

# **Consideration of Long Term Groundwater Monitoring at Wood Treating Sites**

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## ABSTRACT

This study examines the relationship between groundwater velocity and dissolved phase contaminant plume length on wood treating sites. The purpose of the work is to evaluate whether this relationship provides a valid method for estimating plume length.

Wood treatment industries have operated in North America for more than 100 years, producing treated products such as railway ties, utility poles and fence posts. Creosote is the oldest of the common wood preservatives. Its use dates back to the earliest wood treatment operations and it is still widely used today. At many older wood treating sites a substantial amount of creosote was spilled in the first half of the 20th century, before the advent of heightened environmental awareness and stricter regulations. The chemicals associated with creosote are a public health concern because they can be both toxic and carcinogenic. Once these chemicals dissolve into groundwater, they form mobile plumes that may extend hundreds of meters downgradient from the source.

Physical removal of plumes on wood treating sites is usually difficult and expensive. Consequently, natural biodegradation is often identified as the most practical means of cleaning up the groundwater, as long as the contaminants do not pose an unacceptable risk. This approach acknowledges that the groundwater will be contaminated for an extended period, possibly many decades. Over this period, there will be a long term requirement for groundwater monitoring.

The conclusions of this study are intended to contribute to the design of long term monitoring programs on wood treating sites. This study looked at four separate wood treating sites and compared the extent of the dissolved phase plumes at each of them. Naphthalene plumes were chosen for the comparison, as it is one of the main constituents in creosote and had the most extensive dissolved phase distribution. Simple modeling was done to evaluate the stability of the plumes studies. The result of the study shows a strong correlation between groundwater velocity and the extent of the dissolved plumes. These are still preliminary results, and as such, additional work to other sites and with other constituents is highly recommended.

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## **1. INTRODUCTION**

Newly sawed wood typically undergoes some form of preservation or treatment to prevent it from decay and against insects and fungi. The main chemicals involved in these processes are creosote, pentachlorophenol (PCP), and chromate copper arsenate (CCA) which are toxic and can be carcinogenic (Konasewich & Henning, 1988).

Wood treating facilities have been around for over a century, and during the course of this time, poor operating procedure and facility design has resulted in environmental damages due to leaking, spilling, storage, or disposal of these chemicals (Konasewich & Henning, 1988). Once these chemicals reach the groundwater, they form dissolved contaminant plumes. This paper will focus on the contaminant plumes from creosote sources.

Commonly, natural attenuation is used in remediation at these contaminated sites. Natural attenuation describes the process by which contaminant concentrations are reduced by natural, biological, chemical or physical processes such as sorption or dilution (USEPA, 1999). Important factors in natural attenuation are groundwater flow, and biodegradation rates. It should be noted that groundwater monitoring is typically required for the entire period of the natural attenuation remedy. One of the main issues in assessing the applicability of natural attenuation at these contaminated sites is the extent of the dissolved contaminant plume.

This paper assesses the hypothesis that there is a strong remedy relationship between creosote contaminant plume lengths and groundwater velocity. This paper will look at five separate sites and determine the lengths of the dissolved phase plume, as well as how it is related to groundwater velocity. Hydrological and geological properties are discussed as well as they are important issues in natural attenuation and determining the extent of the dissolved phase plumes.

## 1.1. Background Information

### 1.1.1. Wood treating Sites

Wood preservation has occurred since ancient times. The ancient Romans and Chinese both used salts to preserve their wood (Connell, 1991). In the United States, the wood treating industry has been in operation for over a century. Treated wood is used in building and construction industries for products such as railroad ties, telephone poles, and fencing.

The process of treating wood involves the “penetration of preservative solutions into wood to preserve its structural integrity” (Konasewich & Henning, 1988). The wood is put into a pressure vacuum to be treated. Once it has been coated with the chemicals, it is then drip-dried. Waste material is formed during all steps of the wood treating process, including drippage in unlined areas and disposal of sludge into lagoons (Konasewich & Henning, 1988).



## 1.2. Organization

The first chapter of this study introduces the problem. The second chapter looks at previous and similar studies done regarding nature of the contaminants, plume movement, and contamination migration. This chapter will also look at two case studies that are pertinent to this study.

The third chapter of this paper provides the methods by which the results were obtained. The fourth chapter provides complete descriptions of the sites used in this study. These descriptions mainly focus on the geology and hydrogeology at these sites. This chapter includes description of the dissolved plume extent and characterization.

The results of the study are summarized in the fifth chapter. The sixth and final chapter presents a summary of the findings and discusses any future recommendations.

## 2. LITERATURE REVIEW

### 2.1. Creosote

Creosote is a “complex mixture of over 200 different major individual compounds” (Arwin and Flvybjerg, 1992). Typically, creosote is made up of 85% polyaromatic hydrocarbons (PAH), 10% phenols, and 5% heterocyclic compounds. Because of the complex composition of creosote, remediation at these sites poses great challenges. However, it does make these sites a good model for cleanup at other similar sites such as in petrogenic pollutant cleanup, waste oil recovery, and coal gasification sites (Mueller, et. al, 1989).

Creosote is a by-product from the carbonization of coal tar at high temperatures (1000-1200°C). It is used in wood preservation because it has low electrical conductivities and is a mild fire retardant. Other physical properties of creosote that make it useful in the wood preservation industry are its immiscibility in water and high density (Betts, 1991).

### 2.2. Natural Attenuation

The USEPA (1999) describes natural attenuation as “remediation process that involves a variety of physical, chemical or biological processes that under favorable conditions act without human intervention to reduce the mass, toxicity, mobility, volume, or concentration of contaminants in soil, or groundwater.” This process includes biodegradation, dispersion, dilution, sorption, volatilization, radioactive decay, and chemical or biological stabilization, transformation or destruction of contaminants.

The degradation process is considered environmentally preferable, because the constituents of creosote are lost over a certain time period (Mueller, et. al, 1989). Nicholson et al. (1983) showed that contaminant plumes are characterized by “thinning in the vertical direction, and decreasing in the concentration from the refuse.” They noted that as the leachate entered the subsurface, it is subjected to chemical processes such as cation exchange, mineral dissolution, and precipitation as well as physical processes such as dispersion. Both chemical and physical processes act to decrease the concentration of the plume.

Biodegradation is the result of naturally occurring bacteria in the aquifer. This process results in the formation of carbons dioxide and water (Nicholson, et. al. 1983). Microbial degradation is limited by the electron acceptors, chemical structure of the compound, time, temperature, acidity, nutrients, and the presence of toxic compounds. Mueller et. al, (1989) elaborated on other criteria for biodegradation. First there must exist the appropriate organism. Secondly, they note “bioavailability of the potential substrate must be considered.”

Mueller et al, (1989) discuss the factors that limit degradation of creosote compounds in the groundwater. They also note that the available electron acceptors determine which compounds can be degraded and at what rate the degradation proceeds. As well, the degradation of specific compounds is dependant upon their chemical structure. Another important factor is time. The time required for adaptation for bacteria to the pollutants is variable, ranging from days to years (Mueller et al, 1989).

