Environmental Visualization: Applications to Site Characterization, Remedial Programs, and Litigation Support

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Abstract

This paper introduces the application of the visualization technology in the USA environmental consulting industry for site characterization, remedial programs, and litigation support. As a tool visualization allows environmental data that is three-dimensional and transient in nature to be accurately documented, efficiently represented, and effectively communicated to both professionals and the general public. Maximized understanding through enhanced visual perception increases the chance of success in handling complex environmental problems. The key functions, accessibility, and general areas of application of the visualization technology are described and demonstrated with case studies.

Categories and Subject Descriptors (according to ACM CCS): I.3.8 [Computer Graphics]: Application—; J.2 [Computer Applications]: Physical Sciences and Engineering—Engineering

1. Introduction

The rapid advancement of computer technology in recent years has made three-dimensional (3D) visualization widely accessible to the general environmental practitioners. Because mental understanding is inseparable from visual perception [Ber67], the ability of visualization to illustrate the interrelation of heterogeneous geologic, hydrologic, and contaminant conditions is an invaluable asset to the analysis of environmental information [CR05,JL05,LJ05,JLM04,USE00]. This capability allows environmental professionals to clearly and concisely describe and understand complex surficial and subsurface conditions and the associated environmental problems.

In this paper we introduce visualization applications in the surficial and subsurface environments based on our experiences in the USA environmental consulting industry. Our experiences indicate that visualization can greatly enhance the understanding of site and contaminant conditions, streamline data management and interpretation, facilitate remedial and/or monitoring designs, and provide critical arguments in environmental litigation. The following describes in detail the key functions of visualization, its accessibility, and the general areas of application.

2. Key Functions of Visualization

The significance of visualization for information representation lies in its functionality to serve as a storage mechanism, a processing and research instrument, and a communication tool [Ber67]. Specifically, as a tool visualization technology provides three key functions: (1) it enables large volumes of data to be processed and organized in a simple, easy-to-use visual format [MRO*12]; (2) it documents site activities and physical and chemical conditions through time [BHT*96]; and (3) it allows information to be readily communicated [HKCL02].

Visualization technology is capable of transferring site information into a simple image or animation. It can readily document many types of site data, including the ground surface, boring lithology and geologic strata, well construction information, groundwater conditions, and chemical concentrations of soil, water, and vapor. The generated image is typically a compilation of hundreds of pages of information from large and cumbersome reports. As a result, visualization acts as a data management tool that collates, organizes, and displays large volumes of site information.

3D interactive images or transient animations can efficiently document the temporal change in site and con-

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taminant conditions. Boring and monitoring well installation, water levels, contaminant concentrations, the volume of impact, and site remedial activities (e.g., soil excavation) through time can be animated in a short movie or compiled into a 3D interactive image consisting of multiple frames, with one frame for one monitoring or remedial event. The 3D interactive image is particular valuable as it allows the viewer to evaluate site information over time from any point in space, at any angle, and at any scale.

Visualization facilitates technical communication and understanding. Environmental problems at a petroleum refinery, for example, generally require various individuals trained in different disciplines to interact to effectively comprehend, analyze, and remediate subsurface contaminants. This technical team is commonly composed of hydrogeologists, engineers, chemists, and regulatory specialists. Visualization, in an efficient and visually appealing manner, allows a clear understanding of the site conditions such that consensus can be reached among the technical team towards achieving an effective and efficient solution.

3. Accessibility

The popularity and acceptance of the visualization technology is dependent on its level of accessibility to the general environmental practitioners and related individuals. Visualization technology is most accessible when it requires the least computer and software resources. Though the development of visualization may require more resources and training, the generated visualization need to be supported by commercially or publicly available software and can be easily viewed on an average computer by an average individual. Generated animation files that can run on a popular movie player and 3D interactive images supported by a public domain player are the most welcome. From this sense, visualization only running on proprietary software or research-level equipments such as large stereo displays and cave automatic virtual environment (CAVE) [CNLP*93] could limit the accessibility of the technology. However, these research-level tools have unique advantages. For example, recent advances in large display experiences support powerful dynamic data explorations [BBHS05].

