3D SOLIDS & PARAMETER MODELING TO FACILITATE TRIAD-COMPLIANT RAPID SITE CHARACTERIZATION

Todd R. Kincaid[1], Kevin E. Day[1], and Roger Lamb[2]

ABSTRACT

A Triad investigation combining Electrical Resistivity Imaging (ERI), Soil Conductivity/Membrane Interface Probe (SC/MIP), and targeted soil and groundwater analytical sampling was used to aid in redevelopment analysis of a 13-acre property that formerly contained an oil refinery. A digital 3D site conceptual model was developed for the property using the EarthVision™ software in order to more rapidly and effectively visualize and interpret the field data. The initial geologic model consisted of four soil zones in a surficial aquifer over a bedrock surface. The soil zones were created from indicator grids describing the probability of occurrence for each zone based on lithologic contacts described in borehole data. Specific sets of cross-sectional and plan views of the model were then produced to facilitate analysis of key areas of the property. 3D parameter modeling routines were then developed for ERI and SC/MIP data obtained from an initial survey. Those models were correlated to soil and groundwater analytical data to identify site-specific relationships between the ERI and SC/MIP data and petroleum compound concentrations. Afterward, the parameter models were rapidly updated with new data immediately after collection and the resulting figures posted to a project website such that an analysis of the data could be used to guide further data collection at each step of the field effort. The data collection & modeling process was repeated until fuel-impacted soils were satisfactorily constrained in both the horizontal and vertical extent. In total, the delineation process took less than one year, which is estimated to be significantly shorter and therefore less costly than if a standard characterization approach was used. Additional benefits derived from the modeling-based approach included fuel-impacted soil volume estimation per zone (i.e. saturated and unsaturated), expedited figure and graphics production for reports and presentation, and more effective dissemination of results to the responsible regulatory agencies.

INTRODUCTION

Triad Approach: The Triad system was developed by the US Environmental Protection Agency (EPA) to manage decision uncertainty by increasing stakeholder confidence that decisions were made correctly and cost-effectively (Crumbling, 2004). The approach was developed in response to the disappointing duration, cost, and efficacy typical of

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[1] GeoHydros, LLC – Specialized Geological Modeling Group, 27 Keystone Ave Reno NV 89503; PH (775) 337-8803; email: kincaid@geohydros.com; day@geohydros.com

[2] Delta Consultants, 8809 Long Street, Lenexa, KS 66215; PH (913) 492-4251; email: RLamb@deltaenv.com

hazardous waste characterization and remediation efforts. At the core of the approach is the development and evolution of a Comprehensive Site Model (CSM), which is intended to synthesize all existing and new data into a shared understanding of:

1. the distribution and quantity of contamination at a site;
2. how concentrations may be controlled by geologic conditions;
3. the probable fate and migration of the contamination;
4. who might be exposed to the contamination or degradation products; and
5. the options for contaminant cleanup, mitigating exposure, and managing risk.

Implementation of the Triad approach involves three primary components: systematic project planning, dynamic work strategies, and real-time measurement systems. Systematic project planning is the process of comprehensive and ongoing project management, allowing for rapid response to changing project factors. The primary purpose is to have all members of the workgroup (owner, managers, consultants, regulators, etc) agree on a characterization process rather than a specific product. In doing this, the workgroup must understand that the CSM, and thus remediation strategies and goals, will very likely evolve as new data is gathered during the site assessment. The main goal then becomes focused on testing the evolving CSM by designing and implementing targeted data collection strategies rather than scheduling some set of pre-determined or standard data collection efforts.

Dynamic work strategies form the primary product of systematic project planning where the fundamental purpose is to develop data collection strategies that can be easily adapted to accommodate an evolving CSM. Doing this helps to ensure that all field characterization activities continue to produce only the data relevant to testing and/or confirming the CSM.

The final component of a Triad approach, real-time measurement technologies, makes dynamic work strategies possible. These technologies provide the ability to gather, interpret, and share data that support rapid evolution of the CSM and ultimately agile decision-making. By using field analytical instrumentation, in situ sensing systems, geophysics, rapid-turnaround labs, and computer systems for warehousing, processing, and distributing data, Triad projects cut down the time and cost needed for sample analysis as compared to traditional lab-based analytical methods.