### 2.3. Case Studies

In a study by King and Barker (1999), a creosote contaminant source was emplaced into the groundwater at CFB Borden. They monitored the plume development and degradation during the course of four years. The study found that some plumes such as the phenol plumes grew then receded and disappeared after two years. Other plumes such as naphthalene still continued to grow, although at a slower rate, over the same time frame. The authors determined that more sorptive compounds did not migrate and determined plume stability by applying mass balance methods.

Barker et al. (1987) showed that the extent to which the contaminants migrate is dependant on natural attenuation through the processes of advection, dispersion, sorption, and chemical biostransformation. Except for advection, these processes help in natural attenuation by lowering the concentration. In field studies, the constituents showed longer longitudinal spreading than lateral spreading in the sand aquifer. Samples were collected periodically from a monitoring well. The researchers found that after a given number of days, these contaminants were no longer detected. The authors noted that “Initial mass loss rates for benzene, toluene, and perhaps xylene appear to be linear, however then they appear to become non linear.” The lab experiments also yielded similar results, although in the lab the contaminants took slightly longer to disappear.

### 3. METHODS

#### 3.1. Site Selection Criteria

The sites selected for this study were chosen by precise criteria. Firstly, the source of contamination at the site had to be creosote from a wood treating site. Secondly, in order to evaluate the plume accurately, it needed to have a reasonable extent and characterization and also could not be affected by surface water discharge. Thirdly, the sites needed to have a reasonable hydraulic conductivity velocity for evaluation. Finally, the site had to have a simple conceptual model.

#### 3.2. Determination of Hydrogeological Properties

Naphthalene was chosen as the tracer plume as it is the main constituent of the creosote and in all the sites examined the naphthalene plume had the greatest extent. Other constituents of interest include benzene, and xylene.

In all cases, the groundwater velocity was determined from previous environmental studies conducted at the site. The velocity for the specific zone with the most extensive plume was chosen.

The general porosity for a sandy aquifer was determined to be 0.003. This was made constant for each site for simplicity, as this study is more interested in addressing other variables such as velocity and conductivity at the site.

At all sites, the extent of the plume is approximated from data from a site report. The limit of detection for the dissolved constituents chosen was  $1\mu\text{g/L}$ , as amounts any lower than this are essentially nondetectable. Hydraulic conductivity and gradient were also taken from previous site studies and reflect up to date data from these sites as of 2004

#### 4. SITE INFORMATION

There are five main sites in this study. All the sites are Beazer Inc. owned sites and they are located throughout the USA (Fig. 4.1). The selection criteria of the sites was discussed in chapter 3. This chapter will discuss the geology and hydrogeology for each site as determined from previous sites impact studies. Also, this chapter will look at the dissolve phase plume extent of the naphthalene plume at each site.

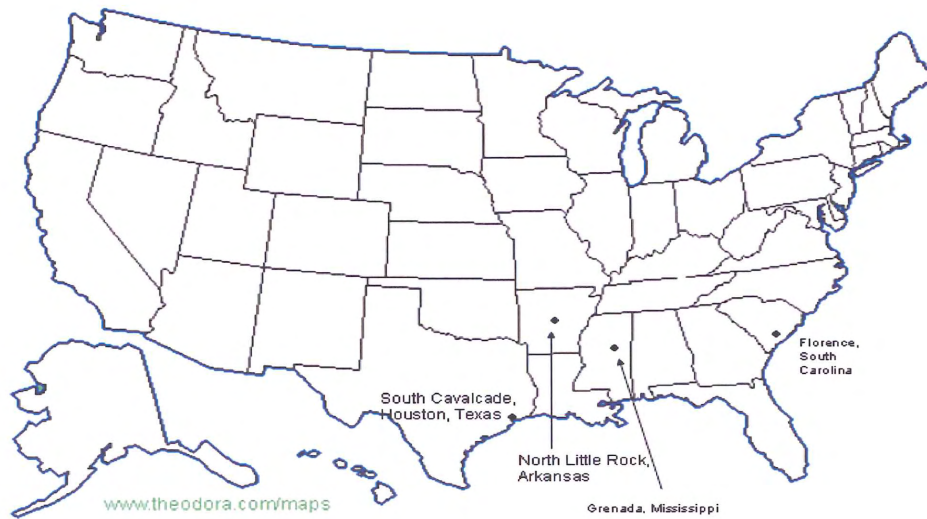


Fig. 4.1 – Map of the United States of America, showing approximate location of all sites studied. (Map from [www.theodora.com/maps](http://www.theodora.com/maps))

#### 4.1. Koppers Industries Inc, Facilities, North Little Rock, Arkansas

##### 4.1.1. Background

This site has been treating wood since 1907. Chemicals used in the wood treating process include creosote and petroleum oils. PCP was used as preservative from the 1960s until 1982 (Dames & Moore, 1994).

The 63 hectares (155-acre) site is located within the city of North Little Rock in Pulaski County, Arkansas. To the south and east of the site there are residential areas that are predominantly single-family dwellings. Areas to the west of the plant are currently underdeveloped (Dames & Moore, 1994).

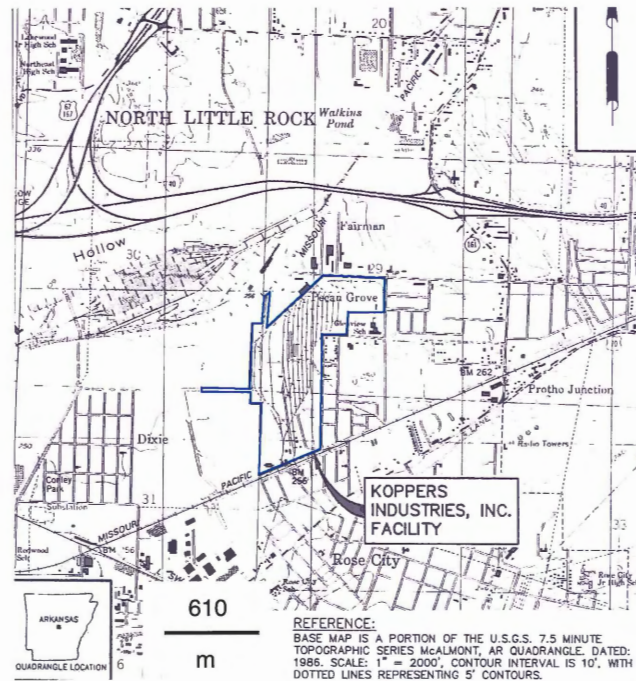


Fig.4.2 - Location of Koppers Industries Inc. Facilities in North Little Rock, Arkansas (Dames & Moore, 1994).



The plant is still an active wood-treating site today. The city of North Little Rock has used the land for storage of glass bottles for recycling in the past. There is no nearby surface water and no water supply well on site. The local water supply is from the city (Dames & Moore, 1994).

#### 4.1.2. Geology and Hydrogeology:

The geology at this site is characterized by Holocene aged alluvial terrace deposits from the Arkansas River. The alluvial deposits show a fining upwards sequence from gravel or coarse sand at the base to fine grained sediments near the surface. The alluvium is 20.4 to 35.1 m thick and is composed of mostly siltstone and silty sandstone. It is heterogeneous, and poorly consolidated. Based on reports, this unit is split arbitrarily into 4 hydrogeological zones (See stratigraphic section below).

