Triple Bottom Line Sustainability to Design and Remediate Contaminated Site with Emerging Technology.

BY

DANIELLE DA SILVA
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THESIS

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Defense Committee:

Dr. Krishna R. Reddy, Chair and Advisor

Dr. Amid Khodadoust, Civil and Materials Engineering

Dr. Joseph Schulenberg, Civil and Materials Engineering

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LIST OF ABBREVIATIONS

ADM	Archer Daniels Midland
CD	Carbon disulfide
CF	Chloroform
COC	Contaminant of concern
CT	Carbon tetrachloride
DNAPL	dense non-aqueous phase liquid
EDB	1,2-dibromoethane
EZVI	Emulsified zero valent iron
GHG	Greenhouse gas
LCA	Life-cycle analysis
MC	Methylene Chloride
PT	Pump and Treat
SEFA	Spreadsheets for Environmental Footprint Analysis
USEPA	United States Environmental Protection Agency
VOC	Volatile organic compound

I. INTRODUCTION

The remediation of contaminated soils and groundwater represents one of the biggest environmental challenges, not only due to the natural complexity of soils, but mostly due to the even more complex characteristics and dynamics of the contaminants themselves. Because of these difficulties, in conjunction with more rigorous federal laws, several remediation technologies have been introduced and used over the last few decades, ranging from simpler technology, such as natural attenuation, to more complex treatments, such as in-situ ground injections, and ex-situ plasma heat treatment.

Contaminated sites can have an immense effect on human and ecosystem health, and these effects range from childhood learning problems to an increase in cancer cases. Contamination of soils and groundwater due to petroleum derivatives, in particular, have been gaining special attention over the last three decades, due to the adverse effects to human health, which primarily include impaired nervous systems and increase risk of skin cancers, lung and kidney cancers, and leukemia[1].

Aside from the challenges faced with the site remediation itself, it is common that from time to time, different methods of assessment are introduced that position different values in the community. For the past several decades, environmental sustainability has gained a central position. In fact, the term sustainability in most cases still refers to environmental sustainability alone. However, a more inclusive way of looking at sustainability is the triple bottom line concept, which places equal or enough weight in not only environmental, but also economic and social

[1] Information for health risks due to contaminants are generally found at the Agency for Toxic Substances and Disease Registry website and publications. https://www.atsdr.cdc.gov/

sustainability. Each component of sustainability can be seen in this project as follows: (1) *Environmental sustainability* refers to any impact each technology has in the environmental and/or local ecosystem, whether short or long-term. Some examples include greenhouse gas emissions, water consumption, and impacts on global warming. (2) *Economic sustainability* refers not only to the cheapest option but to the equilibrium between a given technology being used in this project and risks involved. (3) *Social sustainability* represents the direct and indirect relationship between human capital and any project development. Also, quality of life and public health are correlated with environmental and economic benefits.

Of the three pillars, social sustainability is the newest field, and not enough research, studies and quantifying methods have been done in the United States. Although there are guidelines and requirements for environmental sustainability, especially projects involving the United States Environmental Protection (USEPA), there are no US agencies, currently, requiring the assessment of triple bottom line sustainability. Voluntary programs have been put in place, such as the Voluntary Cleanup Program from the Nebraska Department of Environmental Quality, including not only environmental aspects, but also worker and public safety, and risk assessments[2].

A. PROJECT SCOPE

The primary objective of this project is to develop a framework to assess the overall sustainability of multiple soil remediation technologies, including traditional in-situ and ex-situ alternatives, groundwater remediation, and finally emerging technologies. This assessment follows

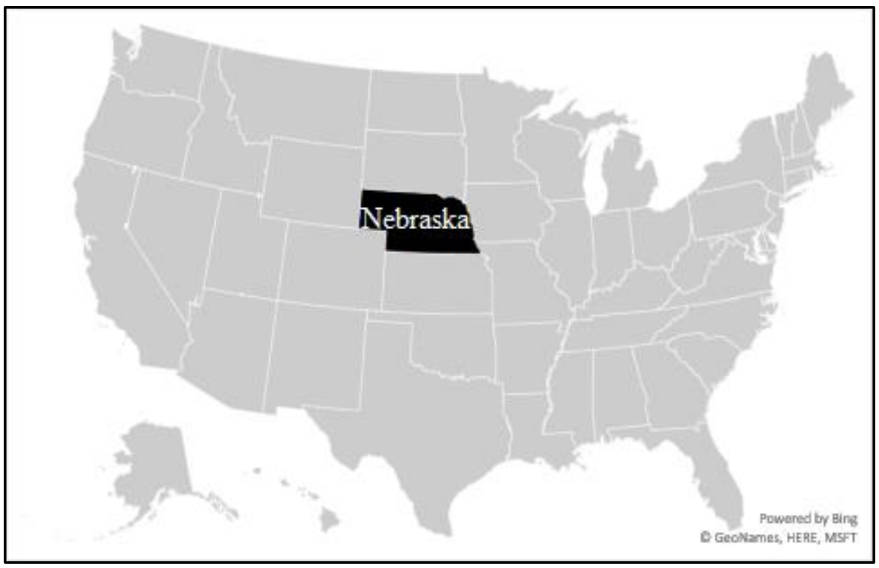
[2] A guidance for the NDEQ Voluntary Cleanup Program can be found at the agency's website: http://www.deq.state.ne.us/Publica.nsf/pages/05-162

the idea of the three pillars of sustainability, and this case study includes examples and tools that can help analyze life-cycle costs, environmental impacts, and social improvements, which can be used in future projects when determining the feasibility of other sites. Generally, there is a consensus nowadays that a more well-rounded assessment should include metrics on the health and wellbeing of individuals and communities. The metrics for reporting social sustainability, however, are currently much less defined and more subjective than environmental and economic assessments and require calibration of opinion and public perception on the subject.

The basic framework for overall sustainability of the remediation options alternatives was developed based on the following 7 parts: (1) *Site Characterization Assessment*, which includes gathering any pertinent information of the site in question and quantifying initial values, such as hydrology and geology profiles, historic background, type and levels of contamination, and rules and regulations research. (2) *Technology Review and Screening* means identifying any technology viable for the project through literature review and applying a screening process to discern the best technologies to be used in the project. (3) *Environmental Sustainability* consists of characterizing the technologies and applying these characterizations to environmental assessment tools, and to quantifying environmental metrics. (4) *Economic Assessment and Sustainability* includes conducting an itemized cost estimate and applying this cost estimate to available tools in order to quantify uncertainty risks, present, and future values. (5) *Social Sustainability*, compares and correlates the activities and results from economic and social sustainability to the impact in human and community lives. (6) *Weighted Results* involves applying the results from steps 3 to 5 into a mathematical model and weighing the results for specific stakeholders. (7) *Initial Design and Pilot Program* include creating a phase I design and incorporating a pilot program to the final remedial technology selected.

B. SITE BACKGROUND

The site considered for remediation in this study was constructed in 1950, to be used primarily for soybean grain elevators. The location of the site is about 5 miles northeast of the city center of Lincoln, Nebraska, and it's currently owned by Archer Daniels Midland (ADM) for soybean extraction, processing, and oil refinery, Figure 1. A field investigation for potential contamination was previously conducted by Huff & Huff, Inc., and a report of the findings was released in 2008, after the United States Environmental Protection Agency (USEPA) discovered possible carbon tetrachloride contamination of water wells, downstream from the facility.



