Using Surfer 8® to Interpret Light Non-Aqueous Phase Liquid Monitoring Data: A Case Study

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Remediation of aviation fuel present in the subsurface as light non-aqueous phase liquid (LNAPL) occurred from 1982 to 1996 at a facility in an industrial section of a small city in eastern Asia. An undetermined amount of the aviation fuel had leaked from underground storage tanks into the unconfined aquifer for an unknown, but extended, period. The release was discovered in 1981, and 57 monitoring wells were eventually constructed, along with a non-aqueous phase liquid recovery system. The recovery system was operated into the late 1990s, when pumping was discontinued because recovery rates had declined to negligible levels. Monitoring data were collected throughout the remediation period, but because of the large and unwieldy amount of data available, the temporal and spatial distribution of the non-aqueous phase liquid was difficult to visualize and the data were never carefully analyzed. Surfer 8® software was used to generate surface models representing non-aqueous phase liquid thicknesses. The significance of using Surfer 8® for the analyses is that it is an "over-the-counter" basic software package that is relatively inexpensive, very easy to learn, requires no special computer skills, and produces a product that is useful to policy makers and others with limited technical expertise. The surface models made it possible to visualize the effects of hydrogeologic factors on the migration and recovery of the non-aqueous phase liquid as well as other features of the contamination that previously had been unrecognized.

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Surfer 8®, produced by Golden Software, Inc. (Golden, Colorado), is a relatively inexpensive and user-friendly contouring and three-dimensional surface mapping software for scientists and engineers. Basic proficiency with Surfer 8® can occur with a few hours of self-tutoring. Various editions of Surfer 8® have been applied to modeling and evaluation of groundwater contamination and other environmental data (Konderla and Hawrysz, 1994; Otvos, Pazmandi, and Tuba, 2003; Shan and Stephens, 1994; Vigneresse, 1994; Woodard, Harris, and Breazeale, 1996). Also, reported applications have typically used Surfer 8® as an interface with other software rather than as a stand-alone analytical tool (Lu and Amter, 1992; Marschallinger, 1991; Yan, Landry, and Tate, 1994). The authors' experience suggests that Surfer 8® is widely used, but this use is not well documented, with only limited reference to its application to environmental data existing in the scientific literature. Products similar to Surfer 8® are available from other software developers, although these products are less popular.

In the present case, Surfer 8® was applied as a stand-alone tool to develop surface models from a very large data set for a facility with historical light non-aqueous phase liquid (LNAPL) contamination. This was done to interpret the data set, not to predict non-aqueous phase liquid movement, with the intent of developing a simple graphical interpretation that would provide visual temporal and spatial images of historical site conditions. Surfer 8® and earlier versions have seen widespread use as a presentation tool, but use as a stand-alone analytical tool applied to non-aqueous phase liquid is uncommon.

This article demonstrates how a relatively technically inexperienced user can effectively use Surfer 8®, or software with similar capabilities, to reduce a large and

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complex data set into an interpretable image format that can be understood by policy makers and others with limited technical background.

Site Background

The contaminated site is located at a facility in an industrial section of a small city in eastern Asia and consists of a group of buildings and underground petroleum storage tanks. The tanks contained JP-4 jet fuel and aviation gas. Leakage from these tanks into the groundwater caused a fatal explosion from gas migration through the subsurface into a confined space on the site in late summer of 1981. Remediation work, consisting of eight product recovery wells, was initiated early in 1982 and continued into 1996, until only slight amounts of LNAPL were being recovered, if any at all. In addition to the extraction wells, 57 monitoring wells were installed. Weekly groundwater elevation and product thickness measurements were recorded for all wells during the 15-year duration of the remediation effort, but because of the large and unwieldy amount of data available, the temporal and spatial distribution of the non-aqueous phase liquid was difficult to visualize and the data were not carefully analyzed until recently. Although contaminant recovery activities ended in 1996, more recent facility environmental managers were interested in quantifying the efficacy of the remediation and assessing the distribution of any residual non-aqueous phase liquid.

