

Utilizing ArcScene and GMS 5.0 to Evaluate Environmental Cleanup Strategies

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Abstract

GIS and the Department of Defense Groundwater Modeling System (GMS) programs were used during an environmental cleanup selection process to evaluate the presence of creosote contamination in the subsurface. These programs were used in concert to: (1) manage and manipulate complex data sets; (2) generate three-dimensional (3D) interpolated solids; (3) produce volume estimates of potential creosote in the subsurface; and (4) create visual animations of the simulated subsurface contamination. During the data interpretation process, several interpolation methods available in GMS were evaluated to determine the most representative interpretation of the dataset (based on field records indicating visual evidence of creosote in the subsurface). Supplemental investigations were completed to test the ability of the numeric model to reproduce site conditions based upon 3D interpolation strategies. Together, these items were combined to produce a comprehensible and informative 3D animation, using ArcScene, for presentation to the engineers, project managers, and clients.

Introduction

Estimation of cleanup costs at contaminated sites is a difficult process due to the great uncertainty associated with estimating the contaminant mass in the subsurface. Often, engineers are in a situation that requires him/her to design a remedial system using values that were obtained from rough approximations, thereby leading to exaggerated cleanup costs. GeoSyntec has developed an innovative solution to assess contaminant mass using the solids module in the Department of Defense (DOD) Groundwater Modeling System (GMS) version 5.0³, and ArcScene, a three dimensional (3D) viewing program embodied within the 3D Analyst extension of ArcGIS, developed by ESRI.

GeoSyntec selected an industrial area in northern Florida ([Figure 1](#)), (hereinafter referred to as “the Site”) to share an in-house, innovative approach for simplifying and visualizing complicated 3D problems. All affiliations to the facility and associated parties have been removed from this paper for confidentiality purposes.

Premise

A large mass of creosote has been detected in the subsurface at the Site and requires active remediation to prevent migration to adjoining properties. Creosote is a thick, black, viscous liquid, generated as a product of high temperature treatment of beech and other woods, coal, or resin from the creosote bush. Long-term exposure to creosote has been documented to cause liver damage, skin irritation, and cancer⁴. Several potentially responsible parties (PRPs) are involved; each of whom hired private consultants to evaluate multiple remedial options for the most cost-effective method to alleviate this burden.

The focus of this discussion is segmented into two phases: Phase 1 (July 2003 soil boring investigation) and Phase 2 (November 2003 supplemental investigation).

The Phase I investigation utilized ArcScene and GMS to:

- evaluate the validity of a previous investigation conducted on the Site;
- analyze the correlation between peat in the subsurface and possible creosote contamination; and to
- visualize contamination in 3D.

The Phase II investigation utilized ArcScene and GMS to:

- validate the conceptual model and reduce the uncertainty associated with interpolation error;
- visualize contamination in 3D; and to
- generate areas of excavation and refine the estimated volume of impacted soil.

Phase I Confirmation Borings (July 2003 Investigation)

The first phase of the investigation conducted by GeoSyntec in July 2003 consisted of advancing 29 soil borings (SB-2 through SB-30) to assess the horizontal and vertical distribution of the creosote plume and to provide confirmation sampling to assess the accuracy of a multi-electrode (MER) resistivity survey, used previously by another consultant, to delineate the creosote contamination at the Site. Two field technicians were responsible for logging the soil cores in ½-ft intervals. The data for this

investigation was limited to either containing or not containing evidence of creosote. Using the recorded data from the field logs, a “zero-one dataset”, using “zero” to represent no evidence of creosote and “one” to represent the contrary, was generated.

Isosurfaces are essentially 3D contours or surfaces of equal value. The process of generating isosurfaces for distinct MER intervals provide little room for subjective error, regardless of the interpolation scheme selected to generate the solid. Conversely, the absence or presence of free product contamination, as demonstrated in our zero-one data set, is not as easily definable. Subjective interpretation is inherent in the appointment of the appropriate isosurface using a zero-one data set because a tangible definition of true and false in the areas of no data cannot be determined.

The interpolation stage is the most critical step in the generation of a three dimensional plume map⁵. For that reason, the added uncertainty of an indefinable boundary needed to be accounted for to substantiate the model’s predictive capabilities. Four techniques (linear, inverse distance weighted, natural neighbor, and kriging) were evaluated to determine the optimal interpolation scheme for these investigations. The statistical approach to achieving an optimal interpolation scheme is beyond the scope of this paper. The discussion will concentrate on tasks that were complemented by the use of 3D visualization programs. However, a chronology of processes will be discussed that will support our selection of the appropriate scheme.

Using ArcScene and GMS in unison, GeoSyntec established a methodology that can be employed in a multitude of scenarios, beyond the environmental arena, to validate a 3D model, reduce uncertainty in model and design, and minimize extraneous expenses associated with the intended use of the model.

Validation of Previous Investigation

The results of the MER investigation were provided to GeoSyntec in spreadsheets. Resistivity measurements were provided in ohm-meters (ohms) at each electrode location at multiple depths. The raw 3D data was imported into the GMS for analysis. Once the data had been re-formatted, a solid was generated by means of interpolating the 3D data to a grid and displaying various isosurfaces representing potential creosote, as defined by the previous consultant.

The results of the Phase 1 soil investigation were initially compared in two dimensions (2D) with the scaled, three-dimensional resistivity data in order to determine whether a positive correlation existed between areas of low resistivity, as measured during the MER survey, and areas of creosote accumulation, as observed during the soil boring investigation. This was accomplished by taking selected horizontal “slices” through the subsurface of the model-generated solid. The MER data within these two-dimensional “slices” was represented in plan view on a map and the soil boring data now becomes a “point” on the plan. In this manner, the presence or absence of free product within a particular “slice” (depth) can be shown superimposed on the resistivity reading for that depth ([Figure 2](#)). Four possible conditions were used to determine correlation:

- False Positive – Creosote predicted, but not found
- False Negative – Creosote not predicted, but found
- True Positive – Creosote predicted and found
- True Negative – Creosote not predicted and not found

The evaluation showed that the MER prediction was consistent with observed data in 20 of 28 borings at 6 ft BLS, and inconsistent with observed data in 21 of 28 borings at 19 ft BLS. Based on the results of our comparison, a definitive correlation did not exist.