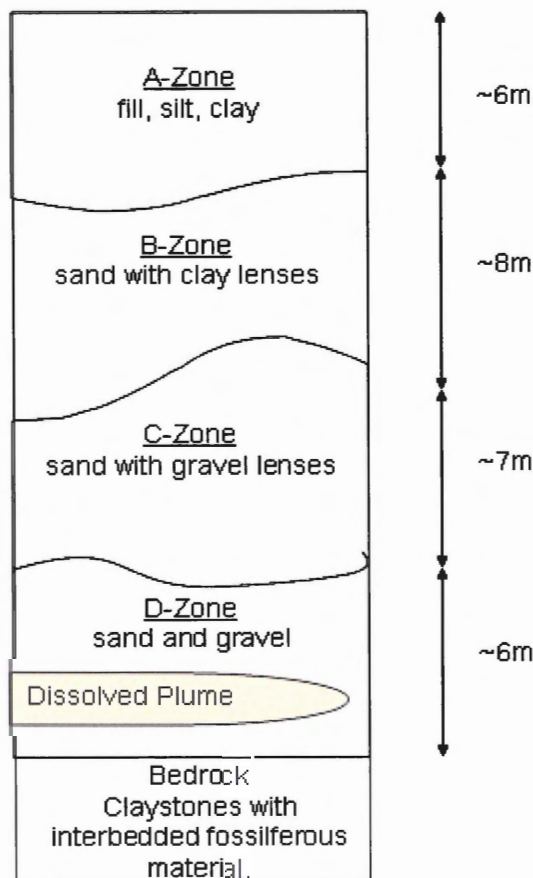


Fig 4.3 - Schematic diagram of the four main hydrogeological zones at the North Little Rock, Arkansas site (Not drawn to scale).

The top 6 m is the A - Zone. This zone is characterized by fill, silt, clay and minor amounts of sand. It is grey, brown, and reddish in color, with the sands typically a light brown to brown color. The B - Zone is composed of sand with occasional clay and silt lenses that between 0.3 - 1.8 m thick and is typically brown in color. The sands are fine to medium grained and are poor to well graded. This zone is located between 6 -14 m below ground surface.

The C - Zone is located 14 - 21 m below ground surface and is primarily composed of fine to coarse sand, with lenses of fine and coarse gravel. The D - Zone, which makes up the final 21 - 27 m below ground surface, is composed of sand and gravel. It is typically grey, brown, or tan in color. The gravel is sub-rounded and poorly to well graded. Hydraulic conductivity is for the A, B and C - Zones is between  $5.6e^{-2}$  and  $5.8e^{-2}$  cm/s and the groundwater velocity in this zone is  $1.54e^{-4}$  cm/s (Dames & Moore, 1994).

This D - Zone directly overlies the bedrock that is comprised of claystone of the Kincaid formation. The bedrock is greenish grey and dark grey clay in places, with interbedded fossiliferous materials and is chiefly composed of sandy glauconitic limestone and calcareous sandstone (Dames & Moore, 1994).

The Arkansas River is the regional discharge zone for the alluvial aquifer. The water table depth is 5 - 6 m below ground surface and hydraulic gradient is 0.0007 towards the South. There are no apparent upward or downward vertical gradient (Dames & Moore, 1994).

#### 4.1.3. General NAPL Occurrence:

The contaminants are most extensive in the D - Zone. The plume is traveling in a southerly direction and is approximately 700 m in length. The contaminants of interest (COI) are naphthalene, with benzene and toluene noted in smaller concentrations nearer to source (Dames & Moore, 1994).

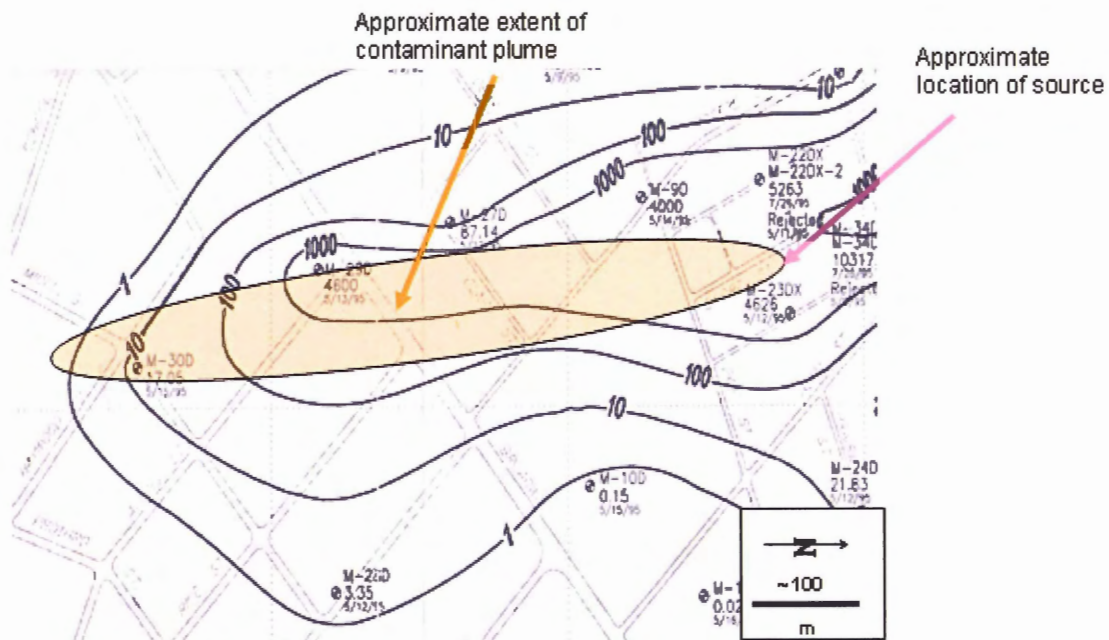


Fig. 4.4 - The plume is traveling in a southerly direction. The extent of the plume is approximately 700 m (Dames & Moore, 1994).

## 4.2. Koppers Facility, Grenada, Mississippi

### 4.2.1. Background

This facility has treated wood since 1904 and still operates today. The 69.2 hectares (171-acre) site is located 1.6 km (1 mile) southeast of Grenada, Mississippi near the rural town of Tie Plant, Mississippi (Fig 4.1). The facility has used creosote and PCP based

preservative in wood treatment processes, however metals such as CCA based preservatives were not used (GeoTrans et. al, 2003).

The Northern Stream and Central Ditch are the two surface water bodies that flow northeast across the site. The closest private well is located 0.8 km (0.5miles) up gradient from the site and on the facility site there is one production well. There are no water supply wells within a 3.22 km (2 mile) radius of the plant (GeoTrans et. al, 2003).

