

# Comparison of Remedial Systems Employed at Drycleaner Sites

## State Coalition for Remediation of Drycleaners

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## **1 Executive Summary**

The State Coalition for Remediation of Drycleaners (SCRD) analyzed data from over one hundred site profiles collected from drycleaning site remediation projects across the United States. The comparative analysis evaluates the various remedial technologies and assessment techniques used at chlorinated and petroleum solvent sites. Site data included physical site characteristics, hydrogeology, geology, soil/groundwater contaminant concentrations and distribution, remedial systems employed, site closures and costs. The paper presents a current snapshot of remedial technologies being employed in most of the states with programs dedicated to remediation of contaminated drycleaning sites. Although conventional remedial technologies have been utilized at many of these sites, chemical oxidation and bioremediation are being employed more frequently as remedies at contaminated drycleaning sites. Bioremediation has been employed at over 23% of the sites in this study; while, chemical oxidation was used at 23.3% of the sites. Other innovative remedial technologies that have been employed at the study sites include recirculating wells, surfactant/cosolvent flushing, a permeable reactive barrier and soil mixing using zero-valent iron.

Site data were analyzed to determine trends regarding remediation successes or failures. Success and/or failure are often difficult to ascertain because of site and program limitations. Some useful observations can, however, be made regarding certain technologies. Graphical analysis of the data can indicate trends in remediation technology selection. The technology selection process is driven by a variety of technical and programmatic factors, such as: physical site limitations, cost, desired cleanup time, risk-based determinations and expertise of remedial design staff or consultants. Ideally, the audience will be able to use the information in this report to help in the decision-making process when selecting a proven remediation technology for their drycleaning site, or at a site with similar characteristics.

## **2 Introduction**

Drycleaning solvent contamination is widespread in urban areas and it has been estimated that 75% of all drycleaning facilities are contaminated (Schmidt, 1999). Beginning in 1994 with Connecticut and Florida, there are now thirteen states with programs devoted to remediation of contaminated drycleaning sites. The State Coalition for Remediation of Drycleaners (SCRD), an organization representing the 13 states with drycleaning solvent cleanup programs, with the assistance of the United States Environmental Protection Agency (EPA) Technology Innovation Office (TIO) maintains a database containing over one hundred profiles collected from drycleaning site remediation projects across the United States. SCRDR analyzed the data to

determine trends in remediation technology implementation with respect to the contaminant source type and magnitude, geologic and hydrogeologic conditions and planned remediation objectives. Caution should always be used when evaluating sites from a wide range of geographical locations and diverse geologic conditions. Remedial objectives can also vary greatly depending upon whether the sites are being remediated through a state trust fund or by the responsible party. Many state trust funds have limited financial resources that result in remedial efforts being conducted in a phased approach, whereas a responsible party may be looking to quickly clean up a site to facilitate a property transaction.

The data in the Site Profile database can be found on the SCRD Web Page at [www.drycleancoalition.org](http://www.drycleancoalition.org) and includes known drycleaning sites that have been undergoing remediation for a minimum of one year. Some of the sites are still in active remediation, while others have already been closed. The list of sites is not comprehensive since there are likely thousands of additional sites across the country that haven't been submitted to the database. The majority of the sites are from states with dedicated drycleaner remediation trust fund programs.

This paper will address three primary areas of interest with regards to the technology selection process, implementation and remediation results. The first general area includes determining the site history and assessing the degree of contamination. The site setting considers the drycleaning facility contaminant data and the type of cleanup program overseeing the contaminant remediation. Assessment activities typically define the geologic and hydrogeologic conditions, identify the contaminant source areas and document the distribution of contaminants in the vadose and saturated zones.

The second area includes the determination of what remedial approach was taken to cleanup the contaminated soil and groundwater. Vadose zone soil remediation and saturated zone remediation are often addressed independently, but they can have a significant impact on each phase of the design and implementation. Most experts will agree that removing the vadose zone source should be a primary objective, but situations arise that may require hydraulic containment or a more aggressive approach to groundwater remediation. Many of the sites will utilize a treatment train approach to address the remediation of the contaminated soil and groundwater. With costs exceeding several million dollars, this approach can help minimize the risk to human health and the environment.

The third area to be considered is results and costs. These areas are highly subjective for many of the same reasons noted above. The type of remediation program, geologic and hydrogeologic controls and severity of the contamination can dramatically impact the success or failure of a project.

The goal of this paper is to provide a resource for regulators, consultants and property owners to evaluate past remedial strategies and use the information to formulate a remedial approach that is viable for other drycleaner sites. No single person has found the magic bullet with respect to a sure-fire cleanup approach. No single technology will work at every site. But with a systematic approach, design engineers can develop a remedial design that can effectively reduce the mass of contaminants in the subsurface. The question remains, "What technology is right for my site?"

### **3 Drycleaner Remediation**

Researchers have proven that remediation technologies will work in the lab. A microbiologist can construct mesocosms and microcosms in the laboratory, some even using soil and groundwater from specific contaminated sites. Scientists have shown that technologies, such as bioremediation and chemical oxidation, can be effective in the lab’s controlled environments. The difficult part is determining how to implement the same remedial approach at the contaminated site. Injection of a biostimulant into a 12-inch diameter by 10-foot high lab cylinder is much different than injecting and effectively dispersing the same biostimulant into a heterogeneous aquifer.

The site setting and past operations at drycleaning facilities have a large impact on the remedial approach. Stumbling blocks include limitations in the knowledge of the operational history of the site, type of solvent releases, and level of assessment completed for the contaminant plume.

State and federal regulatory programs can differ greatly in their remedial approach. Oversight programs typically review the remedial approach suggested by a responsible party’s (RP) consultants. Government-lead programs have more direct involvement and direct the remedial approach. The government’s level of effort is often directly related to the financial ability to implement certain types of technologies.

The data set for the study consists of 114 drycleaning sites and 2 drycleaning wholesale supply facilities where remediation has been conducted for at least one year. The reader should keep in mind the data set for this study is expected to be somewhat skewed because many states address sites based on prioritization. The data set includes a larger percentage of high risk sites due to hydrogeologic conditions that are more favorable for contamination migration, therefore impacting off-site receptors. In the future, a larger data set may see a higher percentage of lower risk sites where the average geologic and hydrogeologic environment may be more heterogeneous or have deeper groundwater, which may inhibit contaminant migration. Low risk sites may not equate to lower cleanup costs, though.

These sites are located in 15 different states as follows:

<u>State</u>	<u># Sites</u>	<u>State</u>	<u># Sites</u>	<u>State</u>	<u># Sites</u>
Colorado	2	Missouri	3	Rhode Island	1
Florida	43 / 1*	Minnesota	6 / 1 **	South Carolina	4
Georgia	1	New York	5	Tennessee	5
Illinois	2	North Carolina	2	Texas	7
Kansas	12	Oregon	13	Wisconsin	8

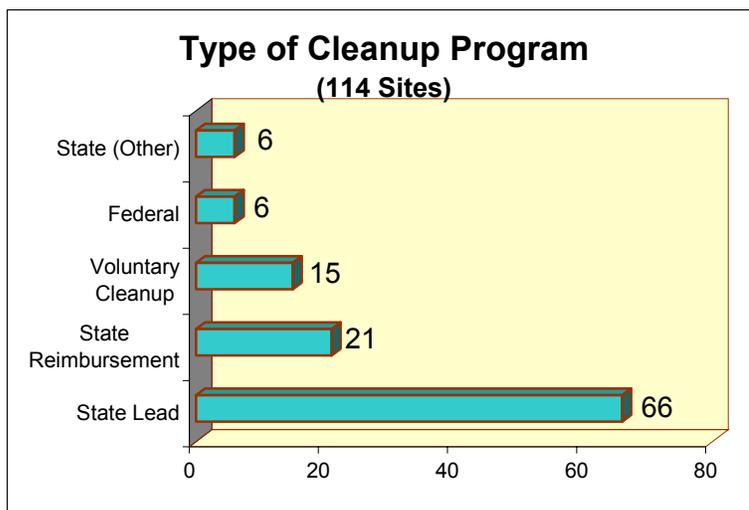
\* 43 drycleaning facility sites, 1 drycleaning wholesale supply site

\*\*6 drycleaning facility sites, 1 drycleaning wholesale supply site

#### ***3.1 Cleanup Programs - The Regulatory Approach***

The primary types of cleanup programs include: 1) State-lead drycleaner remediation programs, 2) State reimbursement drycleaner remediation programs, 3) State remediation programs (non-drycleaner specific), and 4) Federal remediation programs, i.e., Superfund, Department of Defense, etc.