A Comparison of Peat in the Subsurface and MER Measurements

A theory was put forward that low resistivity peat was influenced by organic-rich clays that were noted to occur at approximately 10 to 20 ft below land surface (BLS) consistently throughout the Site. It was suggested that the organic-rich materials may have interfered with the resistivity response within these sediments. This was tested by generating a superimposed peat layer in ArcScene in the MER model that was previously generated ([Figure 3](#)). The green solid in Figure 3 represents the peat and the red solid represents the potential creosote based upon the MER data. Using the “fly-thru” tool, GeoSyntec was able to conclude that a correlation between peat in the subsurface and the MER anomalies could not be confirmed. For that reason, a distinct model, using the information from the Phase I investigation was required.

Solids Generation

The DOD GMS software was used to generate a 3D representation of creosote in the subsurface. The field logs were converted to a zero-one data set and imported as 3D

scatter point data. Visual evidence of creosote, or lack thereof, was reported at each boring location in intervals of 0.5 ft. The spreadsheet was brought into GMS as a 3D scatter point data set to represent information collected during the July 2003 boring investigation. The 3D scatter points were interpolated to a 2ft X 2ft X 2ft grid, encompassing the entire data set, using the inverse distance weighted (IDW) solution with a modified vertical anisotropy of 0.1. The modification of anisotropy was initially investigated by Jones et al⁴ for sample data sets that are clustered along vertical traces, similar to our zero-one data set. Jones et al concluded that modifying anisotropy in the IDW solution reduced the bias in the vertical direction, thereby condensing the geometry in the xy direction. A comparison of the four interpolation methods for this exercise concurs with this conclusion.

The Non-uniqueness Problem

The most difficult aspect of the solids generation, subsequent to the selection of the interpretation scheme, was the selection of an appropriate isosurface value (ranging between 0 and 1) to illustrate the actual extent of the creosote plume. This was tested by bringing the 3D solid generated in GMS into the ArcScene interface. The borehole locations, the virgin data used to generate the solid, the former above-ground storage tanks (ASTs) associated with the contamination, and an aerial photograph were also brought into ArcScene and represented in space in the x,y, and z dimensions. Using tools in ArcScene, the transparency of the solid was increased to validate the model and insure that the final estimated plumes (both liberal and conservative) did not violate the true data. Validation consisted of rotating and zooming in at each borehole location and checking the model interpolation versus the field data. Evidence of creosote was symbolized in red; no evidence of creosote was shown in blue. By increasing the transparency of the interpolated solid, validation was possible. However, a second factor comes to consequence, the non-uniqueness problem.

The non-uniqueness of a solution applies when a large number of parameter combinations, which may differ significantly, can provide equally reasonable matches between model results and field observations.⁶ In the Phase I model, a range of isosurface values between “0” (no evidence of creosote) and “1” (evidence of creosote) satisfied model validation; however, the level of uncertainty in the model’s predictive capabilities was considered excessive. Consistent with McCombie and McKinley⁷, the amount of effort committed to the validation process before the model is considered acceptable is

subjective and depends on the complexity of the system and the initial objective for using the model. That being the case, a second phase of soil borings were advanced to refine the model predictions and reduce the uncertainty in our analysis.

Phase II Investigation

Uncertainty in this model is attributed to the appropriate selection of the isosurface term (i.e. the number assigned to create the surfaces of equal value). The team was presented with a conflict - how much uncertainty was considered sufficient to consider the model acceptable.

As Hassan point out, the cost of collecting data and conducting analyses should be considered in designing validation plans. There is a limit where increased investment does not significantly increase confidence in the model.⁸ Using this approach, it was determined that a second phase of 17 confirmation borings (SB-31 through SB-47) was warranted. This was evaluated by assessing the cost of a second investigation and visually identifying the areas of highest sensitivity.

In November 2003, Phase II investigations were complete. This phase of work consisted of advancing 17 validation soil borings in areas that were determined to be highly sensitive in the model. It was determined that an inverse-distance weighted solution, modifying vertical anisotropy to 0.1 and maintaining a horizontal anisotropy of 1.0 produced the most representative solution to the data set. After a series of iterations and validation steps, conservative (worst case) ([Figure 4](#)) and liberal (best case) ([Figure 5](#)) estimates were formulated. Confidence in the selected interpolation interval was confirmed using the “fly-thru” feature in ArcScene. Interested parties were provided a movie clip showing the animated validation process.

Investigations associated with the sensitivity of the vertical anisotropy used for the IDW solutions (Phase I and Phase II) are ongoing and will be presented separately.

Excavation Areas vs. Estimated Volumes of Impacted Soil

A second goal of this investigation was to provide the engineers with a refined volume estimate of contaminated soil. It is common in the environmental industry to develop excavation areas in plan view (2-dimensions (2D)) that encompass the contaminated regions. This is typically done by generating excavation areas based upon the plan view

representation of contamination, as shown in [Figure 6](#) and [Figure 7](#). Based upon the aerial coverage of impact, it could be estimated the approximate volume of excavated soil that would be removed in order to clean up the contamination; however, some of the remedial options recommended required a more thorough and refined analysis.

One case in particular was the proposed method of in-situ stabilization. In situ-stabilization consists of augering to the intervals of impacted soil at which point grout will be injected and mixed with the native impacted soil to immobilize the transport of creosote in the subsurface. To weigh the costs and benefits of this technique, an approximation of the amount of grout needing to be injected was critical. Therefore, the typical 2D representation of impacted areas would provide a gross overestimation of the volume of grout required to sufficiently stabilize the contamination, if the third dimension was not accurately represented. This can be demonstrated by visualizing the 2D areas of impact, initially, as shown in [Figure 8](#) and [Figure 9](#). Going one step further, GeoSyntec simultaneously viewed the 3D animation aside the 2D aerial representation, rotated the solid at different angles, and zoomed in at specified locations. Using this approach, it was possible to refine the impacted areas in the third dimension. As a final step to verify the intervals of impacted soil for each area, 2D polygons (shown in [Figure 8](#) and [Figure 9](#)) were extruded in the third dimension ([Figure 10](#)), consistent with the specified interval as noted during comparison of the 2D and 3D interpretations.

