ground water

Review Paper/

Remediation of the Wells G & H Superfund Site, Woburn, Massachusetts

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Abstract/

Remediation of ground water and soil contamination at the Wells G & H Superfund Site, Woburn, Massachusetts, uses technologies that reflect differences in hydrogeologic settings, concentrations of volatile organic compounds (VOCs), and costs of treatment. The poorly permeable glacial materials that overlie fractured bedrock at the W.R. Grace property necessitate use of closely spaced recovery wells. Contaminated ground water is treated with hydrogen peroxide and ultraviolet (UV) oxidation. At UniFirst, a deep well completed in fractured bedrock removes contaminated ground water, which is treated by hydrogen peroxide, UV oxidation, and granular activated carbon (GAC). The remediation system at Wildwood integrates air sparging, soil-vapor extraction, and ground water pumping. Air stripping and GAC are used to treat contaminated water; GAC is used to treat contaminated air. New England Plastics (NEP) uses air sparging and soil-vapor extraction to remove VOCs from the unsaturated zone and shallow ground water. Contaminated air and water are treated using separate GAC systems. After nine years of operation at W.R. Grace and UniFirst, 30 and 786 kg, respectively, of VOCs have been removed. In three years of operation, 866 kg of VOCs have been removed at Wildwood. In 15 months of operation, 36 kg of VOCs were removed at NEP. Characterization work continues at the Olympia Nominee Trust, Whitney Barrel, Murphy Waste Oil, and Aberjona Auto Parts properties. Risk assessments are being finalized that address heavy metals in the floodplain sediments along the Aberjona River that are mobilized from the Industri-Plex Superfund Site located a few miles upstream.

Introduction

The Wells G & H Superfund Site in Woburn, Massachusetts, has been in the scientific spotlight since publication of the award-winning book *A Civil Action* (Harr 1995). The book and the movie based on it (Touchstone Pictures 1998) describe the legal battle between eight families in east Woburn, who filed suit in 1982, and two Fortune 500 companies that operated a tannery (Beatrice Foods Inc.) and a manufacturing facility (W.R. Grace & Co.). The plaintiffs alleged that mishandled and improperly disposed of toxic chemicals entered the ground water flow system on the defendants' properties, were captured by municipal wells G and H, and prolonged ingestion of the toxic chemicals led to severe health problems including leukemia. The plaintiffs comprised seven families in which a child contracted leukemia and one family in which an adult contracted the disease. The defendants included Beatrice Foods, owner of the former John J. Riley Leather Co. at the corner of Wildwood Avenue and Salem Street, and W.R. Grace & Co., owner of the Cryovac Plant on Washington Street that manufactured food-processing equipment (Figure 1). UniFirst Corp., owner of an industrial dry-cleaning plant on Olympia Avenue (Figure 1), was enjoined in the lawsuit in April 1985 and settled out of court the following October. The now-famous federal trial began in March 1986 and ended nearly five months later in July. The jury found W.R. Grace liable and Beatrice not liable of contaminating municipal wells G and H. In September, W.R. Grace and the plaintiffs reached a settlement for $8 million after the judge announced his intent to declare a mistrial based on motions filed by W.R. Grace.

Because of the keen interest in the book and movie among ground water professionals and faculty in a variety of academic programs, we thought it would be of general interest to compile and present technical materials not in the book or movie. In this review paper, we describe (1) the technologies being used to clean up contamination at the

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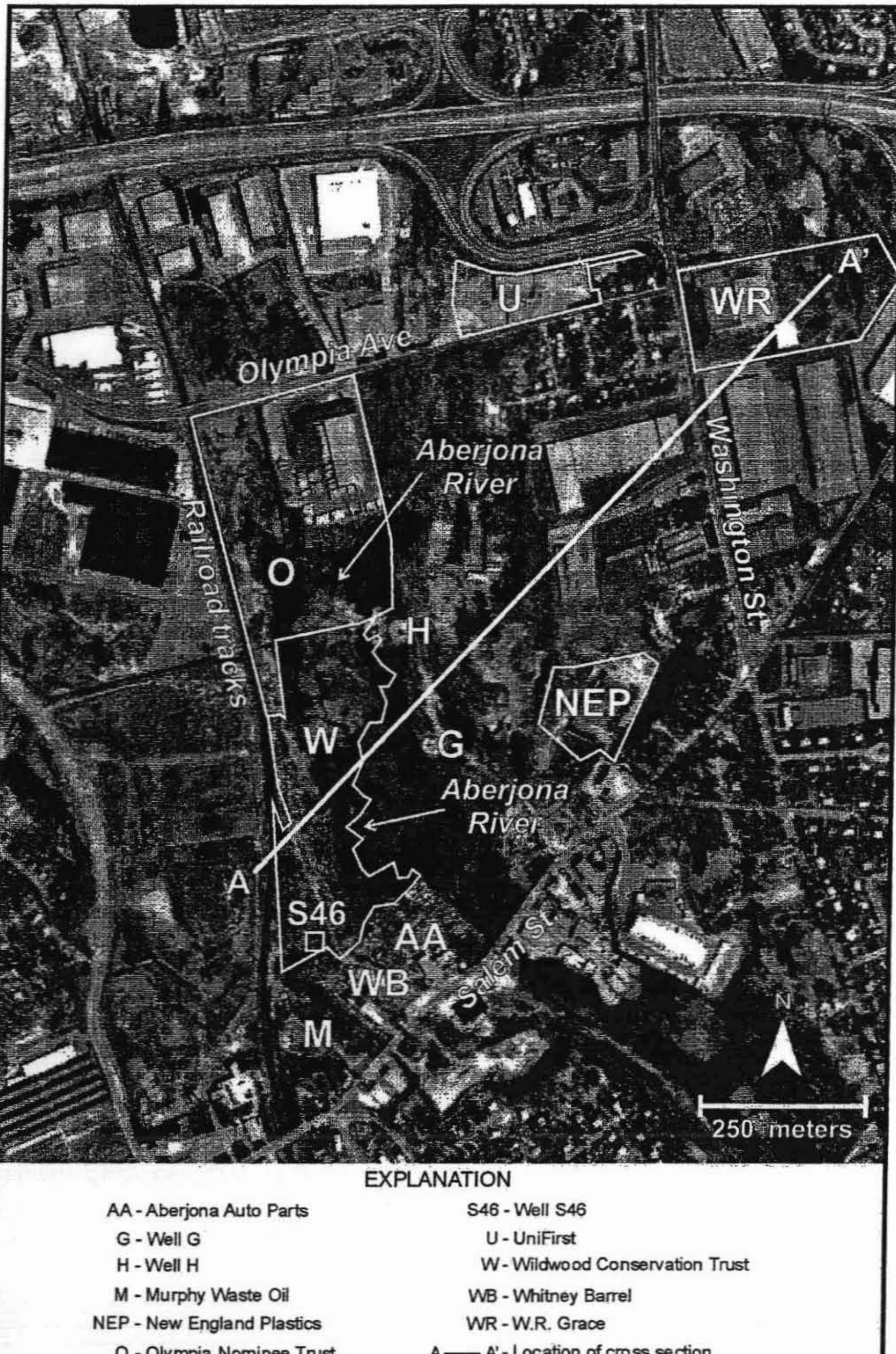

Figure 1. 1978 aerial photograph showing streets, properties of responsible parties, the Aberjona River and wetland.

Wells G & H Superfund Site, (2) differences in the geology and hydrology across the site that influenced the selection of these technologies, (3) the amounts of volatile organic compounds recovered, (4) if made available to us, the costs of various remediation activities, and (5) the status of continuing characterization and risk studies at the site. We integrated much of this information from reports and design plans submitted to the U.S. Environmental Protection Agency (U.S. EPA) Region I by the contractors hired by the responsible parties and by U.S. EPA. Other information is based on ground water flow and contaminant transport work that we have performed at the site.

