Jackson Cleaners Environmental Remediation

A Technical Report submitted to the Department of Civil Engineering

Presented to the Faculty of the School of Engineering and Applied Science

University of Virginia • Charlottesville, Virginia

In Partial Fulfillment of the Requirements for the Degree

Bachelor of Science, School of Engineering

Spring, 2024

Technical Project Team Members

Stephen Branch

Evan Fee

Hannah Hockensmith

Eva Massarelli

Claire Sharp

Brianna Wright

On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

Acknowledgements

Sincere thanks to our faculty mentor Dr. Teresa Culver whose input helped direct our project. Special thanks to Geosyntec consultants Kate Villars and Sam Baushke who offered invaluable guidance and expertise throughout the project.

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I. Acronyms and Abbreviations

cDCE - cis-1,2-Dichloroethylene
COC - Contaminant of Concern
CSM - Conceptual Site Model
DCC - Direct Contact Criteria
DWC - Drinking Water Criteria
DWPC - Drinking Water Protection Criteria
EGLE - Michigan Department of Environment, Great Lakes, and Energy
Geosyntec - Geosyntec Consultants of Michigan, Inc.
GSIC - Groundwater to Surface Water Interface Criteria
GSIPC - Groundwater to Surface Water Interface Protection Criteria
NAPLs - Non-aqueous phase liquids
PCE - Tetrachloroethylene
SVIIC - Soil Volatilization to Indoor Air Inhalation Criteria
tDCE - trans-1,2-Dichloroethylene
TCE - Trichloroethylene
VC - Vinyl Chloride
VOC - Volatile Organic Compound

II. Introduction

Design Problem Statement

The purpose of this project is to design a remediation plan for the soil and groundwater at and surrounding a polluted site called Jackson Cleaners, located at 24 North Huron Street in Ypsilanti, Michigan. Remediation is necessary to eliminate the human health and environmental risks posed by tetrachloroethylene, PCE, and its daughter products which were historically released by a dry cleaning business, Jackson Cleaners, that operated on the site. This five-acre site contains PCE and its daughter products, trichloroethylene, TCE; cis-dichlorethylene, cDCE; and vinyl chloride, VC, which pose a risk to public health due to their toxicity and must be remediated as quickly and as thoroughly as possible.

Design and Site Risks

The contaminants of concern are highly toxic and are a danger to humans. PCE is classified as a likely carcinogen by the U.S. Environmental Protection Agency (EPA). Long-term exposure to PCE can create health issues such as kidney and liver problems, neurological issues, and increased risk of cancer ("Toxicological Profile for Tetrachloroethylene," 2019). Though PCE itself is dangerous, its daughter products are a greater concern. TCE is a carcinogen, and long-term exposure can cause liver damage and cancer ("Toxicological Profile for Trichloroethylene," 2019). VC is considered the most dangerous contaminant, as it has the strictest national drinking water maximum contaminant level. VC is a carcinogen that causes neurological effects, and long-term exposure can also cause liver damage and cancer (*EPA Technical Fact Sheet Re: Vinyl Chloride*, n.d.).

Leaving the groundwater untreated poses many serious risks. These risks include human health risks associated with the migration of vapors from the soil to indoor spaces. Additionally, there are environmental risks, as the pollutant plume could continue to spread in this groundwater system and eventually to other systems, such as the Huron River.

Multiple risks also arise from the potential treatment of the contaminated groundwater surrounding Jackson Cleaners. One of the largest risks of ex-situ treatment (removing the groundwater, treating it, then returning it clean) is that the contaminants will still need to be transported and disposed of, which increases the opportunities for human exposure. Additionally, the expense of this method could be an irresponsible use of public funds. Harm to the groundwater system could also occur from in-situ testing (keeping the water in the system, then treating), as biological processes can lead to the formation of dangerous daughter products of PCE. Along with these technical risks, there is the possibility of social risks. An important aspect of testing the groundwater and its health effects relies on entering homes and businesses. If data collectors are refused entry, the extent of the contamination and the associated risks could be underestimated and inaccurate.

Overall, the risks to human health posed by leaving the groundwater untreated outweigh risks of treating the water, as treatment can be highly engineered and monitored to minimize risks of creating PCE daughter products.

Remedial Action Objectives (RAOs)

RAOs are meant to guide the selection of an environmental remediation design to ensure the end result will aim to protect public health and the environment. RAOs we identified for the Jackson Cleaners site are listed below:

1. Reduce chemical concentration and mitigate migration pathways.
    - Treat site soils that have concentrations exceeding the Michigan EGLE groundwater-surface water interface protection criteria (GSIPC), which indicate the amount of a contaminant that is allowed to be present in soil.
    - Prevent harmful exposure via contact with soil and discontinue the movement of chlorinated solvents to groundwater by reducing concentrations of contaminants in the unsaturated zone to below Michigan EGLE groundwater-surface water interface criteria (GSIC), which represent the minimum allowable quality of surface water (Michigan Department, 2016). The EGLE criteria for soil and groundwater are shown in table 1 below.
    - Reduce concentrations of chlorinated solvents within groundwater to below GSIPC to mitigate risks of contaminants in the groundwater from migrating to the Huron River.

Table 1. EGLE GSIPC and GISC for Contaminants of Concern (COCs) (*Cleanup Criteria*, 2023)

Compound	GSIPC (µg/kg)	GSIC (µg/L)
PCE	1,200	60
TCE	4,000	200
c-DCE	12,000	620
t-DCE	30,000	1,500
VC	260	13
Naphthalene	730	11

2. Implement a long-term protective solution.
   - Provide a cost-effective and reliable cleanup solution that mitigates the risks of chemicals being exposed to humans or the environment.

Design Constraints

One of the constraints that the engineering design team faces is difficulty in gaining access to areas of the site due to the site being divided into numerous parcels. Each parcel owner must grant access to the team, and this may limit areas that we are able to conduct remediation. A major constraint for our design team was our inability to physically access the site as it is located in Michigan. Furthermore, the members of our team do not currently possess the needed OSHA training to work on a hazardous site. Additionally, we were constrained by the limited data we were given by Geosyntec. This means we were required to make some assumptions of the physical conditions of the site in order to design a remediation strategy. Furthermore, though more of a requirement rather than a constraint—the remediation must be designed to reduce the contaminants to federal and state acceptable standards.

Another constraint is that remediation projects are often drawn out due to bureaucratic procedure. Specifically, this site was briefly under EPA control for a time during this investigation. In addition to these constraints, we must also consider our budget when choosing a remediation technique, the most effective solution will be one in which all factors, including costs, are considered.

An additional constraint is the existence of underground utility lines throughout the site. These can be conduits for the migration of contaminants. The topography of the site slopes downward from west to east, and there is a difference of about 30 feet between the western portion of the site and the eastern portion. Contaminants will quickly and readily spread throughout the saturated zone because of the shallow depth of the water table. This shallow nature is largely due to the proximity of the site to the Huron River, creating an interface between surface flow and subsurface flow. Finally, as the site is in the Ypsilanti Historic District, any adverse effects the design may have on the site should be taken into consideration.

Design Stakeholders

This project was conducted under the mentorship of Geosyntec Consultants–an environmental consulting firm in charge of remediating the site. Our capstone team has assisted them in identifying possible remediation techniques using designs backed by relevant site data provided by Geosyntec. Our project was seen as an exploratory exercise with the goal of teaching our group about environmental remediation, rather than being a definitive service being provided to Geosyntec. As Geosyntec will not be implementing a remedial solution until 2025, the company may or may not use our recommendations depending upon whether new data arises after the completion of our work. Although Jackson Cleaners caused the contamination of this site, they have since closed and do not have the resources to fund the cleanup. As a result, the state of Michigan is the "client" of this project. If EGLE likes the proposed plan and associated cost estimate from Geosyntec, they will be funding the remediation implementation. All solutions developed to remediate the contamination must comply with EGLE. EGLE has its own regulations for the maximum contaminant levels of the pollutant of concern in this project and procedure for intervening in this public area. Additionally, the EPA has and will continue to assist with community engagement (US EPA, *Community Involvement Plan*, 2021). Aside from regulatory bodies, the residents and business owners of Ypsilanti, Michigan have a large stake in the project. Any intervention in the area will cause disturbance to their daily lives, but lack of intervention poses extreme risk to their health. If residents oppose intervention for reasons like not-in-my-backyard (NIMBY) or historical preservation, or deny Geosyntec access to their homes or land for testing purposes, it could cause serious delays to the project. If the contamination plume is left untreated, contaminants will enter the Huron River and anyone using the river could become a stakeholder in the remediation efforts.

Conceptual Site Model

Introduction

This conceptual site model (CSM) was developed to help stakeholders in the Jackson Cleaners remediation project understand the sources and nature of the contaminants, the extent of the contamination in the surrounding soil and groundwater, and the exposure pathways and potential receptors so appropriate remedial techniques can be chosen and applied. The extent of the area characterized by this CSM has been limited to the area east of the contaminant source location, a shed behind Jackson Cleaners. Geosyntec completed an initial conceptual site model in the *Site Investigation Report* which was released in April of 2020. Since that report, additional data has been gathered from multiple sources, including monitoring wells, pore water samples, and soil borings, which was used to create this updated model. This model is meant to be improved upon as more information is collected to garner further understanding of the contamination as the remediation process continues.

Description of Contaminant Sources, Pathways, and Receptors

As shown in Figure 1, the site extent in this CSM is the area between Jackson Cleaners and the Huron River. The western boundary is the block of N. Huron St, and the site runs eastward to the Huron River, with Michigan Ave. along the south boundary. The intersection of Pearl St and N. Huron St marks the northwest corner (EPA, n.d.). Jackson Cleaners, located at 24 N. Huron St, Ypsilanti, MI 48197 is in a “Center” zoned area, specified as a mixed-use area with historic buildings (2022, City of Ypsilanti). The parcel has been home to a dry cleaning operation since 1916, where perchloroethylene (PCE), a common cleaning solvent was used (Geosyntec, 2020). In 2019, when a nearby parcel, 2 W. Michigan, was being sold, an inspection found that Recognized Environmental Concerns (RECs) were on the premises. It was discovered that PCE and TCE were in the sub-slab soil gas, indoor air of buildings nearby, and in the groundwater. The source was found to be Jackson Cleaners, specifically a shed behind the premises, shown in Figure 1. The extent of the contaminant plume was studied through groundwater, soil, and exterior soil gas testing conducted by Geosyntec. Immediate mitigation technologies, such as carbon air purifying units (APUs) and sub-slab remediation systems, were implemented in contaminated buildings with owner approval (EPA, n.d.). Since the groundwater on the site is not used for drinking water, no action was immediately taken to address the groundwater contamination. In 2023, more testing was conducted and has been used to create this CSM.

Fig. 1. Google Earth image of site location that marks the contaminant source and proximity to the Huron River.

PCE can undergo reductive dechlorination via anaerobic biodegradation to produce the daughter products of TCE, cis- and trans-DCE, and VC, all of which have been found to be present at the remediation site. These compounds are highly mobile. They are volatile organic compounds (VOCs) meaning they rapidly evaporate under typical atmospheric conditions. In addition, at the source, they can percolate into the soils. Some will become soluble and be carried further in precipitation and groundwater. If contaminated groundwater discharges into the river, the river may too become impaired. Contaminated groundwater can also become a source of contamination to overlying soil, as the VOCs can re-volatilize back up into the soil gases.

The main pathway considered in this CSM is the leaching of the contaminants into the groundwater, and the secondary pathway considered is the groundwater entering the Huron River. Other pathways, not focused on in this CSM, include leaching into the soil gas, volatilization of the contaminants to spread into the soil gas and infiltrate buildings, and erosion of contaminated soil onto nearby land or water resources. See Figure 2 below for a depiction of these pathways.

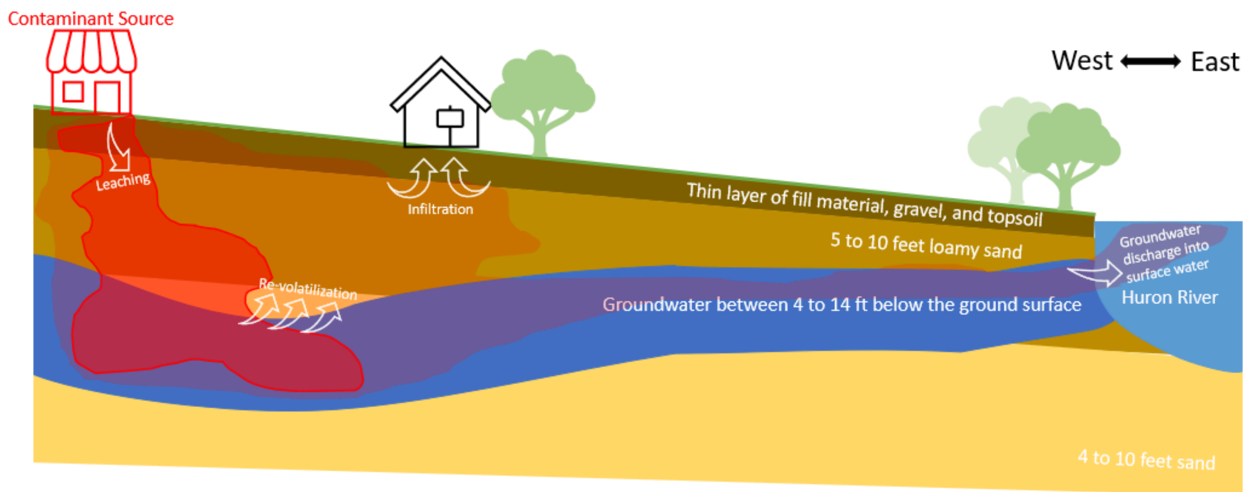


Fig. 2. Contaminant pathways and receptors.

Environmental receptors of the contaminants include the atmosphere, soil, soil gas, indoor air, groundwater, surface water (Huron River), and potentially underground utility pipes; see Figure 3 below for details on the contaminant release mechanisms and exposure media. Human receptors include the people residing or working inside buildings, people disturbing soil nearby, and people using the Huron River for recreational activities. Ingesting the chemical is not a major pathway or concern because city water is provided in place of groundwater use.