Cost Saving Analysis

For internal purposes, a straight-forward cost savings analysis was performed to assess the benefits of incorporating the third dimension in our analysis. The cost-benefit analysis is beyond the scope of this paper; however, a simplified visualization of the methodology used is shown in [Figure 11](#) and tabulated in [Table 1](#). If an estimation of the volume of impacted soil was provided based merely on the aerial coverage of impacted area to the depth of deepest impact, the predictions would have overestimated the actual impact zones by 240%. Keeping in mind the limitations to numerical models and the uncertainties associated with heterogeneities that cannot fully be accounted for, it is apparent that the benefits of incorporating 3D visualization software are justified in this case.

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- ³ Department of Defense Groundwater Modeling System (GMS). 2004, Version 5.0.
- ⁴ Agency for Toxic Substances and Disease Registry Web Site (<http://www.atsdr.cdc.gov/tfacts85.html>)
- ⁵ Jones, Norman L. Davis, Jeffrey R. Sabbah, Walid, “A Comparison of Three-Dimensional Interpolation Techniques for Plume Characterization” *Groundwater: Volume 41*. July-August 2003. pp.411-419.
- ⁶ Zheng Chunmiao. Bennet, Gordon D. *Applied Contaminant Transport Modeling: Theory and Practice*. 1995. p.261.
- ⁷ McCombie, C. and McKinley I. “Validation – Another Perspective”. *Groundwater. Volume 31. No. 4*. pp.530-531.
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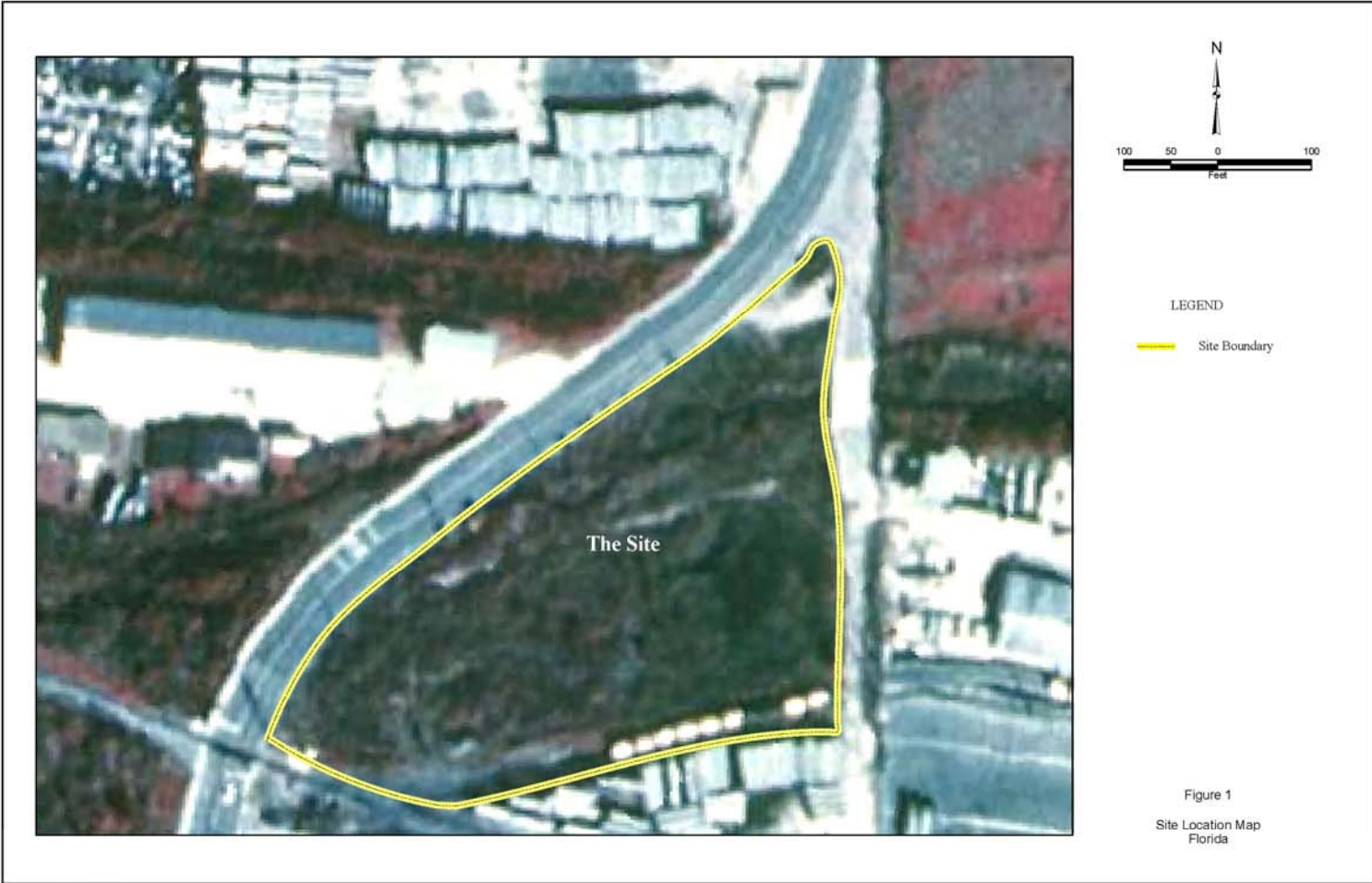
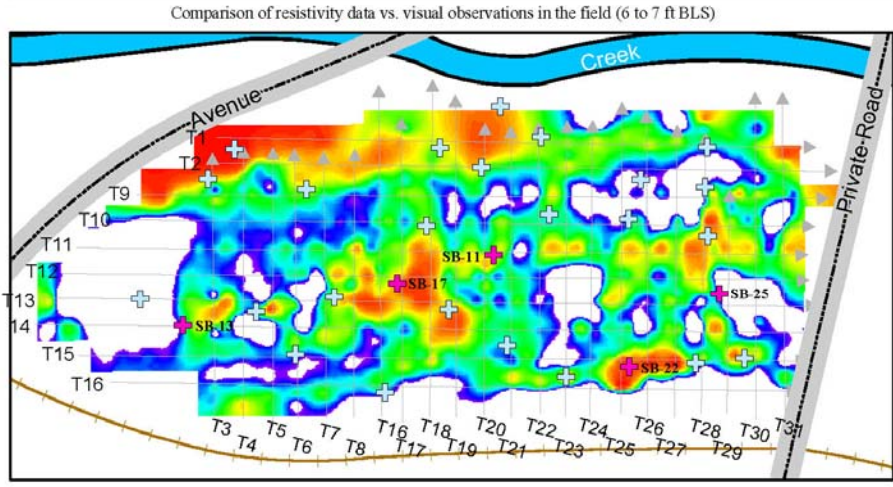
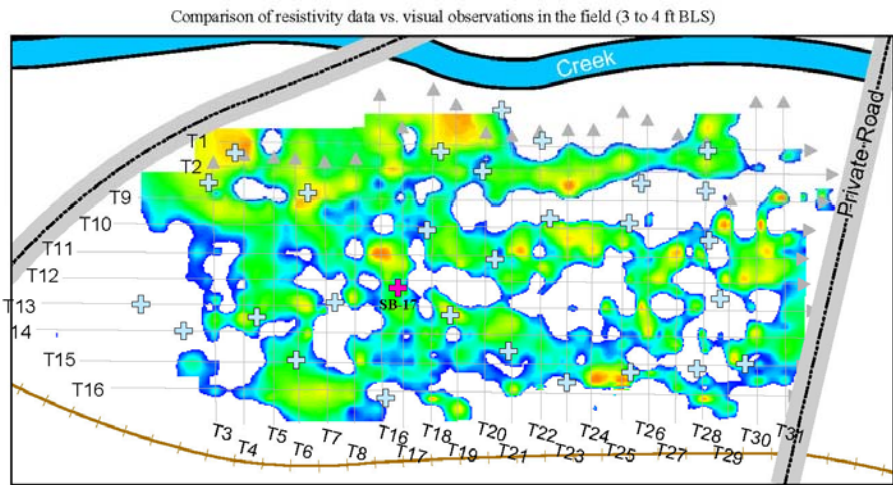