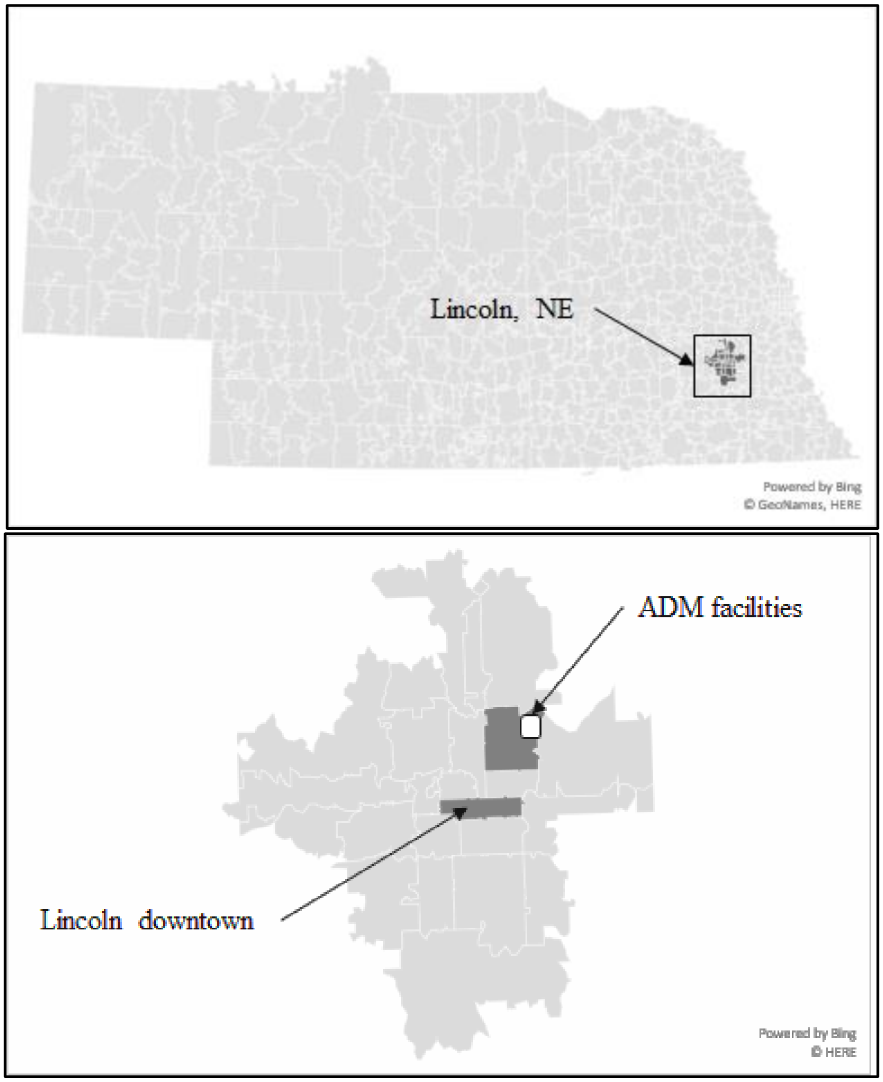


Figure 1. 1.A) Nebraska (top); 1.B) Lincoln, Nebraska (middle); 1.C) Project General Location (bottom).

The property encompasses a total of 40.9 acres, with 25.9 acres being roads and open area, and the main area is currently used as an oil refinery. Historically, the contamination can be divided into two stages or events. The first event is a single accidental petroleum release in 1999, when 750 gallons of #2 fuel was discharged due to broken underground pipes connected to storage tanks. The second event includes the continuous release of carbon tetrachloride (CT) for several years, which was used before ADM ownership as a fumigant. CT was detected by the EPA in private wells north and northwest of the site, and there is a potential of groundwater contamination due to these releases. Figure 2 shows the layout of the facility.

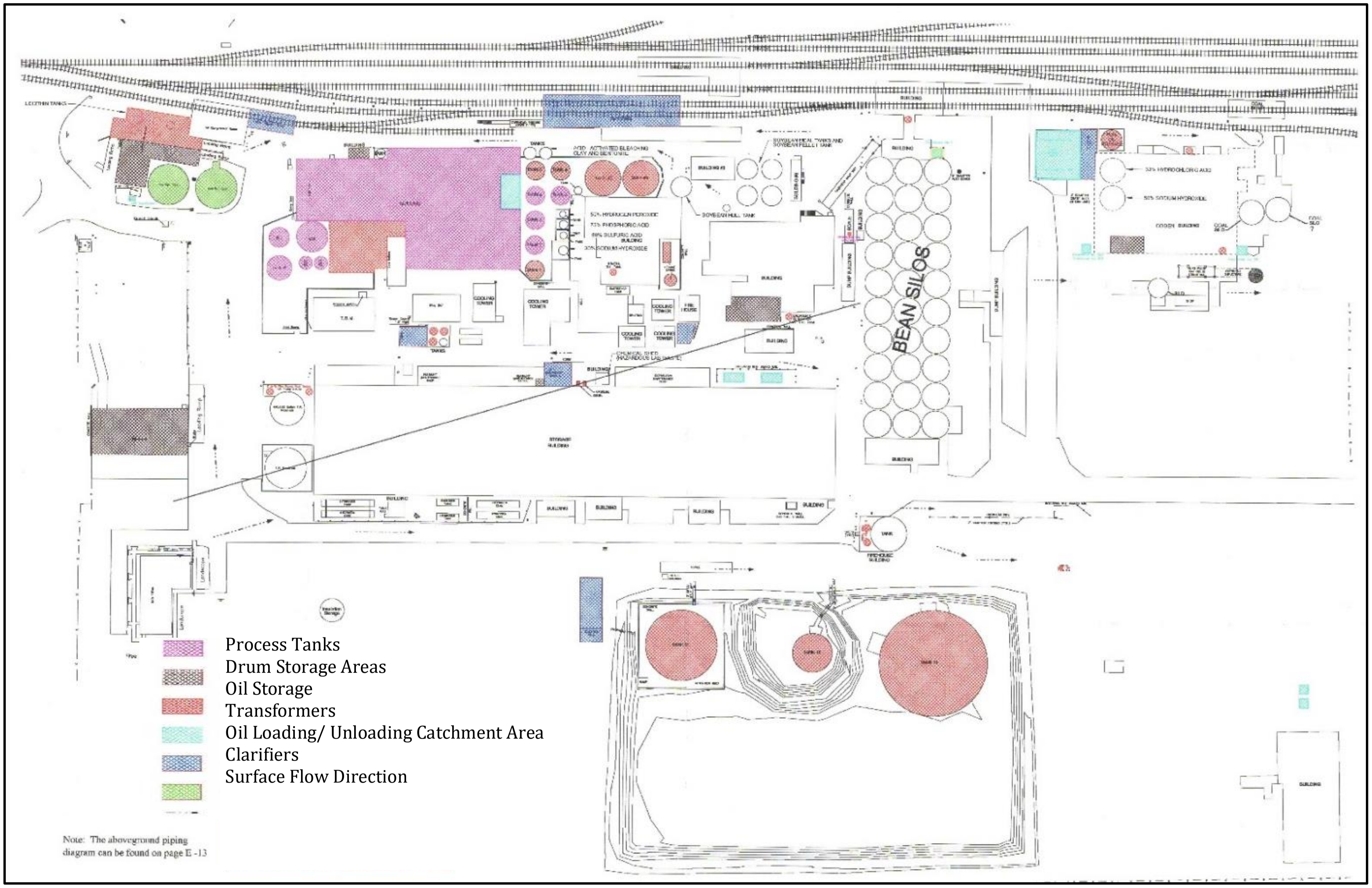


Figure 2. Layout of ADM facility in Lincoln, NE.

The current land uses include residences 500 feet to the west of the potentially contaminated area, agricultural fields to the east and south, and mostly industrial properties to the north, as seen in Figure 3.