- 1) State-lead drycleaner remediation programs typically have staff geologist, scientists and engineers serving as project managers who direct consultants to complete contamination assessments, remedial designs, installation of remedial systems and operation and maintenance of those systems at drycleaning sites within their state trust fund program. The consultants working on these sites have been selected by and work directly for the state cleanup program.
- 2) State reimbursement trust fund programs can be managed in different ways. Some state reimbursement programs are involved with the detailed planning for the assessment and remedial approach. Other reimbursement programs provide reimbursement of eligible costs after the responsible party (RP) or property owner has completed certain phases of the site corrective action. The amount of reimbursement differs among state programs in that limits are sometimes set for a maximum reimbursement amount ranging from \$50,000 to no maximum amount. Many of the programs require competitive bids and pre-approval of work plans prior to implementing the corrective action.
- 3) States that do not have drycleaner remediation programs often manage the corrective action oversight through a state cooperative or a state superfund-type program. These programs are typically oversight programs that review the corrective action work plans and reports and approve the recommended planned activities by the RP or property owner’s consultants. State regulatory agencies also review drycleaning sites undergoing voluntary cleanup, cleanup under a consent order or enforcement action and sites undergoing cleanup under a Brownfields program.
- 4) Sites not addressed by state programs are typically part of EPA’s Superfund Program, Department of Defense (DoD) sites on military bases or are administered under the Resource Conservation Recovery Act (RCRA). EPA Superfund sites have been through the National Priorities Listing (NPL) and typically are not in state-lead programs. Many state drycleaner programs have regulations that prevent a NPL or RCRA site from being accepted into their drycleaner trust fund program. A few sites have been removed from the NPL and then place into a trust fund, when appropriate. Most Superfund drycleaning sites have an EPA lead with some state agency oversight. EPA will typically attempt to recover the corrective action costs from the RP whenever possible. Many military bases had on-site drycleaning operations. State drycleaner remediation programs typically exclude these sites from their programs and the DoD is the primary lead on the corrective action. DoD contractors often interact with state programs that oversee federal facilities, depending upon how the state regulatory agency is organized.

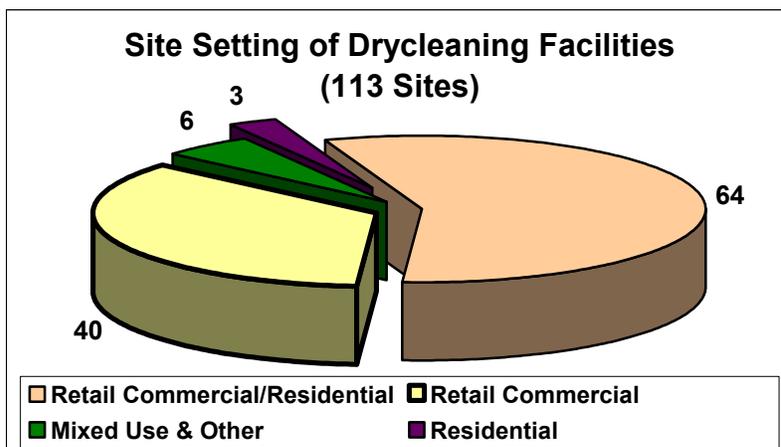


### 3.2 Drycleaning Facilities

The American drycleaning industry originated in the nineteenth century. Petroleum-based solvents were the predominant drycleaning solvent used in the United States until the late 1950s to early 1960s and are still used today. A variety of other solvents such as carbon tetrachloride, trichloroethylene, 1,1,1-trichloroethane and 1,1,2-trichloro 1,2,2-trifluoroethane (Valclene), have also been used in drycleaning but beginning in the late 1950s and early 1960s, perchloroethylene (PCE) became established as the most effective solvent for drycleaning garments. PCE is still the most widely used drycleaning solvent in the United States and it has been the predominant solvent used at study sites. A breakdown of solvent use (historical and current) at the study drycleaning sites revealed 84% of the facilities use only PCE; 3% use only petroleum and 13% use both solvents.

#### 3.2.1 Site Setting

Drycleaning facilities are located in urban areas. The most common setting for the study sites can best be described as retail commercial/residential. Drycleaning facilities are most commonly located in shopping centers or strip malls in close proximity to residential areas. Each setting has different challenges when initiating corrective action. Conducting assessment/remedial work on active drycleaning facilities is advantageous in that the type of solvent utilized is known as well as the equipment layout. Drycleaning business owners and employees are available to answer questions on solvent use, waste management practices and the types and former locations of decommissioned equipment. However, obtaining historical operational information can be difficult if a facility has been in existence for several decades. Drycleaning facilities with long operational histories typically had multiple owners/ operators. Locating and interviewing the former owners or employees for site reconnaissance interviews is problematic. A site reconnaissance visit will include interviews with current and former employees or property owners to help identify historical locations of machines, waste handling areas, storage tanks, etc.



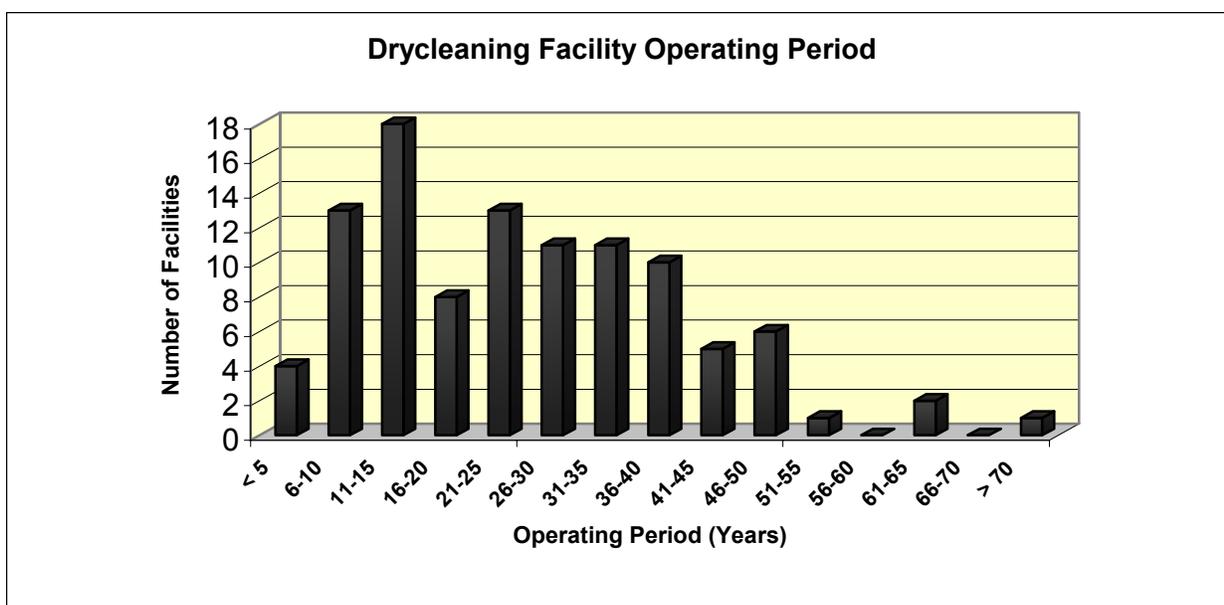
#### 3.2.2 Duration of Operation

The duration of facility operation can also be important, but is not necessarily the deciding factor when estimating the severity of contamination. Regulatory and industry standards have changed over the years with respect to waste management requirements and types of drycleaning equipment. The latest generation dry-to-dry machines are much more efficient than the old transfer machines. Refrigerated condensers and carbon adsorption devices have resulted in lower solvent vapor emissions. Installation of secondary containment pans under machines, solvent storage and waste storage areas and the use of direct-coupled solvent delivery systems have minimized accidental solvent discharges to the environment. When properly maintained and used, separator water treatment units result in lower emissions of solvent to the environment.

**Drycleaning Facility Operating Period (Years)**

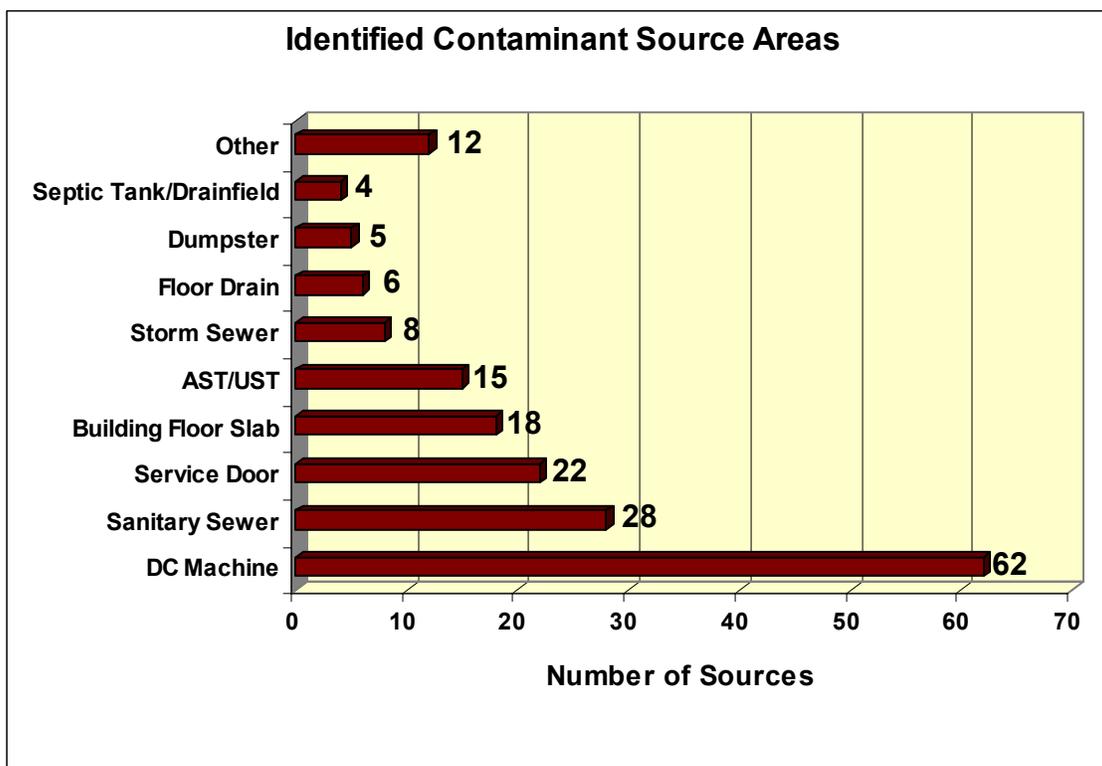
	<u>Range</u>	<u>Mean</u>	<u>Median</u>
Inactive Facilities	2 - 64	24.8	25
Active Facilities	4 > 70	34.7	22
All Facilities	2 > 70	26.3	26