Figure 1
Site Location Map
Florida



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(Adjusted view -20° NNE)

- LEGEND
- +— Railroad
 - █— Creek
 - ▶— Transect Grid
 - +— Soil boring showing no evidence of creosote contamination
 - +— Soil boring showing evidence of creosote contamination

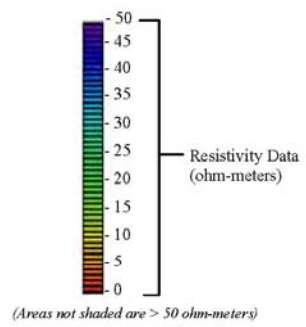
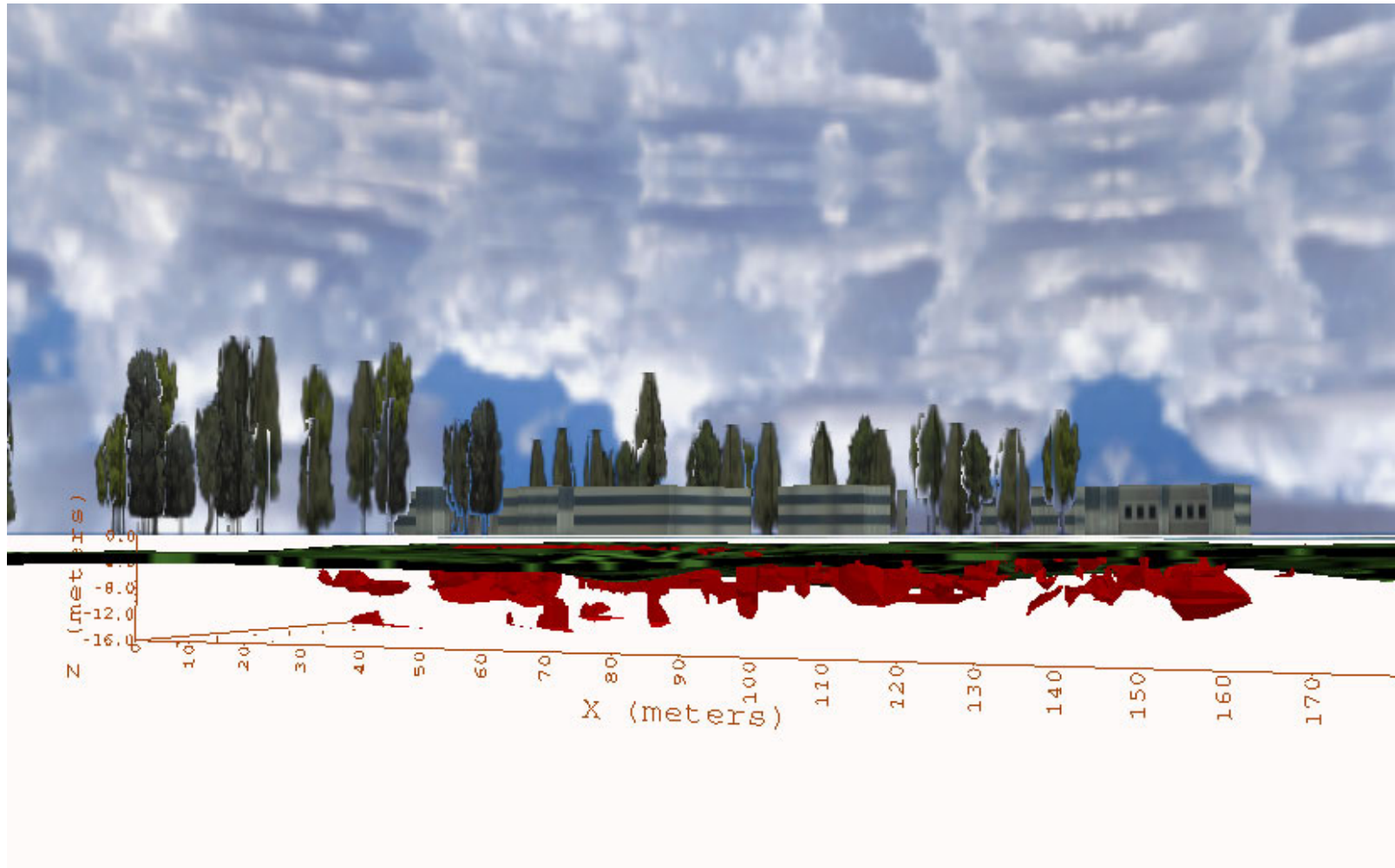


