ORNL/TM-11866

OAK RIDGE NATIONAL LABORATORY

MARTIN MARIETTA

The Effectiveness of Groundwater Pumping as a Restoration Technology

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DEPARTMENT OF ENERGY

ORNL/TM-11866

THE EFFECTIVENESS OF GROUNDWATER PUMPING AS A RESTORATION TECHNOLOGY

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Date Published - May 1991

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* Managed by Martin Marietta Energy Systems, Inc. for the U. S. Department of Energy under Contract No. DE-AC05-84OR21400

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EXECUTIVE SUMMARY

An in-depth analysis of the effectiveness of pumping groundwater for aquifer restoration was conducted based on: (1) performance records for 16 sites where pumping with the objective of aquifer restoration has been implemented for periods of 2 to 12 years, and (2) recent theoretical and modeling studies. The reduction of aquifer concentrations is the primary indicator of effectiveness of groundwater extraction. However, other indicators of effectiveness such as plume containment, mass reduction, and achievement of specific cleanup goals are also components of the evaluation.

At the sites reviewed, the pump and treat systems appear to be effective for containing the contaminant plume, and for reducing the mass of contamination in the aquifer. However, groundwater extraction systems are not effective for aquifer restoration. Data indicate that pumping can achieve concentration reductions of 90% to 99% prior to leveling at sites with high initial concentrations (greater than 1,000 ppb). However, concentrations at these sites remain significantly above health-based levels, and significant masses of contamination remain in the aquifers. At sites with initial concentrations less than 1,000 ppb, concentration reductions of 90% or less are achieved prior to leveling. Once leveling occurs, further significant reduction cannot be accomplished within a reasonable time frame. Even though concentrations may level at relatively low concentrations, when pumps are turned off, the concentrations tend to rise again.

The evidence to date suggests that the primary contributors to the ineffectiveness of pumping for aquifer restoration are phenomena resulting from physical and chemical processes that affect the behavior of contaminants in the subsurface environment. Recent studies show that soils long-contaminated with halogenated organic compounds are resistant to desorption, and the rate of contaminant desorption is controlled by diffusion of contaminants from within soil particles. Non-aqueous phase liquids (NAPLs) that either float on top of the water table or sink to the bottom of the aquifer cannot be effectively mobilized by pumping because they are immiscible in water.

Most aquifers are heterogeneous and have low permeability zones where contaminants become immobilized. Pumping causes preferential flow of groundwater in zones of high permeability, resulting in the trapping of even highly soluble contaminants in low permeability zones. The mass of immobilized contaminants in the subsurface is generally significantly greater than the mass dissolved in the groundwater, and the extraction of all the immobile contaminants is not technically feasible at the present time.

Groundwater modeling had been conducted at two-thirds of the sites reviewed. The models used over-simplified generic assumptions and did not account for the tailing effect observed at the sites. Remedial time frames of 2 years to 30 years were predicted at the sites reviewed. However, recent modeling studies suggest that pumping and treating will not restore aquifers to drinking water standards within these time frames. Pump and treat time frames of 100 years may be needed to lower concentrations by a factor of 100, assuming the ideal conditions of a homogeneous aquifer. For water-insoluble constituents such as jet fuel, thousands of years may be needed to remove the contaminants.

Based on our review of performance records and recent theoretical studies, the following can be concluded regarding the use of groundwater pumping for aquifer restoration:

- Pumping is effective for contaminant mass reduction, plume containment, and extraction of groundwater for point-of-use treatment. Its use for attaining these objectives should be encouraged.
- Groundwater pumping is ineffective for restoring aquifers to health-based levels. This reality needs to be explicitly recognized by regulators.
- The primary contributors to the ineffectiveness of pumping in meeting cleanup goals are the time-dependent decrease in the rate of desorption of contaminants from contaminated soils and the existence of immobile contaminants either in the non-aqueous phase or trapped in zones of low permeability.
- Remedial time frames of 2 years to 30 years were predicted at the sites reviewed. Regulators currently maintain that 20 to 40 years may be needed to reach health-based cleanup goals. However, recent modeling studies estimate pump and treat time frames of 100 to 1,000 years.

1.0 INTRODUCTION

During the past decade, the U. S. has passed legislation to address the remediation of inactive hazardous waste sites. The original emphasis of the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA) was on short-term remedies. However, with the passing of the Superfund Amendments and Reauthorization Act of 1986 (SARA), the philosophy of the program shifted toward long-term solutions to addressing contamination. The new program required that remedial alternatives be "protective of public health and the environment" and "significantly and permanently" reduce the toxicity, mobility, or volume of contaminants. The shift toward seeking permanent solutions occurred, however, before proven technologies were available for permanent remediation of sites.

Although post-SARA remedial action decisions reflect an increase in the selection of treatment remedies, most of these decisions have been made based on weak rationales regarding the effectiveness of the remedies selected. Treatment remedies may, in theory, provide permanent risk reduction; however, the selection of a treatment approach does not necessarily ensure the effectiveness and permanence of a remedy. Now that performance records are becoming available for remedial actions involving treatment technologies, a need exists for more research to evaluate the effectiveness of this approach. One such treatment approach is pumping and treating groundwater with the remedial objective of restoring contaminated aquifers.

1.1 Aquifer Restoration and the Decision Process

CERCLA remedial action decisions addressing groundwater contamination through fiscal year 1985 primarily consisted of containment of the contaminant plume or provision of an interim drinking water supply. Only 14% of the decisions addressed aquifer restoration (Haiges and Knox 1987). The average cleanup time predicted in these decisions was one to five years, although the cleanup times were subject to extension because toxicological data were lacking for many of the priority pollutants and cleanup standards were often not available. The feasibility of aquifer restoration using groundwater pumping and treating was assumed based on limited theoretical, laboratory, and field studies.

However, the number of decisions selecting aquifer restoration as a remedial objective increased during fiscal year 1986, and approximately 68% of remedial action decisions addressing groundwater contamination during fiscal year 1987 involved aquifer restoration (Doty and Travis 1989). Quantitative cleanup goals were established for all of these sites based on applicable or relevant and appropriate requirements (ARARs) or health-based goals derived from site-specific risk assessments. This trend reflects both the change in program philosophy and the progress made in the field of risk assessment. Although more quantitative toxicological data were available, thus facilitating the establishment of health-based cleanup goals for ground water, the effectiveness of the pump and treat approach to achieving aquifer restoration to these levels was no more certain than in earlier decisions.

In the 1987 decisions, rationales for predicting the effectiveness of pumping and treating to restore aquifers to the cleanup levels established in the RODs were not well-supported. The effectiveness of pumping groundwater to restore aquifers was questionable at these sites for one or more of the following reasons:

1. Effectiveness and permanence of the source remedy selected was uncertain.
2. Extent of groundwater contamination had not been confirmed, and additional studies were needed.
3. Contributing sources of contamination had not been determined or fully characterized.
4. Further studies were needed to determine applicability of technology to site conditions.
5. Hydrogeological uncertainties were associated with pumping and treating.

Since the passage of SARA, hundreds of decisions have been made to restore aquifers using the pump and treat method. Although decision-makers have acknowledged that pumping and treating groundwater is a time-consuming and often unpredictable process, this method has essentially been the only available option for aquifer restoration in some cases. More recent studies and field experience (EPA 1989) indicate, however, that aquifer restoration is not as feasible as was previously predicted in remedial action decisions.

1.2 Purpose

The purpose of this project is to provide an in-depth analysis of the effectiveness of pumping groundwater for aquifer restoration based on recent performance records and theoretical studies. Although laboratory, field, and modeling studies have been conducted regarding the feasibility of aquifer restoration using the pump and treat approach, little performance data have been available until recently. In 1989, the Environmental Protection Agency (EPA) conducted a study of 19 sites where pump and treat operations had been implemented for up to six years. The present study differs from the EPA study in two ways. First, we analyze performance records at sites where the pump and treat system was designed specifically for restoration of the aquifers to drinking water standards or to a specified negotiated cleanup goal. Unlike the EPA study, we include no sites where remediation was designed exclusively for containment or wellhead treatment. Second, we update and expand upon EPA's performance record data base.

1.3 Approach

The effectiveness of groundwater pumping and treating as a remedial alternative for aquifer restoration was evaluated by reviewing: (1) performance records for 16 sites where pumping and treating has been implemented for more than one year, and (2) recent theoretical and field studies. Sites selected for evaluation consist of both Superfund and non-Superfund sites where the pump and treat system was designed for restoration. Site descriptions and results for the pump and treat operations reviewed are presented in Appendices A and B. Pertinent literature, performance records, and support documents were reviewed. Existing databases were used, and interviews with regional EPA personnel and/or contractors were conducted to identify sites for evaluation and to obtain necessary data.

The effectiveness of groundwater pumping is typically evaluated in one or more of the following ways: (1) reduction in aquifer concentrations over time; (2) containment of the contaminant plume; (3) reduction of contaminant mass in aquifer; (4) comparison of contaminant mass removed to estimated mass of contaminants lost to the environment; and (5) comparison of aquifer concentrations to specific cleanup goals established.

Because proven technologies are available for treating most hazardous constituents in water to meet drinking water standards once the contaminated water is pumped from the subsurface, the focus of the present evaluation is on the effectiveness of pumping as a method for removing contaminants from the subsurface. The ability of pumping to reduce aquifer concentrations is the primary indicator of effectiveness in the present evaluation. However, the following factors are also components of the analysis: (1) the effectiveness of the system in containing the migration of aquifer contaminants; (2) the effectiveness of the system in reducing contaminant mass over time; (3) the success or failure of modeling in predicting the effectiveness and time frame associated with the approach; (4) the feasibility of attaining established cleanup goals; and (5) factors which influence effectiveness.

The present evaluation of groundwater extraction remedies was limited by the following factors: (1) the small number of sites where pumping has been ongoing for more than one year; (2) the extent of the site investigation on which the remedial design is based; and (3) the protocol used to measure and report the effectiveness of the remedy. Most pump and treat operations have not operated more than two or three years. However, for most systems, patterns in aquifer concentration reduction are evident after a year or two, and these patterns can be considered in light of recent research to predict future pump and treat performance at the sites.

Inconsistencies existed with respect to the availability of data and the ways in which remediation results were reported. Initial concentrations were frequently available for all the primary contaminants, while resulting aquifer concentrations were often reported only in terms of average VOC air stripper influent concentrations. These average concentrations may not be representative of maximum concentrations present in some wells at the sites.

2.0 PUMP AND TREAT SYSTEMS

The sites reviewed and the length of operation to date for the sites are listed in Box 1. Performance records were not available for the entire duration of the operation for some sites. The performance records reviewed range from 2 to 12 years and are limited to those reported in the documents listed in Appendix B. A brief review of the site performance records follows. Additional site descriptions and results for the pump and treat operations reviewed are presented in Appendices A and B.

Box 1 - Performance Records Reviewed

Site	Length of Operation
Amphenol Corporation, NY	3 years
Des Moines TCE, IA	2.5 years
General Mills, MN	4 years
GenRad Corporation, MA	3 years
Harris Corporation, FL	6.5 years
IBM Dayton, NJ	13 years*
IBM San Jose, CA	8 years
Nichols Engineering, NJ	2.5 years
Ponders Corner, WA	6 years
Savannah River, SC	5 years
Sharpe Army Depot, CA	2.5 years
Sylvester, NH	4 years
Twin Cities AAP, MN	2 years
United Chrome, OR	2 years
Verona Wellfield, MI	6.5 years
Wurtsmith AFB, MI	13 years

* Operation ceased for four years during this period.

Amphenol Corporation, NY

LOCATION:	Sidney, NY
TYPE OF SITE:	Electrical connector manufacturing facility (non-NPL)
CONTAMINANTS:	TCE, Chloroform
GEOLOGY:	A 100 to 200 foot thick layer of alluvial materials is underlain by glaciofluvial sands and gravels.

The Amphenol Corporation pump and treat operation is a small system consisting of only two extraction wells. Before the removal of the contaminated soil at the site, initial maximum VOC concentrations were 230 ppb. However, when the pump and treat operation began in 1987, maximum concentrations had declined to 150 ppb. One shallow aquifer extraction well and one deep aquifer extraction well are in operation with a total pumping rate of 200 gpm. Seventeen monitoring wells were initially installed, but some have been discontinued. The system has operated for 3 years. Concentrations began to level off at 50 ppb in 1988.

Des Moines TCE, IA

LOCATION:	Des Moines, IA
TYPE OF SITE:	Municipal wellfield (NPL)
CONTAMINANTS:	TCE, T-1,2-DCE, and vinyl chloride
GEOLOGY:	The area is underlain by a layer of silt and clay and a layer of unconsolidated sand and gravel. These layers are underlain by consolidated shale, siltstone, and sandstone. Below this system lies consolidated dolomite, limestone, sandstone, and shale formations. Three primary aquifer systems are associated with the site, two of which are important sources of drinking water in the area.

An estimated 200 gallons of contaminants were reportedly lost to the soils and groundwater at the Des Moines TCE site. The groundwater is contaminated with TCE, with initial TCE concentrations of approximately 8,500 ppb. Seven recovery wells were initially installed with a total pumping rate of 1,300 gpm. Six of these wells are still in operation at a pumping rate of 1,000 gpm. Pumping for 2.5 years has resulted in the extraction of more than 1,500 gallons of contaminants. However, concentrations have leveled off at between 500 ppb and 1,000 ppb. An additional source of contamination is being investigated.

