker where the Sparta is covered by a thick layer of clay.

At this time, the Sparta aquifer has not been widely affected by perchlorate. The shallow gravel aquifer is more susceptible to contamination than the Sparta and has been widely affected by perchlorate. Periodic monitoring of the Sparta aquifer should be conducted as a measure of safety, and routine monitoring of the gravel aquifer should be conducted to track perchlorate levels and seasonal flow directions.

Groundwater and surface water in the vicinity of Locust Bayou has been affected by synthetic perchlorate from an aerospace industry source, and by perchlorate derived from past agricultural uses of imported Chilean nitrate fertilizer products. A mixture of synthetic and fertilizer based perchlorate was identified in groundwater just upgradient of a residential area. The most well known source of synthetic perchlorate in the area is the past release of perchlorate that occurred at Atlantic Research/Aerojet, which has been transported through the gravel aquifer, and through surface water. Other sources of synthetic perchlorate may exist, but none appear as likely based on sampling data, flow directions, locations of known releases and existing contamination, and the history of perchlorate production and use.

9. REFERENCES

- Albin, D.R., 1964, Geology and Ground-Water Resources of Bradley, Calhoun, and Ouachita Counties, Arkansas, U.S. Geological Survey Water Supply Paper 1779-G.
- Arkansas Public Service Commission, 2008, Class A and B Water Utility Annual Report.
- Atlantic Research Corporation, 2001, Focused RCRA Facility Investigation Report, Open Burn Unit and Building 52 Areas, Prepared by Environmental Alliance, Inc.
- ATSDR, 2007, Health Consultation, Sparta Aquifer Vulnerability Study, Health Implications of Heavy Metals Contamination in Locust Bayou Private Wells, Calhoun County, Arkansas.
- Böhlke, J.K., Sturchio, N.C., Gu, B., Horita, J., Brown, G.M., Jackson, W.A., Batista, J., and Hatzinger, P.B., 2005, Perchlorate Isotope Forensics, in Analytical Chemistry, vol. 77, p 7838-7842.
- EPA 2007a, Site Specific Quality Assurance Project Plan/Sampling Analysis Work Plan for "A Phased Assessment of Groundwater and Subsurface Conditions Involving Protection of the Sparta Aquifer," Shumaker Naval Ammunition Depot, East Camden, Arkansas, prepared by Tech Law Inc., January 31, 2007.
- EPA 2007b, Site Specific Quality Assurance Project Plan/Sampling Analysis Work Plan for "A Phased Assessment of Groundwater, Surface Water, and Isotopic Analyses in Support of the Shumaker Naval Ammunition Depot Vulnerability Study," Shumaker Naval Ammunition Depot, East Camden, Arkansas, prepared by Tech Law Inc., December, 18, 2007.
- EPA 2008a, Safe Drinking Water Information System (SDWIS) report.
- EPA 2008b, Interim Drinking Water Health Advisory for Perchlorate, Prepared by: Health and Ecological Criteria Division, Office of Science and Technology, EPA Office of Water.
- Fitzpatrick, D.J., Kilpatrick, J.M., McWreath, H., 1990, Geohydrologic Characteristics and Simulated Response to Pumping Stresses in the Sparta Aquifer in East-Central Arkansas, U.S.G.S. Water Resources Investigations Report 88-4201.
- Hosman, R.L. and Weiss, J.S., 1988, Geohydrologic Units of the Mississippi Embayment and Texas Coastal Uplands Aquifer Systems, South-Central United States, USGS Open File Report 88-316.

- Joseph, R.L., 2000, Status of Water Levels and Selected Water Quality Conditions in the Sparta and Memphis Aquifers in Eastern and South-Central Arkansas, 1999, USGS Water-Resources Investigations Report 00-4009.
- Massachusetts Department of Environmental Protection, 2006, Perchlorate in Hypochlorite Products Report.
- Motzer, W.E., Mohr, T.K.G., McCraven, S., and Stanin, P., 2006, Stable and Other Isotope Techniques for Perchlorate Source Identification, in Environmental Forensics, 7:89-100.
- Payne, J.N., 1968, Hydrologic Significance of the Lithofacies of the Sparta Sand in Arkansas, Louisiana, Mississippi, and Texas, U.S. Geological Survey Professional Paper 569-A.
- Schumacher, J.C., 1999, History of Establishing a Source of Potassium and Ammonium Perchlorates for use in Solid Propellant Rockets, American Institute of Aeronautics and Astronautics, Paper 99-2926.
- Sturchio, N.C., Böhlke, J.K, Gu, B., Horita, J., Brown, G.M., Beloso, A.D., Patterson, L.J., Hatzinger, P.B., Jackson, A.J., Batista, J., 2006, Stable Isotopic Composition of Chlorine and Oxygen in Synthetic and Natural Perchlorate, in Perchlorate: Environmental Occurrence, Interactions, and Treatment, B. Gu and J.D. Coates Editors, Springer Publishers, New York.
- Tech Law Inc., 2007, Field Activity Trip Report, Shumaker Naval Ammunition Depot Facility, East Camden, Arkansas.
- Tech Law Inc., 2008, Task Order Report, Shumaker Naval Ammunition Depot Facility, East Camden, Arkansas.
- U.S. Army Corps of Engineers, Little Rock District, 2003a, Fact Sheet, Former Shumaker Naval Ammunition Depot, Arkansas.
- U.S. Army Corps of Engineers, Little Rock District, 2003b, Final Decision Document, Former Shumaker Naval Ammunition Depot, East Camden, Arkansas.