Resilient Remediation

PRELIMINARY DESIGN REPORT

May 5th, 2017

Prepared for Terracon
Prepared by Resilient Remediation

May 5, 2017

Andy Safulko
Terracon Consultants, Inc.
1242 Bramwood Place
Longmont, CO 80501

Dear Mr. Safulko,

Please find attached a Preliminary Design Report for Resilient Remediation's (RR) investigation of remedial alternatives at the 1717 15th Street site in Boulder, Colorado. RR has outlined protocol pilot study designs for air sparging, multi-phase extraction, and bioremediation on-site.

This report includes an outline of pilot studies for each remedial technology listed above including information such as total estimated cost, total estimated time for pilot study, and logistics for running each pilot study.

We look forward to hearing from you soon regarding this project. Please contact Amanda Smokoff (Amanda.Smokoff@colorado.edu) for further information.

Thank you.

Sincerely,

Resilient Remediation
College of Engineering & Applied Science
Department of Environmental Engineering
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Boulder, CO 8030

Executive Summary

Resilient Remediation is pleased to present Terracon with this Preliminary Design Report for the 1717 15th Street site in Boulder, Colorado. The former dry cleaning site is contaminated with tetrachloroethylene from disposal methods used for dry cleaning solvents, and benzene and naphthalene are present from an off-site source. On March 24, 2017, RR completed an Alternatives Assessment in which a multi-criteria decision matrix was used to select three remedial alternatives suggested for pilot study. The following Preliminary Design Report provides site-specific pilot study designs for each selected remedial alternative: multi-phase extraction, air sparging and soil vapor extraction, and bioremediation.

Stakeholders such as the identified potentially responsible party, local businesses, Boulder High School, patrons of local businesses, community members, and commuters using roads overlying the contamination plume were considered in the evaluation of each technology and pilot study design. Pilot studies were designed to interfere minimally with nearby stakeholders.

The pilot study for bioremediation has a total estimated cost ranging from $26,000 to $55,200 and a recommended pilot study duration ranging from two to six months. The cost for the full-scale implementation of bioremediation is estimated to range from $400,000 to $800,000 and the estimated time to remediation is two to three years.

The pilot study for multi-phase extraction has a total estimated cost of $38,000 and recommended pilot study duration of four days. The cost for the full-scale implementation of multi-phase extraction is estimated to range from $650,000 to $1,500,000 and the estimated time to remediation is six months to two years.

The pilot study for air sparging and soil vapor extraction has a total estimated cost of $24,500 and recommended pilot study duration of three days. The cost for the full-scale implementation of air sparging and soil vapor extraction is estimated to range from $370,000 to $570,000 and the estimated time to remediation is one to two years.

RR recommends that pilot studies for all three remedial alternatives be implemented on-site. If this is not feasible, a single remedial alternative should be selected for pilot study depending on the prioritization of cost, time to remediation, or ease of implementation. RR suggests that air sparging and soil vapor extraction be selected for pilot study if cost is priority. If time to remediation is the most important aspect, RR recommends implementing multi-phase extraction. For space and ease of implementation considerations, RR suggests implementing bioremediation.

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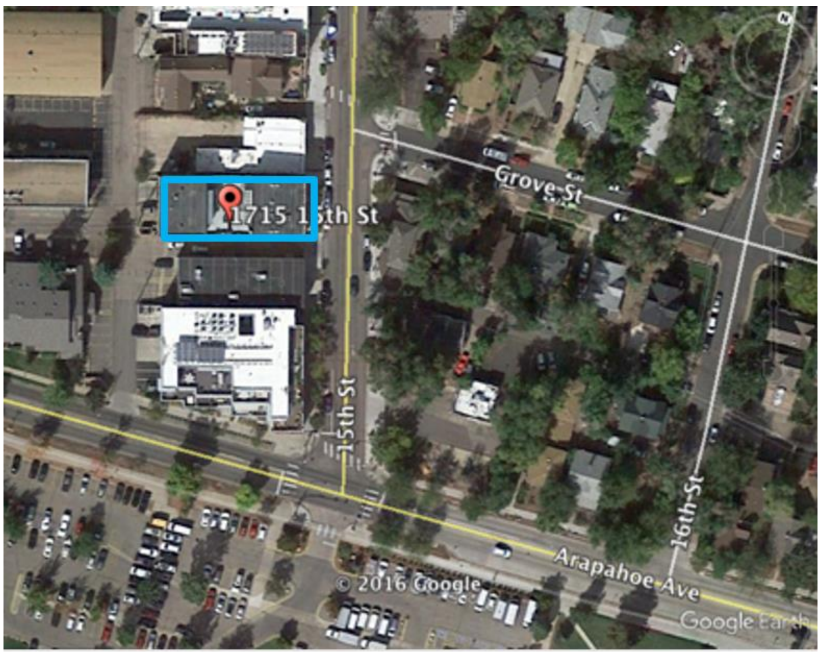
Acronyms

APEN .... Air Pollution Emissions Notice
bgs .... Below Ground Surface
CDPHE .... Colorado Department of Public Health and Environment
cfm .... Cubic Feet per Minute
CWA .... Clean Water Act
DO .... Dissolved Oxygen
GAC .... Granular Activated Carbon
gpm .... Gallons per minute
HRC ® .... Hydrogen Release Compound
MCDM .... Multi-Criteria Decision Matrix
MPE .... Multiphase Extraction
MW .... Monitoring Well
NAAQS .... National Ambient Air Quality Standards
NAPL .... Non-Aqueous Phase Liquid
NESHAP .... National Emissions Standards for Hazardous Air Pollutants
ORP .... Oxidation Reduction Potential
PCE .... Tetrachoroethylene
PVC .... Polyvinyl Chloride
RAP .... Remedial Action Plan
RCRA .... Resource Conservation and Recovery Act
ROI .... Radius of Influence
SVE .... Soil Vapor Extraction
VOC .... Volatile Organic Compound

1. Introduction and Background

The 1717 15th Street site is a former dry cleaning operation located in Boulder, Colorado. The location of the site is depicted in Figure 1. Due to disposal methods of dry cleaning solvents, the groundwater and soil near the site is contaminated with tetrachloroethylene (PCE) above Colorado Department of Public Health and Environment (CDPHE) standards. Further analysis conducted revealed levels of benzene and naphthalene in the groundwater above CDPHE standards from an off-site source.



Source: Google Earth

Figure 1. Site Location

Resilient Remediation recommends three remediation alternatives for pilot study on-site: bioremediation, multiphase extraction (MPE) , and air sparging with soil vapor extraction (SVE). For each technology, a protocol for a pilot study on-site is detailed in this report. Information includes total estimated cost, pilot study duration, equipment necessary for the pilot studies, and logistical information.

1.1 Evaluation of Current Conditions

The original site map and monitoring well (MW) locations are displayed in Figure 14 in the Appendix for reference. Current site conditions, such as soil stratification, hydraulic conductivity, and groundwater characteristics are driving factors in choosing a remediation technology for the site. The designed pilot studies for the technologies account for current site conditions.

1.1.1 Remediation Goals and Site Contaminants

Per guidance of Terracon, remediation will conclude when the contamination is below CDPHE standards. Table 1 outlines the on-site concentrations and percent reduction required to attain remediation standards.

Table 1. On-Site Concentrations

Contaminant	Media	Measured Concentration[(a)]	CDPHE Standard [1]	Percent Reduction Required
PCE	Soil	2.2-32 mg/kg	1.88 mg/kg	14.5-94.1%
PCE	Groundwater	0.726 mg/L	0.017 mg/L	97.7%
Benzene	Groundwater	0.00651 mg/L	0.005 mg/L	23.2%
Naphthalene	Groundwater	0.184 mg/L	0.14 mg/L	23.9%

(a) Data from Analytical Tables provided by Terracon

The contaminants are also assumed to be in the dissolved phase as opposed to their respective non-aqueous phase liquid (NAPL) forms. After further analysis, RR determined the contaminants are all below their respective solubility limits. Table 2 compares the on-site concentrations to the solubility limits of the contaminants.

Table 2. Solubility Limits of Contaminants

Contaminant	Solubility Limit (mg/L) [2]	On-Site Concentration (mg/L) [(a)]
PCE	$2x10^2$	0.726
Naphthalene	31.0	0.184
Benzene	$1.75x10^3$	$6.51x10^{-3}$

(b) Data from Analytical Tables provided by Terracon

Although the plume is now dissolved, the steady (although decreasing) concentrations measured over an extensive period at MW-5 indicate an initial NAPL source. Figure 2 shows the measured concentrations over time, as provided by Terracon's Analytical Tables document.

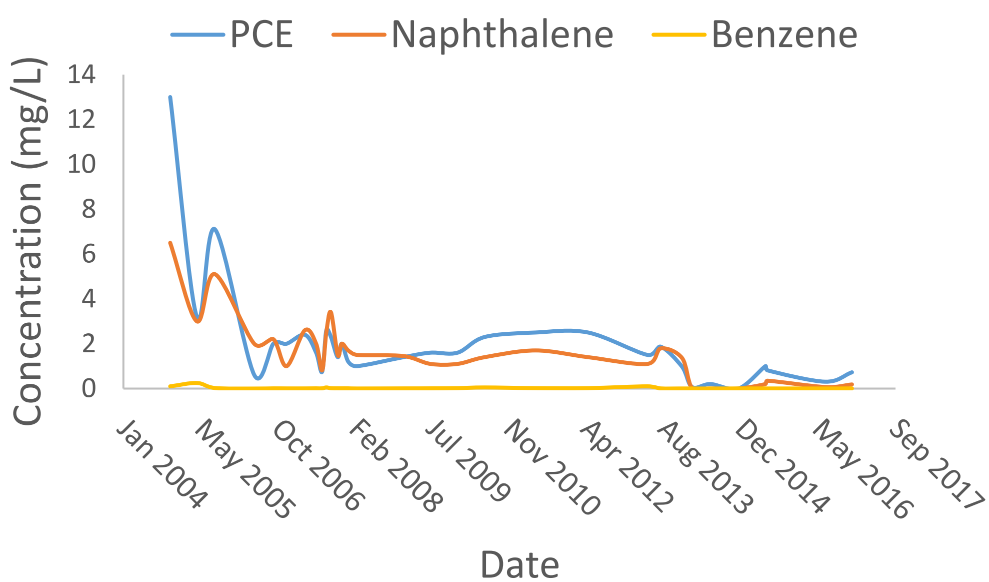


Figure 2. Contaminant Concentration Measured Over Time at MW-5

1.1.2 Extent of Contamination

Through the development of a fate and transport model, RR determined the approximate plume area, as well as groundwater and soil volumes targeted for treatment. These are presented in Table 3 and the modeled contamination plume in groundwater is presented in Figure 3. Although the model displayed in Figure 3 represents PCE, this same region will be targeted for benzene and naphthalene.

Table 3. Summary of Target Treatment Media

Target Treatment Measurements	Approximated Measurement
Area of groundwater contamination	50,000 ft^2
Soil volume	18,000-27,000 ft^3
Groundwater volume	500,000 ft^3

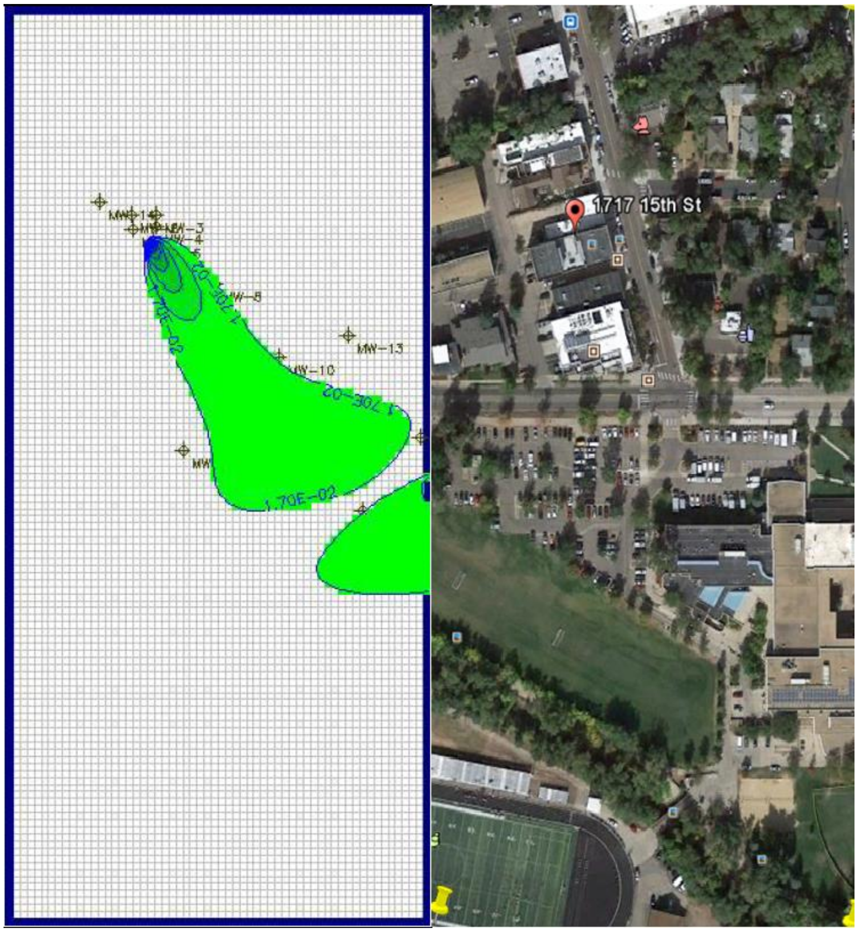


Figure 3. Contamination Plume

1.2 Evaluation of Regulations

In both pilot study phase and full-scale remediation, the technologies must abide by national and state-specific water quality regulations, air quality regulations, and hazardous waste regulations.