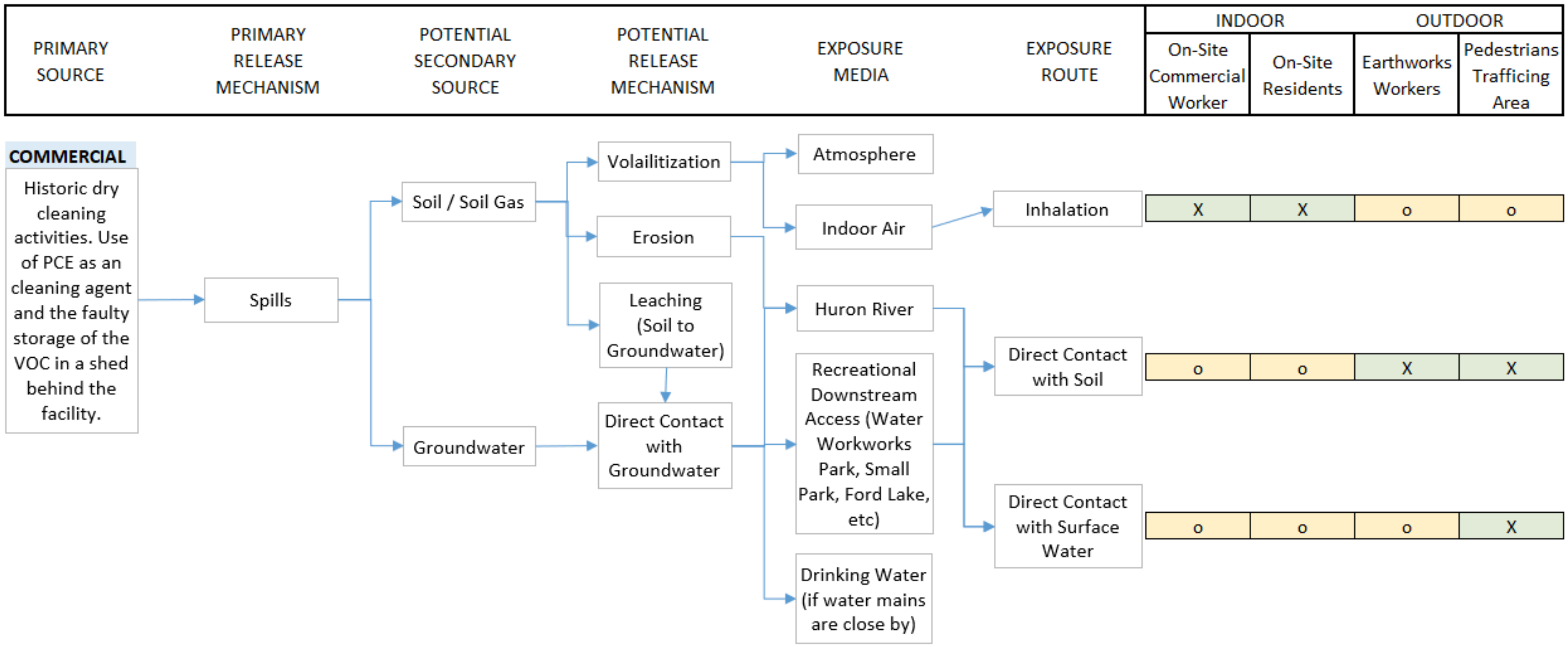


Fig. 3. Contaminant source, release mechanisms, and exposure medias. Green boxes with “X” indicate the identified human receptor may be at risk for chemical exposure through the exposure route.

Site Characterization

Groundwater Elevation

Groundwater elevation, shown below in Figure 4, is important to visualize how water may travel underground. This will help inform the likely movement of the contaminants.

Existing Utilities

Any design produced will have to take into account existing utility lines, see Figure 5. We will avoid utilities as part of our design.

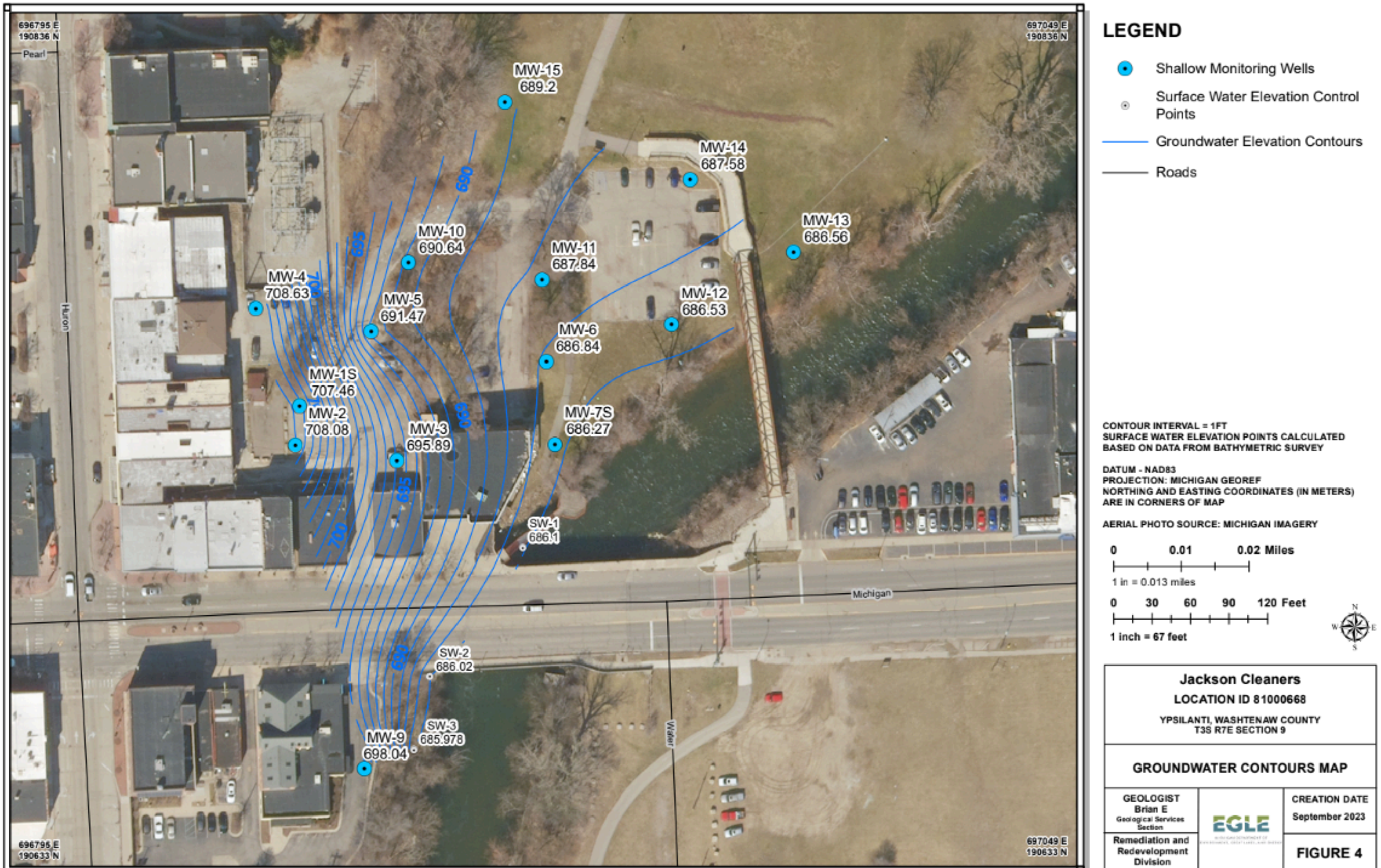


Fig. 4. Groundwater elevation around the Jackson Cleaners site (Geosyntec, *Request for Mixing Zone-Based GSI Criteria*, 2024).

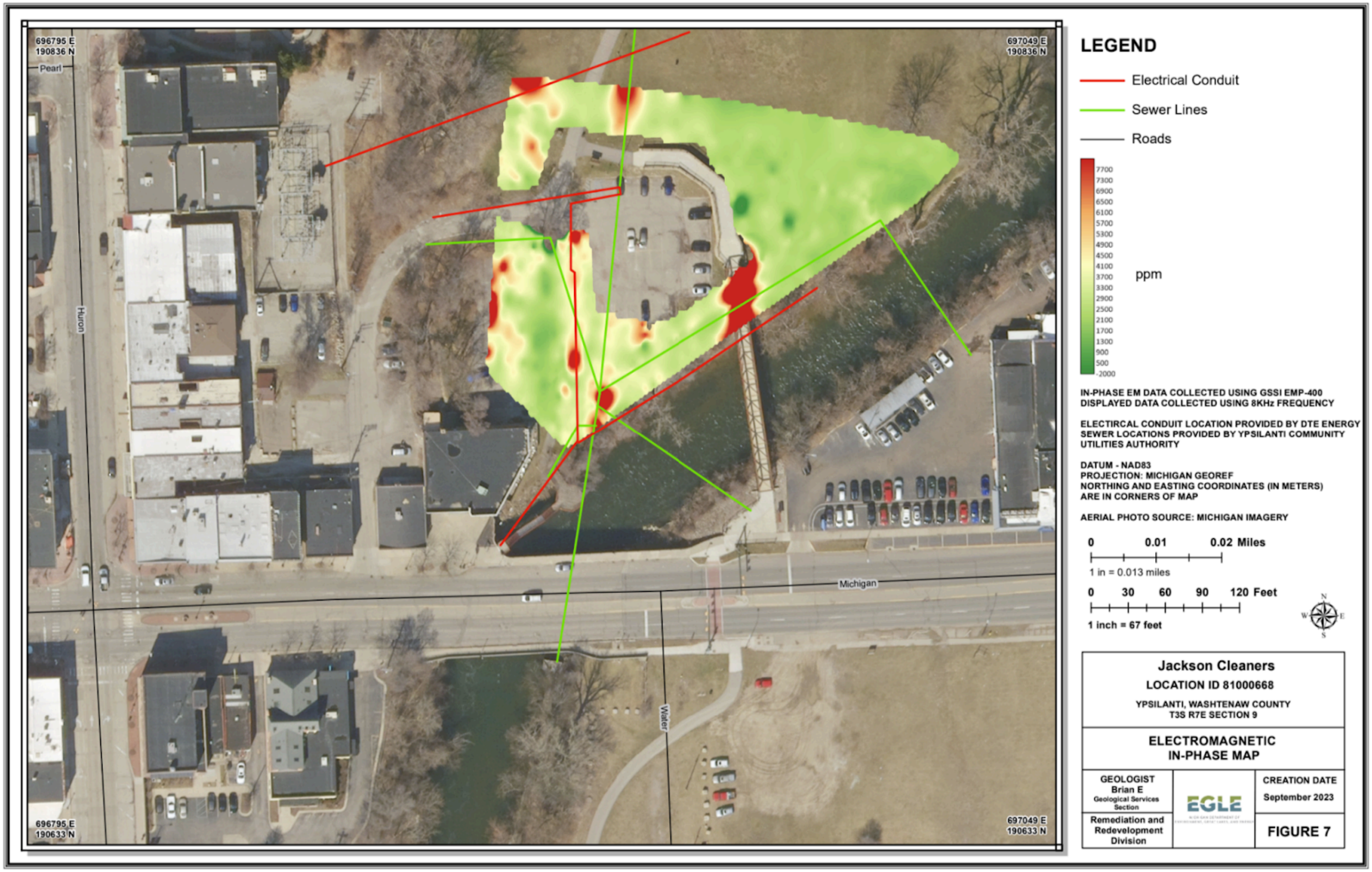


Fig. 5. Location of Electrical and Sewer Lines at the Jackson Cleaners Location (Geosyntec, *Request for Mixing Zone-Based GSI Criteria*, 2024).

Exposure Assessment

Characterization of the Contamination

In early September of 2023, Geosyntec collected field samples of the groundwater from monitoring wells, using a "peristaltic pump and dedicated tubing via a modified low-flow methodology" (Geosyntec, 2023). They also collected porewater samples. In the previous months of July and August, soil boring samples were gathered and tested. All of these samples were analyzed by the Michigan Department of Environmental Quality, and the results pertinent to our limited scope are shown below. Figure 6 shows the monitoring well locations with tables of the contaminant concentrations where they have been detected. Figure 7 depicts the geographical location of soil borings, and a table is provided to summarize the contaminant levels specified by depth below the ground surface. Finally, Figure 8 depicts the locations where porewater samples have been taken and identifies samples where contaminants were detected.

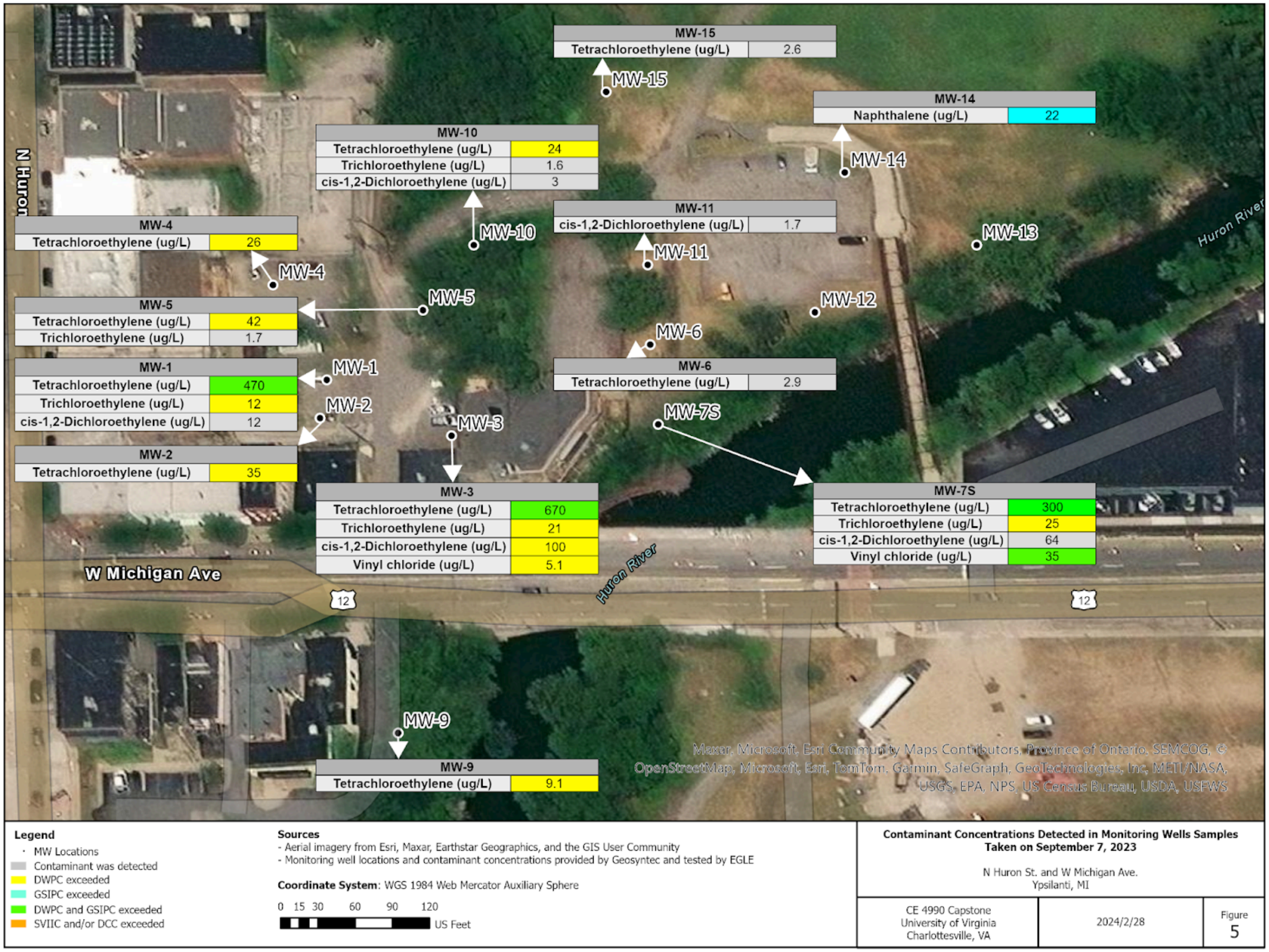


Fig. 6. Visual representation MW locations and contaminant concentrations at wells.

