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"Smart" pump and treat

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Abstract

Lawrence Livermore National Laboratory (LLNL) is approaching the final phase of the Superfund decision-making process for site restoration and will soon initiate full-scale clean-up. Despite some well-publicized perceived failings of the pump and treat approach, we have concluded that intelligent application of this strategy is the best choice for ground water restoration at LLNL. Our proposed approach differs sufficiently from the pump-and-treat methods implemented at other sites that we call it "smart" pump and treat. Smart pump and treat consists of four distinct, but interrelated, elements: three pre-remediation strategies and one applying to the active management of the extraction process. Together, these techniques constitute an integrated program that embodies crucial aspects of contaminant flow and transport to speed up the remediation of contaminated aquifers. The four elements are: (1) a spatially detailed site characterization, linked with regional hydrogeologic simulations; (2) directed extraction, where the extraction and recharge locations are controlled by field-determined hydrogeologic parameters; (3) field-validated simulations that match the complexity of the collected data; and (4) adaptive pumping and reinjection where spatial positions and rates vary with time. Together, these techniques minimize the cost and the time to reach regulatory-directed cleanup goals and maximize the rate of contaminant removal.

1. Background

At LLNL (Fig. 1), we have inherited a legacy of contaminated soil and ground water from years of inadequate toxic materials handling and disposal practices, which are clearly unacceptable by today's standards. Contaminants at LLNL are primarily in the ground water and predominantly comprised of the chlorinated volatile organic compounds (VOCs) trichloroethylene (TCE) and perchloroethylene (PCE). Until we began pilot remediation in 1987, the contaminants migrated naturally for over 40 years and, during that period,

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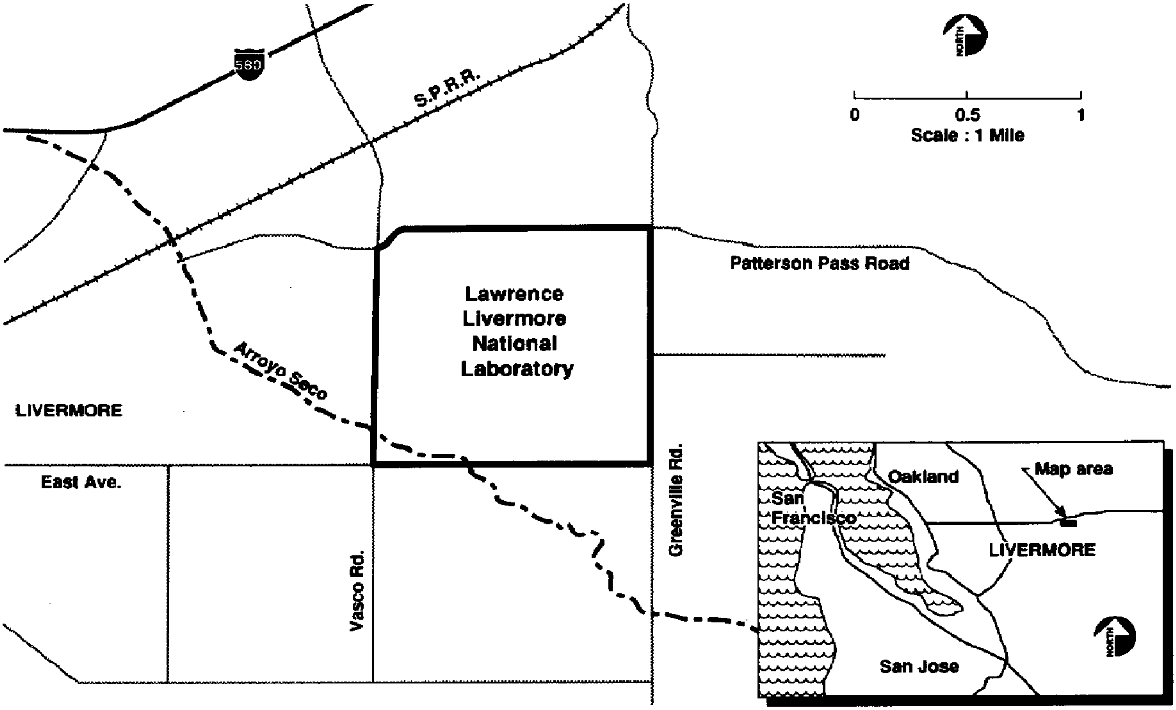


Fig. 1. Location of LLNL.

have dispersed over an area of about 1 mi^2. Contaminants were initially discovered in ground water in 1983, and LLNL was added to EPA's National Priority List in 1987. A formal Remedial Investigation [1], Feasibility Study [2], and Proposed Remedial Action Plan (PRAP, [3]) have been completed. Pilot remediation efforts were initiated in 1987. Over 40 million gallons of ground water have been extracted, treated, and recycled. Surface treatment with ultraviolet light oxidation has purified the ground water, eliminating all measurable VOCs. Results of the pilot studies provide the basis for the pump-and-treat strategy now proposed for ground water restoration. In this paper, we discuss components of this plan and the techniques used in arriving at our decisions.

2. Detailed characterization

The first step in characterizing a site to the level of detail needed to perform smart pump and treat is to conduct regional studies and determine the size and orientation of preferred ground water flow pathways. The Livermore Valley is a relatively flat basin underlain by a complex of alluvial sediments of late Tertiary and Quaternary Age. The thickness of unconsolidated sediments increases from the eastern margins of the Valley westward toward the city of Livermore. VOCs exist in the upper part of the saturated zone, called the Upper

Member of the Livermore Formation, which consists of sand, gravel, silt, and clay deposits with multiple water-bearing zones of relatively high permeability (see Fig. 2). Layers and lenses of low permeability silts and clays act as local aquitards, resulting in semi-confined permeable sediments at depth with horizontal hydraulic communication within water-bearing zones up to 250 m depth. The top of the Lower Member of the Livermore Formation is distinguished from the base of the Upper Livermore Formation by a 5- to 20-m-thick zone of clay-rich blue or greenish sediments with occasional interbeds of sand and silt. These low-permeability sediments comprise a regional confining layer.