1.2.1 Water Quality Regulations

The current contamination includes PCE, benzene and naphthalene, which are all found in concentrations above CDPHE standards [1]. The different technologies will work toward reducing those concentrations to acceptable levels by injecting certain substances underground or extracting the groundwater then reinjecting after treatment. Each step in the implementation of the remediation plan must comply with the Federal Clean Water Act (CWA) as well as the Colorado Water Quality Control Act. As these injections will be performed through injection wells which are considered point sources, the procedure must also follow the Colorado discharge permit system [3].

1.2.2 Air Quality Regulations

The remediation technologies target PCE, benzene and naphthalene in the groundwater and in the volatile phase as well; some plans rely on converting the contaminant to harmless byproducts while others rely on extracting the underground vapor for treatment. After treating any gaseous effluent from the subsurface, the gases released into the atmosphere must be in acceptable concentrations. The contaminants of concern on our site are not listed in the National Ambient Air Quality Standards (NAAQS) or the Colorado Ambient Air Quality Standards, however they are considered hazardous air pollutants and must comply with National Emission Standards for Hazardous Air Pollutants (NESHAP) [4]. Depending on the concentration of contaminants in the effluent gas streams, an Air Pollutant Emission Notice (APEN) or air permit may be required from the Air Pollution Control Division in CDPHE [5].

1.2.3 Hazardous Waste Regulations

Since the main contaminants are considered hazardous substances, when extracting groundwater or bringing contaminated soil to the surface or even filtering the contaminants out of the air or water, other equipment is contaminated and the contaminants may be concentrated in a certain media [6]. The entire remediation process must be regulated by the Resource Conservation and Recovery Act (RCRA**)** regulations for hazardous wastes. Before applying the remediation technology, the state requires a remedial action plan (RAP) which is a RCRA permit that gives authorization to treat, store or dispose of hazardous remediation waste.

1.3 Site Considerations

Due to the location and nature of the contamination, RR is considering the site location and stakeholders when designing the pilot studies for the remedial technologies. RR aims to deliver a remedial solution that will have minimal impact on the surrounding community.

1.3.1 Urban Location

As seen in Figure 3, the plume extends into an urban, highly populated area. Due to the location of the plume, well installation may be difficult off-site due to right of way and property rights. The high-volume foot and vehicle traffic in the area also restricts the amount of space available for remedial technologies, as RR aims to impose minimal impact to businesses and patrons in the area.

1.3.2 Stakeholders

Stakeholders for this project include the former owner of 1717 15th Street, who has been identified as the potentially responsible party, the surrounding business owners, Boulder High School, patrons of the local businesses, and anyone commuting on roads overlying the contamination plume outlined in Figure 3. Stakeholder concerns may include air quality, traffic congestion, reduced parking availability, or possible business losses associated with pilot testing and full-scale activities. In conducting pilot tests, the social, environmental, and economic impact to these stakeholders should be taken into consideration and discussed with relevant persons or establishments.

2. Summary of Alternatives Assessment

RR evaluated eight remediation alternatives as proposed in the document *Alternative Assessment Proposal*. After having screened and eliminated four of these alternatives, RR carried out a more thorough assessment of the remaining alternatives –MPE, air sparging with SVE, chemical oxidation, and bioremediation. This assessment was based on a Multi-Criteria Decision Matrix (MCDM). The MCDM allowed for weighted scoring of each alternative according to a triple bottom line (economic, social, and environmental impact). The categories for evaluation included estimated total cost, time to remediation, ease of implementation, and health/environmental impacts. The MCDM weightings and category explanations are displayed in Table 4.

Table 4. MCDM Criteria

Category	Weight	Description	TBL Aspects Addressed
Estimated Total Cost	0.45	This category is used to rank each alternative based on total estimated project cost including capital cost, operations and maintenance costs, and any additional costs that may be associated with each alternative.	Economic
Time to Remediation	0.30	Each remedial alternative is ranked based on the projected time to remediation.	Social
Ease of Implementation	0.15	This category is necessary to evaluate the size and energy footprint of each remedial alternative, and the permits needed for each remedial alternative.	Social, economic, and environmental
Health/Environmental Impacts	0.10	The remedial alternatives will be evaluated based on potential health impacts such as off-gas emissions, chemical releases, and safety considerations. Environmental impacts will also be taken into place as evaluated by the ENVISION rating system.	Social and environmental

The details of this assessment are found in the document *Alternatives Assessment Report*.

The results of the assessment are displayed in Table 5 through Table 7 and in Figure 4.

Table 5. Estimated Total Cost

Technology	MPE	Air Sparging and SVE	Chemical Oxidation	Bioremediation
Estimated Total Cost	\$650,000-\$1,500,000	\$370,000-\$570,000	\$1,900,000-\$2,900,000	\$400,000-\$800,000

Table 6. Estimated Number of Wells Required

Technology	MPE	Air Sparging/SVE	Chemical Oxidation	Bioremediation
Number of Wells	20-40	20-50	40-70	40-70

Table 7. Estimated Time to Remediation

Technology	MPE	Air Sparging and SVE	Chemical Oxidation	Bioremediation
Estimated Remediation Time (years)	0.5-2	1-2	1-2	2-3

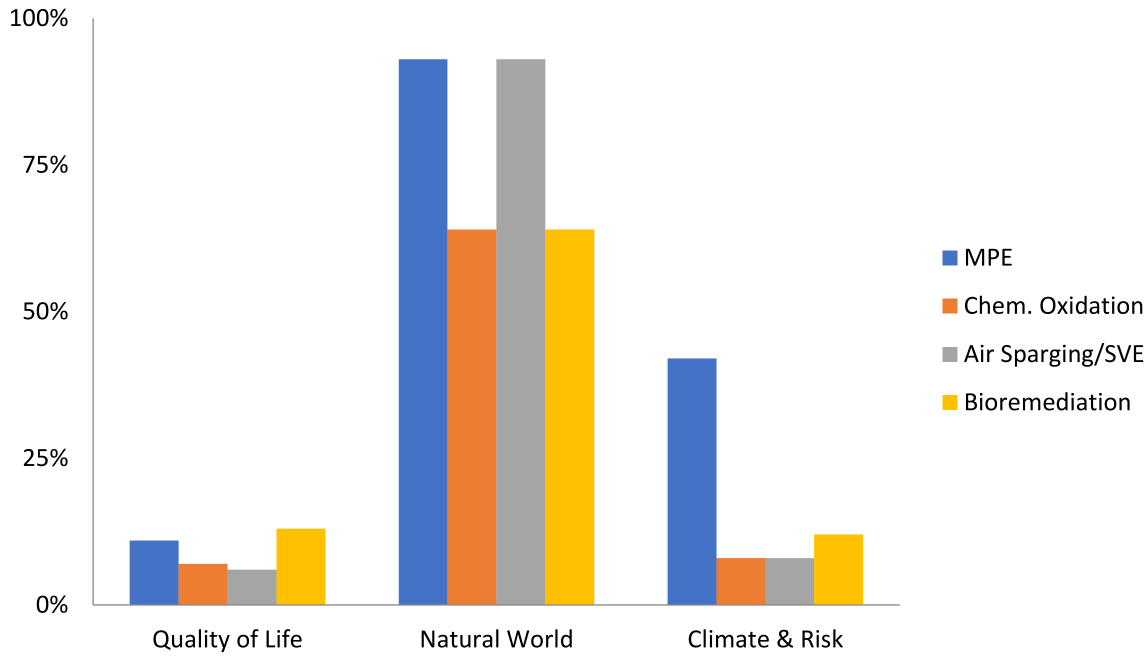


Figure 4. ENVISION Rankings

The MCDM ranking scale definitions are displayed in Table 8, with the final MCDM presented in Table 9.

Table 8. Ranking Scale

Ranking	Total Estimated Cost	Time to Remediation	Ease of Implementation	Health/Environmental Impacts
4	<$500,000	< 1 year	Small above ground area requirements, low permitting requirements, and ease of implementing wells.	High ENVISION ranking, low contaminant off-gas emissions, low safety concerns.
3	$500,000-$1,000,000	1-2 years	Small above ground area requirements, mid-level permitting requirements, and ease of implementing wells.	High ENVISION ranking, some contaminant off-gas emissions, little safety concerns.
2	$1,000,000-$1,500,000	2-3 years	Mid-level above ground requirements, hard to implement wells, large permitting requirements.	Average ENVISION ranking, relatively high off gas-emissions, and multiple safety concerns.
1	>$1,500,000	> 3 years	High number of wells required, large above ground area permits, and high permitting requirements.	Low ENVISION ranking, high contaminant off-gas emissions, many safety concerns,

Table 9. Multi Criteria Decision Matrix

Decision Criteria	Criteria Weight	Multi-Phase Extraction (MPE)	Air Sparging/ SVE	Chemical Oxidation	Bioremediation
Estimated Total Cost	0.45	2	4	1	3
Time to Remediation	0.30	4	3	3	2
Ease of Implementation	0.15	2	2	3	4
Environmental/Health Impacts	0.10	4	2	1	3
Total Score[a]		**2.8**	**3.2**	**1.9**	**2.9**

(a) Rankings are from 1 (least favorable) to 4 (most favorable).

The top three scoring alternatives were air sparging/SVE, MPE, and bioremediation. However, due to close variability in scoring and uncertain effectiveness on-site, RR recommends that Terracon conduct pilot testing to assess the feasibility of using each of these three alternatives at the site. The purpose of this *Preliminary Design Report* is to design a pilot test for each of these three technologies.

3. Pilot Study Design

RR has detailed pilot study protocol for bioremediation, MPE, and air sparging with SVE. The pilot study designs include data needed from the pilot study to do a full-scale design, the recommended site layout, pilot study protocol (including duration and specific tests), the estimated cost of the pilot study, and any known environmental impacts. Pilot testing will provide further information regarding the technology performance on-site, radius of influence, air flow rates, groundwater pumping rates, off-gas emissions rates, and other data needed to design each technology.

3.1 Relevant Site Characteristics

Pilot testing of each technology requires the use of site-specific parameters that relate to the hydrogeological and contaminant plume model. A summary of relevant parameters is presented in Table 10.

Table 10. Summary of Site Characteristics

Characteristic	Value
Velocity	410-450 ft/yr
Soil characteristics [a]	
Porosity	0.3
Hydraulic conductivity	0.01 cm/s
Stratification	Low
Depth to groundwater	9-12 ft.
Hydrostatic Pressure at Well 5[b] (bottom of aquifer)	5.64 psig

(a) From slug test and boring log data provided by Terracon
(b) Assuming a groundwater temperature of 10°C

3.2 Bioremediation

Pilot testing for bioremediation is performed by inducing anaerobic conditions to promote the reduction of PCE via the injection of an organic substrate. RR recommends the use of diluted HRC® (Hydrogen Release Compound) or molasses as the organic substrate for the site. HRC® and molasses have been successfully employed in more field applications compared to other organic substrates [7]. As a result, substantial documentation is available to support the use of HRC® and molasses. RR has designed pilot studies for both substrates, but recommends that a pilot study be conducted for HRC® prior to molasses due to the lower cost and shorter duration of HRC® pilot study. Unknown microbial and geological characteristics may result in unsatisfactory outcomes for the HRC® pilot test. In this case, RR suggests implementation of the molasses pilot study. PCE may be remediated by means of reductive dechlorination following the injection of HRC® or molasses. The process of reductive dechlorination is shown in Figure 5 [8].