The site occupies approximately 74 acres (30 hectares), but most of the monitoring and recovery activity occurred over an area of about 42 acres (17 hectares). Groundwater occurs at a depth varying from 10 ft to 16 ft (3 m to 5 m) and generally flows from southeast to northwest across the site. The unconfined aquifer is approximately 10 ft (3 m) thick. From the ground surface to a confining layer, the soil consists of sandy gravel. The confining layer is non-fractured, dark gray shale. The ground surface elevation of the site is approximately 98 ft (30 m) above mean sea level.

Methods

The raw groundwater elevation and LNAPL thickness measurements were compiled and manipulated by others as part of earlier site assessment and extraction system performance analyses. In particular, zeros were added to the LNAPL thickness data set in an effort to improve boundary control. Before zeros were added to the LNAPL data, poor boundary control resulted in contours plotting off the map. Assigning zeros where LNAPL thickness data entries were anomalous controlled this problem. Zeros were added under the following conditions: (1) groundwater elevation measurements were provided without corresponding LNAPL thickness measurements, (2) the entire data set for a particular well never indicated measurable LNAPL thicknesses, or (3) limited LNAPL thicknesses were recorded followed by prolonged periods of non-measurable thicknesses. The addition of zeros affected data from one of the eight extraction wells and nine of the 57 monitoring wells.

The data set, compiled over the 15-year project life for all 65 wells, resulted in a spreadsheet that was more than 50 columns wide and almost 2000 rows long. An initial survey of the data set, cross-checked with a site map showing the well locations, was used to eliminate wells that were far removed from the LNAPL boundaries or were closely proximate to other wells and provided redundant measurements. This reduced the number of extraction wells from eight to six and the number of monitoring wells from 57 to 48. These remaining 54 wells were then assigned X-Y coordinates, measured from a common origin on the site map to within 0.04 in (1.0 mm), making the site grid accurate to within about 1.6 ft (0.5 m). The wells plotted were within and surrounded the release area so that the greatest occurrence of free LNAPL was generally in the center of any maps generated.

The data were prepared for plotting by segregating annual sets and determining the average groundwater surface elevation and LNAPL thickness for each well. Data for every other year, beginning with the data set for 1982 and ending with the data set 1996, were used. Using every other year reduced the number of plots from 15 sets of two to eight sets of two; temporal changes in LNAPL thickness were more readily apparent over a two-year period than they were from year to year. This was important because the desire was to produce a simple visual model of the site LNAPL status where trends could be readily recognized. The sets of two consisted of a groundwater surface map and a LNAPL surface map. The LNAPL surface was shown relative to the underlying groundwater surface elevations, producing an overlay of the LNAPL onto the groundwater surface.

The full development of the surface maps was accomplished by utilizing the X-Y coordinates to locate points on a two-dimensional plane, then adding a Z coordinate in the form of annual average groundwater elevations and LNAPL thicknesses. The Z coordinate also made possible the generation of contour, wire-frame, and surface plots,