A detailed characterization is unrealistic at the scale of the 2 mi^2 study area; thus, a representative area was investigated (the detailed study area, or DSA), and the results from this area were used to characterize the VOC and lithology distributions, as well as critical sorption and other transport parameters characteristic of the entire site (see Fig. 3). The findings from the DSA provide important information for implementation of an extraction and reinjection program. The choice of the representative area was dependent on our understanding of the regional geologic and depositional environments and the more generalized characterization afforded by approximately 300 monitoring wells spread over the affected areas.

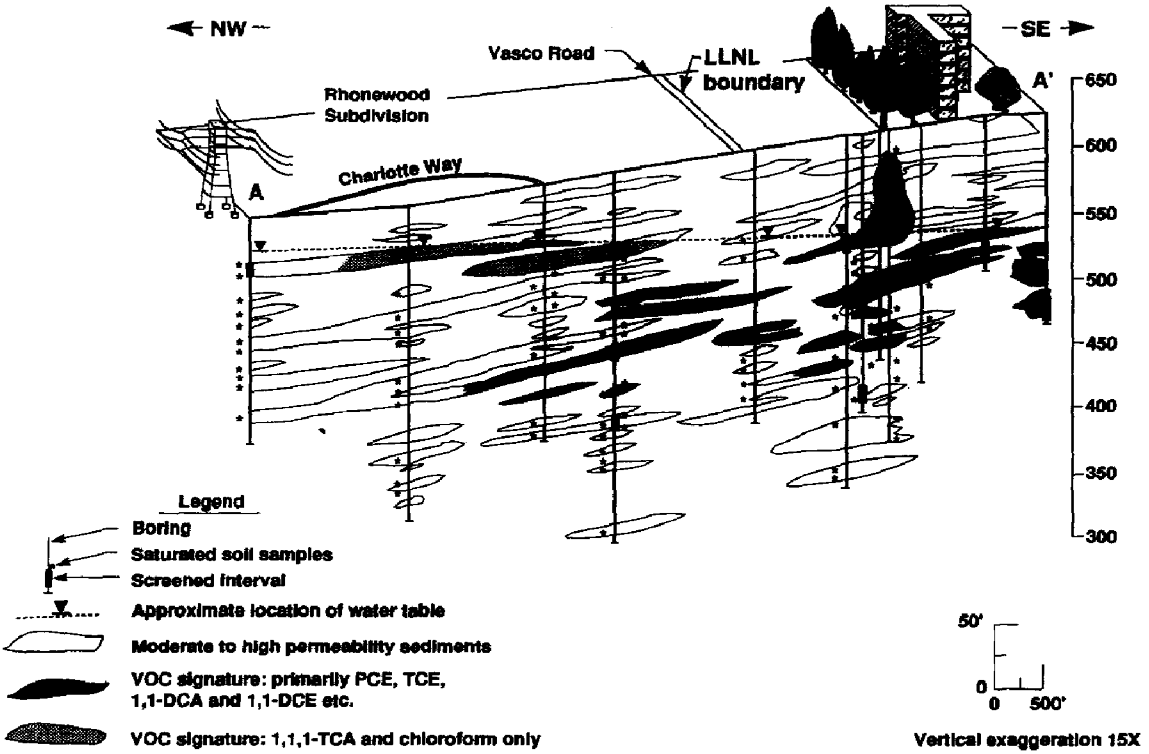


Fig. 2. Generalized geologic section showing distribution of VOCs in the subsurface west of LLNL.