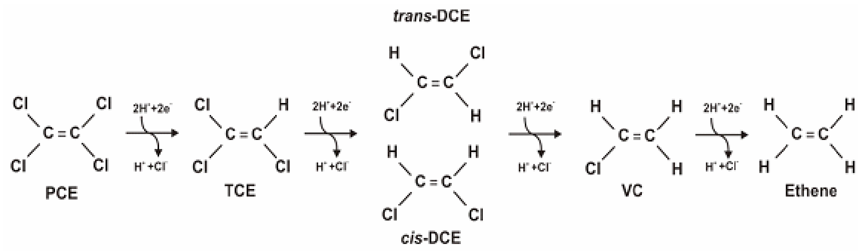


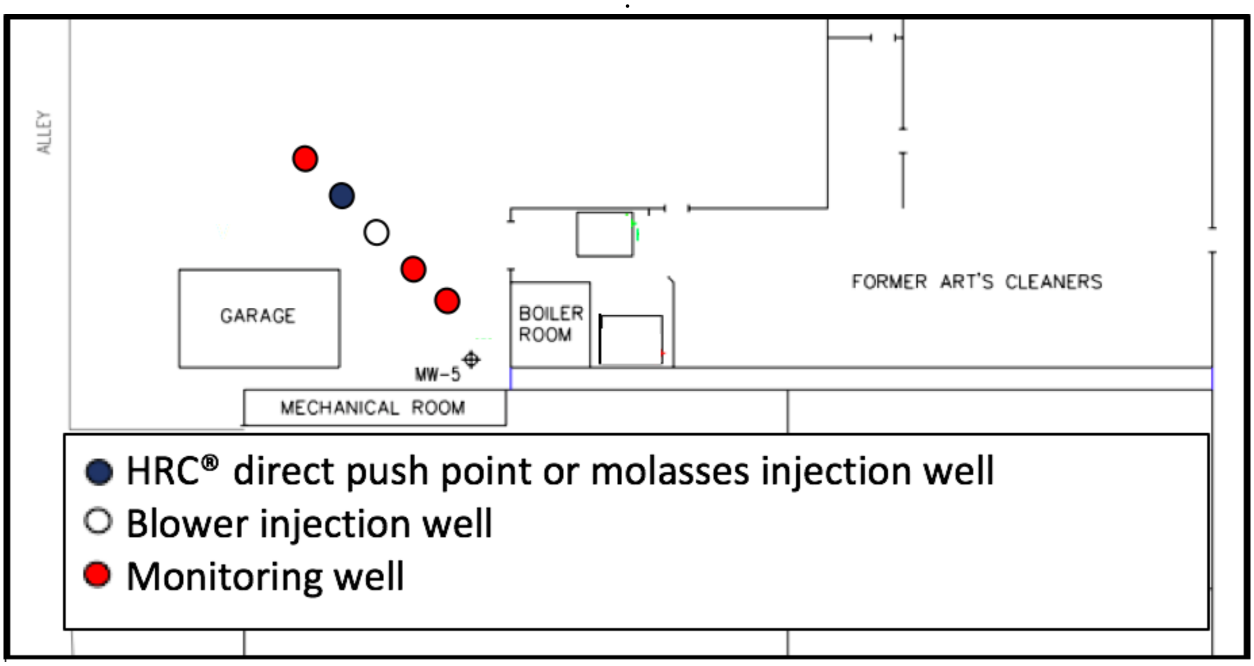
Figure 5. Reductive Dechlorination of PCE

Following the pilot study period for PCE remediation, RR recommends using a blower for the induction of aerobic conditions to enhance the degradation of naphthalene and benzene. Pilot study site layout, protocol, cost, and resulting environmental impacts are detailed below for HRC®, molasses, and the blower.

The bioremediation pilot study provides information on required substrate volume, radius of influence (ROI), injection pressures, and behavior of the microbial community. This information may be used to determine the number of injection wells and equipment requirements for full-scale remediation.

3.2.1 Site Layout

RR recommends that bioremediation pilot testing be performed using one direct push point for HRC®, one temporary injection well for molasses, and three monitoring wells. The HRC® direct push point and molasses injection well may be installed on-site near MW-5 shown in Figure 6, where PCE concentrations are highest. The blower injection well may be installed five feet down-gradient from the HRC® and molasses injection point. The monitoring wells should be installed parallel to groundwater flow [9]. RR recommends that one monitoring well be located five feet up-gradient from the injection well and two monitoring wells located down-gradient at distances of 10 feet and 15 feet, respectively [9]. Monitoring wells should have varying depths so that vertical hydraulic gradients, potential for vertical migration of substrate, and vertical extent of the treatment zone can be determined [9]. The up-gradient and down-gradient monitoring wells may be installed at depths of 10, 15, and 19 feet, respectively. The same monitoring well layout and materials may be used for HRC®, molasses, and the blower. Figure _ depicts the suggested well locations on-site. Final well locations are contingent on utility locates, which may require alterations to the site layout shown below.



**Not to scale*

Figure 6. Bioremediation Site Layout

3.2.2 Pilot Study Protocol

RR recommends the following bioremediation pilot study protocol for use on-site.

3.2.2.1 HRC®

HRC® is a highly viscous, slow-release bioremediation substrate supplied by Regenesis® Remediation Products [9]. Once injected into groundwater, the poly-lactate ester material is consumed by the microbial community, causing a controlled release of hydrogen [10]. This creates an anaerobic environment in which PCE may degrade. Due to its slow-release nature, HRC® can induce reducing conditions for PCE for up to 18 to 24 months using a single injection [11]. HRC® physical characteristics are shown below in Table 11 [11].

Table 11. Physical Characteristics of HRC

Property	Value
Density	10.8 pounds per gallon
Viscosity	20,000 centipoise

3.2.2.1.1 Implementation

Due to the cool climate in Colorado, HRC® should be pre-heated in a hot water bath to lower the viscosity of the substrate for ease of injection [11]. This should be done by placing the unopened containers of HRC® in a 100-gallon plastic storage tank filled with water at a temperature of 130-170°F [11]. The HRC® is suitable for injection upon reaching a minimum temperature of 95°F [11].

RR recommends that HRC® be injected by means of direct push technology using a Geoprobe® [9]. In the area of highest PCE concentration, the Geoprobe® rod should be pushed to a depth of 19 feet, then withdrawn three to six inches to allow adequate space for HRC® injection [11]. The pre-heated HRC® may then be poured into the Geoprobe® pump hopper and injected into the groundwater at a rate of 4 pounds HRC® per vertical foot [9] [11]. RR recommends a total of 86.4 pounds HRC® be injected for the pilot study [9]. See Appendix C for calculations used to determine the recommended mass of HRC®.

Upon the completion of HRC® injection, the Geoprobe® rod should be slowly withdrawn [11]. The injection point may be sealed with bentonite and capped with concrete or asphalt if desired [11]. See Table 12 for a summary of equipment necessary for the HRC® pilot study.

Table 12. Summary of Equipment for HRC® Pilot Study

Description	Equipment	Quantity	Citation
HRC® Preparation	100-gallon plastic tank	1	[11]
Wells and Installation	Geoprobe®	1	
	Monitoring well (2 in. diameter PVC with 5 ft. screened interval)	3	[12]
	Bentonite seal	1	[11]
	Concrete or asphalt cap (optional)	1	[11]

3.2.2.1.2 Monitoring

RR recommends that three monitoring wells be installed by means of direct push technology [12]. Wells may be constructed of two-inch diameter polyvinyl chloride pipe (PVC) with varying depths of 10, 15, and 19 feet [12]. Each monitoring well should have a five-foot screened interval. The monitoring wells will be used to take measurements for temperature, specific conductivity, dissolved oxygen, pH, and oxidation reduction potential (ORP) [12]. Table_ provides the injection and monitoring schedule for HRC®. RR recommends that effects of HRC® injection be monitored over a two-month period with measurements taken once per month.

Table 13. HRC® Injection and Monitoring Schedule

Day of Testing	Objective	Description
1	Baseline sampling Monitoring well installation HRC® injection	Sample temperature, pH, DO, VOC concentrations, specific conductivity, ORP Install 1 direct-push well Install 3 monitoring wells Inject 86.4 lbs HRC®
30	Monitoring well sampling	Sample temperature, pH, DO, VOC concentrations, specific conductivity, ORP
60	Monitoring well sampling	Sample temperature, pH, DO, VOC concentrations, specific conductivity, ORP

3.2.2.2 Molasses

Molasses is a soluble substrate which exists in an aqueous phase. Molasses is diluted with potable water prior to injection [7]. Once injected, molasses serves as a sucrose and carbohydrate source for existing microorganisms [7]. Consumption of molasses by existing microorganisms lowers DO levels. Once oxygen levels have been lowered, a different subset of microorganisms ferments the remaining molasses and produces hydrogen [7]. The hydrogen is then used as the electron donor in the reductive dechlorination of PCE.

3.2.2.2.1 Implementation

The design for this pilot study is based off a pilot study conducted at the Naval Weapons Industrial Plant (NWIP) in Dallas, TX. RR recommends that one injection well be placed near the area of highest contamination at a depth of 19 ft. The diluted solution may be stored in two 300-gallon tanks with propeller mixers. A pneumatic pump and an automatic timer can be used to facilitate automated injections [7]. An estimated total of 600 gallons of 10% diluted molasses solution may be injected every three days at 30-gallon intervals, until conditions for reductive dechlorination are achieved. Table 14 [9] shows conditions necessary for reductive dechlorination.

Table 14. Parameters for Reductive Dechlorination

Parameter	Dissolved Oxygen Concentration	Oxidation Reduction Potential	pH
Required Value	< 1 mg/L	-60 to 40 mV	5-9

3.2.2.2.2 Monitoring

Three monitoring wells may be installed by means of direct push technology [7]. Wells will be constructed of two-inch diameter PVC with a five-foot screened interval, at varying depths of 10, 15, and 19 feet [12]. The monitoring wells may be used to take groundwater samples and measurements for temperature, specific conductivity, dissolved oxygen, pH, and oxidation reduction potential (ORP) [7]. Groundwater samples will be analyzed for VOC concentrations, dissolved gases, metals, and other geochemical parameters [7]. Table 15 provides a summary of injections and monitoring events.

Table 15. Molasses Injection and Monitoring Schedule

Duration	Event and Frequency	Description
Upon initiation	Groundwater sampling and analysis	VOC concentrations, dissolved gases, metals, and other geochemical parameters
Upon initiation	Baseline sampling	Temperature, dissolved oxygen, pH, ORP, specific conductivity, VOC concentrations
Two months	Injections every three days	30 gallons of 10% dilute molasses solution per injection
	Measurements weekly	Temperature, dissolved oxygen, pH, ORP, specific conductivity
Until reductive conditions are achieved (2-4 months)	Measurements monthly	Temperature, dissolved oxygen, pH, ORP, specific conductivity, VOC concentrations
Upon conclusion	Groundwater sampling and analysis	Temperature, dissolved oxygen, pH, ORP, specific conductivity, VOC concentrations

Concentrations may need to be adjusted throughout the study to maintain reductive conditions. Table 16 provides a summary of required equipment for the molasses pilot study.

Table 16. Summary of Equipment for Molasses Pilot Study

Description	Equipment	Quantity	Citation
Wells and Installation	Injection well (1-inch diameter PVC)	1	[7]
	Monitoring well (2-inch diameter PVC with 5 ft screened interval)	3	[12]
	Geoprobe®	1	[7]
Storage and Delivery	Pneumatic Pump	1	[7]
	Automatic timer	1	[7]
	300-gallon storage tank with propeller mixers	2	
Sample Collection	Peristaltic pump	1	[7]
	Polyethylene tubing	N/A	[7]
	Multiprobe	1	[7]
	Water-level meter	1	[7]

3.2.2.3 Blower

3.2.2.3.1 Implementation

After PCE is remediated, a blower can be used to induce aerobic conditions for biodegradation of naphthalene and benzene [12]. A compressor may be used to continuously deliver pressurized air into one injection well. RR recommends a rotary vane compressor for its low cost, low emissions, and ability to provide high flows at low pressures [13]. Injections are commonly made at five feet below the lowest depth of contamination [12]. RR suggests injections at the depth of the aquifer will be sufficient considering low naphthalene and benzene concentrations and the presence of low-permeability clay directly below the aquifer. A minimum of three monitoring wells at varying depths is required [12]. Table 17 outlines required equipment for the blower.

