Database Design & Management for 3-D Hydrogeologic Modeling at the DOD DSCP Facility, Philadelphia, Pennsylvania

Todd R. Kincaid, PH.D, Hazlett Kincaid, Inc.
204 South Seventh Street
Akron, PA 17502
Phone: (717) 859-1413 (now 775-337-8803)
e-mail: kincaid@hazlett-kincaid.com (now kincaid@geohydros.com)

Michael Heffron, P.G., Foster Wheeler Environmental Corporation
One Oxford Valley, Suite 200
Langhorne, PA 19047
Phone: (215) 702-4000
e-mail:mheffron@fwenc.com

Abstract

Cleanup activities at the Defense Support Center Philadelphia (DSCP) facility in South Philadelphia involve a light non-aqueous phase liquid (LNAPL) plume covering an area over 60-acres. Characterizing the extent and volume of the plume has been problematic and involved the work of more than six environmental consultants over the past 7 years with an accurate plume volume estimate hindered by the complexity of the geology in the shallow subsurface.

In order to more accurately characterize the site hydrogeology, and design an effective remediation strategy, a relational database was used to archive the shallow subsurface geology and the LNAPL plume morphology information. An Enviro Data® database, based on Microsoft Access® was used to store the information. EarthVision® geologic modeling software was then used to develop 3-dimensional visualizations of the site conditions and calculate an estimate of the plume volume. The database also serves as the framework for dissolved-phase groundwater contaminant fate and transport modeling using FEFLOW® and the evaluation of LNAPL plume remediation strategies through other forms of multi-phase flow modeling. The combination of modeling efforts provides a superior method of characterizing geologic, hydraulic, and engineered subsurface complexities and then articulating those complexities in a flow-modeling environment. The result is significantly improved predictive capability and a more reliable decision-support tool.

This paper will focus on the steps in the modeling process, including the exhaustive data compilation involving the boring logs, monitoring well construction logs, historical LNAPL thickness, groundwater and soil analyses, etc. dispersed among numerous hard copy reports and disorganized digital files. The paper will also discuss the advantages and disadvantages of using the EnviroData® database.

Background

The Former Defense Support Center Philadelphia (DSCP) Site is an approximately 86.5 acre facility centrally located in the southern portion of Philadelphia, Pennsylvania, known as South Philadelphia. Land use in the region has included a mix of industrial, commercial, and residential including petroleum refineries in close proximity to the site. During its operation, The former DSCP facility was responsible for the worldwide distribution of supplies for the Department of Defense (DoD). The facility has undergone closure under the Base Realignment and Closure Program and is awaiting re-development. The Defense Energy Supply Center (DESC) is currently responsible for the cleanup activities at the site. DESC purchases, stores and distributes petroleum products for the various DoD agencies. In this capacity, DESC also retains the cleanup responsibility and acts as an agent for DoD for releases of petroleum product at all government sites.

A light non-aqueous phase liquid (LNAPL) plume is located atop the shallow groundwater underlying the DSCP facility, and the Passyunk Housing area to the south. The LNAPL is described as a light naphtha (Malcolm Pirnie, 1997). The water table and LNAPL layer, where present, range from approximately 13 feet below grade in the eastern portion of the DSCP and 20 feet below grade in the western and central portion of the Passyunk Homes area. The LNAPL plume, which is estimated to be greater than one million gallons in volume, extends across the southern area of the DSCP, under a major highway, and beneath a portion of housing area. Apparent plume thickness ranges up to several feet. There is a large combined sewer system located on the southern portion of the LNAPL plume, and appears to limit the migration of the LNAPL plume. The Packer Avenue sewer is a 12-ft. by 8 ft-concrete combined sewer that is situated at an elevation that typically allows groundwater to flow under the sewer, but can act as a barrier to the LNAPL movement (Schreffler, 2001).

Problem

The primary problem currently confronting the DESC at the DSCP facility is the characterization and remediation of the LNAPL plume underlying the site. The problem is complicated by three factors; (1) the magnitude of the plume, (2) irregular groundwater flow patterns generated by the operation of remediation systems at adjacent industrial facilities and the position of large diameter sewers systems along the western and southern site boundaries, and (3) heterogeneity of the hydraulic conductivity in the shallow subsurface. The most significant aspect of this geologic heterogeneity is a variably thick silt layer situated above the plume. Both the sewer systems and the silt layer are believed to have affected plume migration and are thus significant aspects of the site conceptual model.

The DoD has contracted with six consultants over the past seven years in an effort to investigate and remediate numerous environmental sites and to characterize the plume and develop an effective remedial design. A large amount of hydrogeologic data has been collected as a result of these efforts, however little progress was made on synthesizing the data into a holistic understanding of site complexities. This lack of synthesis hindered characterization, remedial design, and even volume estimation efforts.