General Mills, MN

LOCATION:	Minneapolis, MN
TYPE OF SITE:	Food research laboratory (non-NPL)
CONTAMINANTS:	TCE, TCA, PCE
GEOLOGY:	Thirty to fifty feet of unconsolidated alluvial and glacial deposits are underlain by a sequence of fractured sandstone, shale, dolomite, and limestone.

TCE is the primary groundwater contaminant with initial maximum concentrations of 1,300 ppb in the shallow aquifer and lower (Carimona) aquifer concentrations of 2,300 ppb. Five shallow aquifer extraction wells and one extraction well in the Carimona aquifer are in operation. Pumping at 300 gpm in the shallow aquifer and 50 gpm in the Carimona aquifer has resulted in substantial reduction of TCE concentrations. However, aquifer concentrations remain above target levels and remain as high as 460 ppb in one area.

Genrad Corporation, MA

LOCATION:	Bolton, MA
TYPE OF SITE:	Scientific and medical equipment mfg.
CONTAMINANTS:	TCE
GEOLOGY:	Unconsolidated glacial deposits overlie metamorphic rocks. In low-lying areas, organic sediments overlie sands and gravels. Depth to groundwater is generally only five feet.

Although two plumes, the eastern plume and the northern plume, are present at the site, only the eastern plume is addressed by the present system. Initial VOC concentrations were 1,000 ppb and TCE concentrations were 270 ppb. Two extraction wells have been in operation for three years in the eastern plume area at a pumping rate of 30 gpm. Sixteen monitoring wells are also in operation. TCE concentrations began to level in 1988 at approximately 100 ppb.

Harris Corporation, FL

LOCATION:	Palm Bay, FL
TYPE OF SITE:	Manufacturing facility (NPL)
CONTAMINANTS:	TCE, TCEA, vinyl chloride, methylene chloride, chlorobenzene, xylene, and ethylbenzene
GEOLOGY:	The upper sand aquifer, which is an unconfined aquifer, is used locally as a water source. Below the upper aquifer is a 22-foot thick sandy clay layer that acts as a leaky aquitard, retarding groundwater flow between the upper aquifer and the 30-foot thick unconsolidated lower sand aquifer. Underlying the lower sand aquifer is the Hawthorne formation, a clay confining layer up to 200 feet thick. The fifth layer is the Floridan aquifer, a 1,000-foot thick sequence of limestone and dolomite.

Groundwater at the site is contaminated with VOCs at a maximum initial concentration of 10,000 ppb. The pump and treat system has been operating for 6.5 years. The current system consists of 11 extraction wells, four of which are deep aquifer barrier wells. The remaining wells recover groundwater from both the shallow and deep aquifers. The pumping rate has remained constant since startup at 300 gpm.

Although the average treatment system influent VOC concentrations have declined and leveled at approximately 500 ppb, concentrations remain above 1,000 ppb in one shallow extraction well, two deep aquifer extraction wells, and one deep aquifer monitoring well. In one of the temporary onsite shallow monitoring wells installed in 1987, VOC concentrations fluctuated between 1 and 30,000 ppb during 1988 and 1989 and remained at 14,000 ppb during 1989. This contamination has been attributed almost exclusively to xylene and ethyl benzene, as opposed to TCE, DCEA, and vinyl chloride in the extraction wells (Harris Corporation 1990).

<u>IBM Dayton, NJ</u>

LOCATION:	South Brunswick, NJ
TYPE OF SITE:	Electronics manufacturing facility (non-NPL)
CONTAMINANTS:	1,1,1-TCA and PCE
GEOLOGY:	The shallow unconfined aquifer is comprised of the two upper geologic units which consist primarily of clay, silt, and gravel. These units are underlain by a thin discontinuous clay layer. The lower semi-confined aquifer consists of a sand and gravel unit underlain by relatively impermeable shale.

The site was contaminated with approximately 400 gallons of VOCs, primarily 1,1,1-trichloroethane (TCA) and tetrachloroethylene (PCE), with maximum ground water concentrations ranging from 9,590 ppb for TCA to 6,132 ppb for PCE. The initial system installed in 1978 consisted of 13 shallow aquifer extraction wells, one deep aquifer extraction well, one offsite production well, and 100 monitoring wells. The average pumping rate was 300 gpm with a maximum pumping rate at the offsite well of 500-600 gpm. Pumping between 1978 and 1984 lowered VOC concentrations to below 100 ppb. However, subsequent to shutdown of the operation in 1984, PCE concentrations rose to 13,558 ppb in 1988. Pumping was resumed in 1989, but the remedial objective was changed from restoration to containment.

<u>IBM San Jose, CA</u>

LOCATION:	San Jose, CA
TYPE OF SITE:	Electronics manufacturing facility (Non-NPL)
CONTAMINANTS:	Freon 113, TCA, 1,1-DCE, and TCE
GEOLOGY:	The valley floor is underlain by a sequence of alternating sand and gravel layers separated by silt and clay layers. Bedrock in the area consists of consolidated sandstones, shales, cherts, serpentinite, and ultrabasic rocks. Contamination is distributed throughout five aquifers at the site.

The IBM San Jose site is contaminated with freon, TCA, 1,1-DCE, and TCE. Although the site involves relatively low-level contamination, the distribution of contaminants throughout several geologic layers is complex, and contaminants have migrated more than two miles offsite. Initial maximum concentrations of TCE, the primary contaminant of concern, were 100 ppb in the B aquifer, where an action level was set at 50 ppb. Although more than 8,000 lbs. of contaminants have been extracted, and B aquifer concentrations have declined to 50 ppb, contamination leaking from the A aquifer acts as a continued source of contamination. Pumping has caused dewatering of the shallow aquifer, and therefore, pumping in the A aquifer has been reduced to a minimum. Pumping continues in areas with concentrations of less than 50 ppb, but no change in concentrations has been observed.

Nichols Engineering, NJ

LOCATION:	Hillsborough, NJ
TYPE OF SITE:	Combustion research facility (non-NPL)
CONTAMINANTS:	Carbon tetrachloride, PCE, chloroform
GEOLOGY:	Silty soil overlies fractured shales, siltstone, and sandstones.

The primary contaminant at the Nichols Engineering site is carbon tetrachloride, with maximum initial concentrations of 980 ppb. One recovery well was installed initially with a pumping rate of 65 gpm. Two more extraction wells were installed in 1989 with a pumping rate of 70 gpm. Although 80% to 90% reductions of concentrations have been observed in some wells, average carbon tetrachloride concentrations have leveled at between 100 and 200 ppb and have remained unchanged in one well.

Ponders Corner, WA

LOCATION:	Pierce County, WA
TYPE OF SITE:	Dry cleaning facility (NPL)
CONTAMINANTS:	PCE; TCE; 1,2-trans-DCE
GEOLOGY:	The uppermost geologic unit, the Steilacoom gravel unit, is generally unsaturated but has some perched saturated zones. The underlying Vashton Till, a semi-confining layer that has discontinuous saturated zones, is composed of silts and clays with sand and gravel lenses. The third geologic unit, the Advance Outwash unit, is the primary aquifer in the area. This unit is from to 20 to 90 feet thick and lies at depths of 25 to 84 feet below the land surface. The Colvos unit underlies the Advance Outwash aquifer. This fine sand aquifer is less permeable than the Advance Outwash aquifer and may help prevent migration to deeper units.

Groundwater at the Ponders Corner site is contaminated with an estimated 1,500 lbs. of contaminants, primarily PCE, with initial maximum concentrations of 500 ppb. Two extraction wells are in operation with a total pumping rate of 2,000 gpm. Forty-two monitoring wells were originally installed, but some of these wells have been discontinued recently. The pump and treat system has been operating for 6 years. However, a portion of the plume is not being captured by the system, and PCE concentrations have leveled between 50 and 100 ppb. PCE concentrations remain persistent in the well closest to the source and in wells with low concentrations. It is estimated that 90 percent of contaminants are contained in low permeability zones.

Savannah River Plant, SC

LOCATION:	Aiken, SC
TYPE OF SITE:	Department of Energy research and weapons manufacturing facility (NPL)
CONTAMINANTS:	TCE, PCE
GEOLOGY:	Permeable and impermeable layers: sands, silts, and clays with a water table 60 to 120 feet below the land surface.

One of the most highly contaminated sites reviewed is the Savannah River Plant in South Carolina. Permeable and impermeable layers were contaminated with solvents, with initial TCE concentrations as high as 250,000 ppb. The estimated volume of contaminated groundwater is 182 million gallons.

The pump and treat system consists of 11 recovery wells with a total pumping rate of 400 gpm and 236 monitoring wells. Although maximum concentrations have been reduced by as much as

86%, and more than 193,000 lbs. of contaminants have been extracted, no significant reductions in the average concentrations and the size of the plume have been observed after 5 years of pumping. Average VOC concentrations have leveled at approximately 40,000 ppb. The plume is not captured and has migrated into a deeper aquifer. The system is being re-designed and the objective of the pump and treat operation has been changed from restoration to containment and mass reduction.

Sharpe Army Depot, CA

LOCATION:	Lathrop, CA
TYPE OF SITE:	Army vehicle maintenance
CONTAMINANTS:	TCE
GEOLOGY:	Underlain by a complex sequence of interbedded sand, silt, and clay.

Permeable and impermeable layers are contaminated with TCE at average initial concentrations of 290 ppb. The original goal of the system was to prevent off-site migration of the plume. However, the objective of the remediation was subsequently changed to restoration. The present system consists of 15 extraction wells with a total pumping rate of 200 gpm. Early results were promising, and the system has been successful in preventing migration of the plume. However, after pumping for 2.5 years, concentrations have leveled at approximately 100 ppb, and concentrations in the lower aquifer are not meeting expectations.

Sylvester, NH

LOCATION:	Nashua, NH
TYPE OF SITE:	Hazardous waste dump
CONTAMINANTS:	Tetrahydrofuran, toluene, TCE
GEOLOGY:	Silt, sands, and interbedded sediments overlying fractured rock.

More than 800,000 gallons of hazardous wastes were disposed of at the Sylvester site. Groundwater at the site is highly contaminated, with the following initial maximum concentrations: 1,500,000 ppb tetrahydrofuran, 29,000 ppb toluene, and 15,000 ppb TCE. A 3-foot slurry wall was constructed around the 20-acre site, and Alternate Concentration Limits (ACLs) were established for the contained groundwater. The pump and treat system, which consists of eight extraction wells with a total pumping rate of 300 gpm, has been in operation for 4 years. Therefore, the two-year time frame projected for reaching ACLs within the contained area has already been exceeded by two years. Average THF concentrations remain at 15,000 ppb, average toluene concentrations are 50,000 ppb, and average TCE concentrations are 3,000 ppb. These contaminant levels are significantly above the established the ACLs.

Twin Cities AAP, MN

LOCATION:	New Brighton, MN
TYPE OF SITE:	Ammunition production (NPL)
CONTAMINANTS:	TCE
GEOLOGY:	Organic soils, sands, and clays are underlain by cohesive and relatively impervious till. The third unit consists of glacial outwash and/or valley fill materials 100 to 350 feet below the land surface. This unit is underlain by a bedrock unit consisting of weathered and fractured dolomite overlying sandstone. Little hydraulic separation exists between the overburden and bedrock units.

Groundwater is contaminated with TCE, with initial maximum outwash aquifer concentrations of 20,000 ppb and bedrock concentrations of 100 ppb. The pump and treat system has been in operation for two years. The system originally consisted of six boundary extraction wells; however, three months later, more wells were added to the system. Currently, 12 boundary wells and 5 wells downgradient of interior source areas are operating at a total pumping rate of 2,700 gpm. The plume has been captured by the system, and more than 21,000 lbs. of VOCs have been extracted to date. However, maximum TCE concentrations remain as high as 18,000 ppb, and average VOC influent concentrations remain unchanged at approximately 1,000 ppb.

United Chrome, OR

LOCATION:	Corvallis, OR
TYPE OF SITE:	Chrome plating facility (NPL)
CONTAMINANTS:	Chromium (hexavalent)
GEOLOGY:	Upper unconfined zone consists of clayey silt alluvium with a saturated thickness of 15 to 18 feet during winter and decreasing during the summer; during winter, saturated zone often reaches the ground surface. Lower confined aquifer ranges from 29 to 45 feet below the ground surface.

Both shallow and deep aquifers are contaminated with hexavalent chromium with maximum concentrations of 6,860 ppm and average concentrations of 1,923 ppm. The system currently consists of 23 upper zone and 7 lower aquifer extraction wells with a total pumping rate of 17 gpm. Average groundwater concentrations have declined steadily since the beginning of the operation. However, although the average concentration was 576 ppm at the end of 1989 and a total of 13,376 lbs of chromium had been removed, concentrations have either increased or remained constant in many of the upper zone wells. Highly contaminated soils still serve as a major source of contamination at the site. A more extensive characterization of deep aquifer has been recently conducted.

Verona Wellfield, MI

LOCATION:	Battle Creek, MI
TYPE OF SITE:	Municipal wellfield (NPL)
CONTAMINANTS:	1,1-DCA; 1,2-DCA; 1,1,1-TCA; 1,2-DCE; 1,1-DCE; TCE; and PCE
GEOLOGY:	Sand and gravel aquifer overlies an upper sandstone aquifer with clay lenses, a confining siltstone bed, a lower sandstone aquifer, and a layer of shale; sandstone contains extensive horizontal and vertical fracturing.