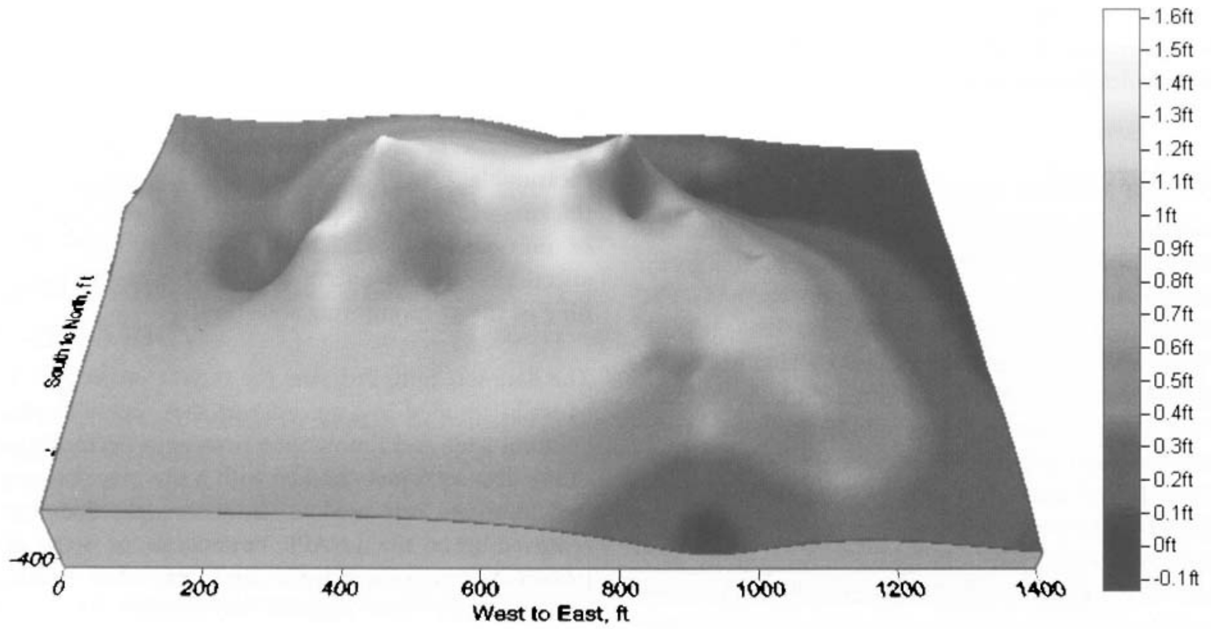

Figure 1. Light non-aqueous phase liquid (LNAPL) surface map for 1982 monitoring data. The LNAPL thickness is shown relative to groundwater, with thicknesses indicated by the side bar scale.

consistent with customary applications in Surfer 8®. The Surfer 8® "kriging" defaults were retained to produce the plotted surface grid files. Kriging is a statistically based gridding method used to produce reasonable contour shapes and defaults in Surfer 8®, including a linear variogram with no nugget effect, no standard deviation grid, and point kriging. These defaults were defined to generate a reasonable grid under common circumstances and would ordinarily not be changed by the novice user.

Discussion

Although eight sets of two maps were developed, only selected LNAPL maps are presented here, in the interest of brevity. Figures 1 through 6 present the LNAPL surface maps for 1982, 1984, 1988, 1990, 1992, and 1996, respectively. For these maps, the shades represent differences in LNAPL thickness relative to the underlying groundwater surface. This allows one to view the relationship between the surface of the groundwater and the LNAPL location. In these maps, the color scale is shown in gray-tone varying from dark (low LNAPL thickness) to light (high LNAPL thickness).

From an examination of the maps, some conclusions become immediately apparent. The first of these is that the site remediation progressed quite well. Sequential examination of the LNAPL surfaces from Figures 1 through 6 reveals a steady reduction in product thickness over time. This is illustrated by the dominant lighter shades in Figure 1 transitioning to darker shades in Figure 6 in the center of the maps, around the vicinity of the recovery wells. Especially noticeable is the reduction in product thickness when 1982 data (Figure 1) are compared to 1988 data (Figure 3). Figure 6 shows that by 1996 the LNAPL had been reduced in all monitored wells to a relatively uniform thickness near the center of the monitored area, but greater thicknesses remained at the eastern edge of the site. These conclusions could have been reached without the maps, but it would have required a cumbersome statistical comparison of the data from each well for each year. Instead, the graphical presentation allowed for a quick and comprehensive assessment of site conditions and facilitated an easy temporal and spatial comparison over the entire monitoring period.

A second conclusion made possible from examining the LNAPL maps is that there seems to be another LNAPL source, either latent and influenced by fluctuating groundwater elevations or originating from an unknown location generally east of the monitored area. This possible new source is pronounced in the sequence beginning in 1988 (see Figure 3) and continuing through 1996 (Figure 6). This condition was not previously recognized, becoming evident only after the LNAPL surface maps were prepared, and may not have been discovered otherwise.