Figure 2
MER/Soil Boring Comparison
(3 to 4 ft BLS) and (6 to 7 ft BLS)
Florida






Conservative Estimate of Creosote in Subsurface

(Upper Aquifer: ~ 15,000 cubic yards)

(Limestone: ~ 2,800 cubic yards)



-  Approximate location of former above-ground storage tank (AST)
-  Model-interpolated extent of creosote contamination in the upper aquifer zone
-  Model-interpolated extent of creosote contamination in the limestone






Liberal Estimate of Creosote in Subsurface

(Upper Aquifer: ~ 5,800 cubic yards)

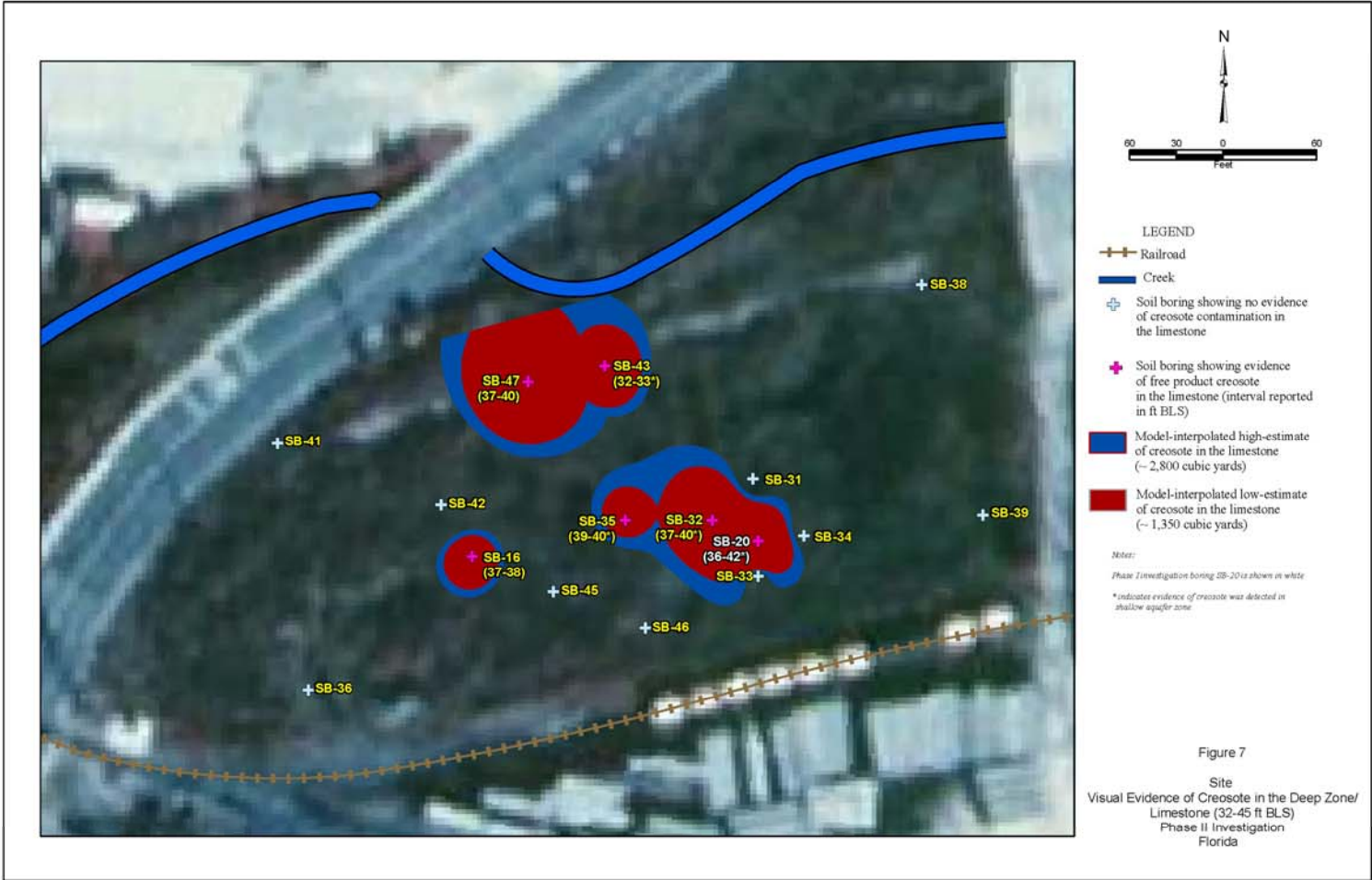
(Limestone: ~ 1,350 cubic yards)



-  Approximate location of former above-ground storage tank (AST)
-  Model-interpolated extent of creosote contamination in the upper aquifer zone
-  Model-interpolated extent of creosote contamination in the limestone