Groundwater at the Verona Wellfield site was contaminated with an estimated 3,900 lbs. of contaminants, with VOC maximum concentrations of 19,000 ppb. A pump and treat system has been operating for 6.5 years, and a vapor extraction system has been operating for 2.5 years. The pump and treat system consists of five barrier wells and nine groundwater extraction wells screened in the water-table aquifer with a total pumping rate of 400 gpm. A vapor extraction system has also been installed. More than 10,000 lbs of contaminants have been removed from the groundwater, and 40,000 lbs have been removed from the soil.

The efficiency of the pump and treat system has increased since installation of the vacuum extraction system. However, average total VOC concentrations remain at approximately 2,500 ppb. According to modeling conducted at the site, concentrations of 100 ppb were expected after 3 years of operation.

Wurtsmith AFB, MI

LOCATION:	Wurtsmith, MI
TYPE OF SITE:	Underground storage tank (non-NPL)
CONTAMINANTS:	TCE, DCE
GEOLOGY:	A sand and gravel unit is underlain by a clay unit at approximately 62 feet below the land surface. Clay beds exist in the sand and gravel unit in the northern part of the site at depths of 5 to 15 feet below the land surface. The clay unit separates the aquifer from the underlying bedrock.

Groundwater is contaminated with both TCE and trans-1,2-dichloroethene, primarily TCE. Two separate plumes exist at the site. Initial average TCE concentrations in the Arrow Street area were approximately 18,000 ppb in 1978 when a two-well system began operation, pumping water into an aeration reservoir. In 1982, the Arrow Street Purge Well System was installed with a pumping rate of 1200 gpm. Concentrations in this area have been reduced to approximately 70 ppb over a period of 12 years. The Mission Street system, a separate system installed in 1988, consists of five extraction wells at a pumping rate of 220 gpm. Concentrations in this area have been reduced from 800 ppb to between 500 and 700 ppb after two years of pumping.

3.0 INDICATORS OF PUMP AND TREAT EFFECTIVENESS

3.1 Reduction of Aquifer Concentrations Over Time

The reduction of aquifer concentrations over time is the primary indicator of the effectiveness of a pump and treat system in restoring an aquifer to a specified cleanup level. The ideal scenario would be a steady decrease in contaminant concentrations until the target level is attained. However, performance records have suggested that although concentrations may drop initially, this decline is followed by a leveling of concentrations with little or no further decrease in concentrations (EPA 1989).

For the purpose of characterizing concentration leveling patterns, we examined the relationship between initial concentration and leveling concentration for sites where concentrations have declined sharply and remained constant for periods of six months to several years (Table 1). These sites have performance records of 2 to 12 years and initial concentrations ranging from 5 ppb to 250,000 ppb. The analysis is based on the comparison of both maximum and average initial concentrations to the average concentrations at which leveling occurred. This approach may overestimate the reduction of maximum concentrations but provides a reasonable basis for comparison to average concentration reductions.

Table 1

Leveling of VOC Concentrations

Site	Contaminant	Initial Concentration*	Concentration Leveling (ave.)	Reduction Prior to Leveling
Wurtsmith AFB, MI	TCE	29,300 (max.) 4,000 (ave.)	400	99% 90%
IBM Dayton, NJ	VOCs	15,700 (max.) 300 (ave.)	100	99% 67%
	TCA	9,600 (max.) 200 (ave.)	50	99% 75%
	PCE	6,132 (max.) 100 (ave.)	50	99% 50%
Savannah River, SC	VOCs	400,000 (max.) 46,500 (ave.)	35,000	91% 25%
	TCE	250,000 (max.) 32,500 (ave.)	25,000	90% 23%
	PCE	150,000 (max.) 14,000 (ave.)	10,000	93% 29%
Verona Wellfield, MI	VOCs	100,000 (max.) 19,000 (ave.)	2,900	97% 85%
Harris Corporation, FL	VOCs	10,000 (max.) 3,786 (ave.)	500	95% 87%
Des Moines TCE, IA	VOCs	10,562 (max.)	740	93%
	TCE	8,467 (max.)	650	92%
	T-1,DCE	2,000 (max.)	90	96%
General Mills, MN	TCE	2,300 (max.)	300	87%
Nichols Engineering, NJ	CCl_4	980 (max.)	150	85%
Genrad, MA	TCE	990 (max.)	150	85%
Sharpe Army Dep., CA	TCE	900 (max.) 290 (ave.)	100	89% 66%
Ponders Corner, WA	VOCs	400 (max.) 280 (ave.)	50	88% 82%
	PCE	370 (max.) 270 (ave.)	50	86% 81%
Amphenol, NY	VOCs	150 (max.) 85 (ave.)	35	77% 59%
IBM San Jose, CA	VOCs	175 (max.)	90	49%
	TCA	100 (max.)	50	50%
	Freon 113	70 (max.)	35	50%
	1,1-DCE	5 (max.)	5	0%

* Concentrations in ppb

Savannah River, SC

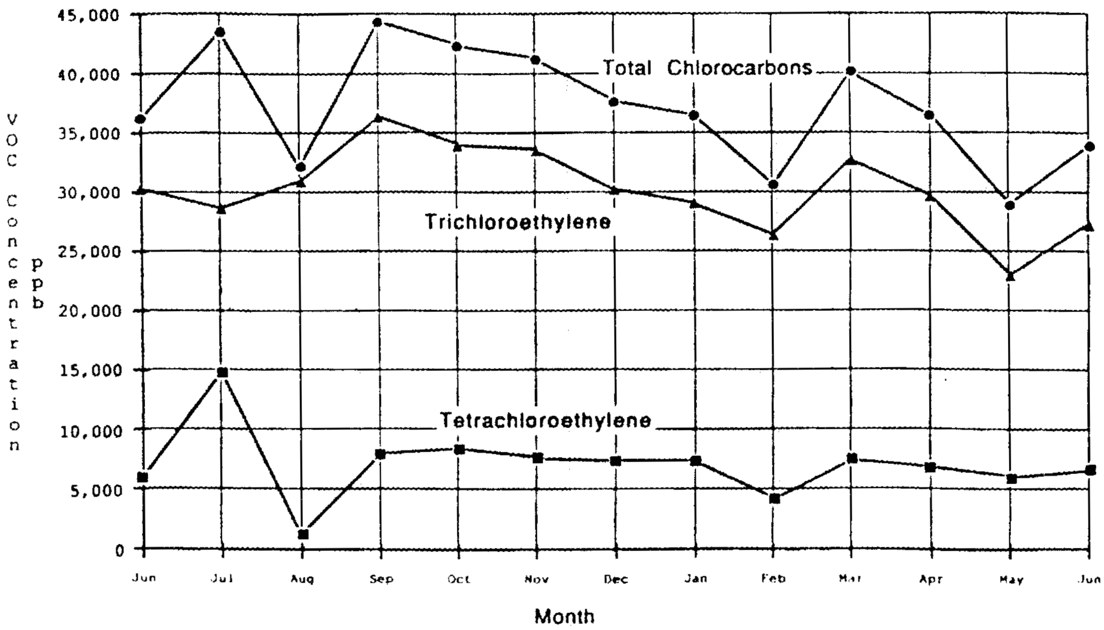
The Savannah River performance record provides an example of a site where concentrations have leveled at high concentrations. The Savannah River site is contaminated with VOCs, with initial concentrations as high as 400,000 ppb. The pump and treat operation has been in operation for five years at the site. After approximately two years of pumping, VOC concentrations leveled at 35,000 ppb (Figure 1), with a maximum concentration reduction of 91% and a reduction of average concentrations by only 25% prior to leveling (Table 1). No significant change in average concentrations has been observed since the concentrations leveled in 1987. The unusually low rate of average concentration reduction prior to leveling can be attributed to the low pumping rate (400 gpm) at the site.

Wurtsmith AFB, MI

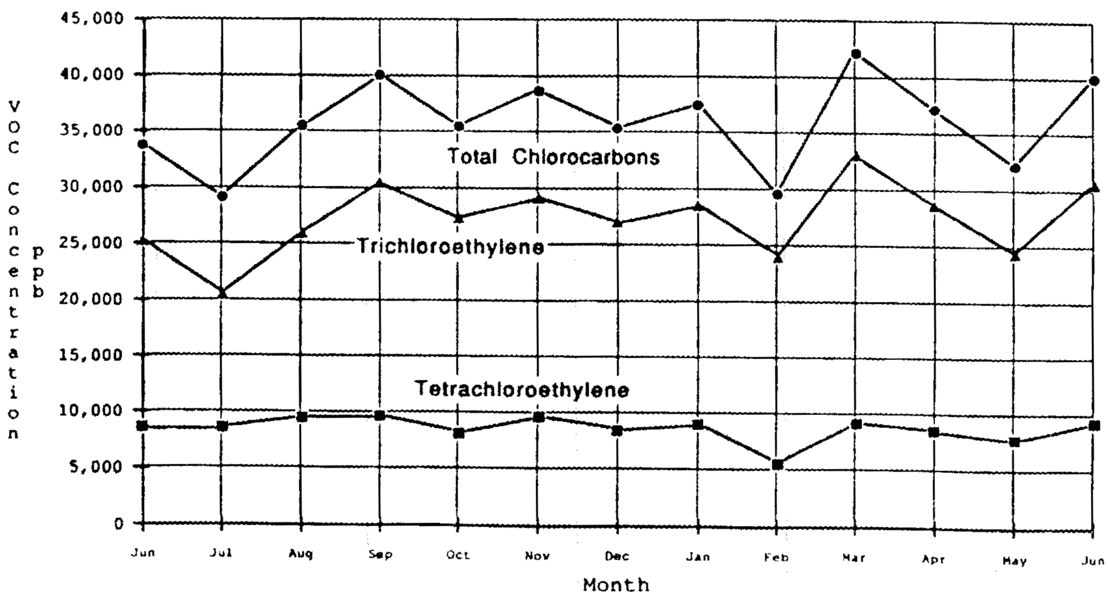
The pump and treat operation at the Wurtsmith AFB site has been operating for 13 years. At the Arrow Street area of the site, maximum initial TCE concentrations were approximately 29,300 ppb. Concentrations leveled after six years of pumping, with maximum concentration reductions of 99% and average concentration reductions of 90% (Table 1). Concentrations remained constant at approximately 400 ppb for five years until 1989, when concentrations dropped to approximately 70 ppb (Figure 2).

Harris Corporation, FL

The Harris Corporation site is contaminated with VOCs, with an initial maximum concentration of 10,000 ppb. After three years of pumping, VOC concentrations leveled at approximately 500 ppb, after a 95% reduction in maximum concentrations and an 87% reduction in average concentrations (Table 1 and Figure 3).



VOC Concentrations in Well RWM-3
(June 1988 to June 1989)



Average VOC Concentrations in Air Stripper Influent
(June 1988 to June 1989)

Figure 1. Leveling of VOC Concentrations, Savannah River Plant.
From: U. S. Department of Energy Savannah River Plant (1989). M-Area Hazardous Waste Management Facility Post-Closure Care Permit: Groundwater Monitoring and Corrective Action Program, Second Quarter 1989 Report.

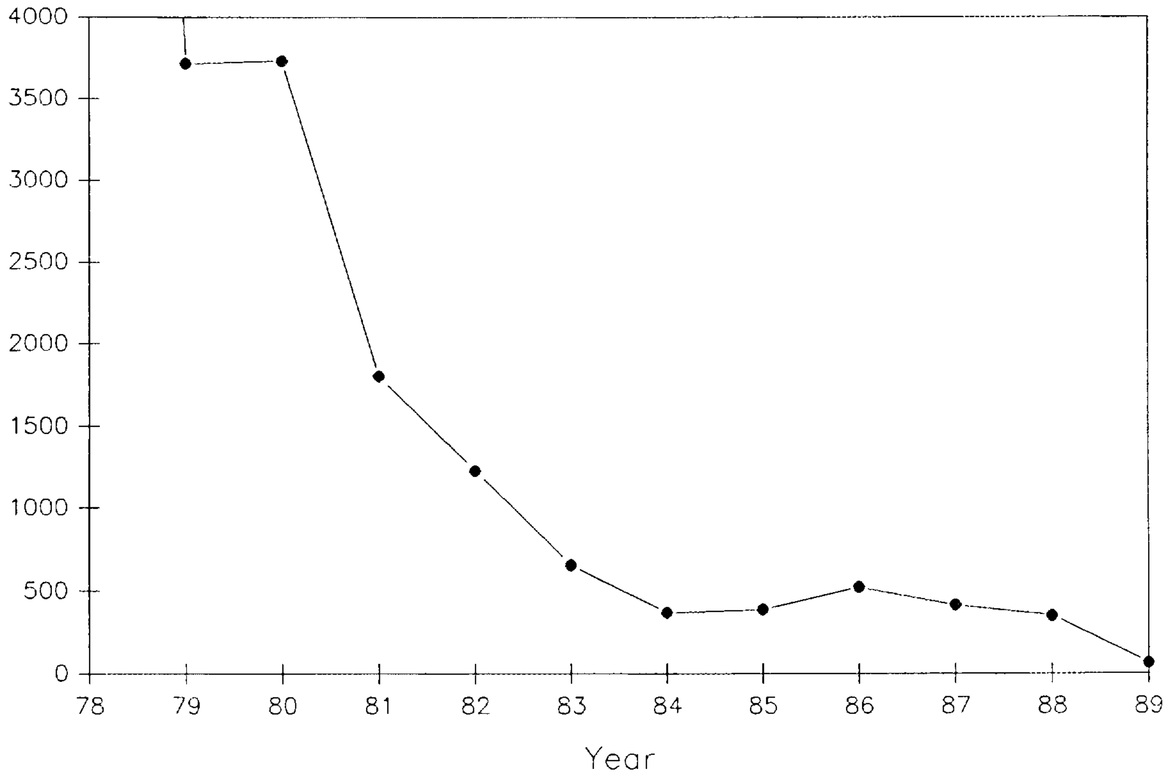


Figure 2. VOC Influent Concentrations, Arrow Street Area, Wurtsmith AFB.
Source: Wurtsmith AFB, 1990a.