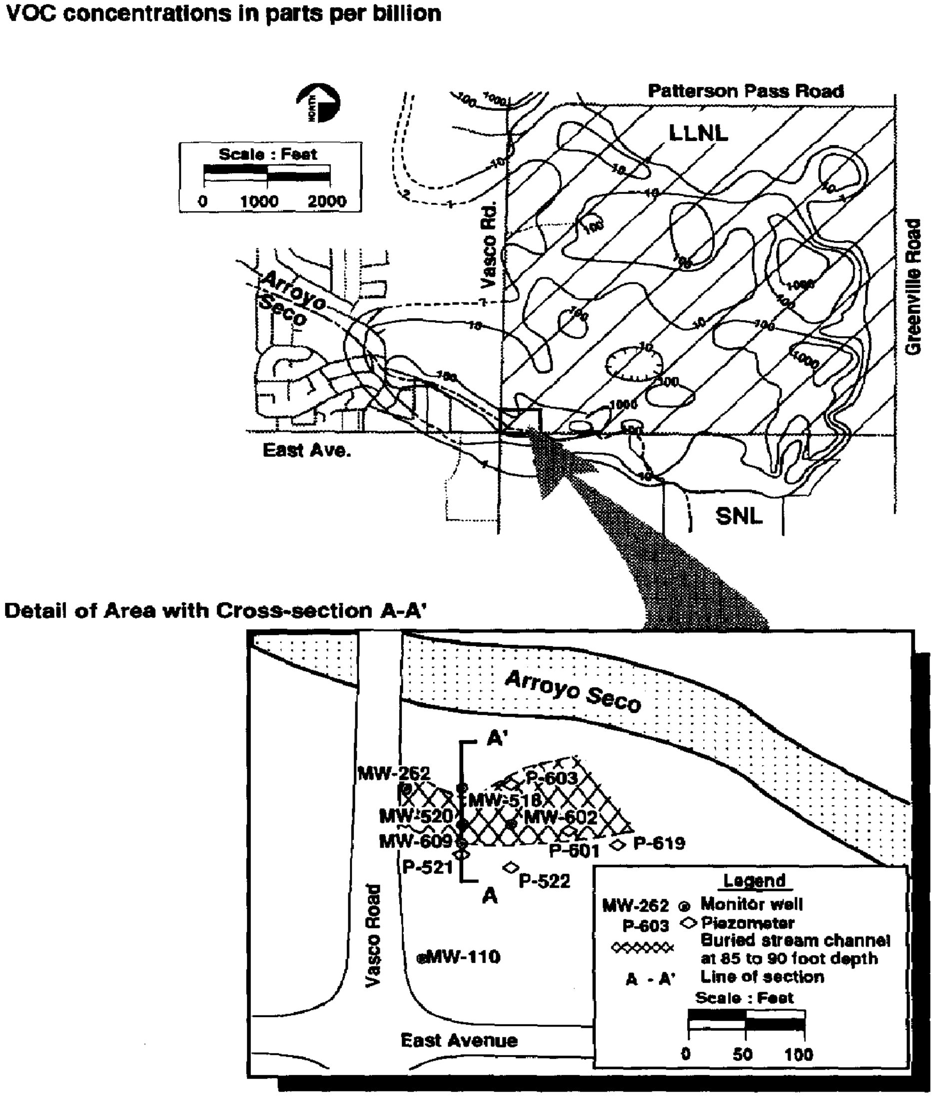


Fig. 3. Isoconcentration boundary map of total VOCs with location of detailed study area and detail of possible buried stream channel location.

We used technology developed by LLNL to collect sediment samples for characterization of the DSA. Our depth-sampling method allowed us to collect saturated samples from each water-bearing zone without contamination from other zones and without removing the drill rod from the borehole during sampling [4]. At the DSA, we found that, within a water-bearing zone of permeable sediments, changes in VOC concentrations occur on a vertical scale of 1 to 3 ft (see Fig. 4). In addition, VOCs have migrated less than 3 ft into the low-permeability sediments (see Fig. 5). Consequently, the spatial distribution of VOCs is strongly related to the distribution of permeable materials.

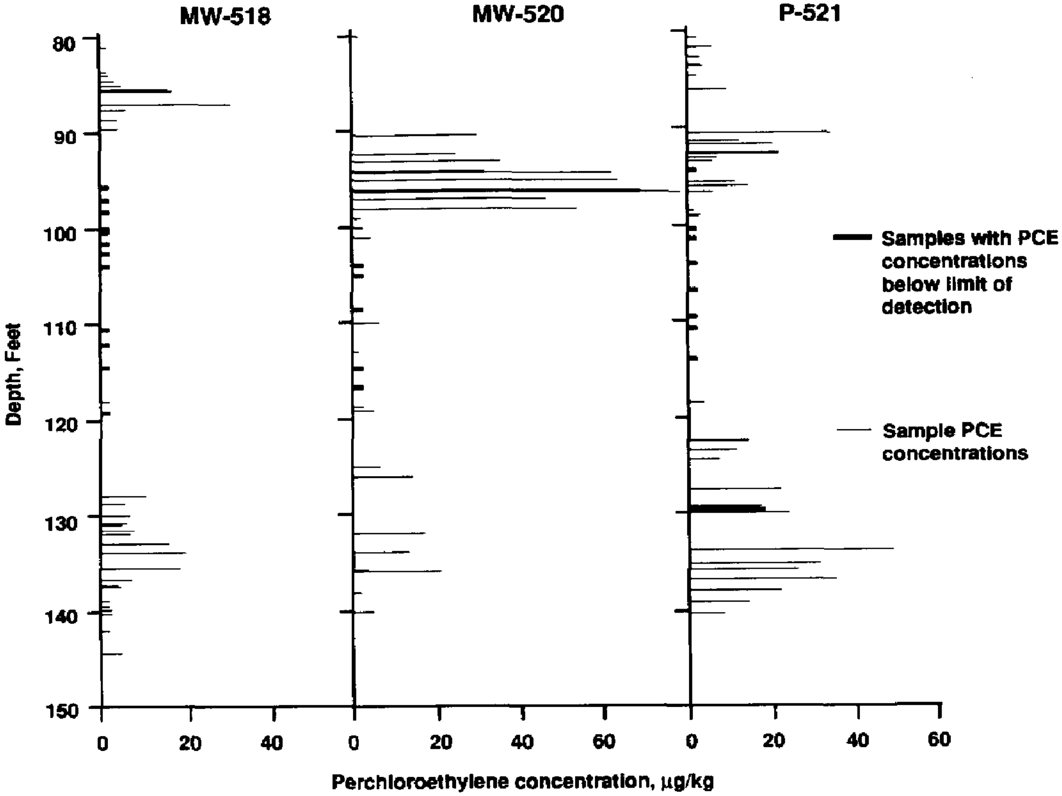


Fig. 4. Vertical distribution of PCE in three adjacent boreholes.