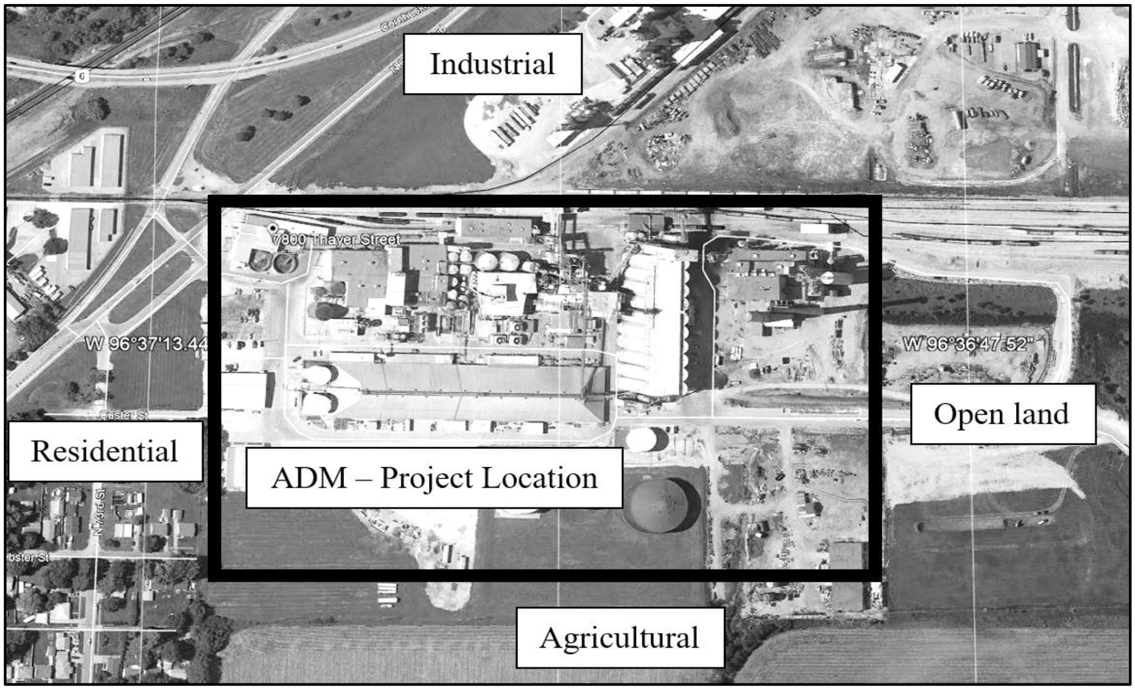


Figure 3. Project location nearby land use

II. SITE CHARACTERIZATION

This project follows a general 4 phase methodology for site characterization[1]. As is the case with many site contamination projects, little is known about the area and contaminants. Therefore, an investigation is generally required.

Phase I includes the purpose and work plan, and a preliminary assessment. The preliminary assessment studies any literature review, such as geological information, site records, soil maps, utilities, nearby surface and underground waterlogs, images, and any other relevant background information. Phase II requires an engineer to conduct a site visit, as well as a survey, and documented records of any surface features found on the site, including contamination sources. Phase II also consists of a detailed scope and site investigation to collect site-specific data. In this investigation, engineers collect samples, determine testing and pertinent lab procedures, and written work plans, including health and safety plan[3], QC/QA, and preliminary design plans. Once these two phases have been reviewed, the engineer determines if additional site-specific data is needed to further develop the remediation design plan. If so, a detailed site investigation is scheduled, or Phase III. In this phase, the characterization of geology, hydrology, and contaminants are evaluated, through a variety of methods for collection of boring logs, radars, monitoring, lab testing and detailed documentation[4]. If the first three phases are inconclusive, Phase IV is used for additional site sampling collection and testing, as well as the further definition of project scope, and local permits and compliance. The background information for this project and a detailed site characterization were already previously conducted by Huff & Huff, Inc. in 2008[2], and are summarized in the following sections.

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[3] Per USEPA guides, 1984

[4] Source: Sharma and Reddy, GeoEnvironmental Engineering (2004), from *Summary of laboratory test methods for analysis of soil and groundwater samples*, Chapter 10, Table 10.1.

A. GEOLOGY

The project site and surroundings sit on the layers, shown in Table I:

TABLE I. LOCAL GEOLOGY FORMATION AND DEPTHS

Geological Layer	Thickness, FT	Depth, FT
Silty Clay	19	0-19
Sandy Clay	2	19-21
Sand	37	21-58
Dakota Sandstone	>40	45-90

B. HYDROLOGY

The Principal Quaternary aquifer thickness in area is 100 ft or less and contains fine-grained material, primarily glacial till, yielding low quantities of water. Dakota sandstone is the surface bedrock and reaches a max of 300 feet thick. This water, however, is mineralized and unfit for drinking. Beneath this, a Pennsylvanian sandstone system is encountered and reportedly contains moderately good aquifers. Stevens Creek is the main local surface water body. However, it is now identified as impaired by the USEPA, and the project area does not sit in a floodplain, but the facility does sit partially on special flood hazard area just east of the bean silos. In addition, the potential migration of the contamination plume includes an area northeast of the property which sits along the floodplain[5].

[5] Per FEMA, from the local Flood Insurance Rate Map (FIRM). Lancaster county, panel 326 of 625, map number 31109C0326F.

C. TOPOGRAPHY AND WATER FLOW

The terrain downgrades north, while the water flows in the same direction from south to north at first, then diverges northeast towards Stevens Creek. ADM Facility lies in part of Stevens Creek Watershed, with Stevens Creek being 0.75 miles northeast of the facility. The water flows north to merge into Salt Creek, with a daily discharge of 2,718 cfs, and there is one wetland located on the property. Beyond that, the facility is located outside the 500-year floodplain[3].

D. CHEMICAL CHARACTERISTICS

Table II shows the contaminants found on the site, and along the water flow direction.

TABLE II. CONTAMINANTS FOUND ON SITE

Contaminants of Concern	Groundwater	Soil
Carbon Tetrachloride (CT)	Yes	Yes
Carbon Disulfide (CD)	Yes	No
Chloroform (CF)	Yes	Yes
Methylene Chloride	Yes	Yes
1,2-dibromoethane (EDB)	Yes	Yes

The contaminants were found primarily in 2 areas: Source area and deep zone. In the source area, the region in the southwest corner of the bean silos presented the highest concentrations of each contaminant. A more detailed view can be seen in Figure 4. Furthermore, the contaminant plume from the source area extends about 0.75 miles northeast and intersects Stevens Creek, as seen in Figure 5.

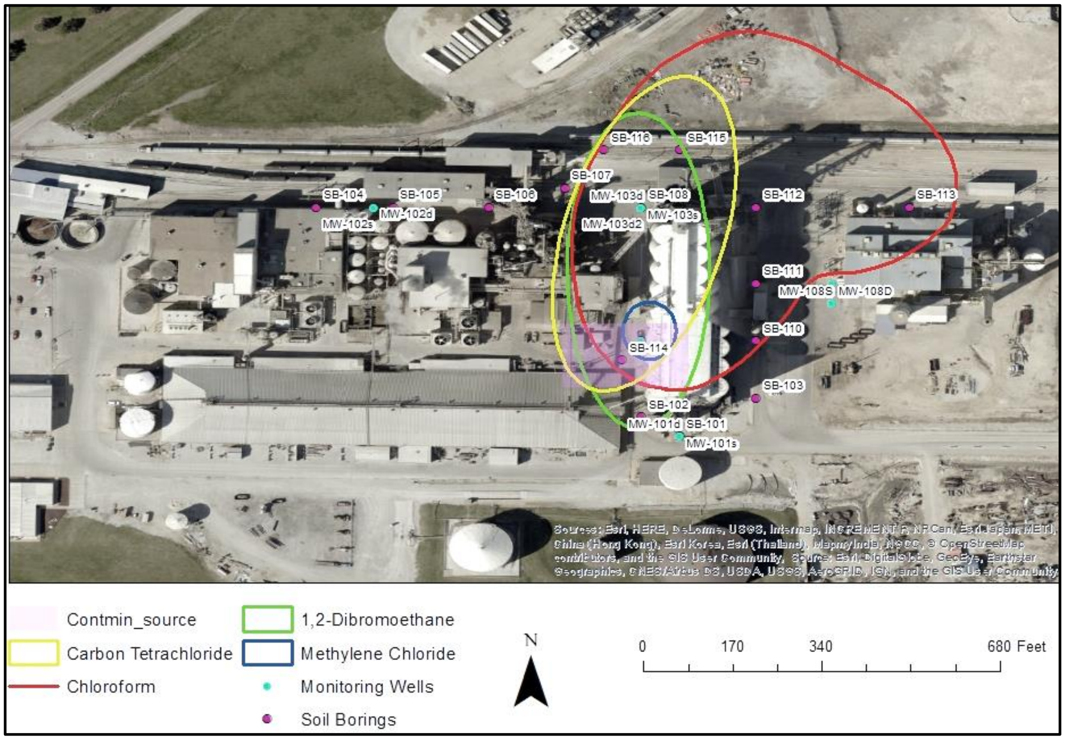

Figure 4. Source area/ soil contamination boundaries.

