Hydrostratigraphic Analysis-Implementing Cost-Effective Superfund Ground Water Cleanup

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ABSTRACT

Implementation of cost-effective ground water clean-up is dependent on a thorough understanding of the hydrogeologic factors controlling the site-specific subsurface flow and transport of contaminants. At Lawrence Livermore National Laboratory (LLNL), a methodology termed hydrostratigraphic analysis is employed to divide the heterogeneous alluvial sediments beneath LLNL into hydrostratigraphic units (HSUs). HSUs are defined as sedimentary sequences whose permeable layers show evidence of hydraulic communication and interconnection. In contrast, hydraulic communication between HSUs is restricted across HSU boundaries. HSUs are based on a comprehensive analysis and integration of chemical, geological, geophysical, and aquifer test data.

The seven HSUs identified at LLNL form operational units relevant to the ground water cleanup. Within each HSU, boreholes and wells are positioned to define the relationship between source areas and individual ground water contaminant plumes. The locations of extraction wells have been optimized to hydraulically contain and isolate individual source areas and to methodically clean up the individual ground water contaminant plumes derived from these source areas. Borehole and well locations are based on detailed mapping of higher-permeability sediment distribution, ground water gradients, and contaminant distributions in soil and ground water in each HSU.

Improved understanding of the subsurface features controlling contaminant flow and transport is enabling LLNL to more effectively implement remediation plans, decrease cleanup times, and reduce overall project costs. During the last 8 years, significant progress has been made towards hydraulically containing and cleaning up the contaminant plumes along the western margin of LLNL. This progress is clearly evidenced by isoconcentration time series maps, hydraulic capture maps, and mass removal rate plots for each HSU. Through these maps, hydrostratigraphic analysis has become a key tool for demonstrating cost-effective ground water cleanup to DOE, the regulators, and the community.

BACKGROUND

Site History

LLNL is located in Livermore, California about 40 miles east of San Francisco, where ground water is used for drinking water and agriculture. The area to be remediated covers about 1.5 square miles. In 1982, multiple plumes of volatile organic compounds (VOCs), predominantly trichloroethene (TCE) and tetrachloroethene (PCE), were discovered in ground water beneath the LLNL site. LLNL was placed on the U.S. Environmental Protection Agency’s (EPA) National Priority List in 1987. A Federal Facility Agreement to facilitate compliance under the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) was signed with state and federal regulatory agencies in November 1988. As part of the CERCLA process, the LLNL Environmental Restoration Division has completed a series of documents, including the Remedial Investigation (Thorpe et al., 1990), the Feasibility Study (Isherwood et al., 1990), the Proposed Remedial Action Plan (Dresen et al., 1991), the Record of Decision (ROD) (U.S. DOE 1992), and the Remedial Action Implementation Plan (RAIP) (Dresen et al., 1993). Pump and treat is the selected primary remedial technology. A series of Remedial Design (RD) Reports have been completed (Berg et al., 1993, 1994a, 1994b, 1995, 1997). Each report contains engineering design specifications for the planned treatment facilities and their extraction wells and piezometer networks.

To effectively implement the remediation plan selected in the ROD, a detailed, comprehensive, conceptual model of VOC distribution, and ground water flow and transport in the subsurface at each
treatment facility area was needed. The hydrostratigraphic analysis methodology was developed during the RD process to address the detailed level of subsurface understanding needed to successfully and cost-effectively plan and design the remediation system. A site-wide study was also initiated to integrate individual treatment facility area studies and ensure consistent site-wide HSU interpretations and nomenclature. The primary goals of these analyses were to 1) position extraction wells to optimize VOC mass removal and hydraulic capture of plumes, and 2) to minimize the number of monitor wells needed for site cleanup and compliance monitoring.

Site Hydrogeology

LLNL is underlain by a thick sequence of heterogeneous sediments known as the Upper and Lower Livermore Formations, a Plio-Pleistocene sequence of alluvial fan, fluvial, and lacustrine deposits. A regional confining layer consisting of about 20 to 30 ft of clay is present in the upper part of the Lower Livermore Formation. VOCs are not known to occur beneath this confining layer.