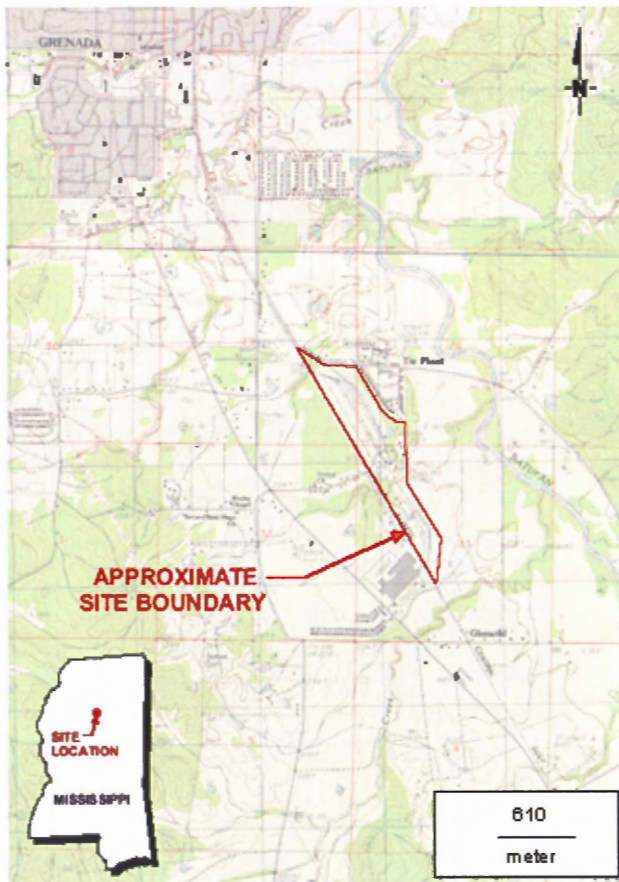


Fig. 4.5 - Location of Koppers Facility in Grenada, Mississippi (GeoTrans et. al, 2003).

#### 4.2.2. Site Geology and Hydrogeology

The site is located on a terrace deposit that is approximately 3 - 5 m above the floodplain of the Batupan Bogue. The Quaternary material is mostly made up of channel-fill and is composed of clay sandstone, marl, and muddy limestone. Quaternary material is poorly consolidated. This Quaternary material is separated into six lithologic zones (Fig 4.6) (GeoTrans et. al, 2003).

In stratigraphic order from top to base:

- (1) The fill zone is chiefly composed of debris material.
- (2) The Uppers Silt Zone is typically 1 – 2 m thick and contains some sand. It is possibly a loess deposit.
- (3) The Upper Sand Zone is composed of fine silty quartz sands and silty sands. It is approximately 2 - 5 m thick. Hydraulic conductivity is measured at  $1.3e^{-2}$ cm/s.
- (4) Upper Low Permeability Zone is a combination of silty fine sand, sandy silt, and silty clay beds, and together they range in thickness from zero to approximately 5 m. It is laterally persistent over most of the central portion of the site.
- (5) The Lower Sand Zone is an aquifer comprised of silty fine sand, fine-to-medium grained sand, and has occasional thin discontinuous sandy silt and clay beds. The upper few meters are composed of poorly consolidated sand and this zone becomes more consolidated with depth. The Lower Sand Zone ranges in thickness from 27 - 50 m thick. The hydraulic conductivity in this zone is  $6.94e^{-4}$  cm/s(36ft/day)
- (6) The Lower Confining Zone is comprised of a sequence of fine-grained sediment including siltstone, claystone, and shale interbedded with minor well-consolidated

sand and sandstone. The thickness is uncertain, however at the one boring site it appears, the zone was over 46 m thick.

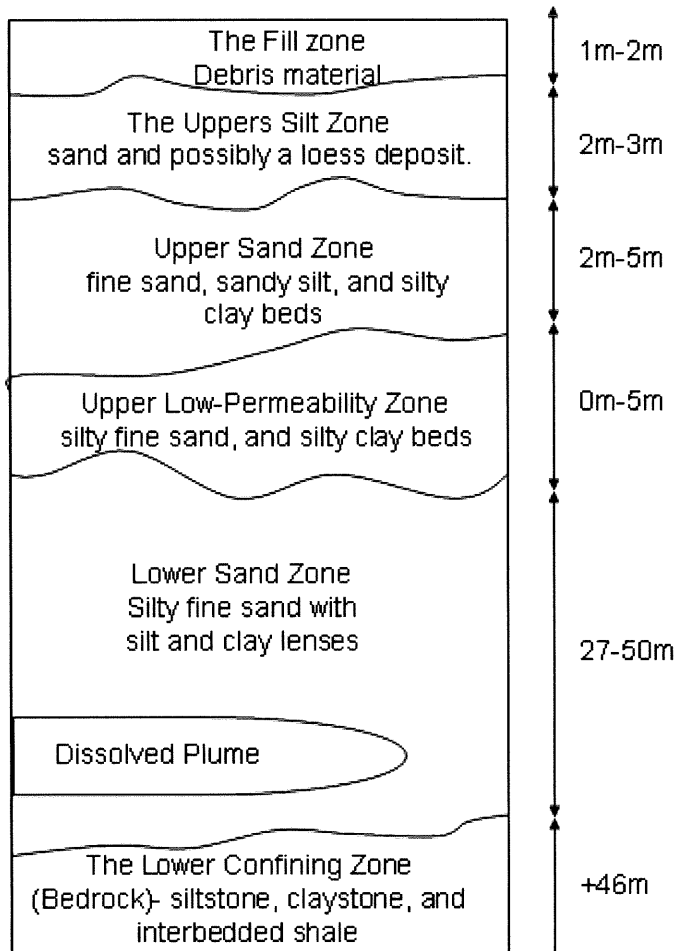


Fig.4.6 - Schematic diagram of the six lithologic zones at Grenada, Mississippi site (Not drawn to scale).

Water table depth is approximately 3 m below ground surface in the shallow clay, and shows upward groundwater flow. The hydraulic gradient at the site is 0.0014 and the velocity at the site is  $5.93e^{-5}$  cm/s (GeoTrans et. al, 2003).

#### 4.2.3. General NAPL occurrence:

The contaminants are most extensive in the Lower Sand Zone (Fig 4.7). The contaminant plume extends approximately 132 m from site. The naphthalene plume dissipated the

furthest of the constituents. Other COI include benzene and toluene (GeoTrans et. al, 2003).