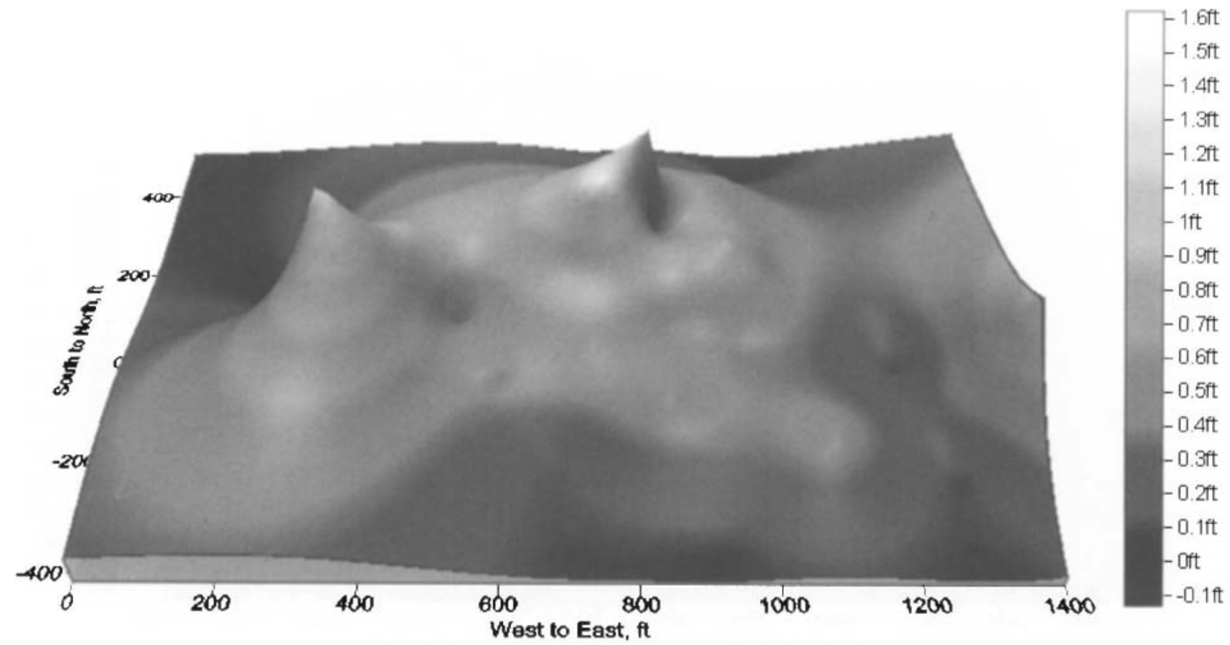

Figure 2. Light non-aqueous phase liquid (LNAPL) surface map for 1984 monitoring data. The LNAPL thickness is shown relative to groundwater, with thicknesses indicated by the side bar scale. Note the increase in LNAPL thickness to the east compared to 1982 data (Figure 1).

Examination of the LNAPL surface maps of Figures 1 through 6 reveals an expected trend in decreasing LNAPL thicknesses in all but the easternmost part of the monitored area. The hydraulic gradient of the area is generally from east to west. The east to west gradient would be exaggerated by the eastern recovery well, and given that the LNAPL gradient would generally mimic that of the groundwater, any free LNAPL to the east of the