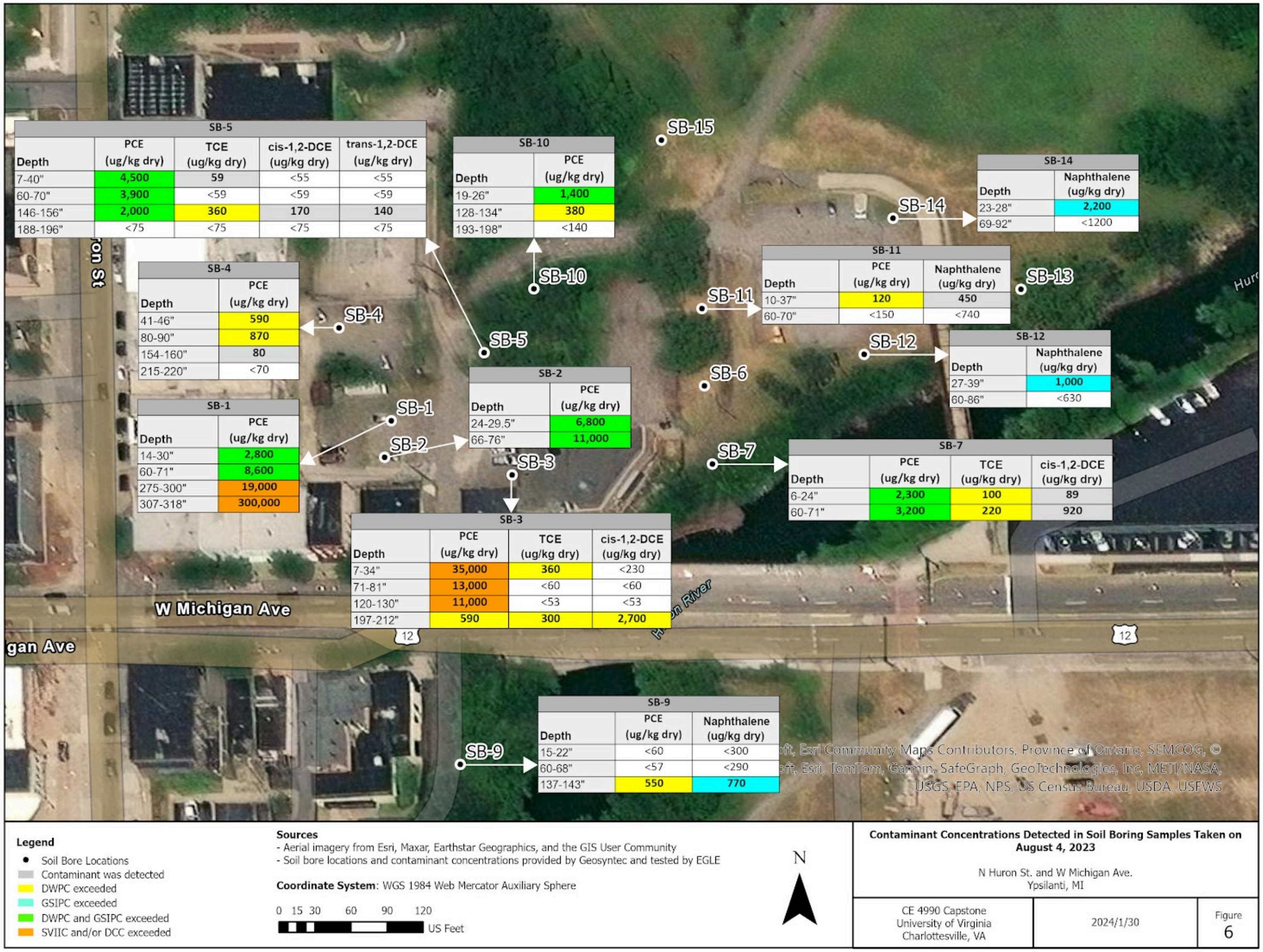


Fig. 7. Visual representation of contaminants at different depths in soil borings.

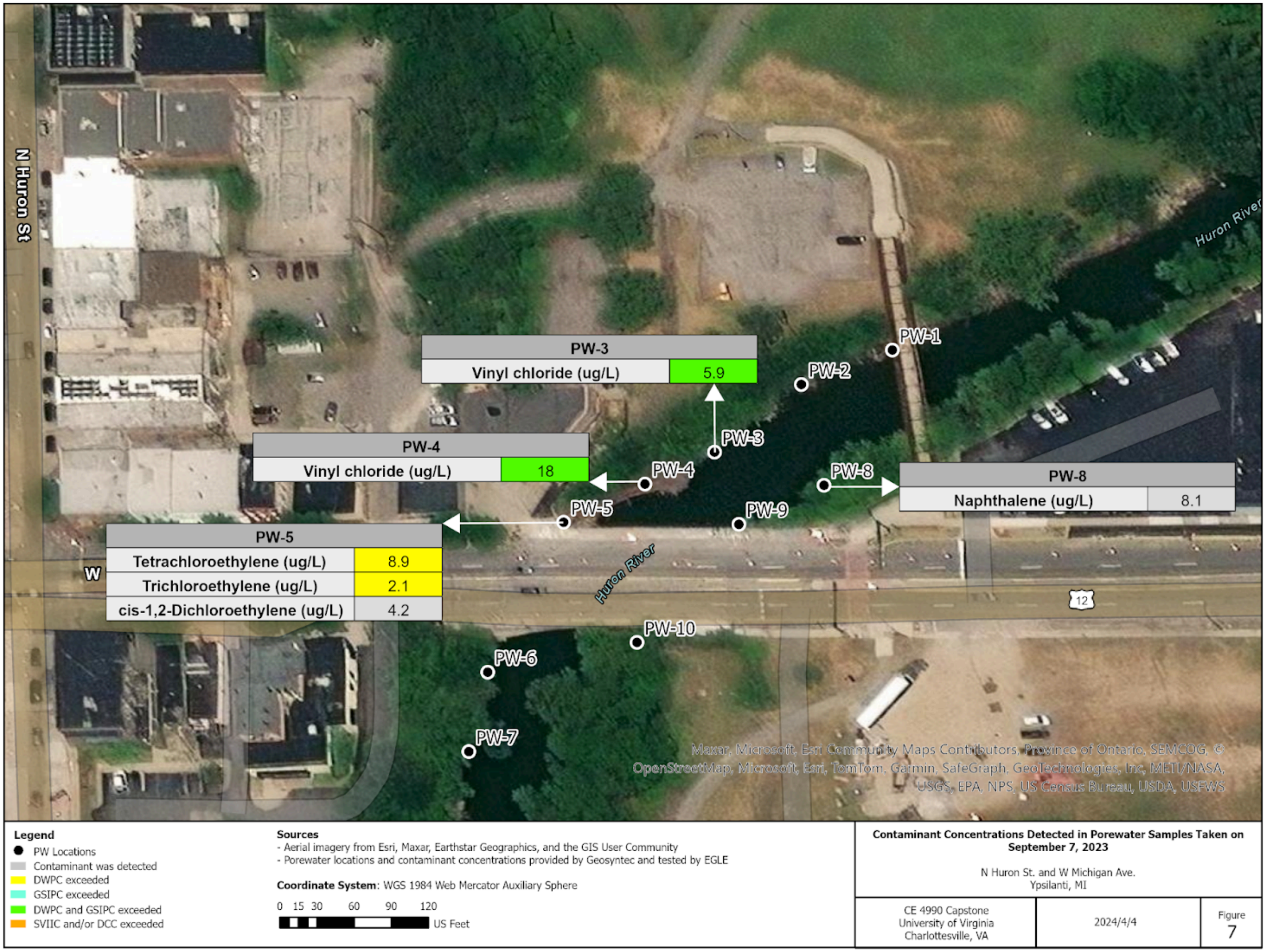


Fig. 8. Contaminant concentrations found in porewater samples in unsaturated zones.

III. Design

Comparative Analysis of Remedial Alternatives

In order to select a remediation technique appropriate for the characteristics and contamination of the Jackson Cleaners site, a remediation decision matrix was employed (Appendix B). The matrix examines a wide range of remedial technologies in three categories: chemical and biological techniques, physical removal techniques, and containment techniques. The categories and technologies explored were based on recommendations in the EPA guidebook, "Selecting Remediation Techniques for Contaminated Sediment." In the first round of evaluations, each technique was then evaluated based on its: 1) suitability for treating PCE and TCE; 2) longevity, including how often the system should need maintenance or replacement; 3) cost; 4) availability and relative ease of implementation; 5) ability or need to be coupled with other remediation methods; and 6) concerns or constraints that may limit its effectiveness for the particular site in Ypsilanti.

Several technologies were eliminated during this screening phase (Appendix B, Figure 18). Low-permeability barrier walls were removed from consideration because they only contain contaminants as opposed to reducing them, and these walls have limited effectiveness in the unsaturated zone. The pump and treat method was originally discounted due to it being a lengthy and costly process with high likelihood of rebound. However, when combined with other methods as reinforcement, it remained in consideration. In-situ chemical oxidation risks the creation of excess heat and gasses that can rise to the ground surface and create health concerns for both residents and the environment. The freezing of the ground during Michigan winters does not create suitability for excavation during winter months, in addition to the fact that excavation does not directly address aqueous or vapor phase contaminants. Six remediation technology combinations emerged as potential solutions for the Jackson Cleaners site: 1) Institutional and Engineering (I&E) controls 2) Multiphase Extraction 3) In-situ bioremediation 4) In-situ chemical reduction 5) Monitored Natural Attenuation (MNA) 6) Thermal conductivity/electrical resistance heating

The six alternative methods underwent a second screening phase which was done in discussion with Geosyntec consultants and a representative from EGLE. The thermal conductivity/electrical resistance heating was discounted for being too expensive. MNA leaves too much risk to the safety of the community in the lengthy time that would be required to see significant changes in contaminant levels. As a result of not being able to run any physical tests with the design at the site such as how the contaminants react to a particular biological medium, in-situ bioremediation was also ruled out. The two remaining methods of reducing COCs are permeable reactive barriers (PRBs) and soil vapor extraction (SVE), which were selected to proceed to design considerations.

Summary of Remedial Alternatives

1. **Institutional Controls**

The EPA defines institutional controls (ICs) as “non engineered instruments, such as administrative and legal controls, that help to minimize the potential for exposure to contamination and/or protect the integrity of a response action.” They are usually designed to limit land and/or resource use by providing information that guides or modifies human behavior at a contaminated site.

There are four main categories of institutional controls: proprietary controls, governmental controls, enforcement and permit tools with IC components, and informational devices. Proprietary controls are controls on land use that are private in nature because they typically apply to a single parcel of property and are created through a private agreement between the property owner and a second party who can enforce the rules. Governmental controls institute restrictions on land or resource use under the authority of a government entity. Enforcement and permit tools with IC components are legal tools that restrict certain site activities and require other activities. Informational devices provide information usually as recorded notice in property records or as advisories to local communities and other interested parties that contamination remains on site.

There were four institutional controls that were designed for this site. The first institutional control is a restrictive covenant detailing a resource use restriction. The groundwater at the Jackson Cleaners site was tested and found to contain levels of PCE, TCE, cDCE, VC, and lead that exceed the EGLE Residential Drinking Water Protection Criteria. A restricted zone should be created in which no drinking water wells can be installed due to the contaminated groundwater (Following Ypsilanti City Code Chapter 106, Article III, Division 3, Groundwater Wells). This institutional control addresses the drinking water pathway (ASTM 4.1.1).

The second and third institutional controls are also restrictive covenants, but they detail a land-use restriction. Soil samples that were collected at the site also contained levels of contaminants that exceeded EGLE criteria. Excavation activities on the site should be prohibited, unless required due to remedial activities. While surface water testing of the Huron River has not been conducted yet, given the ability of the contaminated groundwater to travel to the surface water, it is highly probable that the river is also contaminated. Porewater samples that were collected along the river adjacent to the site revealed contamination. Recreational use of the Huron river adjacent to the site should be restricted in order to protect the public.

Finally, informational devices should be instituted for the Jackson Cleaners site. These should include but are not limited to inputting the contamination into EGLE's Environmental Mapper system and a notice of contamination.

2. **Permeable Reactive Barrier (PRB)**

Preliminary Technical Assessment

The design of the permeable reactive barriers follows the methods in *An Overview of Permeable Reactive Barriers for In Situ Sustainable Groundwater Remediation*, *Design Guidance for Application of Permeable Reactive Barriers for Groundwater Remediation*, and *Zero-Valent Iron Permeable Reactive Barriers for In-Situ Treatment of Organics and Metals in Groundwater* (Obiri-Nyarko et al., 2014; Gavascar et al., 2000; Przepiora, A. et al., 2024).

The first step in designing a permeable reactive barrier for a contaminated site is the technical assessment. This involves initial research into the contaminants and site conditions. First, the contaminants must be identified in scientific and technical literature as amenable to degradation by suitable reactive media. The contaminants at this site are PCE, TCE, VC, and cDCE. These have all been identified as amenable to degradation by suitable reactive media (EPA, 2024). Next, the plume must be characterized by width and depth. Using data provided by Geosyntec, the plume is 330 ft. wide and 7 ft. deep. Very wide or very deep plumes will significantly affect the cost of application, but this plume is neither very wide nor very deep. Geologic features at the site could make installation more difficult. In the initial site investigation report, it was noted that there were some construction materials observed in multiple boreholes, so this will need to be considered when planning the installation. If the groundwater velocity is too high, the reactive cell thickness required to obtain the desired design residence time may also be high, causing the barrier to become costly. The groundwater velocity in the aquifer was calculated to be 0.75 ft./day, calculations shown below. This falls below the acceptable upper limit of 1 ft./day. With this preliminary technical assessment complete, a more in-depth characterization of the site can occur.

Characterization of the Site

Organic composition of the groundwater

The types and concentrations of chlorinated solvent compounds at the site are shown in table 2 below. This information will assist in the selection of an appropriate reactive media and the calculation of the thickness of the barrier.

Table 2. Organic Composition of the Groundwater

Well ID	PCE (ug/L)	TCE (ug/L)	c-DCE (ug/L)	t-TCE (ug/L)	VC (ug/L)	Naphthalene (ug/L)
MW-1	470	12	12	<1.0	<1.0	<5.0
MW-2	35	<1.0	<1.0	<1.0	<1.0	<5.0
MW-3	670	21	100	<1.0	5.1	<5.0
MW-4	26	<1.0	<1.0	<1.0	<1.0	<5.0
MW-5	42	1.7	<1.0	<1.0	<1.0	<5.0
MW-6	2.9	<1.0	<1.0	<1.0	<1.0	<5.0
MW-7S	300	25	64	<1.0	35	<5.0
MW-9	9.1	<1.0	<1.0	<1.0	<1.0	<5.0
MW-10	24	1.6	3	<1.0	<1.0	<5.0
MW-11	<1.0	<1.0	1.7	<1.0	<1.0	<5.0
MW-12	<1.0	<1.0	<1.0	<1.0	<1.0	<5.0
MW-13	<1.0	<1.0	<1.0	<1.0	<1.0	<5.0
MW-14	<1.0	<1.0	<1.0	<1.0	<1.0	22
MW-15	2.6	<1.0	<1.0	<1.0	<1.0	<5.0

Note. Figure 6 above shows this same data. Grey indicates contaminant was detected. Yellow indicates contaminant exceeds DWC. Blue indicates contaminant exceeds GSIC. Green indicates contaminant exceeds both DWC and GSIC.