At the time site assessment work was initiated at the study sites, active drycleaning operations were being conducted at 55 sites or 47.4% of the sites. Drycleaning operations had ceased at the remainder of the sites prior to site assessment work. The drycleaning facility operating period was calculated as the number of years that drycleaning was performed at the facility as of the initiation of site assessment activities. The data was available for 103 of the sites.



**3.2.3 Sources of Contamination**

Spills, leaks and discharges of pure solvent can be problematic due to the high concentration of solvent being released to the environment. A study of reported leaks, spills and discharges at over 300 Florida drycleaning sites found that discharges were primarily the results of equipment failure, machine operation, solvent transfer, solvent storage, equipment maintenance and waste discharges (Linn, 2002). Based on site assessment data, 181 different contaminant source areas were identified at 113 facilities in the site profile database. In general, the most common contaminant source areas identified at these sites were in the soils beneath the drycleaning facility floor slab in close proximity to the drycleaning machines or solvent storage areas; sanitary sewer lines (a historical discharge point for drycleaning wastes); and the area near the service door of the facility (solvent deliveries and historical storage and surface discharge of drycleaning waste streams).

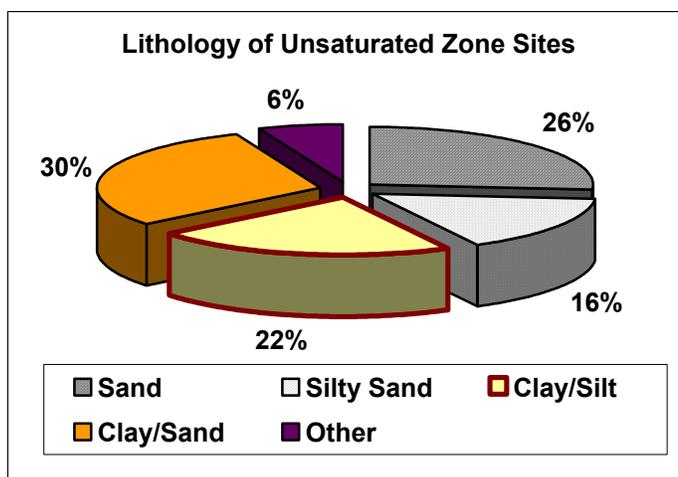


## 4 Hydrogeologic and Geologic Setting

The hydrogeologic and geologic setting for a site can significantly impact the severity of the soil and groundwater contamination. Project managers often try to compare site conditions when evaluating the type of remedial system to be considered for a site. General assumptions can be made, but site-specific conditions can greatly impact the remedial design. For example, a site with a silty-clay soil may require much different chemical oxidants depending upon the natural oxidant demand. The hydraulic gradient and groundwater velocity at a site can greatly effect the retention time needed for effective bioremediation of the contaminants.

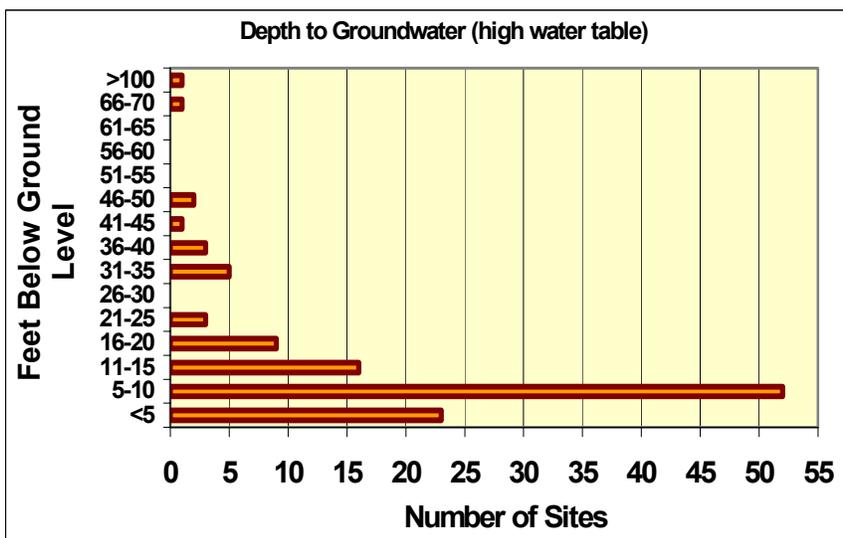
### 4.1 Unsaturated Zone

In general, the unsaturated zone at the study sites is predominantly composed of unconsolidated clastic materials (sands, silts, and clays). Although sand is present in the unsaturated zone at most of the sites (approximately 72%), finer-grained sediments (silt and clay) are present in the unsaturated zone at approximately 68% of these sites and these fine-grained sediments predominate at over half (52%) of the sites.



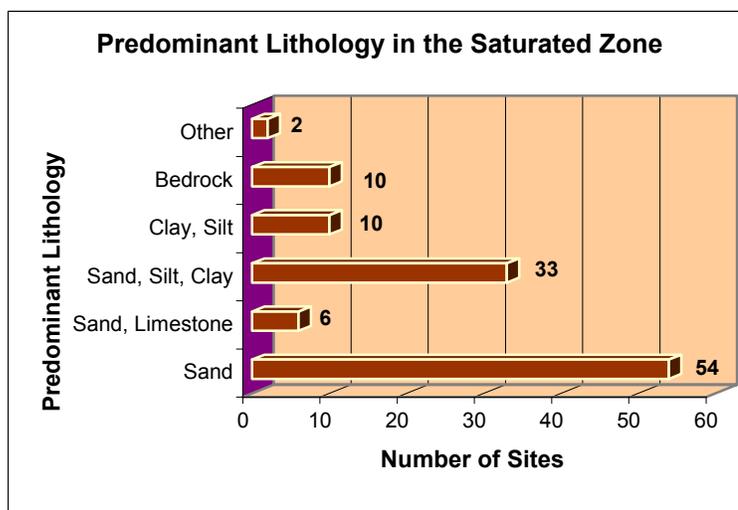
### 4.2 Saturated Zone

**Depth to Water:** Although the depth to water at the sites in the data set varied from 2 to 150 feet below land surface, the average depth to water was 13.5 feet. The median depth to water was eight feet. In general, the water table was encountered at relatively shallow depths, less than twenty feet at most sites. The lack of a significant number of sites at deeper depth to groundwater may be a function of greater distance for contaminants to travel through the unsaturated zone and that sites with more complicated hydrogeology may not be as far along in the remedial process.



**Hydraulic Gradient:** The horizontal hydraulic gradients for the study sites (104 sites in data set) ranged from 0.001 to 0.337 feet/foot (ft. /ft.), with a mean horizontal hydraulic gradient of 0.017 and a median horizontal hydraulic gradient of 0.004 ft/ft.

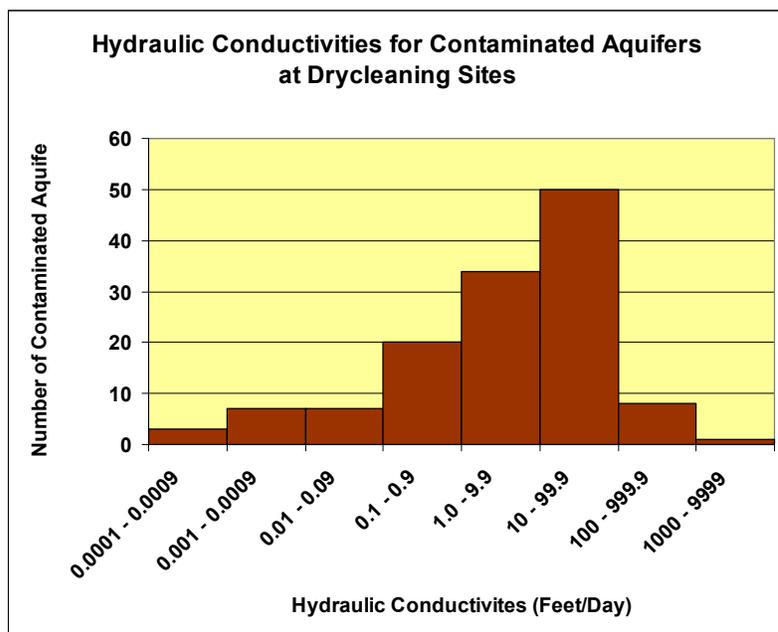
**Lithology:** The saturated zone lithology of the contaminated aquifers at the study sites is also dominated by unconsolidated clastics, such as clays, silts, sands, and gravels. The predominant lithology at nearly 84% of the sites is unconsolidated clastics. Carbonate and bedrock aquifers are present at only slightly greater than 16% of the sites. Sand is the most common clastic material present at study sites (47 % of the sites). Fine-grained clastics (clay and silt) are the predominant lithology of aquifers at approximately 37% of the sites.