DESC took over cleanup responsibility at this site in December 1999 and contracted with Foster Wheeler Environmental Corporation (Foster Wheeler) for all investigative and remediation activities at the site. At the outset of the current contract, it was decided to take a step back, synthesize and evaluate all the available data, and then develop a comprehensive and digital site conceptual model through which the site complexities and their inter-relationships could be quantitatively evaluated. Foster Wheeler retained Hazlett Kincaid, Inc. to develop the database and assist with the various tasks outlined in this paper.

This paper describes: (1) the development of a database for site and regional geologic and hydrogeologic data obtained from the previous consultants and published sources, (2) the synthesis of that data into a digital site conceptual model, which we call the "Geologic Framework Model" and (3) application of the modeling approach to evaluating plume morphology with respect to the position of the sewers and the silt layer and the estimation of LNAPL volume.

Site Hydrogeology

The site is situated in the Coastal Plain Physiographic Province, near the confluence of the Schuykill and Delaware Rivers. This area of the Coastal Plain Physiographic Province is comprised of unconsolidated clastic sediments of Cretaceous or younger age. The topography of the site is relatively flat with topographic contours ranging from approximately 20 to 25 feet above sea level.

The regional stratigraphy consists of alternating layers of sand, gravel, silt, and clay. The youngest deposits at the site are classified as the Holocene alluvium consisting of fine sand, silt and clay. The Holocene alluvium at the site has been designated as silt with variable amounts of clay (Malcolm Pirnie 1997). This silt layer, which varies in thickness, is present in the vadose zone above the water table over the entire DSCP and Passyunk Homes area. The water table in the northeastern and southeastern portion of the site intersect this silt layer (Malcolm Pirnie 1997).

The Trenton Formation underlies the Alluvium. The Trenton Formation (the unconfined aquifer) is comprised of gray to brown poorly sorted sand with considerable sub-angular to rounded gravel. The grain size distribution of the Trenton gravel is highly variable, and results in varying hydraulic conductivity and yields. Yields between 1 gpm and 1,370 gpm have been observed in wells tapping the Trenton Formation (Paulachock 1991). The Trenton Formation is not used as a drinking water aquifer in the region because of water quality problems.

The depth to groundwater at the site varies from 13 to 20 feet below ground surface (bgs). The general groundwater flow at the site is from the northwest to the southeast in the water table aquifer. There is a west to east flow component in the central portion of the site, most likely the result of heavy groundwater pumping operations occurring in the upper aquifer at the Sunoco refinery to the west (Malcolm Pirnie, 1997). Residual hydrocarbons were detected in the aquifer matrix, up to 15 feet below the current water table, indicating that at least a portion of the LNAPL releases occurred when the water table elevations were at a much lower altitude then present day (Schreffler, 2001).

Data Compilation & Database Development

An exhaustive data compilation effort was undertaken as the first step in the modeling process. Data included boring and monitoring well construction logs, historical groundwater level and LNAPL thickness records, groundwater and soil analyses, etc. that were dispersed among numerous hard copy reports and disorganized digital files. The Enviro Data® database was implemented at the site in order to manage and disseminate the large volumes of geological, hydrogeologic, and analytic data that were collected. Enviro Data® is a proprietary database system developed by Geotech Computer Systems Inc. of Englewood, Colorado, which uses MS Access® as a front-end user interface and any ODBC-compliant database such as MS Access, SQL Server, or Oracle as the back-end database server. EnviroData® was chosen as the database tool because it is particularly suited to geologic data, provides an easily adaptable data model structure to accommodate specific project needs, and is relatively simple to learn and operate.

Data entry was a formidable problem due to the variable data types and variable formats of the data sources. To confront this problem, data tables in the EnviroData® database system were modified to suit data categories and project goals, and customized spreadsheets were designed from which the data was uploaded to the database. The spreadsheet interfaces became a crucial part of the data entry process because they were tailored to match the format of the various data sources, making it easier for data entry personnel, and contained formulas that automatically reformatted the data to conform to EnvioData® upload protocols.