Table 17. Blower Equipment

Equipment	Quantity	Description
Injection well	1	2-inch diameter with 2 feet long screened interval [12]
Monitoring well	3	2-inch diameter PVC with 5 feet screened interval [12]
Rotary vane compressor	1	5 to 20 cfm of air at 15 psi [12] equip with pressure gauge and flow meter [12]
Multiprobe	1	Measure dissolved oxygen
Water level meter	1	Measure groundwater pressure

3.2.2.3.2 Monitoring

A water level meter can be used to conduct a groundwater pressure response test. The results of the groundwater pressure response test determine the distribution of air in the subsurface. Water levels which return to baseline levels within several minutes to several hours are indicative of homogenous soils and conical air distribution [12]. Elevated water levels of several tens of centimeters for more than eight hours indicate irregular soil stratification and inefficient air distribution [12].

A multi-meter can be used to measure DO content. The DO measurements determine the ROI of the air injection well [12]. Higher flow rates have been shown to have superior performance, but cost more to implement [12]. Flow rates of 5, 10, and 20 acfm may be tested to determine the most effective and least expensive flow rate [12]. The tests may be performed over the course of three days. Parameters may be measured at all three monitoring wells [12]. Table 18 shows the monitoring schedule.

Table 18. Blower Monitoring Schedule

Time (hours)	**Flow Rates (acfm)** [12]	**Measured Parameters** [12]
0	0 (baseline)	Air pressure, air flow rate, DO, groundwater pressure
Every 5-10 minutes until flow pressure and flow stabilize	5, 10, 20	Air pressure, Air flow rate, DO, groundwater pressure, time until stabilization
Hourly for a maximum of eight hours, or until water-levels stabilize	5, 10, 20	Air pressure, Air flow rate, DO, groundwater pressure

3.2.3 Estimated Cost of Study

3.2.3.1 HRC®

The total pilot study cost using HRC® for the remediation of PCE is shown below in Table 19. Cost calculations are based off a pilot study using HRC® performed at a dry-cleaning site in Portland, Oregon [9]. Site specific cost calculations include one direct push point for the application of 86.4 pounds of HRC®, three monitoring wells, and corresponding equipment, labor, and lab analysis costs required for a two-month monitoring period. The cost estimation does not include project planning, laboratory analysis, or reporting expenses. The cost analysis provided is Class 3 AACEI cost analysis with a 20% contingency. Detailed cost calculations can be found in Appendix C.

Table 19. Estimated HRC® Pilot Study Cost

Description	Unit Cost	Total Cost[(a)]
Substrate HRC ® and Shipping [9]	$10.50 per pound of HRC®	$900
Geoprobe® Rental [14]	$1,200 per day	$1,200
Injection Point [9]	$400 per injection	$400
Monitoring Well Installation and Labor [7]	$2,500 per 25 feet	$4,400
Substrate Heating Tank [15]	$120 per tank	$120
Sampling Equipment and Supplies [9]	$2,500	$2,500
Baseline Sampling [9]	$6,500	$6,500
Surveying [9]	$1,300	$1,300
Mobilization [9]	$2,600	$2,600
Laboratory Analysis [9]	$520 per day	$1,040
Installation Labor [9]	$1,800 per day	$1,800
Monitoring Labor [9]	$1,000 per day	$2,000
Total		**$24,760**

[(a)] 2017 dollars. The basis for inflation calculations can be found in Appendix B.

3.2.3.2 Molasses

NWIP provides a summary of estimated cost which is applied to the current site. In the site specific cost analysis, well costs have been adjusted. The cost analysis provided is Class 3 AACEI cost analysis with a 20% contingency. Table 20 provides a summary of additional costs associated with implementation of the molasses pilot study. Detailed cost calculations can be found in Appendix C.

Table 20. Estimated Additional Molasses Pilot Study Cost

Description	Unit Cost	Quantity	Factors Included in Cost	Total Cost[(a)]
Injection well	$2,000 per 25 ft [7]	1 (19 ft)	Geoprobe®, labor and materials for installation [7]	$1,500
Storage and delivery equipment	$900 per injection per point [7]	20	Labor and materials [7]	$18,000
Sampling equipment	$400 [7]	1	Labor and equipment for sample collection [7]	$400
Baseline Sampling	$6500 per sampling event [7]	1	Sampling [9]	$6,500
Groundwater Sampling	$400 per sampling event	2	Labor and equipment	$800
Analytical Fees	$1,000 per analytical event	2	Analytical cost	$2,000
Total				**$29,200**

[(a)] 2017 dollars. The basis for inflation calculations can be found in the Appendix Section X.X

3.2.3.3 Blower

Unit costs for the blower system components are provided in a cost sheet from New Hampshire Petroleum Reimbursement Fund Program. See the HRC® cost estimate for monitoring well and equipment costs. The cost analysis provided is a Class 3 AACEI cost analysis with a 20% contingency. Table 21 outlines the costs associated with the blower system. Detailed cost calculations can be found in Appendix C.

Table 21. Blower System Cost

Description	Unit Cost [14]	Total Cost[(a)]
Compressor	$80 per half day rental	$480
Injection wells	$12.00 per foot	$230
Geoprobe® Rental	$1,200 per day	$1,200
Monitoring Labor	$115 per day	$350
Total		**$2,300**

(a) 2017 dollars. The basis for inflation calculations can be found in Appendix B.

As previously stated, the bioremediation pilot study can result in two outcomes: with and without implementation of the molasses pilot study. Table 22 summarizes total cost with and without implementation of the molasses pilot study. Detailed cost calculations can be found in Appendix C.

Table 22. Total Cost for Bioremediation with and Without Molasses Pilot Study

Technologies	Total Cost
HRC and blower	$26,000
HRC, blower, and molasses	$55,200

3.2.4 Environmental Impacts

Employing bioremediation at the site has a relatively low environmental impact since the majority of remediation is driven by natural processes. The Geoprobe® uses a gasoline engine with a power output of 6.5 kW at 3,600 revolutions per minute [16], which produces carbon emissions. The application of HRC® requires approximately 100 gallons of hot water to lower the viscosity of the substrate for ease of installation [11]. In addition, an estimated total of 540 gallons of water may be used to dilute the molasses. The rotary vane compressor is the most sustainable compressor option for the blower because it does not require fuel [13]. It does, however, have a small carbon footprint associated with the 2.2 kW power requirement [17]. In addition, the carbon emissions for substrate and equipment delivery must also be considered.

3.3 Multiphase Extraction

Implementing MPE with granular activated carbon (GAC) filtration for contaminant removal from extracted liquid and vapor is expected to be an effective remedial approach for the contamination on site. The flexibility in the design of the MPE system make is suitable for such an urban area, as well as the moderate cost and duration of the technology.

To apply the MPE technology, a pilot test will need to be conducted to determine certain parameters to proceed with the full-scale system. The pilot test can be used to determine the ROI, the extraction flow rate, reinjection flow rate, as well as the GAC filtration removal efficiency [18] [19]. Soil properties such as the hydraulic conductivity, soil permeability, storage coefficients, specific yield, transmissivity, capillary forces, effective porosity, moisture content, and groundwater flow direction and gradient can also be confirmed [18]. These parameters can help specify the vacuum power requirements necessary to maximize the performance of the MPE system.

3.3.1 Site Layout

For a pilot study, well placement is determined by the location of the highest concentration of contaminant in both soil and groundwater [12]. Based on the groundwater model in Figure 3, RR, and the results from the onsite utility locate, RR would be able to select more accurate placement of the pumping well, with three monitoring wells surrounding the well, as well as an injection well, if deemed necessary [12] [20]. Figure 7 outlines ideal placement of each of these wells.

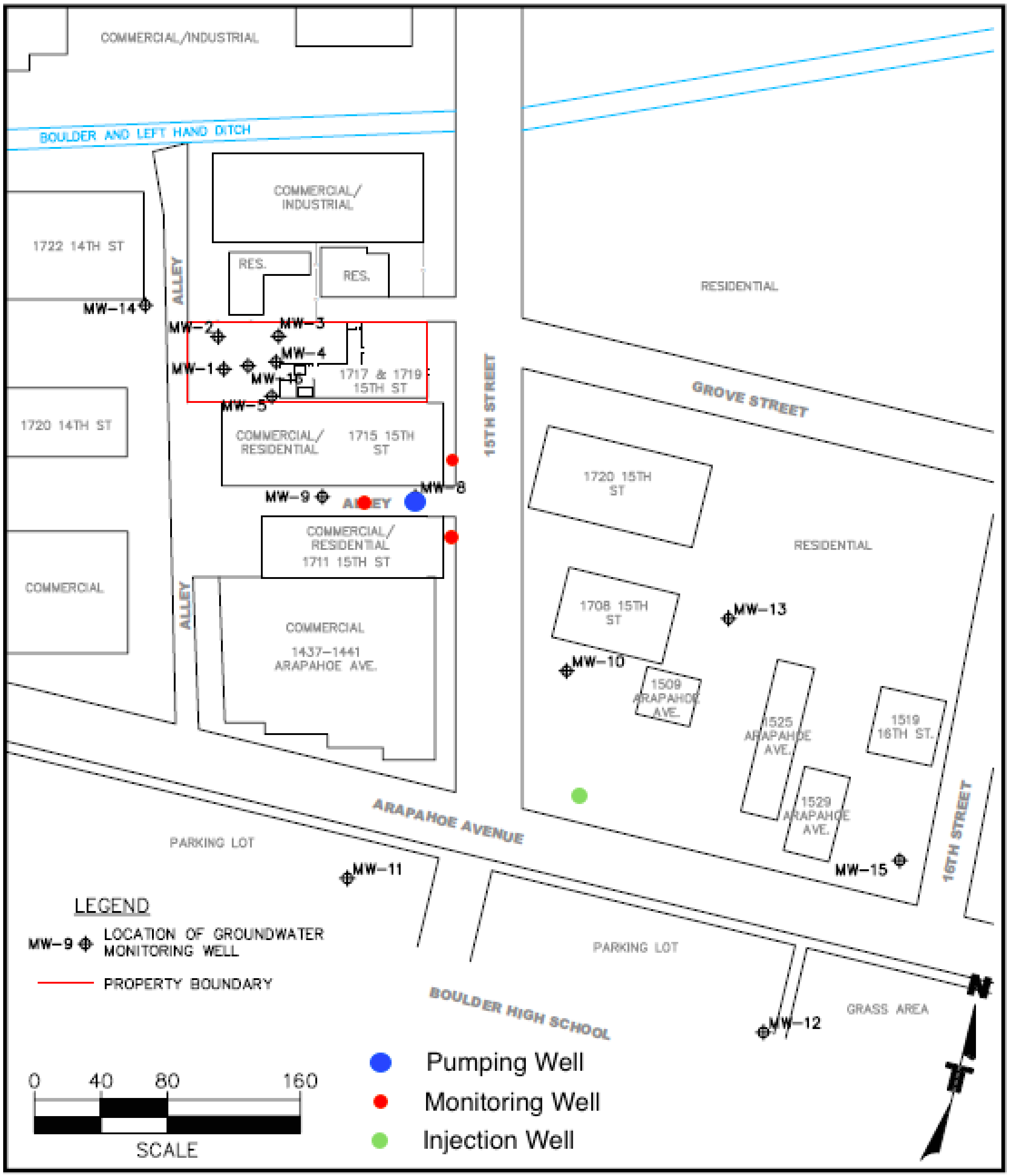


Figure 7. Site Layout with Ideal Placement of Wells in MPE System.

The center of the plume lies in the high school parking lot and the highest concentration of the contaminant can be found by MW-5, as seen in Figure 3. The pumping well would be placed near high contaminant concentrations, as shown. Three monitoring wells can be placed in an equilateral triangle 10 feet away or less from the pumping well, with some slight variations due to underground and above ground utilities and infrastructure. The injection well will be placed down-gradient of the pumping well, to induce flow towards the pumping well. The distance away from the pumping well that the injection well will be placed depends on the resulting ROI from the pumping well [20]. Monitoring wells can also be converted to injection wells, while still monitoring the conditions from the pumping well [21].

3.3.2 Pilot Study Protocol

In cooperation with CDPHE regulations, the three monitoring wells should be installed with two wells upstream and one downstream along the groundwater flow [12]. A single pumping well would be installed for the pilot test stage and an injection well if deemed necessary and applicable.