There are several general purpose environmental and geological visualization tools available in the USA; examples include EarthVision, Environmental Visualization System (EVS) [USE00], Petrel, and RockWare. There are many environmental modeling tools that provide task-specific visualization capability; examples include Visual MODFLOW and Groundwater Modeling System (GMS). These tools can generate animation files of multiple formats that can be played on an average computer. However, not every tool can generate 3D interactive images or allow them to be viewed out of the software environment. The authors use the 4DIM Player that comes with EVS. As long as the 3D interactive image is generated using the EVS software under a certain authorization level, it can be viewed by anyone on a different computer with the free 4DIM Player; these image files are typically small and can often be transferred by email.

The animation files and 3D interactive images described above may also be realized in stereo. With stereo displays getting more and more affordable these days, stereo 3D visualization technology for the general environmental practitioners should also be developed; in such a scenario, an environmental professional would be able to develop a stereo visualization for an average individual with a pair of stereo glasses to view on his or her computer. In our vision, this should be a future direction of environmental visualization.

4. General Areas of Application

4.1. Stratigraphic and Structural Analyses

Surficial and subsurface strata and structures include topography, bathymetry, geologic units, and hydro-stratigraphic units among others. They are generated based on information from elevation survey, boring logs, downhole logging instruments (e.g., cone penetrometer), and geophysical measurements (e.g., gamma ray). Fence diagrams and interpolation techniques such as kriging and inverse distance weighted (IDW) [Mat63] are utilized to develop the stratigraphic and structural units. Control points when necessary are often used to confine the interpolation and/or extrapolation. Once developed, iso-elevation or iso-thickness contours of the surficial or subsurface structures can be generated as well as cross sections through any transect. These analyses enable more accurate correlation of the structural units and the delineation of surficial or subsurface features influencing water flow and contaminant transport.

Figure 1 presents the hydrogeologic units (exploded view) near a costal area in the western USA. This stratigraphic model, based on hundred of borings, covers an area of hundreds of square kilometers to a depth of hundreds of meters. The color structures are water-bearing units or aquifers while the silver structures are aquitards. The holes or gaps in the aquitards indicate the connections between aquifers. This model was the basis for the finite difference grid of a regional groundwater model to study contaminant transport originating from a major petroleum refinery in this region.

4.2. Hydrogeologic Analyses

Hydrogeologic analyses focus on water movement under natural conditions or artificial stresses [Bat98]. Fluid level measurements from monitoring wells and/or surface water bodies are analyzed to generate potentiometric surfaces and gradient vectors to understand flow directions, spatial and temporal fluctuations, and the communication among different hydro-stratigraphic units. These analyses provide important insights in characterization studies, contaminant release and transport, and remedial designs.

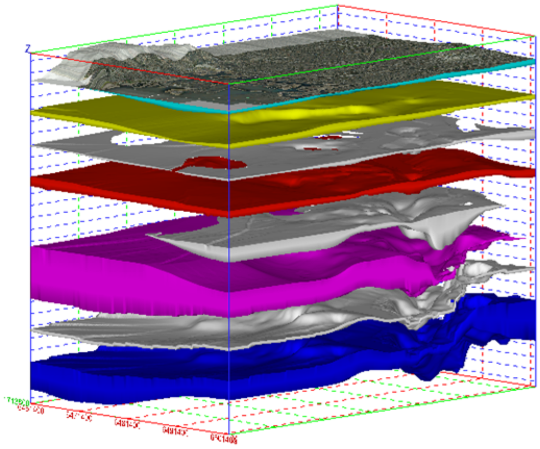

Figure 1: *Stratigraphic units (exploded view) near a costal area in the western U.S. An aerial photo of the region is shown on the top layer. The color structures are aquifers and the silver structures are aquitards.*

Figure 2 illustrates the potentiometric condition in an upper sand unit beneath a petroleum fuel terminal in the northwestern USA. A clay unit that lies beneath the upper sand prevents the downward transport of contaminants. Storm and sanitary sewers are present in shallow depths that may interact with the water table and serve as preferential pathways. By visualizing the water table fluctuation over time, the sections of sewers that may intercept the water table were identified. The hydro-stratigraphic units and potentiometric conditions from the visualization were used as inputs to a groundwater flow model for the design of a dual-phase extraction (DPE) system at the river front.