Background

In December 1982, U.S. EPA added the Wells G & H Site to its list of priority sites eligible for cleanup under the 1980 federal Superfund legislation. The site includes 130 hectares (ha) straddling the Aberjona River (Figure 1). Ground water beneath the site contained high concentrations of trichloroethene (TCE), 1,2-dichloroethene (1,2-

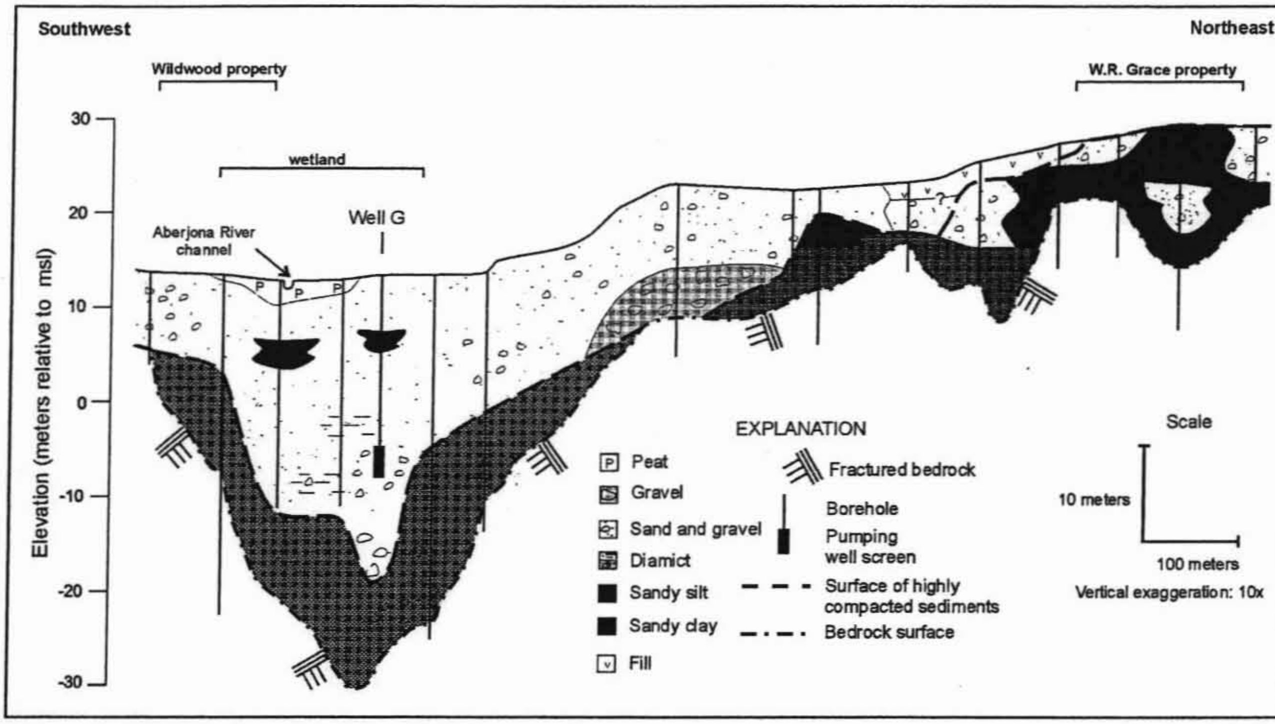

Figure 2. Geologic cross section along line A–A′ in Figure 1 (after Metheny 1998).

DCE), tetrachloroethene (PCE), and other volatile organic compounds (VOCs). Soils at the site contained VOCs, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), pesticides, and high concentrations of lead, chromium, zinc, mercury, and arsenic (U.S. EPA 1993).

This news added to the anxiety of residents in east Woburn, who months earlier learned that the 100 ha Industri-Plex Site, located <2 km upstream of wells G and H, was put on the Superfund priority list. From 1853 to 1931, companies that manufactured arsenic-based insecticides, sulfuric acid, phenols, TNT, and chemicals for the leather-tanning industry occupied this area of Woburn. From 1927 to 1968, the site was used to manufacture glue and grease from raw and chromium-tanned animal hides (Davis et al. 1994). Environmental concerns at the Industri-Plex Site were the erosion and transport of sediments containing arsenic, chromium, and lead from abandoned waste lagoons, migration of heavy metals and VOCs in ground water, and the stench of hydrogen sulfide produced by tons of rotting animal hides (Roux Associates 1991, 1992; Davis et al. 1994; Aurilio et al. 1994; Spliethoff and Hemond 1996).

In 1991, after several years of characterization studies, U.S. EPA negotiated a settlement with four parties to pay for the cleanup of the Wells G & H Superfund Site: Wildwood Conservation Corp., which purchased the 6 ha Riley property from Beatrice Foods, UniFirst, W.R. Grace, and New England Plastics. Of the total estimated settlement costs of $70 million, $58.4 million was for cleanup operations, $6.4 million for EPA monitoring of the cleanup activities, $2.65 million for reimbursement of EPA's incurred investigation costs, and the remainder for performing additional studies (U.S. EPA 1993). Settlement with a fifth party, Olympia Nominee Trust, remains under negotiation.

Beatrice Foods, with oversight from U.S. EPA, is conducting characterization studies at three other properties: Aberjona Auto Parts, Murphy Waste Oil, and the former Whitney Barrel Co., on the north side of Salem Street, just south of the Wildwood property and across the river from well G (Figure 1). Subsequently, U.S. EPA will perform risk assessments on these properties (Garren 2002).

Under the federal remediation plan, the Superfund site was divided into three operable units. The cleanup operations at the five responsible parties are collectively called Operable Unit #1. The Aberjona River and its riparian wetland comprise Operable Unit #3. All other areas of contamination within the site are designated Operable Unit #2, which is also known as the "Central Area." The primary objectives of the cleanup operations are to remove the contaminant sources and to prevent off-site migration. The technologies used to accomplish these objectives differ depending on the contaminants present, geologic conditions, permeabilities, depth to ground water, and proximity to surface water.

Geologic Settings

The central and western portions of the Wells G & H Site overlie a buried bedrock valley partially filled with heterogeneous, discontinuous layers and lenses of glaciofluvial and glaciolacustrine sediments that are overlain by modern floodplain and wetland deposits. The eastern portion of the Wells G & H Site overlies a bedrock upland on which till was deposited. The composition of the bedrock varies across the site. The eastern portion of the site near the W.R. Grace property is underlain by slightly to moderately fractured granodiorite, whereas the western and northern portions of the site near the Olympia and Wildwood properties are underlain by moderately to highly fractured gabbrodiorite (Ecology and Environment 1982). Schist is observed in some core samples and probably represents foliation along shear zones within the gabbrodiorite (Ecology and Environment 1982).

The buried bedrock valley has the shape of a bowl elongated in a north-south direction. Bedrock is deepest under the center of the present valley at depths of 42 to 45 m. The depth to bedrock decreases along the eastern and western margins of the area. Bedrock occurs at depths of 6 to 20 m under the W.R. Grace property and at depths of 9 to 24 m under the 6 ha Wildwood property. At Olympia, bedrock occurs at a depth of ~30 m. Outcrops of the granodiorite and the gabbrodiorite can be found within several hundred meters east and west of the site.

Figure 2 is a southwest-northeast geologic cross section that extends from the Wildwood property, across the wetland, through well G, to the W.R. Grace property (along line A-A′ in Figure 1). This figure shows the shape of the bedrock surface and a simplified depiction of the sediments deposited in the buried valley and on the bedrock upland. A discontinuous layer of highly compacted sediments, remnants from a Wisconsinan glacial advance (Chute 1959), occurs along the bottom and the margins of the bedrock valley. Blow counts of split-spoon samples taken in these materials typically range from 50 to 120 per 15 cm of penetration, whereas in the overlying loose materials deposited by a subsequent glacial retreat, blow counts typically range from 20 to 50 per 15 cm of penetration (Metheny 1998).

The lithologies of the loose materials and the highly compacted materials vary laterally and vertically (Figure 2). The W.R. Grace property is underlain by highly compacted sandy silt and silty sand with some gravelly sand, which together range in thickness from 6 to 20 m. Under the UniFirst property, the highly compacted silty sand and diamict thicken rapidly to the west as the bedrock surface becomes deeper. At the Wildwood property, between 1.5 and 18 m of loose material overlie up to 12 m of highly compacted, discontinuous layers of diamict, and sand and gravel, which cover the bedrock surface (Metheny 1998). The loose materials are composed of discontinuous lenses of silty sand, sand, diamict, and sandy gravel that are 1 to 6 m thick. Highly compacted sediments occur in a few boreholes at New England Plastics, which is underlain by 2 to 11 m of loose sand and gravel with some silt.

Contamination and Remediation: Operable Unit #1

Some or all of the VOCs described previously occur in the ground water at each of the five responsible parties. Cleanup of VOC-contaminated ground water, VOC-contaminated soil, and mixed contaminated soils on the properties of four of the responsible parties is under way. The remediation systems at UniFirst and W.R. Grace began operation in late 1992. Those at New England Plastics and Wildwood became operational early in 1998.