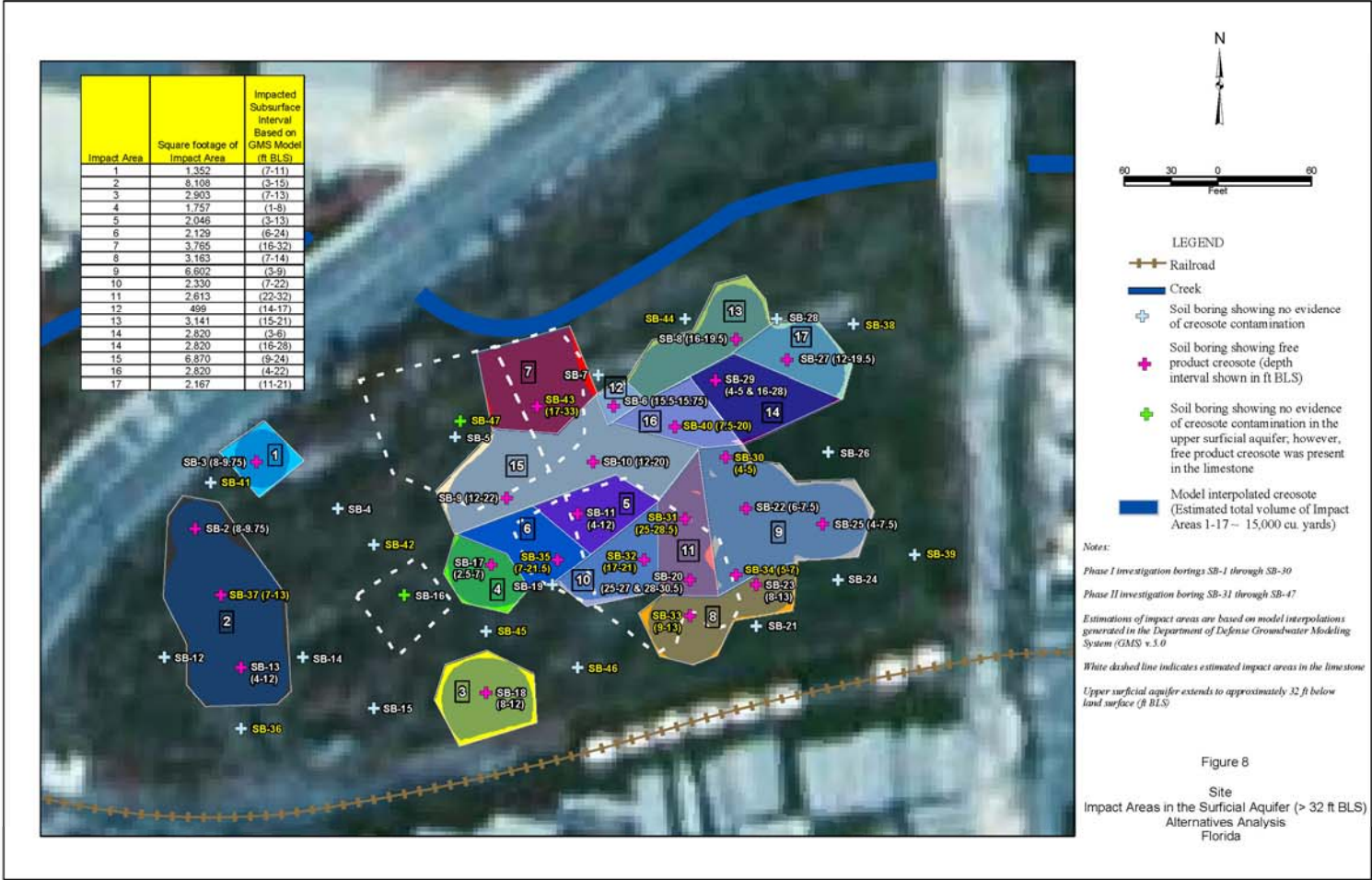
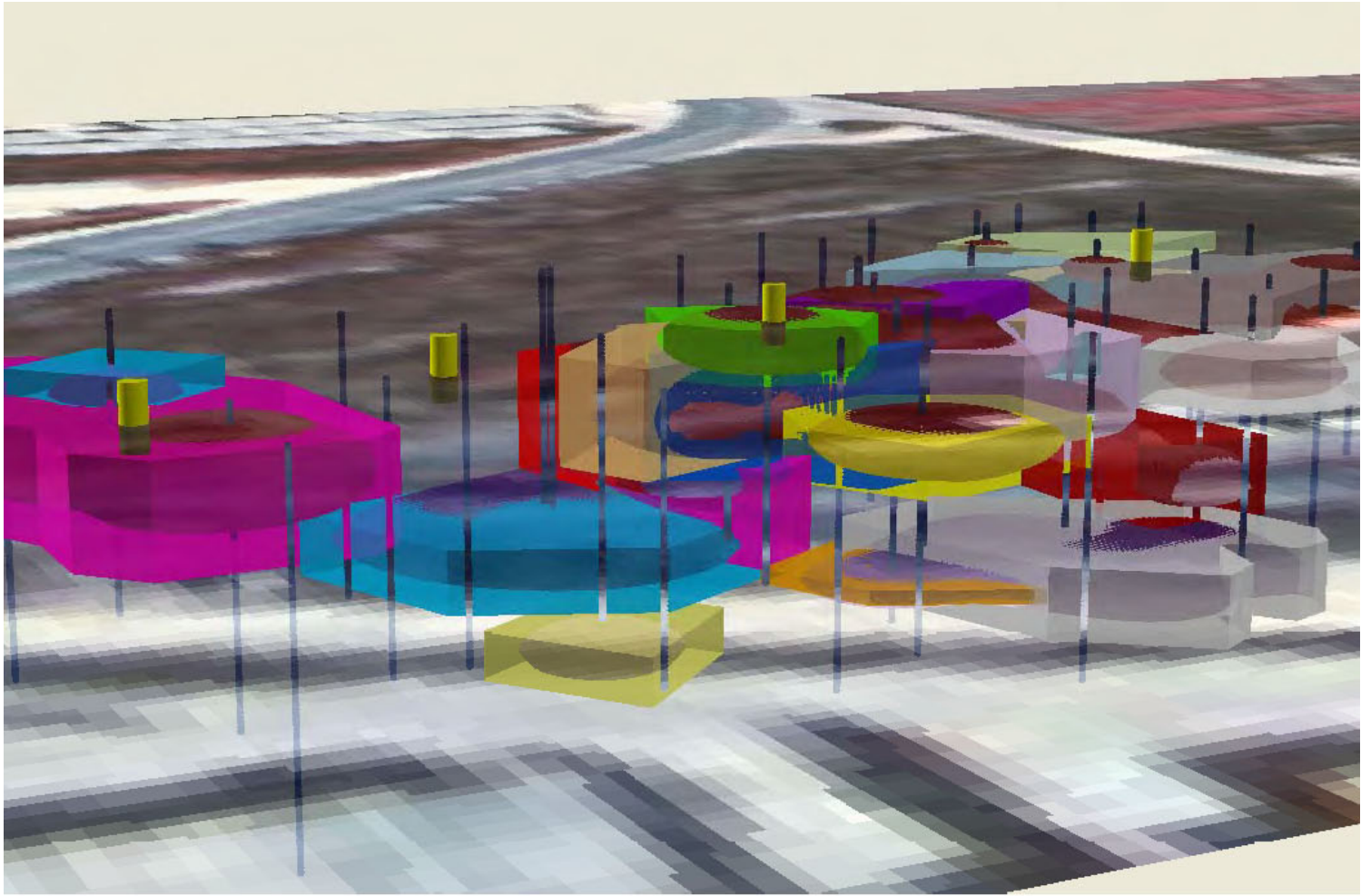