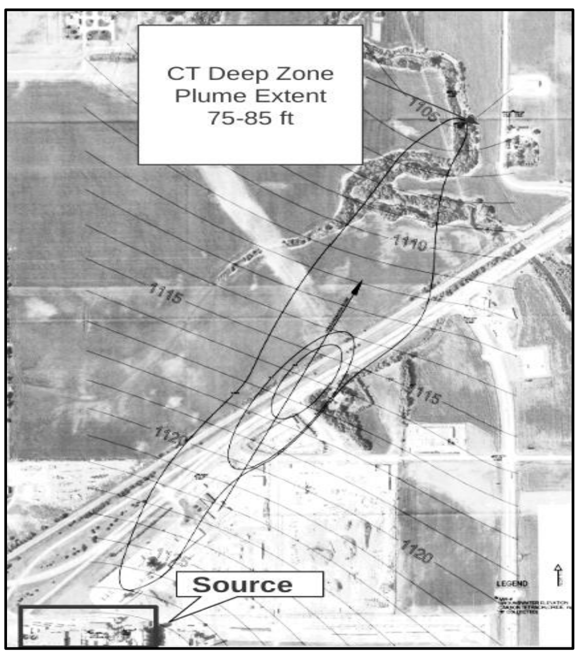

Figure 5. Deep zone/groundwater contamination boundaries.

The nature of contaminants, as described by further evaluation of chemical characteristics from USEPA reports, determined that CT was the carrier chemical for fumigation operations [4].

CD was the actual fumigant [5]. CF, and MC were both co-products of CT. EDB is believed to be used in the grain elevator as a general pest control [6]. All contaminants found have specific gravity greater than water, and have a viscosity lower than water, which means they will sink in (move downwards) faster than water. All contaminants have high concentrations near the southeast corner of the building just west of the lower left corner of the bean silos, except for a small amount of EDB in the grain elevator.

From the environmental media of the contaminants and migration paths standpoint, the top first 13 feet - which is clay in the source area - will make the COCs disperse slowly, but once the plume hits the sandy soil the plume movement accelerates until it hits the bedrock. All COCs got to groundwater by leaching into the ground. Also, because the contaminants are volatile organic compounds (VOCs), there were some concerns of vapor intrusion, but after further analysis of air quality inside nearby buildings and basements, it was determined that this was not a major factor during the time the samples were taken.

E. APPLICABLE LAWS AND REGULATION

Federal Laws and Regulations - The project follows the federal regulations listed below:

Occupational Safety and Health Act (OSHA), 29 U.S.C.651, 1970 - Ensures workers and workplace safety, site safety plan and training, air monitoring, health hazards standards practice and monitoring. Since this project deals with VOCs, Level C is recommended during decontamination, which requires workers to wear protective clothing such as coveralls, gloves. hard hat, and steel-toed boots and breathe air-purifying respirators. During the monitoring period, Level D is recommended, which entails of wearing protective clothing above, but does not require air protection.

Clean Air Act (CAA), 1970, 1977, 1990 - Regulates air emissions levels for criteria pollutants and creates standards and monitoring for other air pollutants without specified limits. The 1990 amendments also require permits to reduce the release of volatile organic compounds (VOCs), oxides, nitrogen, and carbon monoxide.

Clean Water Act (CWA), 1977, 1981, 1987 - Regulates pollution discharge into Water of the US (WOUS), tributaries, wetlands, and other water bodies potentially degraded by a project. Discharge of water is only allowed with an NPDES permit and must meet effluent standards as specified in 40 CRF 125.3; 40 CEF 122.44.

Safe Drinking Water Act (SDWA), 1974, 1977, 1986 - Assures quality of drinking water and establishes maximum contaminant goals (MCLGs) and maximum and secondary concentration levels in any water potentially used as a drinking water source, including aquifers. The list of MCLGs is found in 40 CRF 141, and levels are found in 40 CRF 143.

Solid Waste Disposal Act (RCRA), 1976, 1980, amended by the **Hazardous and Solid Waste Amendment (HSWA) of 1984 -** USEPA regulations for soils and hazardous waste, Section 3008(h). This act and amendment prohibit the land disposal of untreated liquid and solid hazardous waste and requires proper storage and new technology standards for disposal facilities. O&M plan includes: CMI Scope of Work, and Quality Control/Quality Assurance.

State Laws and Regulations - In addition, the project must follow the Nebraska Department of Environmental Quality (NDEQ) guidelines and regulations for soil and groundwater remediation, as established by the Nebraska Voluntary Cleanup Program as part of the **Remedial Action Plan Monitoring Act**, (*Section 1, Attachment 1-5 RAPMA Statute*). This program includes the following:

- Investigation Report (IR) and Approval of the Remedial Action Plan (RAP).
- Risk-Based Corrective Action (RBCA) At Petroleum Release Sites.
- Groundwater Quality Standards and Use Classifications.
- Rules and Regulations for Underground Injection and Mineral Exploration Wells.

Uniform Environmental Covenants Act - For the use of Institutional Controls, and defined by the NDEQ as “non-engineered instruments, such as administrative and/or legal controls, that help to minimize the potential for human exposure to any contamination left in place and/or to protect the integrity of a remedy”.

III. RISK ASSESSMENT AND REMEDIAL GOALS

A. BASELINE RISK ASSESSMENT

The baseline risk assessment is a procedure described by the USEPA and quantifies any exposure of contaminants to human health. Four steps are used in this procedure, as shown in Figure 6:

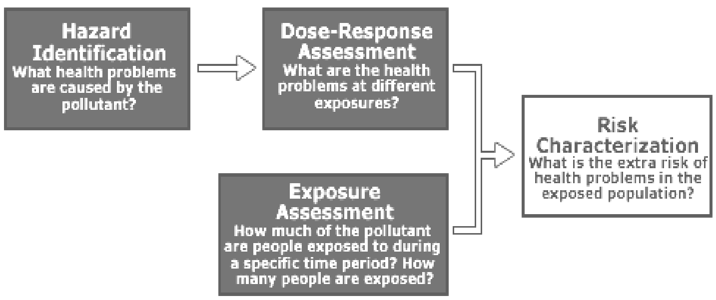

Figure 6. The Four-Step risk Assessment Process

Step 1, *Data Collection*, encompass reviewing of all the site-specific data collected on the potential contaminants, including identity, concentration, and characteristics of both the contaminants and the environment.

Step 2, *Exposure Assessment*, includes all relevant exposure information, such as source, route, and migration, until reaching a receptor. The detailed schematic in Figure 7, shows how the COCs move and which groups are most at risk. It starts by leaking from the source area and infiltrating into the ground. From there, the COCs in the surface soil were examined. These could reach the receptors by volatilization into the outdoor air, or stormwater runoff. Another route of contamination comes from stormwater runoff, which can potentially affect all receptor groups. Once the COCs go deeper into the subsurface soil, it percolates into the groundwater, and can also affect all receptor groups.

Step 3, *Toxicology Review*, includes a review of the toxicology of the COCs, and the determination of reference doses[6]. These reference doses are used to estimate the magnitude of the contaminant levels found on-site and develop a relationship between these contaminants and adverse health effects of the exposed group. Step 4, *Risk Characterization*, is the final step after determination of COCs levels and whether these were above or below the limits determined by EPA. The lab results from Huff & Huff, Inc. assessment determined they were all well above the threshold specified of 10^{-6} for carcinogens, and over 1 for non-carcinogens. Table III shows the results of the contaminants found when applied to risk assessment.

TABLE III. RISK CHARACTERIZATION AND CURRENT NON-CARCINOGEN AND CARCINOGEN LEVELS.