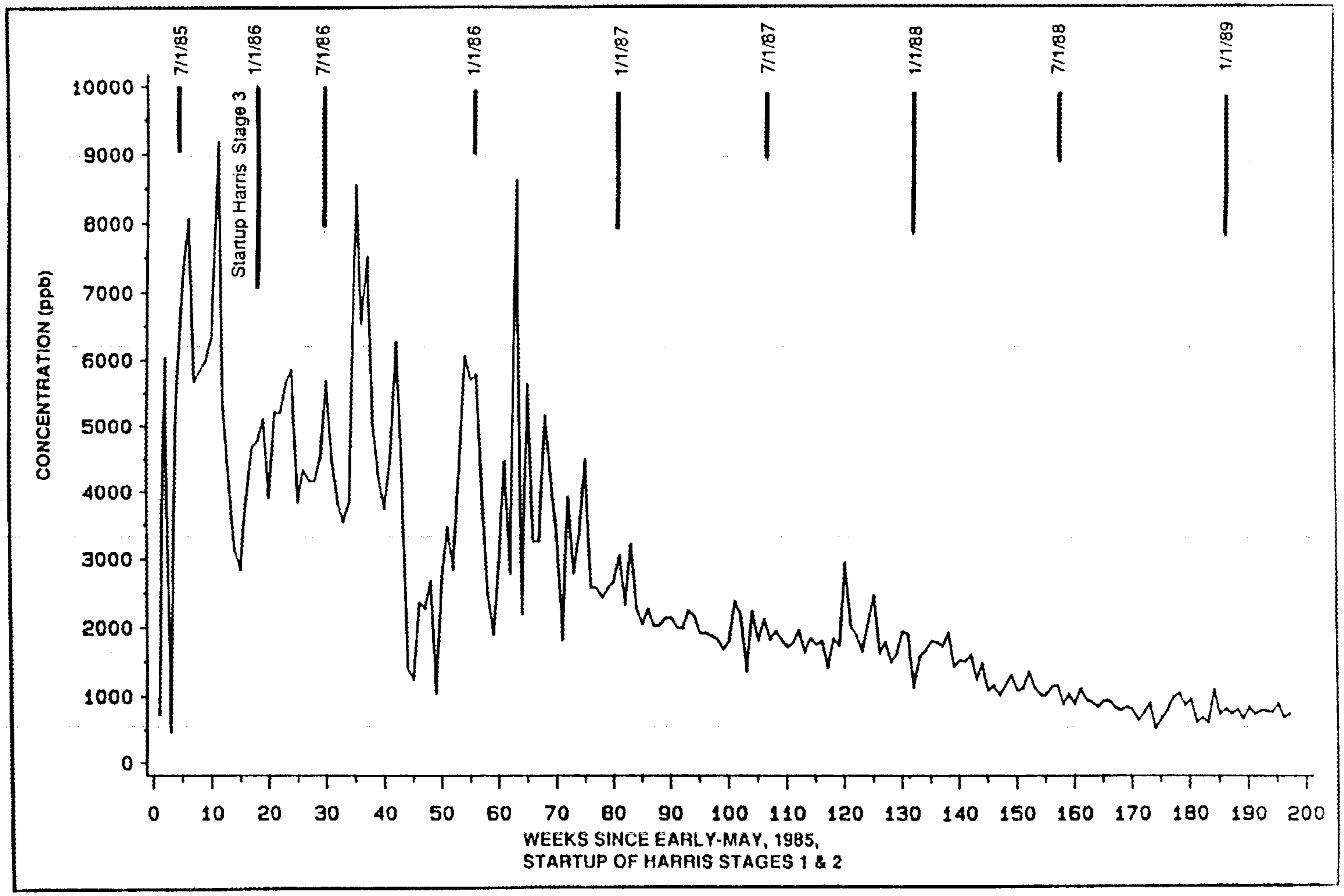


Figure 3. VOC Influent Concentrations, Harris Treatment System, Harris Corporation Site. From: EPA 1989.

IBM Dayton, NJ

Initial maximum VOC concentrations at the IBM Dayton site concentrations were 15,700 ppb. Concentrations decreased to approximately 500 ppb after four years of pumping, increased slightly, and then leveled at approximately 100 ppb for several years prior to the discontinuation of the operations. Leveling of maximum concentrations took place after a reduction of 99% (Table 1). However, an average concentration reduction of only 67% was observed. When the pumps were turned on again two years later, PCE concentrations rose to over 13,000 ppb (Figure 4).

Amphenol, NY

The Amphenol site is a small site with initial VOC concentrations of 150 ppb. Although the contaminated soil was removed prior to the installation of the pump and treat system, concentrations leveled at approximately 35 ppb after one year of pumping (Figure 5). An average concentration reduction of 59% was attained prior to concentration leveling (Table 1).

3.1.1 Leveling Patterns

Leveling has taken place at 13 of the sites reviewed. Two of the sites involving organic constituents did not have available performance records that were complete enough for an analysis of concentration leveling. The performance record for the United Chrome site indicates a steady decline in concentrations since the beginning of the operation. However, chromium concentrations were 576 ppm at the end of 1989.

The concentration at which leveling occured and the point in the performance record that it occured varied, depending on site-specific factors such as the system design, the characteristics of the chemicals present, and the site conditions. However, several trends in concentration leveling were observed. Although a 99% reduction of maximum concentrations was attained prior to

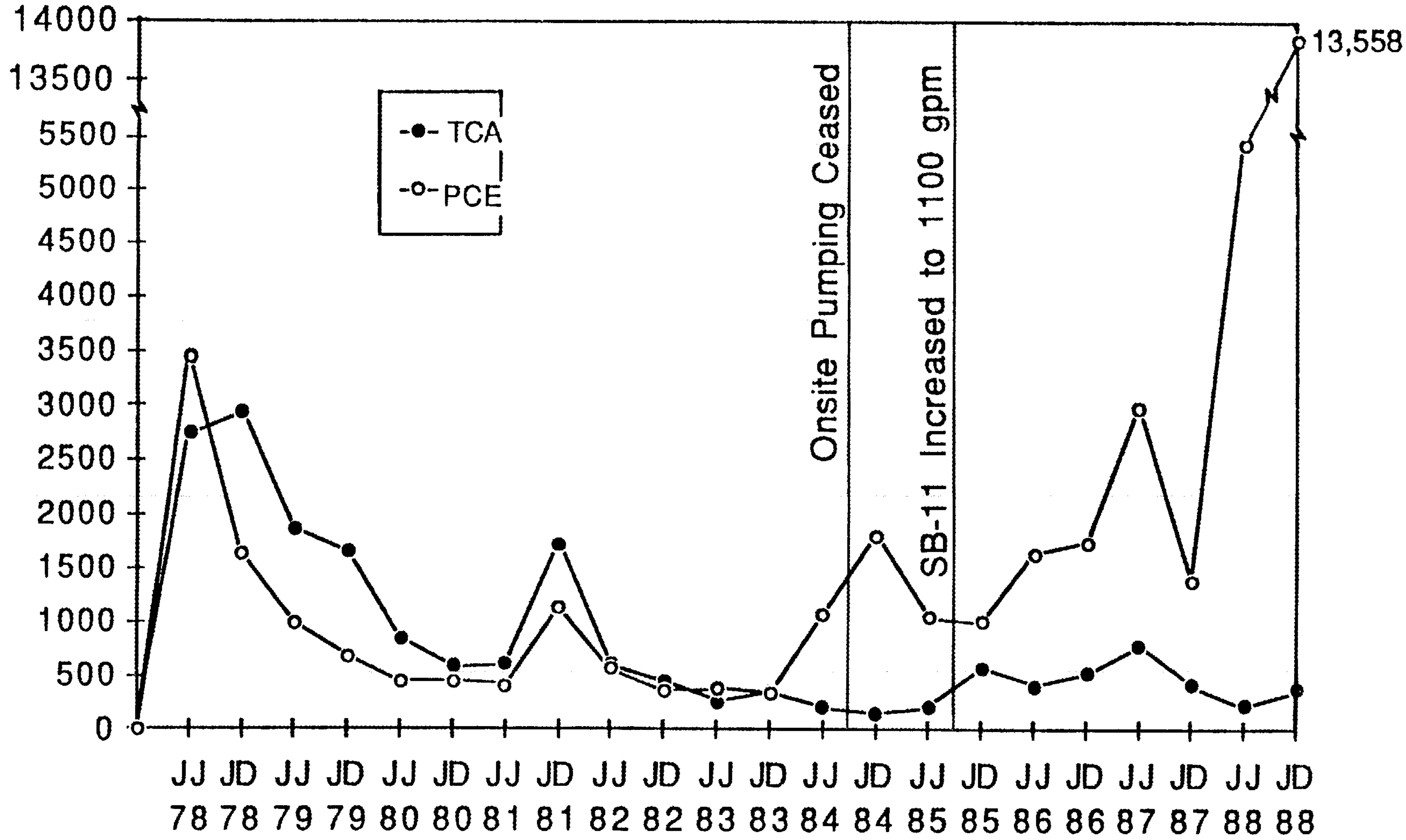


Figure 4. TCA and PCE Concentrations (ppb), Extraction Well GW32, IBM Dayton Site. From: EPA 1989.

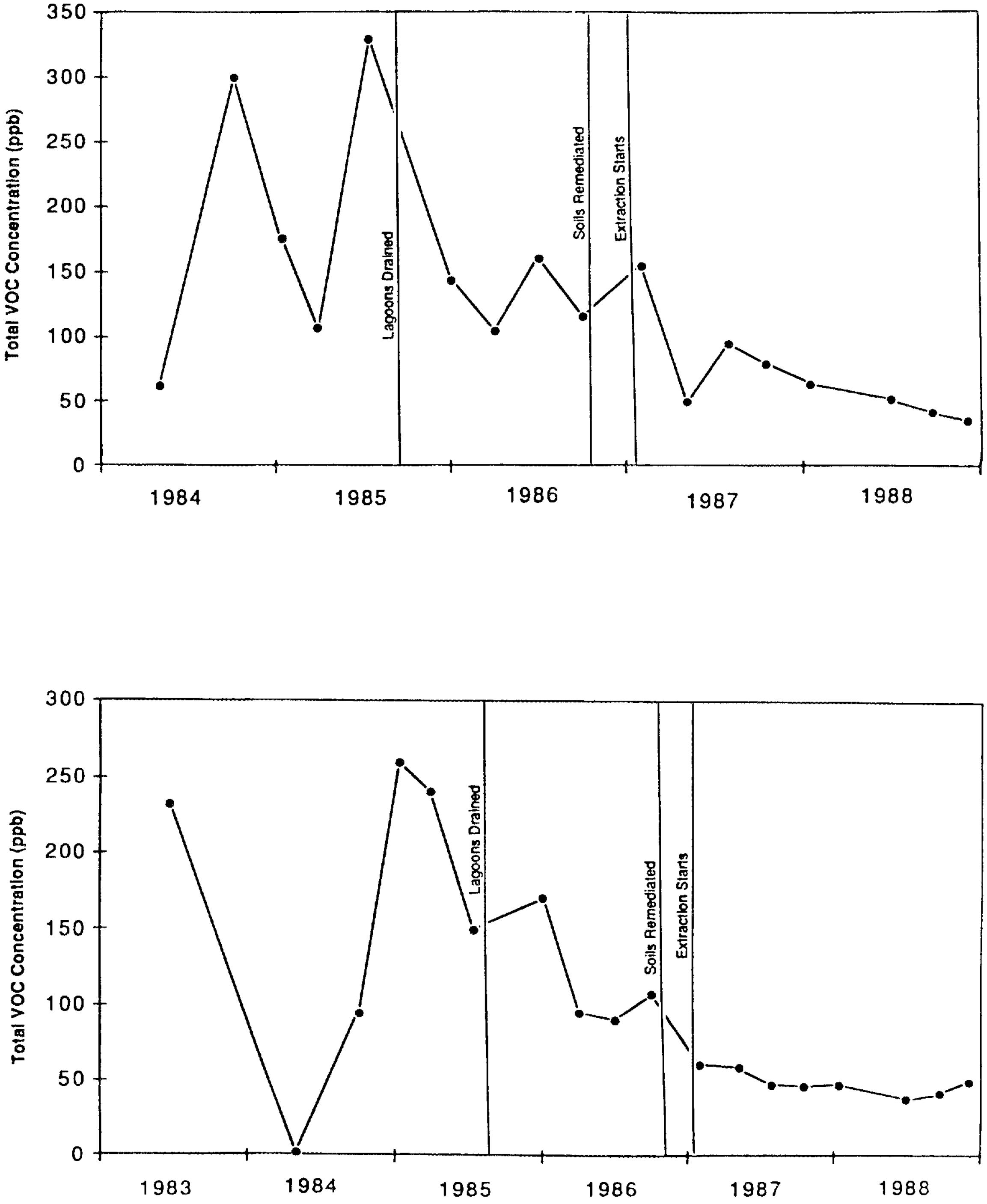


Figure 5. VOC Concentrations in Shallow Aquifer Wells 17-S and 1-S, Amphenol Corporation Site. From: EPA 1989.

leveling at some sites, the greatest reduction of average concentrations at a site was 90%. The following patterns in concentration leveling were observed:

- At all sites with maximum initial concentrations greater than 10,000 ppb, the concentrations leveled after maximum concentration reductions of 90% to 99%.