**Hydraulic Conductivity:** Calculated horizontal hydraulic conductivities at the study sites ranged from 0.0001 to over 1,200 feet/day. Hydraulic conductivities ranging from 10<sup>-4</sup> through 10<sup>-2</sup> feet/day represent glacial tills, clays, loess and silt. Remediation of contaminated groundwater in aquifers composed of these materials will be difficult. Hydraulic conductivities in the 10<sup>-1</sup> feet/day range represent silty sand and clay/sand mixtures. Multi-phase extraction is a common remedial technology utilized at sites with these types of aquifers. Aquifers with hydraulic conductivities ranging from one to ten feet per day in the study data set are generally composed of sands with some finer grained material, silt or minor amounts of clay. Aquifers

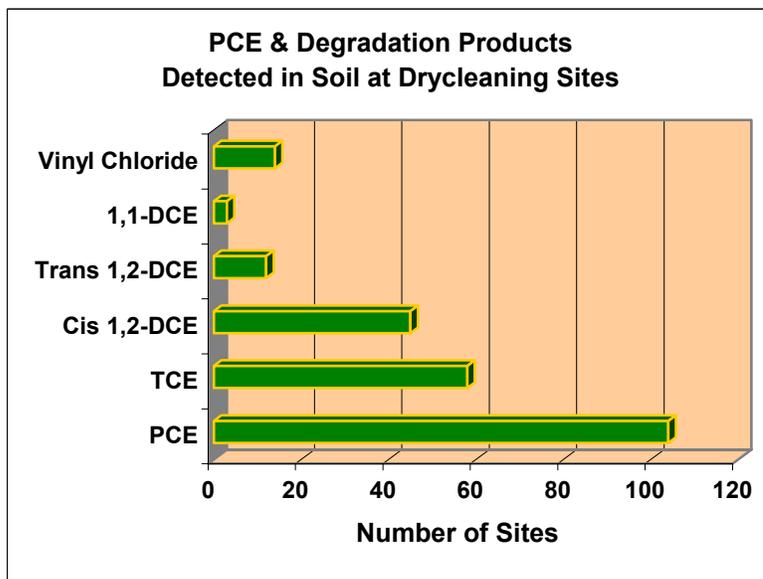
with hydraulic conductivities ranging from  $10^2$  to  $10^3$  feet per day generally represent relatively clean sands or carbonates with good secondary porosity development. Aquifers in the study group with hydraulic conductivities in the range of  $10^4$  or higher generally represent sands, gravels, sand/gravel mixtures or carbonates with highly developed dissolution porosities.

Approximately 80% of the study group aquifers have horizontal hydraulic conductivities in the range of  $10^{-1}$  to  $10^2$  feet per day, which is representative of silty sands and relatively clean sands or mixtures of sand and sometimes gravel with minor amounts of finer-grained sediments.



## 5 Soil Contamination

Soil contaminants were detected at 99 (85.3%) of the drycleaner remediation sites. PCE was the primary contaminant present at the study sites. PCE was the sole contaminant detected in soil at 36 (36.6%) of the 99 sites. PCE degradation products were detected in soil samples at over 63% of the sites with contaminated soil. In terms of frequency of occurrence, trichloroethylene (TCE) was the most common PCE degradation product in soils, followed by cis 1,2-dichloroethylene, vinyl chloride, trans 1,2-dichloroethylene and 1,1-dichloroethylene. Most of the non-PCE related contaminants detected in soil samples were petroleum-related compounds. Petroleum solvents have been utilized as a primary drycleaning solvent and in spotting agents and detergents. Other petroleum compounds detected in soils at drycleaning sites are derived from fuel oil, commonly used as boiler fuel or heating oil and from gasoline. Some drycleaners have operated fleets for pick-up and delivery of clothing and fuel has been stored onsite in underground storage tanks. The most common petroleum-related compounds



found in drycleaning solvents were: naphthalene, ethylbenzene, xylene, 1,3,5-trimethylbenzene, toluene 1,2,4-trimethylbenzene.

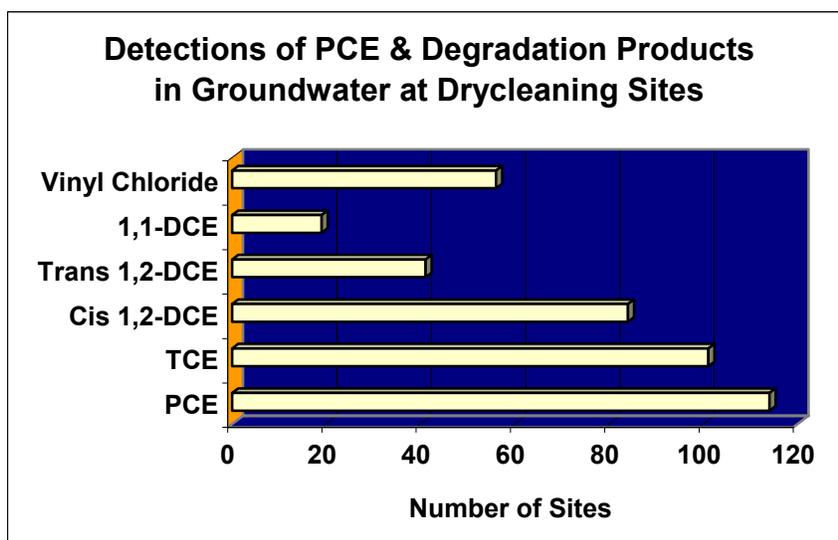
An unsaturated zone contaminant source area(s) will be present at virtually all drycleaning sites with associated groundwater contamination. Failure to locate and address these source areas will very likely result in a failure to achieve cleanup and closure of the site. If solvent in the unsaturated zone is not addressed through remediation, seasonal fluctuations of the water table and infiltration from surface water and leaky sewer lines will continue to leach contaminants from the source areas. Conversely, remediation of unsaturated zone contaminant source areas at some drycleaning sites has resulted in dramatic declines in contaminant concentrations in groundwater that have precluded the need for groundwater remediation.

## 6 Groundwater Contamination

Drycleaning-related contaminants were detected in groundwater at all the study sites, which is not surprising considering groundwater is the primary reason many sites are identified and directed to corrective action. The primary drinking water aquifer was contaminated at approximately 43.8% of the sites. Data was not thoroughly evaluated regarding the source of drinking water at study sites. Some of the sites in the study are located in areas where drinking water is obtained from surface water sources, rather than groundwater.

### 6.1 **Contaminants**

The most frequently detected contaminant in groundwater was PCE, detected at 114 of the sites (98.3% of sites). This includes all three sites that reportedly exclusively used petroleum drycleaning solvent. PCE is a common active ingredient in spotting agents. PCE degradation products were detected in groundwater at 92.2% of the sites. In order of frequency of reported occurrence, PCE was most common contaminant detected in groundwater, followed by trichloroethylene (TCE), cis 1,2-dichloroethylene and vinyl chloride. The non-PCE related compounds most commonly detected in groundwater were xylenes, toluene, ethylbenzene, naphthalene, 1,2,4-trimethylbenzene, and 1,3,5-trimethylbenzene, similar to the non-PCE related compounds most commonly found in soil samples.



## 6.2 NAPL

One of the questions asked in the preparation of the Site Profiles was “Is non-aqueous phase liquid (NAPL) present?” The criteria for presumptive evidence of NAPL in groundwater were the presence of the parent solvent compound in groundwater at a concentration of 1% or more of its aqueous solubility. Given these criteria, DNAPL is inferred to be present when a PCE concentration of 1.5 mg/L is present in the groundwater. Within the data set of 113 PCE sites, 71 (61.2%) of the sites have presumptive evidence of DNAPL.

## 6.3 Contaminant Plumes

Groundwater contaminant plume lengths ranged from 25 to 14,000 feet. The average plume length was 1,034 feet and the median plume length was 450 feet. One of the parameters recorded on the Site Profiles was “Deepest Significant Contamination” in depth below ground surface. No attempt was made at defining what constituted “significant” groundwater contamination. Based on the maximum length, width and thickness of the groundwater contaminant plume, a gross contaminant plume volume was calculated.