W.R. Grace & Co.

Characterization studies performed in 1985 showed that concentrations of TCE and 1,2-DCE at W.R. Grace

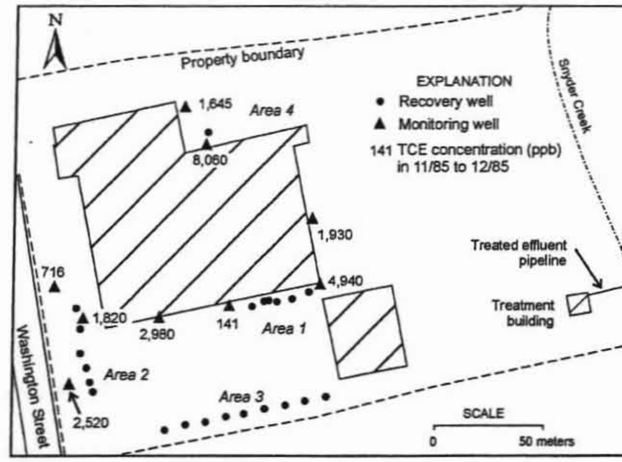

Figure 3. Design of the extraction well network at W.R. Grace and concentrations of TCE measured in late 1985 (after GeoTrans Inc. 1995).

varied considerably across the 4 ha property. As shown in Figure 3, the highest concentrations measured in 1985 occur in two areas, one on the south side of the main building (Area 1) and another on the north side (Area 4). In these areas, TCE concentrations exceeding 8000 μg/L and 1,2-DCE concentrations exceeding 12,000 μg/L were found. Elsewhere on the property concentrations of TCE and 1,2-DCE are lower, in the range of hundreds to several thousand micrograms per liter. Vinyl chloride (VC) also occurs under the W.R. Grace property. In 1985, VC concentrations typically ranged from hundreds to several thousand micrograms per liter. W.R. Grace estimates ~380 L of TCE were dumped on the land surface, most in small aliquots outside the back doors at the north and south ends of the plant (Johns 2000). Lesser concentrations of TCE were found in monitoring wells drilled near a pit in the back of the property where six 210 L drums were buried. Both (*cis*) 1,2-DCE and VC found in ground water at W.R. Grace occur from the dehalogenation of TCE.

The soils developed on the highly compacted glacial deposits on the W.R. Grace property are poorly drained. The property, which is ~30 m higher than the wetland in the Aberjona River valley, was used for agricultural production prior to 1960 and contains two west-to-east agricultural drains that lowered the water table during wet periods. The water table is normally ~4 m below land surface and ground water flow across most of the property is to the west-southwest toward the Aberjona River valley. Slug tests indicate that the hydraulic conductivity of the highly compacted materials is low and typically ranges from 0.03 to 1.5 m/day (GeoTrans and ReTec 1994; GeoTrans 1995).

The remediation system recovers and treats contaminated ground water from the highly compacted materials and shallow, fractured bedrock. Because of the low permeability of the glacial deposits, extraction wells had to be placed close together. The 22 extraction wells are located in four areas, including the two major hot spots and along the western and southern borders of the property to prevent off-site migration (Figure 3). These wells generally range from 9 to 15 m deep. Twenty extraction wells have 6 m screens that straddle the interface between the highly compacted

Table 1
Summary of Ground Water Pumpage and VOC Removal at W.R. Grace[1,2]

Year of System Operation[3]	Treated Volume Ground Water (Liters Pumped)	VOC Mass Removed (kg)	VOC Volume Equivalent Removed (liters)	Removal Efficiency[4]
1993	16,294,000	8.26	5.91	0.36
1994	10,567,000	4.72	3.37	0.32
1995	9,986,000	3.72	2.65	0.27
1996	12,922,000	2.27	1.63	0.13
1997	17,562,000	1.54	1.10	0.06
1998	16,266,000	3.73	2.65	0.16
1999	9,921,000	1.75	1.25	0.13
2000	12,160,000	1.65	1.17	0.10
2001	12,380,000	2.28	1.67	0.13
Totals	**118,059,000**	**29.91**	**21.43**	

[1]HSI GeoTrans Inc. 2001
[2]Garren 2002
[3]Recorded from October 1, 1992, to September 30, 2001
[4]Liters of VOCs removed per million liters of water pumped

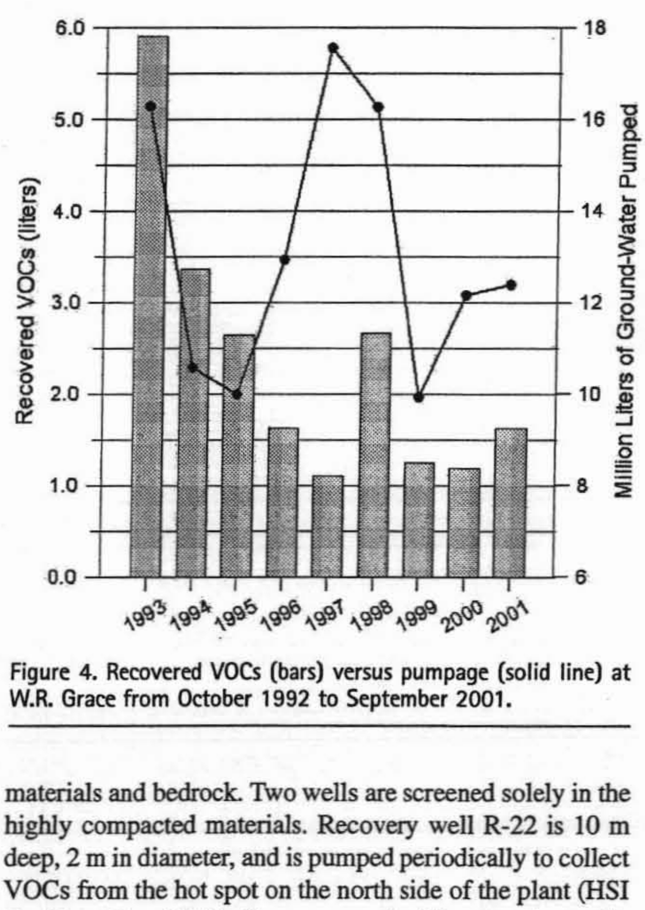

Figure 4. Recovered VOCs (bars) versus pumpage (solid line) at W.R. Grace from October 1992 to September 2001.

materials and bedrock. Two wells are screened solely in the highly compacted materials. Recovery well R-22 is 10 m deep, 2 m in diameter, and is pumped periodically to collect VOCs from the hot spot on the north side of the plant (HSI GeoTrans Inc. 2000). On average, the 22 extraction wells together produce ~23 to 30 L/min. A control unit in the water-treatment building operates the pneumatic pumps in the extraction wells (Figure 3). Deeper ground water flow in the fractured bedrock underlying the property is captured by a deep bedrock extraction well on the UniFirst property (GeoTrans 1995). An agreement between W.R. Grace and UniFirst covers the cost of treatment of deeper ground water flow to the UniFirst well. An unidentified source of VOCs exists just south of the W.R. Grace property (Geo Trans 1995).

In 1992, the first year of operation, influent VOCs contained 44% TCE, 42% 1,2-DCE, 8% PCE, and minor amounts of VC, 1,1-dichloroethene, and 1,1,1-trichloroethane (1,1,1-TCA). The average yearly influent VOC concentration has declined from 507 µg/L in the first year of operation to 205 µg/L in the ninth year of operation. Influent pumped by the extraction wells to the treatment system first passes through a bag filter. A solution of 50 mg/L hydrogen peroxide then is injected into the contaminated water before it is exposed to two 5000-watt UV lamps, configured in series, which destroy the VOCs. The treated water is filtered before release to Snyder Creek, a short distance to the east of the treatment building (Figure 3). No carbon polishing is done because the primary contaminants, TCE and 1,2-DCE, are strongly affected by UV oxidation. Because the ground water contains minor concentrations of dissolved iron and manganese, it is necessary to mechanically scour the surface of the glass sheaths protecting the UV lamps to prevent buildup of iron and manganese precipitates that decrease the effective intensity of the UV light. The renovated water meets U.S. EPA Record of Decision (ROD) cleanup levels for the site of <5 µg/L for TCE and PCE, and <70 µg/L for 1,2-DCE (Metcalf & Eddy Inc. 1998). In the first nine years of system operation, 30 kg of VOCs were removed from more than 118,059,000 L of ground water (Table 1 and Figure 4).