Purpose: This paper presents the results of a Triad approach to site characterization performed at a 13-acre former oil refinery site that combined the use of geophysical and insitu field data collection with computer-generated 3D site conceptual modeling to develop, evolve, and interpret a CSM. The real-time measurement technologies used in this investigation included a combination of Electrical Resistivity Imaging (ERI) and Soil Conductivity/Membrane Interface Probe (SC/MIP). 3D parameter modeling was used to rapidly evaluate the geophysical and insitu data, correlate it to analytical data collected from a smaller set of analytical data, and update the CSM. The modeling therefore formed the basis for a dynamic work strategy in which field data was rapidly interpreted within the context of the CSM and those interpretations were used as the basis for determining subsequent data collection objectives and strategies.

The purpose of the investigation was primarily two-fold. The first was to meet regulatory criteria for delineating the magnitude and extent of the petroleum impacted area. The second was to develop a reliable understanding of the potential financial obligations associated with redevelopment and sale of the property.

The purpose of the modeling work that is presented and discussed here was also two-fold. The first was to develop a platform for the rapid evaluation, analysis, and interpretation of the data in order to expedite the field characterization program. The second was to provide a transparent and readily understandable means of disseminating the findings of the study to key program managers and regulators.

Site Conditions: The site consists of a 13-acre open lot in the industrial district of a medium-size city that housed an oil refinery from 1905 to 1955. Available data indicated that the site produced gasoline, kerosene, aviation fuel, and benzene and that the finished products were conveyed by pipelines to rail cars at a transfer facility immediately adjacent to the site to the east (Utne, 2008). The refinery facilities were razed sometime in the 1970’s after which the site was used as a railroad siding yard until sometime between the early 1980’s and mid 1990’s when the site was abandoned and became overgrown (Utne, 2008).

At the outset of this investigation, the site contained areas of heavy vegetation, rail road tracks, foundation pads, unmapped sewers, and product piping. These combined with wet ground conditions and limited entrance access rendered the implementation of a traditional drilling and sampling plan impossible without substantial preliminary clearing work. Alternatively, site conditions were amenable to surface geophysics and geoprobe drilling because there were no substantial structures limiting access for surface resistivity transects and the smaller geoprobe rigs were able to gain access to the site and negotiate the terrain without substantial clearing work.

WORK PLAN

Data Collection: The field data collection program consisted of four phases of work conducted between April 2007 and January 2008. In the first phase, a series of surface geophysical transects using an ERI tool were conducted to identify the general locations of petroleum-impacted soils where areas containing petroleum compounds were identified by anomalously low ERI response (Sauk, 1998; 2000). Once the primary source areas were identified, multiple series of geoprobe boreholes were installed during three field characterization periods to identify the distribution and volume of petroleum-contaminated soil and groundwater across the site.

A SC/MIP tool was advanced in every geoprobe hole to refusal, which was assumed to be the surface of the weathered shale bedrock. The tool collected soil conductivity, photo-ionization, and flame ionization readings at a rate of 20 readings per foot where each parameter provided an independent measure of petroleum-impacted soil. Soil and groundwater water samples collected from a subset of the geoproble borings were analyzed at an onsite analytical laboratory for gasoline and diesel fuel constituents. Additional samples were sent to offsite analytical laboratories for comparison. Analytically defined total gasoline range organics (GRO) concentrations were used to develop a correlation between the SC/MIP parameter readings and petroleum compound concentrations.

Approximately 13,500 linear feet of ERI transects were installed across the site during the first phase of the investigation (Utne, 2008). By the end of the characterization study, a total of 166 geoprobe borings were installed from which all were sampled with the SC/MIP tool and 70 were sampled for soil and groundwater analytical analyses. The borings were installed over the course of 15 individual field data collection events performed in the three field characterization periods: 12 during the first period, 2 during the second, and 1 during the third. Figure 1 provides a site map showing the location of the ERI transects, SC/MIP borings, and GRO sampling locations.