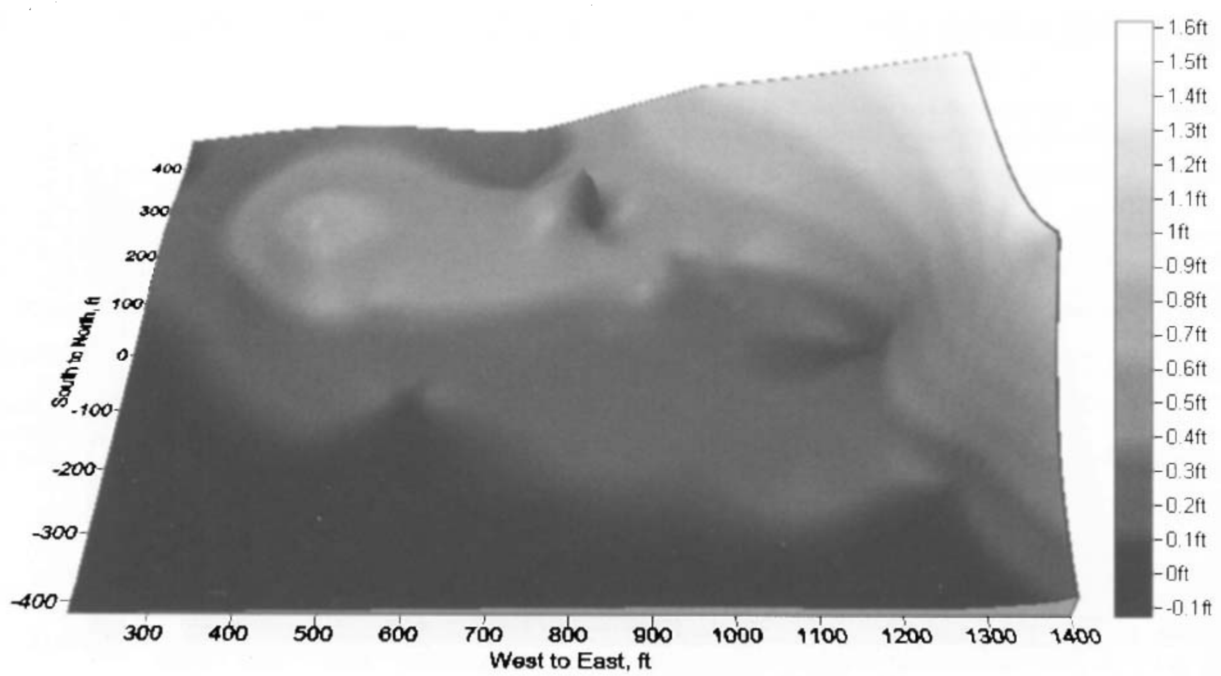

Figure 3. Light non-aqueous phase liquid (LNAPL) surface map for 1988 monitoring data. The LNAPL thickness is shown relative to groundwater, with thicknesses indicated by the side bar scale. A potential new off-site source is indicated by the increased product thickness entering the monitoring area from the northeast (upper right corner).