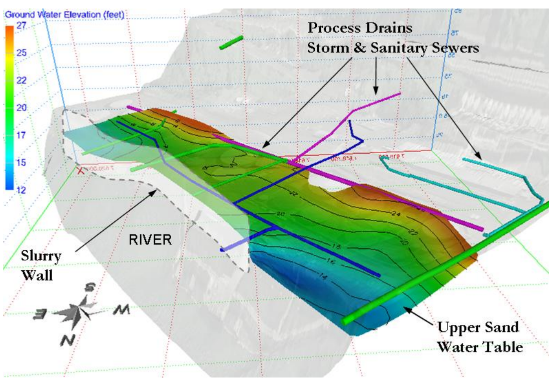

Figure 2: *Potentiometric condition in an upper sand unit at a petroleum fuel terminal in the northwestern U.S. The transparent surface is the upland topography and river bathymetry.*

4.3. Contaminant Distribution

Delineating the spatial extent of soil, dissolved, vapor, and non-aqueous phase liquid (NAPL) impacts in the subsurface is the key to remedial investigation and designs [CBvBvH11]. Chemical data from soil, groundwater, and vapor samples and NAPL measurements from borings or wells are interpolated to infer the contaminant distribution or plume in the subsurface. Contaminant volume and mass can then be calculated to support remedial designs and cost estimation. If the interpolation method is kriging, an uncertainty analysis of the volume and mass may be conducted to provide a range of possibilities. Data from screening level technologies such as laser-influenced fluorescence (LIF) and membrane interface probe (MIP) can also be interpolated to provide an initial assessment of the impact, based on which further investigations can be targeted.

Figure 3 presents the distribution of light-NAPL (LNAPL, density less than water) beneath a former gas plant in the southwestern USA. The LNAPL plume indicates the distribution of liquid-phase hydrocarbons near the water table with thicknesses indicated by colors (blue to red indicating small to large). The LIF responses indicate the potential LNAPL saturation in soil, mostly for the unsaturated zone, with a higher response indicating a larger LNAPL saturation. Visualizing the LNAPL plume over time provided a better understanding of the effectiveness of the site LNAPL recovery effort and the mobility and recoverability of the plume. The visualization analyses were crucial in the development of a site conceptual model and an improved LNAPL recovery strategy.

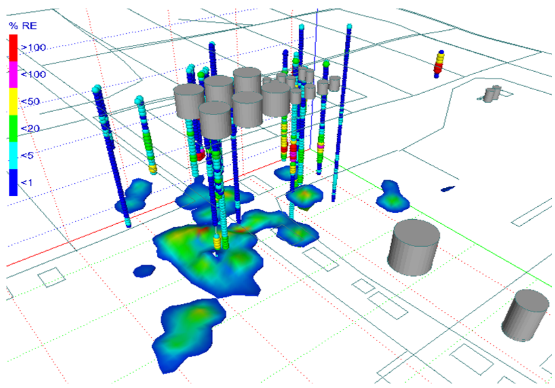

Figure 3: *LNAPL plume (color blobs), LIF responses (tubes of color spheres), and former aboveground storage tanks (ASTs) at a former gas plant in the southwestern U.S.*

4.4. Remedial and Monitoring Designs

Visual representation of the interrelation between geologic strata, contaminant distribution, and groundwater conditions facilitates the development or refinement of the site conceptual model and enables environmental professionals to conduct remedial designs efficiently. A visual site model also allows data gaps to be quickly and accurately identified, so that further needs for investigation and monitoring can be proposed in a timely manner.