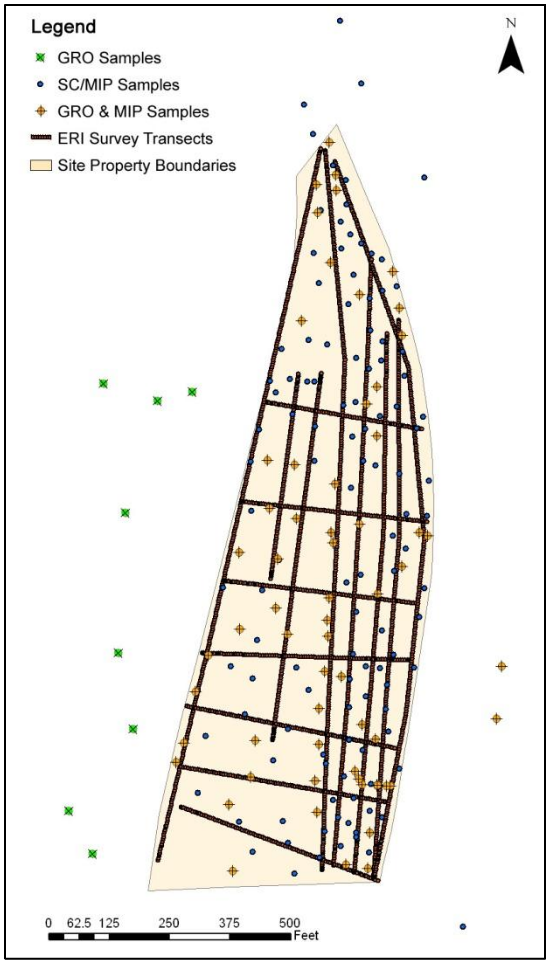

Figure 1. Site map showing the relative locations of ERI transects, SC/MIP sampling locations, and GRO analytical sampling locations.

Modeling: The initial CSM described the site as a block of heterogeneous fluvial sediments overlying weathered shale bedrock in which the fuel-impacted soils were assumed to be restricted to the surficial sediments. Rather than relying on a progressive drilling and analytical analysis strategy, the overall goal of the field characterization program was to rely on geophysical data collected from the rapid deployment of surface transects and geoprobe borings that could be correlated to traditional laboratory analytical data and lithologic descriptions collected from a limited number of wells and boreholes.

The initial CSM was articulated as a 3D geologic model constructed with the EarthVision™ modeling software. The static model identified the topographic and weathered bedrock surfaces as defined by high-resolution LIDAR and the ERI data, and the distribution of sand, silt, and clay in the surficial zone as defined by lithology logs derived from geoprobe borings. The static model then incorporated a 3D layer describing the chargeability of soils as defined by the surface resistivity data derived from the ERI transects. The dynamic component of the CSM included additional unique 3D layers describing the GRO analytical data and each of the geotechnical parameters collected with the SC/MIP tool during the field investigation. Those parameters included flame and photo ionization detector responses and electrical conductivity.

Once the initial model was created, specific image templates were created through interaction between the modeler, onsite technicians, and the program manager, and then computer routines were written to automate the development of the dynamic 3D layers and the generation of image output conforming to the pre-determined formats and views. This allowed the model and corresponding image output to be updated daily as new data became available from the field. Unix shell scripts were also used to automatically post image output to a secure project website for use by the project manager and field team in planning the next steps of the data collection program. The process of field data collection, modeling, and analysis was then repeated until the model results indicated that the extent of petroleum-impacted soils at the site had been delineated horizontally and vertically.

TOOLS & METHODS

SC/MIP: The MIP is a direct push technology-based sampling method developed by Geoprobe Systems (Christy, 1996). The MIP system consists of a thin film fluorocarbon polymer membrane mounted on a stainless-steel rod at the drilling rod. The rod is advanced using a direct-push (geoprobe) boring machine. To perform the measurements, the membrane is heated to between approximately 100°C and 120°C and a clean carrier gas (nitrogen, helium, or purified air) is circulated across the surface of the membrane. Volatile organic compounds (VOCs) partition across the membrane and are subsequently measured by conventional detectors such as gas chromatograph /mass spectrometer (GC/MS), a photoionization detector (PID), a flame ionization detector (FID), or an electron capture device (ECD) at the ground surface. A continuous log of VOC detections versus depth is generated where the density of the measurements is dependent on the rate of geoprobe advancement but tends to be approximately 20 per foot. Soil conductivity and penetration rate information are also provided by use of a conductivity dipole and other sensors, providing real-time lithology-based data for interpretation.