In late 1997, U.S. EPA permitted W.R. Grace to shut down the six extraction wells in Area 1, which together contributed ~20% of the flow to the treatment system but only a few percent of the contaminant load. This is the reason for the decrease in pumpage after the sixth year of operation (Table 1). In 2000, W.R. Grace petitioned U.S. EPA to replace the UV oxidation system with a GAC system because the concentration of influent VOCs became much lower than in 1992, when the original treatment system was designed. The carbon system is equally effective at removing VOCs at the lowered concentrations and costs less to operate and maintain. U.S. EPA is evaluating this request and a request to modify the sampling equipment and procedures.

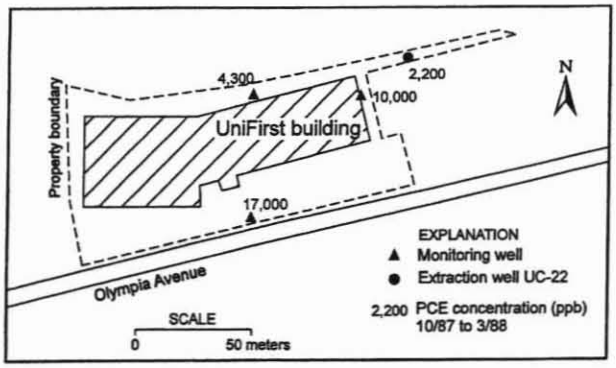

Figure 5. Location of recovery well UC-22 at UniFirst and concentrations of PCE measured in 1987-1988 (after GeoTrans Inc. and RETEC 1994).

The UV oxidation system cost $90,000. Construction of the pump-and-treat system, including the prefabricated building, cost $1.3 million. Each 5000-watt UV lamp costs $1700 and must be replaced every three months. Electricity costs about $2000 per month to operate the entire pump-and-treat system (Johns 1998).

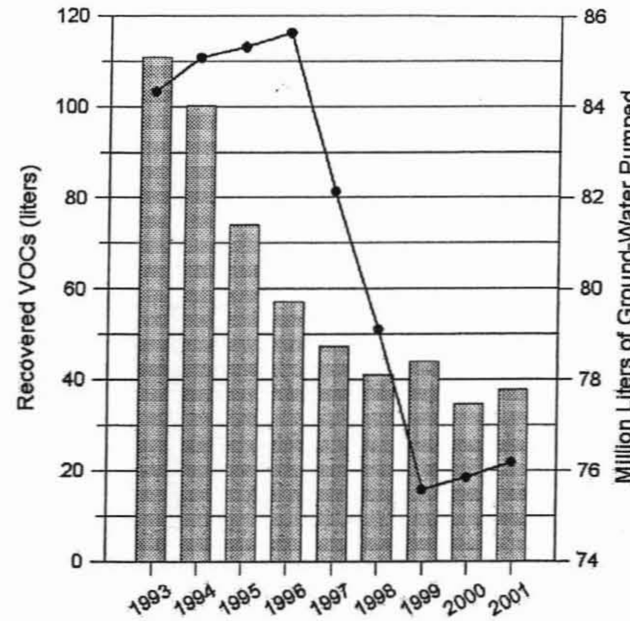

Figure 6. Recovered VOCs (bars) vs. pumpage (solid line) at UniFirst from October 1992 to September 2001.

UniFirst Corp.

UniFirst Corp., known as Interstate Uniform Service Corp. (IUS) prior to 1986, occupies a 1.2 ha site abutting Route 128 and Olympia Avenue (Figure 1). The original IUS building was constructed in 1965 with additions in 1966 and 1978. Historic aerial photographs show that the property was not used commercially prior to construction of the original building, although debris piles and small excavations are evident, particularly during construction of Route 128 in 1954 and its widening in 1961-62. Aerial photographs from 1964 reveal a soil-stained area extending from the northeastern corner of the IUS property near the highway on-ramp and off-ramp embankments, where Massachusetts Department of Public Works records indicate construction debris was placed, to the south and west toward Olympia Avenue (ENSR Consulting & Engineering 1993). Between 1977 and 1982, IUS maintained a 190,000 L indoor storage tank at the east end of the building that was used to store PCE. In late 1979, a PCE spill of ~380 L occurred inside the building and was cleaned up by employees. The fill pipe for the indoor PCE tank was located at a nearby outside loading dock. The asphalt under the fill pipe was scarred from PCE spilled during transfer of the solvent. The PCE tank was removed in late 1982 or early 1983 (ENSR Consulting & Engineering 1993). UniFirst ceased operations on the property in 1989. Concentrations of PCE measured in monitoring wells in late 1987 and early 1988 ranged from 2200 to 17,000 μg/L (Figure 5).

The thickness of the glacial materials varies across the UniFirst site. At the eastern end, bedrock is only a few meters below land surface and lithologic logs indicate that much of the material above bedrock is engineered fill, whereas at the western end the glacial materials attain a thickness of 22 m. The glacial deposits are generally composed of a layer of loose ablation till, which is underlain by highly compacted materials that lie directly on bedrock. Fractured granodiorite and gabbrodiorite underlie the property. Fractures in shallow excavations appear weathered and bedrock becomes more competent with depth. The unconsolidated deposits and fill beneath the eastern end of the property remain unsaturated throughout the year. The water table in the glacial deposits underlying the site varies from 3 to 4 m below land surface. The general direction of shallow ground water flow in the glacial deposits is to the southwest toward the Aberjona River (ENSR Consulting & Engineering 1993).

UniFirst and W.R. Grace operate separate treatment systems, but operate an integrated ground water pumping system because the extraction well at UniFirst captures deep flow in the fractured bedrock from the W.R. Grace site. At UniFirst, UC-22, a 58 m deep extraction well completed as an open borehole through 53 m of fractured bedrock, produces 130 to 170 L/min of contaminated water containing PCE, TCE, and minor amounts of other VOCs. During test pumping of UC-22, water levels declined in several of the bedrock monitoring wells at W.R. Grace. Subsequent testing showed that the contributing area of UC-22 extends beyond the UniFirst and W.R. Grace properties and UC-22 captures VOCs emanating from the W.R. Grace property flowing in fractured bedrock (Harvard Project Services 2000).

Over the nine years of pumping, PCE and TCE compose approximately 95% and 5%, respectively, of the VOCs in the influent water, with minor amounts of 1,1-dichlorothene, 1,2-DCE, and 1,1,1-TCA. Influent concentrations of PCE and TCE have declined from more than 2500 and 130 μg/L, respectively, in the first year of operation, to less than 500 and 30 μg/L, respectively, in the eighth year (Harvard Project Services 2000). Much of the TCE is likely from flow in the deeper bedrock at the W.R. Grace site or from dehalogenation of PCE.

The water-treatment system at UniFirst is similar to that at W.R. Grace. After filtering, hydrogen peroxide is

Table 2
Summary of Ground Water Pumpage and VOC Removal at UniFirst[1,2]

Year of System Operation[3]	Treated Volume Ground Water (liters pumped)	VOC Mass Removed (kg)	VOC Volume Equivalent Removed (liters)	Removal Efficiency[4]
1993	84,339,000	159.26	110.76	1.31
1994	85,096,000	143.88	100.05	1.18
1995	85,323,000	106.41	74.00	0.87
1996	85,626,000	82.15	57.12	0.67
1997	82,143,000	67.95	47.24	0.58
1998	79,115,000	58.97	41.00	0.52
1999	75,595,000	63.14	43.91	0.58
2000	75,860,000	49.67	34.56	0.46
2001	76,200,000	54.11	37.63	0.49
Totals	**729,297,000**	**785.53**	**546.23**	

[1]Harvard Project Services 2000
[2]Garren 2002
[3]Recorded from October 1, 1992 to September 30, 2001
[4]Liters of VOCs removed per million liters of water pumped