	Soil		
Chemical	Oral HQ	Oral Risk	Inhalation Risk
Carbon Tetrachloride	3.33E+05	3.03E+01	3.03E+01
Chloroform	5.82E+02	3.55E-02	4.71E-01
Methylene Chloride	1.87E+01	8.40E-03	1.85E-03
1,2 - Dibromoethane	-	2.63E+04	2.38E+02
	Groundwater		
Chemical	Oral HQ	Oral Risk	Inhalation Risk
Carbon Tetrachloride	8.76E+03	7.97E-01	7.97E-01
Chloroform	4.15E+01	2.53E-03	3.36E-02
Methylene Chloride	9.18E+00	4.13E-03	9.09E-04
1,2 - Dibromoethane	-	1.15E+01	1.04E-01

[6] Reference dosage determined by the USEPA and found in the Integrated Risk Information System (IRIS). 1999. https://www.epa.gov/iris

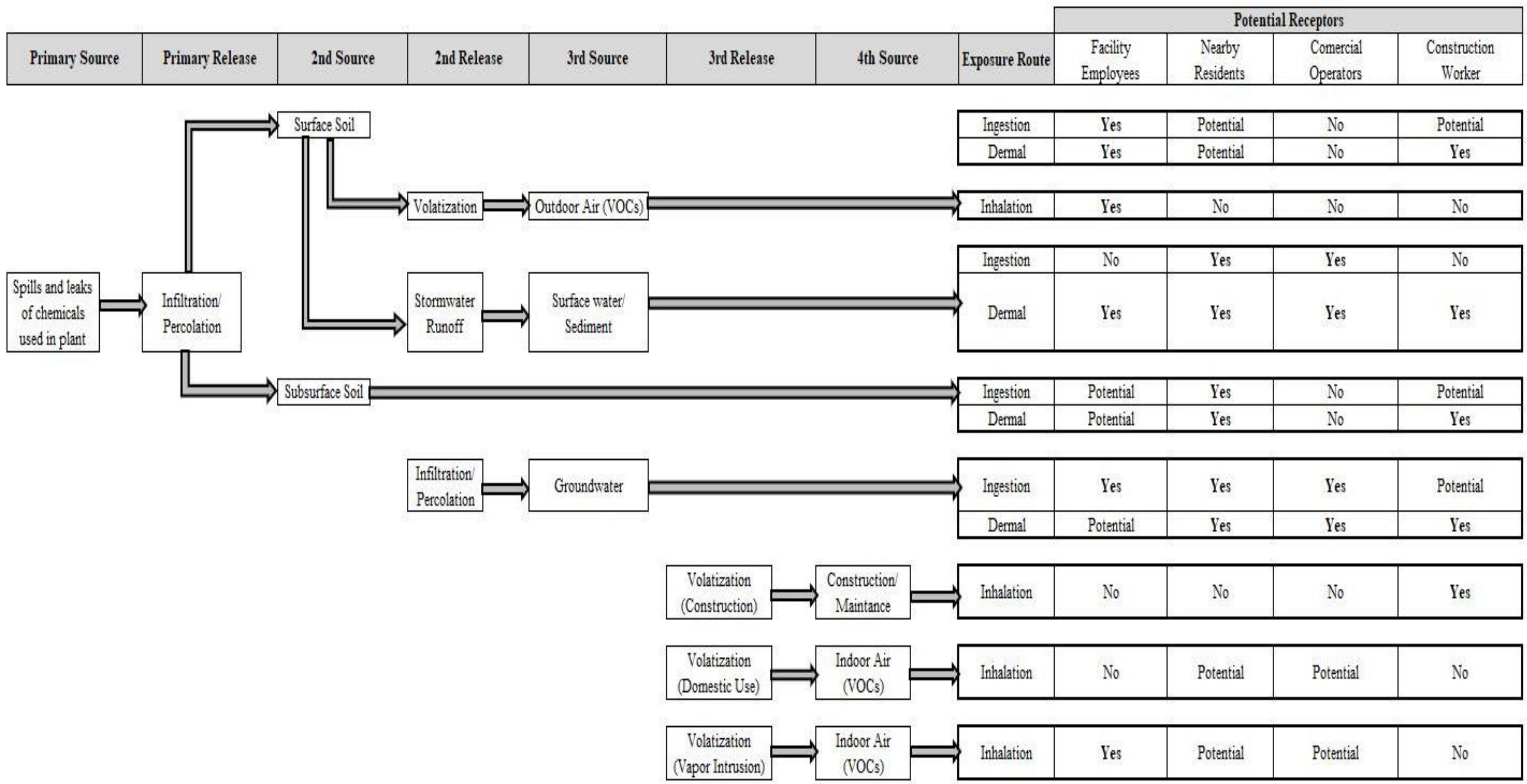

Figure 7. Baseline risk assessment contaminant transport diagram.

B. ECOLOGICAL RISK ASSESSMENT

Similarly, for ecological risk assessment, the USEPA has guidelines put in place to help analyze the effects of contaminants in the local and regional ecosystem. This process is divided into three phases. Phase 1, *Problem Formulation*, helps identify the endpoint of COCs to determine what ecological area is at risk. Phase 2, *Analysis*, helps determine which animals and plants are being exposed, and the level of exposure from the contaminants in question. Finally, Phase 3, *Risk Characterization*, concludes how much of a threat the contaminants are for the local environment, plants and animals[7]. Figure 8 summarizes the progression of this process.

For this project's ecological risk assessment, the land preservations and nearby bodies of water were identified, as well as any threatened species. The following were found: wetlands were found adjacent to facility. There are no endangered species in this area. There is a marsh located 0.75 miles from facility. Three threatened species were potentially identified, one insect and two plants in the vicinity, in the salt marsh. However, it is not located in a downgrade, and therefore, not of immediate concern. Another surface body of water was identified, Stevens Creek, which is 0.75 miles northeast of ADM, but no Total Maximum Daily Limits were surpassed. Other water features of concern include a small tributary that intersects the groundwater, but the contamination plume moved towards the soil layer below the tributary branch.

From the information above, a schematic was created, as seen in Figure 9, and it was determined that no terrestrial species is at risk. However, there is a possibility of aquatic risk of contamination due to the plume intersecting with Stevens Creek.

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[7] General guidance for ecological risk assessment found at the USEPA website: https://www.epa.gov/risk/ecological-risk-assessment

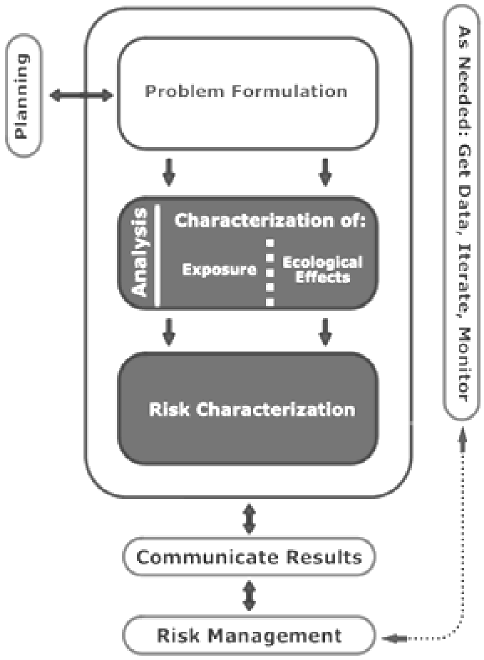

Figure 8. Ecological risk assessment process.

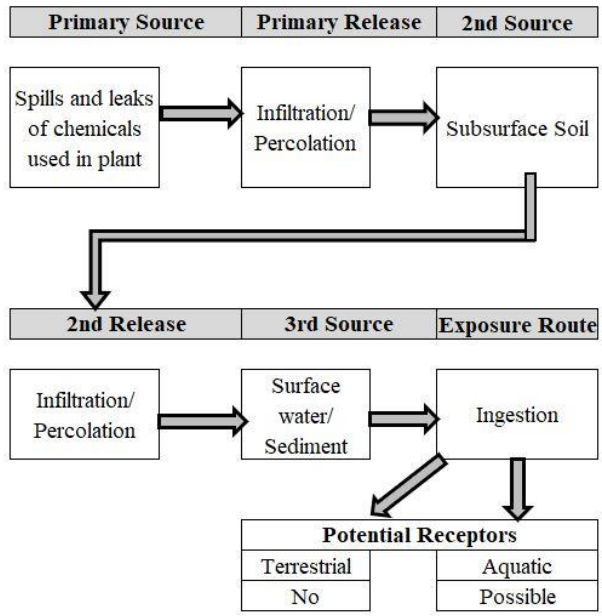

Figure 9. Ecological risk assessment contaminant transport diagram.