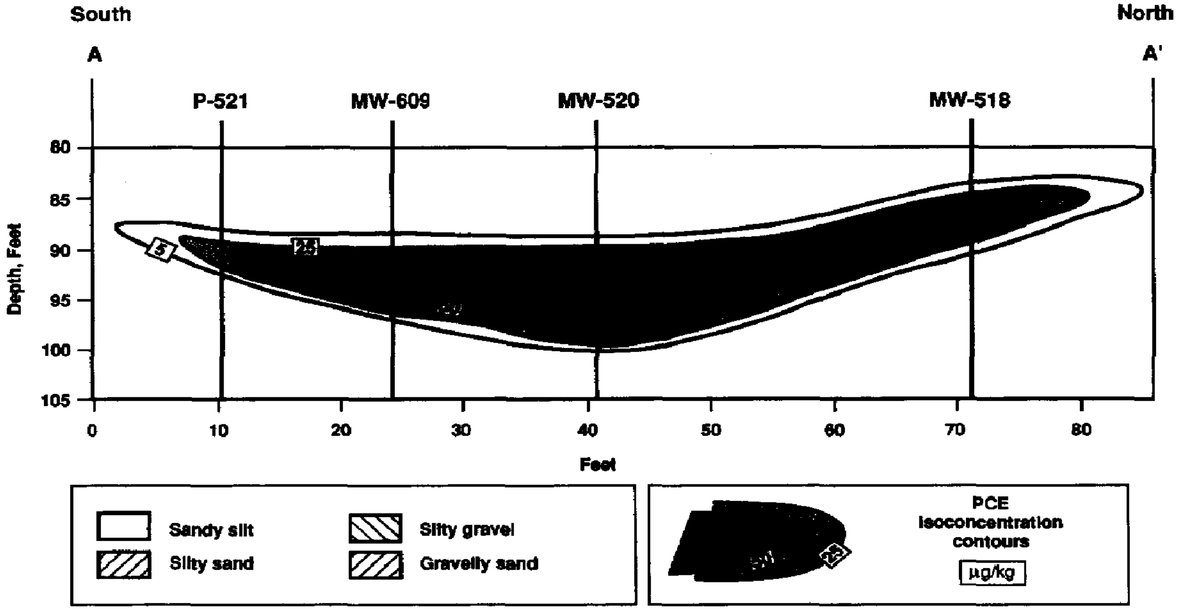


Fig. 5. Idealized model of buried stream channel cross-section, looking west.

TABLE 1

Summary of detailed study area average sediment properties

Lithology		PCE sediment concentration (μg/kg)	TCE norm K_d	PCE norm K_d	Porosity (%)	Perm ($\times 10^{-7}$)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	CEC[a] (meq/100 g)	Org. C[b] (%)
Sandy gravel	Average:	0.0232	0.22	0.91	27.7	763.1	56	33	6	5	5.93	0.04
	Count:	17	10	9	6	8	12	11	11	11	11	11
Gravelly sand	Average:	0.0183	0.42	1.42	27.1	267.3	29	53	9	8	8.87	0.052
	Count:	28	13	9	7	13	15	14	14	14	14	14
Silty gravel	Average:	0.009	–	–	–	11.7	–	–	–	–	–	–
	Count:	11	–	–	–	6	–	–	–	–	–	–
Silty sand	Average:	0.0096	0.74	1.99	29.7	10.6	6	53	26	16	17	0.06
	Count:	28	23	16	6	13	23	21	21	21	21	21
Clayey sand	Average:	0.0207	0.76	1.94	–	7.5	12	48	19	21	17.5	0.06
	Count:	2	2	2	–	1	2	2	2	2	2	2
Gravelly silt	Average:	0.0003	–	0.91	–	2.3	–	–	–	–	–	–
	Count:	5	–	–	–	4	–	–	–	–	–	–
Sandy silt	Average:	0.0047	0.83	2.48	30.3	2.6	3	42	36	20	22.3	0.07
	Count:	65	27	20	12	39	28	26	26	26	27	27
Clayey silt	Average:	0.007	0.78	2.4	30.3	4.25	1	39	40	20	20.9	0.11
	Count:	23	6	1	6	17	7	7	7	7	7	7
Sandy clay	Average:	0.0017	1.11	3.03	30	1.3	2	30	29	39	29.7	0.07
	Count:	3	3	3	1	3	3	3	3	3	3	3
Grand average:		0.0098	0.67	1.96	29.2	96.0	15	45	25	16	16.7	0.06
Grand count:		182	84	60	38	104	90	84	84	84	85	85

[a] Cation exchange capacity.

[b] Organic carbon.