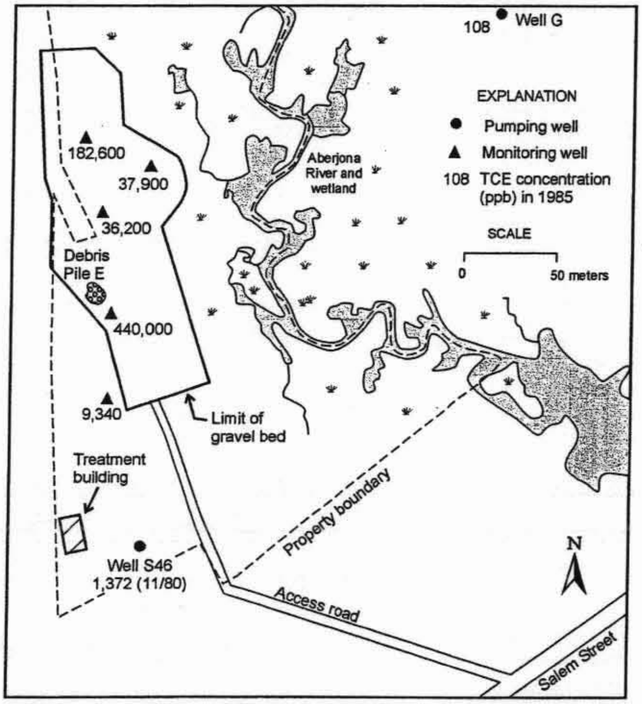

Figure 7. Locations of treatment building, well G, and well S46; outline of raised gravel bed; and concentrations of TCE measured at the Wildwood property in 1985 (after Remediation Technologies 1998d, GeoTrans Inc. 1995).

added to the influent water before it is exposed to a series of UV lamps. The six 10,000-watt UV lamps are constructed in two series of three lamps. The exposure time of the contaminated water in the UV chambers is ~45 seconds. Afterward, the water is filtered and passed through two carbon adsorption units before it is released to a storm sewer. The effluent meets U.S. EPA ROD criteria (Metcalf & Eddy Inc. 1998) for PCE, TCE, 1,2-DCE, and the other VOCs (Harvard Project Services 2000). In the first nine years of operation, nearly 729,300,000 L of ground water were pumped and 786 kg of VOCs were removed (Figure 6 and Table 2). The total amounts of PCE and TCE removed from ground water during this period are 748 kg and 36 kg, respectively (Harvard Project Services 2000; Garren 2002).

VOCs occur in the shallow unsaturated materials at UniFirst and are believed to be the result of upward vapor migration from contaminated ground water (ENSR Consulting & Engineering 1993). The most effective manner to remove these contaminants is a point of discussion between UniFirst and U.S. EPA.

Wildwood Conservation Corp.

In 1983, Wildwood Conservation Corp. purchased the 6 ha property between the railroad tracks and the Aberjona River from the John J. Riley Leather Co. The Wildwood property borders Olympia Nominee Trust on the north and Aberjona Auto Parts, Whitney Barrel Co., and Murphy Waste Oil on the south (Figure 1). The John J. Riley Leather Co. owned the property from 1908 until 1979, when it was sold along with the nearby tannery and its property to Beatrice Foods Corp. Historic aerial photographs show that the property was accessible by a dirt road extending from Whitney Barrel and Murphy Waste Oil northward to Olympia Avenue. The aerial photographs, reports, and trial testimony indicate the property was used for unauthorized storage of drums, tanks, and other materials and unauthorized dumping of debris, drums, and chemical wastes (Metcalf & Eddy Inc. 1998) were found on both sides of the dirt road. A county sewer line and an old city sewer line transect the site parallel to the river. The entire 6 ha property lies within the floodplain of the river (Figure 7). The only structure on the property was an industrial well (S46 on Figures 1 and 7) built in 1958, which supplied water to the tannery until operations ceased in 1989 (ReTec 1994).

In 1993, 231,300 kg of debris, 45 drum carcasses, and 895,400 kg of contaminated soil were removed from the Wildwood property (U.S. EPA 1993). The soil was con-

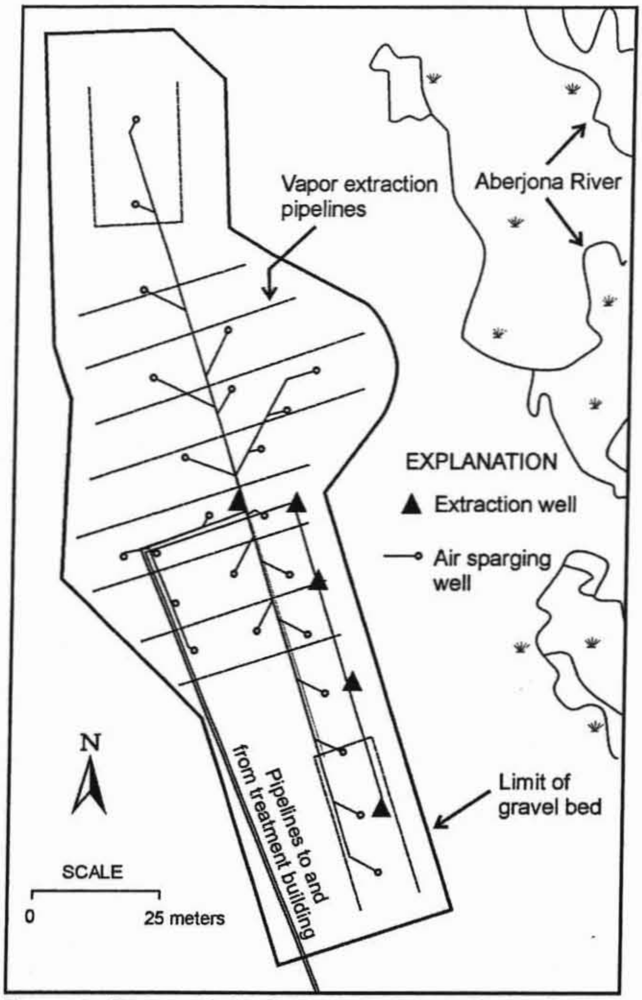

Figure 8. Design of the integrated air sparging, soil-vapor extraction, and pump-and-treat system at Wildwood Conservation Trust (after Remediation Technologies 1998a, 1998b, 1998c).

taminated with TCE, 1,2-DCE, PCE, 1,1,1-TCA, PAHs, PCBs, chlordane, and DDT (Ebasco Services Inc. 1988). Six drums contained TCE (Block 1996). Concentrations >830,000 mg/kg TCE were detected in the soil. Multilevel monitoring wells were drilled on the property between 1983 and 1985. The highest TCE concentrations in soil and ground water were detected at the location of a former debris pile, referred to as Debris Pile E (Figure 7) during the federal trial, which is suspected to be a primary source area (Ebasco Services Inc. 1988). TCE concentrations measured in shallow monitoring wells near the debris piles in 1985 ranged from several hundred micrograms per liter to more than 440,000 μg/L (Figure 7) and concentrations of 1,2-DCE, PCE, and other VOCs were in excess of U.S. EPA maximum contaminant levels. In 1985, TCE concentrations measured in bedrock monitoring wells near the debris piles ranged <100 μg/L to >2700 μg/L. By 1995, after the debris piles and contaminated soil were removed, TCE concentrations in shallow monitoring wells decreased to a maximum of 19,300 μg/L, whereas TCE concentrations in bedrock monitoring wells increased to a maximum of 120,000 μg/L. It appears that the contaminated soil removed in 1993 was a primary TCE source contributing to shallow ground water contamination and that the high concentrations of TCE in the shallow part of the ground water flow system had moved downward into bedrock fractures over time.

The Wildwood property is underlain by 9 to 24 m of glacial deposits in the buried bedrock valley. The shallow sediments consist of medium to fine sand with discontinuous deposits of sand and gravel. Sand and gravel beds predominate at depths of 7 to 15 m, or more in some locations. Slug tests in these deposits yield hydraulic conductivities of 6 to 30 m/day (GeoTrans and RETEC 1994). These permeable materials are underlain by highly compacted glacial deposits, which overlie fractured gabbrodiorite (Metheny 1998). Ground water occurs at depths of <1 m across most of the property and flows toward the Aberjona River (Myette et al. 1987).

Because of the large thickness and high permeability of the subsurface materials underlying the Wildwood property and its close proximity to the wetland and river, the remediation system is designed to remove most of the contaminants in ground water through air sparging and vapor extraction, rather than by extraction wells. The logic underlying this design is that air is easier and cheaper to move than water and there is simply too much available ground water and surface water at this location to pump and treat in an economical manner. The air sparging system consists of 24 shallow (vertical) wells that aerate contaminated soils and ground water (Figure 8). These wells are screened in sand and gravel to depths up to 22 m. The vapor extraction system consists of 460 m of slotted plastic pipe (Figure 8), which is set in a raised gravel bed that is underlain by a geotextile fabric and overlain by a HDPE liner. The raised bed is up to a meter thick and covers 1.2 ha. The HDPE liner is covered with a layer of sand and crushed stone to prevent erosion during flood events. Five deep ground water extraction wells extend through the raised gravel bed into bedrock to depths of 30 m (Figure 8). Together, these wells produce ~140 L/min. One of these wells produces <4 L/min but with TCE concentrations in the milligrams per liter range (Block 1997), suggesting that TCE may occur as free product beneath the Wildwood site.