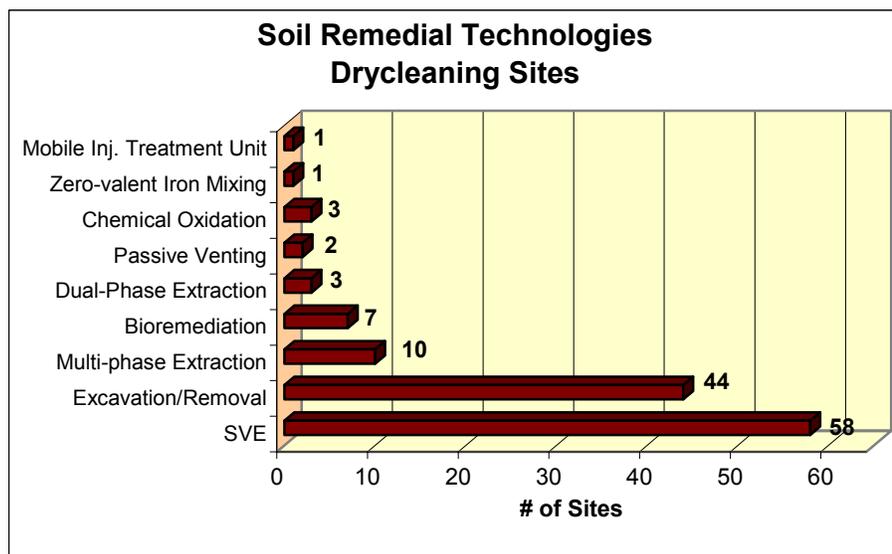
	<b>Deepest Significant Groundwater Contamination</b> (Feet below ground surface)	<b>Gross Contaminant Plume Volume</b> (Cubic yards)
Range	7 to > 200	153 – 24,074,074
Mean	52.34	123,851
Median	41	74,815

Of the 106 sites where data were available, 71 sites (67%) sites had contaminated groundwater migrating off the drycleaning facility property.

## 7 Soil Remediation

Remediation has been conducted in soil (unsaturated zone) at 100 (86.2%) of the study sites.

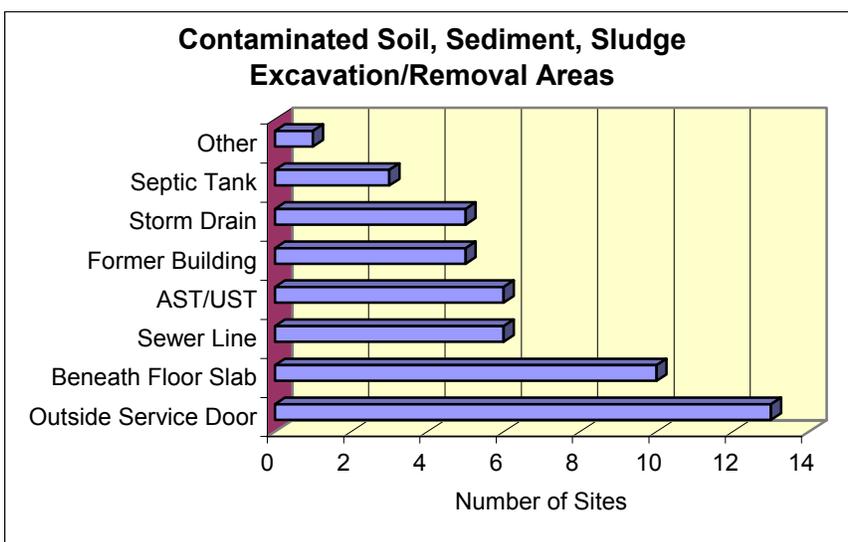
Technologies used to remediate contaminated soil include: excavation/removal (44 sites), soil vapor extraction/passive venting including multi-phase extraction (63 sites), biostimulation (6 sites), *in situ* chemical oxidation (6 sites), zero-valent iron soil mixing (1 site), and mobile-injection treatment unit (1 site).



### 7.1 Excavation/Removal

Excavation includes the removal of contaminated soil, sediments or sludge, thereby removing the *in situ* source of contamination. Its use at drycleaning sites is often limited because these sites are located in urban areas where access to the contaminated soils is limited. The sites are often occupied by active businesses and are served by buried utilities. Despite these limitations, some form of excavation/removal was conducted at nearly 38% of the study sites. Removal typically targeted common drycleaning contaminant source areas identified in Section 3.2. The volume of contaminated soil, sediment or sludge removed at study sites varied from the removal of a small volume of contaminated sediment (0.3 cubic yards) from a storm water drain at a Florida site to a major excavation (27,290 cubic yards) of contaminated soil at a Tennessee drycleaning site. The mean volume of contaminated material removed at study sites was 1,193.4 cubic yards and the median volume removed was 89 cubic yards.

The best opportunity for contaminated soil removal at these types of sites is when a building or shopping center is razed. At the Cedarburg Cleaners site in Wisconsin, a Mobile Injection Treatment Unit was utilized to treat solvent contaminated soil in place after a shopping center had been razed. Excavated contaminated soil was treated via ex-situ soil vapor extraction systems at five of the study sites.



### 7.2 Soil Vapor Extraction

Soil vapor extraction (SVE) has been the most widely used soil remedial technology at the study sites, with sixty-three systems installed. SVE involves the removal of contaminated soil vapor by applying a vacuum to the pore spaces in the unsaturated zone. This includes passive venting systems; vapor extraction combined with air and ozone sparge systems, and multi-phase extraction systems. A United Cleaners site in Illinois utilized a “heated” SVE system with in-ground heating coils enhancing VOC removal from fine-grained soil.

Approximately two-thirds of the SVE systems at study sites were installed in soils described as containing at least some fine-grained sediments, silt and/or clay. The average thickness of the unsaturated zone at the study sites was 19.4 feet. The median thickness of the unsaturated zone at study sites was 12.5 feet. Approximately 61.5% of the SVE systems utilized vertical vapor extraction wells. The number of vapor extraction wells employed in the SVE systems ranged from one to fifteen, with the average number of vapor extraction wells of 4.5 and the median number of three vapor extraction wells. Approximately 32.7% of the SVE systems utilized only horizontal vapor extraction wells and 5.8% of the systems utilized both horizontal and vertical vapor extraction wells. Fifteen of the sites that were closed used SVE systems to remediate soils.

The operating period for these systems ranged from 4 to 60 months. The average SVE operating period for closed sites was eighteen months and the median operating period was twelve months. Estimated volatile organic compound (VOC) mass recovery for the SVE systems at the closed sites ranged from 0.4 to 1,800 pounds and averaged 212.8 pounds.

### **7.3 Chemical Oxidation - Soils**

Chemical oxidation is the introduction of chemical oxidants into the subsurface to transform contaminants into less harmful constituents. Chemical oxidation has been utilized to remediate soils at six of the study sites. Chemical oxidants were generally utilized at sites with one or more of the following characteristics: a shallow water table, lower permeability soils, excavation sites with limitations on depth of excavation or accessibility to the contamination. Chemical oxidants were injected into both the unsaturated zone and saturated zone at four of the six sites. Injection occurred via injection wells (1 site), direct push (3 sites), combination of injection wells and direct push (1 site) and open excavation (1 site).

#### **7.3.1 Oxidants**

Oxidants injected into the soils included sodium permanganate (3 sites), potassium permanganate (2 sites) and Fenton's reagent (1 site). Chemical oxidants were effectively continuously injected at two of the sites over a two and four month period. The other four sites had two or less injection events. Only one site has been closed where chemical oxidants was injected into the unsaturated zone.