Inorganic composition of the groundwater

The inorganic composition of the groundwater is important for evaluating the long-term performance of the PRB and for selecting an appropriate reactive media. Certain inorganics can affect precipitate formation which may alter the reactivity and hydraulic performance of the PRB. The selected reactive media may also affect the geochemistry of groundwater after implementation. The following characteristics are affected by zero-valent iron (ZVI), which is the selected reactive media (discussed further in the section "selection of reactive media"): 1) dissolved oxygen (DO); 2) pH; 3) dissolved H_2; 4) dissolved Fe(II); 5) carbonate alkalinity; 6) NO_3^-; and 7) SO_4^{2-}. The interaction of inorganic substances with the selected reactive media is discussed in more detail in the "Effects of Reactive Media Implementation" section. We do not know groundwater composition for substances 3 through 7, so we assume that these conditions are ideal for the purposes of site design. However, we do have data for pH and DO, shown in Table 3.

Table 3. Dissolved Oxygen and pH of groundwater (Geosyntec, *Jackson Cleaners Investigation Report*, 2020).

Well ID	DO (mg/L)	pH
MW-1	1.39	7
MW-2	4.72	7.23
MW-3	2.15	7.18
MW-4	N/A	N/A
MW-5	1.31	7.45
MW-6	1.14	6.96
MW-7S	0.31	7.06

Table 3 (continued).

MW-9	2.97	7.24
MW-10	4.12	7.25
MW-11	1.17	7.16
MW-12	0.74	7.01
MW-13	0.86	6.98
MW-14	0.64	7.13
MW-15	0.74	7.06

Geotechnical and Topographic Considerations

Near the river there are a number of sewer lines and electrical conduits that will need to be avoided during installation of the PRB, see Figure 5. In the initial site investigation report from Geosyntec, foundation and construction material were noted in multiple boreholes from the parking lot behind 24 N. The debris was observed approximately 1 to 5 ft below ground surface, interfering with the collection of groundwater samples which could present difficulties in the installation and monitoring of a PRB. The site's soil classification consists of 5 to 10 ft of loamy sand, followed by 4 to 10 ft of sand. There is precedent for the installation of PRBs at other locations with similar soil types. A cross-section depicting soil type and our proposed location for the PRB is depicted below in Figure 9.

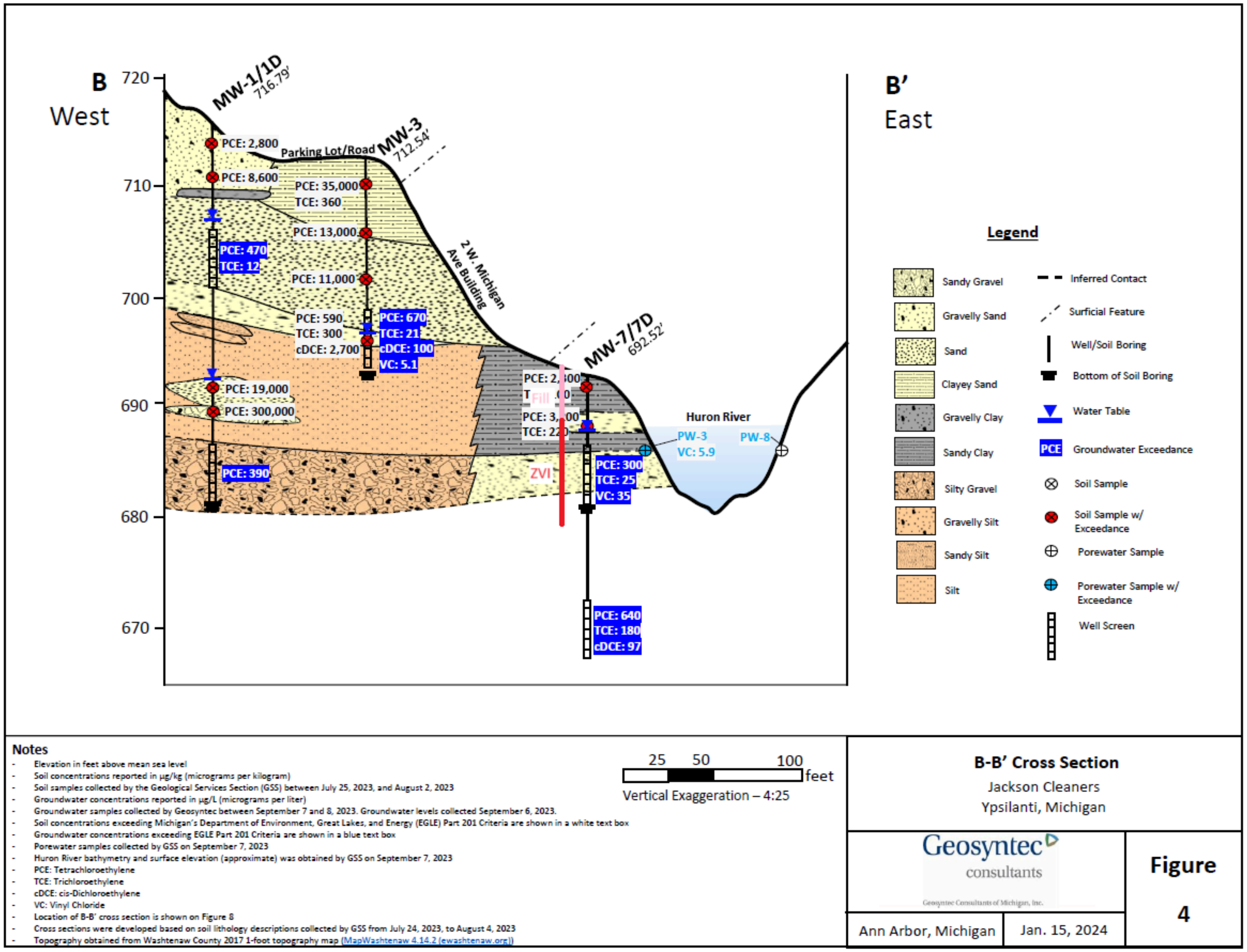


Fig. 9. Image of site cross-section generated by Geosyntec (Geosyntec, *Request for Mixing Zone-Based GSI Criteria*, 2024). PRB depth is shown with a red overlaid line. Fill depth shown in pink.

The topography at the site gradually slopes downward from west to east in the direction of the Huron River, with approximately 30 ft of elevation gain at the west end. Consideration of the slope must be taken into account when designing the PRB location and fill material.

Aquifer characteristics

The groundwater depths and hydraulic conductivities were acquired from data shared by Geosyntec. The velocity was calculated, with equation 1 below:

$$v = \frac{KI}{n_p} \quad \text{[equation 1]}$$

where K is the reactive media's hydraulic conductivity; I is the hydraulic gradient across the PRB; and n_p is the reactive media porosity. Hydraulic conductivity, K, was found to be 4.4 ft per day using an average of three of the geomean horizontal hydraulic conductivities calculated by Geosyntec that are closest to our proposed PRB location (*Request for Mixing Zone-Based GSI Criteria*, 2024).

$$K = \frac{K(MW6)+K(MW7)+K(MW11)}{3} = \frac{0.315\frac{ft}{day}+11.879\frac{ft}{day}+1.129\frac{ft}{day}}{3} = 4.44\frac{ft}{day}$$

To find the hydraulic gradient needed for the velocity equation, equation 2 was used:

$$I = \frac{h_{upgradient}-h_{downgradient}}{\Delta L} \quad \text{[equation 2]}$$

where I is the hydraulic gradient, h is the piezometric head, and ΔL is the horizontal distance between the two head locations. To find hydraulic heads, the averages of groundwater elevations from 3 monitoring wells upslope and downslope of the proposed PRB location, MWs 3, 5, and 10 for $h_{upgradient}$ and MWs 6, 7, and 11 for $h_{downgradient}$ (Monitoring Well_coords.xlsx data was used to calculate groundwater elevation, see Appendix D).

$$average\ h_{upgradient} = \frac{h(MW3)+h(MW5)+h(MW10)}{3} = \frac{695.89ft+691.47ft+690.64ft}{3} = 693ft$$

$$average\ h_{downgradient} = \frac{h(MW6)+h(MW7)+h(MW11)}{3} = \frac{686.84ft+686.27ft+687.84ft}{3} = 687ft$$

The distance between the points is averaged from the distances from MW-10 to MW-11, MW-5 to MW-6, and MW-3 to MW-7S. Distances were found using ArcGIS Pro's measure tool. Results of the tool are shown below in Figure 10.

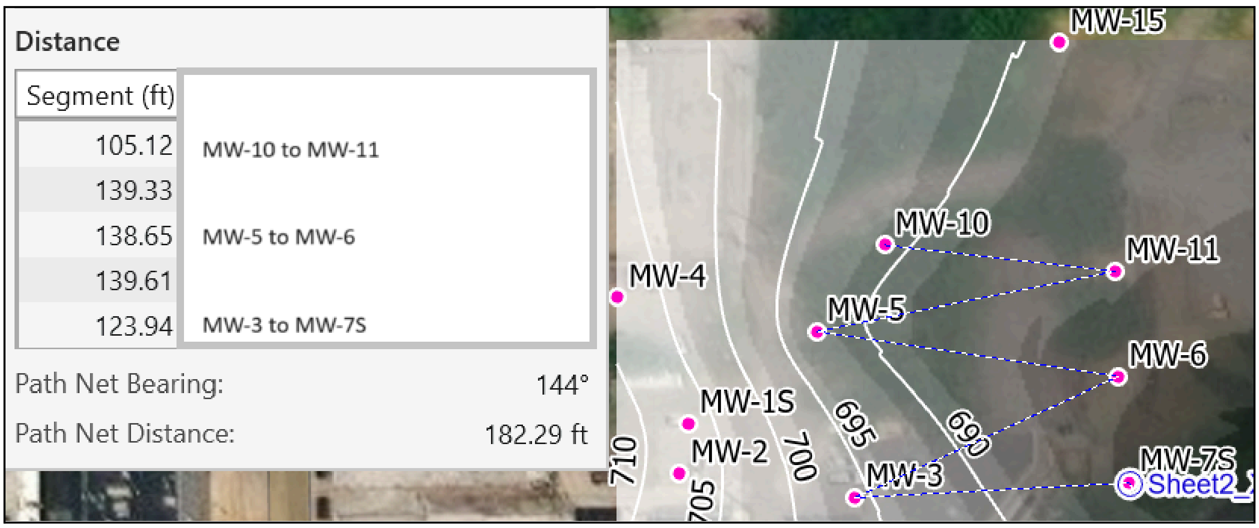


Fig. 10. Distances between wells were found using the measure tool on ArcGIS Pro.

$$average\ \Delta L = \frac{105ft+139ft+124ft}{3} = 123ft$$

$$I = \frac{h_{upgradient} - h_{downgradient}}{\Delta L} = \frac{693\ ft - 687\ ft}{123\ ft} = 0.05$$

Porosity was found using a weighted value of estimated porosities by soil type. At MW-7, the soil was found to be gravelly sand (Geosyntec, 2023). Porosity for sand is 0.31 and porosity of gravel is 0.285 (Woessner, W. W., & Poeter, E. P., 2020). Averaging the two, the soil porosity was calculated to be 0.30.

With the equation 1 variables known, we calculated aquifer velocity to be 0.75 ft per day.

$v = \frac{(4.44\frac{ft}{day})(0.05)}{0.3} = 0.75\ ft/day$ calculated with porosity around MW-7.

Selection of Reactive Media

Once the site has been characterized, the next step in the design of a PRB is to identify and select reactive media types. The three types of reactive media that were considered were zero-valent iron (ZVI), granular activated carbon (GAC), and biobarriers. All of these were found to be effective for the contaminants at the site, except biobarriers. Biowalls were screened out because they can cause vinyl chloride stall—where the contaminant does not degrade beyond vinyl chloride, another harmful constituent. ZVI can treat all of the contaminants of concern at the site. Due to ZVI's demonstrated effectiveness on VOCs, it was selected as the PRB media.

Geochemical conditions must be evaluated to determine whether conditions are favorable for the sustained performance of ZVI. High dissolved oxygen (>2 mg/L) can lead to rapid iron corrosion and formation of low density iron oxide precipitates. There were two monitoring wells that measured DO levels significantly higher than 2 mg/L - MW-2 and MW-10. MW-10 and MW-2 have DO levels of 4.2 mg/L and 4.72 mg/L respectively. They are both upslope of the PRB, so the PRB will need to be monitored closely for corrosion and formation of precipitates. The pH of the groundwater for the site falls between the range of 6.96-7.57, which is suitable for the ZVI PRB.

ZVI is widely available, as it is one of the most used mediums in PRBs. However, ZVI has many variations and must be selected based on both size and surface area. For this project, granular ZVI will be employed which ranges from 0.1 to 2 mm in size. Granular ZVI is widely used in PRBs constructed through excavation and backfill installation, which is the chosen method for our site.

More information on the selection of the construction technique will be discussed later in this report. The surface area influences the reactivity—a smaller surface area leads to a higher reactivity rate. Based on calculations discussed in the next sections, the reactivity rate of granular ZVI yields a residence time and cell wall thickness that are appropriate. Size and surface area influence cost, with the granular ZVI being the most cost effective. The typical cost range for granular ZVI is $1,200 to $1,500 per ton. However, cost is highly dependent on the exact specifications of the ZVI. To acquire ZVI and obtain an accurate price estimate, a supply company will need to provide a quote. Additionally, a ZVI material should be tested at the site for compatibility before full implementation.

Treatability Studies

Treatability studies, such as lab batch and column tests for our remediation strategy, are crucial to designing a PRB in order to confirm that design specifications are compatible with site conditions. We would also need reactivity data for the ZVI source to ensure the contaminant is completely degraded. We do not have the ability to conduct these tests for this site. As a result, we were required to make assumptions about feasibility of designs which we have documented in the design process.

Effects of Reactive Media Implementation

ZVI does not selectively react with chlorinated contaminants. Instead, ZVI will react with metal oxy-anions and cause geochemical changes to the groundwater by creating gradients between the aquifer and the PRB. The groundwater components specified in the "inorganic composition of groundwater" section are affected most significantly by ZVI. After immediate implementation, ZVI will increase the pH of groundwater surrounding the PRB to around 9-10 (Przepiora, A., Wildman, C.F. and M. Hart, 2024). If sand is mixed with the ZVI, a more neutral reaction will occur. The increased pH will cause carbonate precipitation. From field tests, carbonate precipitates are the largest secondary minerals present in groundwater with PRBs installed (Gillham et al. 2010, Wilkin et al. 2003). Mixing ZVI with sand can also decrease the formation of carbonate precipitates. SO_4^{2-} will be reduced to sulfide in mature PRBs, which then creates iron sulfide precipitates. As precipitates continue forming, they will begin clogging up the pores of the ZVI thereby decreasing the porosity of the material and consequently reducing the flow through the PRB.

ZVI will also remove all DO within a short distance of the PRB. NO_3^- will be reduced to ammonia and cause ZVI oxidation. Over time this leads to the reduction of surface area of the ZVI which then reduces its reactivity. It has also been observed that dissolved organic carbon and silica can build up in the ZVI material (Tratnyek et al. 2001) and reduce its reactivity by forming precipitates, films, and microbial buildup on the grains. Both the reduction in porosity and the reduction in reactivity will affect the longevity of the PRB, but the extent of lifetime reduction will depend on existing site geochemistry, knowledge of which is currently limited.