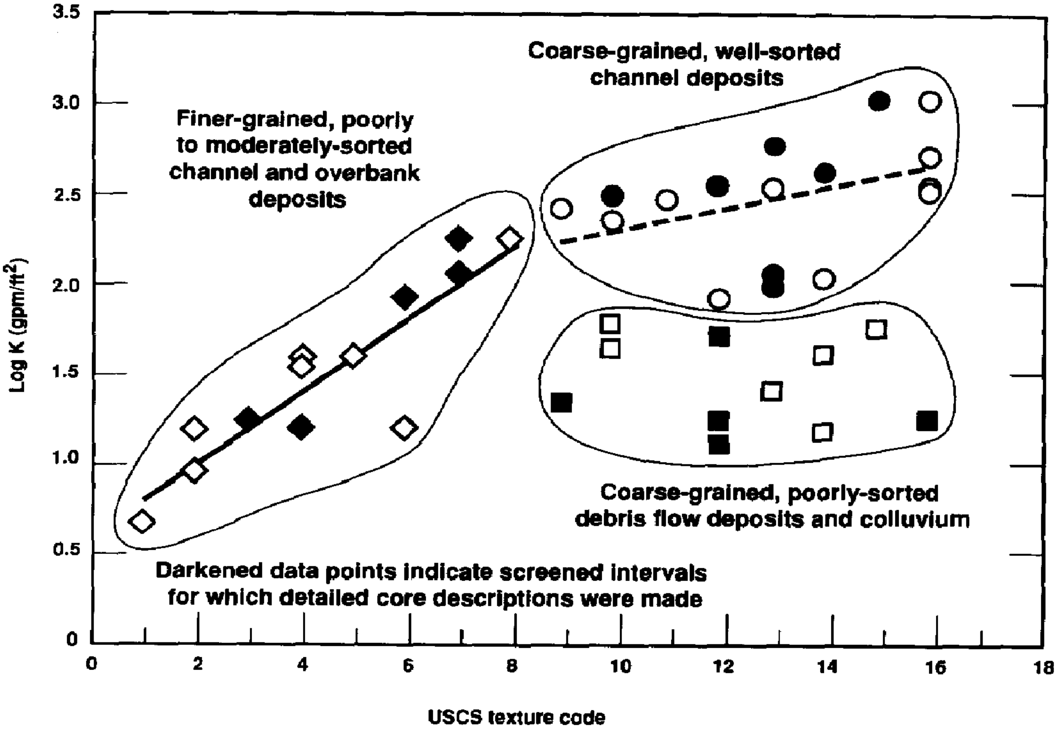
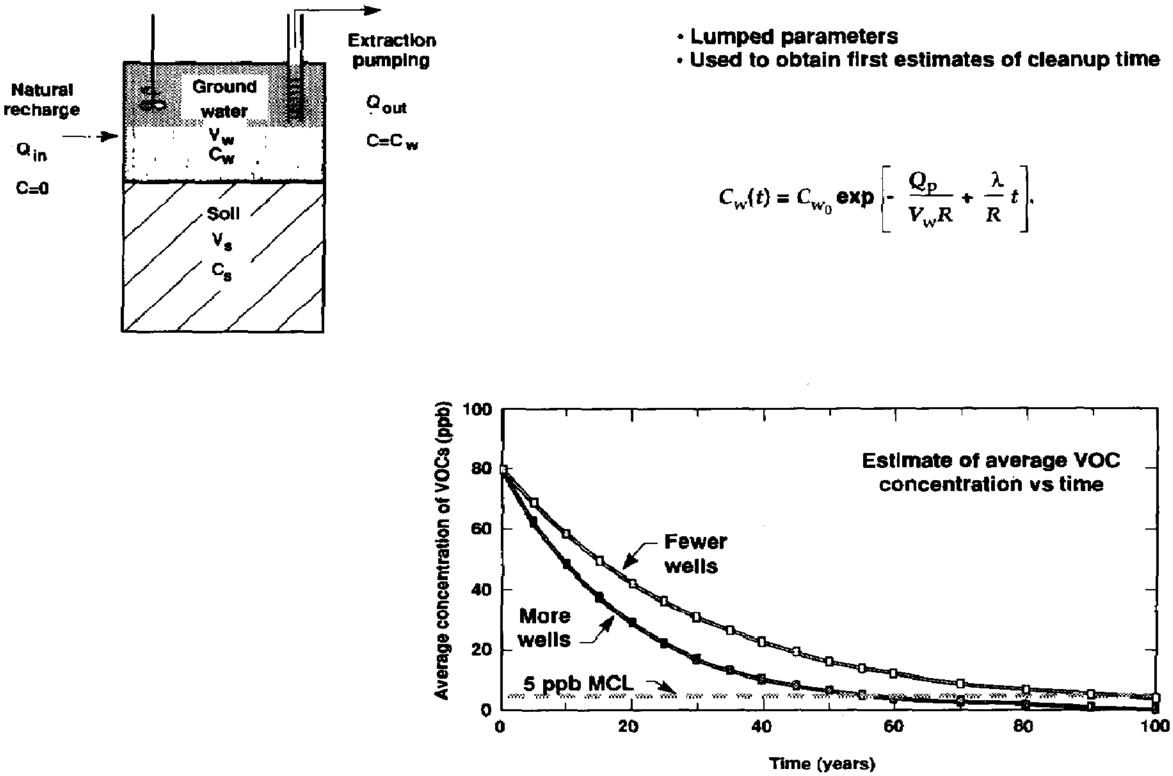


Fig. 6. Cross-plot of log K versus sedimentary (USCS) textures with depositional facies interpretations superimposed.

Other information from the DSA impacted our proposed pump-and-treat plan. Our correlation analysis of lithology versus sediment parameters is summarized in Table 1. Results indicate that sediment PCE concentrations, bulk density, normalized TCE and PCE K_d (sorption constant) values, organic carbon, and carbon exchange capacity are highly correlated with lithology ($P \leq 0.0001$). We also found that sorption constants are related to percent silt and clay and cation exchange capacity [5]. In fact, these variables can be used to predict spatially varying sorption. In addition, a strong correlation has been observed between observed lithological facies and hydraulic conductivity, k (see Fig. 6) [6].

3. Field-validated simulations

We found it essential to initially use the least-complex simulation that the data can support. We started with very simplistic simulations and gradually increased the complexity and sophistication of simulations employed as the data and desired results required. At each stage, the simulation was further calibrated with new field results. Estimates of certain input parameters can be made by comparing predictions with field data.



$$C_w(t) = C_{w_0} \exp\left[- \frac{Q_P}{V_w R} + \frac{\lambda}{R} t\right].$$

Fig. 7. A zero-dimensional model: the "well-mixed tank".

All simulations used assume that VOCs partition between sediment and ground water according to a linear equilibrium isotherm, resulting in a constant retardation factor. In addition, VOCs are assumed to transform into non-toxic compounds according to a first-order decay rate.

We initially used a zero-dimensional "well-mixed tank" model to obtain an estimate of the time necessary to reduce concentrations within the plume to concentrations below regulatory prescribed limits (see Fig. 7). The contaminant plume was idealized as a single, homogeneous volume of sediment and ground water. This volume was estimated using a three-dimensional volume integrator from the measured VOC concentrations in samples of ground water and sediment, with interpolations constrained by "soft" geologic data, such as sediment type and soil VOC samples. The plume volume is flushed with clean water at a rate equal to the expected extraction flow rate under a particular pumping scenario. Given the above assumptions, the average water concentration can then be predicted based on a simple analytical expression. The concentration as a function of time for this simulation decreases exponentially.

A two-dimensional, semi-analytical model of VOC transport was used to predict contaminant concentrations for a "no action" alternative, as part of a baseline public health risk assessment. Ground water flow was assumed to advect at a uniform velocity throughout the region of interest. Initial VOC concentrations were defined by current field measurements, and transport was assumed to occur by one-dimensional advection and two-dimensional dispersion. In addition, VOCs were allowed to adsorb and transform. Simulations were performed to forecast VOC concentrations that may occur in hypothetical receptor wells downgradient of the plume.