### **7.4 Bioremediation - Soil**

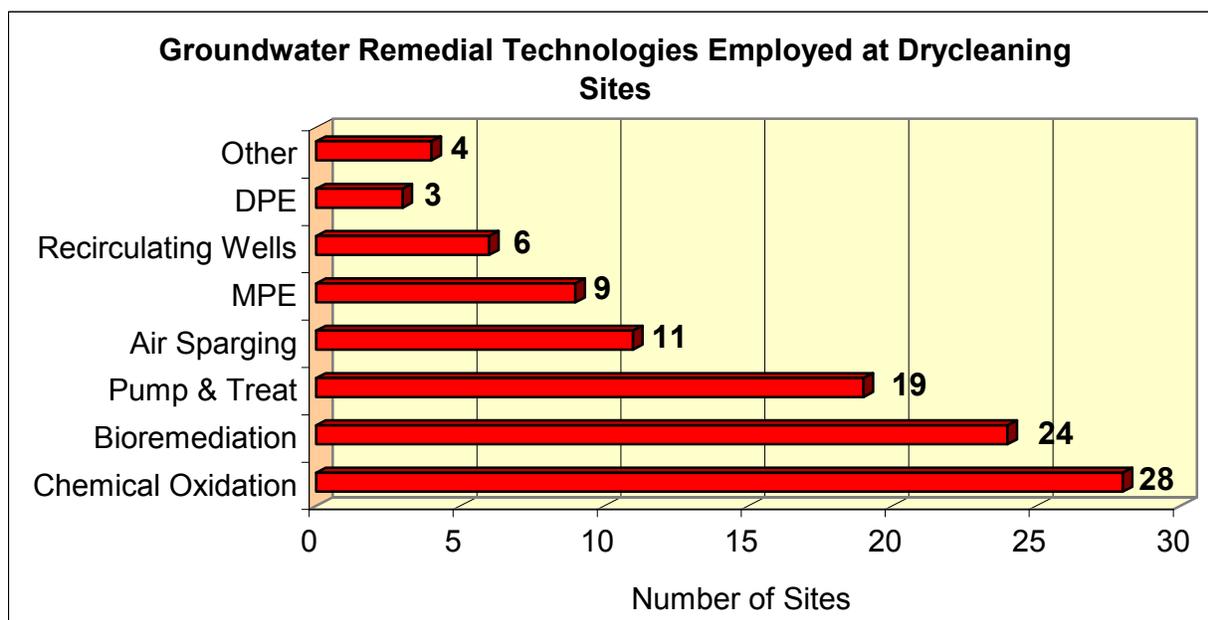
Bioremediation is the introduction of biostimulants or bioaugmentation products into the subsurface to stimulate the biological degradation of contaminants. Biostimulation is the primary bioremediation technology used in the unsaturated zone, but had limited use at study sites. Biostimulation has been attempted in the unsaturated zone at three of the study sites. Hydrogen Release Compound (HRC<sup>®</sup>) was injected via direct push into the unsaturated zone at a Texas drycleaning site. HRC<sup>®</sup> was mixed with rock backfill (1% by weight) to fill a soil excavation at the former Foreman's Cleaners site in Oregon. Bio-Rem H-10<sup>™</sup> was introduced into the unsaturated zone via trenches and also injected into the groundwater via injection wells at the Carousel Cleaners site in Oregon.

### **7.5 Other Technologies - Soil**

Other technologies have been used to remediate contaminated soil at drycleaning sites in the data set. A zero-valent iron soil mixing pilot test was performed at the former location of a drycleaning facility in Camp Lejeune, North Carolina. A Wisconsin drycleaning site utilized a Mobile Injection Treatment Unit (MITU), which used a chain trencher to break up and pulverize the soil and air heated up to 700 F was forced into the trench and across the soil particles to volatilize the VOCs. New technologies or variations of technologies are likely to bring new approaches to the often difficult unsaturated zone remediation. Trial and error at the contaminated sites will hopefully lead to efficient soil remediation alternatives.

## 8 Groundwater Remediation

Groundwater remediation has been conducted at eighty-seven (75%) of the sites in the data set. Both conventional and innovative remedial technologies have been employed. Conventional groundwater remedial technologies employed at drycleaning sites include groundwater recovery (pump & treat) at eighteen sites, air sparging at eleven sites, and multi-phase extraction at thirteen sites. The “innovative” groundwater remedial technologies employed at drycleaning sites include: recirculating wells (in-well sparging) at six sites, chemical oxidation at twenty-seven sites, bioremediation at twenty-six sites, co-solvent/surfactant flushing at two sites, co-oxidation (combination of co-solvent flushing and chemical oxidation) at one site and a permeable reactive barrier (zero valent iron) at another site.



It is notable that less than half (48.2%) of the groundwater remedial systems installed at study sites are conventional remedial technologies, as previously defined. The trend over the last ten years has been toward the use of in-situ remedial technologies, particularly bioremediation and chemical oxidation. The shift to in-situ remedial technologies has reduced periodic operation and maintenance costs. This includes electrical costs associated with pumping and treating groundwater and maintenance costs associated with fouling, scaling and mechanical repairs. Bioremediation and chemical oxidation account for over sixty percent of the groundwater remedial systems employed at study sites. It is also notable that chemical oxidation and bioremediation were used at over 73% of the sites that have been closed where groundwater remediation was performed.

### 8.1 *Pump & Treat*

Pump and treat technology has widely been criticized over the years as being inefficient and too expensive, especially when considering long term O&M costs. Many recent pump and treat designs are used to hydraulically contain contaminant plumes or to help distribute oxidants and amendments through the aquifer. Hydraulic containment is mandatory at times when a plume is still migrating and the system must protect a sensitive receptor, such as public water supply or

industrial wells. Pump and treat is commonly used with granular activated carbon vessels or air stripper systems (packed towers, tray strippers, or hydraulic venturi units) to treat the water.

Pump and treat remedial systems have been employed at seventeen of the study sites. Pump and treat was the exclusive groundwater remedial technology at nine of the sites and part of a treatment train approach at eight sites. Other groundwater remedial technologies that have been used in conjunction with pump and treat sites include: chemical oxidation - 3 sites, biostimulation - 4 sites, and air sparging - 2 sites. A pump and treat system was used to circulate carbon amendments, such as ethyl lactate at two Florida sites (Sixty Minute Cleaners and Village Green Shopping Center) and dextrose at an Oregon drycleaning site. A pump and treat system at the former One Stop Cleaners site in Florida was used for hydraulic containment and to facilitate distribution of a potassium permanganate. Pump and treat was utilized at only one of the thirty-seven study sites that have been closed.

## **8.2 Multi-Phase Extraction**

(MPE) is the second most common type conventional groundwater remedial system employed at study sites (thirteen sites). MPE involves the removal of multiple media phases such as vapor and water in a combined system. MPE was used as the exclusive groundwater remedy at only four of the study sites. Other remedial technologies used at MPE sites were: biostimulation, air sparging and chemical oxidation.

The number of recovery wells employed in the MPE systems ranged from one to thirteen. The average number of MPE wells utilized at a site was 7.6 and the median number of wells was nine. MPE was not used at any of the study sites that have been closed.

## **8.3 Air Sparging**

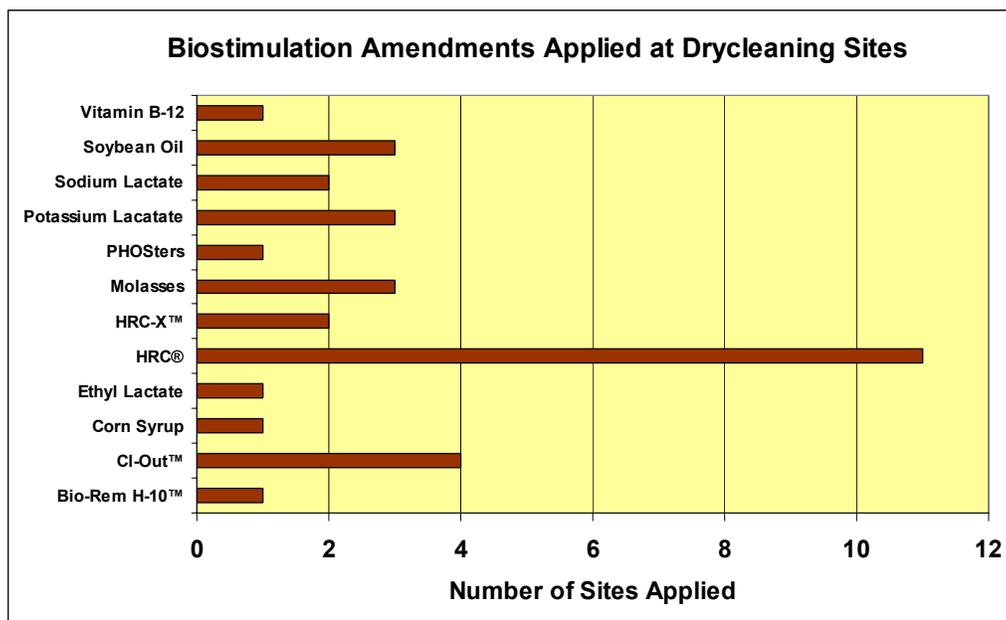
Air sparge technology involves the injection of air into the saturated zone to transfer dissolved-phase contaminants from the groundwater to a vapor form and then subsequent removal via a SVE system. Air sparge technology was utilized at eight of the study sites. The number of sparge wells employed varied from two to six. Typical sparge rates were from two to ten cubic feet per minute per sparge point. Only one of the thirty-seven sites in the study that closed used air sparging as a groundwater remedy.

Recirculating wells (in-well sparging) were used as a groundwater remedial technology at six study sites. In this technology, contaminated groundwater enters the well through a screen in the lower portion of the well and discharges to the aquifer through an upper screen. In the case of the recirculating wells in the study, the water is treated within the well by air sparging. Volatile organic vapors stripped from the contaminated groundwater were routed to a carbon treatment unit. The number of recirculation wells utilized in study sites varied from one to eleven. A Rhode Island drycleaning site was able to achieve closure using this technology in conjunction with soil vapor extraction.

## **8.4 Bioremediation**

Bioremediation in the saturated zone is the introduction of biostimulants or bioaugmentation products into the groundwater to stimulate the biological degradation of contaminants. Bioremediation has become a very common groundwater remedial technology utilized at

drycleaning sites. A wide variety of amendments have been utilized at the study sites to stimulate biodegradation including: soybean oil, sodium lactate, molasses, ethyl lactate, potassium lactate, corn syrup, vegetable oil, dextrose (CI-Out™), tri-ethyl phosphate (PHOSter's process), polylactate esters (HRC® and HRC-X™), and vitamin B-12. Bioaugmentation is the injection of specific strain(s) of bacteria to enhance the bioremediation process and was implemented at five of the sites using Pseudomonas, Bio-Rem H-10™, and Bio-Dechlor Inoculum™.