The extraction well would be used accommodate the single pump MPE system [19]. The single pump system is composed of a 1 foot wide well casing surrounding a Schedule 80 PVC well with a pump for extraction of water and vapor, as shown in Figure 8 [19]. The well casing includes a sand pack around the well screen of 12 feet, 5 feet of bentonite and 2 feet of concrete as a surface seal around the top of the well. The PVC well should be 8 inches in diameter, 19 feet long, and includes a cap/plug at the bottom of the well. The bottom of the well should also have 11 feet of slotted screen PVC for extracting vapor and water, and the remaining 8 feet would be solid PVC for the impermeable portion of the well, where the bentonite and concrete casing is. Within the PVC well there is an extraction tube that leads to a suction line, which is attached to a vacuum pump, which can induce pumping in the well. Attached to the suction line is a vacuum gauge, to monitor pressure in the well. A basket strainer should be installed as well to ensure no particles or sediments interfere with the extraction of the liquid and vapor streams [22].

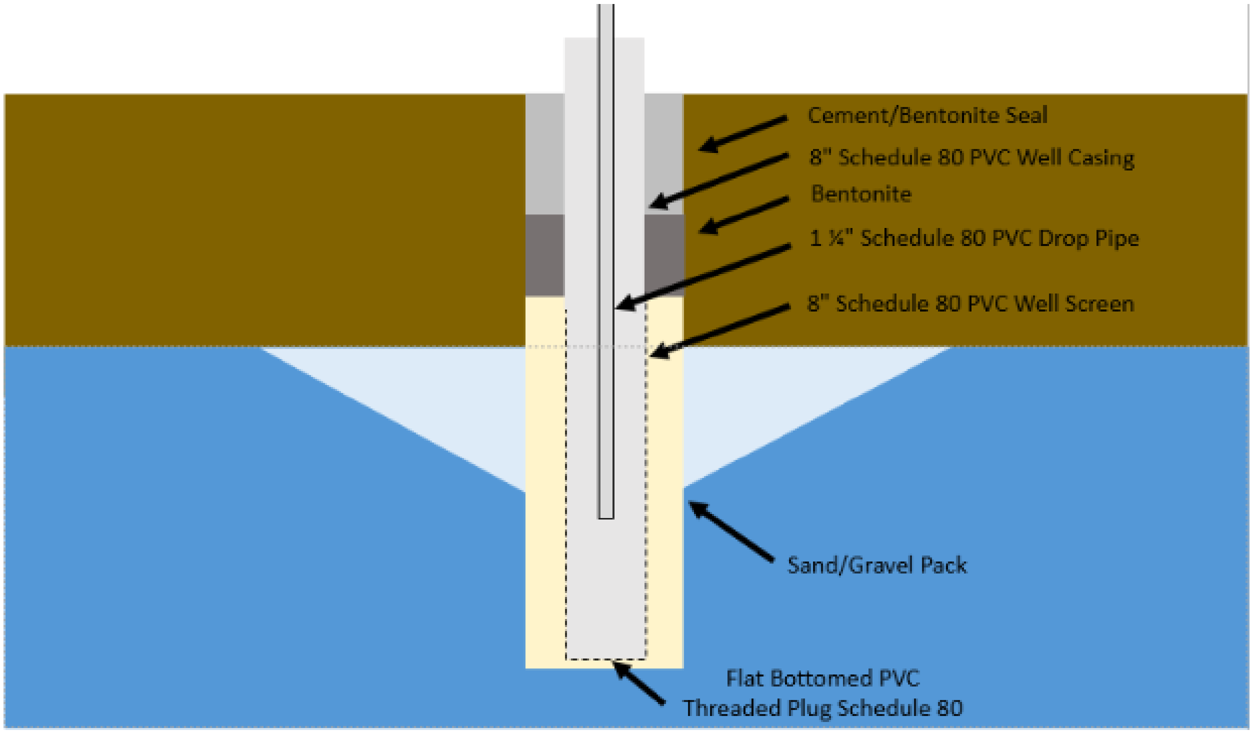


Figure 8. Detailed Diagram of MPE Pumping Well

Each monitoring well would be designed similarly to the extraction well, but smaller. The diameter of the monitoring wells for MPE will be 4 inches, to allow for reinjection [21].

A moisture separation system will also be needed to separate the liquid and vapor being extracted from the subsurface along with pumps to help move the fluids through the piping system [23]. A power supply unit would be needed to power all the pumps installed for the pilot testing [22]. Two separate GAC filtration systems would also be necessary as well to remove the contaminants from the liquid and vapor streams, and the efficiency of the GAC filters would also need to be determined [19]. The general schematic of the pumping well and GAC filters is shown in Figure 9 [24].

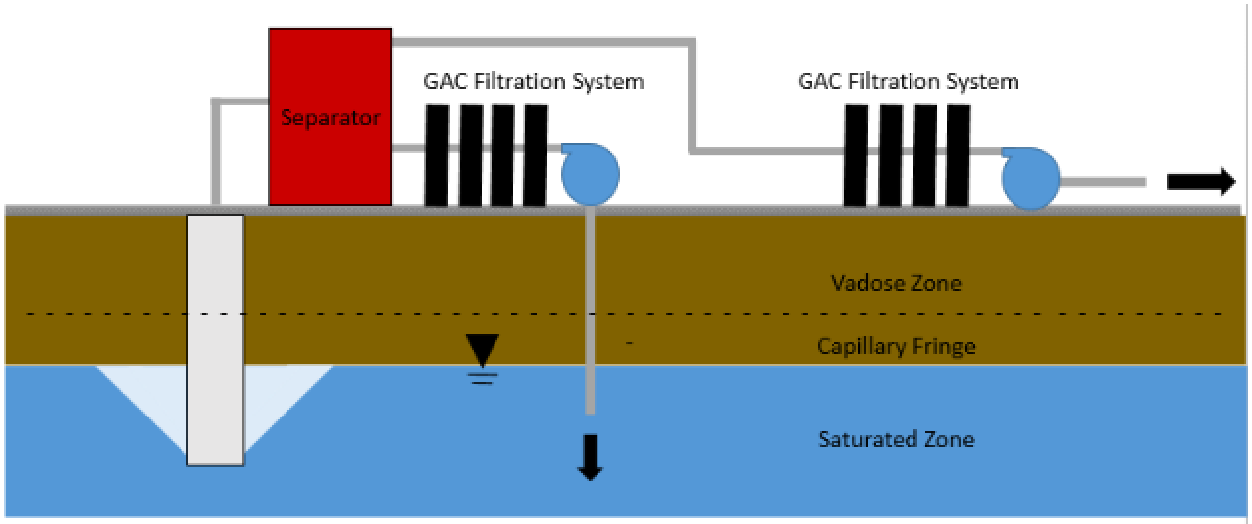


Figure 9. MPE System Diagram of Pumping Well and GAC Filtration System

Other equipment such as differential pressure gauges, pressure transducers and water level meters should be used to measure the pressure and water levels [18]. Hot wire anemometers and photo-ionization devices can be utilized during the testing procedures to get the air flow rate and quality by measuring the concentrations of substances such as organic carbon [18].

The recommended pilot test is expected to last for 4 days. Over the course of these 4 days, RR will implement pilot study tests outlined in Table 23.

Table 23. Overview of Pilot Testing Objectives and Testing Methods Needed Throughout Pilot Test Duration.

Day of Testing	Objective	Applicable Testing Method
1	Soil properties: hydraulic conductivity, transmissivity, porosity. Flow velocity, recovery and drawdown measurements, ROI, optimal extraction flow rate	Constant Rate Pumping Test
2	Optimal extraction flowrate (for dual phase recovery), effluent air flowrate and quality, recovered liquid flow rate (after separation), vacuum readings (applied and observed), extraction well drawdown.	Modified Step Drawdown Test
3	Extraction well flow rate (average), extraction well drawdown, vacuum readings (applied and observed), ROI (based on distance vs. vacuum graphs), effluent air flowrate and quality, recovered liquid flow rate (after separation), effective vacuum influence, groundwater flow changes.	Dual Phase Recovery Test
4	Injection capacity, injection depth, change in groundwater elevation, pressure changes, and total organic vapor changes.	Reinjection Examination Test

The constant rate pumping test may be performed at any of the monitoring wells to estimate the aquifer parameters such as the hydraulic conductivity and transmissivity as well as the radius of influence at a constant pumping rate [18]. Both the recovery and drawdown measurements are taken at specified time intervals using pressure transducers or water level meters to record water levels. An optimal flow rate would be determined at this stage as well.

The modified step drawdown test is performed in a similar manner to the previous test but the pumping at the extraction well occurs at higher flow rates [18]. The valves on the pump setup are used to increase the flow for nearly equal time steps to assess the optimal flow rate for the following dual phase recovery test. The effluent stack is measured for the flow rate and quality using a hot wire anemometer and photo-ionization device.

From the previous testing a specific flow rate in the dual phase recovery test should be decided on. During this phase of testing it would be decided if equal water and air flows cause a similar radius of influence [18]. Both water and vacuum levels in wells are measured in this case using pressure transducers and differential pressure gauges.

Before considering whether reinjection is possible or not, certain effects need to be tested to ensure the injection is performed in a way that does not negatively impact the subsurface [20]. This would be determined in the reinjection examination test. Initially, the well must be designed for optimum steady state injection capacity. The injection capacity of the well must be tested by injecting potable water for a at rate increasing flows for increasing time periods (50 gpm for one hour then 100 gpm for two hours) [20]. The reinjection step can then be considered feasible if the injected water does not back up and exceed the extraction well in head [20]. As reinjection can cause a rise in the elevation of groundwater, it should be monitored to ensure that this does not cause any rapid increases in pressure or total organic carbon [20].

3.3.3 Estimated Cost of Study

RR has broken down the cost for the MPE system using a Class 3 AACEI cost analysis, with a 20% contingency. A detailed cost analysis can be found in Appendix D, which outlines the cost of each individual part. Table 24 outlines a simplified cost analysis, which results in an estimated total cost for the MPE pilot study to be $38,173.

Table 24. Multi-Phase Extraction Pilot Study Cost Breakdown

Item	Estimated Cost[(a)]	Units	Site Cost
Well Installation			
Well Materials [25] [26] [27] [28] [29] [30] [31]	$3,795	N/A	$3,795
Mobilization (including excavation) [12]	$1,720	N/A	$1,720
10 HP Centrifugal Pump [32]	$4,310	1 unit	$4,310
3.0 HP Single Stage Liquid Ring Vacuum Pump [33]	$1,510	1 unit	$1,510
10.0 HP Single Stage Liquid Ring Vacuum Pump [33]	$4,930	1 unit	$4,930
500 Gal Liquid Gas Separator [34]	$1,000	1 unit	$1,000
5000 Gal Water Storage Tank [34]	$1,900	1 unit	$1,900
Testing Equipment			
Differential pressure gauge [35]	$45	1 unit	$45
Pressure transducers [36]	$90	1 unit	$90
Water level meters [37]	$510	1 unit	$510
Hot wire anemometers [38]	$510	1 unit	$510
Photo-ionization detector [39]	$3,500	1 unit	$3,500
GAC System [40]	$815	2 units	$ 1,630
Labor [41]	$12,723	N/A	$12,723
TOTAL			$38,173

[(a)] *2017 dollars. The basis for inflation calculations can be found in Appendix B.*

3.3.4 Environmental Impacts

MPE has minimal release of VOCs or contaminated water, since it simply extracts the contaminated water and vapor. Emissions exiting the GAC filter would have to be compliant with EPA standards, which assures that vapor emissions would not be harmful or toxic to the environment. RR would determine if water use is necessary to induce flow in the aquifer, and, if deemed necessary, can use the treated water that was previously extracted from the groundwater, which would help ensure no recontamination, and would help dilute the contaminant remaining in the aquifer, reducing the concentrations down to EPA standards.

Energy required for the MPE system depends on how easily water and vapor can extracted. The full energy requirement can be estimated after performing the Modified Step Drawdown Test, which would determine the optimal flowrate, as described in Table 23. Based on the energy required for the three pumps, the electricity source of the acquired energy would lead to the release of a certain level of carbon emissions throughout the procedure.

3.4 Air Sparging and Soil Vapor Extraction

To determine the effectiveness and collect data needed for full-scale design of air sparging and SVE on-site a pilot study is recommended. The implementation of air sparging and SVE will also include utilizing a GAC filtration system to treat off-gas emissions. Since the contaminants are listed as Hazardous Air Pollutants, using a GAC filter is necessary.

Goals of the air sparging and SVE pilot study are to determine the optimal air flow rate, radius of influence, horizontal well site applicability, and SVE effectiveness. The possible application of a horizontal well on-site makes air sparging preferable for use in an urban area.

3.4.1 Pilot Study Considerations

Implementation of air sparging includes using an air compressor to deliver air flow to the subsurface. When choosing a blower for the site, the pressure applied to the subsurface must be in between the minimum pressure needed to induce air flow (P_{min}) and the pressure applied that could fracture the aquifer ($P_{fracture}$). These parameters will need to be determined through further investigation of site parameters and installed well characteristics.