In the nearby treatment building (Figure 7), contaminated ground water and condensate from the soil-vapor system pass through an air-stripping unit and two carbon adsorption tanks. The effluent, which meets U.S. EPA ROD criteria (Metcalf & Eddy 1998), is released to a storm sewer that discharges to the Aberjona River. Soil vapor from the vacuum extraction system is combined with air from the air-stripping system and treated by catalytic oxidation. This integrated system began operation in May 1998. Table 3 lists the mass of VOCs removed from the system during the first three years of operation. During this period, nearly 108 million liters of ground water were pumped and treated.

Characterization of the Wildwood property cost $1 million. Surface cleanup costs exceeded $1 million and construction costs including a pilot treatment system were $2 million (Block 1997).

Olympia Nominee Trust

Hemingway Transport has been a long-term tenant on the Olympia Nominee Trust property on the south side of

Table 3
VOCs Removed at Wildwood Conservation Trust[1]

Year of System Operation	VOC Mass Removed–Air (kg)	Mass VOCs Removed–Water (kg)	Total VOC Mass Removed (kg)
1999	334	33	367
2000	247	7	254
2001	238	7	245
Total	**819+**	**47**	**866**

[1]Personal communication, Mary Garren, U.S. EPA Region I, 2001 and 2002

Olympia Avenue. The Olympia property covers 8.5 ha and straddles the Aberjona River (Figure 1). A portion of the eastern area is used as a trucking terminal. The 3.2 ha on the west side of the Aberjona River abut the Wildwood property and are undeveloped but accessible by the dirt road paralleling the railroad tracks between Olympia Avenue and Salem Street.

The geology of the western portion of the Olympia property is similar to that at Wildwood. The area overlies a deep part of the buried valley that contains 24 to 30 m of permeable sand and gravel deposits, which are underlain by 6 to 9 m of highly compacted sediments (Metheny 1998). Ground water occurs at depths of 0 to 2 m and flows in a converging pattern toward the river (Myette et al. 1987).

The Hemingway Transport Co. held permits for three underground storage tanks. In May 1983, the 24,000 L gasoline storage tank was found to contain water and was removed. In April 1985, U.S. EPA discovered 12 exposed drums in various stages of corrosion in the southwestern portion of the property on the west floodplain of the Aberjona River (near the "O" in Figure 1). Adjacent to the drums was a small pile of caps from pesticide containers (U.S. EPA 1987). Aerial photographs show the presence of drums in this area in 1969.

The drums and underlying soil contained TCE, PCE, 1,1-dichloroethane, 1,1,1-TCA, toluenes, xylenes, PCBs, and chlordane (U.S. EPA 1986). In December 1986, five more drums were found buried in the same general area of the property (U.S. EPA 1987). Soil samples revealed significant concentrations of PCBs (31,000 µg/kg), chlordane (51,000 µg/kg), and TCE, PCE, 1,2-DCE, 1,1,1-TCA, trichlorobenzene, and methyl naphthalene (Ebasco Services Inc. 1988).

No remediation systems are yet in operation at Olympia Nominee Trust. Negotiations are proceeding between the property owners and U.S. EPA. In the winter and spring of 2002, several more multilevel monitoring wells were drilled and sampled in the wetland downgradient from the location of the former drum piles. Concentrations of VOCs measured in 2002 in two shallow monitoring wells and a new test well on the west side of the Olympia property at the site of the 17 drums are listed in Table 4.

New England Plastics Co.

The 1.6 ha NEP property is located west of Washington Street, about 150 m east of well G (Figure 1). Office

Table 4
VOCs Measured in Monitoring Wells in 1987 at Olympia Nominee Trust[1]

Monitoring Well	TCE (µg/L)	PCE (µg/L)	Total Xylenes (µg/L)
TW1	12,000	14	150
OL2	7,900	—	—
OL3	13	—	—

[1]Sullivan (2002)

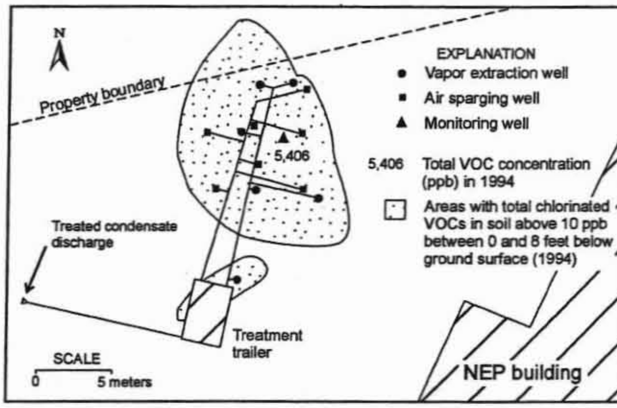

Figure 9. Design of NEP remediation system and measured concentrations of VOCs in 1994 (after Woodard & Curran 1997).

buildings and parking lots surround the property. Site investigations and historic aerial photographs identified a source of VOCs at the former location of a storage trailer owned by Prospect Tool & Die Co., a tenant on the property from 1962 to 1989 (HMM Associates 1990). Investigations indicated contaminated soil and sediment extending to a depth of 4 m, slightly below the local water table (Figure 9).

The NEP property overlies permeable sand and gravel deposits that range in thickness from 2 to 11 m (Metheny 1998). The hydraulic conductivity of the underlying sediments ranges between 0.6 to 18 m/day. The water table occurs at depths varying from 2 to 5 m below land surface. Ground water flow is generally to the south and southwest (Woodard & Curran 2000).

PCE is the primary contaminant. Total VOCs measuring 5406 µg/L were detected in 1994 in a monitoring well installed in the source area (Figure 9). Total VOCs in monitoring wells within 90 m downgradient of the source area commonly ranged from 10 to 200 µg/L in the glacial materials and from 20 to 270 µg/L in the bedrock (Woodard & Curran 2000).

After 230 m^3 of contaminated soil were removed from the site, the source area was paved over with asphalt and a soil-vapor extraction system coupled with air-sparging wells was constructed (Figure 9). The system consists of seven vertical 6 m deep air-sparging wells and six vertical vacuum extraction wells. In a small trailer, soil vapor and condensate from the vapor-extraction system pass through separate carbon adsorption units. The system began operation in February 1998. In 15 months of operation, nearly 36 kg of VOCs were removed (Woodard & Curran 1999). The system was turned off in 1999 because ROD cleanup levels

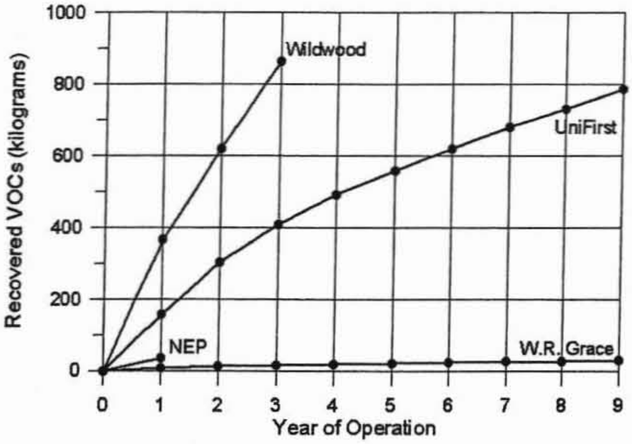

Figure 10. Cumulative recovered mass of VOCs at the Wells G & H Superfund Site by responsible party.