Modeling Software: EarthVision® (EV) is an integrated software system produced and distributed by Dynamic Graphics Inc. of Alameda, California. EV is specifically designed for earth science professionals seeking to synthesize a wide variety of geo-spatial data into comprehensive conceptual models through which data can be visually and quantitatively analyzed through either deterministic or geo-statistical interpolation schemes. The parameter models in this study were developed using a 3D deterministic interpolation scheme called 3D Minimum Tension Gridding (Paradis and Belcher, 1990; Belcher and Paradis, 1992). This scheme was chosen because it provides a robust method of generating deterministic interpolations that minimize extrapolation error.

Minimum-tension gridding uses a two-step interpolation process to assign estimated parameter values at grid nodes in a 2-D or 3-D model. The first step is an initial estimate of the parameter value based on the value of the nearest data points encountered in a progressively broadening octant search pattern. The initial estimates are based only on the nearest data points but the search distance will increase until a data point is encountered. In the second step, a biharmonic cubic spline function is fitted to the grid node values and the process is iterated using feedback from the initial scattered data until a balance is achieved between the initial scattered data and the curvature (2nd derivative) of the function (Briggs, 1974). The resolution of the grids and thus the model components is defined by the spacing between nodes where the optimal spacing is ½ the distance between the closest set of data points showing significant variation.

The 3D grids were clipped with the overlying and underlying control surfaces (topography and weathered shale) and converted into file formats suitable for visual analysis in EV’s 3D Viewer. The Viewer provides the ability to rotate, slice, and parse the gridded values along any axis, pre-define path or parameter value. Each of these processes can be performed in real-time in the Viewer or by one of EV’s individual programs thereby allowing each function to be called from commands incorporated in customized computer scripts. For this project, computer scripts were developed to build the modeling datasets from the raw data files received from the field technicians, generate the 3D parameter models using pre-defined boundary files and grid-node spacings, calculate the volume of petroleum-impacted soil, process the resulting models into a consistent set of cross-sectional, plan-view, and perspective images, and upload all of the images and volumetric analyses to a secure website.

MODELING RESULTS

MIP-GRO Correlations: MIP readings were visually compared to GRO concentrations identified by soil sampling and laboratory analysis at several of the initial wells and geoprobe holes across the site. This was done by installing MIP geoprobe holes as close to the soil borings as possible, independently modeling each set of results, and then visually comparing the resulting plots, cross-sections, and plan-view maps. In each subsequent phase of data collection a new round of analytical data was collected from one borehole for every two to three geoprobe borings to confirm the initial correlation. Figure 2 provides an example of one of those comparisons based on cross-sections plotted for GRO and MIP-FID.

All three geotechnical measurements visually correlated to the GRO readings as expected in that FID and PID readings were highest and EC readings were low where GRO was detected at high concentrations. FID was chosen as primary parameter of interest because it generally correlates most strongly with GRO (O’Shay and Hoddinott, 1994). Critical values for FID that correlated to the GRO action level (150 mg/kg) established by the regulatory agency were then established such that the probable distribution of GRO in soil as defined by FID could be readily identified. The critical FID value marking GRO concentrations above the 150 mg/kg was 1E+6 micro-volts (μv).

Delineating Petroleum-Impacted Soils: For delineation purposes, the critical MIP-FID value was used to map the extent of petroleum-impacted soils. Values at or above the threshold were assumed to mark locations where petroleum compounds were present and values below the threshold were assumed to mark locations where they were not present. Each of the parameter layers were however updated with each consecutive round of field data. At least one set of comparative plots was generated for each of the primary perspectives of the model: X and Y cross-sections, and plan-view maps (Figure 3).