C. <u>Remedial Goals</u>

Table IV shows the maximum level of contaminants desired for this area, according to USEPA[8]. In addition, it was determined that the project will likely use an In-situ remediation due to the depth of the contamination plume, which would likely make ex-situ remediation complex and expensive. However, excavation was analyzed as a potential ex-situ technology for a possible combination with other technologies. Lastly, institutional controls and monitored natural attenuation (MNA) were considered as post remediation strategies.

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[8] From the USEPA Regional Screening Levels (RSLs): https://www.epa.gov/risk/regional-screening-levels-rsls-generic-tables

TABLE IV. CONTAMINANTS LEVELS REQUIRED. CONCENTRATION IN MG/KG.

Contaminants of Concern	Soil -Industrial	Soil - Mitigation	Groundwater
Carbon Tetrachloride (CT)	6.4	0.0066	0.005
Chloroform (CF)	5.5	0.0012	0.00021
Methylene Chloride	240	0.023	0.005
1,2-dibromoethane (EDB)	0.29	0.00026	0.00005

IV. REMEDIAL OPTIONS

A. REMEDIATION TECHNOLOGIES AND FIRST SCREENING

The first technology screening is a literature review of remediation technologies available that can remediate the COCs at hand. Table V shows the summary of ten soil and groundwater remediation technologies applicable to this project, based on contaminant characteristics, along with each technology’s pros and cons. A brief explanation of each technology and how it can be used in the project site is listed below:

Air Sparging (AS): the USEPA describes AS as “an in-situ remedial technology that reduces concentrations of volatile constituents in petroleum products that are absorbed to soils and dissolved in groundwater.” In-situ air stripping and in-situ volatilization are also common names for this technology, which uses the injection of non-contaminated air into the soil saturated zone, to sequester hydrocarbons from the contaminated soil and groundwater, and to transform them into vapor phase from a dissolved phase, then releasing them through vents. Air sparging is often used with soil vapor extraction (SVE), but it can also be used with other remedial technologies[8].

Bioremediation: this is a technique can be both in-situ and ex-situ, and uses microorganisms (bacteria, fungi and yeast) and enzymes to transform contaminants into substances with low or no toxicity. to remediate contaminated sites. This technology is often used in integrated approaches and combined with chemical oxidation[9].

Electrokinetic Remediation: this remediation uses vertical wells that dissipate electricity that heat the subsurface in order to vaporize contaminants. This technology can be used in most depths and soil types, and very effective in removing most organic with low and high boiling points, such as gasoline, PCBs and chlorinated solvents[10].

Excavation: this ex-situ process involves removing the contaminated topsoil, where this soil will either be treated outside of the contaminated site, or disposed in a landfill. This process is often done when in-situ technologies do not work fast enough or are too expensive. Excavation is also used in combination with other methods, and allows for a faster site remediation by removing the layer with the highest concentration of contamination or the contamination source[11].

Emulsified Zero Valent Ion (EZVI): this is an in-situ NASA patented technology. This technology is one of the few methods available that can treat dense non aqueous phase liquid (DNAPL) contaminants at their source, in both soil and groundwater. This technology works by mixing a combination of ZVI, a food-grade vegetable oil and water until an emulsion occurs. While in the emulsified state an oil membrane is formed around an aqueous phase ZVI droplet. Because the DNAPL are miscible in oil, the chlorinated hydrocarbon will penetrate the oil membrane and be exposed to react with ZVI. Secondly, the vegetable oil will in the long-term break down as an electron donor during a fermenting process allowing for further degradation of COCs. Finally, the increased viscosity of the emulsion retards mobility of the contaminant. This technology can be applied in four ways: (1) direct push, (2) pneumatic fracturing. (3) pressure pulse technology. (4) liquid automation[12].

Permeable Reactive Barriers (PRB): PRB technologies include “continuous trench” and “funnel and gate” methods. With continuous trench, a wall is placed in a trench downstream from the contaminated groundwater plume with a reactive medium. The water flows through the medium, decreasing the level of contaminants. With funnel and gate method, low permeability walls act like a funnel and direct the plume into a treatment zone. Funnel and treat can remediate multiple contaminants at once. The remediation can happen in multiple ways, lower level of pollutants, sorption, precipitation, and biochemical degradation [13].

Phytoremediation: this in-situ technology uses plants and their associated soil microbes to remove organic and metals from contaminated soils. Depending on the contaminant and levels of contaminants, phytoremediation can be used as retention (phytostabilization), attenuation (phytodegradation) or removal (phytovolatilization and phytoextraction) of contaminants. The plants can be harvested for biomass[14].

Pump and Treat: this is one of the most used technologies for remediating groundwater. This is accomplished by pumping the contaminated groundwater to the surface and treating before releasing it back to the site. The pumping works as a remediation option by hydraulic containment, preventing the movement and expansion of contaminated groundwater. Traditionally, these systems require can be used in three different configurations: (1) a pumping well alone, (2) a subsurface drain combined with a pump well, and (3) a well within a barrier wall system. Treating the pumped water reduces the concentrations of contaminants[15].

Soil Washing/In-Situ Soil Flushing: this technology involves adding a solution to contaminated soils in order to remove the contamination by reaction. In-situ soil flushing requires no excavation of soils, instead the solution is injected into soil via wells. The solution then flows through the soil layers picking up contaminants as it moves to extraction wells. Soil washing is most effective on soils with low silt or clay content. and it can treat several types of contaminants, including metals, organics, solvents and PCBs. [16]

Soil Vapor Extraction (SVE): with this technology, contamination in the subsurface is removed by high power vacuums that convert the contaminants to vapor which are extracted by extraction wells connected to the vacuum. This technology, however, it’s only effective in coarse grained soils, and above the water table, but it can be used to treat volatile contaminants[17].

TABLE V. SUMMARIZED SOIL AND GROUNDWATER REMEDIATION TECHNOLOGY REVIEW.

Remedial Technology	Pros	Cons	Notes/ Preliminary Conclusions
Air Sparging	Minimal site disturbance and exposure. Simple equipment; easy to operate. Requires short treatment time.	Challenges with contamination in low-permeable soils. Spreading of contaminants to clean areas.	Soil and groundwater. In-situ remedy. Not ideal for site.
Bioremediation	May degrade organics to nontoxic by-products. Minimal mechanical equipment and site disturbance.	Potential for degradation to more toxic by-products. Extensive monitoring required. Requires longer treatment time.	Soil and groundwater. Organics may be resistant to degradation. Difficult to design, predict and implement.
Electrokinetic remediation	Applies to low-permeable soils, Site-specific tailored. Can be coupled with other technologies.	Uncertainty of pH changes. Complex geochemical reactions. Requires pump and treatment units.	Soil and groundwater. Difficult to assess. Needs more research. Works well with organics.
Excavation/ Extraction	Simple, fast. Cost effective (small volume) . Permit easy to obtain.	Expensive (large volume) . Regulations require soil treatment before disposal. Site disturbance.	Soil only. Impractical solution. Ex-situ remedy.
EZVI – Emulsified Zero Valent Ion	Significant decrease in flux due to VOCs partitioning into oil. Long-term biodegradation provided by oil. Complete reduction to non-toxic end products. Minimal labor and waste disposal.	Not cost-effective for dispersed plumes. Cost of ZVI material can be high. Viscosity can make injection hard. Well-characterized source zone needed.	Soil and groundwater. (EZVI) both sequester and degrade CVOCs. Multiple injection technology options are available, depending on soil type.
Permeable Reactive Barriers	Treats variety of contaminants. No above ground structures. Low operating cost and no disposal cost for successfully treated wastes.	Lengthy treatment. Potential for loss of media reactivity. Barrier depth limitation.	Site geology makes assessment of use difficult. Site media may need adjustments.
Phytoremediation	In-situ technology. Relatively inexpensive. Likely accepted by public.	Relatively shallow cleaning depth. Slow process of remediation. Potential food chain contamination.	Soil only. Not a realistic, permanent solution.
Pump and Treat	Useful for containment/restoration Requires simple equipment Effective for source zone removal, near free-phase contamination.	Residual contamination due to tailing and/or rebound Relatively long remediation High cost for treatment and O&M	Groundwater only. Air stripping may help with organics removal. Can supplement other technologies.
Soil Washing/ In-Situ Soil Flushing	Significantly reduces the volume of contaminated soil. Can remove organics and inorganics. Few permits required.	Difficult to implement in soils with high clay content Relatively expensive. Long remediation time.	Soil and groundwater. Chemical reduction techniques. Modified method may be more useful.
SVE –Soil Vapor Extraction (Dual Phase)	Remediate soil and groundwater. Minimal site disturbance.	Ineffective in low- permeable soils Air emission permits required more.	Soil and groundwater. Not a permanent solution. Can be coupled with other technologies.