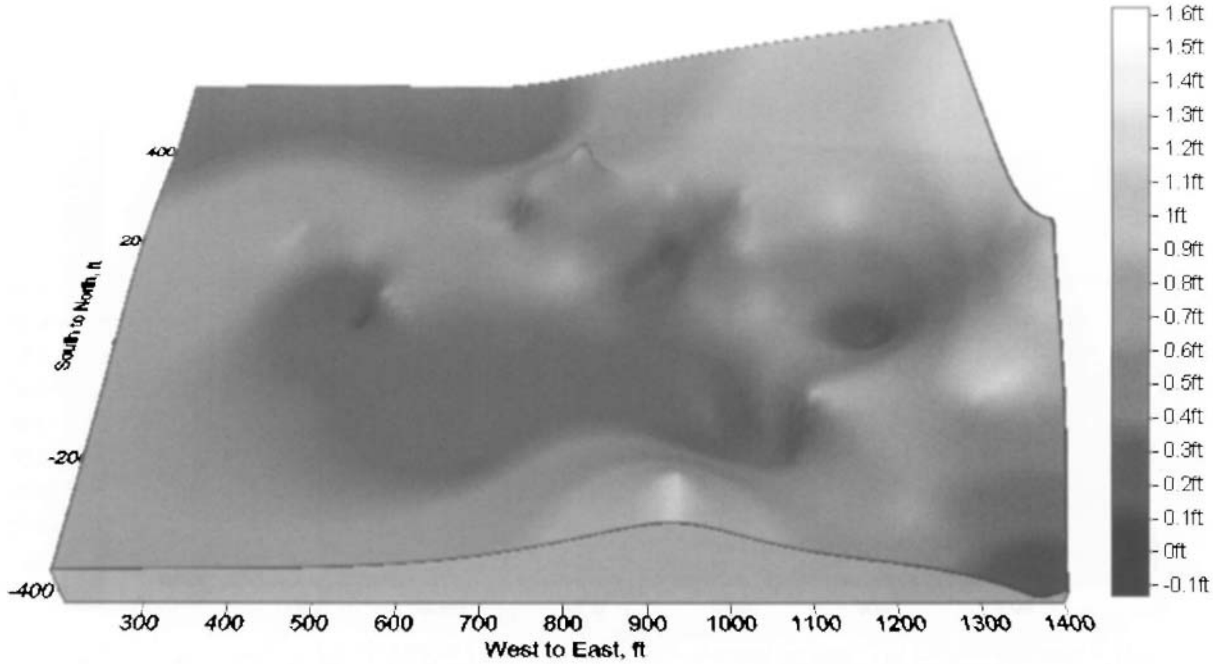

Figure 4. Light non-aqueous phase liquid (LNAPL) surface map for 1990 monitoring data. The LNAPL thickness is shown relative to groundwater, with thicknesses indicated by the side bar scale.

monitored area would migrate toward the recovery wells. The sequence from Figure 1 through Figure 6 suggests that non-aqueous phase liquid migration into the monitored area was occurring. The data demonstrate that from 1988 to 1996 the greatest LNAPL thicknesses occurred along the eastern edge of the monitored area.

Conclusion

Surfer 8® was very functional as a visual diagnostic tool in reducing the large data set into a format that allowed meaningful interpretation. Surface maps of the LNAPL developed using Surfer 8® made it possible to visually trace