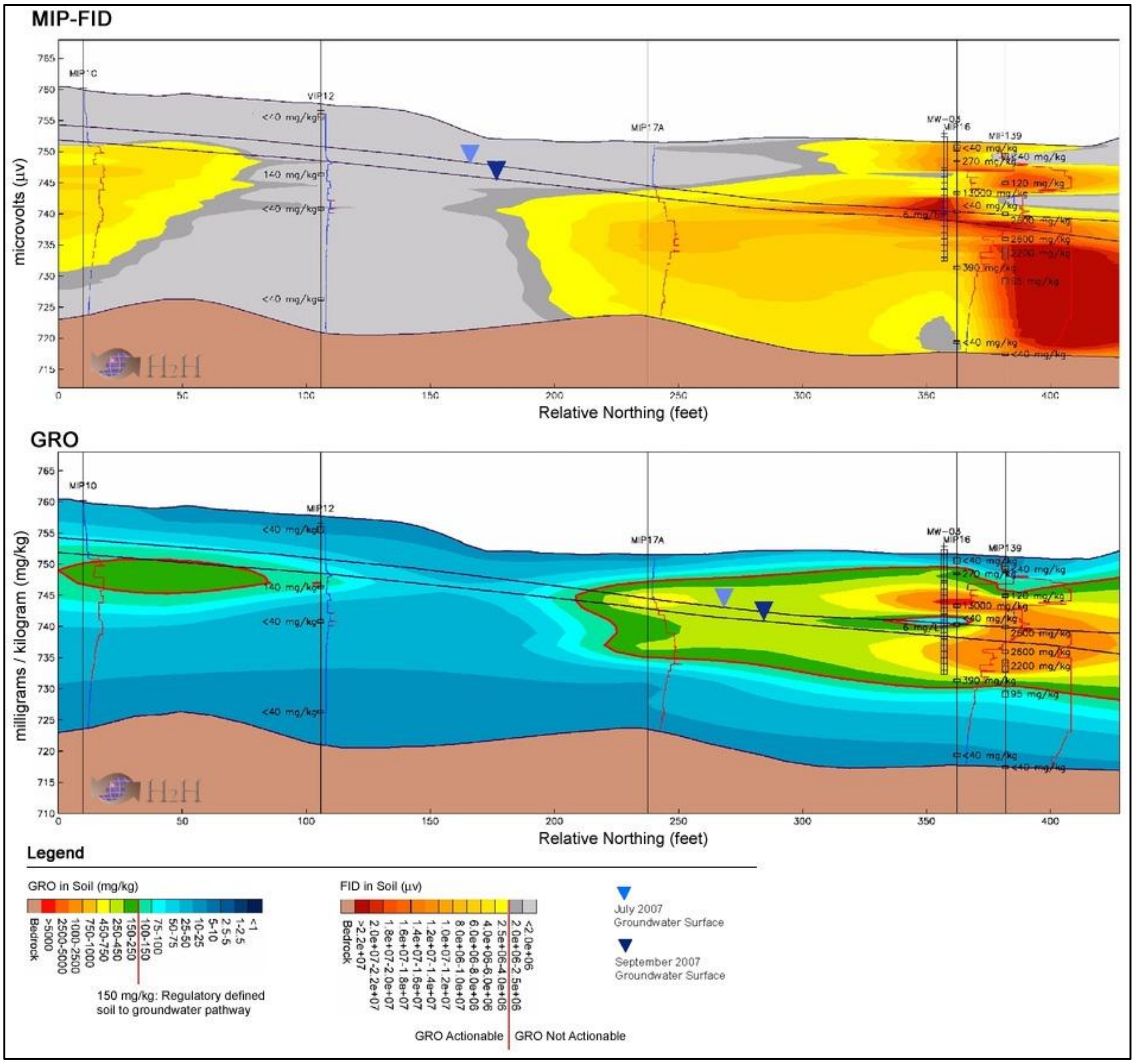

Figure 2. Example north-south cross-sections at the same location through the 3D models of the site constructed from analytical results for GRO (bottom) and MIP-FID measured insitu from geoprobe holes (top). Plots such as these repeatedly confirmed the correlation between FID readings and analytical measurements for GRO.

Each MIP boring produced between approximately 1400 and 2800 data points between the land surface and the underlying weathered shale. The plots of that data revealed more hot spots of fuel-impacted soils than were identified by the analytical data but that the shape of the overall petroleum-impacted zone was significantly more complex than would have been surmised from the analytical data alone. Each series of geoprobe MIP borings produced data that either delineated previously unidentified petroleum-impacted zones or refined the prior delineation or did both. The data collection and modeling process was repeated until no new zones were identified and very little