Engineering Design

To calculate the dimensions of the PRB shown in Figure 11, the hydraulic capture zone and residence time must be determined. The capture zone is the width of contaminated groundwater that will pass through the barrier. Determining the capture zone is critical to ensure the contaminant plume goes through the wall instead of around it. Additionally, to make sure groundwater does not avoid the barrier, the PRB material must be more permeable and porous than the surrounding aquifer, and the depth of the PRB should extend to at least below the contaminant extent. Both the capture zone and depth were found directly from looking at data acquired from MWs and SBs. Next, we found the rate constants for dechlorination of the COCs with granular ZVI. Finally, we solved for the required residence time, which is the amount of time the groundwater must be in contact with the barrier to be treated to meet regulatory requirements, which is required to find barrier thickness. See below for detailed methodology and calculations.

Fig. 11. Approximate location of the PRB.

PRB Reactive Cell Thickness

Width of capture zone

To determine the capture zone, we used the Geosyntec provided resource shown below in table 4. They used the most conservative values, from MWs 7S, for these values. It was found that 330 ft. was the capture zone and 7 ft. was the depth. The soil boring profile used to determine plume height is listed in Appendix D. At the MWs of interest, the contaminant levels were tested and are listed in table 2, and regulatory concentration limits are listed in table 1 above.

Table 4. Mixing Zone Calculations for Jackson Cleaners Plume at MW 7 (Geosyntec Consultants of Michigan, 2024).

Variable	Symbol	Source and Method of Derivation	Value when Plume Has Highest K Value	Units
Plume Width	l	Length along the riverbank between PW-2 and PW-6	330	ft
Plume Height	h	Saturated aquifer thickness	7	ft
Groundwater Discharge	Q_d	Calculated using Darcy's Law	0.033	ft^3/s

Notes

1. *Saturated thicknesses of the aquifer is 6.51 feet (rounded to 7), obtained from groundwater gauging on September 6, 2023. The bottom of the aquifer is unknown, so the bottom is set at bottom of well screen.*
2. *Highest K value from site used to estimate concentration conservatively*

Residence time

In order to be treated to the specified requirements listed above in table 1, the residence time was found for each contaminant. The residence time for PCE was found to be approximately 1.5 days.

Finding the value of residence time requires lab treatability studies that determine rate constants and conversion factors from parent to daughter products. Lab testing is not able to be completed for this assignment, so some assumptions had to be made. To determine an estimated residence time for this project we used equation 3 below to relate half-life ($t_{1/2}$) with the rate constant, k.

$$t_{\frac{1}{2}} = \frac{ln(2)}{k} \quad \text{[equation 3]}$$

Half-life values for the contaminants of concern were calculated from half-life values listed in table 5 below.

Table 5. Half-life values used for calculations (Directly extracted from table 6 in Przepiora, A., Wildman, C.F. and M. Hart, 2024).
Example Results of Column treatability for 100% Granular ZVI at room temperature.

Compound	Influent Concentration (μg/L)	Half-life (hours)	Molar Conversion
PCE	905	0.95	–
TCE	59	0.79	PCE to TCE = 25%
cDCE	20	1.5	TCE to cDCE = 10%
VC	5	1.8	cDCE to VC = 7%

Notes: Data from internal testing by Geosyntec Consultants for a site in California.

Using table 5, we estimated the half-life value of 5.04 hours for PCE by summing the half-life values until VC degradation. These values are at room temperature (~22 degrees Celsius), while the aquifer's temperature ranged from 15 to 21 degrees Celsius according to September 2023 purge log data (Geosyntec, *Purge Logs*, 2023). To account for this temperature difference, we corrected these values using the assumption that the half-life doubles every temperature drop of 6 to 8 degrees Celsius (Przepiora, A., Wildman, C.F. and M. Hart, 2024). This resulted in a PCE half-life of 10.08 hours.

$$k\ using\ PCE\ half\text{-}life = \frac{ln(2)}{t_{\frac{1}{2}}} = \frac{ln(2)}{10.08\ hrs} = \frac{0.069}{hr}$$

Using the derived k value, residence time was found using equation 4 below:

$$t_{res} = -\frac{ln(\frac{C_T}{C_o})}{k} \qquad \text{[equation 4]}$$

where C_T is the downgradient target concentration, C_O is the contaminant concentration entering the PRB, and k is the rate of reaction. Table 1 provides the PCE GSIC value of 60 µg/L, which is used as C_T. C_O is 670 µg/L, derived from MW-3 which has the highest concentration of PCE found at all of the wells, see table 2. Alternatively, we could have taken the average concentrations of PCE from MWs 3, 4, 6, 7, 10, and 11, shown in table 2, because values and distances between these wells are consistently used in this section in barrier design. However, we decided to use the most conservative values for safety.

$$\text{PCE } t_{res} = -\frac{ln(\frac{60\frac{\mu g}{L}}{670\frac{\mu g}{L}})}{0.069\frac{1}{hr}} = 35\, hrs = 1.5\, days$$

Reactive Cell Thickness

Using the calculated residence time and the velocity, the reactive cell was calculated to be 4 ft. thick for the PCE degradation. The reactive cell thickness was calculated using equation 5:

$$b = v \times t_{res} \times SF \qquad \text{[equation 5]}$$

where v is velocity of the aquifer, t_{res} is residence time, and SF is the safety factor. We used the calculated aquifer velocity value of 0.75 ft. per day, calculated residence time of 1.5 days, and a safety factor of 3 to find the wall thickness. A safety factor (SF) of 3 was used after consulting with our mentors on an appropriate value, as 2 to 6 are typically industry standards. The velocity of the aquifer is used as a conservative estimate to account for the expected decrease in the porosity of the ZVI over time, which would reduce flow and alter thickness calculations.

$$b = 0.75\, ft/day \times\ 1.5\, days \times\ 3 = 3.4ft$$

Due to the reality of excavator bucket sizes and for an conservative estimate, we recommend rounding this value up to give a wall thickness of 4 ft. It is also important to note that sand is commonly mixed with ZVI when filling in PRBs, but for simplicity we have excluded sand from our calculations. See Figure 12 for a visualization of the overall required dimensions.

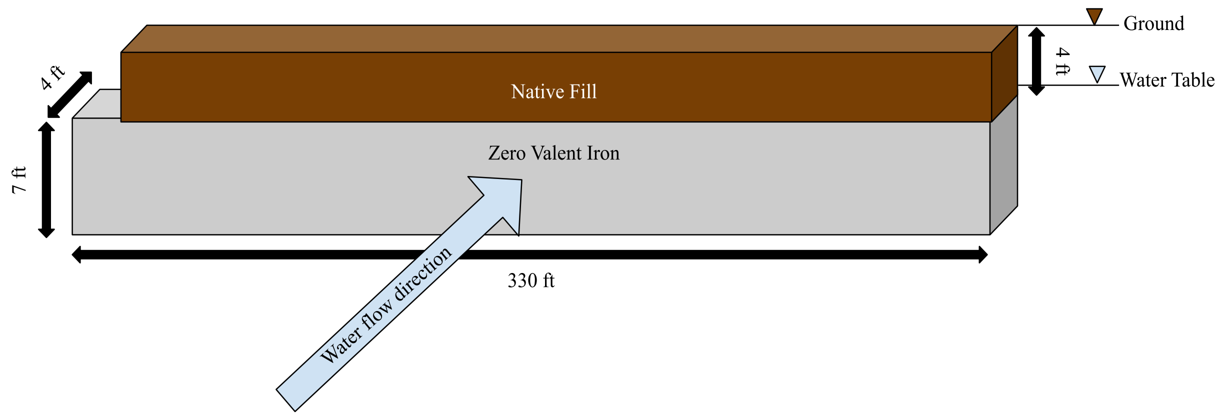


Fig. 12. Depiction of the PRB with dimensions required to treat contaminants at the site.

The trench dug to complete this design will have to be approximately 11 ft. deep. This dirt will be hazardous waste that will need to be disposed of off-site. The bottom fill layer of the trench will be the PRB. This means the trench must be filled with 7 ft. of granular ZVI and topped with approximately 4 ft. of native fill, which will be compacted and leveled to grade. We decided a simple trench line is the preferred construction method, instead of a funnel-and-gate system, as our proposed location is parallel to electric and sewer utility lines and we do not want to interfere with the existing utilities. The cost to dig a trench and install the PRB is extremely difficult to predict without contacting companies. However, the cost of a similar site reported by the EPA can be used as a model. The Haardkrom site used a continuous trench and fill method to treat TCE with a PRB that was 9.8 ft. deep and 164 ft. wide. These parameters are very similar to our site, except the width is about half of ours. The total installation cost for the project was $250,000, but was installed in 1999. We can use inflation data and equation 6 to adjust this cost into a present value.

$$Future\ Value\ (FV) = Present\ value\ (PV) * (1 + i)^{years} \quad \text{[equation 6]}$$

The average inflation rate from 1999-2024 is 2.5% (BLS, 2024).

$$250{,}000*(1.025)^{25} = \$463{,}486$$

Given the amount of excavation doubles for a PRB of double length, we round our installation cost estimate up to $930,000.

Source Treatment Discussion

In order to reduce the thickness of the PRB and lower contaminant levels more widely and effectively in the future, injected ZVI could be implemented in the source zone. Source treatment could consist of micro-scale ZVI injected into the aquifer to effectively degrade chlorinated solvents. Calculations for injected ZVI were beyond the scope of this project, but the team felt it was important to mention that this was considered to be a viable source zone treatment option. Source treatment would also allow the PRB to withstand a longer period of time between replacement.

PRB Monitoring Plan

PRBs must be monitored to ensure that they are performing effectively. This is done through a network of monitoring wells. There is currently a network of 16 monitoring wells, 2 of which are nested monitoring wells. Two additional wells will need to be installed, one that is 1.5 to 3 meters upgradient of the PRB and one that is 1.5 to 3 meters downgradient of the PRB (Przepiora, A., Wildman, C.F. and M. Hart, 2024). These wells will be used to monitor the effectiveness of the PRB.

For the first two years after installation, the water level, pH, temperature, redox potential, and dissolved oxygen need to be measured quarterly, and if the PRB is operating as expected after the initial two years, then the frequency of this measurement can be decreased. These measurements need to be collected from all monitoring wells. The concentrations of PCE, TCE, cDCE, and VC also need to be measured quarterly for the first two years of operation, but can be measured less frequently if stable after two years. These measurements also need to be collected from all monitoring wells. Finally, the inorganics need to be measured following this same timeline, but they only need to be measured at one or two representative transects.

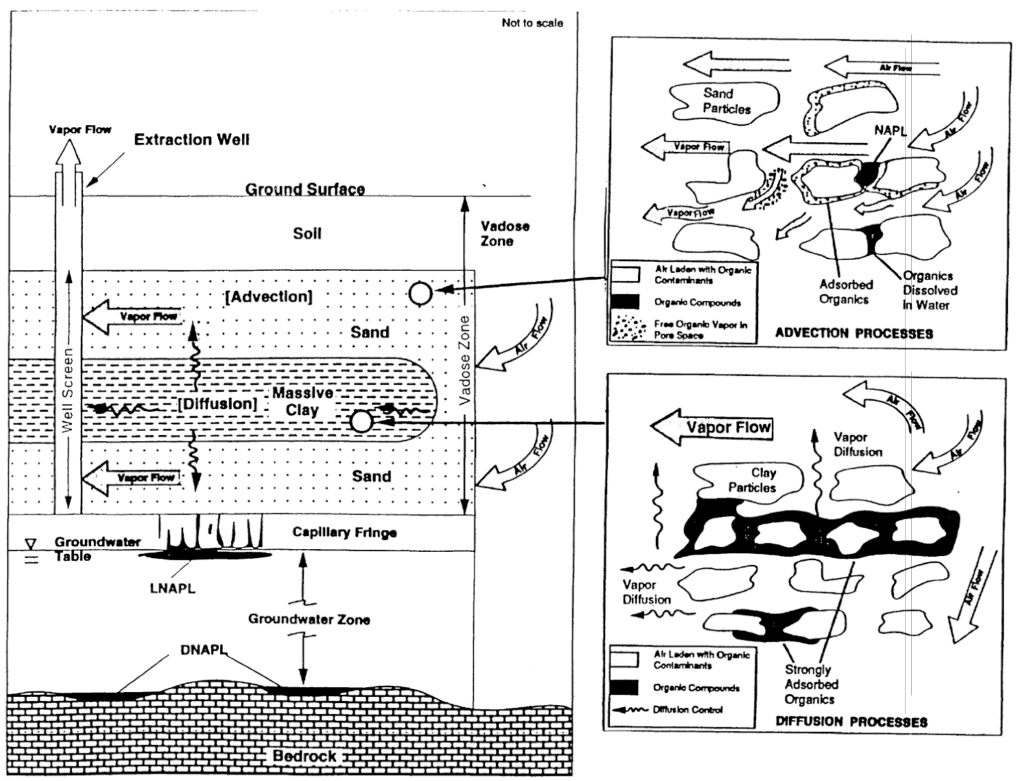
3. Soil Vapor Extraction

Preliminary Technical Assessment

The design of the Soil Vapor Extraction (SVE) system and following offgas treatment follows the methods in *Engineering and Design - Soil Vapor Extraction and Bioventing* (United States Army Corps of Engineers, 2002) and *Off-Gas Treatment Technologies for Soil Vapor Extraction Systems: State of the Practice* (EPA, March 2006).

The first step in designing a SVE system for a contaminated site is the technical assessment. The technical assessment involves initial research into the contaminants and site conditions. First, the contaminants must be identified as amenable to SVE in scientific and technical literature. The contaminants at this site are PCE, TCE, VC, and cDCE, all of which are considered amenable to SVE as defined in SVE/BV design documentation from the U.S. Army Corps of Engineers. The prevalence of any contaminants incompatible with SVE must also be noted (e.g. heavy metals), none of which have been identified on this site.

After assessing whether SVE is suitable for the site, a location for the treatment of the subsurface environment must be chosen. There are multiple factors that go into this decision, including: contaminant levels, depth to the water table, surface obstacles (buildings), subsurface utilities, soil properties, etc. The most important of these factors is often considered the soil properties, specifically air permeability of the soil type. As seen in Figure 13, SVE is essentially a vacuum that pulls the contaminated gasses out of the ground, which is then replaced with "clean air" via the air flow through void spaces from the ground surface. Therefore, it is necessary to know the soil properties in order to determine how much air or pressure needs to be extracted from the subsurface system. Although the assessment will not be completed for the design, it is often beneficial to conduct pilot tests for these systems to ensure adequate and efficient gaseous movement throughout the subsurface. The preliminary technical assessment of SVE is now complete and a more in-depth characterization of the site can occur.



Source: after USEPA 1991c

Fig. 13. Diagrams depicting SVE moving contaminants out of the subsurface system (*Soil Vapor Extraction and Bioventing,* 2002).

Characterization of the Site

As mentioned in the preliminary technical assessment, the discussion of soil characteristics and the location of the water table in relation to the surface are important inputs to the design of a SVE system. In Figure 14 below, the soil types and water table can be seen in a cross section view. In Figure 15 below, a plan view map of depth to groundwater from the surface is shown. These figures, either provided directly from Geosyntec or created with their data, show the important characteristics of the site, which are necessary for the rest of the design process. As seen in Figure 14, "near-surface" as a qualifier and the contaminant in soil concentrations are highest in the deep samples at SB-1/MW-3, one of the testing wells for the site. For the design, it is necessary that the system extends far enough below the surface in order to prevent gases from the surface directly above from infiltrating the system. Additionally, it is important that there is air flow beneath the surface, but pulling air straight down can prevent the removal of contaminated gases. It is crucial to prevent interference with the groundwater table in order to ensure water is not being pulled into the treatment system, as the focus for this system is the contaminated soil vapors.