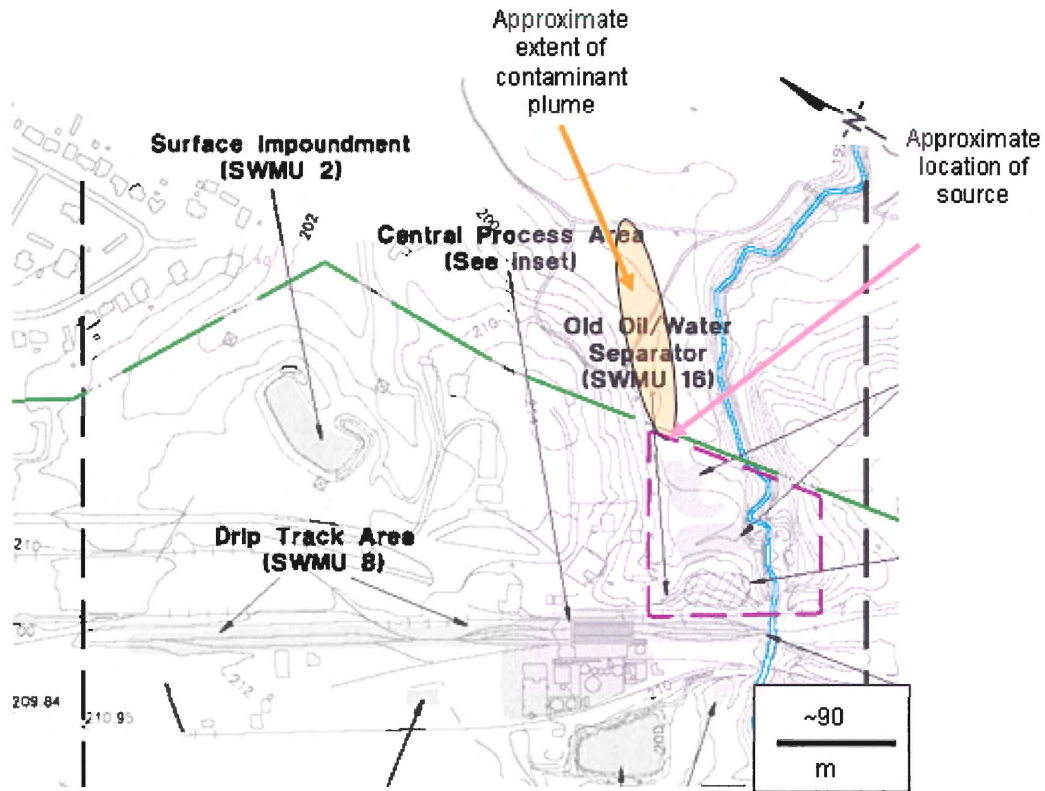


Fig. 4.7 - The dissolve phase plume is traveling in an easterly direction. The extent of the plume is approximately 132 m from the site (GeoTrans et. al, 2003).

### 4.3. Koppers Facility, Florence, South Carolina

#### 4.3.1. Background information

This site began operations in 1946. The facility used creosote, in addition to PCP and CCA in its wood treating operations. The plant is located 2.4km (1.5 mile) east of Florence, South Carolina (Fig 4.7) and sits on an 81 hectares (200 acre) site (The RETEC Group, Inc. & AMEC Earth and Environmental, Inc., 2003).

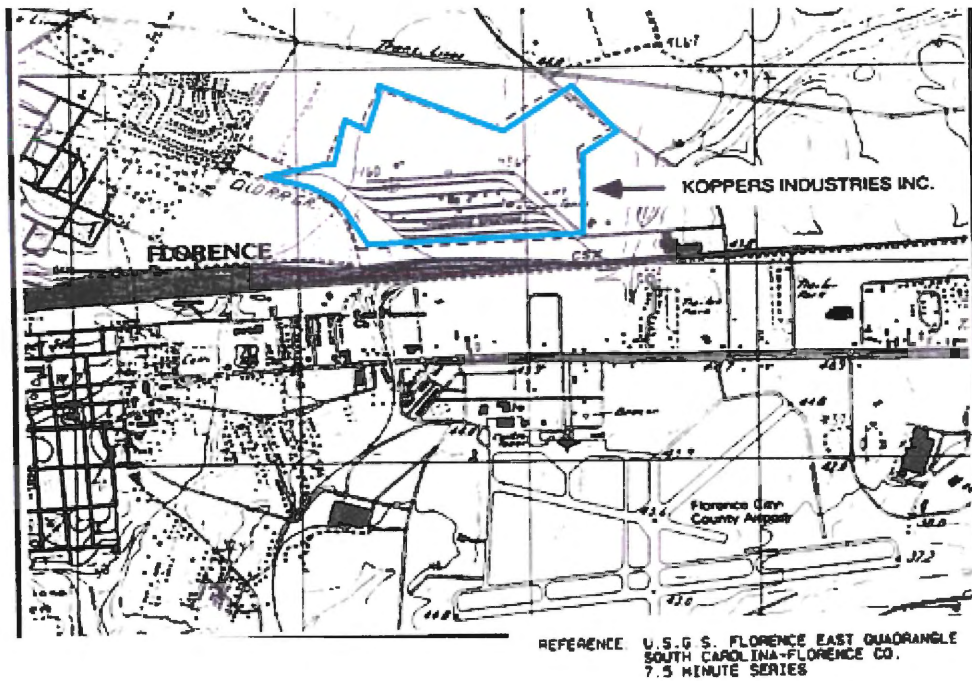


Fig.4.8 - Site location for Koppers Facility in Florence, South Carolina (Chester Environmental, 1993).

A mixture of industrial, commercial, residential and transportation areas surround the still active plant. Residential areas are found to the northwest of site and immediately west, north and east are underdeveloped areas. There is airport to the south of the plant. The local water supply is from the Midderndorf aquifer, with the nearest wells approximately 1.6 km (1 mile) southwest of the property (The RETEC Group, Inc. & AMEC Earth and Environmental, Inc., 2003).



#### 4.3.2. Geology and Hydrogeology

The site is underlain by the Atlantic Coastal Plain Province, which is an easterly thickening wedge of unconsolidated sediments made up of erosional material from highland areas west of the depositional sequence (The RETEC Group, Inc. & AMEC Earth and Environmental, Inc. 2003).

The hydrological units are described below:

- 1) Upper water bearing unit is split into two zones
  - i) A-Zone: this zone is 3 - 6 m thick and is composed of silty clay and clayey sand.  
The hydraulic conductivity in this zone approximately  $1.32e^{-2}$  cm/s.
  - ii) B-Zone: composed of fine to coarse sand and is 9 -15 m thick. The hydraulic conductivity in this zone is approximately  $1.32e^{-2}$  cm/s
- 2) Clayey confining unit
- 3) Lower water bearing unit (also known as the C - Zone) is composed of fine to coarse sand and is 8 m thick.

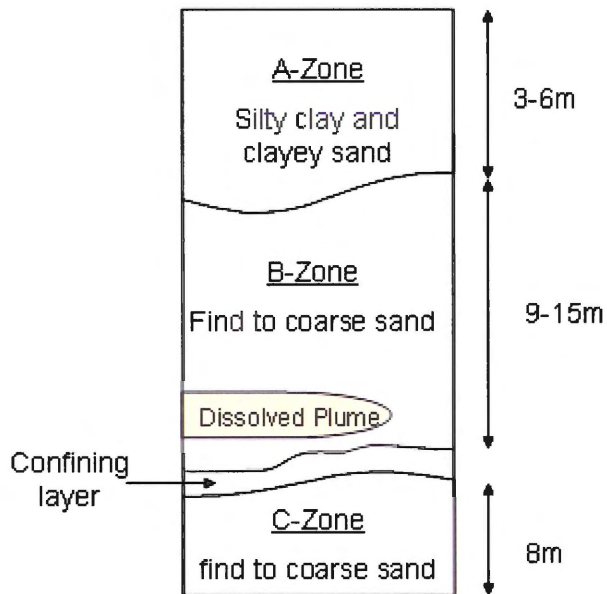


Fig 4.9 - Schematic diagram for the three main lithologic zones at this site (Not drawn to scale).