Figure 4 illustrates the chlorinated solvent contamination in the form of dense-NAPL (DNAPL, density greater than water) beneath an industrial facility in the northeastern USA. The image visualizes the presence of DNAPL (red layer and yellow blob) relative to the aquitards beneath the site. The red DNAPL plume perched on the thin shallower aquitard originated from an offsite source; the yellow blob sitting on top of the main aquitard was the volume of soil with trichloroethene (TCE) saturation exceeding a certain limit. In-situ chemical oxidation was proposed to target the yellow blob, and the horizontal extent and depth interval for the ISCO application were determined from this visual site model.

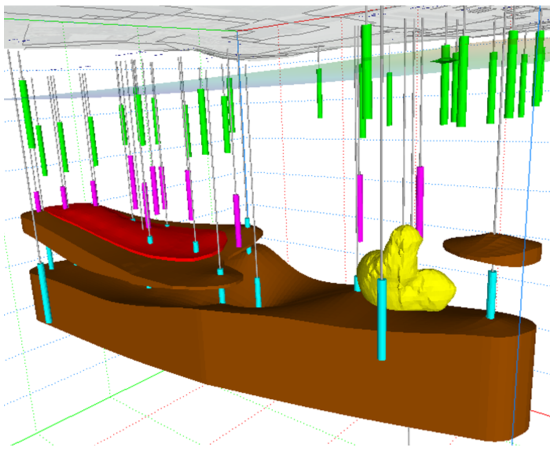

Figure 4: *Chlorinated solvent DNAPL contamination (red layer and yellow blob) beneath an industrial facility in the northeastern U.S. The brown layers are aquitards and the color tubes represent the screen intervals of monitoring wells.*

4.5. Litigation Support

Visualization, as an excellent tool for communicating technical information to the non-technical professionals and the general public, is very valuable in environmental litigation support. Visualization clarifies critical site conceptual features and facilitates understanding of complex physical and chemical interrelationships. Animations and 3D interactive images are preferred in the interaction with the legal team and can be readily incorporated in court presentations and exhibits.

Figure 5 presents the structural model for a railroad site in the northern Midwest of the USA used in a major class action case. The structural model consisting of an upper clay/silt unit and a lower sand unit was developed based on lithologic information from hundreds of borings. Visualization based on this model was utilized to identify multiple release locations and the movement of LNAPL in the subsurface. The visualization was critical in illustrating the results of various technical analyses to delineate the location of contamination in the subsurface and the natural hydrologic barriers that inhibited LNAPL movement toward critical property locations. An exact physical replicate (approximately 0.6 meters square) of the structural model was developed using rapid prototyping technology (i.e., 3D printing). These tools were valuable in presenting the case to the jury. As a result, a favorable decision was obtained by the client.

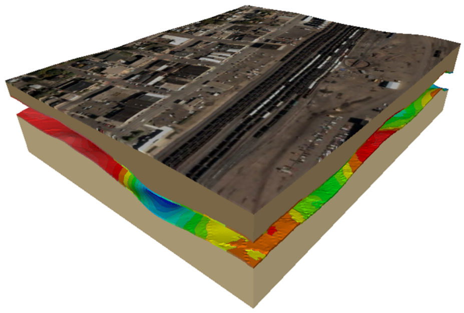

Figure 5: *A two-unit structural model for a railroad site in the northern Midwest of the U.S. An aerial photo of the site was shown on the upper surface; the contact between the two units was illustrated as a series of colored iso-elevation contours.*

5. Conclusions

The use of visualization in the environmental industry is getting more popular and affordable with the advances in computer technology. Visualization is an excellent tool for synthesizing a large amount of environmental information and presenting it in an efficient and effective manner to both technical and non-technical people. Visualization helps enhance the understanding of site and contaminant conditions, streamline data management and interpretation, facilitate remedial and/or monitor3Ding designs, and provide critical arguments in environmental litigation. The trend from traditional text, data tables, and 2D figures to 3D visualization that is interactive or even stereo is unavoidable. The development of equipments and software that can increase the accessibility of this technology will expedite this transition.

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