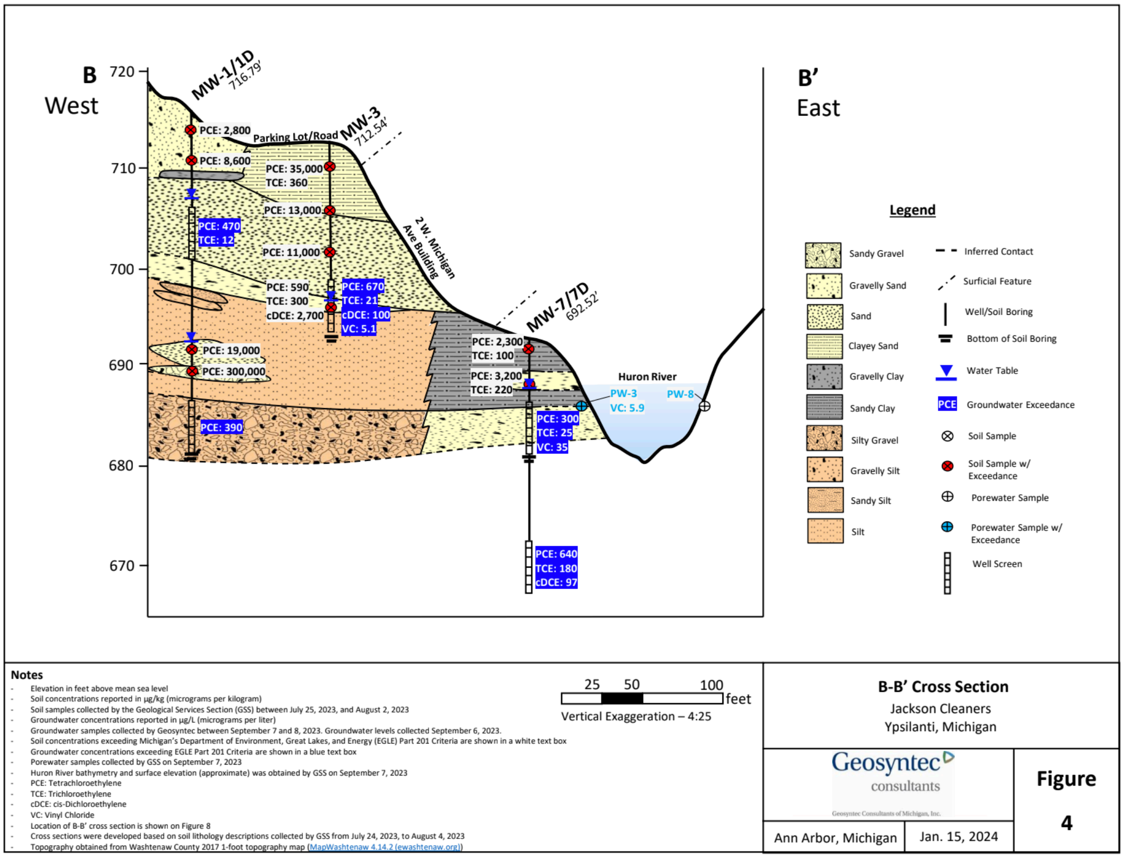


Fig. 14. Cross section of site, with subsurface characteristics (Geosyntec, *Request for Mixing Zone-Based GSI Criteria*, 2024).

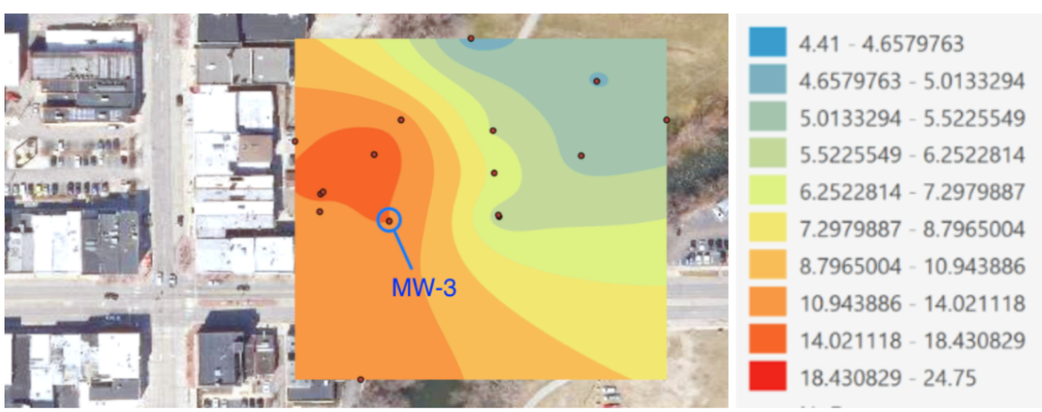


Fig. 15. Depth to groundwater map in feet, with MW-3 marked for reference

Along with these natural features, underground utilities serving the city could interfere with the placement of wells, so this should be considered in the final location of the system. Due to the lack of utilities near MW-3, this area is optimal for the implementation of the design. The underground facilities can be seen in Figure 5.

Selection of System Location

Figures 14 and 15 show that the contaminant levels around MW-3 are fairly high in comparison to other locations on the site. The surface to groundwater depth at MW-3 is also greater relative to much of the site. Figure 14 also provides data on contaminant levels at different depths beneath the ground surface: another reason this location was chosen. The MW-3 location is also free of any underground utilities, meaning that wells can be installed directly into the ground without any major (unnatural) obstacles. As noted previously, the direct pulling of air straight down from the surface is undesirable. The surface location surrounding MW-3 is covered with an impermeable paved parking lot. This pavement can be used as a cap surrounding the well, preventing the immediate intrusion of clean surface level air. With the above characteristics being taken into consideration, it would be most beneficial to install the proposed system in the general vicinity of MW-3, however not using the current well. Now that the location and the characteristics of the soil are known, values that will determine the desired flow rate through the soil must be calculated. As specific information pertaining to soil data such as air-filled porosity was not provided, certain assumptions have been made about these properties.

SVE System Flow Rate

Due to the chosen location and assumed values, one well is recommended. This well will extend from the ground surface close to the location of MW-3 and extend downward to three feet above the water table. This separation from the water table is important to ensure that large amounts of moisture are not extracted like the soil vapor. An estimation of flow rate can be calculated using equation 7.

$$Q_v^* = \frac{\pi r^2 b n_a}{t_{ex}} \quad \text{[equation 7]}$$

Equation 7 has several key parameters: the radius of influence (r), the depth to the water table (b), the air-filled porosity (n_a), and the required time for a single pore volume exchange (t_{ex}). Given the contaminant location, a 30 foot radius of influence centered on MW-3 encompasses not only areas of high soil concentration near the surface, but also upstream contamination closer to the pollutant origin (at greater depth). Based on the USACE documentation for SVE, for a typical site, the recommended pore volume exchanges per day is 10, therefore $t_{ex} = 0.1$. To determine the air-filled porosity of the soil, several calculations were made. According to soil boring logs provided by Geosyntec, the percent total solids of the soil around the proposed installation site is 93.5%. With this information and three key assumptions: the dry mass of the soil being equal to 1 kg, the density of the soil being approximately that of sand (ρ_S = 1600 kg/m^3), and the porosity of the soil being an average of the ranges given for sand and clay in table 6 (n = 0.375).

Table 6. Typical soil porosity values (Fitts, 2012).

Material	***n* (%)**
Narrowly graded silt, sand, gravel	30–50
Widely graded silt, sand, gravel	20–35
Clay, clay–silt	35–60
Sandstone	5–30
Limestone, dolomite	0–40
Shale	0–10
Crystalline rock	0–10
Massive granite	0–0.5

$$M_{total} = \frac{M_{dry}}{\%\,solids} = \frac{1\,kg}{0.935} = 1.07 \text{ kg}$$

$$M_W = M_{total} - M_{dry} = (1.07 - 1) \text{ kg} = 0.070 \text{ kg}$$

$$V_W = \frac{M_W}{\rho_W} = \frac{0.070\,kg}{1000\,\frac{kg}{m^3}} = 7.0\text{x}10^{-5} \text{ m}^3$$

$$V_S = \frac{M_{dry}}{\rho_S} = \frac{1\,kg}{1600\,\frac{kg}{m^3}} = 6.2\text{x}10^{-4} \text{ m}^3$$

$$e = \frac{n}{1-n} = 0.60$$

$$V_V = eV_S = 3.7\text{x}10^{-4} \text{ m}^3$$

$$V_A = V_V - V_W = 3.1\text{x}10^{-4} \text{ m}^3$$

$$\text{Air ratio} = \frac{V_A}{V_V} = 0.81$$

$$n_a = 0.81n = 0.31$$

Based on the above calculations, the air-filled porosity of the soil is equal to 0.31. Soil boring indicates that the depth to the water table (the thickness of the vadose zone) lies between 12-18ft, therefore, to maintain a conservative estimate, b = 12 ft.

$$Q_v^* = \frac{\pi(30^2)(12)(0.31)}{0.1} = 100{,}000 \text{ cfd}$$

$$= 100{,}000 \text{ cfd } \frac{day}{24h}\frac{h}{3600s} \approx 1.2 \text{ cfs}$$

Design and Treatment

The treatment of the extracted soil vapor will take place on the Jackson Cleaners site, avoiding transportation of gases causing further pollution. Granular activated carbon (GAC) is an effective option for treating the offgas from the SVE system. In the treatment system for this site, a GAC treatment cylinder will be used, where the offgas will pass through a large cylinder filled with GAC pellets, allowing for the absorption of contaminants from the extracted soil vapor. The EPA says that linear bed velocities for carbon absorption (treatment of offgas in absorbing contaminants) can range from 8 to 100 ft./min. In order to determine the flow rate from this velocity, the cross-sectional area of the GAC tank must be calculated. Already having determined the desirable flow rate, 1.2 cfs, from equation 6, the size of the GAC tank can be calculated by solving for the cross sectional area. In finding the diameter of the GAC tank, the linear bed velocity is assumed to be 60 fpm, a value around the median of the common range as outlined by the EPA.

$$1.2\ ft^3/sec\ =\ 72\ ft^3/min$$

$$72\ ft^3/min\ =\ 60\ ft/min\ \times\ \pi r^2$$

$$1.2\ ft^2\ =\ \pi r^2$$

$$0.3819\ ft^2\ =\ r^2$$

$$r\ =\ 0.618\ ft \qquad d\ =\ 1.24\ ft$$

In continuing treatment, Michigan's EGLE standards for offgas are needed to ensure that the offgas post-treatment (post GAC tank passthrough) falls within the contaminant levels allowed for venting as outlined in these standards. These standards will provide guidance for how long each period of treatment will be, and the residence time in the treatment system for the offgas needed for desirable treatment. As shown in Figure 16, the system for this site will include five major steps: vapor extraction (causing horizontal air flow), vapor liquid separation, suction via the blower, treatment via the GAC cylinder, and final pass through of the offgas contaminant check. With this model in mind, further assumptions including specific design details and pricing can be made.

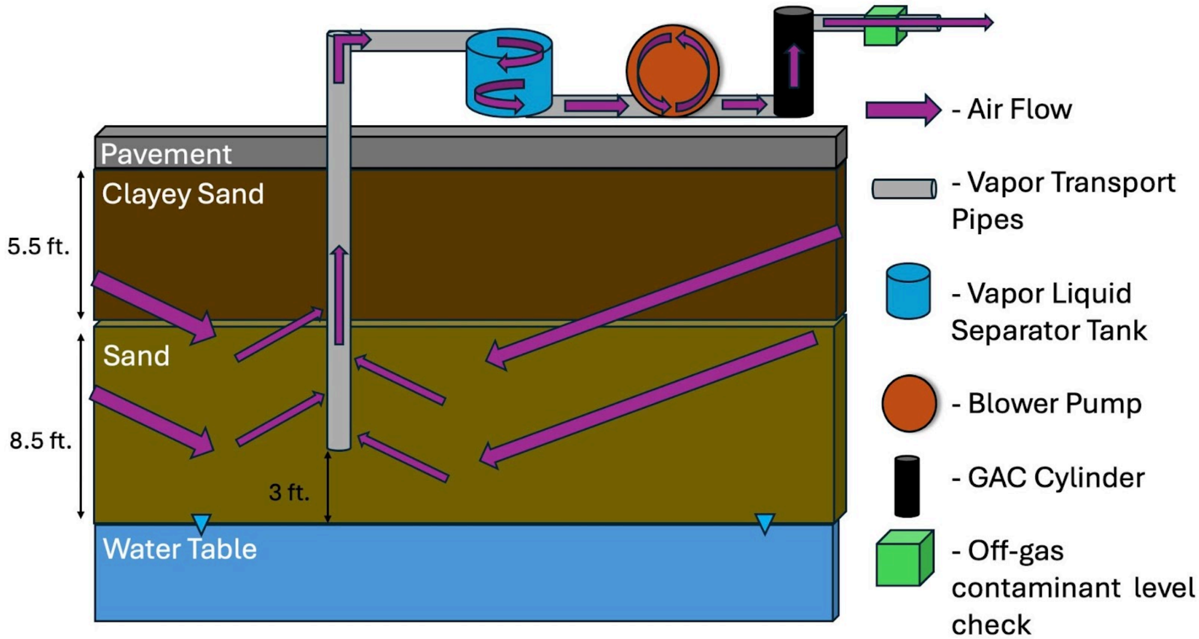


Fig 16. Design model of SVE system at the Jackson Cleaners Site

A well is to be drilled allowing for a roughly 12 foot pipe to be extended into the subsurface, staying 3 feet above the groundwater. Holes will be drilled toward the bottom of this pipe to allow for the suction of soil gas. Small screens will need to be installed over these holes to prevent the extraction of solids, but still allow for the passage of the soil vapors. With the calculated flow rate from above, the well/pipe should be approximately 4 inches in diameter, including the pipes connecting the pieces of the system on the surface. Monitoring probes installed via 2 inch wells will also need to be installed surrounding the main extraction well, measuring contaminant levels, vacuum pressure, temperature, etc. The probes will also help in determining the potential intermittent operation of the system, as the volatilized contaminants in the soil take a long period of time to build up in the subsurface system, and therefore constant treatment could be unnecessary. For example, due to temperature and its effects on the subsurface system, it is likely that the system can sit dormant in the winter and then reactivate in the summer.

Based on a report from California's Water Resources Control Board, the total cost for installing the system, including components, would be approximately $100,000 (*California State Water Resources Control Board*, 2020). Operating and maintenance costs would be roughly $6,000 per month. However, these estimates are for a system larger than the one designed here, so the costs would likely be lesser.

More work needs to be completed if this system is to be implemented on the site. Pilot testing needs to take place to give a final determination that SVE will be suitable for this site. Official design drawings with engineering specifications will need to be drawn, along with the detailed design of the soil probes. Further research of GAC and its effectiveness need to take place to determine if enough contaminants will be removed from the soil vapor, how often the GAC needs to be replaced after sorption, and the residence time within the GAC needed which will inform the length of the cylinder for a desirable volume.