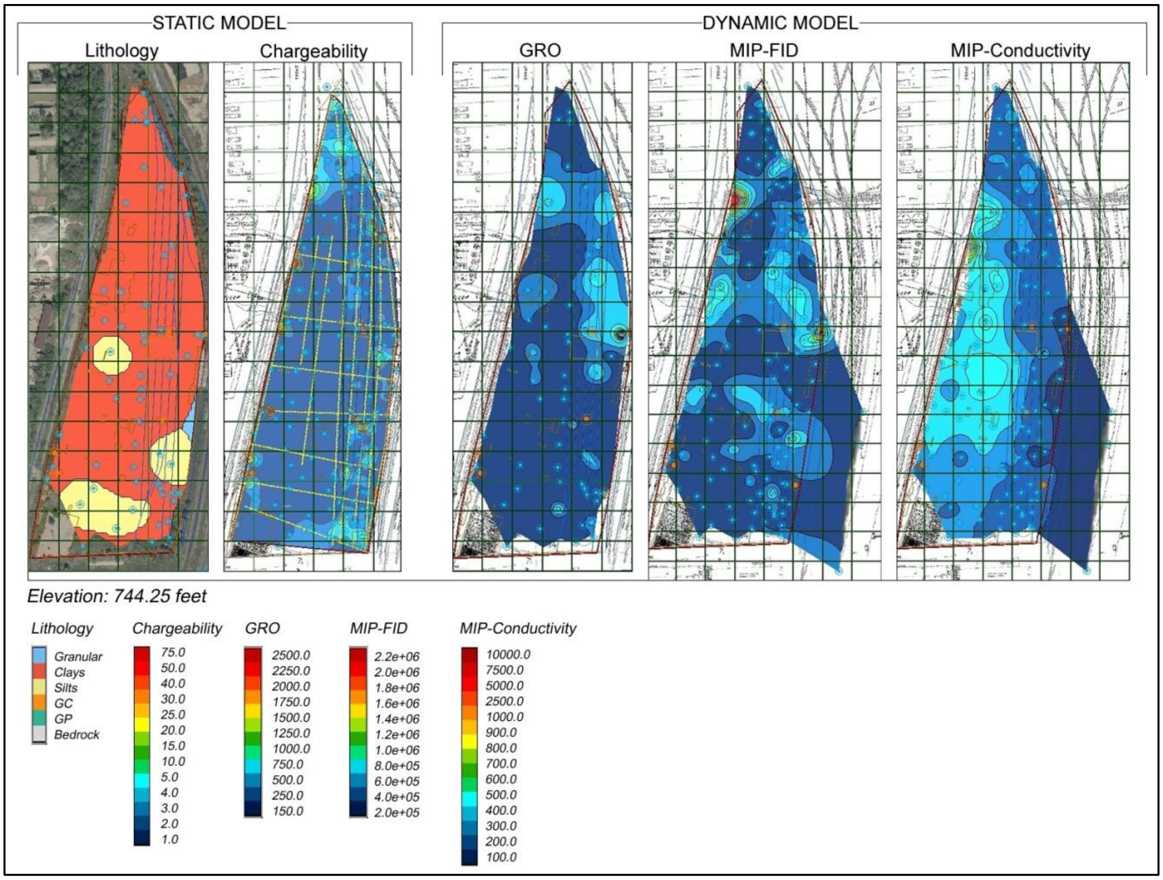

Figure 3. Example plan-view comparison of static lithology and ERI resistivity and dynamic models constructed for GRO, MIP-FID, and MIP-Conductivity. Plots such as these were created after every day of field data collection such that the CSM and the data collection strategy could be revised before the following day's agenda was set.

zone refinement was achieved. At that point, the complete analysis was summarized and submitted to the regulatory agency as proof of compliance with the statutory regulations. Figure 4 provides a plan view comparison of the MIP-FID and GRO models from the last round of field data collection, which shows ten unique hotspots identified by the MIP-FID data but only six identified by the analytical GRO data. The difference between the two sets of plots is demonstrative of the data density. The significance is not only apparent in the graphical analyses but more importantly, also in the corresponding calculations of petroleum-impacted soil volumes. Calculations based solely on the GRO data indicated that the total volume of soils impacted with GRO above 150 mg/kg was approximately 5.6 million ft^3 (>200,000 yd^3) where as the MIP-FID model indicated that the corresponding volume was less than half of that figure (2.5 million ft^3 or <93,000 yd^3). Figure 5 provides a 3D perspective view of the final MIP-FID