- Reduction of average concentrations ranged from 23% to 90% at sites with maximum concentrations greater than 10,000 ppb.

- At sites with initial maximum concentrations of 1,000 ppb to 10,000 ppb, leveling occurred after maximum concentration reductions of 85% to 99%. Reductions of average concentrations at these sites ranged from 50% to 87%.

- At sites with initial maximum concentrations between 100 ppb and 1,000 ppb, reductions in maximum concentrations range from 49% to 89%. Reductions of average concentrations ranged from 59% to 82%.

- At sites with initial maximum concentrations of 100 ppb, concentrations leveled after 0% to 50% reductions in concentrations.

Leveling patterns in the performance records reviewed illustrate the ineffectiveness of groundwater extraction in reducing average concentrations more than 90%. Even though leveling may take place at or near the cleanup goal (see Section 3.4), significant masses of contamination remain in the aquifer, and when pumps are turned off, concentrations rise again. Once concentrations level at a site, further significant reduction in concentrations is unlikely and cannot be accomplished within a reasonable time frame.

3.2 Capture and Containment of Contaminant Plume

An essential objective of pump and treat operations implemented for aquifer restoration is capture and containment of the contaminant plume. At the sites reviewed, analysis indicates that pumping can effectively contain the contaminant plume at most sites. At 75% of the sites reviewed, the performance record indicated that the plume is being effectively contained.

The Savannah River site is the only site reviewed with evidence of significant contaminant migration since the beginning of the operation. At this site, the plume is not contained, and contamination has migrated to lower aquifers. Although more than 168,000 lbs of contaminants have been extracted, the pumping rate of 400 gpm has proven to be inadequate for capturing the plume. Migration may also be attributable to the puncturing of the confining layer between the A and B aquifers and subsequent mobilization of perched NAPLs to deeper aquifers. The system has been recently re-designed with the objectives of containment and mass reduction.

At the Ponders Corner, IBM San Jose, and Harris Corporation sites, small portions of the plumes are not captured. At the IBM San Jose site, a small portion of the onsite plume does not appear to be captured, but is thought to be captured by the offsite wells. Likewise, at the Harris Corporation the portion of the plume not captured by the onsite system is captured by the wellhead treatment system on the adjoining property. A low-level portion of the plume is not captured at the Ponders Corner site.

The performance records reviewed indicate that adequate hydraulic plume containment is feasible using pump and treat systems at most sites. However, problems be may associated with pumping at the high rates needed for plume containment in some cases. Pumping at a rate high enough to contain a plume may result in aquifer dewatering and the recovery of larger amounts of mildly contaminated water to be treated.

3.3 Reduction of Contaminant Mass

Initial estimates of the contaminant mass present in the groundwater and cumulative measures of the mass extracted are often part of site performance records. These data can be useful for some purposes. However, the performance records reviewed indicate that these data are of limited use in determining the overall effectiveness of pumping in meeting cleanup objectives.

3.3.1 Comparison of Mass Estimates to Mass Extracted

Few of the sites reviewed documented both an initial estimate of the mass or volume of contaminants present in the groundwater and a summary of the mass of chemicals extracted to date (Table 2). Of the four sites for which such information is available, the initial inventory of contaminants was grossly underestimated. At the Verona Wellfield site, more than twice the originally estimated mass of contaminants has been extracted to date. At the Des Moines TCE site, concentrations have leveled after extraction of more than seven times the volume of contamination estimated to be present in both soil and groundwater.

At the Savannah River site, the original estimate has already been exceeded by more than a factor of three, and concentrations have leveled after less than half the revised inventory of contaminants have been extracted. This site is the only site reviewed where estimates of contaminant mass were updated after the initial estimate was made. However, a mass inventory analysis conducted in 1988 indicates that the revised estimate of 460,000 lbs is also inaccurate. Although air stripper mass-balance calculations showed that 138,000 lbs had been removed, the inventory indicated that 441,000 lbs were still present in the groundwater. Therefore, the latest estimate indicates an original contaminant mass of 580,000 lbs.

3.3.2 Mass Reduction vs. Concentration Reduction

Considerable reductions in the contaminant mass were being attained during the early stages of the operation at the sites reviewed (Table 2). However, reductions in contaminant mass are not indicators of reductions in aquifer concentrations. Although more than 193,000 lbs of VOCs have been extracted at the Savannah River site, average concentrations have leveled after reduction of 25%. At the Twin Cities AAP site, average concentrations remain unchanged after the extraction of more than 19,510 pounds of VOCs (Tables 2 and 3). At the IBM San Jose site, 84 lbs of 1,1-DCE have been extracted with no reduction in groundwater concentrations.

Table 2
Inventory of Contaminants in Groundwater

Site	Predicted Volume/ Mass of Contamination	Mass/Volume Extracted to Date
Savannah River, SC	59,000 lbs. (orig. est.) 460,000 lbs. (revised est.)	>193,000 lbs.
Verona Wellfield, MI	3,900 lbs. gw	>10,000 lbs.
United Chrome, OR	No estimate	>13,000 lbs.
Ponders Corner, WA	1,534 lbs. gw	Not reported
Sylvester, NH	800,000 gal. total	Not reported
Twin Cities AAP, MN	75,000 lbs. gw	21,000 lbs.
Des Moines, TCE, IA	200 gal. total	1,500 gal.
IBM Dayton, NJ	400 gal. total	Not reported
GenRad Corporation, MA	No estimate	2.6 lbs.
IBM San Jose, CA	No estimate	7,700 lbs.

3.3.3 Mass Extraction Rates

Measures of the contaminant mass extracted, especially when used to determine the rate of contaminant extraction at a site, can be useful in determining the efficiency of a pump and treat operation. Table 3 illustrates the efficiency of pump and treat operations at sites with varying contaminants and initial concentrations during the first few years of operation. The difference between the extraction rates for the United Chrome site and the other sites listed in the table can be attributed to both the contaminant involved and the high initial concentrations. Contaminant extraction rates, although generally proportional to the initial concentrations, are much higher for inorganic contaminants than for organic constituents. For organics, large volumes of water must be pumped in order to extract a relatively small mass of contaminants.

Table 3
Mass Extraction Rates and Initial Concentrations at Selected Sites

Site	Vol. of Groundwater extracted (gal.)	Mass Extracted (lbs.)	Max. Initial Concentration	Extraction Rate lbs/mil. gal
United Chrome, OR	1,664,000	13,376 ($Cr6^{+}$)	7,000 ppm	8,136
Savannah River, SC	782,000,000	168,000 (VOCs)	300,000 ppb	214.83
Twin Cities, MN	1,062,622,000	19,510 (VOCs)	20,000 ppb	18.36
IBM San Jose, CA	12,147,000,000	7,700 (VOCs)	100 ppb	.63
		84 (1,1-DCE)	5 ppb	.003
GenRad Corporation, MA	12,000,000	2.6 (VOCs)	1,000 ppb	.15

Our analysis indicates that contaminant mass reduction data is of limited use in determining the overall effectiveness of the pumping operation in reaching cleanup goals, but can be useful in determining the relative efficiency of a specific system. Because of the unreliability of initial mass estimates, the comparison of initial mass to the mass extracted is not an appropriate indicator of pump and treat effectiveness. These comparisons do, however, exemplify the difficulty in characterizing groundwater contamination and designing strategies to address the contamination. The analysis also indicates that cumulative measures of mass extracted are not reliable indicators of reductions in aquifer concentrations but that they are useful for deriving mass extraction rates. The mass extraction rates for the performance records reviewed illustrate the differences in efficiency among systems and the difficulty of extracting organic constituents at low concentrations.

3.4 Meeting Cleanup Goals

All the sites reviewed have aquifer restoration as the remedial objective. However, not all the sites have established health-based cleanup goals for the site. Quantitative cleanup goals were not established at two of the sites. Forty-four percent of the sites established cleanup goals at a negotiated level above health based standards for at least a portion of the site (Box 2). Another 44% of the sites established health-based cleanup goals (Box 3).

Achieving concentration reductions to meet the cleanup goals for the sites is unlikely, even at sites where goals were established at levels significantly higher than drinking water standards (Box 2). The cleanup goal for the majority of the sites with drinking water standards as goals require concentration reductions to 5 ppb for contaminants such as TCE, PCE, and carbon tetrachloride (Box 3). At sites where the plume is contained and initial concentrations are at least 100 ppm, average VOC concentrations have leveled at concentrations of 35 ppb or greater in onsite-wells (Table 1), and

Box 2 - Status of Sites With Goals Above Health-Based Levels

United Chrome, WA:
- Goal - 10 ppm Chromium
- Results - Leveled at 600 ppm

Savannah River, SC:
- Goal - Extract 99% of cont. mass
- Results - Leveled after <25% red.

Sylvester, NH:
- Goal - ACL of 1,500 ppb TCE
- Results - 3,000 ppb; has exceeded predicted time frame by 100%

IBM Dayton, NJ:
- Goal - 100 ppb VOCs
- Results - Leveled at 100 ppb; after pumps were shut off, conc. rose to 13,000 ppb

Twin Cities AAP, MN:
- Goal - 27 ppb TCE
- Results - Although one-third of the estimated mass has been removed, concentrations unchanged at approx. 1,000 ppb

General Mills, MN:
- Goal - 270 ppb TCE shallow 27 ppm deep aquifer
- Results - Leveled above 500 ppb

Harris Corporation, FL:
- Goal - 500 ppb VOCs
- Results - Leveled at 1,000 ppb in three wells; 14,000 ppb in one well

large masses of contamination remain in the aquifer. When pumps are turned off, the concentrations rise again.

4.0 PRIMARY FACTORS INFLUENCING EFFECTIVENESS

Several factors can contribute to the ineffectiveness of pumping for restoring aquifers (Table 4). The presence of unaddressed soil contamination and inadequately designed systems were often cited as primary contributors to the ineffectiveness of operations. Most of the ongoing pump and treat operations were designed based on limited site investigations, and determining the extent to which inadequate system design contributes to inefficiency is difficult. However, the primary contributors to the failure to meet cleanup goals are phenomena resulting from physical and chemical processes that affect the behavior of contaminants in the subsurface environment, such as contaminant sorption, contaminants in the non-aqueous phase, and zones of low permeability. All the sites reviewed have leveling patterns or other documented evidence to suggest that at least one of these factors is a major contributor to the ineffectiveness of the operation (Tables 1 and 4). Although systems can be designed to optimize efficiency, these fundamental processes and the problems they present serve

Box 3 - Status of Sites With Drinking Water Standards as Cleanup Goals

Verona Wellfield, MI:
- Goal - MCLs VOCs
- Results - Leveled at 2,500 ppb; conc. increased in some wells

Sharpe Army Depot, CA:
- Goal - 5 ppb TCE
- Results - Leveled at 100 ppb

Ponders Corner, WA:
- Goal - 5 ppb PCE
- Results - Leveled at 50 ppb

Des Moines TCE, IA:
- Goal - 5 ppb TCE
- Results - Leveled at 500 to 1,000 ppb

Amphenol Corporation, NY:
- Goal - 5 ppb TCE
- Results - Leveled at 50 ppb

Nichols Engineering, NJ:
- Goal - 5 ppb carbon tetrachloride; 10 ppb total VOCs
- Results - 80% to 90% reduction in some wells; overall, leveled at 150 ppb

IBM San Jose, CA:
- Goal - 50 ppb TCA
- Results - Concentrations have decreased to 50 ppb; however, contamination in shallow aquifer is acting as a continuous source of contamination.

Table 4
Known Factors Contributing to the Ineffectiveness
of Pumping Groundwater at the Sites Reviewed

Site	NAPLs	Areas of Low Permeability	Plume not Contained	Soils not Remediated	Fractured Rock
Savannah River, SC	X	X	X	X	
Verona Wellfield, MI	X	X		X	X
Sharpe Army Depot, CA		X		X	
United Chrome, WA		X		X	
Ponders Corner, WA		X	X	X	
Sylvester, NH	X	X		X	X
Twin Cities AAP, MN				X	
Harris Corporation FL	X			X	
Wurtsmith AFB, MI				X	X
Des Moines TCE, IA				X	
IBM Dayton, NJ	X			X	
General Mills, MN	X			X	X
GenRad Corp., MA				X	
Amphenol, Corp., NY					
Nichols Engineering, NY	X			X	X
IBM San Jose, CA		X	X	X	

to greatly increase the remedial time frame and may not be overcome by additional site characterization and design modifications.

4.1 Continued Sources of Contamination

A major contributor to the ineffectiveness of pump and treat operations reviewed is the presence of a continued source of groundwater contamination. These sources consist of contaminated soils (the primary source), and immobilized contaminants in the vadose zone and subsurface (secondary sources). The remediation of surface or subsurface soils had been completed at only one of the sites reviewed (Table 4). Soils at the Amphenol Corporation had been excavated prior to startup of the pump and treat operation (Figure 5). Although soils had been excavated at the IBM San Jose site, significant vadose zone contamination was still suspected. Source remediation is underway at most of the sites reviewed but has not been completed.

Although completion of soil remediation is likely to increase the efficiency of the systems, at all the sites reviewed, contaminants sorbed to aquifer material, trapped in low permeability zones, or pooled in the non-aqueous phase serve as a continued secondary source of contamination. Because eliminating these secondary sources of contamination is technically infeasible at the present time, this factor will continue to be the primary contributor to the ineffectiveness of pump and treat systems, even after soil remediation is complete.