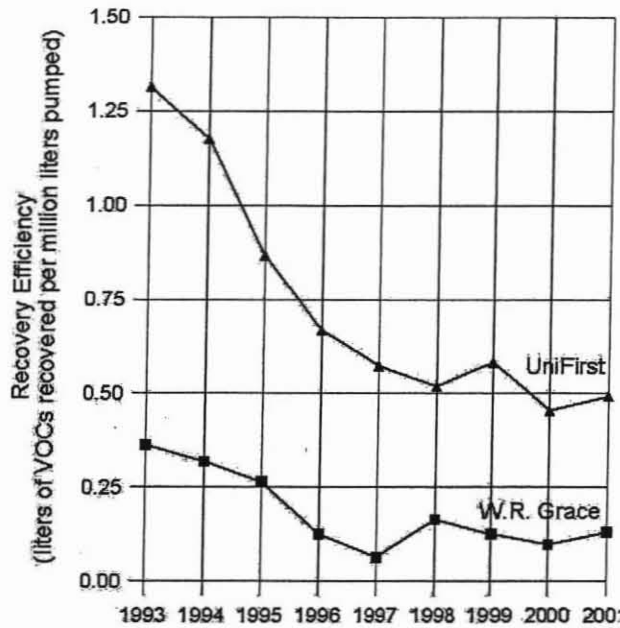

Figure 11. Efficiency of remediation systems at W.R. Grace and UniFirst during first nine years of operation.

in the unsaturated sediments were achieved. Some residual ground water contamination still exists but appears to be diminishing over time due to dispersion and natural attenuation (Woodard & Curran 2000).

The intent of the remediation system was to reduce the concentration of contaminants in the unsaturated sediments to ROD cleanup levels and to reduce the concentration of contaminants in the source area ground water to the greatest extent possible. Ground water samples collected in August 2000 indicate that total VOCs in the source area have declined to approximately 20 μg/L. These samples showed that PCE exceeds U.S. EPA ROD criteria in only two of five overburden wells and two of eight bedrock wells (Woodard & Curran 2000). U.S. EPA permitted NEP to turn off the air-sparging/soil-vapor extraction system in 2001, depending on quarterly analysis of ground water samples to determine whether VOC concentrations remain low.

Contamination and Remediation: Operable Units #2 and #3

The three properties on the north side of Salem Street—Murphy Waste Oil, Whitney Barrel, and Aberjona Auto Parts (Figure 1)—are in Operable Unit #2 and under the purview of U.S. EPA Region I. Samples from eight shallow monitoring wells taken in 1993 show TCE concentrations of a few micrograms per liter in most wells, whereas samples from seven deeper monitoring wells commonly show TCE concentrations up to several hundred micrograms per liter. Low concentrations of PCE also were found in most of the deeper monitoring wells (RETEC 1994). Remedial investigations and risk assessments are proceeding at each of these properties (Garren 2002).

Several studies document the presence of heavy metals (arsenic, chromium, and lead) in elevated concentrations in the sediments underlying the Industri-Plex Superfund Site, located a few kilometers upstream of the Wells G & H Superfund Site, and in modern sediments deposited along the floodplain of the Aberjona River and in the Mystic Lakes, located several kilometers downstream of the Wells G & H Superfund Site (Knox 1991; Aurilio et al. 1994; Davis et al. 1994; Spliethoff and Hemond 1996). The source of the heavy metals is a former chemical manufacturing plant on the Industri-Plex Superfund Site that produced arsenic-based pesticides, sulfuric acid, phenols, TNT, and other chemicals in the early 1900s (Tarr 1987).

Many other sources of contamination exist within the upper reaches of the Aberjona River watershed upstream of the Wells G & H Superfund Site. These sources include tanneries, piggeries, a drum refurbishing company, and unregulated landfills among other industries (Tarr 1987). VOCs have been found in the East Drainage Ditch and Landfill Creek, two tributaries to the Aberjona River that flow across the Industri-Plex Site (Kim 1995).

The environmental impact on the Aberjona River watershed of Woburn's once prolific leather-tanning and chemical manufacturing industries was first documented by the Massachusetts Division of Fisheries and Wildlife in 1919–1922, when it published 160 annotated photographs showing animal carcasses, breached waste lagoons, exposed piles of mineral ores and waste products, saline drainages from tanneries, and tarry sediments lining the beds of tributary streams to the Aberjona River (Commonwealth of Massachusetts 1922). Since then, several other studies have documented the impact of land usage and manufacturing practices on the watershed (DeFeo 1971; Warrington 1973; Tarr 1987; Cherry et al. 1989; Knox 1991; Roux Associates 1991, 1992; Davis et al. 1994; Spliethoff and Hemond 1996).

Cleanup of Operable Unit #3 is also proceeding within the U.S. EPA Superfund framework. Characterization and risk assessment of the portion of the Aberjona River and wetland in the Wells G & H Superfund Site is being managed by U.S. EPA Region I in a more holistic manner, combining it with similar tasks at the Industri-Plex Superfund Site. Using this approach, the entire river is to be examined and risks posed by sediments in specific segments of the river can be treated in different ways (LeMay 2001). A comprehensive assessment of risks to human health and ecological risks was due to be released by U.S. EPA in 2002 (LeMay 2002).

Conclusion

The construction and operation of the remediation systems at the Wells G & H Superfund Site show that the intent of the Superfund legislation is working in east Woburn. Figure 10 shows the cumulative mass of VOCs recovered at the W.R. Grace, UniFirst, Wildwood, and NEP properties. As can be seen by these curves, the rate of recovery of VOCs declines steadily. This "tailing effect" is a common problem at sites contaminated by nonaqueous phase liquids and greatly prolongs expected cleanup times (Wiedemeier et al. 1999). The impact of this decline in recovered mass also can be seen in Figure 11, which shows the decline in the efficiency of the remediation systems at W.R. Grace and UniFirst, where efficiency is defined by the liters of VOCs recovered per million liters of contaminated water pumped.

The source areas of VOCs within the Wells G & H Superfund Site occur in a variety of hydrogeologic settings. The remediation strategies used to recover and treat VOCs at W.R. Grace, UniFirst, Wildwood, and NEP reflect differences in the depth to ground water, in the flow rates of ground water to extraction wells, the availability of nearby sources of (clean) surface water that could be induced to flow to extraction wells, and the occurrence of VOCs in underlying fractured bedrock. As a result of these differences, each of the remediation systems employed at the Wells G & H Superfund Site is custom designed to remove VOCs from the source areas, prevent off-site migration of VOCs, and treat the recovered water/air in an economical manner. This decentralized strategy was preferred by the responsible parties and by U.S. EPA to an alternative strategy that called for a series of deep, large capacity extraction wells to be located along the axis of the buried valley. These centralized wells would have induced large volumes of uncontaminated water to flow from the wetland and river into the aquifer, would have transported VOCs down into the deeper parts of the aquifer (which is not highly contaminated), and would have required treatment of large volumes of ground water containing very low concentrations of VOCs.

The limitations of the technologies employed at the Wells G & H Superfund Site and the difficulty in removing VOCs and other sorbing contaminant compounds commonly necessitates that these remediation systems operate for decades even though drinking water standards may never be attained. It is unlikely that the aquifer underlying the Aberjona River valley will be restored to a pristine state until other areas of contamination within the Wells G & H Superfund Site (Whitney Barrel, Aberjona Auto Parts, and Murphy Waste Oil) are remediated and until the heavy-metal contamination in the upper several meters of the wetland are removed or treated. It is entirely possible that after tens of years of treatment and expenditures greatly exceeding the initial estimate of $70 million that the aquifer in this one part of the Aberjona River watershed will not be completely restored.

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References

Aurilio, A.C., R.P. Mason, and H.F. Hemond. 1994. Speciation and fate of arsenic in three lakes of the Aberjona watershed. *Environmental Science and Technology* 28, no. 4: 577–585.

Block, R. 1996. Personal communication, RETEC.

Block, R. 1997. Personal communication, ThermoReTec.

Cherry, J.A., M.L. Johnson, and R.J. Jaeger. 1989. Technical report on the Woburn, Massachusetts, wells G & H site, prepared for UniFirst Corp., submitted to U.S. EPA Region I, Boston, Massachusetts.

Chute, N.E. 1959. Glacial geology of the Mystic Lakes–Fresh Pond area, Massachusetts, U.S. Geological Survey Bulletin 1061-F, 187–216.

Commonwealth of Massachusetts. 1922. Pollution survey of the Aberjona River, 1921–1922. Division of Fisheries and Wildlife, Westboro, Massachusetts.

Davis, A., J.H. Kempton, A. Nicholson, and B. Yare. 1994. Groundwater transport of arsenic and chromium at a historical tannery, Woburn, Massachusetts, U.S.A. *Applied Geochemistry* 9, no. 5: 569–582.

DeFeo, F.L. 1971. The establishment and operation of the Aberjona River Commission. M.S. thesis, Department of Civil Engineering, Tufts University, Medford, Massachusetts.

Ebasco Services Inc. 1988. Final supplemental RS for feasibility study, wells G & H site, Woburn, Massachusetts, submitted to U.S. EPA Region I, Boston, Massachusetts.