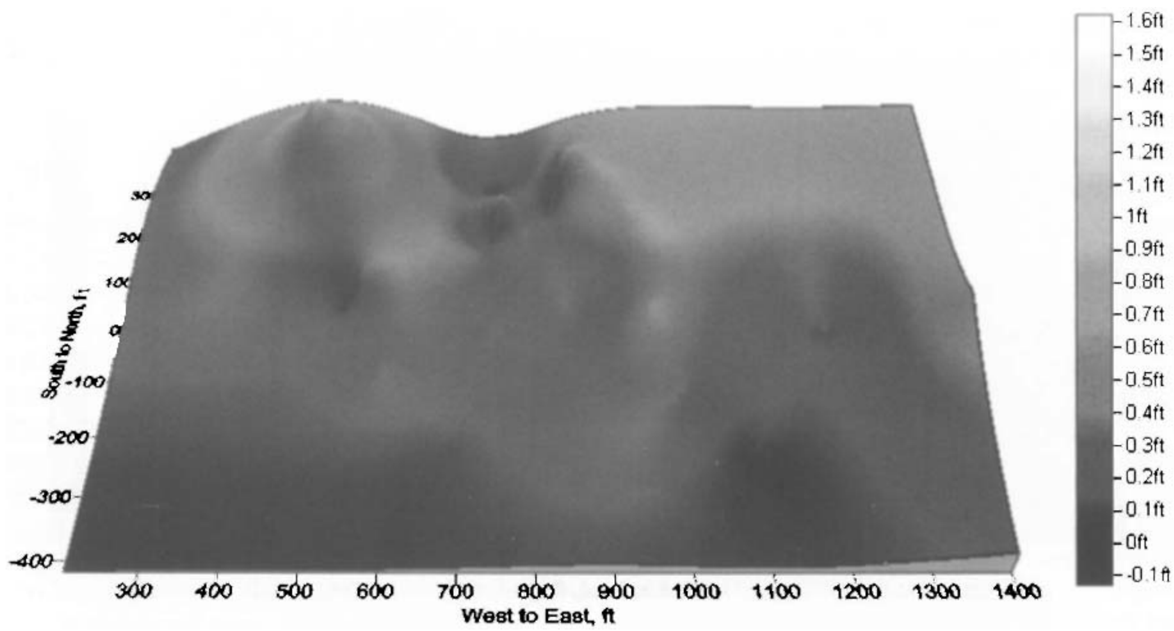

Figure 5. Light non-aqueous phase liquid (LNAPL) surface map for 1992 monitoring data. The LNAPL thickness is shown relative to groundwater, with thicknesses indicated by the side bar scale.

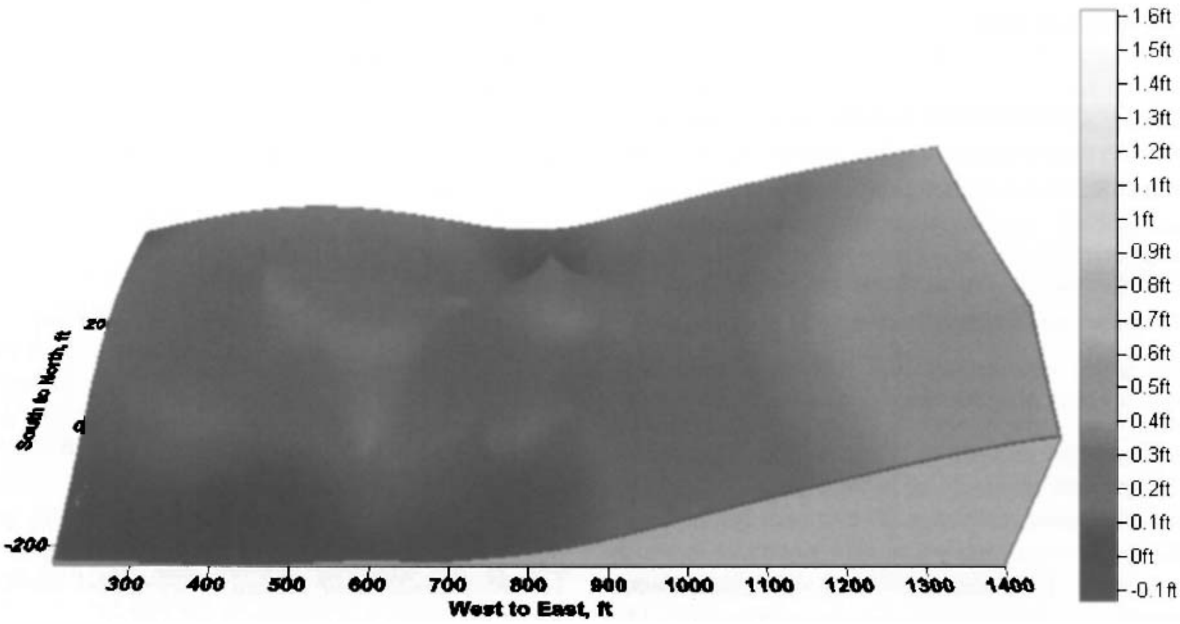

Figure 6. Light non-aqueous phase liquid (LNAPL) surface map for 1996 monitoring data. The LNAPL thickness is shown relative to groundwater, with thicknesses indicated by the side bar scale.

the effects of remediation. The maps showed the progress of recovery and the distribution of the remaining LNAPL, and they also revealed a previously unknown potential LNAPL source outside the monitored area.

Preparation of the data and production of the surface maps could be performed by any groundwater professional with limited computer modeling experience. Surfer 8® is relatively inexpensive, can be loaded into a laptop computer, and can be mastered with a few hours of self-tutoring. The surface maps were generated without using complicated mathematical algorithms and did not require sophisticated programming acumen. The maps present the results in a format that allows easy communication to policy makers, local residents, and other interested stakeholders.

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