The alluvial sediments consist of complexly interfingered sand and gravel channel deposits within lower-permeability silt and clay. These higher permeability channel deposits are pathways for VOC transport; however, due to their complex geometry, it is difficult to trace individual channels laterally. Our analyses showed that some of the channel deposits that appeared distinct and separate from borehole log data were actually hydraulically connected, whereas other channel deposits had no hydraulic connection. Hydraulic interconnection between or within permeable layers is measured directly from response to ground water pumping, or inferred indirectly from VOC concentrations or hydrographs.

We have used hydrostratigraphic analysis to organize this very heterogeneous sequence into operational units that are relevant to the ground water cleanup. Of primary interest was to group together packages of sediments whose permeable layers showed evidence of hydraulic communication, and to define significant regional or local aquitards. Thicker aquitards were defined as separate HSUs. Minor aquitards define HSU boundaries across which little or no vertical hydraulic communication was observed from aquifer tests.

METHODOLOGY

The LLNL subsurface has been subdivided into seven HSUs based on a systematic analysis using multiple, independent data sets to reduce the uncertainty in our subsurface correlations. The independent data sets used in our analysis include:

1) lithologic core descriptions (most boreholes at LLNL are continuously cored and logged in detail);
2) geophysical wire-line borehole logs, including resistivity, induction, gamma ray, spontaneous potential, and caliper logs;
3) hydraulic test data, including evaluation of the response of observation wells during aquifer tests to determine the extent of hydraulic communication;
4) ground water elevation data, including individual well hydrographs;
5) VOC concentrations in soil and ground water; and
6) Plume signatures based on ratios of VOC concentrations.

Initial subsurface correlations were made using geophysical, lithologic, and hydraulic test data. To facilitate this analysis, detailed cross sections displaying lithologic and geophysical data were constructed for the site. These initial interpretations were then checked and further constrained using the other independent data sets, primarily chemical and ground water elevation data. Thus, the multiple independent data sets were used in an iterative manner to cross-check and verify or modify initial correlations.

In addition to the cross sections, maps were constructed showing VOC distributions, ground water elevations, and isopach maps were developed showing the geometry of high-permeability channels for each HSU. These maps are used to optimize extraction well and monitor well locations, to ensure adequate hydraulic control of plumes, and to maximize contaminant mass removal. As new data become available, the hydrostratigraphy is updated and revised. The method is also used to identify data gaps that may affect remedial well field design.

RESULTS

Implementing Cleanup

The seven HSUs form remediation management units for implementing the LLNL ground water cleanup. To ensure that extraction and monitor wells are located in the areas of greatest concern, isosconcentration maps of VOCs above MCLs were made for each HSU. These maps were prepared by subtracting the MCL for each detected compound from its measured concentration, and then adding the residual values together. The residual values from each well were then contoured. These maps, therefore, help pinpoint areas with elevated VOC concentrations above MCL. Areas where VOC concentrations are all below their respective MCLs,
and therefore do not require cleanup, do not appear on these maps. Time series maps of VOC plumes above MCLs are being used to demonstrate cleanup in treatment facility areas, and are also effective tools for optimizing operation of a remedial well field.

Figure 1 is a block diagram of the site showing the relationship of known or suspected source areas to the distribution of VOCs above MCLs in HSUs as viewed along the southern boundary of the site. Figure 1 shows that the structural configuration of the HSUs beneath the site exerts a strong control over VOC transport at the site. Due to the general westward dip of the stratigraphic sequence, HSUs located at depth in the western portion of the site become unsaturated in the eastern portion of the site. Once VOCs migrate from source areas through the vadose zone and encounter the saturated zone, VOC transport is influenced by ground water advection and dispersion. In addition, the hydraulic properties of the HSU where the saturated zone is first encountered also strongly influences the distribution and rate of VOC transport. VOCs will tend to migrate down dip within an HSU, not horizontally. In certain areas of LLNL, VOCs initially present near the surface are found at increasing depths towards the west. Understanding this has been essential for installing and screening extraction wells in the appropriate intervals to intercept and remediate VOC plumes.