A two-dimensional numerical model of ground water flow was next developed to provide a basis for future simulations of various ground water restoration alternatives [7]. This model allows for spatially varying velocity, permeability, and sorption constants, as well as sinks and sources where extraction and recharge wells are placed. Each feature of the conceptual and numerical simulation is based on careful evaluation of the field data. The effective hydraulic conductivity of the basin sediments compares closely with predictions based on stochastic theory [8]. Calibration of the model has yielded a good match to observed water levels. The simulation is now being used to forecast the response of the ground water basin to different remediation pumping scenarios. The CFEST code being used for this task also allows for future extension to three dimensions as results warrant.

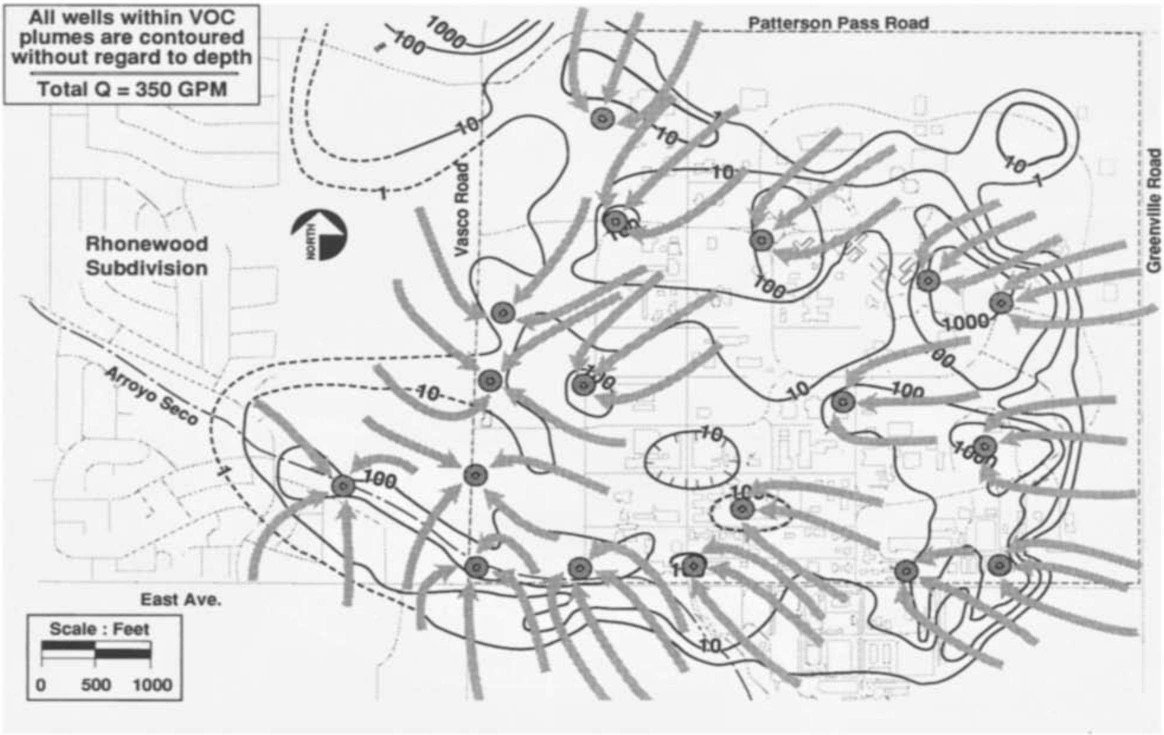


Fig. 8. Two-dimensional vertically integrated models of ground water flow and VOC distribution are used to identify approximate locations of extraction well clusters.

4. Directed extraction

For directed extraction, the information on the spatial distribution of hydrogeologic, geologic, chemical, and sorption parameters gathered during detailed characterization are used to establish the initial distribution of extraction and recharge wells. Two-dimensional vertically integrated simulations (CAPTURE and two-dimensional plume contour maps) of ground water flow and VOC distribution are used to identify the approximate locations of extraction well clusters (see Fig. 8).

If only simplified two-dimensional homogeneous isotropic models are used, one might choose initial well locations that cause contaminants to be transported from coarse-grained permeable materials into fine-grained, highly sorptive sediments, where VOCs may become more difficult to remove. The use of a three-dimensional conceptual model of the VOC distribution, derived from depth sampling, two-dimensional cross-sections, and three-dimensional interpolation, focuses the extraction locations on discrete water-bearing zones in order to maximize VOC mass removal and to minimize transport of VOCs into highly sorptive sediments (see Fig. 9). Wells screened in coarse-grained materials take advantage of natural pathways of preferred flow that originally distributed the VOCs. Near source areas, fully screened extraction wells may be used because sampling has shown all sediments to contain VOCs. Away