IV. Conclusion and Discussion

In this paper, we have characterized the Jackson Cleaners site and have selected the remediation methods of institutional controls, a PRB, and a SVE system based on their effectiveness of reducing chlorinated contaminants or exposure to contaminants and their relative ease of implementation. We have begun the initial designs of these systems using the data available to us and by using educated assumptions. However, we acknowledge further work and data is needed to prepare these technologies to be implemented in real-world conditions. Below are the major conclusions and recommendations of further work for the PRB and SVE systems.

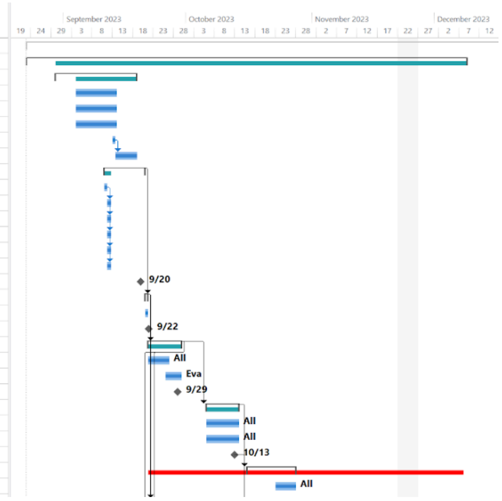
A PRB was selected to reduce the risks of the groundwater to surface water pathway. The PRB has been designed for the specific characteristics of the Jackson Cleaners site, including: 1) choosing ZVI as the suitable reactant media for treating PCE, TCE, VC, and DCE; 2) ensuring compatibility with dissolved oxygen levels, hydraulic conductivity, aquifer and groundwater depths, and soil type; and 3) considering placement that aligns with the groundwater flow, minimizes both surface and sub-surface level disruption, and avoids sewer or electrical lines. Future work is needed for designing accompanying source treatment, acquiring a more accurate cost estimate, and identifying effects of adding sand to the barrier mix.

A SVE system was selected to target the vapor intrusion pathways in buildings near the Jackson Cleaners site. For SVE, more research along with pilot testing will need to be completed as outlined in the SVE design section to ensure GAC will perform as intended. This research and pilot testing pertains to the subsurface system. Additionally, more specific subsurface locations for the system need to be decided, but it will likely be in the area of highest contaminant concentration surrounding the testing well of MW-3. Lastly, to account for O&M costs as well as other design parts, retrieving accurate and up to date price estimates will need to be gathered for cost predictions that cannot be made from research solely.

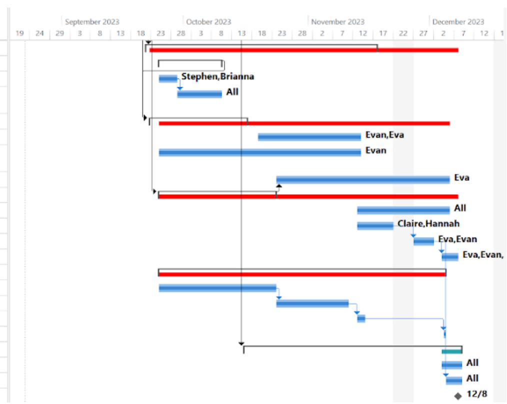
Appendices

Appendix A - Detailed Schedule

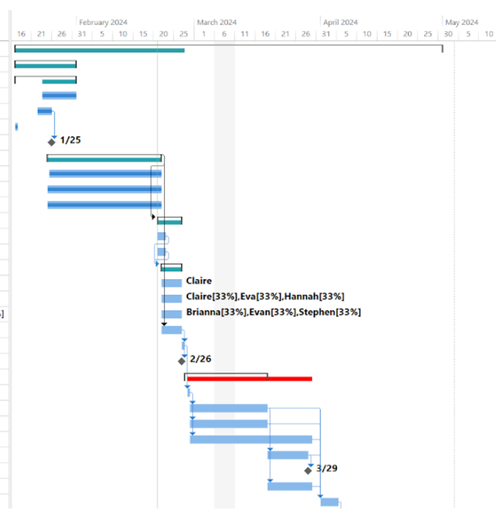
Task Name	Duration	Start	Finish	Predecessors	Resource Names
Capstone Scheduling Assignment	**168.75 days?**	**Wed 8/23/23**	**Fri 5/3/24**		
Fall Semester	**81 days?**	**Wed 8/23/23**	**Fri 12/8/23**		
Initial Research	**15.75 days?**	**Wed 8/30/23**	**Mon 9/18/23**		**All**
Research chemicals at Jackson Cleaners	9 days?	Mon 9/4/23	Wed 9/13/23		
Research regulatory information	9 days?	Mon 9/4/23	Wed 9/13/23		
Research remediation methods	9 days?	Mon 9/4/23	Wed 9/13/23		
Meet Geosyntec contacts and learn about the Superfund site	1 day?	Wed 9/13/23	Wed 9/13/23		
Summarize Geosyntec report	3.5 days?	Wed 9/13/23	Mon 9/18/23	6	
Scoping Assignment	**9 days?**	**Mon 9/11/23**	**Wed 9/20/23**		**All**
Meet with Geosyntec to discuss project and roles	1 day?	Mon 9/11/23	Mon 9/11/23		
Develop scoping statement	1 day?	Mon 9/11/23	Tue 9/12/23	9	
Identify project deliverables	1 day?	Mon 9/11/23	Tue 9/12/23	9	
Identify project risks	1 day?	Mon 9/11/23	Tue 9/12/23	9	
Identify project constraints	1 day?	Mon 9/11/23	Tue 9/12/23	9	
Identify project stakeholders	1 day?	Mon 9/11/23	Tue 9/12/23	9	
Scoping Assignment Due	0 days	Wed 9/20/23	Wed 9/20/23		
Complexity Assignment	**1 day?**	**Thu 9/21/23**	**Thu 9/21/23**	**8**	**All**
Make Complexity Assignment Submission Document	1 day?	Thu 9/21/23	Thu 9/21/23		
Complexity Assignment Due	0 days	Fri 9/22/23	Fri 9/22/23		
Scheduling Assignment	**6.88 days?**	**Thu 9/21/23**	**Fri 9/29/23**	**16**	
Identify milestones	3.5 days?	Thu 9/21/23	Tue 9/26/23		All
Create schedule on Project	4.5 days?	Tue 9/26/23	Fri 9/29/23		Eva
Scheduling Assignment Due	0 days	Fri 9/29/23	Fri 9/29/23		
Interim Progress Report	**6.75 days?**	**Fri 10/6/23**	**Fri 10/13/23**	**19**	
Create write up	6.75 days?	Fri 10/6/23	Fri 10/13/23		All
Aggregate finished deliverables	6.75 days?	Fri 10/6/23	Fri 10/13/23		All
Interim Progress Report Due	0 days	Fri 10/13/23	Fri 10/13/23		
Learning Needs Assessment	**11.25 days?**	**Mon 10/16/23**	**Fri 10/27/23**	**23,26**	
Do assessment	5.63 days?	Mon 10/23/23	Fri 10/27/23		All



Task Name	Duration	Start	Finish	Predecessors	Resource Names
Preliminary Tasks	**42.88 days?**	**Thu 9/21/23**	**Fri 11/17/23**	**16**	
ASAP Tasks	**10.69 days?**	**Mon 9/25/23**	**Tue 10/10/23**		
Type up data from PDF to Excel	5.06 days?	Mon 9/25/23	Fri 9/29/23		Stephen,Brianna
Take a look at data and understand what the data indicates	5.63 days?	Fri 9/29/23	Tue 10/10/23	31	All
Mapping	**16 days?**	**Fri 9/22/23**	**Mon 10/16/23**	**19,30**	
Create groundwater potentiometric map	18.56 days?	Thu 10/19/23	Mon 11/13/23		Evan,Eva
Find data for utilities, ground elevation, floodplain boundaries, etc.	37.13 days?	Mon 9/25/23	Mon 11/13/23		Evan
Create maps of impact extent	30.38 days?	Tue 10/24/23	Tue 12/5/23	37	Eva
Create Conceptual Site Model	**21.38 days?**	**Mon 9/25/23**	**Mon 10/23/23**	**19**	
Identify and evaluate receptors	15.75 days?	Mon 11/13/23	Tue 12/5/23		All
Understand potential pathways	7.88 days?	Mon 11/13/23	Tue 11/21/23		Claire,Hannah
Create schematic of conceptual site model	5.63 days?	Mon 11/27/23	Fri 12/1/23	39	Eva,Evan
Write up CSM	4.5 days?	Mon 12/4/23	Thu 12/7/23	40	Eva,Evan,Brianna
Create Technology Matrix	**50.63 days?**	**Mon 9/25/23**	**Mon 12/4/23**		**Hannah,Claire,Stephen**
Research remediation technologies	21.38 days?	Mon 9/25/23	Mon 10/23/23		
Develop matrix criteria and fill out	14.63 days?	Tue 10/24/23	Fri 11/10/23	43	
Review matrix with advisors	2.25 days?	Mon 11/13/23	Tue 11/14/23	44	
Update matrix with advisor input	1 day?	Mon 12/4/23	Mon 12/4/23	45	
End of Semester Report	**40.5 days?**	**Mon 10/16/23**	**Fri 12/8/23**	**23**	
Create write up	5.63 days?	Mon 12/4/23	Fri 12/8/23		All
Aggregate finished delieverables	4.5 days?	Tue 12/5/23	Fri 12/8/23	40	All
End of Semester Report Due	0 days	Fri 12/8/23	Fri 12/8/23		



Task Name	Duration	Start	Finish	Predecessors	Resource Names
Spring Semester	**78.75 days?**	**Wed 1/17/24**	**Tue 4/30/24**		
Regroup for semester	**12.38 days?**	**Wed 1/17/24**	**Wed 1/31/24**		
Make edits to fall report	**12.38 days**	**Wed 1/17/24**	**Wed 1/31/24**		
Make maps contaminant specific	7 days	Tue 1/23/24	Wed 1/31/24		
Create presentation materials for EGLE	4 days	Mon 1/22/24	Thu 1/25/24		
Create Remediation Objectives	1 day?	Wed 1/17/24	Wed 1/17/24		
EGLE Presentation on Fall Deliverables	0 days	Thu 1/25/24	Thu 1/25/24	55	
Narrow down technologies	**22.5 days**	**Thu 1/25/24**	**Wed 2/21/24**		
Research Permeable Reactive Barriers	22.25 days	Thu 1/25/24	Wed 2/21/24		
Research Soil Vapor Extraction	22.5 days	Thu 1/25/24	Wed 2/21/24		
Research Multiphase Extraction	22.5 days	Thu 1/25/24	Wed 2/21/24		
Create Designs	**4.5 days?**	**Wed 2/21/24**	**Mon 2/26/24**	**58**	
Compile site information	2.25 days	Wed 2/21/24	Thu 2/22/24		
Identify all codes/requirements	2.25 days	Wed 2/21/24	Thu 2/22/24		
Draft 3 Possible Designs	**3.38 days?**	**Thu 2/22/24**	**Mon 2/26/24**	**63,64**	
Institutional Controls	3.38 days?	Thu 2/22/24	Mon 2/26/24		Claire
Permeable Reactive Barrier	3.38 days?	Thu 2/22/24	Mon 2/26/24		Claire[33%],Eva[33%],Hannah[33%]
Soil Vapor Extraction	3.38 days	Thu 2/22/24	Mon 2/26/24		Brianna[33%],Evan[33%],Stephen[33%]
Draft Report	3.38 days?	Thu 2/22/24	Mon 2/26/24	58	
Send to GeoSyntec	1 day?	Tue 2/27/24	Tue 2/27/24	69	
Draft Design Report #1 Due	0 days	Mon 2/26/24	Mon 2/26/24	69	
Revise Initial Designs	**10.25 days?**	**Tue 2/27/24**	**Mon 3/18/24**		
Review feedback from Geosyntec and ask clarifying questons	1 day?	Wed 2/28/24	Wed 2/28/24	70	
Implement Changes	9 days?	Thu 2/29/24	Mon 3/18/24	73	
Make Design Schematics	9 days	Thu 2/29/24	Mon 3/18/24	73	
Make post-remediation plan	19.13 days?	Thu 2/29/24	Fri 3/29/24	73	
Update Standards and Constraints	9 days?	Tue 3/19/24	Thu 3/28/24	75	
Standards and Constraints Assignment Due	0 days	Fri 3/29/24	Fri 3/29/24	77	
Make reccomendation for design implementation	10.13 days?	Tue 3/19/24	Fri 3/29/24	74	
Update Report with Updated Designs	5 days	Mon 4/1/24	Fri 4/5/24	74,75,76,77,	



Task Name	Duration	Start	Finish	Predecesso	Resource Names
Draft Design Report #2 Due	0 days	Fri 4/5/24	Fri 4/5/24	80	
Review feedback	1 day?	Wed 4/10/24	Wed 4/10/24	81	
Implement changes	5.63 days?	Thu 4/11/24	Wed 4/17/24	82	
Update report	7 days	Thu 4/18/24	Fri 4/26/24	83	
Make poster	7 days	Thu 4/18/24	Fri 4/26/24	83	
Poster Symposium	0 days	Fri 4/26/24	Fri 4/26/24		
Final Design Report Due	0 days	Wed 5/1/24	Wed 5/1/24		
Class Exit Tasks (Peer eval, course eval, exit survey)	3 days	Wed 5/1/24	Fri 5/3/24	87	