HSU-5 in the eastern portion of Figure 1 shows this relationship. A source area near a salvage yard in southeastern LLNL has introduced VOCs into HSU-5 in this area. Once in the saturated zone, ground water carries these VOCs downgradient within HSU-5. Because of limited hydraulic communication between HSU-5 and adjacent HSUs, VOCs occur at higher concentrations and are found further downgradient in HSU-5 than in adjacent HSUs. HSU-2, for example, which is unsaturated in the above mentioned source area, does not contain high concentrations of VOCs in this area of LLNL. Extraction wells which target VOCs in HSU-5 close to the source area as well as near the high concentration (greater than 100 ppb) downgradient edge of the VOC plume have been installed.

In the western part of LLNL, the saturated zone is first encountered in HSUs 1B and 2, and VOCs originating from source areas in this part of LLNL are found in these units (Figure 1). In this area, HSU 3A forms a significant barrier or aquitard to further downward migration of VOCs. VOC concentrations in HSU 3A are above MCLs in only a few isolated wells. Plumes in these three HSUs are being remediated by extraction wells located in the Treatment Facility A (TFA) area (Fig. 1).

Figure 2 is a block diagram showing both cross-sectional and map views of HSU-2 VOC plumes along the western margin of the site. Similar to Figure 1, Figure 2 also shows that elevated VOCs are limited to HSUs 1B and 2 in the western portion of LLNL. Treatment Facility A, B, and C (TFA, TFB and TFC, respectively) extraction wells all target the highest concentrations in these plumes.

The Figure 2 block diagram also shows ground water flow direction and extraction well locations in HSU-2. Based on our analysis of this unit, we have optimized the location of extraction wells to hydraulically control and cleanup the HSU 2 plumes with the fewest number of wells. By contouring ground water elevations for wells screened in this interval, we can more accurately define the capture zones for each extraction well placed in HSU 2. Pumping rates are being managed on an ongoing basis to maximize VOC mass removal rates and ensure hydraulic capture in each treatment facility area.

Status of Cleanup

Figure 3 shows VOC concentration time series maps for HSU-1B in TFB. The figure depicts a significant decrease in concentration and collapse of the VOC plume since ground water extraction was initiated in 1993. Figure 4 is a mass removal plot for TFB. As shown, mass removal rates for the area significantly exceed rates predicted by ground water flow and contaminant transport simulations of the site (Tompson et al., 1995). Similar results are being observed at the other site treatment facilities. Figure 6 depicts a ground water elevation contour map showing hydraulic capture areas associated with extraction wells completed in HSU-1B. In September 1996, western margin hydraulic capture at LLNL was achieved when extraction wells associated with TFC were activated. As contaminant plumes along the western margin of the site continue to collapse, cleanup resources will be re-directed to remediation of high-concentration VOC plumes in the interior of the site.

CONCLUSIONS

Seven HSUs have been defined at LLNL based on available hydrogeologic, geophysical, and chemical data. Although the conceptual hydrogeologic model developed for the RI report proved to be a sound basis for planning remediation at LLNL, actual implementation of this plan has required more detailed analysis. By focusing this detailed characterization work on site cleanup goals, our better understanding of the subsurface has helped us improve VOC mass removal and hydraulic control of individual plumes, which in turn is reducing overall cleanup time. Hydrostratigraphic analysis has proven to be a cost-effective tool, allowing managers to make better informed and timely decisions regarding cleanup. These decisions include:
1) improving the placement and limiting the number of extraction and monitor wells,
2) prioritizing the order of installation of extraction and monitor wells,
3) prioritizing the construction and startup of remediation systems,
4) managing extraction flow rates and pumping locations; and
5) evaluating the effectiveness of innovative remediation technologies.

Hydrostratigraphic analysis is also a systematic method for integrating large complex data sets into a coherent manageable framework that is based on measured hydrogeological properties. Hydrostratigraphic analysis has enabled us to understand the complex LLNL hydrogeologic environment, and plan and implement an effective cleanup. The hydrostratigraphic framework for the site has proven an effective visualization tool for presenting complex hydrogeologic and remediation issues to DOE, regulatory agencies, and the community.

One of the major benefits of this analysis is that fewer extraction and monitor wells are now necessary to implement our original remediation plan outlined in the ROD. At TFA, for example, the number of extraction and monitor wells has been decreased by about 20%. VOC mass removal rates exceeding projected levels and rapid reduction of VOC plume size in the subsurface have demonstrated the utility and cost-effectiveness of this approach. In summary, by analyzing data within the context of the HSUs, we are better able to plan, implement and monitor the cleanup.

REFERENCES


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