3.4.2 Site Layout

RR recommends the site layout displayed in Figure 10 to conduct the air sparging pilot study. However, in the absence of utility locates, the recommended well placement must be reviewed to ensure there is no obstruction of above ground or underground utilities.

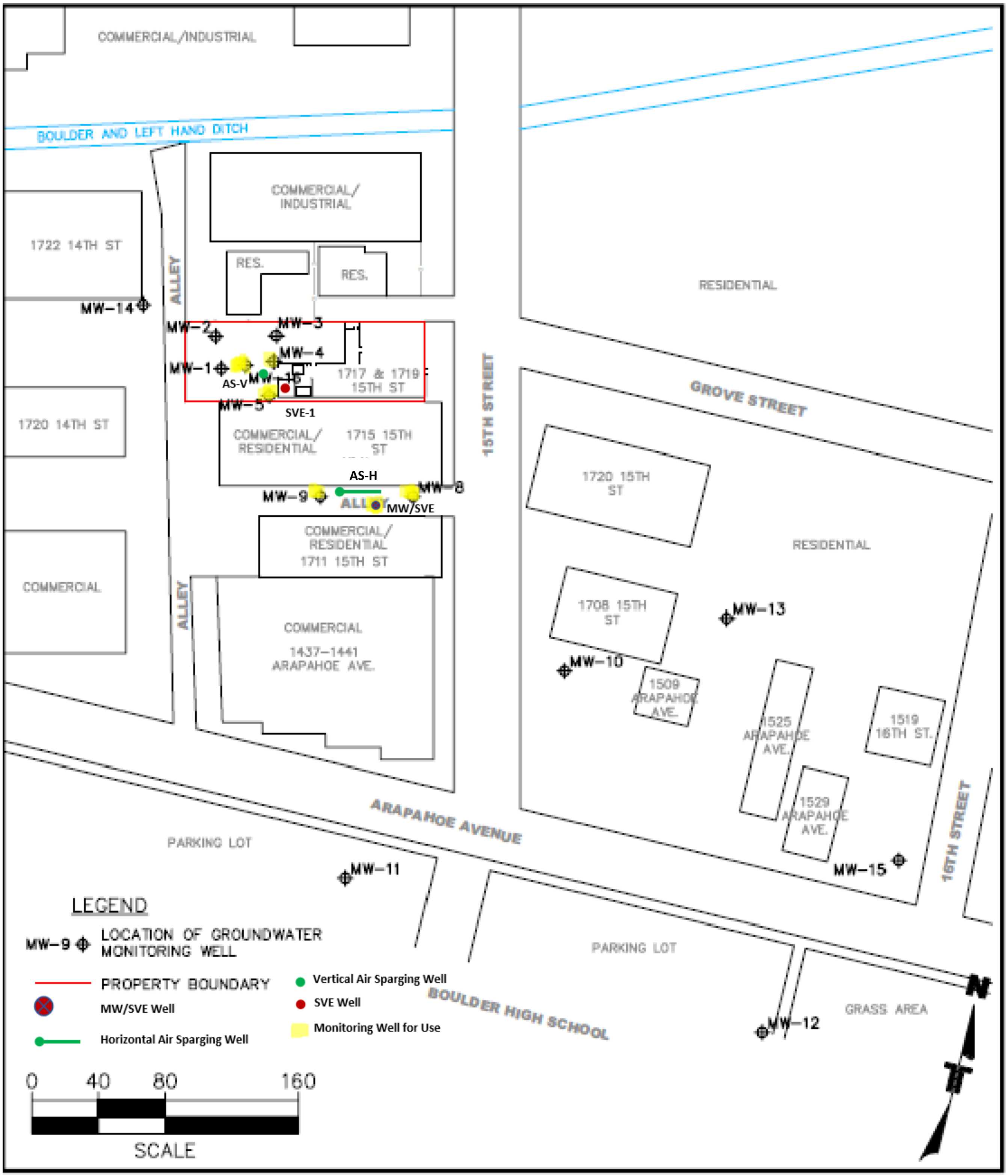


Figure 10. Air Sparging Pilot Study Layout

To reduce installation and equipment costs, RR recommends using existing infrastructure when possible. Each air sparging well will be surrounded by three monitoring wells, one upgradient, and two downgradient of the air sparging well. This is to ensure effects from the air sparging well can be monitored radially, providing information for air dispersion in multiple directions. The vertical air sparging well installed should be located in between monitoring wells 4, 5, and 16. The location of the vertical air sparging well is depicted as AS-V in Figure 10. For the vertical well, a 4-inch diameter PVC well casing will be used with 3 feet of screening beginning 1 foot below the water table to deliver optimal air flow. The total depth of the well will be 13 feet below ground surface (bgs). RR's recommended vertical air sparging well design is depicted in Figure 11.

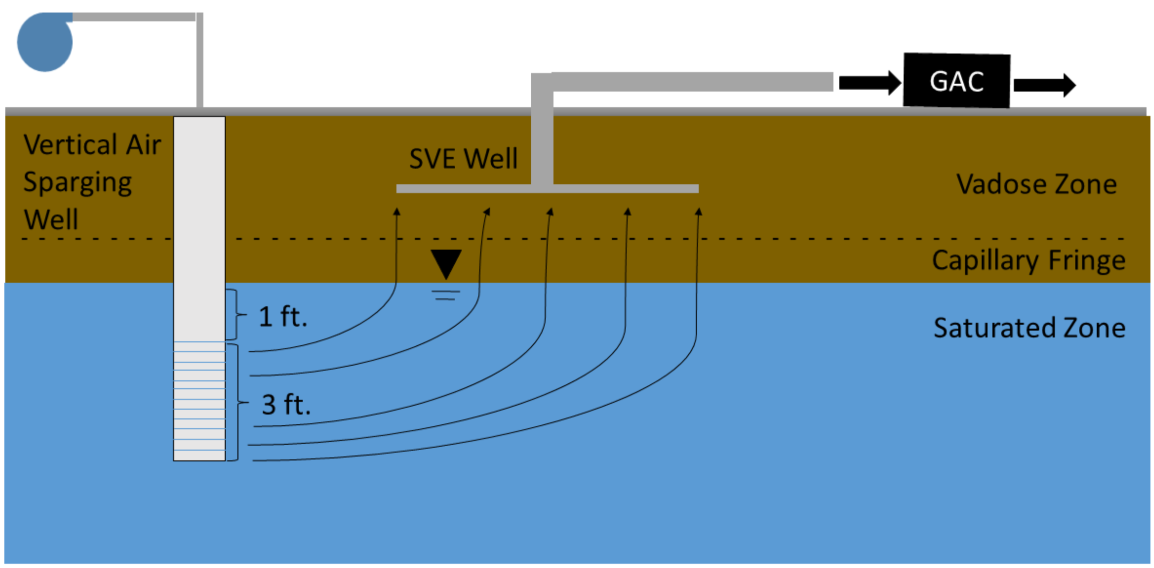


Figure 11. Vertical Air Sparging Well Recommendation

Per guidance of the CAP report provided by Terracon, there may be a SVE well located in the boiler room. This well should be utilized if the well is determined to be in acceptable, working condition. If not, RR recommends installing another SVE well in the boiler room with the same specifications as the previously installed SVE well (depicted as SVE-1). To avoid horizontal well placement under off-site buildings during pilot study, RR recommends installing a horizontal well in the alley (AS-H) as depicted in Figure 10 above. The horizontal well will utilize a 4-inch diameter PVC casing, installed to a total depth of 10 feet bgs, with 20 feet of well screening (shown in Figure 12).

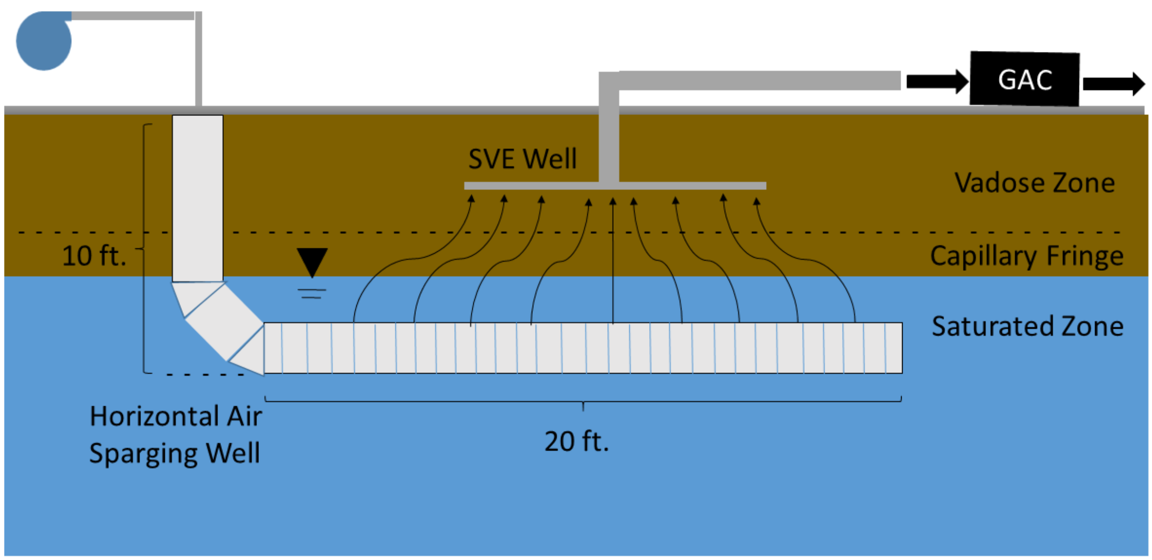


Figure 12. Horizontal Air Sparging Well Recommendation

Although this well placement does not initiate at the source of contamination, placing the well in the alley along the contamination plume will allow for use of two prior installed monitoring wells, only requiring the installation of one additional monitoring well (depicted as MW/SVE in Figure 10). RR proposes that the installed well should be fit with SVE equipment if determined the horizontal air sparging well is desirable on-site.

Three vapor monitoring points should also be installed around each air sparging well. Due to the shallow depth to groundwater and site geology, RR recommends installing the vapor monitoring points with hand augers where accessible, and measuring soil vapor contaminant concentrations with a photoionization detector.

3.4.3 Pilot Study Protocol

The air sparging and SVE pilot test is a three-day operation with objectives outlined in Table 10. This schedule does not account for baseline testing, which includes DO measurements and pressure transducer readings, because Terracon has conducted these measurements in the past. The temperature, DO, and groundwater level data previously gathered by Terracon serve as baseline measurements. The schedule also does not account for well installation, which would need to be completed before the pilot study.

Table 25. Pilot Test Schedule

Day of Testing	Objective	Applicable Testing
1	Air Sparging Horizontal Well Testing	DO Monitoring Soil Gas Monitoring Air Injection Flow Rate Air Injection Pressure Helium Tracer Testing Off-Gas Emissions
2	Air Sparging Vertical Well Testing	DO Monitoring Soil Gas Monitoring Air Injection Flow Rate Air Injection Pressure Off-Gas Emissions
3	Air Sparging Well Test with SVE	Helium Tracer Testing

Necessary equipment for pilot study includes a compressor that can deliver up to 25 cfm of air flow, sampling equipment, well installation equipment, helium injection equipment, and soil vapor extraction equipment including a vacuum to extract 20 cfm of soil vapors. RR will be using 20 cfm for the SVE system flow rate, as predetermined by an earlier pilot test conducted on-site by Terracon.

3.4.2.1 Well Testing

The first two days include testing both a horizontal and vertical air sparging well to determine which performs better on-site. Horizontal wells allow access to the plume located underneath buildings, and would be optimal for use on-site [12]. However, horizontal wells may not be feasible due to lack of uniform air distribution in certain geological conditions [42]. Each well may undergo one day of testing performed in 2-hour cycles of air sparging pulses. Air injection pulsing has been shown to increase contaminant removal by changing air distributions and inducing macro-scale mixing within the aquifer [43]. Each sparging setup is recommended to run on a 2-hours on, 2-hours off cycle. RR also recommends using the SVE and GAC system during these two days to reduce the risk of soil vapor intrusion. The first two days of the pilot study will include the applicable testing outlined in Table 25.

3.4.2.1.1 Air Injection Flow Rate Optimization

Typical air sparging operations use air flow rates ranging from 3 to 25 cubic feet per minute (cfm) [44]. To determine the optimal flow rate, RR recommends testing three flow rates: starting with 20 cfm, and adjusting to fit pressure requirements. Each rate should be tested for 2 hours, unless the imposed pressure is less than the minimum pressure needed to induce air flow, or greater than the fracturing pressure. Pressure measurements should be taken at the monitoring wells every 10 minutes from startup and shutdown of air flow until the pressure and flow stabilize [43].