The number of injection events conducted at bioremediation sites varied from one to nine. Note, though, that many of the site profiles for sites with a bioremediation remedy were submitted after the first injection event and multiple injections will likely be required at most sites to complete the remediation of the sites. Based on the data set available at the time this paper was written, multiple injection events occurred at twelve of the twenty-seven sites. The quantities of amendments injected were reported in either pounds or gallons (concentrations not always specified). Quantities of amendments injected ranged from 39 gallons to over 25,000 pounds.

Amendments were introduced into the aquifer using a variety of methods including: injection wells (8 sites), direct push technology (8 sites), combination of injection wells and direct push (5 sites), open excavation and injection wells (2 sites), open excavation (1 site), injected into open borehole using a packer (1) site, direct push and infiltration gallery (1 site) and via sparging (PHOSter's process – biosparging using tri-ethyl phosphate and nitrous oxide (1 site). Three of the sites used recirculation systems in an attempt to obtain better distribution of amendments in the contaminated aquifer. The amendments were injected either in or immediately hydraulically upgradient of the contaminant source area and recovery wells were located hydraulically downgradient of the source area.

Of the thirty-seven drycleaning sites that have been closed, nine (23.7%) used bioremediation as a groundwater remedy. The amendments utilized at the closed sites include: Bio-Rem™, potassium lactate, molasses, and HRC®.

## 8.5 Chemical Oxidation

Chemical oxidation is the introduction of chemical oxidants into the groundwater to transform contaminants into less harmful constituents. Chemical oxidation was used to remediate contaminated aquifers at twenty-seven of the study sites. The following oxidants have been utilized at study sites: potassium permanganate (6 sites), sodium permanganate (5 sites), Fenton's Reagent (9 sites), hydrogen peroxide (1 site), and ozone (6 sites). Injection of potassium permanganate followed by Fenton's Reagent in a treatment train approach was utilized at one of the drycleaning sites. Oxidants were delivered using the following methods: injection wells (9 sites), direct push technology (8 sites), injection wells and direct push (3 sites), and ozone sparge wells (6 sites).

The number of injection events ranged from one to six. The number of injection wells/points ranged from as few as two as many as sixty-four. Ozone sparging was a continuous operation at the sites where it was employed. The number of ozone sparge points ranged from three to as many as twenty-eight. The ranges of the concentrations of chemical oxidants injected were as follows:

- Fenton's Reagent (H<sub>2</sub>O<sub>2</sub>): 1% to 35%
- Potassium Permanganate 0.5 to 10%
- Sodium Permanganate 4% to 10%

The volumes of oxidants injected were reported in either gallons of solution or pounds of oxidant. Total injection volumes of chemical oxidants ranged from as little as 1,057 gallons of a 1% hydrogen peroxide solution used to polish low contaminant concentrations, to as much as 64,000 pounds of potassium permanganate. Chemical oxidants were injected into both the unsaturated zone and saturated zone at four sites. Two of the study sites that were closed used the potassium permanganate and Fenton's Reagent to remediate contaminated groundwater.

## 8.6 Other Technologies

Another innovative technology used to remediate groundwater at study sites included: Co-solvent/surfactant flushing. Ethanol was used as the co-solvent at the former Sages Drycleaners site in Florida. There were two injection events and recovered groundwater was treated using a polymer filter system. The former drycleaning and laundry center at Camp Lejeune in North Carolina remediation approach used custom surfactant and isopropanol in a Surfactant-enhanced Aquifer Remediation (SEAR) process. The presence of DNAPL had been documented at both the Florida and the North Carolina site.

A "co-oxidation" pilot test was run at Butler Cleaners in Florida. The co-solvent, tert butyl alcohol was mixed with a solution of potassium permanganate and then was heated prior to injection to increase the mass transfer rate of the DNAPL to the aqueous phase to allow for rapid oxidation of the PCE.

A 200-foot long permeable reactive barrier, using iron filings, was installed at the former Finger Lakes Laundry & Cleaners site in New York.

## 9 Drycleaning Site Closures

Thirty-seven of the sites in the data set have been closed. These sites are located in the following states: Colorado, Florida, Kansas, Minnesota, Missouri, Oregon, Rhode Island, Texas, and Wisconsin. Thirteen of the thirty-seven closure were conditional requiring engineering and/or institutional controls. The types of cleanup programs under which sites were closed follow:

- State-Lead Cleanup Programs      19 sites
- State Reimbursement Programs      7 sites
- Voluntary Cleanup Programs      9 sites
- Other State Programs:              1 site
- Unknown                                  1 site

Soil (unsaturated zone) remediation was conducted at all but 5 of these sites. Technologies utilized to remediate contaminated soil, sediment and/or sludge at the sites that were closed included:

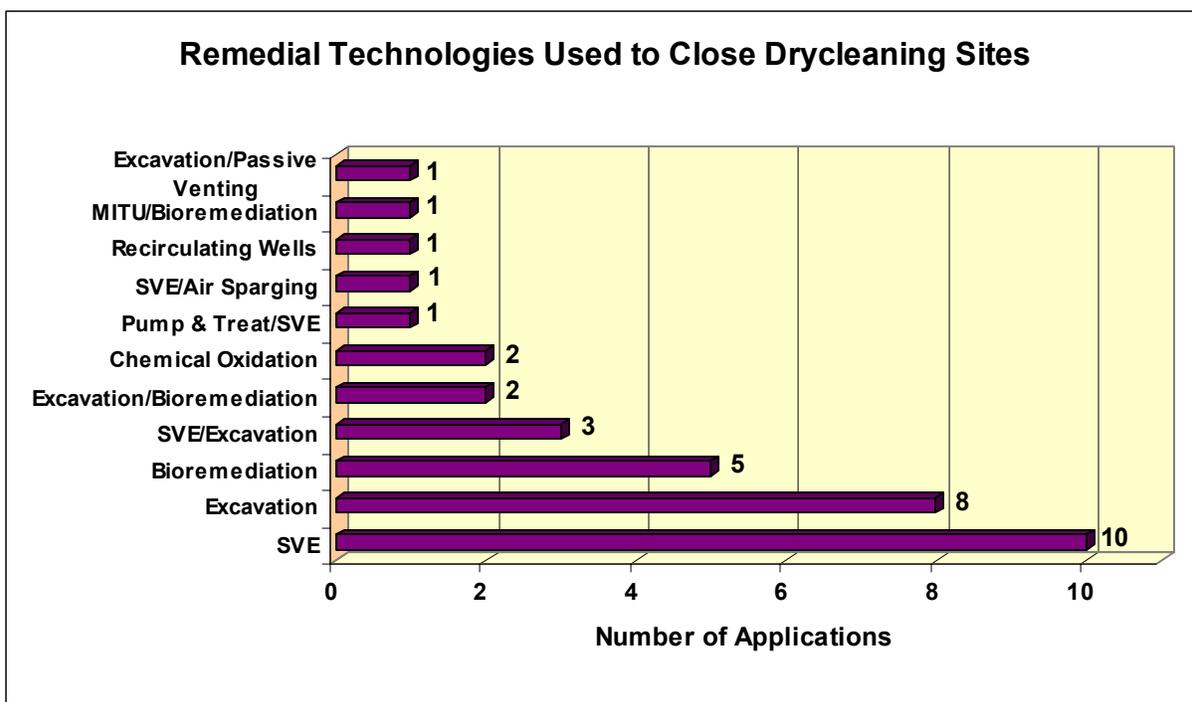
- Soil Vapor Extraction      17 sites
- Excavation/Removal      15 sites
- Bioremediation                      1 site
- Mobile Injection Treatment Unit      1 site

A combination of two or more remedial technologies, such as excavation and soil vapor extraction were conducted at some of these sites. Twenty-three of the sites (62.1%) of the sites were closed solely through soil remediation.

Groundwater remediation was conducted at fifteen of the thirty-seven sites that have been closed (40.5% of the closed sites). Groundwater remedial technologies utilized to close sites include:

- Bioremediation - potassium lactate, HRC, & molasses      9 sites
- Chemical Oxidation - potassium permanganate, Fenton's Reagent      2 sites
- Pump & treat                                  2 sites
- Air Sparging                                  1 site
- Recirculating Well                          1 site

Both soil and groundwater remediation was conducted at ten (27%) of the thirty-seven sites that were closed. Three of the closed sites had presumptive evidence of DNAPL, based on the criterion of the presence of the parent solvent in groundwater in concentrations exceeding 10% of its aqueous solubility. These three sites are the Cypress Village Shopping Center in Missouri, Abe's Main Street Cleaners in Oregon and Cedarburg Cleaners in Wisconsin. All three of these sites were closed conditionally.