Figure 8
 Site
 Impact Areas in the Surficial Aquifer (> 32 ft BLS)
 Alternatives Analysis
 Florida



Figure 9
Site
Impact Areas in the Limestone
Florida



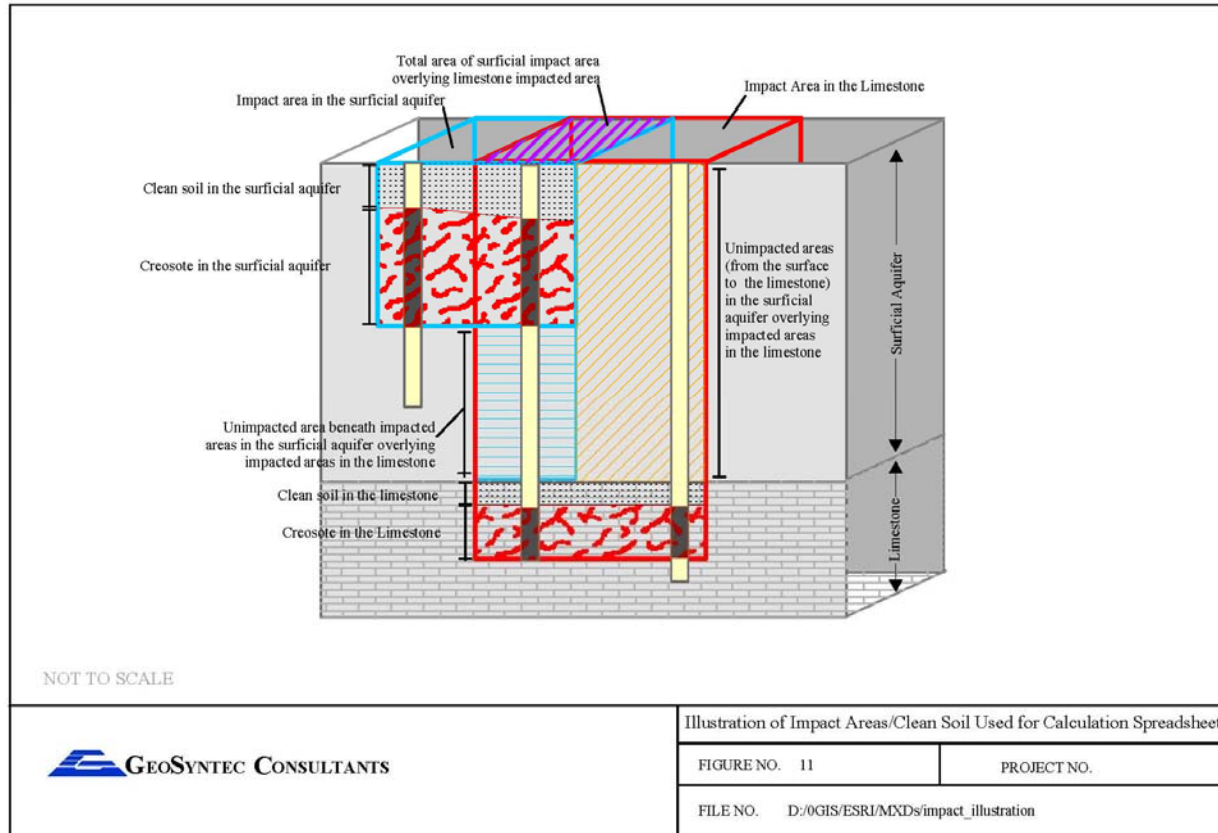


TABLE 1a - GMS MODEL INTERPOLATED CREOSOTE ESTIMATES AND CALCULATED VOLUME OF IMPACTED AREA IN THE SURFICIAL AQUIFER

Id	Impact Area (ft2)	Interval (ft BLS)	Thickness of creosote (ft)	Depth (ft BLS)	Total Volume of Impacted Area to Depth (clean soil and creosote)	Estimated Clean Soil in Impact Area (cubic ft)	Estimated Creosote in Impact Area (cubic ft)	Total Volume to Depth in Impact Area (cubic yards)	Volume Clean Soil in Impact Area (cubic yards)	Volume Creosote in Impact Area (cubic yards)
1	1,352	(7-11)	4	11	14,888	9,462	5,407	561	350	200
2	8,108	(3-15)	12	15	121,626	24,325	97,301	4,505	901	3,604
3	2,903	(7-13)	6	13	37,740	20,322	17,419	1,398	753	645
4	1,757	(1-8)	7	8	14,054	1,757	12,298	521	65	455
5	2,046	(3-13)	10	13	26,602	6,139	20,463	985	227	758
6	2,129	(6-24)	18	24	51,084	12,771	38,313	1,892	473	1,419
7	3,765	(16-32)	16	32	120,488	60,244	60,244	4,463	2,231	2,231
8	3,163	(7-14)	7	14	44,287	22,144	22,144	1,640	820	820
9	6,602	(3-9)	6	9	59,420	19,807	39,613	2,201	734	1,467
10	2,330	(7-22)	15	22	51,254	16,308	34,946	1,898	604	1,294
11	2,613	(22-32)	10	32	83,623	57,491	26,132	3,097	2,129	968
12	499	(14-17)	3	17	8,488	6,990	1,498	314	259	55
13	3,141	(15-21)	6	21	65,968	47,120	18,848	2,443	1,745	698
14	2,820	(3-6)	3	6	16,919	8,460	8,460	627	313	313
14	2,820	(16-28)	12	28	78,957	45,119	33,839	2,924	1,671	1,253
15	6,870	(9-24)	15	24	164,888	61,833	103,055	6,107	2,290	3,817
16	2,820	(4-22)	18	22	62,038	11,280	50,758	2,298	418	1,880
17	2,167	(11-21)	10	21	45,514	23,840	21,673	1,686	883	803
TOTAL	55,087	-	-	-	1,050,901	438,491	612,410	38,922	16,240	22,682
BASED ON GMS MODEL INTERPOLATED CREOSOTE ESTIMATES AND CALCULATED VOLUME OF IMPACTED AREA IN THE SURFICIAL AQUIFER								38,922	23,922	15,000

Note: Impact Area 14 has two zone in upper aquifer that show evidence of creosote
 Estimated creosote in impact area assumes consistent thickness of creosote within entire impact area

TABLE 1b - GMS MODEL INTERPOLATED CREOSOTE ESTIMATES AND CALCULATED VOLUME OF IMPACTED AREA IN THE LIMESTONE

Id	Area (ft2)	Interval (ft BLS)	Thickness of creosote (ft)	Depth (ft BLS)	Total Volume of Impacted Area to Depth in Limestone (>32 ft BLS) (clean soil and creosote)	Estimated Clean Soil in Impact Area (cubic ft)	Estimated Creosote in Impact Area (cubic ft)	Total Volume to Depth in Impact Area (cubic yards)	Volume Clean Soil in Impact Area (cubic yards)	Volume Creosote in Impact Area (cubic yards)
1	8,096	(35-43)	8	43	89,053	24,287	64,766	3,298	900	2,399
2	3,162	(52-34)	2	34	6,323	0	6,323	234	0	234