B. TECHNOLOGY SCREENING

Before any further technology analysis is conducted, a more detailed screening is used to narrow down the options available. For this project, two matrix screening were examined, the Federal Remediation Technologies Roundtable (FRTR) Matrix[9] and the EPA/CERCLA nine-point criteria screening used in Superfund site remediation[18]. The FRTR matrix combines the collective efforts of several U.S. Government agencies, and it can be used in a variety of different sites, to help determine possible treatment technologies, compares between emerging and conventional technologies, and assigns a relative probability of success based on data, use, and engineering judgment available. The FRTR Matrix focuses on implementation, capability of technology pairing, and direct costs. Table VI shows the criteria used in the FRTR screening and the results of the preliminary technology chosen. The scoring criteria is as follows: 1=Above Average, 0= Average, -1=Below Average, N/A=Not Applicable, I/D=Insufficient Data.

TABLE VI. FEDERAL REMEDIATION TECHNOLOGIES ROUNDTABLE (FRTR) MATRIX FOR SOURCE AREA/SOIL (LEFT), AND DEEP ZONE/GROUNDWATER (RIGHT).

			Relative Overall Cost & Performance										
	Development Status	Treatment Train	O&M	Capital	System Reliability & Maintanability	Relative Cost	Time	Availability	Halogenated (Chlorinated) VOC	Halogenated (Chlorinated) SVOC	Fuels	Inorganics	Total Score
Excavation	1	1	1	1	1	*	1	1	0	0	0	0	7
Thermal	1	-1	-1	-1	1	0	1	1	1	1	1	-1	3
Electrokinetic	1	-1	-1	0	0	-1	0	0	0	0	-1	1	-2
Soil Flushing	1	1	-1	0	0	0	0	1	1	0	0	1	4
SVE	1	-1	-1	0	1	1	0	1	1	-1	1	-1	2
EZVI/ Fracturing	1	0	0	-1	0	0	0	1	0	0	0	0	1
* Levels of effectiveness highly dependent upon specific contaminant and its applications													

			Relative Overall Cost & Performance										
	Development Status	Treatment Train	O&M	Capital	System Reliability & Maintanability	Relative Cost	Time	Availability	Halogenated (Chlorinated) VOC	Halogenated (Chlorinated) SVOC	Fuels	Inorganics	Total Score
MNA	1	1	-1	0	0	1	*	1	0	0	1	-1	3
Pump & Treat	1	0	-1	-1	1	-1	-1	1	0	*	0	0	-1
Air Spurging	1	0	0	-1	0	0	-1	1	0	-1	0	-1	-2
Electrokinetic	1	-1	-1	-1	0	0	1	1	1	1	1	-1	2
PRB	1	1	0	-1	1	0	-1	1	1	1	0	*	4
Bioremediation	1	1	-1	0	0	1	*	1	*	*	1	*	4
SVE	1	-1	-1	-1	0	0	0	1	1	1	1	-1	1
EZVI	1	1	1	1	0	1	-1	1	0	0	0	0	5
* Levels of effectiveness highly dependent upon specific contaminant and its applications													

[9] From the FRTR website – Table 3-2 Treatment Technologies Screening Matrix: https://frtr.gov/matrix2/section3/table3_2.pdf

From the FRTR screenings above, excavation and soil flushing seem to be the likely technologies for further investigation. However, because EZVI ranked highest for the groundwater treatment and has an above average treatment train, this technology was chosen for both soil and groundwater. Soil flushing was initially discarded due to the site's space constraints reaching the contaminants. In addition, pump and treat was chosen for groundwater due to the wide use of the technology and its effectiveness in removing the contaminants on this site. PRB was initially discarded due to the depth of the contaminant plume. However, it can be paired with EZVI injection for greater groundwater depth. Both monitoring and bioremediation will be considered as post treatment option but will not be further evaluated beyond the screening process.

The second screening is a matrix developed by EPA/CERCLA as part of the National Contingency Plan (40CFR300.430(e)(9)) used for Superfund sites cleanup. The nine-criteria table helps identify the most feasible remedial option. However, this is a guideline, not a rule, and a point system was created to help visualize the results better. The points are on a scale from 1 to 5, 1 being not favorable to this project, and 5 being very favorable to this project. Literature review of each technology and similar implemented past projects were used to calibrate the scores. For the source area, which includes only contaminated soil, electrokinetic remediation and EZVI scored the highest and were chosen for further evaluation. In addition, excavation was selected due to higher scores in the FRTR screening, and for being a commonly used method in shallow, and small areas. For the Deep Zone area, which includes a groundwater contamination plume, EZVI and pump and treat were chosen for further analysis. Table VII shows the scores for both the source area and deep zone.

TABLE VII. EPA 9-POINT CRITERIA SCORES FOR SOURCE AREA/SOIL (LEFT); DEEP ZONE/GROUNDWATER (RIGHT)

Evaluation Criteria	Monitoring	Excavation	Air Sparging	Electrokinetic	Soil Flushing	Bioremediation	SVE	EZVI
Overall Protection of Human Health and the Environment	1	3	3	5	3	3	4	5
Compliance with ARARs	2	3	3	4	3	3	4	4
Long-term Effectiveness and Performance	2	4	3	5	3	3	4	5
Reduction of Toxicity, Mobility, or Volume Through Treatment	2	4	3	3	3	2	4	4
Short-term Effectiveness	1	4	3	4	3	1	3	3
Implementability	5	1	4	3	3	3	4	4
Cost	5	3	3	3	4	5	3	3
State Acceptance	1	5	3	4	3	4	4	3
Community Acceptance	1	2	3	5	3	3	4	5
Total Score	**20**	**29**	**28**	**36**	**28**	**27**	**34**	**36**

Evaluation Criteria	Monitoring	Pump and Treat	Air Sparging	Electrokinetic	Permeable Reactive Barrier	Bioremediation	SVE
Overall Protection of Human Health and the Environment	2	4	2	4	4	4	2
Compliance with ARARs	1	3	3	2	3	3	2
Long-term Effectiveness and Performance	2	3	3	5	5	5	2
Reduction of Toxicity, Mobility, or Volume Through Treatment	1	4	4	4	4	2	2
Short-term Effectiveness	1	3	3	4	3	1	3
Implementability	5	5	2	2	3	3	3
Cost	3	3	5	2	3	4	5
State Acceptance	3	4	3	3	3	4	3
Community Acceptance	3	3	3	3	4	4	5
Total Score	**21**	**32**	**28**	**29**	**32**	**30**	**27**

V. SUSTAINABILITY ASSESSMENT

From the technologies selected in the previous section, a sustainability analysis, utilizing the triple bottle line of sustainability was conducted for the environmental, economic, and social aspects.

For the environmental sustainability analysis three tools were used and compared, SEFA (Spreadsheets for Environmental Footprint Analysis), SiteWise, and SimaPro. Both SEFA and SiteWise are Microsoft® Excel-based tool workbooks that calculate and analyze environmental footprint based on site-specific information provided. SEFA uses the USEPA methodology, which encompasses the following steps to be entered in the workbooks: (1) Setting the goals and scope of analysis, (2) gathering information on the technologies considered, (3) quantifying onsite materials and waste, (4) quantifying onsite water usage, (5) quantifying energy usage and air parameters, (6) describing the effects on ecosystem, (7) calculating results.

Similarly, with SiteWise, water, energy and waste parameters are characterized and entered into the workbooks using the Navy, U.S. Army Corps of Engineers, and Army approach. In this approach, the assessment is broken down into modules, and the footprint is calculated for each module separately. The modules, inputs and outputs are summarized in Table VIII.