Water table depth is approximately 2 m below ground surface, and gradient in the shallow unit is 0.004 towards southeast. There is downward vertical gradient of approximately 0.014 - 0.066 between the A and B Zones, and 0.202 between B and C zones. The velocity is  $1.53 \times 10^{-4}$  cm/s (The RETEC Group, Inc. & AMEC Earth and Environmental, Inc., 2003).

#### 4.3.3. General NAPL Occurrence:

The contaminant plume primarily occurs in the B - zone. The naphthalene plume extends approximately 701 m in a Southwest direction from the site (Fig 4.10) (The RETEC Group, Inc. & AMEC Earth and Environmental, Inc. 2003).

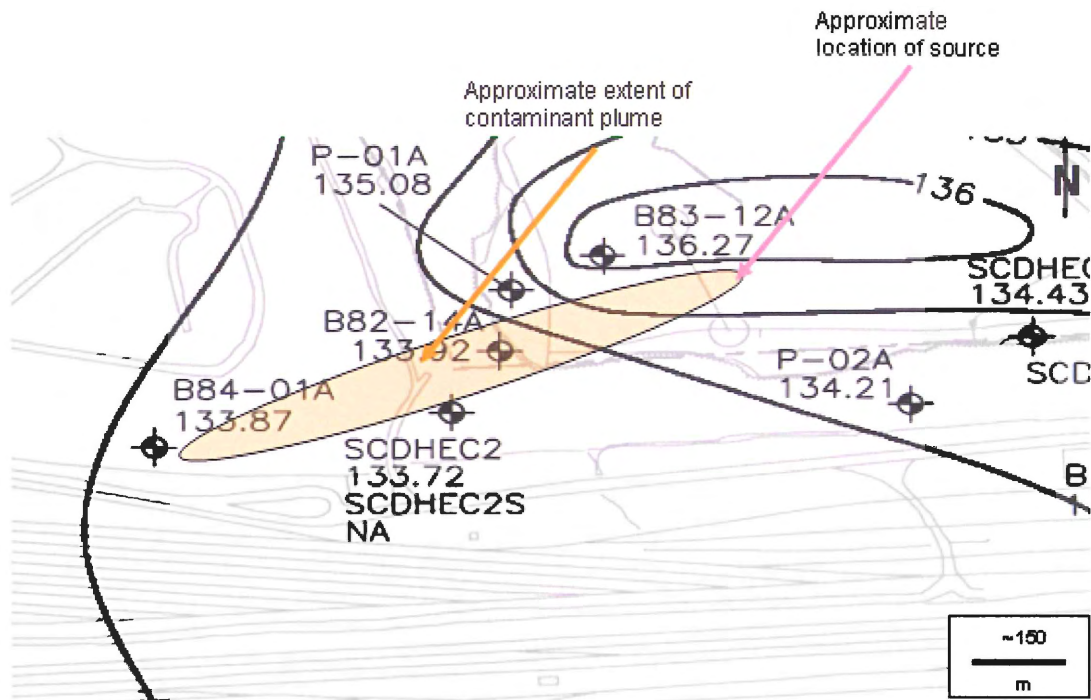


Fig 4.10 - Plume is traveling south west of the source. The extent of the plume is approximately 701m from the source. (The RETEC Group, Inc. & AMEC Earth and Environmental, Inc 2003)

#### 4.4. South Cavalcade Superfund Site, Houston, Texas

##### 4.4.1. Background

This site has been in operation since 1910 and has employed the use of creosote and other various metal salts in its wood treating processes. The 26 hectares (66-acre) site is 4.83 km north of downtown Houston. For the purpose of this study, this site is separated into a north site and a south site because there are two separate significant plumes at the plant that correspond with the North and South areas of the plant (Key Environmental Inc & Groundwater Insight, 2000).

Primarily commercial, industrial, and residential areas neighbor the site. The nearest residence is about 643 km (400 mi) west of the plant. There are no current operations at the site. The nearest downgradient discharge is a stream named little Whiteoak Bayou, which is 2.26 km (7400 ft) from the North site and 1.25 km (4100 ft) from the South site (Key Environmental Inc & Groundwater Insight, 2000).

Water is supplied locally by the city of Houston. The groundwater is from pumping wells (deeper than 304 m below surface). There are no on site water supply wells and The City of Houston supply wells are located hydraulically upgradient from the site with respect to shallow groundwater flow (Key Environmental Inc & Groundwater Insight, 2000).

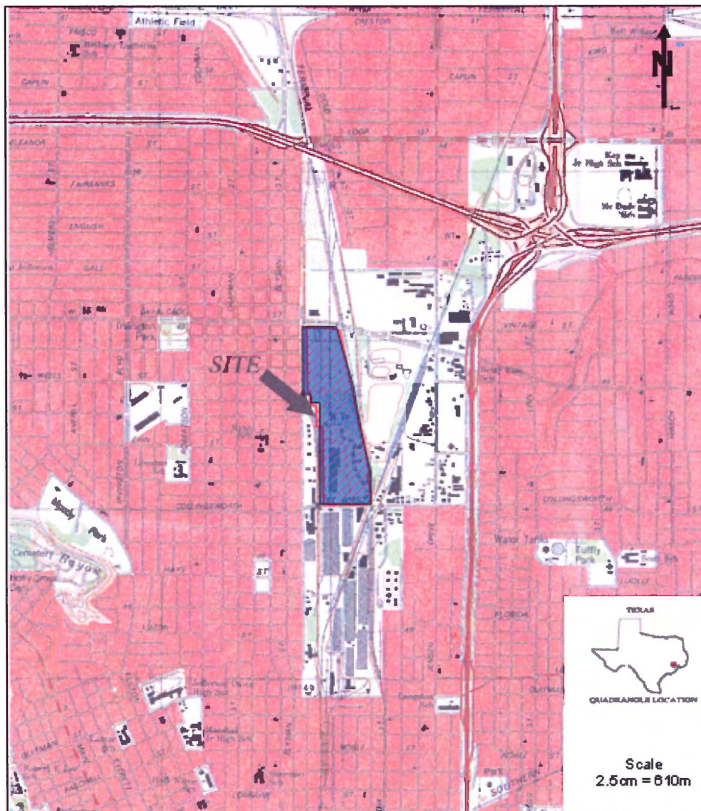


Fig 4.11 - Site location of South Cavalcade Superfund Site, in Houston, Texas (Key Environmental Inc & Groundwater Insight, 2000).

#### 4.4.2 Geology and Hydrogeology

The main hydrologic unit is the shallow zone. This zone is composed of the interbedded clays, silts and sands of the Beamont Formation. The two aquifers that underlie the site are the Chicot and Evageline, which is the principal groundwater source. This zone is approximately 6 m (20ft) below ground surface (Key Environmental Inc & Groundwater Insight, 2000).

The South site is mostly composed of brownish silty /clayey sand, brown-grey silty sand, and brownish-grey silty clay or clay silt and traces of sand, with orange mottles with manganese nodules noted. The fill is composed of shelly materials. The hydraulic conductivity of the South site is  $1.6e^{-3}$  cm/s (Key Environmental Inc & Groundwater Insight, 2000).