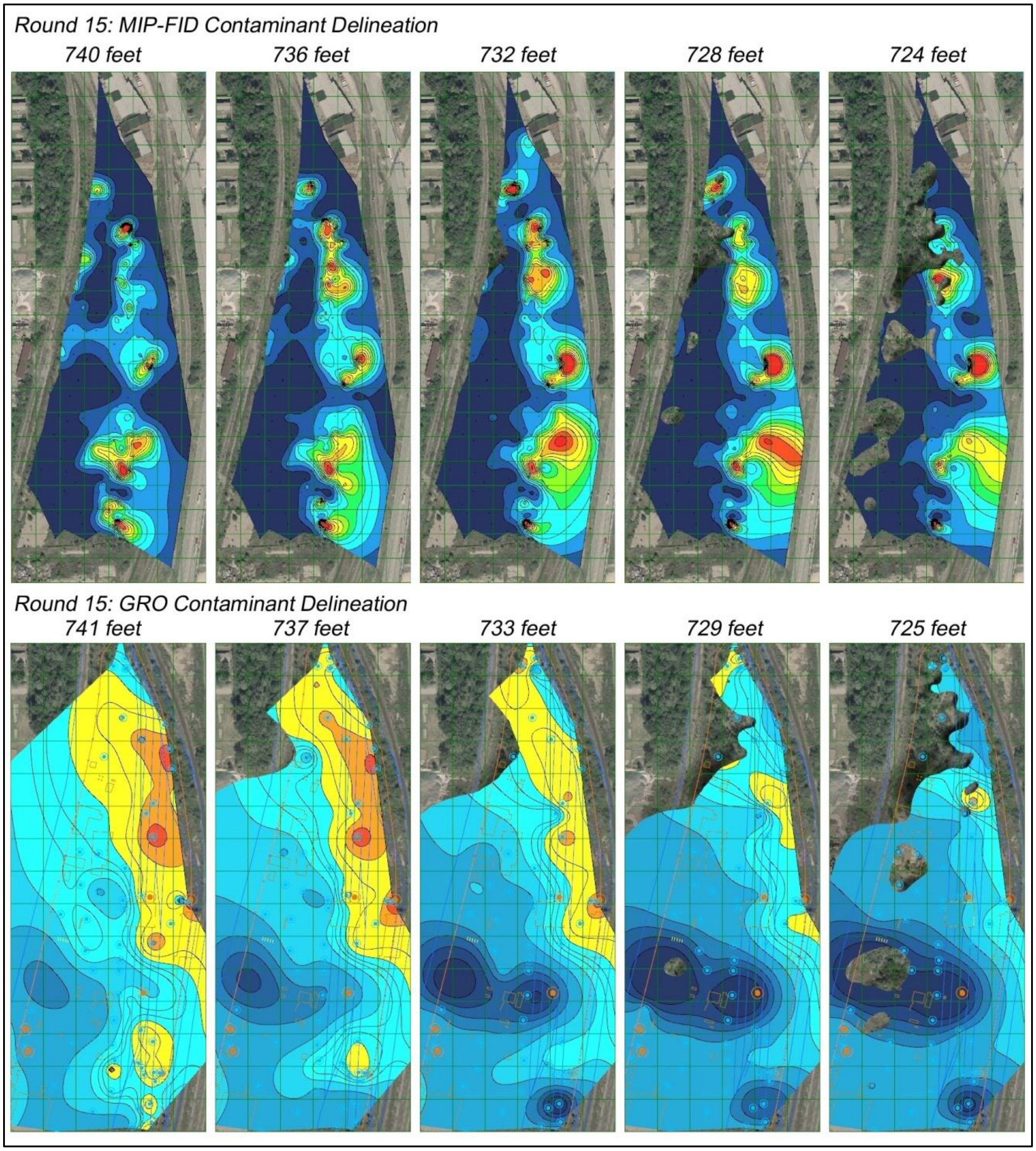

Figure 4. Comparison of plan-view slices from the final MIP-FID model (top) and the GRO model (bottom) showing the respective locations of high-concentration contamination across the site where the models have been clipped along polygons defined by the distribution of data points. The MIP-FID model correlates to all of the hot spots identified by the GRO model but also reveals additional contaminated locations that the GRO model missed and that the zones identified in the GRO model were smaller than indicated.

model showing that the petroleum compounds had become localized in pockets both horizontally and vertically across the site.