3.4.2.1.2 Groundwater Pressure Measurements

Groundwater pressure measurements provide information on permeability and distribution of air flow on-site. Measurements should be taken in each of the three surrounding monitoring wells during start up and shut down. These measurements can be used to determine at what time the air flow reaches steady-state within the subsurface by measuring the time it takes the groundwater to reach pre-air sparging pressure measurements [43].

3.4.2.1.3 Helium Tracer Testing and Dissolved Oxygen Monitoring

RR recommends helium tracer testing for determining the effectiveness of horizontal well air sparging on Day 1. The helium test will be conducted in a one hour segment of the day, following the air flow rate testing. Using helium as the injected substance for the air sparging system allows for simplified detection of air distribution on-site. Since there is uncertainty in distribution of air along the entire screened section of the horizontal well, measuring for helium at the three monitoring wells will allow for detection of air distribution along the entire screened portion. RR also recommends installing vapor monitoring points along the screened section of the well to test for helium.

Dissolved oxygen monitoring is recommended for both Day 1 and Day 2 to determine the extent of air movement using the horizontal and vertical air sparging wells. Dissolved oxygen measurements are recommended every hour throughout the entire testing period.

3.4.2.1.4 Off-Gas and Soil Vapor Sampling

Off-gas emissions should be sampled while the air sparging system is running to ensure minimal contaminant emissions are released, and that all off-gas emissions are in compliance with national standards. Soil vapor monitoring should be used to measure volatilized contaminants in the subsurface soil vapors.

3.4.2.1.5 Determining Well Configuration

RR recommends the use of the horizontal well if the air is distributed throughout the entire screening section of the well. The use of a horizontal well for full scale remediation would allow for less wells to be installed. However, if air distribution is not throughout the entire screened section, RR recommends further testing of the vertical air sparging well with the SVE system.

3.4.2.2 Air Sparging with SVE Testing

The effectiveness of the SVE system in conjunction with the most suitable air sparging operation will be tested on the third day. A helium tracer test can be used to determine the radius of influence for the air sparging and SVE system. Helium was chosen as the tracer due to the low cost and can be detected through readily available equipment [43]. A typical setup for helium tracer testing is depicted in Figure 9 [43].

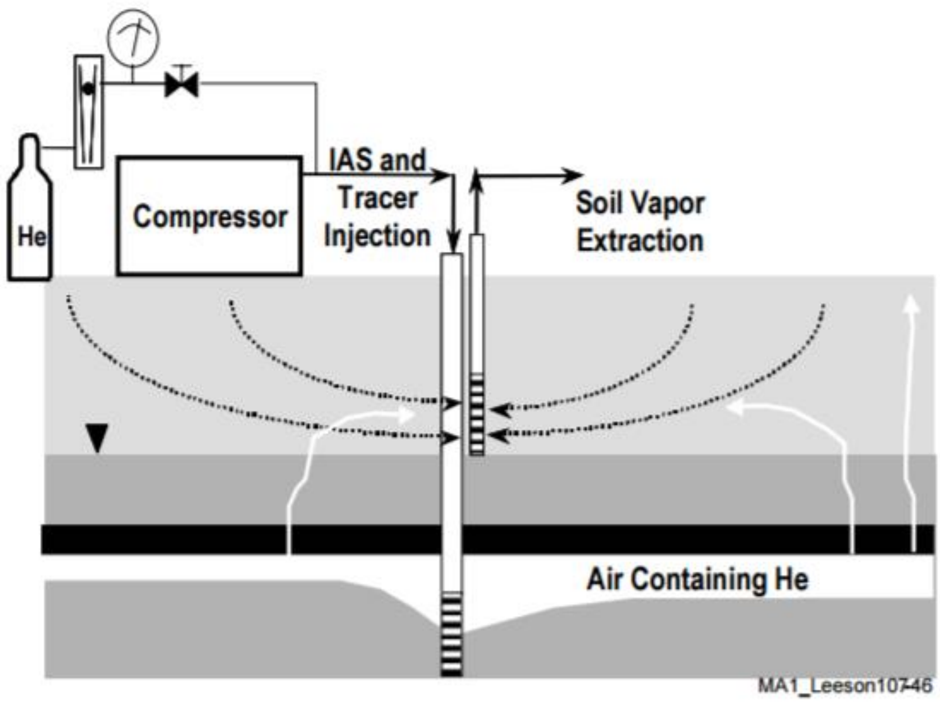


Figure 13. Typical Helium Tracer Testing for SVE Effectiveness

The air sparging well can be used to inject helium at a predetermined rate (from previous data from pilot testing). The helium concentration needs to be below 10% by volume to ensure absence of buoyancy affects in the vadose zone [43]. The SVE recovery can be calculated using

Equation 3 below [43]. If the percent recovery is determined to be greater than 80%, the SVE system is efficiently recovering the lateral movement of air below ground surface.

$$\% Recovery = \frac{SVE\ Flowrate}{Trace\ Injection\ Rate} * \%\ tracer\ in\ offgas * 100 \tag{3}$$

3.4.4 Estimated Cost of Study

The estimated cost for the air sparging and SVE pilot study was conducted by comparison to equipment used in other pilot tests comparable to the 1717 15th street site, EPA design guidance documents, and equipment retailer costs. This Class 3 AACEi cost analysis has a 20% contingency. A specific breakdown of the cost estimate is available in Table 25. The total estimated cost for the pilot study is $24,435.

Table 26. Air Sparging Pilot Study Cost Breakdown

Item	Estimated Cost[(a)]	Units	Site Cost
Well Installation			
Monitoring Well [12]	$48/ft depth	18 ft.	$870
Horizontal Air Sparging Well [45]	$124/ft length	20 ft.	$2,480
Vertical Air Sparging Well [12]	$35/ft depth $1,719 Mobilization	13 ft.	$2,175
Helium Tracer Test [46]			$560
Helium Cylinder:	$52	1 unit	
Flowmeter:	$131	1 unit	
Pressure Gauge:	$78	1 unit	
Helium Detector:	$235	1 week rental	
Fittings/tubing:	$63	1 unit	
Monitoring Equipment			
Pressure Transducer [36]	$90	1	$90
Photoionization Detector [39]	$3,500	1	$3,500
Labor [41]	$12,723	N/A	$12,720
SVE System [47]	$800	1 week rental	$800
Air Sparging System [47]	$800	1 week rental	$800
GAC System [48]	$22/cfm	20 cfm	$ 440
TOTAL			$24,435

[(a)] 2017 dollars. The basis for inflation calculations can be found in the Appendix Section B

3.4.5 Environmental Impacts

Due to contaminant volatilization, soil vapor intrusion is a major concern when implementing air sparging, especially in densely populated areas. However, implementation of soil vapor extraction can reduce the risk of soil vapor intrusion by capturing the soil vapors. Another major concern is off-gas emissions collected by the SVE system. Although RR recommends using a GAC filter rated for 20 cfm (the flow rate of the SVE system), the GAC system is not 100% efficient. RR will ensure all off-gas emissions are below EPA standards.

Energy requirements for air sparging and SVE are mainly contributed to the air compressor and vacuum. The use of this equipment and energy source also contributes carbon emissions.

4. Pilot Study Design Summary

RR recommends implementing all designed pilot studies (MPE, bioremediation, and air sparging) if feasible. A summary of the cost and time requirement for each pilot test is outlined in Table 26.

Table 27. Pilot Study Cost and Duration

	Air Sparging and SVE	**Bioremediation**	**Multi-Phase Extraction**
Estimated Total Cost for Pilot Test	$24,500	$26,000 - $55,200	$38,000
Pilot Test Duration	3 days	2 – 6 months	4 days

Review of the designed pilot studies must be completed before implementation. The suggested well location sites and depths must be verified through a utility locate and groundwater depth measurements before each pilot test is conducted.

It is important to note the cost listed for each pilot test is not the full scale remediation cost. These costs are in addition to the estimated full scale remediation cost presented in Table 5. The pilot test duration time is also in addition to the estimated full scale remediation times listed in Table 7.

5. Conclusion

RR has designed three different pilot studies for the remediation technologies found to be most favorable through the different criteria valued by Terracon.

The pilot studies have been designed to determine the parameters needed to evaluate the applicability and efficiency of the technology to remediate the contamination on site as well as provide sufficient information to take the technology to a full-scale application. The pilot test may be modified as more information about the utility locates is received.

If all three pilot tests may not be conducted, the choice for the pilot test to be applied will depend on the priorities of the client as well as the financial capability. If the client was to choose the alternative with the lowest pilot study cost, air sparging and SVE would be recommended. Multi-phase extraction would be a better choice to test if the time to remediation is most important to the client. In the case that a more easily implemented technology is preferred, with smaller impact to the surrounding area, bioremediation would be the recommended technology for pilot study.

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Appendix

Appendix A: Site Map

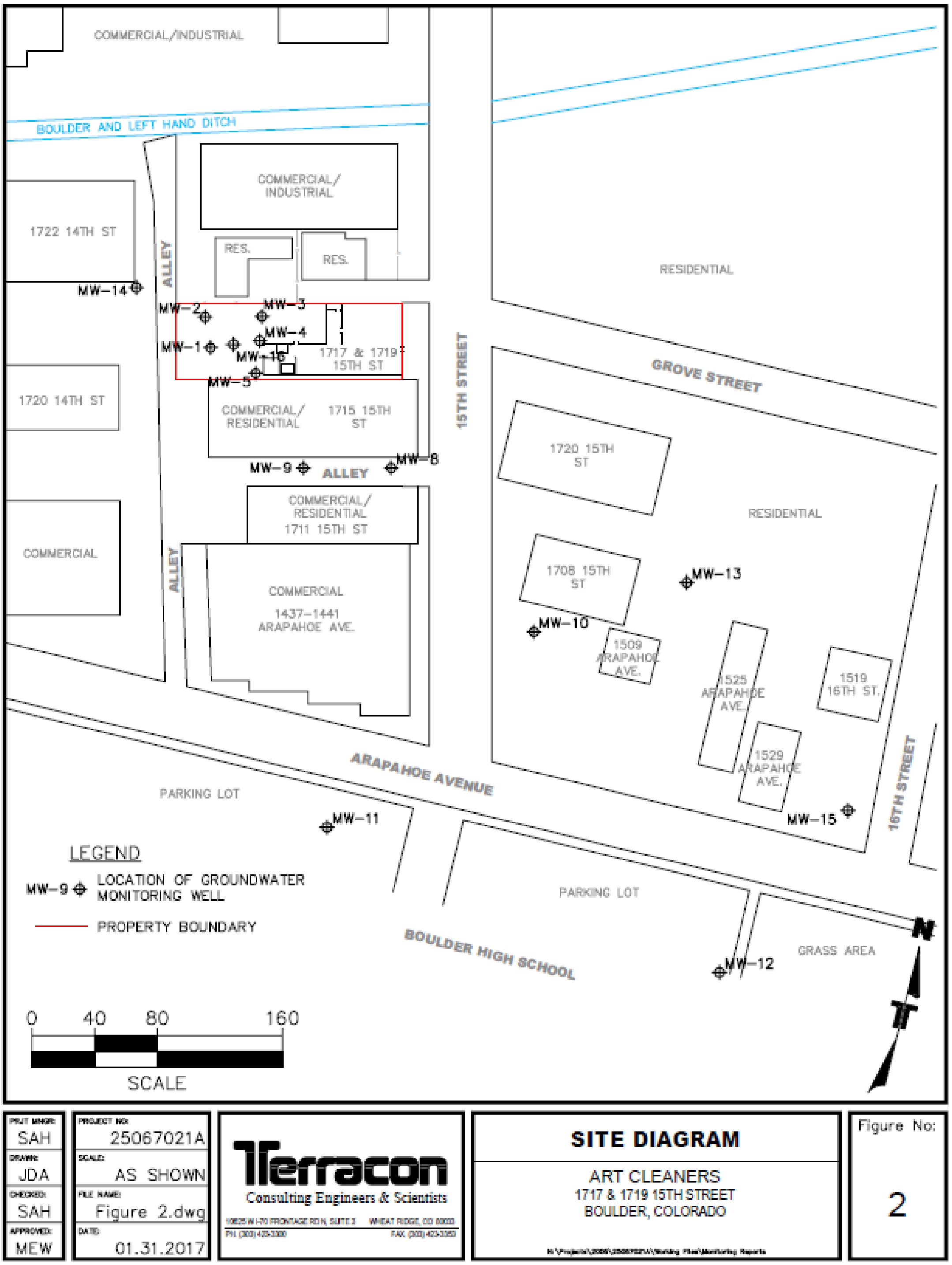

Figure 14. Terracon's Site Map

Appendix B: Inflation Calculations

$$Price_{2017} = Price_{year\ x} * \frac{CPI_{2017}}{CPI_{year\ x}}$$

Table 28. CPI Values for Inflation Calculations

Year X	CPI X
2001	177.1
2004	188.9
2009	214.37
2012	229.59
2013	232.96
2017	243.8