4.2 Contaminant Sorption and Desorption

Contaminants in groundwater partition between the water and organic matter in soils. Organic contaminants tend to preferentially sorb to the aquifer material, causing a reduction of the mobility of the contaminants relative to the flow of the groundwater. As groundwater is pumped, the chemicals are held back (retarded) by their adherence to the soil particles. The mass of contaminant sorbed to the aquifer material is generally significantly greater than the mass in solution. Thus, the aquifer materials act as a continuing source of contamination to groundwater.

Retardation is typically expressed in terms of a retardation factor, derived by dividing the average velocity of the groundwater by the average velocity of the contaminant (Mackay 1989). For example, TCE has been shown to have a retardation factors ranging from 1 to 40, depending on the composition of the aquifer material (McCarty 1989).

Sorption and retardation studies have shown, however, that retardation factors for organic solutes have a tendency to increase over time (Roberts et al. 1986), that soil long-contaminated with halogenated organic compounds is resistant to desorption (Pavlostathis and Jaglal 1991), and that the tailing of organic solutes is controlled by diffusion limitations (Goltz and Roberts 1986; Wu and Gschwend 1986; Pignatello 1990a,b). These studies suggest that contaminant desorption rates decrease over time and are limited by molecular diffusion from remote areas in the soil matrix. This results in concentration leveling and decreased contaminant extraction rates over time.

Although groundwater concentrations drop initially, large masses of contaminants may remain in the aquifer materials, and many pore volumes of water must be brought into contact with the soil particles in order to extract the contaminants. This process results in the recovery of very large volumes of mildly contaminated water (Table 3). The number of pore volumes of water that must be removed during a pump and treat operation depends on the sorptive tendencies of the contaminant, the volume of contamination in the non-aqueous phase, and groundwater flow velocities. However, the kinetic limitations of desorption result in lengthy and inefficient pumping operations. At the IBM San Jose site, combined pumping rates of 2,000 gpm at two boundary wells have pumped more than 5 billion gallons of groundwater over a four-year period. However, less than 800 lbs. of contaminants were extracted (EPA 1989).

4.3 Non-aqueous Phase Liquids

Many of the organic chemicals found at hazardous waste sites are immiscible in water and are likely to be present in a non-aqueous phase. They are, however, slightly soluble in water, and partitioning of components from the non-aqueous phase may result in the development of a dissolved plume in addition to the immiscible phase that acts as a continuous source of contamination. Contaminants such as chlorinated solvents, creosotes, and PCB oils are denser than water and sink to the bottom of the aquifer, leaving behind ganglia of residual contamination and becoming trapped in pore spaces by capillary action. Contaminants such as benzene, xylene, and toluene are lighter than water and float on top of the water table. The mass of contamination in the non-aqueous phase may be considerably greater than in the dissolved phase (Mackay and Cherry 1989).

Aquifer restoration within a reasonable time frame is infeasible at sites involving NAPLs. At best, even if eventual restoration were conceivable, predicting how long pumping and treating will take to restore an aquifer is not possible (MacKay and Cherry 1989). Although some success has been achieved in removing a portion of floating NAPL layers, little success has been achieved in locating dense NAPLs (DNAPLs), much less extracting them. When large pools of DNAPLs are present at the bottom of an aquifer, meeting drinking water standards is unachievable at any cost (Freeze and Cherry 1989).

Removing trapped NAPLs from the subsurface is infeasible because NAPLs cannot be mobilized under typical aquifer conditions. NAPL mobilization is controlled by mass transfer limitations in liquid phase dissolution (Hunt and Sitar 1988). The following calculation illustrates the time frame associated with DNAPL dissolution. For a site with only 1 m^3 of sandy soil contaminated with TCE at 30 l/m^3, assuming groundwater flow through the soils at a rate of 0.03 m/d, hydraulic conductivity of 10^{-3} cm/s, a hydraulic gradient of 1%, porosity of 30%, and dissolution of DNAPLs into the groundwater to 10% of their solubility, approximately 122 years would be needed for dissolution of DNAPLs into the groundwater (EPA 1990). This scenario is far more favorable than for the site conditions and the volume of DNAPLs that are likely to be present at the average hazardous waste site.

Forty-four percent of the sites reviewed involved either documented NAPLs or evidence suggesting the existence of NAPLs (Table 4). However, because of the constituents involved, the mass of contaminants, and the fact that contaminants have migrated into the deeper aquifers at the sites, the likelihood of pooled DNAPLs is great at all of the remaining sites involving chlorinated solvents as the primary contaminants.

4.4 Low Permeability Zones

The rate at which contaminants can be extracted using pump and treat is affected by advection, the process by which moving groundwater transports dissolved solutes (Fetter 1988). In heterogeneous systems where layers of varying permeabilities exist, pumping causes preferential flow in areas of high permeability. The more layered the geologic system, the longer the tailing effect (EPA 1990). The contaminants that remain in low permeability zones are removed very slowly by molecular diffusion. Even highly soluble contaminants may become trapped in the finer pore structure (Hall 1988). At the sites reviewed, at least 35% of the sites involved significant portions of the contaminant mass in such areas of low permeability (Table 4). As much as 90% of the contaminant mass is estimated to be present in zones of low permeability at the Ponders Corner site.

4.5 Fractured Rock

One third of the sites reviewed involved fractured bedrock (Table 4). At such sites, dissolved contaminants may enter the rock matrix by diffusion and be stored there by adsorption, greatly decreasing the likelihood that the contaminants can be removed (Mackay and Cherry 1989). When NAPLs enter fractured rock aquifers, they flow deep into the fractures, and little or no water can penetrate and flush these areas, further complicating the mobilization of NAPLs.

5.0 PREDICTING REMEDIAL TIME FRAMES

5.1 Groundwater Modeling at the Sites Reviewed

Modeling had been conducted at two-thirds of the sites reviewed. However, all but one used flow models with over-simplified and generic assumptions, resulting in a failure to consider the tailing effect observed at the sites. Thus, the overall time frames for the sites are underestimated by at least a factor of three. At the sites that projected remedial time frames, 25% of the sites have already exceeded remedial milestones by as much as a factor of two (Box 4). The underestimation of time frames can be attributed to both inadequate models and inadequate site characterization.

Box 4 - Remedial Time Frames at Sites Reviewed

Site	Length of Operation	Projected Time Frame
Amphenol Corp., NY	3 years	5-10 years
Des Moines TCE, IA	2.5 years	not projected
General Mills, MN	4 years	not projected
GenRad Corp., MA	2 years	>5 years
Harris Corp., FL	6.5 years	not projected
IBM Dayton, NJ	13 years*	6-11 years
IBM San Jose, CA	8 years	10 years
Nichols Eng., NJ	2.5 years	2.25 years
Ponders Corner, WA	6 years	10 years
Savannah River, SC	5 years	30 years
Sharpe Depot, CA	2.5 years	30 years
Sylvester, NH	4 years	ACLs 2 years
Twin Cities, MN	2 years	not projected
United Chrome, OR	2 years	5 years
Verona Wellfield, MI	6.5 years	100 ppb in 3 years
Wurtsmith AFB, MI	13 years	--

* Operation ceased for four years during this period.

At present, numerous factors which affect the transport of contaminants in the subsurface and the remedial time frame are not accounted for in groundwater models (Keely 1989; McCarthy and Zachara 1989; Mercer and Skipp 1990; van der Heijde et al. 1989). Such models typically:

- Consider only adsorption and advection
- Use generic retardation factors
- Do not consider dispersion, diffusion, or degradation
- Do not consider influences in vertical flow caused by partially penetrating wells
- Do not consider non-aqueous phase liquids
- Assume homogeneity
- Assume that aquifer is confined
- Assume uniform thickness
- Assume a steady-state flow field
- Do not consider colloidal transport of contaminants
- Are usually based on inaccurate mass inventories and inadequate site characterization.

Estimates of contaminant retardation are essential to predicting the length of time required to clean up an aquifer. At best, for a plume containing only dissolved and sorbed contaminants in a uniform homogeneous aquifer, the volume that has to be removed will equal the contaminated volume times the retardation factor, not considering hydrodynamic dispersion. However, retardation factors vary from site to site for the same chemicals and appear to increase over time. Although sorption was considered in the remedial design for at least two thirds of the sites reviewed, the retardation factors used in the analyses were generic and did not account for intra-particle diffusion. To date, no methods have been developed that would allow site-specific estimates of contaminant retardation over time, and predictions of cleanup time frames based on generic retardation factors are unreliable. The lack of a reliable method for estimating contaminant retardation over time is the primary factor contributing to the gross underestimation of remedial time frames in the sites reviewed.

5.2 Recent Modeling Studies

Recent modeling studies suggest that pumping and treating will not restore aquifers to drinking water standards within a reasonable time frame. Pump and treat time frames of 100 years may be needed in order to lower concentrations by a factor of 100, assuming a homogeneous aquifer (Mackay and Cherry 1989, McCarty 1989). For water-insoluble constituents such as jet fuel, assuming a 10-acre area with a 55-foot thick aquifer, 10% residual saturation, a pumping rate of 100 gpm, a soil: water partition coefficient of 0.75, oil: water partition coefficients of 3,000 and 11,000 for toluene and o-xylene respectively, and one year to exchange the fluid one time, thousands of years would be needed to remove the contaminants (Hall 1988).

6.0 EFFECTS OF PUMPING AND TREATING

Several phenomena associated with pumping and treating can complicate the cleanup effort or cause ecological damage. The following effects of pumping and treating have been observed:

- A large volume of uncontaminated water, many times the volume of contaminated water, must be used to flush the aquifer.
- Dewatering resulting from pumping can cause serious land subsidence and other ecological damage.
- When perched NAPLs exist, drilling can puncture the bed causing the pool to drain to a lower aquifer (Mackay and Cherry 1989).
- When the water table is lowered from a position above perched NAPLs, the NAPLs can become remobilized and drain to a deeper aquifer (Mackay and Cherry 1989).

Pumping causes changes in the flow and distribution of groundwater that can be ecologically damaging. The potential effects of dewatering are land subsidence and the loss of habitats for some local species. Pumping at the IBM San Jose site has resulted in the dewatering of the A aquifer. A ground-water balance estimate for the Santa Teresa Basin showed that 6,900 to 29,900 acre-feet of overdraft occurred in 1985 (EPA 1989).

The Savannah River site shows evidence of mobilization of contamination to deeper aquifers. Although the total mass of VOCs decreased during the first three years of operation, the mass increased in three of the deeper aquifers (Box 5). Although a discontinuous layer consisting of 70% silt and clay separates the Upper and Lower Congaree Units, the contaminant mass in the lower unit increased by 17,000 lbs. The Ellenton Sand unit is 32 to 95 feet thick and contains two major clay layers, one of which is the principal confining unit for the underlying Black Creek Formation. This unit, which is an important water-producing zone, was not contaminated before the pump and treat operation began and is now contaminated.

These effects should be considered and weighed against the benefits of pumping, given the infeasibility of aquifer restoration within a reasonable time frame. Although the need for the use of pumping and treating for plume containment or wellhead treatment may outweigh the potentially detrimental effects, the technology should not be used routinely or indiscriminately.

Box 5 - VOC Mass (lbs.)
Savannah River Site

Unit	1985	1988
Water table	179,000	208,336
Upper Congaree	259,400	188,854
Lower Congaree	23,500	41,084
Ellenton Sand	1,800	3,010

Source: USDOE, 1989

7.0 CONCLUSIONS

Although we conducted an extensive survey of pump and treat operations, we were unable to locate an aquifer in the U. S. that has been confirmed to be successfully restored through pumping and treating. Although the B and B Chemical site, an NPL site in Florida, is claimed by the responsible party to be cleaned up, the claim has not been substantiated by EPA, and the extent of remediation is questionable because the responsible parties failed to submit appropriate monitoring documentation (Personal communication, D. Danner, EPA Region 4). Another site, Emerson Electric, a site in Florida involving low-level contamination, is also claimed to be cleaned up. However, the validity of this claim is also questionable because doubt exists as to whether the plume was captured by the system, and confirmation sampling was inadequate (EPA 1989).

Although pumping and treating has generally been effective for containing the contaminant plume and reducing the mass of contamination at the sites reviewed, little success has been achieved in reducing aquifer contaminant concentrations to the established cleanup goals. Two of the review sites with the longest performance records, the IBM Dayton site and the Savannah River Plant site, have changed the remedial objective from restoration to reduction of contaminant mass because of the ineffectiveness of the pump and treat operation in meeting the remedial objectives.

At all the sites with performance records of more than two years, concentrations have leveled after an initial decline. For some sites, leveling may take place at relatively low concentrations, even though as much as 50% of the contaminant mass may still be present in the aquifer. Typically, once the pumps are turned off, concentrations rise again, often to levels higher than initial concentrations.

Based on our review of performance records and recent theoretical studies, the following can be concluded regarding aquifer restoration :

- Groundwater pumping is ineffective for restoring aquifers to health-based levels.
- Pumping is effective for contaminant mass reduction, plume containment, and extraction of groundwater for point-of-use treatment.
- Although significant removal of the contaminant mass may be achieved, contaminant concentrations may not be significantly reduced.
- At sites where contaminant concentrations have leveled, concentrations remain significantly above drinking water standards.
- Even if target concentrations are reached, when pumps are turned off, concentrations rise again, often to levels higher than initial concentrations.

- The primary contributors to the ineffectiveness of pumping for aquifer restoration are phenomena resulting from physical and chemical processes, such as contaminant sorption and the existence of non-aqueous phase liquids and zones of low permeability.