3	2,024	(36.5-39.5)	3	40	16,188	10,118	6,071	600	375	225
4	2,027	(38-40)	2	40	16,219	12,164	4,055	601	451	150
5	7,608	(35-43)	8	43	83,689	22,824	60,865	3,100	845	2,254
TOTAL	22,916	-	-	-	211,473	69,393	142,079	7,832	2,570	5,262
BASED ON GMS MODEL INTERPOLATED CREOSOTE ESTIMATES AND CALCULATED VOLUME OF IMPACTED AREA IN THE LIMESTONE								7,832	5,032	2,800

TABLE 1c - UNIMPACTED AREAS IN THE SURFICIAL AQUIFER OVERLYING IMPACTED AREAS IN THE LIMESTONE

Surficial Aquifer Impact Area ID	Area (sq ft)	Depth of Surficial Impact (ft BLS)	Volume of Unimpacted Area Beneath Impacted Areas in Surficial Aquifer Overlying Impacted Areas in the Limestone (cu ft)	Limestone Impact Area ID	Area (sq ft)	Total Area of Surficial Impact Areas Overlying Limestone Impacted Areas (sq ft)	Total Area of Unimpacted Areas (from the surface to the limestone) in the Surficial Aquifer Overlying Impacted Areas in the Limestone (sq ft)	Total Volume of Unimpacted Areas (from the surface to the limestone) in the Surficial Aquifer Overlying Impacted Areas in the Limestone (cu ft)	Total Volume of Unimpacted Areas in the Surficial Aquifer Overlying Impacted Areas in the Limestone (cu ft)	Total Volume of Unimpacted Areas in the Surficial Aquifer Overlying Impacted Areas in the Limestone (cu yards)
15	2,140	24	17,117	1	8,096	3,114	4,982	159,417	176,533	6,538
7	974	32	0							
15	805	24	4,840							
7	2,557	32	0	2	3,162	3,162	0	0	4,840	179
10	392	22	3,925							
6	1,270	24	10,156	4	2,027	1,971	56	1,787	21,748	805
5	309	13	5,879							
8	1,311	14	23,593	5	7,608	6,990	618	19,785	99,858	3,698
6	24	24	192							
9	307	9	7,061							
10	1,925	22	19,245							
11	1,827	32	0							
5	1,585	13	29,727							
15	32	24	255							
(no overlying impacted areas)			0	3	2,024	0	2,024	64,768	64,768	2,399
								TOTAL	367,747	13,620

TOTAL FOR SITE (UPPER AND LIMESTONE UNITS)	Impact Area (ft2)	Interval (ft BLS)	Thickness of creosote (ft)	Depth (ft BLS)	Total Volume of Impacted Area to Depth (clean soil and creosote)*	Estimated Clean Soil in Impact Area (cubic ft)	Estimated Creosote in Impact Area (cubic ft)	Total Volume to Depth in Impact Area (cubic yards)	Volume Clean Soil in Impact Area (cubic yards)	Volume Creosote in Impact Area (cubic yards)
	62,900	-	-	Max (43 ft BLS)	1,630,122	-	-	60,375	42,575	17,800

* Total Impact Area includes estimated creosote and clean soil within the impact areas in the surficial aquifer (Table 1A), the limestone (Table 1B), and the estimated clean soil in areas in the surficial aquifer that overlay the limestone impact areas that were not accounted for in Table 1A (Table 1C) - (below the surficial impact areas, but above the limestone or areas that do not spatially overlap surficial impact areas, but overlay the impact areas in the limestone)