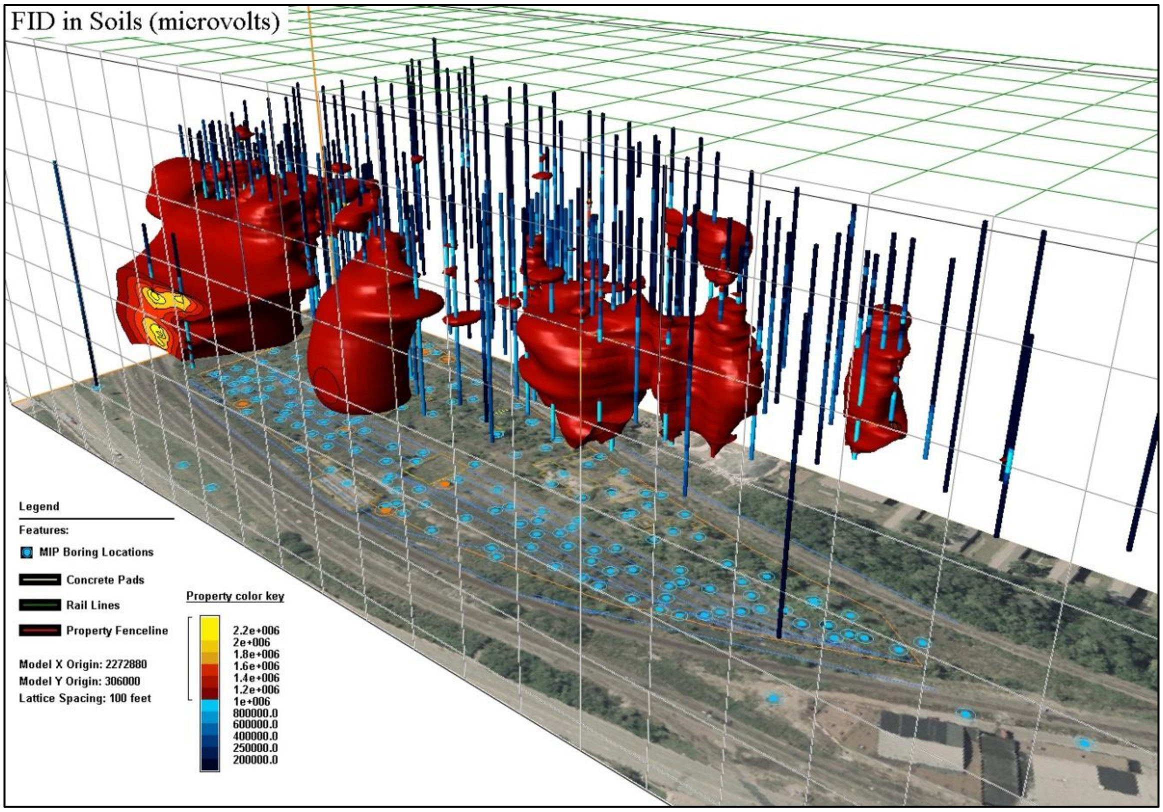

Figure 5. 3D perspective of the final MIP-FID model showing only the distribution of soils with FID readings higher than 1.0E6 μv, which corresponds to petroleum-impacted soils with critical levels for GRO of 150 mg/kg. The total volume of the soils depicted above is approximately 2.5 million ft^3, which is less than half of what was indicated by the GRO model and demonstrative of the value of the high-density SC/MIP data.

DISCUSSION

We believe that the modeling based Triad approach to characterization used at this site significantly facilitated the site characterization process by maximizing the utility of the high density SC/MIP data and minimizing the time required to process and interpret the data in between each day of data collection. The results were well received by both the regulatory agency and the client. On the regulatory side, the model output allowed the responsible regulators to observe the results from every step of the data collection process and evaluate the conclusions presented in the site reports, presentations, and applications in the context of their own interpretations. On the client side, the transparency provided by the regularly updated model visualizations inspired confidence that the approach provided the most cost-effect way of performing the site characterization and complying with stipulations of their voluntary cleanup agreement. Moreover it also demonstrated that the total volume of petroleum-impacted soils was significantly less than would have been predicted by interpretations of the analytical data alone.

The keys to the success of this investigation were:

- a program management plan that embraced the approach more so than a pre-determined set of specific data collection objectives;
- the use and applicability of high-density SC/MIP data to measure parameters indicative of petroleum compounds;
- 3D modeling of the SC/MIP parameters to identify the horizontal and vertical distribution of petroleum-impacted soils and determine the volume of those soils; and
- the ability to automate the model development and output generation processes such that the CSM could be refined on a daily basis while the field data collection program was underway.

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