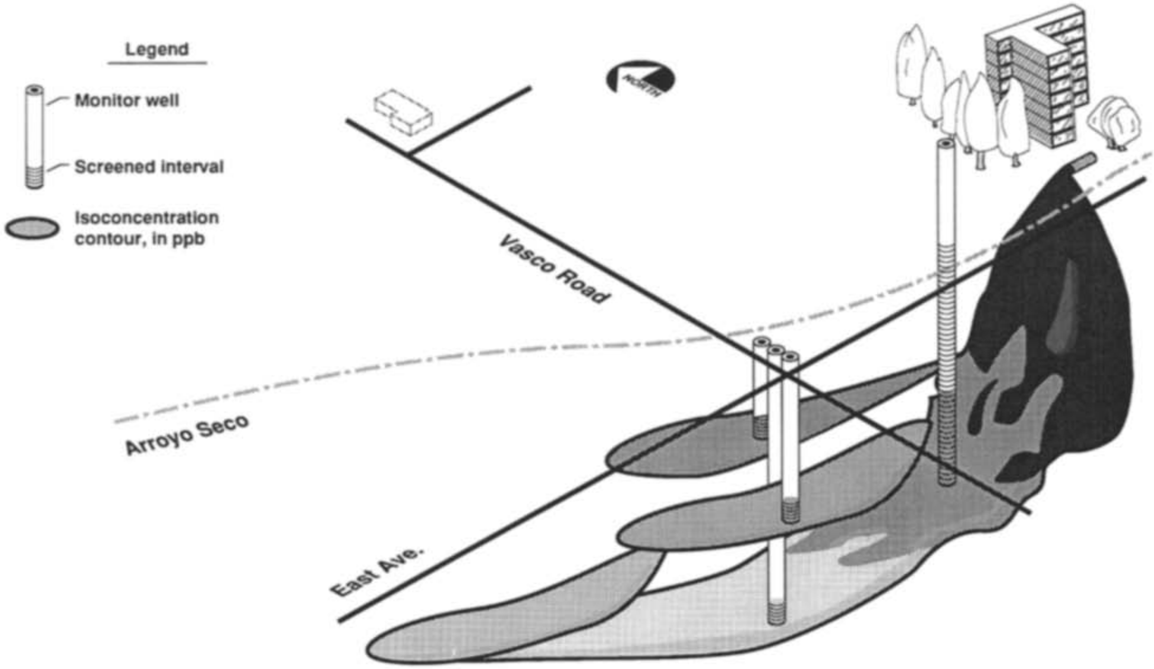


Fig. 9. Wells are sited during directed extraction to minimize transport of VOCs into highly sorptive sediments.

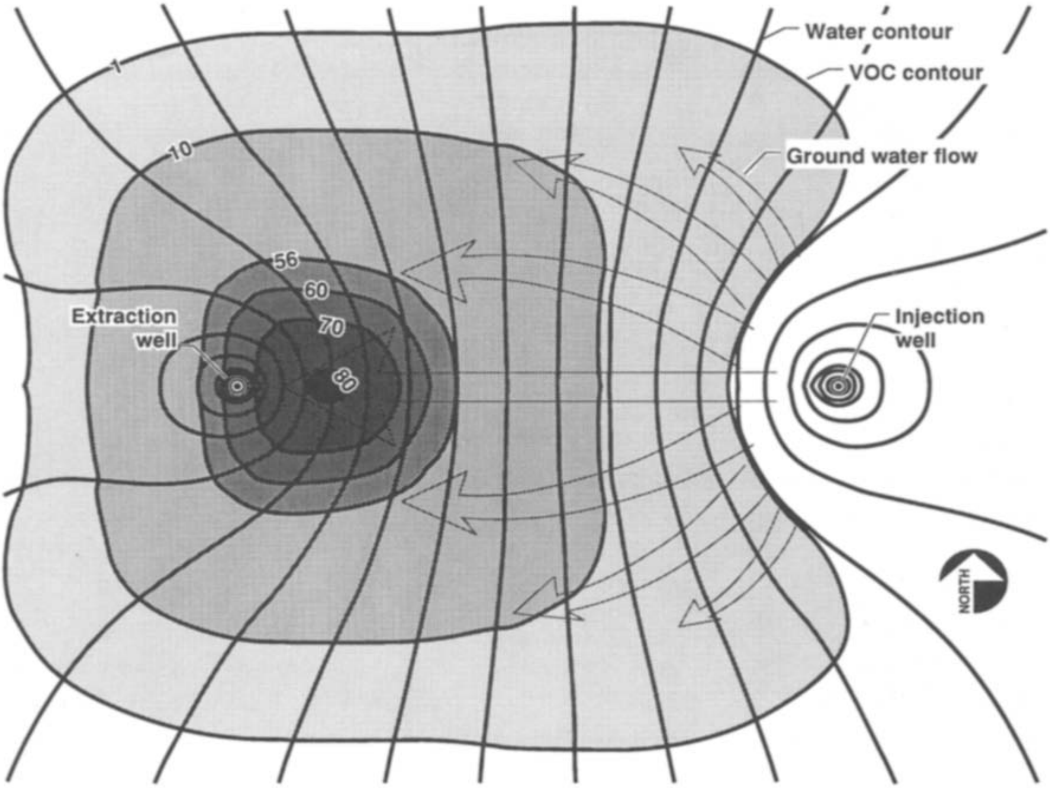


Fig. 10. Plan view of recirculation cell to enhance cleanup.

from source areas, extraction cluster wells are more effective if screened in permeable zones requiring remediation only.

In cases where VOCs have migrated into fine-grained sediments to a significant degree, increased flushing by recirculation cells can significantly increase mass removal (see Fig. 10). The addition of heat is being explored as a means of decreasing viscosity and sorption and increasing molecular diffusion, thus reducing cleanup times (see Fig. 11).

5. Adaptive pumping

Our simulations demonstrate that by varying the locations and pumping rates of the extraction and recharge wells, the time required to reach cleanup goals can be reduced. We call this technique adaptive pumping. Adaptive pumping minimizes the negative effects of stagnation zones and well-to-well interference zones by actively "herding" the contaminant plume. Resources are conserved by turning off extraction wells and treatment facilities when they are no longer effective in achieving the cleanup goals.