- The longest remedial time frame predicted in the performance records reviewied was 30 years. Recent modeling studies, however, estimate that pump and treat time frames of 100 to 1,000 years may be needed to restore aquifers.

Both performance records and modeling studies indicate that the pump and treat approach is ineffective for aquifer restoration within a reasonable time frame. No evidence exists that pumping can restore aquifers to a condition compatible with health-based standards. Containment, mass reduction, and wellhead treatment are presently feasible objectives for pump and treat systems, and future groundwater remedial action decisions and pump and treat system designs should be limited to these objectives.

8.0 REFERENCES

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Appendix A

Summary of Effectiveness

Site	Primary contaminants	Initial concentrations	Cleanup Goal	Duration of Operation	Pumping Rate	Status of Operation
Savannah River, SC	TCE PCE	250,000 ppb (max.) 150,000 ppb	Level acceptable to State of SC and/or removal 99% of contam. mass	5 years	400 gpm	Permeable and impermeable subsurface layers are contaminated with an estimated 260,000 to 464,000 pounds of solvents, and no significant reduction in concentrations or size of plume have been observed. VOC concentrations have leveled off with average influent concentrations at 40,000 ppb, and the system has not effectively captured plume. It is being re-designed with the remedial objective changed from restoration to reduction of contaminant mass.
Verona Wellfield, MI	VOCs	19,000 ppb (max.)	MCLs; 100 ppb after 3 yrs.	6.5 years	400 gpm	Substantial reduction of contaminant mass has been achieved. Overall, concentrations have leveled off above 2,500 ppb, and concentrations have increased in some wells.
Sharpe Army Depot, CA	TCE	290 ppb (ave.)	5 ppb	2.5 years	200 gpm	Original goal was emergency response to keep plume from drifting off-base. Although the plume is being contained and initial results were encouraging, concentrations have leveled off above 100 ppb and it now appears unlikely that the aquifer will be restored to meet drinking water standards. Concentrations in lower aquifer are not meeting expectations.
United Chrome, OR	Chromium (Cr6+)	6,860 ppm (max.) 1,923 ppm (ave.)	10 ppm (upper) 0.05 ppm (lower)	2 years	10 gpm	Although the average concentration for extracted groundwater was 576 ppm at the end of 1989 and a total of 13,376 lbs of chromium had been removed, concentrations have either increased or remained constant in many of the upper zone wells.

Site	Primary contaminants	Initial concentrations	Cleanup Goal	Duration of Operation	Pumping Rate	Status of Operation
Ponders Corner, WA	PCE	500 ppb PCE (max.)	5 ppb	6 years	2,000 gpm	A portion of the plume is not being captured by the system and PCE concentrations are remaining persistent in the well closest to the source. It is estimated that 90 percent of contaminants are contained in low permeability zones.
Sylvester, NH	tetrahydrofuran toluene TCE	1,500,000 ppb (max.) 29,000 ppb (max.) 15,000 ppb (max.)	-- 2,900 ppb 1,500 ppb	4 years	300 gpm	A slurry wall was constructed, and ACLs were established for contaminated groundwater within the contained area. However, the estimated 2 year cleanup period has already been exceeded by 2 years.
Twin Cities AAP, MN	TCE	20,000 ppb (max.) outwash aquifer; 100 ppb (max.) bedrock aquifer	27 ppb	2 years	2,700 gpm	Maximum TCE concentration remains at 18,000 ppb; average influent concentrations have shown no decline and remain at approx. 1,000 ppb.
Harris Corporation, FL	VOCs	10,000 ppb (max.)	500 ppb	6.5 years	300 gpm	Pumping has reduced the VOC plume. Average VOC concentrations have leveled off above 500 ppb during the past two years. However, concentrations have leveled above 1,000 ppb in 3 extraction wells.
Wurtsmith AFB, MI	TCE	840 ppb (ave.)	--	2 years	--	Average influent concentrations remain at 70 ppb in one area and between 500 and 700 ppb in a second area.
Des Moines TCE, IA	TCE	8,467 ppb	5 ppb	2.5 years	1,000 gpm	Concentrations have leveled at between 500 ppb and 1,000 ppb. An additional source of contaminated is being investigated.

Site	Primary contaminants	Initial concentrations	Cleanup Goal	Duration of Operation	Pumping Rate	Status of Operation
IBM Dayton, NJ	TCA PCE	9,590 ppb (max.) 6,132 ppb (max.)	100 ppb	13 years	1,000 gpm	Six years of pumping lowered VOC concentrations to below 100 ppb. However, subsequent to shutdown of the operation in 1984, PCE concentrations rose to 12,558 ppb. Pumping was resumed in 1989 with the remedial objective changed from restoration to containment.
General Mills, MN	TCE	1,300 ppb (max.) shallow aquifer; 2,300 ppb (max.) Carimona aquifer	270 ppb (shallow) 27 ppb (Carimona)	4 years	300 gpm (shallow); 50 gpm (Carimona)	Substantial reduction of TCE concentrations has been achieved. However, aquifer concentrations have leveled off above target levels and remain as high as 460 ppb in one area.
GenRad Corporation, MA	VOCs (primarily TCE)	1,000 ppb (total) 270 ppb	--	2 years	30 gpm	TCE concentrations have been reduced to approximately 100 ppb.
Amphenol Corporation, NY	VOCs (primarily TCE)	230 ppb (max.)	5 ppb	3 years	200 gpm	VOC concentrations have leveled off at 50 ppb.
Nichols Engineering, NJ	CCl_4 PCE Chloroform	980 ppb (max.)	5 ppb	2.5 years	65 gpm	Average CCl_4 concentrations have leveled off at approximately 150 ppb and concentrations remain unchanged in one well.
IBM San Jose, CA	TCA	100 ppb	5 ppb	8 years	1,600 gpm	Average concentrations have leveled at 50 ppb. However, the 10 ppb portion of the plume has remained unchanged.

Appendix B

Abstracts for Performance Records Reviewed

SITES REVIEWED

NAME OF SITE:	Savannah River Plant (A/M Area)
LOCATION:	Aiken, SC
TYPE OF SITE:	Department of Energy research and weapons manufacturing facility (NPL)
CONTAMINANTS:	TCE, PCE
GEOLOGY:	Permeable and impermeable layers: sands, silts, and clays with a water table 60 to 120 feet below the land surface
SYSTEM DESIGN:	11 recovery wells with 400 gpm total pumping rate; 236 monitoring wells
STATUS:	Plume is not effectively contained. Average total chlorocarbon concentrations have leveled at approximately 15,000 ppb, and concentrations remain as high as 40,000 ppb in one well. System is being re-designed with the goal of remediation changed from restoration to contaminant mass reduction.
REFERENCES:	U. S. Environmental Protection Agency (1989). Evaluation of Groundwater Extraction Remedies, Vols. 1 and 2; Office of Solid Waste and Emergency Response; EPA/540/0289/054; Washington, DC, 1989. U. S. Department of Energy Savannah River Site (1989). M-Area Hazardous Waste Management Facility Post-Closure Care Permit: Groundwater Monitoring and Corrective Action Program Second Quarter 1989 Report. U. S. Department of Energy (April 1987). Application for a Post-Closure Permit, M-Area Hazardous Waste Management Facility, Volume III, Savannah River Plant. Personal communication (1989). Victor Weeks, Environmental Protection Agency, Region 4.

NAME OF SITE:	Verona Wellfield, MI
LOCATION:	Battle Creek, MI
TYPE OF SITE:	Municipal wellfield (NPL)
CONTAMINANTS:	1,1-DCA; 1,2-DCA; 1,1,1-TCA; 1,2-DCE; 1,1-DCE; TCE; and PCE
GEOLOGY:	Sand and gravel aquifer overlies an upper sandstone aquifer with clay lenses, a confining siltstone bed, a lower sandstone aquifer, and a layer of shale; sandstone contains extensive horizontal and vertical fracturing.
SYSTEM DESIGN:	Five barrier wells; 9 groundwater extraction wells screened in the water-table aquifer with total pumping rate of 400 gpm. A vapor extraction system has also been installed.
STATUS:	Substantial reduction of contaminant mass has been achieved. Efficiency of system has increased since installation of the vacuum extraction system. However, average total VOC concentrations have leveled off around 2,500 ppb.
REFERENCES:	U. S. Environmental Protection Agency (1989). "Evaluation of Groundwater Extraction Remedies" Vols. 1 and 2; Office of Solid Waste and Emergency Response; EPA/540/0289/054; Washington, DC, 1989. Environmental Protection Agency (1985). Record of Decision, Verona Wellfield, MI. Guerriero, Margaret (1989). In-Situ Soil Vacuum Extraction System, Verona Well Field Superfund Site, Battle Creek, Michigan. Final Report for NATO/CCMS Pilot Study on Remedial Technologies for Contaminated Soil and Groundwater.

NAME OF SITE: Sharpe Army Depot, CA

LOCATION: Lathrop, CA

TYPE OF SITE: Army vehicle maintenance

CONTAMINANTS: TCE

GEOLOGY: Underlain by a complex sequence of interbedded sand, silt, and clay.

SYSTEM DESIGN: System consists of 15 extraction wells with a total pumping rate of 200 gpm.

STATUS: Although initial results were promising and the system has been successful in preventing migration of plume, concentrations in lower aquifer are not meeting expectations.

REFERENCES:

U. S. Army Toxic and Hazardous Materials Agency (USATHAMA) 1988. Remedial Investigation/Feasibility Study, Sharpe Army Depot, Lathrop, CA.

Sharpe Army Depot (1990). Summary and Discussion of Results, NPDES Permit # CA 0081931.

Personal communication (1990). Craig McPhee, USATHAMA.

NAME OF SITE: United Chrome, OR

LOCATION: Corvallis, OR

TYPE OF SITE: Chrome plating facility (NPL)

CONTAMINANTS: Chromium (hexavalent)

GEOLOGY: Upper unconfined zone consists of clayey silt alluvium with a saturated thickness of 15 to 18 feet during winter and decreasing during the summer; during winter, saturated zone often reaches the ground surface. Lower confined aquifer ranges from 29 to 45 feet below the ground surface.

SYSTEM DESIGN: System currently consists of 23 upper zone and 7 lower aquifer extraction wells with a total pumping rate of 17 gpm.

STATUS: Average groundwater concentration was 576 ppm at the end of 1989 and a total of 13,376 lbs of chromium had been removed. However, concentrations have either increased or remained constant in many of the upper zone wells. A more extensive characterization of deep aquifer has been recently conducted.

REFERENCES:

City of Corvallis (1989). Monthly Operations Report, United Chrome Groundwater Extraction and Treatment Facility.

CH2M Hill (1990). Deep Aquifer Report, United Chrome Products Site.

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Environmental Protection Agency (1986). Record of Decision, United Chrome, OR.

NAME OF SITE:	Ponders Corner, WA
LOCATION:	Pierce County, WA
TYPE OF SITE:	Dry cleaning facility (NPL)
CONTAMINANTS:	PCE; TCE; 1,2-trans-DCE
GEOLOGY:	The uppermost geologic unit, the Steilacoom gravel unit, is generally unsaturated but has some perched saturated zones. The underlying Vashton Till, a semi-confining layer that has discontinuous saturated zones, is composed of silts and clays with sand and gravel lenses. The third geologic unit, the Advance Outwash unit, is the primary aquifer in the area. This highly layered fine to coarse sand and gravel unit is from 20 to 90 feet thick and lies at depths of 25 to 84 feet below the land surface. The Colvos unit underlies the Advance Outwash aquifer. This fine sand aquifer is less permeable than the Advance Outwash aquifer and may help prevent migration to deeper units.
SYSTEM DESIGN:	Two extraction wells are in operation with a total pumping rate of 2,000 gpm. Forty-two monitoring wells were originally installed, but some of these wells have been discontinued recently.
STATUS:	A portion of the plume is not being captured by the system and PCE concentrations have leveled between 50 and 100 ppb. It is estimated that 90 percent of contaminants are contained in low permeability zones.
REFERENCES:	Alliance Technologies Corporation (1989). Draft Case Summary, Ponders Corner (Lakewood) Site, Ground Water Extraction with Air Stripping, Soil Vacuum Extraction. CH2M Hill (1988). Final Aquifer Cleanup Assessment Report, Ponders Corner, Washington. Ecova Corporation (1989). Lakewood SVES Operation Summary. SEA645112.PM Environmental Protection Agency (1985). Record of Decision, Ponders Corner, WA. U. S. Environmental Protection Agency (1989). Evaluation of Groundwater Extraction Remedies, Vols. 1 and 2; Office of Solid Waste and Emergency Response; EPA/540/0289/054; Washington, DC, 1989. Environmental Protection Agency (1989). PERC and TCE Concentrations Measured in H1/H2 (Influent database), Ponders Corner, WA, Region 10.

NAME OF SITE:	Sylvester, NH
LOCATION:	Nashua, NH
TYPE OF SITE:	Hazardous waste dump (NPL)
CONTAMINANTS:	Tetrahydrofuran, toluene, TCE
GEOLOGY:	Silt, sands, and interbedded sediments overlying fractured rock
SYSTEM DESIGN:	Remediation consists of a 3-ft. slurry wall around the 20-acre contaminated area. Eight extraction wells are in operation with a total pumping rate of 300 gpm.
STATUS:	The two-year timeframe projected for reaching ACLs within the contained area has been exceeded by 2 years. Average THF concentrations remain at 15,000 ppb, average toluene concentrations are 50,000 ppb, and average TCE concentrations are 3,000 ppb.
REFERENCES:	Environmental Protection Agency (1982). Superfund Record of Decision (EPA Region 1) Sylvester Site, Nashua, New Hampshire (Initial Remedial Measure) Environmental Protection Agency (1988). Monthly Operations Summary, Gilson Road Groundwater Treatment Facility. Environmental Protection Agency (1990). Personal communication, Chester Janowski, Region 1.