The database model is divided into four main tables (Figure 1) with all entries keyed to a unique station (well or borehole) name. The *Sites* table is used to designate regions from which the data was obtained; i.e. regional data included all data outside the site boundary but not associated with other specific environmental investigations, which were designated by individual site name. The *Stations* table contains all data descriptive of the individual boreholes or monitoring wells, i.e. easting, northing, land surface elevation, etc. The *Samples* table contains the spatial and temporal descriptions of every sample regardless of sample type and is the primary table used for geologic data including lithologic descriptions and stratigraphic delineations. The *Analyses* table contains the results of chemical, and geotechnical, and synoptic measurements, i.e. hydraulic conductivity, groundwater and soil analytical results, etc. Soil and lithologic samples are keyed to sample top and sample bottom depth measurements. Individual groundwater and product samples are keyed to the sample date.

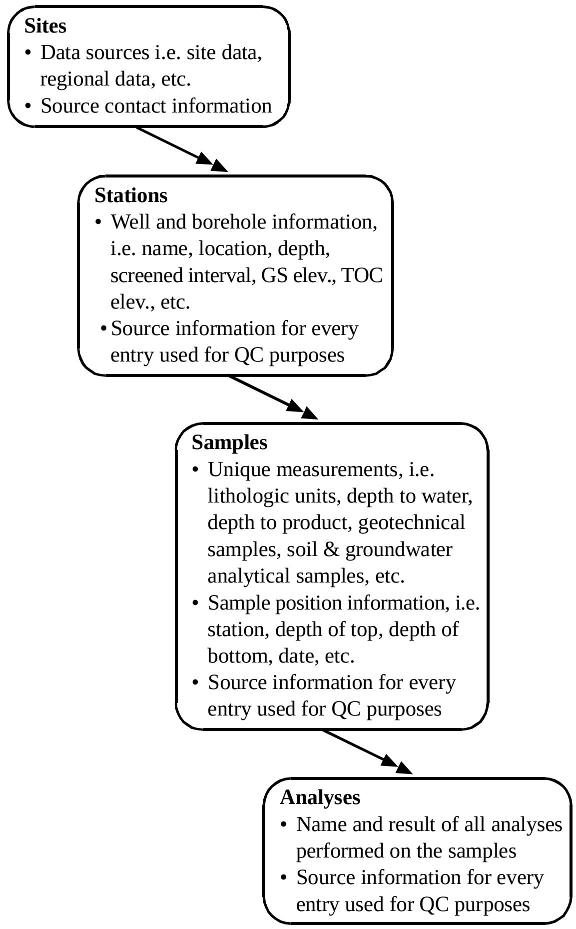

Figure1. Basic structure of database model.

The spreadsheet interface is also separated into individual tables; however, the subdivisions are defined by the structure of the raw data rather than the database model. For example, geologic data was typically contained on paper borehole logs while groundwater and product synoptic data was typically contained in MS Excel spreadsheets or paper data tables. A unique spreadsheet interface table was therefore created for each category of data making it easier for data entry personnel and therefore quicker and more cost-effective. Once the data was entered, spreadsheet formulas were used to automatically process the data into the required format for upload to the EnviroData database.

Data from more than 400 wells and boreholes were entered into the database system. The geologic data was the most problematic data type to process into the database system. Project goals demanded that lithologic (soil) types as well as geologic units be identified vertically across the site. Both forms of data were recorded in most of the boring and well construction logs that were collected, however the criteria for identifying lithologic types was not consistent between logs generated by different consultants and often not even internally consistent for logs collected by the same consultant. To address the inconsistency problem, a project geologist evaluated each of the boring and well construction logs and re-assigned lithologic classifications based on the written descriptions provided by the logger for each unique stratigraphic section described in the logs and the Unified Soil Classification System (USCS) prior to entering data into the spreadsheet interface. The final stratigraphic sequence at the site contained 11 stratigraphic layers and 26 unique lithologic categories. Other data types included parametric samples that were derived from laboratory measurements on more than 58 Shelby tube samples collected from various locations and depths across the site, and synoptic samples included depth-to-water and depth-to-product measurements.

All sample elevation data were entered in terms of depth from land surface or top-of-casing (TOC) elevation and the actual elevations, which are needed for modeling, were calculated from the land surface or TOC elevations. Sample top and bottom elevations, measured and corrected water table elevations, etc. were then calculated with specially designed queries using structured query language (SQL) and added to the EnviroData® program. This was done because there were inconsistencies identified in the datum elevations used by the previous consultants and government agencies from which data was collected. By entering the raw depth information, all sample elevations can be quickly corrected if datum errors are encountered by correcting the datum elevations in the Stations table and then re-running the data queries.

Ultimately, the efforts invested in database development and streamlining the database upload process are believed to have significantly streamlined the modeling, characterization, and remedial efforts, which in turn will result in the more expedient and cost-effective achievement of the DESC's remedial objectives.