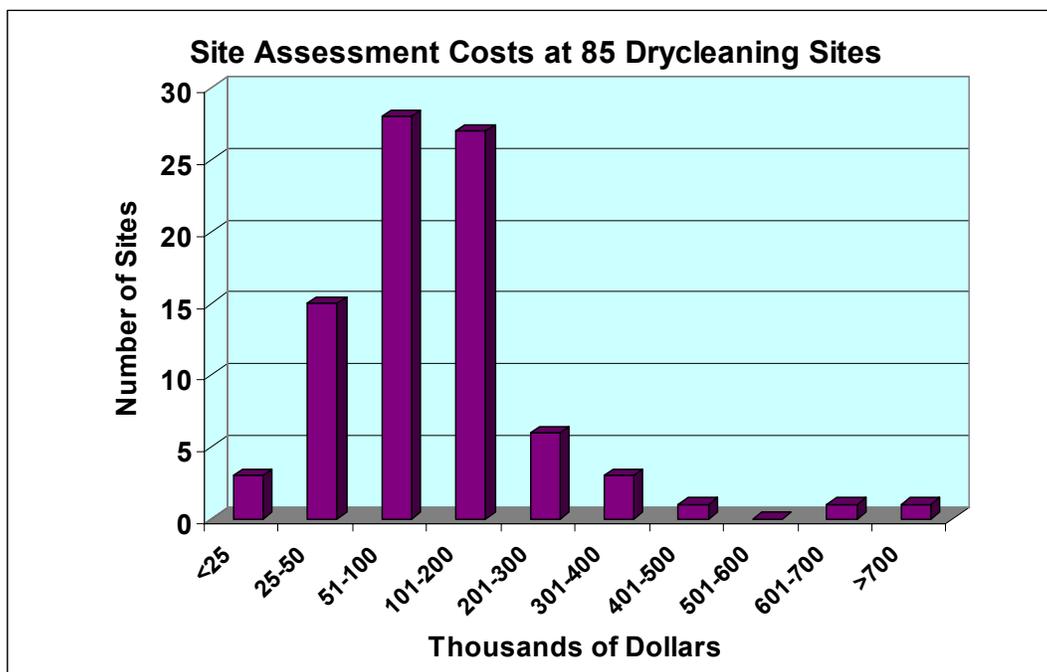


## 10 Cost Data

Available cost data for the 116-site data set is limited. Most of the cost data presented is from the state-lead cleanup programs sites. Cost data for voluntary cleanup sites and even for federal sites is difficult to obtain. Another problem with tracking and comparing assessment and remedial costs at these sites is the variability of how costs are allocated or assigned by the various states. For example, at many sites, the cost of monitor well installations is included in site assessment costs, whereas at other sites these costs are included under remediation. Costs for assessment work completed prior to the drycleaning solvent cleanup work are generally not included in any of the cost data. At some of these sites, data collected for remedial design and studies conducted to review remedial alternatives are included under site assessment costs. Comprehensive cost data is available for only twenty-eight of the thirty-seven the sites in the data set that have been closed.

### 10.1 **Site Assessment**

Site assessment costs were available for 89 of the 116 sites. Of the 89 site profiles, cost data from eighty-five sites was deemed reliable. These sites are located in nine states: Florida, Illinois, Kansas, Minnesota, New York, Oregon, South Carolina, Tennessee and Wisconsin. The sites represent a wide range of hydrogeological conditions, degree of contamination, and plume sizes and are believed to be generally representative of conditions found at contaminated drycleaning sites across the United States. Assessment costs ranged from \$21,300 to \$786,000. The average cost for a site assessment was \$127,700 and the median cost was \$92,100. Assessment work was conducted at some of these sites well over 10 years ago. The actual cost of site assessment work performed at comparable sites today will be higher.



## 10.2 Remediation

Remedial design and implementation costs were available for eighty-nine sites. Given that multiple remedial technologies were utilized at many sites (typically at least one soil remedial technology and one groundwater remedial technology) and that comprehensive cost data were not available for a number of sites, it is difficult to provide a meaningful cost breakdown for a particular technology. Comprehensive costs were available for ten sites where soil vapor extraction was used as the exclusive remedial technology. Following are average costs for these SVE systems:

### 10.2.1 SVE Remedial Costs

- Design & Implementation \$83,400
- Operation & Maintenance \$43,640
- Total Closure Cost (includes site assessment): \$183,510

Comprehensive cost data was also available for 8 sites where excavation/removal was used as the exclusive remedial technology. Following are average costs for these systems:

### 10.2.2 Excavation/Removal Costs

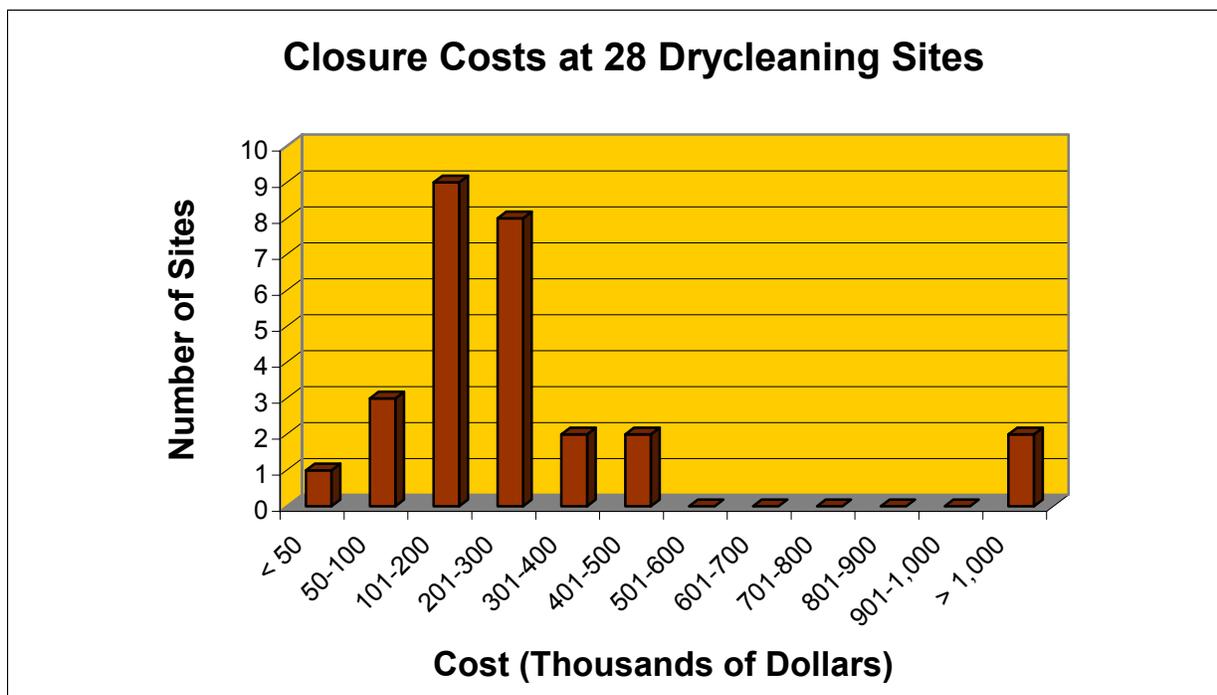
- Design & Implementation \$29,988
- Monitoring \$27,188
- Total Closure Cost (includes site assessment): \$124,850

### 10.2.3 Comprehensive Cleanup Costs

Comprehensive cleanup costs, including costs for assessment, remedial design/installation, monitoring and operation/maintenance were available for only 28 of the 116 sites in the data set. Total cleanup costs for these sites ranged from \$46,200 to \$1,662,000. The average cleanup cost was \$216,900 and the median cleanup cost was \$202,000. Of the twenty-eight sites soil-only

remediation was conducted at twenty sites, two of these sites only had groundwater remediation and six sites conducted both soil and groundwater remediation.

These comprehensive cleanup costs were derived from a small number of drycleaning sites where remediation has been completed. Highly contaminated drycleaning sites will require remediation of both soil and groundwater. Depending on a state’s cleanup target levels and closure procedures, remediation may not be completed for many years. Remediation costs at the highly contaminated sites will generally be far higher than the average cleanup costs presented in this paper. The cleanup costs presented here mostly represent low-end cleanup costs for sites that can be closed with limited soil/groundwater contamination.



## 11 Conclusion

In summary, this comparison of the site profile data reveals remediation of drycleaning solvent-contaminated sites can be achieved using traditional or innovative technologies, and often is a combination of technologies. One single technology cannot work at every site. The technology selection process is driven by a variety of technical and programmatic factors, such as: physical site limitations, cost, desired cleanup time, risk-based determinations and expertise of remedial design staff or consultants. The remedial engineer must thoroughly evaluate these issues prior to choosing the cleanup approach. Consultants are constantly evaluating and changing the use of technologies to better fit their individual sites. The use of multiple technologies in a treatment train remediation approach can be a good method to tailor a technology to specific site conditions. Information regarding the site profiles in the data set, as well as newly added site profiles can be found on the SCRD Web Page at [www.drycleancoalition.org](http://www.drycleancoalition.org).

## **12 Acknowledgements**

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