NAME OF SITE:	Twin Cities Army Ammunition Plant, MN
LOCATION:	New Brighton, MN
TYPE OF SITE:	Ammunition production (NPL)
CONTAMINANTS:	TCE
GEOLOGY:	Organic soils, sands, and clays are underlain by cohesive and relatively impervious till. The third unit consists of glacial outwash and/or valley fill materials 100 to 350 feet below the land surface. This unit is underlain by a bedrock unit consisting of weathered and fractured dolomite overlying sandstone. Little hydraulic separation exists between the overburden and bedrock units.
SYSTEM DESIGN:	Six boundary extraction wells were originally installed; three months later, more wells were added to the system. Currently, 12 boundary wells and five wells downgradient of interior source areas are operating at a total pumping rate of 2,700 gpm.
STATUS:	Although the plume has been captured and more than 21,000 lbs. of VOCs have been extracted to date, maximum TCE concentrations remain as high as 18,000 ppb; average VOC influent concentrations remain unchanged at approximately 1,000 ppb.
REFERENCES:	U. S. Army Toxic and Hazardous Materials Agency (USATHAMA), 1986. Twin Cities Army Ammunition Plant Ground Water Remedial Action Alternatives Analysis. Twin Cities Army Ammunition Plant, 1990. Installation Restoration Program, Twin Cities Army Ammunition Plant Groundwater Recovery System (TGRS) 1989 Annual Monitoring Report and Monitoring Plan, Vols. 1 and 2. New Brighton, MN. Personal communication, 1990. Juan Boston, USATHAMA.

NAME OF SITE:	Harris Corporation, FL
LOCATION:	Palm Bay, FL
TYPE OF SITE:	Manufacturing facility (NPL)
CONTAMINANTS:	TCE, TCEA, vinyl chloride, methylene chloride, chlorobenzene, ethylbenzene, xylene
GEOLOGY:	The upper sand aquifer, an unconfined aquifer, is used locally as a water source. The layer below the upper aquifer is a 22-foot thick sandy clay layer that acts as a leaky aquitard, retarding groundwater flow between the upper aquifer and the 30-foot thick unconsolidated lower sand aquifer. Underlying the lower sand aquifer is the Hawthorne formation, a clay confining layer up to 200 feet thick. The fifth layer is the Floridan aquifer, a 1,000-foot thick sequence of limestone and dolomite.
SYSTEM DESIGN:	The current system consists of 11 extraction wells, four of which are deep aquifer barrier wells. The remaining wells recover ground water from both the shallow and deep aquifers. The pumping rate has remained constant since startup at 300 gpm.
STATUS:	Although the average treatment system influent VOC concentrations have declined and leveled at approximately 500 ppb, concentrations have leveled above 1,000 ppb in one shallow extraction well, two deep aquifer extraction wells, and one deep aquifer monitoring well. In one of the temporary onsite shallow monitoring wells installed in 1987, VOC concentrations fluctuated between 1 and 30,000 ppb during 1988 and 1989 and remained at 14,000 ppb during 1989. This contamination can be attributed almost exclusively to xylene and ethyl benzene, as opposed to TCE, DCEA, and vinyl chloride in the extraction wells.
REFERENCES:	U. S. Environmental Protection Agency (1989). Evaluation of Groundwater Extraction Remedies, Vols. 1 and 2; Office of Solid Waste and Emergency Response; EPA/540/0289/054; Washington, DC, 1989. Harris Corporation (1990). May 1990 Quarterly Sampling of Groundwater Monitoring Wells. Melbourne, Florida.

NAME OF SITE:	Wurtsmith AFB, MI
LOCATION:	Wurtsmith, MI
TYPE OF SITE:	Underground storage tank (non-NPL)
CONTAMINANTS:	TCE, DCE
GEOLOGY:	A sand and gravel unit is underlain by a clay unit at approximately 62 feet below the land surface. Clay beds exist in the sand and gravel unit in the northern part of the site at depths of 5 to 15 feet below the land surface. The clay unit separates the aquifer from the underlying bedrock.
SYSTEM DESIGN:	A two-well system began operation in 1978 at a pumping rate of 280 gpm. At that time, water was pumped into an aeration reservoir. A second aeration system was installed by 1979, consisting of six more wells with a pumping rate of 125 gpm. Later in 1979, the U. S. Geological Survey installed 217 monitoring wells both onsite and offsite. In 1981, the second aeration system was removed from service, and in 1982, the Arrow Street Purge Well System was installed with a pumping rate of 1200 gpm. A second system, the Mission Street system, consists of five extraction wells at a pumping rate of 220 gpm.
STATUS:	Concentrations remain at 70 ppb at the Arrow Street site after 13 years of pumping and between 500 and 700 ppb after two years of pumping at the Mission Street site.
REFERENCES:	Wurtsmith Air Force Base, 1990a. Groundwater Cleanup Factsheet. Wurtsmith AFB, MI. Wurtsmith Air Force Base, 1990b. 379 Strategic Hospital/SGPB, Wurtsmith AFB, Michigan, Water Sampling Information. Wurtsmith Air Force Base, 1989. Wurtsmith AFB, MI; 4853-5300; 1989 Water Quality Data. Personal communication, 1990. Mike Niclo, Wurtsmith AFB. U. S. Geological Survey, 1983. Groundwater Contamination at Wurtsmith Air Force Base, Michigan. Water Resources Investigation Report 83-4002, Lansing, MI.

NAME OF SITE:	Des Moines, TCE, IA
LOCATION:	Des Moines, IA
TYPE OF SITE:	Municipal wellfield (NPL)
CONTAMINANTS:	TCE, T-1,2-DCE, and vinyl chloride
GEOLOGY:	The area is underlain by a layer of silt and clay and a layer of unconsolidated sand and gravel. These layers are underlain by consolidated shale, siltstone, and sandstone. Below this system lies consolidated dolomite, limestone, sandstone, and shale formations. Three primary aquifer systems are associated with the site, two of which are important sources of drinking water in the area.
SYSTEM DESIGN:	Seven recovery wells were initially installed with a total pumping rate of 1,300 gpm. Six of these wells are still in operation at a pumping rate of 1,000 gpm.
STATUS:	Concentrations have leveled at between 500 ppb and 100 ppb. An additional source of contamination is being investigated.
REFERENCES:	U. S. Environmental Protection Agency (1989). Evaluation of Groundwater Extraction Remedies, Vols. 1 and 2; Office of Solid Waste and Emergency Response; EPA/540/0289/054; Washington, DC, 1989. Dico Company, Inc., 1989. Performance Evaluation Report No. 3, Groundwater Recovery and Treatment System, Des Moines TCE Site, Des Moines, Iowa. Dico Company, Inc., 1990. Performance Evaluation Report No. 4, Groundwater Recovery and Treatment System, Des Moines TCE Site, Des Moines, Iowa.

NAME OF SITE:	IBM Dayton, NJ
LOCATION:	South Brunswick, NJ
TYPE OF SITE:	Electronics manufacturing facility (non-NPL)
CONTAMINANTS:	1,1,1-TCA and PCE
GEOLOGY:	The shallow unconfined aquifer is comprised of the two upper geologic units which consist primarily of clay, silt, and gravel. These units are underlain by a thin discontinuous clay layer. The lower semi-confined aquifer consist of a sand and gravel unit underlain by relatively impermeable shale.
SYSTEM DESIGN:	Initial system installed in 1978 consisted of 13 shallow aquifer extraction wells, one deep aquifer extraction well, 1 offsite production well, and 100 monitoring wells. The average pumping rate was 300 gpm with a maximum pumping rate at the offsite well of 500-600 gpm.
STATUS:	Six years of pumping lowered VOC concentrations to below 100 ppb. However, subsequent to shutdown of the operation in 1984, PCE concentrations rose to 12,558 ppb. Pumping was resumed in 1989 with the remedial objective changed from restoration to containment.
REFERENCES:	U. S. Environmental Protection Agency (1989). Evaluation of Groundwater Extraction Remedies, Vols. 1 and 2; Office of Solid Waste and Emergency Response; EPA/540/0289/054; Washington, DC, 1989.

NAME OF SITE:	General Mills, MN
LOCATION:	Minneapolis, MN
TYPE OF SITE:	Food research laboratory (non-NPL)
CONTAMINANTS:	TCE, TCA, PCE
GEOLOGY:	Thirty to fifty feet of unconsolidated alluvial and glacial deposits are underlain by a sequence of fractured sandstone, shale, dolomite, and limestone.
SYSTEM DESIGN:	Five shallow aquifer extraction wells are operating with a pumping rate of 370 gpm. One extraction well is in operation in the lower (Carimona) aquifer with a pumping rate of 50 gpm.
STATUS:	Substantial reduction of TCE concentrations has been achieved. However, aquifer concentrations have leveled off above target levels and remain as high as 460 ppb in one area.
REFERENCES:	U. S. Environmental Protection Agency (1989). Evaluation of Groundwater Extraction Remedies, Vols. 1 and 2; Office of Solid Waste and Emergency Response; EPA/540/0289/054; Washington, DC, 1989.

NAME OF SITE:	GenRad Corporation, MA
LOCATION:	Bolton, MA
TYPE OF SITE:	Scientific and medical equipment mfg. (non-NPL)
CONTAMINANTS:	TCE
GEOLOGY:	Unconsolidated glacial deposits overlie metamorphic rocks. In low-lying areas, organic sediments overlie sands and gravels. Depth to groundwater is generally only five feet.
SYSTEM DESIGN:	Two plumes are present at the site. Two extraction wells have been installed to address the eastern plume at a pumping rate of 30 gpm. Sixteen monitoring wells are in operation. Northern plume discharges to a nearby river, and is not being addressed by the system.
STATUS:	TCE concentrations have been reduced to approximately 100 ppb after two years of pumping.
REFERENCES:	U. S. Environmental Protection Agency (1989). Evaluation of Groundwater Extraction Remedies, Vols. 1 and 2; Office of Solid Waste and Emergency Response; EPA/540/0289/054; Washington, DC, 1989.

NAME OF SITE:	Amphenol Corporation, NY
LOCATION:	Sidney, NY
TYPE OF SITE:	Electrical connector manufacturing facility (non-NPL)
CONTAMINANTS:	TCE, Chloroform
GEOLOGY:	A 100 to 200 foot thick layer of alluvial materials are underlain by glaciofluvial sands and gravels.
SYSTEM DESIGN:	One shallow aquifer extraction well and one deep aquifer extraction well are in operation with a total pumping rate of 200 gpm. Seventeen monitoring wells were initially installed, but some have been discontinued.
STATUS:	Although initial maximum VOC concentrations were only 230 ppb, concentrations have leveled off at 50 ppb.
REFERENCES:	U. S. Environmental Protection Agency (1989). Evaluation of Groundwater Extraction Remedies, Vols. 1 and 2; Office of Solid Waste and Emergency Response; EPA/540/0289/054; Washington, DC, 1989.

NAME OF SITE:	Nichols Engineering, NJ
LOCATION:	Hillsborough, NJ
TYPE OF SITE:	Combustion research facility (non-NPL)
CONTAMINANTS:	Carbon tetrachloride, PCE, chloroform
GEOLOGY:	Silty soil overlies fractured shales, siltstone, and sandstones.
SYSTEM DESIGN:	One recovery well was installed initially with a pumping rate of 65 gpm. Two more extraction wells were installed in 1989 with a pumping rate of 70 gpm.
STATUS:	Average carbon tetrachloride concentrations have leveled at between 100 and 200 ppb and have remained unchanged in one well.
REFERENCES:	U. S. Environmental Protection Agency (1989). Evaluation of Groundwater Extraction Remedies, Vols. 1 and 2; Office of Solid Waste and Emergency Response; EPA/540/0289/054; Washington, DC, 1989.

NAME OF SITE:	IBM General Products Division, CA
LOCATION:	San Jose, CA
TYPE OF SITE:	Electronics manufacturing facility (non-NPL)
CONTAMINANTS:	Freon 113, TCA, 1,1-DCE, and TCE
GEOLOGY:	The valley floor is underlain by a sequence of alternating sand and gravel layers separated by silt and clay layers. Bedrock in the area consists of consolidated sandstones, shales, cherts, serpentinite, and ultrabasic rocks. Contamination is distributed throughout four aquifers at the site.
SYSTEM DESIGN:	The extraction system consists of three components: an onsite system at the source areas, a boundary system, and an offsite system. The original system consisted of three wells in the source areas screened in the A aquifer, 19 boundary wells screened in the A, B, and C aquifers, and four offsite wells screened in the B and C aquifers. The total pumping rate was approximately 6,000 gpm. Pumping in many of these wells has been discontinued, however, because of dewatering. Pumping in the source areas has been continued, and only one A aquifer well is still in operation. The current total pumping rate is approximately 1,200 gpm.
STATUS:	Average concentrations have leveled at 50 ppb. However, the 10 ppb and 1 ppb portions of the plume have remained unchanged.
REFERENCES:	U. S. Environmental Protection Agency (1989). Evaluation of Groundwater Extraction Remedies, Vols. 1 and 2; Office of Solid Waste and Emergency Response; EPA/540/0289/054; Washington, DC, 1989.

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