Geologic Framework Model (GFM)

A GFM, as defined in this paper, is a digital site conceptual model that synthesizes all available data (geologic, contaminant, geotechnical, and structural) and professional interpretations into a centralized, visually and quantitatively query-able set of digital model files. The GFM is used directly to evaluate geo-spatial relationships between any combination of site data and indirectly for process modeling (groundwater flow, fate and transport, etc.), wherein the digital geologic framework and hydrogeologic parameter distributions exported from the GFM provide the conceptual framework for the process models. Since the model contains all available site data and is query-able, it is a crucial part of the database system.

The GFM for DSCP was developed with EarthVision® solids and parameter modeling software developed by Dynamic Graphics, Inc. (DGI). The strength of EarthVision is the capability to integrate diverse types of two- and three-dimensional data into grid files that can be quantitatively manipulated and visually evaluated. Grid development options include: krigging, trend gridding, and a proprietary method that DGI labels 2- and 3-Dimensional Minimum Tension Gridding (Paradis and Belcher, 1990; Belcher and Paradis, 1992). All of the grids for the DSCP project were generated with the Minimum Tension algorithms, which use 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 defined by half the distance between the closest set of data points showing significant variation in value.

The DSCP GFM currently contains several 3-D grids describing the distribution of parametric data across the site and in between the land surface and the bedrock surface. Parametric grids were calculated for each of the following parameters: hydraulic conductivity, porosity, residual water content, saturated water content, and the Van Genuchten (VG) parameters alpha and N. Rather than using the parametric data directly from the database, the grids were generated from the lithologic data wherein parameter values were assigned to each lithologic zone based on the measured values from the Shelby tube samples or on values reported in the literature for each lithology. Value assignments were made by assigning the median of all measured parameter values corresponding to a particular lithologic zone to the respective zone or the average or all values reported in the literature for each lithology for which the Shelby tube samples did not provide a value. The 3-D Minimum Tension Gridding algorithm was then used to model the distribution of each parameter both horizontally and vertically across the site. Once the parametric models were calculated, the geo-spatial relationship between key site features such as hydraulic conductivity, the silt layer, and sewers were evaluated in the GFM environment. Visualizations of the resulting parameter distribution models contained in the GFM are provided on Figures 2.

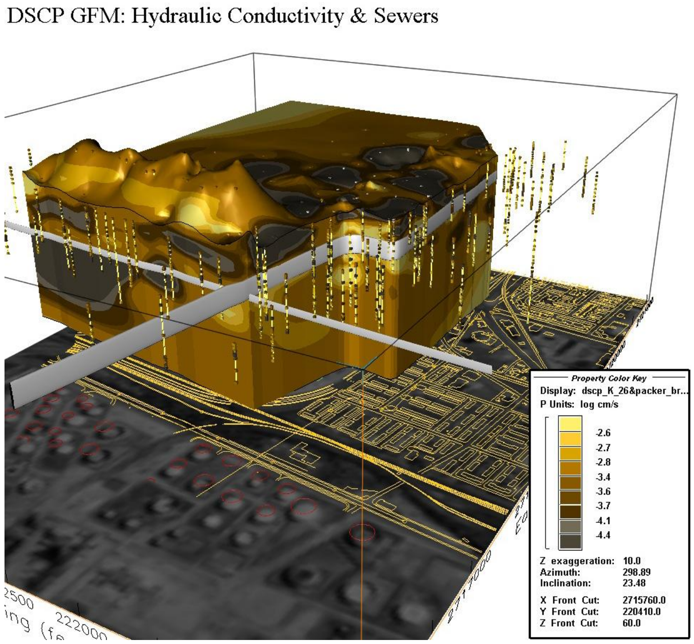

Figure 2. Visualization of 3-D hydraulic conductivity sliced along the Packer Avenue and 26th Street Sewers, Defense Support Center Philadelphia (DSCP), Philadelphia, Pennsylvania. View is from southeast to northwest across the 26th Street sewer. Vertical exaggeration is 10 times.

LNAPL Plume Characterization and Volume Estimate

One of the main focuses of the GFM modeling effort was to evaluate the LNAPL plume over time and also determine the volume of free-phase LNAPL at the site. The LNAPL component of the GFM is a structural model that combines 2-D gridded surfaces representing the tops of the unsaturated zone (topographic surface), LNAPL plume, and saturated zone (water table surface). A water table surface grid for all historical synoptic events was calculated directly from the depth to water measurements that were entered into the EnviroData® database. LNAPL thickness values for each synoptic period were exported from the database using a specially designed SQL query and used to generate LNAPL thickness grids. The upper surface of the LNAPL plume was then calculated for each synoptic period by adding the respective LNAPL thickness grids to the modeled water table surface grids. The surface grids were then combined with the EarthVision® modeling software to produce a 3-D model of the LNAPL plume morphology for each synoptic event, which by visualizing in sequence within the GFM allowed for an evaluation of the change in LNAPL morphology over time. Figure 3 provides a view of the LNAPL morphology as recorded during one of the sampling events relative to slices from the 3-D model of hydraulic conductivity.