Ecology and Environment. 1980a. Preliminary site assessment of Aberjona Auto Parts, 270 Salem St., Woburn, Massachusetts, submitted to U.S. EPA Region I, Boston, Massachusetts.

Ecology and Environment. 1980b. Preliminary site assessment of Whitney Barrel Co., 256 Salem St., Woburn, Massachusetts, submitted to U.S. EPA Region I, Boston, Massachusetts.

Ecology and Environment. 1982. Field investigations of uncontrolled hazardous waste sites, FIT Project: 25 June 1982, 68-01-6056/TDD/F1-8109-02, submitted to U.S. EPA Region I, Boston, Massachusetts.

ENSR Consulting & Engineering. 1993. UniFirst Corp., RD/RA Year 1 Annual Report: Groundwater Monitoring and Capture System Performance for the UniFirst Site Remedial Action of the Northeast Quadrant of the Wells G & H Site, Woburn Massachusetts, submitted to U.S. EPA Region I, Boston, Massachusetts.

Garren, M. 2001. Personal communication, U.S. EPA Region I.

Garren, M. 2002. Personal communication, U.S. EPA Region I.

GeoTrans Inc. 1987. Review of EPA report titled, "Wells G & H Site Remedial Investigation Report Part I, Woburn, Massachusetts," submitted to U.S. EPA Region I, Boston, Massachusetts.

GeoTrans Inc. 1995. W.R. Grace Remedial Action Wells G & H Site, Woburn, Massachusetts, Annual Report for October 1, 1994–September 30, 1995, prepared for W. R. Grace & Co., Connecticut, submitted to U.S. EPA Region I, Boston, Massachusetts.

GeoTrans Inc. and ReTec. 1994. Wells G & H Site central area remedial investigation phase IA Report Vol. I-III, prepared for Beatrice Corp., UniFirst Corp., and W.R. Grace & Co., Connecticut, submitted to U.S. EPA Region I, Boston, Massachusetts.

GHR. 1988. Site assessment report of the former Whitney Barrel Co. site, 256 Salem St., Woburn, Massachusetts.

Harr, Jonathan. 1995. *A Civil Action*. New York: Random House.

Harvard Project Services. 2000. RD/RA Year 8 Annual Report for the UniFirst Site, submitted to U.S. EPA Region I, Boston, Massachusetts.

HMM Associates. 1990. New England Plastics, Wells G & H site hydrologic site investigation, February.

HSI GeoTrans Inc. 2000. W.R. Grace Remedial Action, Wells G & H Superfund Site, Woburn, Massachusetts, Annual Report October 1, 1999-September 30, 2000, prepared for W.R. Grace & Co., Connecticut, submitted to U.S. EPA Region I, Boston, Massachusetts.

Johns, M. 2000. Personal communication, W.R. Grace & Co.

Kim, H. 1995. Discharge of volatile organic compounds from a contaminated aquifer and their fate in a stream. Ph.D. dissertation, Massachusetts Institute of Technology, Cambridge, Massachusetts.

Knox, M. 1991. The distribution and depositional history of metals in surface sediments of the Aberjona River watershed, M.S. thesis, Department of Civil Engineering, Massachusetts Institute of Technology.

LeMay, J. 2001. Personal communication, U.S. EPA Region I.

LeMay, J. 2002. Personal communication, U.S. EPA Region I.

Metcalf & Eddy Inc. 1998. Draft Field Operations Plan Remedial Design/Remedial Action (RD/RA) Oversight Support, Wells G & H Superfund Site, Woburn, Massachusetts, July 1998; prepared for U.S. Environmental Protection Agency, contract no. 68-W6-0042.

Metheny, M.A. 1998. Numerical simulation of ground-water flow and advective transport at Woburn, Massachusetts, based on a sedimentological model of glacial and glaciofluvial deposition. M.S. thesis, Department of Geological Sciences, Ohio State University.

Myette, C.F., J.C. Olimpio, and D.G. Johnson. 1987. Area of influence and zone of contribution to Superfund-site Wells G and H, Woburn, Massachusetts. U.S. Geological Survey Water-Resources Investigations Report 87-4100.

NUS Corp. 1986. Wells G & H Site Remedial Investigation Report Part I, Woburn, Massachusetts, TDD No. F1-8607-07, U.S. EPA Site No. MAD980732168.

Remediation Technologies Inc. 1994. Draft Remedial Investigation, Southwest Properties, Wells G & H Superfund Site, Woburn, Massachusetts, prepared for Beatrice Co. Concord, Massachusetts.

Remediation Technologies Inc. 1996. Attachment F, aquifer test report, Wildwood Property, Wells G & H Superfund Site, Woburn, Massachusetts, Volume I. Technical report, April 1996, prepared for Beatrice Co., by Remediation Technologies Inc., Concord, Massachusetts, and Hydroanalysis Inc., Acton, Massachusetts.

Remediation Technologies Inc. 1998a. 100% design drawings, Wildwood Property, Wells G & H Superfund Site, Woburn, Massachusetts. Drawing number S-4, soil vapor extraction layout, prepared for Beatrice Co., by Remediation Technologies, Inc. Concord, Massachusetts.

Remediation Technologies Inc. 1998b. 100% design drawings, Wildwood Property, Wells G & H Superfund Site, Woburn, Massachusetts. Drawing number S-3, air sparging, prepared for Beatrice Co., by Remediation Technologies Inc. Concord, Massachusetts.

Remediation Technologies Inc. 1998c. 100% design drawings, Wildwood Property, Wells G & H Superfund Site, Woburn, Massachusetts. Drawing number S-5, groundwater extraction layout, prepared for Beatrice Co., by Remediation Technologies Inc. Concord, Massachusetts.

Remediation Technologies Inc. 1998d. 100% design drawings, Wildwood Property, Wells G & H Superfund Site, Woburn, Massachusetts. Drawing number S-1b, construction layout and limits of clearing, prepared for Beatrice Co. Concord, Massachusetts.

Roux Associates. 1991. Remedial investigation: Ground-water/surface-water investigation plan, Phase 1, prepared for U.S. EPA Region I, Boston, Massachusetts.

Roux Associates. 1992. Remedial investigation: Ground-water/surface-water investigation plan, Phase 2, prepared for U.S. EPA Region I, Boston, Massachusetts.

Spliethoff, H.M., and H.F. Hemond, 1996. History of toxic metal discharge to surface waters of the Aberjona watershed. *Environmental Science and Technology* 30, no. 1: 121–128.

Sullivan, D. 2002. Personal communication, TRC.

Tarr, J.A. 1987. History of pollution in Woburn, Massachusetts, report prepared for W.R. Grace & Co., included as Appendix B to GeoTrans.

ThermoReTec. 1999. Wells G & H Superfund Site, RD/RA for Wildwood Property, letter from Michael Devir to Ms. Mary Garren, U.S. EPA Region I, Boston, Massachusetts.

Touchstone Pictures. 1998. *A Civil Action*, Screenplay by Steve Zaillian, directed by Steve Zaillian.

U.S. Environmental Protection Agency. 1986. Environmental News, U.S. EPA Region I, Boston, Massachusetts, February.

U.S. Environmental Protection Agency. 1987. Environmental News, U.S. EPA Region I, Boston, Massachusetts, February.

U.S. Environmental Protection Agency. 1993. Cleanup begins at Wells G & H, one year after landmark New England settlement: Superfund at Work-Hazardous Waste Cleanup Efforts Nationwide, EPA 520-F-92-015, Winter.

Warrington, R.A. 1973. Hydraulic survey of the Aberjona River and operation of the Aberjona River Commission. M.S. thesis, Department of Engineering, Tufts University, Medford, Massachusetts.

Wiedemeier, T.H., H.S. Rifai, C.J. Newell, and J.T. Wilson. 1999. *Natural Attenuation of Fuels and Chlorinated Solvents in the Subsurface*. New York: John Wiley & Sons.

Woodard & Curran. 1997. New England Plastics Corp., Woburn, Massachusetts, Source control remedial design, Project 96032.04, soil vapor extraction and air sparge systems, 100% Design, prepared for New England Plastics Corp., by Woodard & Curran, Portland, Maine.

Woodard & Curran. 1999. New England Plastics Corp., Remedial Action Monthly Report for November 1999. Letter to Mary Garren from Henri Vincent.

Woodard & Curran. 2000. Groundwater monitoring report, New England Plastics Corp., Wells G & H Superfund Site, Woburn, Massachusetts, October 2000, prepared for New England Plastics Corp., by Woodard & Curran, Portland, Maine.