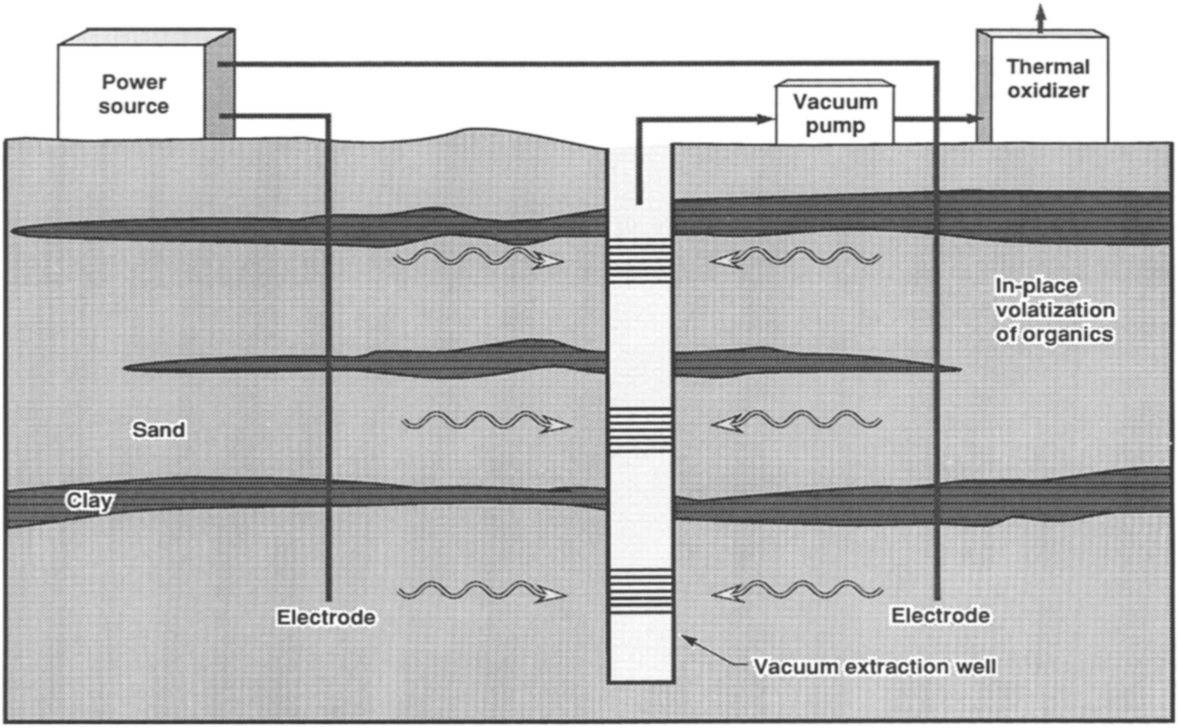


Fig. 11. Induction heating to enhance removal of VOCs.

The total cleanup effort is divided into management periods of one to five years. After each management period, the previously existing extraction/injection scenario is evaluated, optimized, and changed to reflect new information. Preliminary simulation results suggest that adaptive pump and treat versus an invariant pump and treat scheme can reduce cleanup time by up to 50% (see Fig. 12). More formal optimization techniques are being explored.

6. Summary and conclusion

Ground water pump-and-treat methods can be most effective if they are based on detailed characterization, field-validated simulation, directed extraction, and use of adaptive pumping schemes. Detailed characterization must be linked to regional, geologic and hydrologic simulations and should include geology, chemistry, hydraulic conductivity, degradation, and sorption measurements.

Field-validated simulations tightly integrate field data collection with standard simulation techniques. The simulation complexity must be commensurate with the available detail in the data and the level of understanding. Directed extraction uses the results gathered from detailed characterization and field-validated simulation to select the initial locations and pumping rates of the

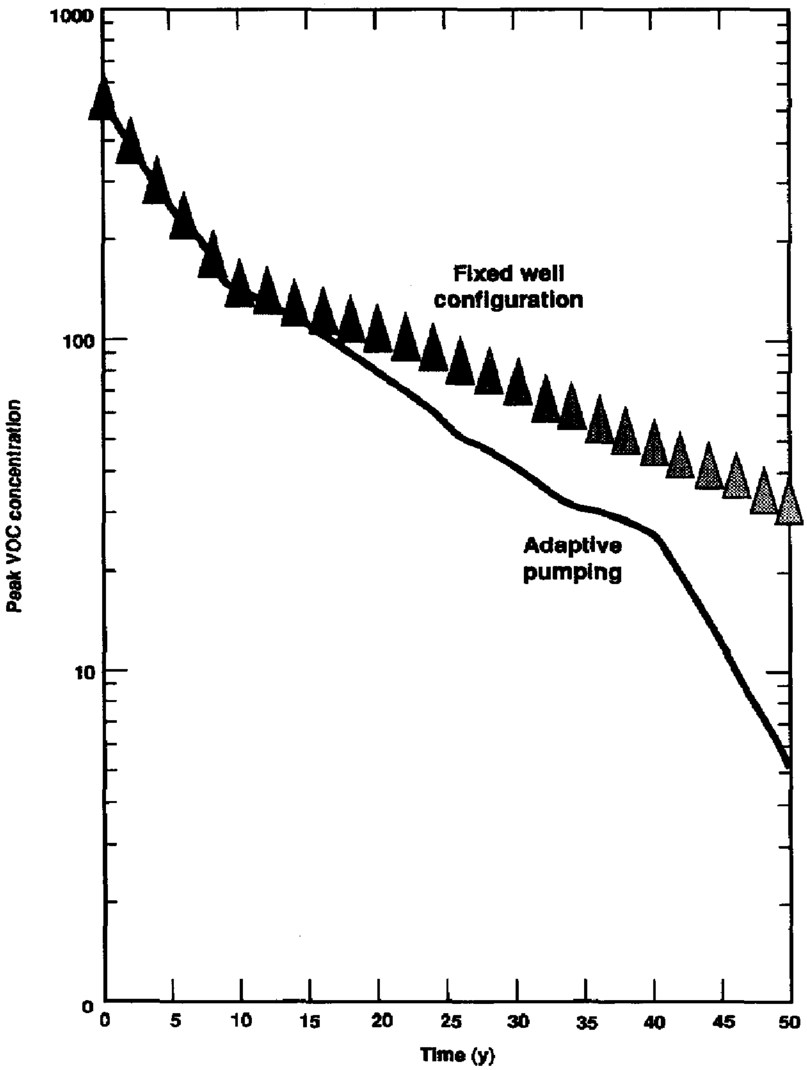


Fig. 12. Effect of adaptive pumping on clean-up time.

extraction and recharge wells. Adaptive pumping optimizes the ground water extraction in both time and space to reduce the effects of stagnation and interference zones. Choice of an optimal pumping strategy can make pump and treat effective by dramatically reducing the time and cost of cleanup.

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