In the North site, the fill layer comprises the upper few meters. The main units are predominant brownish grey clay sand, which is between 1 - 3 m. There is also a clayey silt unit and fine sand layer of brownish grey coloring. Bedrock is composed of red-brown clay. The hydraulic conductivity is approximately  $7.8e^{-3}$  cm/s in the North site (Key Environmental Inc & Groundwater Insight, 2000).

The peizometric surface is located 1.2 m below ground surface. The hydraulic gradient in the shallow unit is approximately 0.00457 towards the southwest. The downward vertical hydraulic gradient has been measured between the shallow aquifer and the

underlying discontinuous sand unit, which lies at a depth of 12 - 15 m below ground surface (Key Environmental Inc & Groundwater Insight, 2000).

#### 4.4.2. General NAPL Occurrence

The plume primarily occurs in the bottom half of the shallow aquifer zone unit. The extent of the plume in the South site is 53.8 m. In the North site, the extent of the plume is 164 m. The COI at this site include benzene, toluene, ethylbenzene, and xylene (BTEX). No additional movement of DNAPL is anticipated over, as it has been over 38 years since the plant was last used, the plume has most likely reached steady state (Key Environmental Inc & Groundwater Insight, 2000).

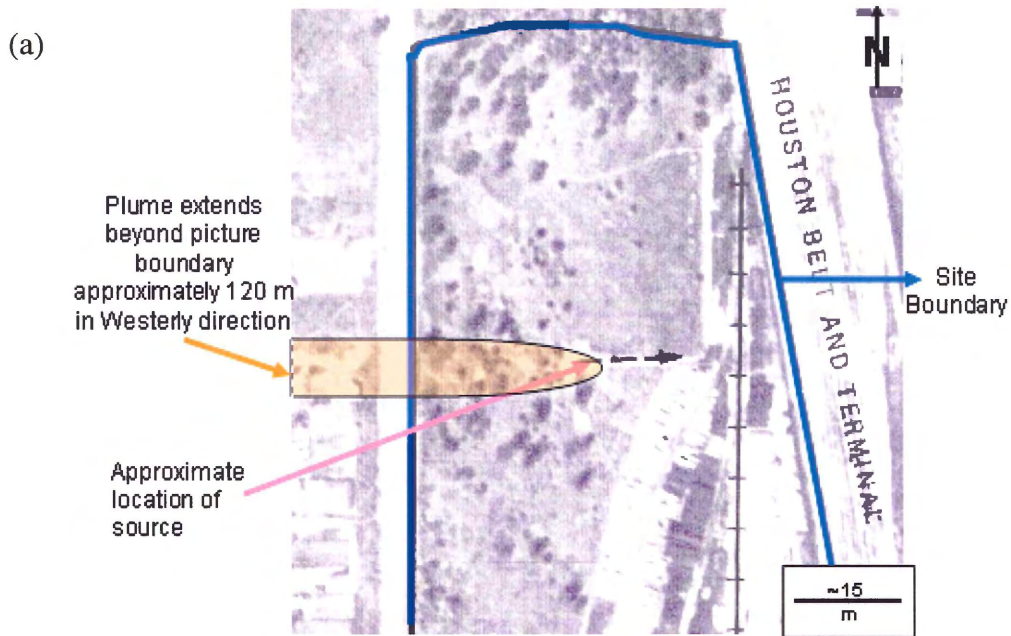


Fig.4.12 - (a) Approximate location of the dissolved plume in the North portion of the site. The plume is traveling in a westerly direction and extends approximately 164 m from the source. (b) Approximate location of the dissolved plume in the south portion of the site. The plume is traveling in a South West direction and extends approximately 53.8 m from the source (airphoto, 1949 ).

A short summary is provided in the table below for the all the sites.

<b>Site</b>	<b>Geological Properties</b>	<b>Hydrogeological Properties</b>	<b>Plume Extent</b>
South Site, Texas	Mostly silty/clayey sand; late Pleistocene aged; fill material composed of shell material	Hydraulic Conductivity: 0.0016 cm/s gradient: 0.00457 Velocity (cm/s)2.4e-5	54m
Grenada, Mississippi	Channel fill deposits of clay sandstone, marl muddy limestone; poorly unconsolidated; separated into 6 lithologic zones; Lower Sand zone (longest plume comprise of silty fine sand to fine to medium sand, with occasional thin discontinuous sandy silt and clay beds, thickness range from 27-50m	Hydraulic Conductivity: 0.0127 cm/s Gradient: 0.0014 Velocity: 5.92e-5 cm/s	133m
North Site, Texas	Late Pleistocene aged interbedded clay and sand.	Hydraulic Conductivity: 0.0078cm/s Gradient: 0.00157 Velocity: 4.08e-5 cm/s	165m
Florence, South Carolina	Easterly thickening wedge of unconsolidated material Pleistocene	Hydraulic Conductivity: 0.0132 cm/s Gradient: 0.00132 Velocity: 1.76e-4 cm/s	701m
North Little Rock, Arkansas	Holocene aged alluvial terrace material, composed of mostly siltstone and silty sandstone, sand and gravel, heterogenous, and poorly unconsolidated	Hydraulic Conductivity: 0.0580 cm/s Gradient: 0.000796 Velocity: 1.59E-4 cm/s	700m

Table 4.1 - Summary of hydrogeological and geological properties of all sites. Table also provides a summary of the extent of all dissolved plume lengths at each site.



## 5. Results and Discussion

### 5.1. Estimate of Time to Reach Steady State

#### 5.1.1. Results

First order decay process is often used to approximate the biodegradation of dissolved phase constituents and it is expressed as the time it takes for the initial concentration to decrease by one half. This measure is known as the constituents' half life ( $t_{1/2}$ ) and it is related to the first order decay constant ( $\lambda$ ) according to the expression:

$$\lambda = \ln(2) / t_{1/2}.$$

Based on this relationship, the dissolved phase concentration ( $C$ ) at any time ( $t$ ) can be estimated from the initial concentration ( $C_0$ ) as shown in the expression:

$$C = C_0 e^{-\lambda t}$$

Using this equation, the time ( $t$ ) for plume to reach steady state can be approximated by re-arranging the expression, where ( $C / C_0$ ) describes the fraction of decrease in concentration:

$$t = \ln(C / C_0) / -\lambda$$

The graph below shows a strong positive correlation between solute half life and the time required for the plume to stabilize. For this model, a source plume with an initial

concentration of 12mg/L was used, as it is a typical value for naphthalene (King and Barker, 1999).