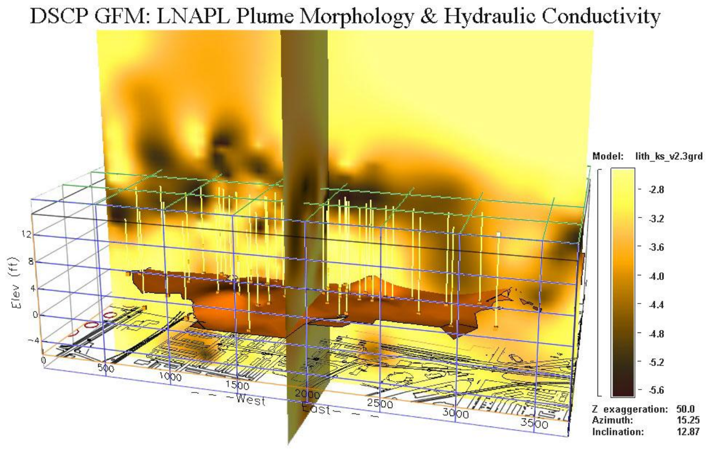

Figure 3. Visualization of a 3-D LNAPL morphology model relative to the hydraulic conductivity, Defense Support Center Philadelphia, Philadelphia, Pennsylvania. The LNAPL plume is depicted as the rust-colored shape along the x-axis. The position of the silt layer is marked by the dark band above the LNAPL plume. Plume thickness is modeled to less than 0.01 feet. Vertical exaggeration is 50 times.

Various LNAPL volume estimating techniques had been used at the DSCP in the past, though accurate plume volume estimates were hindered by the complexity of the geology in the shallow subsurface. Our approach utilized the Van Genuchten method supported by the detailed parameter models and LNAPL thickness grids contained in the GFM. Three-dimensional grids for each of the parameters required by the Van Genuchten method were created for the region encompassed by the LNAPL plume resulting in an interpolated data set for each parameter value at a resolution of 50x50x5 feet. The interpolated parameter data sets along with interpolated data exported from the LNAPL thickness grids at a resolution of 50x50 feet was then processed with specially developed software using the Van Genuchten method to estimate LNAPL volume for each of the synoptic periods modeled. Utilizing the Van Genuchten method and the EarthVision software, an estimate of approximately 1 to 1.5 million gallons of free phase LNAPL was established for the site as of September 2001. The results provided a more confident estimation of LNAPL volume and suggest a decline in volume over time at DSCP.

Conclusions

While the data entry of all the existing boring and monitoring well construction logs and historical groundwater and LNAPL was a tedious effort, the benefits of this effort are long lasting and will result in a significant saving to the project over time. The EnviroData® was chosen as the database tool because it is particularly suited to geologic data, provides an easily adaptable data model structure to accommodate specific project needs. While the customization of variable formats of spreadsheets were necessary to uploaded some of the data to the EnviroData® database, this task was made easier because the program uses MS Access® as a front-end user interface. Additional data can be added to the existing database throughout the life of the project as well as enable specific information to be queried for future modeling efforts at the site.

The geologic framework model for DSCP in EarthVision® provides a valuable tool for visualizing the various parameters and structures entered into the geologic framework model. The visualization capabilities of the EarthVision® model enabled the demonstration of site features to the public in a manner that can be readily explained.

EarthVision® was used at DSCP to demonstrate the complexity of the subsurface geology at DSCP as well as explain the LNAPL estimation effort and the fact that the historical data indicated that the LNAPL plume is neither expanding nor migrating. Various still and movie visualizations were utilized at DSCP for meetings with the public as well as with regulators.

Since the baseline LNAPL estimate was established, the LNAPL component of the geologic framework model can be re-assessed over time, comparing the estimated LNAPL volume with the actual LNAPL being removed at the site with existing and future LNAPL remediation systems. It is more accurate to estimate the effectiveness of a LNAPL recovery system based upon the recovered LNAPL to date divided by the estimated recoverable LNAPL instead of depending upon historic LNAPL thickness maps (Testa and Paczkowski, 1992). Data input to both models will continue throughout the life of the LNAPL remediation effort in order to continue to accurately monitor the plume, utilize the data for other potential modeling efforts, and communicate the remediation process to the public.

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