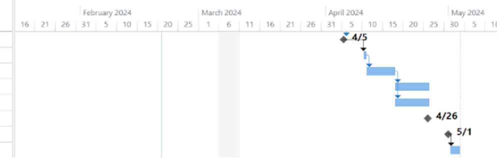


Fig. 17. Detailed Schedule

Appendix B - Design Evolution

Technology	Response Action	Technology Type	Suitable for PCE and TCE?	Implementation Summary	Time Frame	Technology Lifespan	Short-term Impacts	Technology Train?	Cost	Availability	Concerns/Constraints	Retained?
Low-Permeability Barrier Walls	Containment	Subsurface Vertical Barrier	☑	Slurry walls could be implemented by the river to keep contaminants from entering the river area or they could be implemented at the source zones.	Immediately after built	Replacement after 15-30 years	Increased truck traffic and construction noise, possible vibrations	Yes - Pumping wells, gravity drains	x	Commercially Available	Only contains contaminants, does not reduce them. Limited effectiveness in the unsaturated zone.	No
Pump and Treat	Ex-Situ	Physical/ Chemical	☑	Extraction wells are installed on-site to extract the contaminated groundwater. The water is then treated and released into the Huron River.	A few years - decades	Rebound is very common	Increased truck traffic and construction noise	Yes - In-situ chemical oxidation	$570,000 per year	Commercially Available	Long term and expensive, high chance of rebound. Preferential pathways can reduce the efficiency of contaminant recovery.	No
Multiphase Extraction	Ex-Situ	Physical/ Chemical	☑	Perform pump and treat to facilitate volatilization and removal of chlorinated solvents through SVE.	Years	N/A	Less intrusive than other mitigation systems. Potential for increase in noise levels	Yes - MNE	$1.87 per gallon treated. Depends on site specific characteristics.	Commercially Available	If installed at a source, it can significantly help the contaminated site. Additional reporting and testing is necessary.	Yes
In-Situ Stabilization	In-Situ	Physical/ Chemical	☑	Mixing and fixating of reactive admixtures into the soil matrix. Use chemical amendments to oxidize or reduce contaminant concentrations.	Weeks - months	N/A	Increased truck traffic and heavy equipment	In-situ chemical oxidation	$15 per ton + cost of reagents	Commercially Available	Contaminants are not destroyed or removed, may not be particularly effective for our class of contaminants. Due to the heat generated during mixing with reactive chemicals, volatile organic compounds may be emitted. May inhibit future, more comprehensive restoration of sensitive areas.	No
In-Situ Chemical Reduction (Permeable Reactive Barriers)	In-Situ	Physical/ Chemical	☑	A permeable reactive barrier could be placed in an area before the groundwater reaches the river, treating the contaminants as they move across the barrier.	Direct inject - months, PRB - years	Replace PRB after 15 years	Low community disruption, installing barriers or inseritng chemicals is extent of invasion	Maybe, if PCE and TCE are treated seperately. Can also be combined with other chem/bio methods to create more effective process	$5,000 annually, after $50 - $250 thousand capital	Commercially Available	One of PCE reduction products is Vinyl Chloride which is even more harmful. The avoidance of Vinyl Chloride may make this method more difficult and expensive.	Yes
In-Situ Chemical Oxidation	In-Situ	Physical/ Chemical	☑	Uses chemicals called "oxidants" to help change harmful contaminants into less toxic ones.	Months to years	Rebound likely - will need to do multiple injections	Medium disruption, low if not coupled with mechanical methods	Yes - pump and treat or mechincal soil mixing	$25-$100 thousand annually, after $25-$100 thousand	Commercially Available	May create excess heat and gases that can rise to surface. Use of catalyst or mechanical methods can increses cost	No
In-Situ Bioremediation	In-Situ	Biological	☑	Engineered technology that modifies environmental conditions (physical, chemical, biochemical, or microbiological) to encourage microorganisms to destroy or detoxify organic and inorganic contaminants in the environment.	Years	Degradation of VC may not be complete until all PCE is gone, so might need to add something later to treat this	Involves modifying site conditions, some digging, still low disruption	Possibly, since two different contaminants are present. Reduction is common	$30-100 per cubic meter	Commercially Available	Unreliable, needs to be closely monitored as many things can get in the way of progress	Yes
Thermal Conductivity/Electrical Resistance Heating	In-Situ	Thermal	☑	TCH technology uses heating elements in direct contact with the soil to raise the temperature in oder to mobilze and remove the contaminants. ERH technology applies electrical energy among electrodes.	Months	Sometimes the contaminents are just moved during treatment and can cause higher concentrations in different areas	Lots of power consumption	Yes - Volatization + vapor extraction	$10 per cubic foot (Depends on local vendors)	Commercially Available	Possibilites of making concentrations worse in some areas.	Yes
Institutional Controls	LUCs	Non-Technical Instruments	☑	Non-engineered instruments such as administrative and legal controls that help minimize the potential for human exposure to contamination and/or protect the integrity of the remedy.	N/A	N/A	Some social changes required	Would be coupled with other technologies. Does not stand on its own	None	Available		Yes, but only when coupled with another method
Monitored Natural Attenuation	MNA	Soil and Groundwater Monitoring	☑	Relies on natural processes to decrease or "attenuate" concentrations of contaminants in soil and groundwater.	Several years to decades	N/A	Residents may need to leave area for the beginning years	Can be the last part of the train - after levels have been reduced to below the limits, but needs frequent monitoring to ensure contaminent concentrations are decreasing	$10 - $25 thousand a year for monitoring and reporting	Commercially Available	Works best where source of contamination has been removed and only traces of contaminant remain. Site conditions must be suitable for natural degredation. Must consider the potential of PCE to break down into a more harmful version. Must be an anaerobic condition.	Yes, but only when coupled with another method
Excavation	Removal	Excavation	☑	Contaminants in the source zone are removed by excavation, and then transported off-site for disposal.	Days to years	If source removed, rebound is not likely. If the source is not removed, then it is likely	Fairly invasive (cannot be done near buildings)	Yes - Excavation, then offsite treatment via multiple technologies	$25-$50 per cubic meter for removal and fill, $50-$250 per ton for disposal	Commercially Available	Does not directly address aqeous-or vapor-phase contaminents. Excavation is not used for plume areas due to the relatively low contaminent mass in those parts.	No

Fig. 18. First screening of remediation technologies

Appendix C - Engineering Standards

- ASTM E1689-20: Conceptual Site Model Standards
    - 4.2: The complexity of a conceptual site model should be consistent with the complexity of the site and available data.
    - 4.3: The concerns of ecological risk assessment are different from those of human-health risk assessment, for example, important migration pathways, exposure routes, and environmental receptors. These differences are usually sufficient to warrant separate descriptions and representations of the conceptual site model in the human health and ecological risk assessment reports. There will be elements of the conceptual site model that are common to both representations, however, and the risk assessors should develop these together to ensure consistency.
- Michigan EGLE Environmental Contamination Response Activity
    - R 299.44 Generic groundwater cleanup criteria
    - R 299.46 Generic soil cleanup criteria for residential category
        - We used these criteria to develop our Remedial Action Objectives for the site cleanup.
- Institutional Controls Standards (ASTM E2091-22)
    - ASTM Standard 4.1.1 states "eliminate exposure pathways for, or reduce potential exposures to, chemicals of concern identified in the conceptual site model." This standard was followed through the creation of restrictive covenants that address the drinking water pathway and exposure to surface water.

    - ASTM Standard 4.1.6 states “identify the site uses and activities which should NOT occur in the future (unless further evaluation and remedial action, as appropriate, are undertaken), as those activities and uses may result in the exposure of persons or ecological receptors to chemicals of concern at or near the site in a manner that is inconsistent with a condition of ‘acceptable risk’ or ‘no significant risk.’” This standard was followed through identification of drinking groundwater and recreation in the river as activities which should not occur in the future and the creation of restrictive covenants to prevent these activities.
- <u>SVE Standards</u>
    - Construction of the Well
        - ASTM D 2241 - Use for the selection of PVC Pressure-Rated Pipe to ensure the pipes to and inside the well can withstand the blower and vacuum pressures. This will be followed when identifying the pipe needed for the SVE system at the Jackson Cleaners site.
        - NSF Standard 14 - Use for the selection of pipe related materials (plastics, piping components and related items). Will be used in conjunction with pipe selection.
        - ASTM C 150 - Specification for Portland Cement. Follow these guidelines when surrounding the well with cement to ensure stability. Will be used for system construction design.
        - ASTM D 2487 - Use for classification of soils for engineering purposes. Used in identifying the soils on the site (Geosyntec). Also used in the assumptions of soil characteristics.

        - Institute of Electrical and Electronics Engineers (IEEE) C.2 - National Electrical Safety Code. Will be used in the design of source of electricity for the SVE system (blowers, vacuum, monitoring equipment, etc.)
        - 29 CFR 1910 - Follow safety guidelines to ensure health and safety of designers/workers when constructing and/or operating the system. Will be used if the system is installed.
    - Soil Vapor and subsurface airflow
        - ASTM D 7758-17 - Follow guidelines and techniques when sampling gases in the Vadose Zone. This can be used for initial identification and monitoring after installation/treatment. This is what we would have used if the team were the ones collecting data.
        - ASTM D 5719-13 - Follow guidelines and techniques for calculating/simulating subsurface airflow while pumping and pulling gases from the soil system. Used by the team in initial subsurface flow rate calculations, and assumptions made to calculate that value.

Appendix D - Project Supporting Technical Deliverables

Data Used for PRB Design Calculations

To find the averaged hydraulic heads used in the hydraulic gradient calculation, we calculated the groundwater elevation by subtracting “SWL (ft btoc)” from “Top of Casing Elevation,” shown in Figure 19.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	Location ID	Longitude	Latitude	Easting	Northing	Max_PDOP	Corr_Type	GPS_Date	GNSS_Heigh	Vert_Prec	Horz_Prec	Ground Elevation	Top of Casing Elevation	SWL 8/4/23 (ft btoc)	Calculated GW Elevation
2	MW-1D	-83.612446210	42.241490720	696863.168	190741.576	3.2	Postprocessed Code	8/4/2023	218.142	0.1	0.1	716.95	716.55	24.82	691.73
3	MW-1S	-83.612435199	42.241498988	696864.049	190742.520	2.9	L1L2 Postprocessed Carrier Float	8/4/2023	218.156	0.1	0.1	716.79	716.42	8.96	707.46
4	MW-2	-83.612450303	42.241415454	696863.069	190733.213	4.8	L1L2 Postprocessed Carrier Float	8/4/2023	217.979	0.1	0.1	716.02	715.70	7.62	708.08
5	MW-3	-83.612159768	42.241375803	696887.156	190729.497	5.9	Postprocessed Code	8/4/2023	216.636	0.1	0.1	712.54	712.24	16.35	695.89
6	MW-4	-83.612554012	42.241709166	696853.583	190765.568	5.5	Postprocessed Code	8/4/2023	219.507	0.1	0.1	721.86	721.47	12.84	708.63
7	MW-5	-83.612223404	42.241653242	696881.027	190760.141	4.3	L1L2 Postprocessed Carrier Float	8/4/2023	216.314	0.1	0.1	711.44	711.15	19.68	691.47
8	MW-6	-83.611721587	42.241577691	696922.653	190752.939	3.0	Postprocessed Code	8/4/2023	211.054	0.1	0.1	694.28	693.93	7.09	686.84
9	MW-7D	-83.611700237	42.241393788	696924.998	190732.578	3.8	L1L2 Postprocessed Carrier Float	8/4/2023	210.733	0.1	0.1	692.49	692.20	5.26	686.94
10	MW-7S	-83.611703322	42.241400748	696924.721	190733.343	5.0	L1L2 Postprocessed Carrier Float	8/4/2023	210.611	0.1	0.1	692.52	692.08	5.81	686.27
11	MW-9	-83.612278191	42.240719504	696879.473	190656.374	4.8	Postprocessed Code	8/4/2023	217.099	0.3	0.2	713.82	713.54	15.50	698.04
12	MW-10	-83.612110405	42.241797266	696889.889	190776.393	3.1	L1L2 Postprocessed Carrier Float	8/4/2023	214.322	0.1	0.1	705.82	705.45	14.81	690.64
13	MW-11	-83.611726766	42.241753243	696921.668	190772.412	4.9	L1L2 Postprocessed Carrier Float	8/4/2023	211.118	0.1	0.1	694.01	693.73	5.89	687.84
14	MW-12	-83.611357872	42.241648884	696952.423	190761.700	1.8	L1L2 Postprocessed Carrier Float	8/4/2023	210.365	0.1	0.1	692.10	691.72	5.19	686.53
15	MW-13	-83.611000684	42.241797113	696981.411	190778.995	6.3	L1L2 Postprocessed Carrier Float	8/4/2023	210.343	0.1	0.1	691.90	691.61	5.05	686.56
16	MW-14	-83.611292160	42.241957754	696956.862	190796.137	4.2	L1L2 Postprocessed Carrier Float	8/4/2023	210.685	0.1	0.1	692.86	692.52	4.94	687.58
17	MW-15	-83.611819124	42.242135138	696912.838	190814.581	3.5	L1L2 Postprocessed Carrier Float	8/4/2023	211.064	0.1	0.1	694.03	693.80	4.60	689.20

Fig. 19. Monitoring well data taken on August 8, 2023 (Geosyntec, 2023).

The soil boring profile shown below in Figure 20 was used to identify the PRB depth and trenching depth required to ensure the groundwater and the full plume would move through the PRB reactive material.

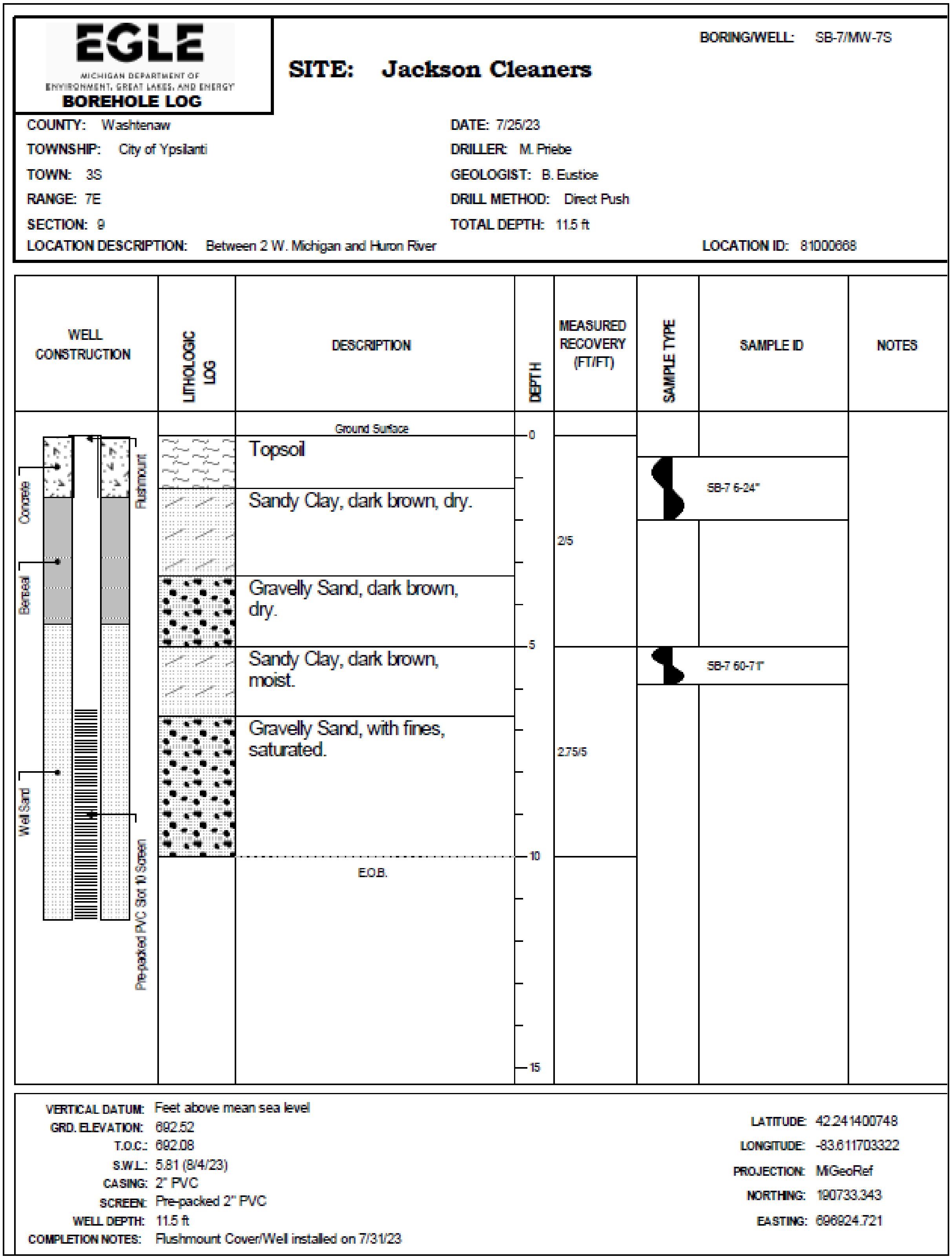


Fig. 20. Soil boring profile (Geosyntec, 2023)

Appendix E - Assumptions

1. In the selection of a reactive medium for the permeable reactive barrier, no batch tests or column tests were able to be performed. Due to this constraint, some assumptions were made about the performance of the reactive media at our site.
2. We did not have soil porosity values, so typical porosity values were used based on the cross-sections provided of soil types.

Appendix F - Citations

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