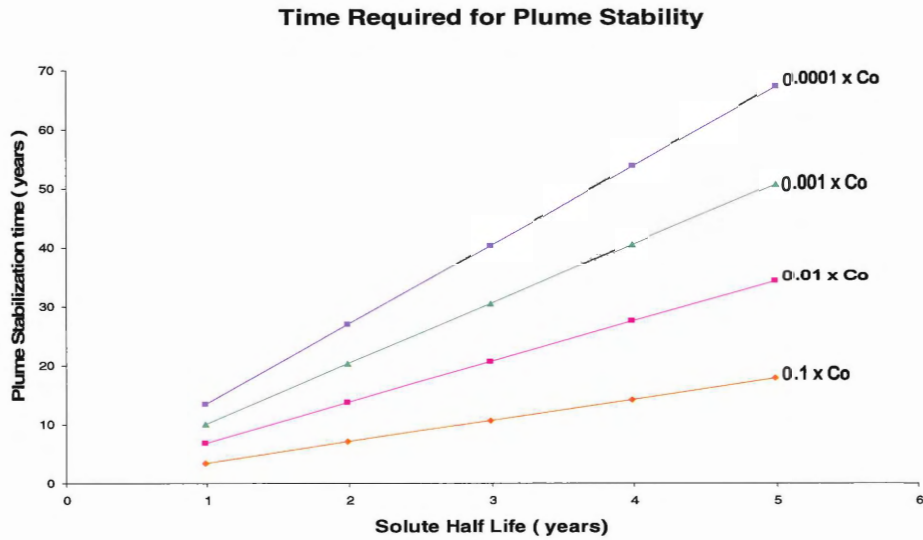


Fig.5.1- Graph's reflects the strong positive correlation between solute half life and time for concentration of dissolve phase plume to stabilize. The results provide an estimated time for plume to reach steady state.

The results show various concentrations of dissolved plume constituents, and the estimated time for the plume to stabilize. For example, for the plume with 0.001 x  $C_o$ , and a half life of 2 years, the estimated time for plume to reach steady state would be 20 years.

### 5.1.2. Discussion

In order to properly evaluate this study, it is important that the dissolved plumes studied have reached steady state, as this study looks to evaluate the processes of natural attenuation for the purpose of remediation.

The contaminants have likely been present at each site since each facility began its operations well over a century ago. Based on the model for plume stability, dissolved contaminant plumes should reach steady state between 20 and 60 years, depending on the concentration of the contaminants in the groundwater. Since the contaminants in this study have been present much longer than that, it can be safely assumed that they are now stable.

Further evidence for plume stability is shown by the King and Barker (1999) study of creosote contaminants in the Borden aquifer. Their research showed that the constituents of the creosote, while showing initial growth, in the course of 4 years of the authors study, these constituents began to show a trend of reducing in size and in concentration.

## 5.2. Plume extent

### 5.2.1. Results

The lengths of the plumes were measured against the velocity of the groundwater at each of the sites. The graph below shows a strong positive relationship between the plume extent and the groundwater velocity (Fig 5.2).

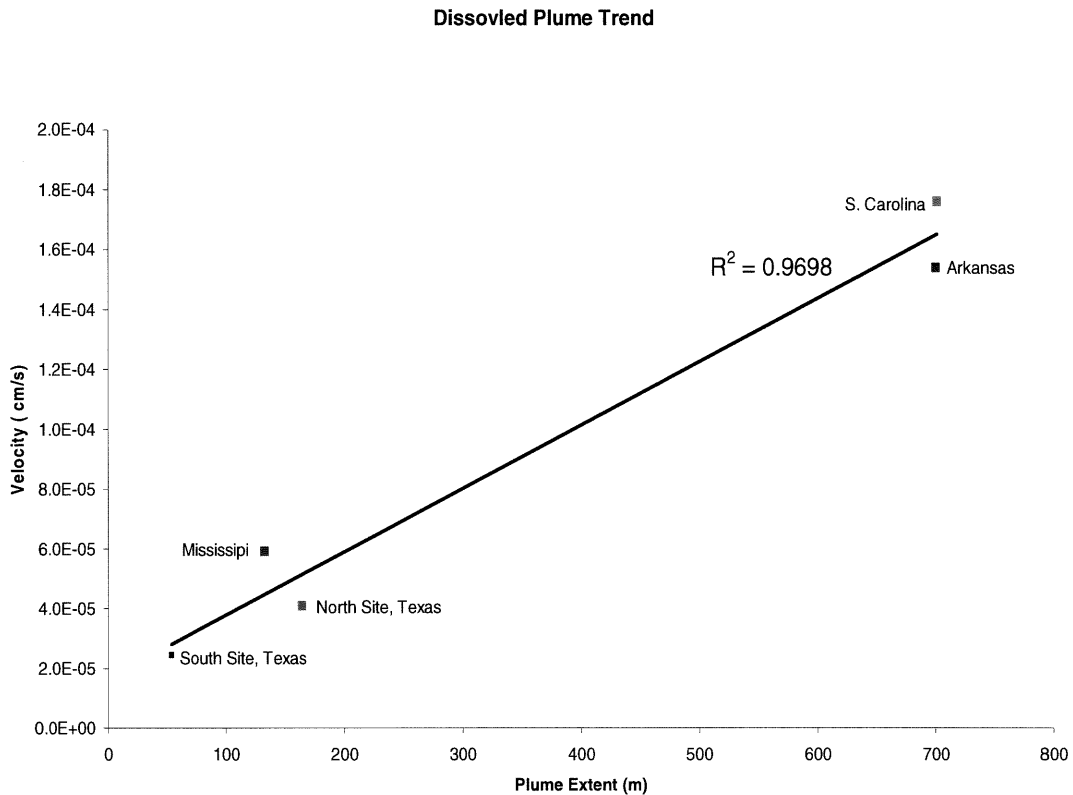


Fig.5.2 - Extent of plumes from each of the site studied is shown to have a strong positive correlation to velocity of groundwater at the sites.

The three sites located at the lower half of the graph, are the sites with the lower groundwater velocity and show shorter plume extent. On the top right, the two sites with the highest groundwater velocity noted also had the longest plume extent.

### 5.2.2. Discussion

The strong positive correlation between the extent of the plume and the velocity is important in providing preliminary estimates of maximum plume length and for identifying effective long term monitoring locations. It can also indicate that it may not be critical to collect samples on a frequent basis.

The data show that there is a strong positive correlation between the dissolve plume lengths and groundwater velocity. The trend is showing that the lower the groundwater velocity, the less the plume grows. This makes sense, as the contaminants will not move as quickly or move far because they undergo biodegradation before groundwater can move the contaminants further.

## 6. CONCLUSION

One of the difficulties mentioned regarding natural attenuation as a remediation method is the often considerable time it takes. Therefore, continued monitoring of contaminants is very important at creosote contaminated sites. This study also suggests that groundwater velocity can be used as a predictive tool for dissolved contaminant plume modeling.

The stability of the plume is an important factor in this study. In order to show the plume had indeed stabilized, simple modeling was done. The model used the relationship between the first order decay and the concentrations of the contaminants to estimate time for the plume to reach steady state (King, et. al. 1999). For a plume with a final concentration of 0.001 of the initial concentration (which were the detection limits used in this study) and a biodegradation rate of 2, the plume should stabilize after 20 years. The sources in this study have been emplaced for well over century, so based on the modeling, the plumes should be well stabilized by now.

The data collected from the five sites studied show that there is a strong positive correlation between the dissolve plume lengths and groundwater velocity. Lower groundwater velocity produces shorter dissolved phase plume lengths. Alternately, sites with higher velocities show longer dissolved phase plumes. This likely occurs as contaminants undergo natural attenuation before groundwater moves them further. Additional sites are recommended to further evaluate the conclusions of this study.

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