Appendix C: Bioremediation Pilot Study

C.1. HRC®

*Calculations based off Portland, Oregon pilot study using HRC®

**Costs in 2004 dollars, converted to 2017 dollars for report content

***Quality check by: Sarah Jaraha

Mass of HRC® for one injection:

$$\frac{Mass\ of\ HRC^{®}}{Number\ HRC^{®}\ injection\ points} = \frac{1{,}900\ lbs\ HRC^{®}}{22\ injection\ points} = 86.4\ lbs\ HRC^{®}$$

Cost of HRC® and shipping:

$$Cost\ of\ HRC^{®}\ per\ pound * pounds\ HRC^{®} = \frac{\$21{,}000}{2{,}600\ lbs\ HRC^{®}} * 86.4\ lbs\ HRC^{®} \approx \$700$$

Cost for injection point:

$$\frac{Cost\ of\ injection\ points}{Total\ number\ injection\ points\ (HRC^{®}\ and\ \mathrm{HRC-X^{™}})} = \frac{\$8{,}000}{27\ injection\ points} \approx \$300$$

Installation labor for one day:

$$\frac{Cost\ of\ installation\ labor}{days\ of\ labor} = \frac{\$4{,}000}{3\ days} \approx \$1400$$

Monitoring Labor:

$$Monitoring\ labor\ cost\ per\ day * Number\ of\ days = \frac{\$6{,}500}{8\ days} * 2\ days \approx \$1{,}600$$

Lab Analysis:

$$Cost\ per\ well\ per\ day * number\ of\ days * number\ of\ wells\ = \frac{\$12{,}800}{8\ wells * 4\ days} * 2\ days * 1\ well$$
$$= \$800$$

C.2. Molasses

*Calculations based off NWIP pilot study using molasses

**Costs in 2001 dollars, converted to 2017 dollars for report content

***Quality check by: Sierra Flori

Injection well cost:

$$Price\ of\ well\ per\ foot * number\ of\ feet = \frac{\$2000}{25\ feet} * 19\ feet \approx \$1{,}500$$

Storage and delivery of equipment:

$$Price\ per\ injection\ point * number\ of\ injections$$
$$= \frac{\$900}{injection\ per\ point} * 20\ injections * 1\ point = \$1{,}800$$

Groundwater sampling:

$$Price\ per\ sampling\ event * number\ of\ sampling\ events$$
$$= \frac{\$400}{sampling\ event} * 2\ sampling\ events = \$800$$

Analytical Fees:

$$Price\ per\ analytical\ event * number\ of\ analytical\ events$$

$$= \frac{\$1000}{analytical\ event} * 2\ sampling\ events = \$2000$$

Water requirement:

$$600\ gallons\ of\ 10\%\ diluted\ solution - 0.1(600) = 540\ gallons\ water$$

C.3. Blower

*Calculations based off cost sheet from New Hampshire Petroleum Reimbursement Fund Program

**Costs converted to 2017 dollars for report content

***Quality check by: Sierra Flori

Compressor:

$$Price\ per\ half\ day\ rental * number\ of\ half\ days = \frac{\$80}{half\ day\ rental} * \ 6\ half\ days = \$480$$

Injection wells:

$$Price\ of\ well\ per\ foot * number\ of\ feet = \frac{\$12}{foot} * 19\ feet \approx \$230$$

Labor:

$$Price\ per\ day\ of\ labor * days\ of\ labor = \frac{\$115}{day} * 3\ days \approx \$350$$

C.4. All bioremediation technologies

*Calculations based off NWIP pilot study using molasses

**Costs in 2001 dollars, converted to 2017 dollars for report content

***Quality check by: Sierra Flori

Monitoring well cost (HRC®, molasses, and blower):

$$Price\ of\ well\ per\ foot * number\ of\ feet = \frac{\$2500}{25\ feet} * 44\ feet \approx \$4{,}400$$

Table 22 Total Costs:

$$Total\ HRC\ and\ blower\ cost = cost\ of\ HRC + cost\ of\ blower = 23{,}760 + 2{,}260\ \approx 2{,}600$$

$$Total\ HRC, blower, and\ molasses\ \ cost = cost\ of\ HRC + cost\ of\ blower + cost\ of\ molasses$$
$$= 23{,}760 + 2{,}260 + 29{,}200\ \approx 55{,}200$$

Appendix D: MPE Pilot Study

Cost of Well Casing

Assume 19 ft deep wells, and in each well 2 ft cement seal, 5 ft bentonite/soil slurry, and 12 ft gravel/sand pack.

Volume of cement for pumping well = $[\pi r_{outer}^2 - \pi r_{inner}^2]*D$

= $[\pi(1\text{ft } 4\text{ in})^2 - \pi(4\text{in})^2]*2\text{ ft} = 10.5\text{ ft}^3$

Volume of cement for monitoring and injection well = $[\pi r_{outer}^2 - \pi r_{inner}^2]*D*4$ wells

= $[\pi(1\text{ ft } 2\text{ in})^2 - \pi(2\text{ in})^2]*2\text{ ft}*4 = 33.5\text{ ft}^3$

Total Volume of cement = $10.5\text{ ft}^3 + 33.5\text{ ft}^3 = 44\text{ ft}^3 = 1.7\text{ yd}^3$, assume 2 for excess

Cost of cement = volume * cost/volume = $2\text{ yd}^3 * \$90/\text{yd}^3 = \$180$

Surface area of bentonite/soil slurry for pumping well = $2\pi rD = 2\pi(4\text{ in})(5\text{ ft}) = 10.5\text{ ft}^2$

Surface of bentonite/soil slurry for monitoring and injection well = $2\pi rD$ * 4 wells

$= 2\pi(2\text{ in})(5\text{ ft})(4) = 20.9\text{ ft}^2$

Total surface area of bentonite/soil slurry = $10.5\text{ ft}^2 + 20.9\text{ ft}^2 = 32\text{ ft}^2$

Cost of bentonite/soil slurry = Surface Area * Cost/ft^2 = 32 ft^2 * \$6/ft^2 = \$192

Volume of gravel pack for pumping well = $[\pi r_{outer}^2 - \pi r_{inner}^2]*D$

$= [\pi(1\text{ft }4\text{ in})^2 - \pi(4\text{in})^2]*12\text{ ft} = 62.8\text{ ft}^3$

Volume of gravel pack for monitoring and injection well = $[\pi r_{outer}^2 - \pi r_{inner}^2]*D*4$ wells

$= [\pi(1\text{ ft }2\text{ in})^2 - \pi(2\text{ in})^2]*12\text{ ft}*4 = 201.1\text{ ft}^3$

Total Volume of gravel pack = $62.8\text{ ft}^3 + 201.1\text{ ft}^3 = 263.9\text{ ft}^3 = 10\text{ yd}^3$, assume 10.5 for excess

Weight of gravel pack = yards of gravel pack *density of gravel pack = $10.5\text{ yd}^3 * 1.5 = 16$ tons

Cost of gravel pack = price per ton * tons = \$12.50/ton *16 tons = \$200

Cost of well casing = cost of cement + cost of bentonite/soil slurry + cost of gravel pack

= \$180 + \$192 + \$200 = \$572

Cost of Piping

In each well, 11 ft of screen PVC, 8 ft of blank PVC

In pumping well, 18 ft of drop pipe

Assume 100 ft of 4" PVC above ground

Cost of screen pipes = 11 ft * $15.00/ft + 11ft * $5.50 * 4 wells = $230

Cost of blank pipes = 8 ft *$14.00/ft + 8 ft * $5.00/ft * 4 wells + 100 ft * $5.00/ft = $775

Cost of plugs = $260 + 4 * $90 = $620

Cost of drop pipe = 18 ft * $2.10/ft = $37.80 = $40

Total cost of pipes = cost of screen + cost of blank + cost of plugs + cost of drop pipe

= $230 + $775 + $620 + $40 = $1665

Total cost of wells and piping = cost of piping + cost of well casing = $572 + $1665 = $2240

Sizing of GAC liquid filter [24]

Radius = 4 inches = 1/3 ft

Surface Area = $\pi r^2 = \pi(0.333 \text{ ft})^2 = 0.349 \text{ ft}^2$

Height = 4 ft

Volume = $0.349 \text{ ft}^2 * 4 \text{ ft} = 1.396 \text{ ft}^3$

To install 4 units, total Volume = 5.585 ft^3

Density of GAC filters = 125 lb/ft^3

Total mass = $125 \text{ lb/ft}^3 * (5.585 \text{ ft}^3) = 698.13$ lb

Price of Carbon = $1/lb (2007) = $1.17/lb in (2017)

Total Cost = $1.17/lb in (2017)* 698.13 lb = $81 (2017)

Table 29. MPE Cost Data

Item	Cost
10 HP Centrifugal Pump [32]	$4,310
3.0 HP Single Stage Liquid Ring Vacuum Pump [33]	$1,510
10.0 HP Single Stage Liquid Ring Vacuum Pump [33]	$4,930
Basket strainer [31]	$1,555
500 Gal Liquid Gas Separator [34]	$1000
GAC filter (Gas Treatment) [40]	$815
GAC filter (Liquid Treatment) [40]	$815
5000 Gal Water Storage Tank [34] Mobilization (including excavation) [12]	$1,900 $1,720
Labor [41]	$12,723
Total	$31,278
Well Material	
4" PVC Schedule 80 Blank [25]	$5/ft
8" PVC Schedule 80 Blank [25]	$14/ft
1 1/4" PVC Schedule 80 Drop Pipe [26]	$2.10/ft
4" PVC Schedule 80 Screen	$5.50/ft
8" PVC Schedule 80 Screen	$15/ft
4" PVC Schedule 80 Threaded Plug [27]	$90
8" PVC Schedule 80 Threaded Plug [27]	$260
Bentonite/soil slurry [28]	$6/ft^2
Cement [29]	$90/yd^3
Gravel/Sand Pack [30]	$12.50/ton
Total	$2240
Testing Equipment	**Cost**
Differential pressure gauge [35]	$45
Pressure transducers [36]	$90
Water level meters [37]	$510
Hot wire anemometers [38]	$510
Photo-ionization detector [39]	$3,500
Total	$4655
Total Cost	$38,173

Appendix E: Air Sparging Pilot Study Cost

*Calculations performed by Erin Johnson

**Calculations checked by Amanda Smokoff

***Please see Table 30 for references used to determine cost.

Well Installation Costs

Monitoring Well Cost = $48/ft * 18 feet = $870

Horizontal Air Sparging Well = $124/ft * 20 feet = $2,480

Vertical Air Sparging Well = $1,719 + ($35/ft * 13 feet) = $2,175

Helium Tracer Test Cost

Total Cost = Helium Cylinder Cost + Flowmeter + Pressure Gauge + Helium Detector + Fittings/Tubings

Monitoring Equipment

Pressure Transducer Cost = $90

Photoionization Detector Cost = $3,500

Labor = $12,723

SVE System = $800 for one week rental

Air Sparging System = $800 for one week rental

GAC System = $22/cfm * $20 cfm = $440

Table 30. Air Sparging Cost Data

Item	Estimated Cost(a)	Units	Site Cost
Well Installation			
Monitoring Well [12]	$48/ft depth	18 ft.	$870
Horizontal Air Sparging Well [45]	$124/ft length	20 ft.	$2,480
Vertical Air Sparging Well [12]	$35/ft depth $1,719 Mobilization	13 ft.	$2,175
Helium Tracer Test [46]			$560
Helium Cylinder:	$52	1 unit	
Flowmeter:	$131	1 unit	
Pressure Gauge:	$78	1 unit	
Helium Detector:	$235	1 week rental	
Fittings/tubing:	$63	1 unit	
Monitoring Equipment			
Pressure Transducer [36]	$90	1	$90
Photoionization Detector [39]	$3,500	1	$3,500
Labor [41]	$12,723	N/A	$12,720
SVE System [47]	$800	1 week rental	$800
Air Sparging System [47]	$800	1 week rental	$800
GAC System [48]	$22/cfm	20 cfm	$ 440
TOTAL			$24,435