TABLE VIII. SITEWISE WORKBOOK PARAMETERS SUMMARY TABLE.

MODULES:	RI	remedial investigation
	FS	feasibility study
	CMS	corrective measures study
	RAC	remedial action construction
	RA-0	remedial action operations
	LTM	long-term monitoring
INPUTS:	1	production of materials required
	2	transportation of the required materials, equipment and personnel to and from the site
	3	all on-site activities to be performed
	4	management of the waste produced by the activity
	5	Materials usage is considered only for materials that are completely consumed
OUTPUTS	1	GHG emissions
	2	energy use
	3	air emissions
	4	water consumption
	5	resource consumption
	6	worker safety

SimaPro V.9.0.0 is a life-cycle assessment and life-cycle cost assessment that follows steps defined by ISO 14040 (2006). As with any LCA, the first step is to determine the goals and the boundaries for analysis. Figure 10 shows the boundaries used in the LCA model. The SimaPro software is installed with a set of inventory library databases for different processes, use, energy, water, and waste [10]. SimaPro separates the analysis into two parts, (1) analysis of process or production phase, (2) analysis of entire life cycle, (comparison of different products/ methods/ technologies and perform of sensitivity analysis. The first part requires not only a definition of scope but characterization of the inputs. Figure 11 shows an example of the LCA workflow for the excavation and for EZVI technology.

[10] For this project, the USEPA TRACI's 2.1 (Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts) was the method of calculation used.

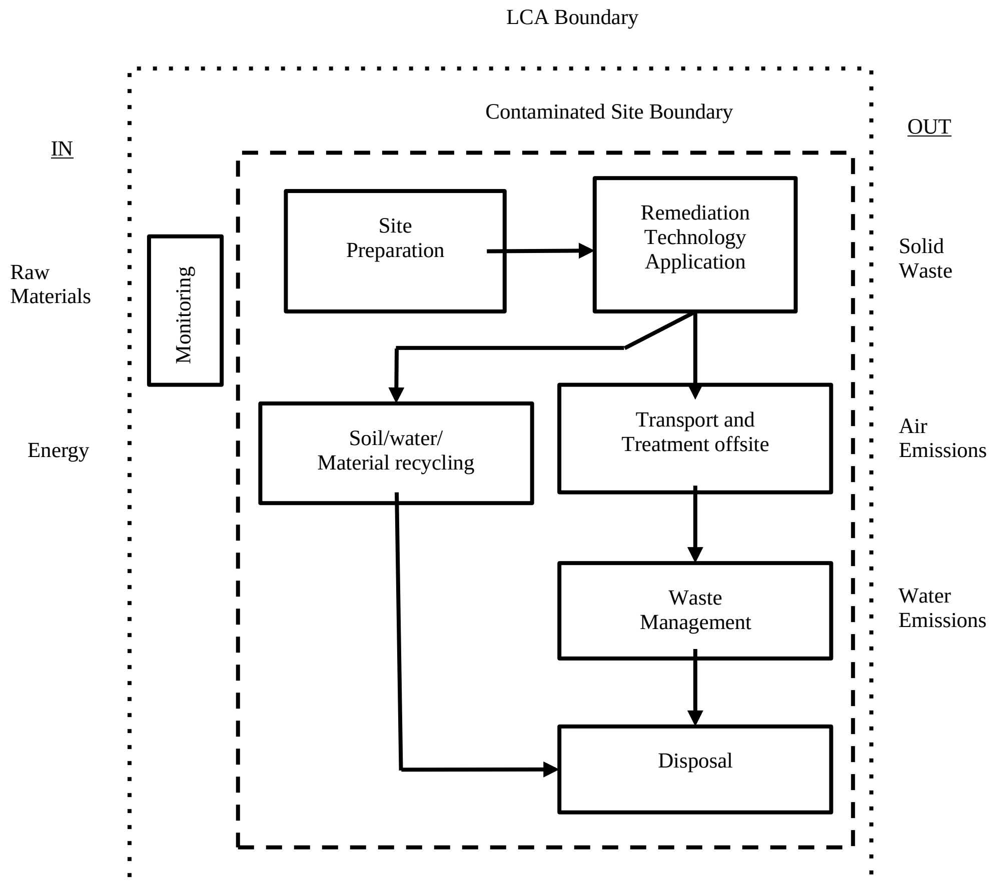
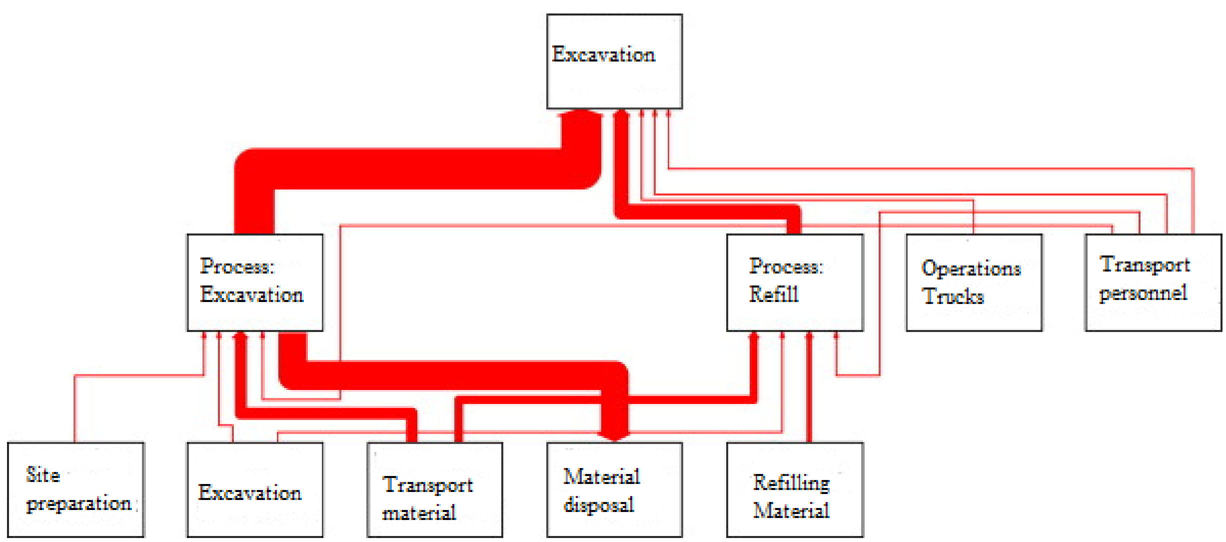


Figure 10. Remediation boundaries considered in the SimaPro Life-Cycle Assessment Model



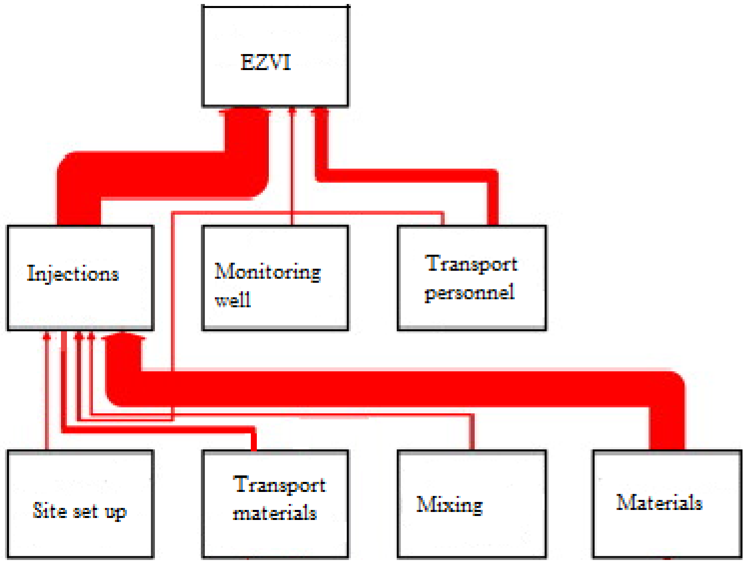


Figure 11. SimaPro LCA workflow diagrams. 11.A) Excavation; 11.B) EZVI

The economic sustainability component of this project uses both calculated results given by SiteWise modeling, and direct cost calculation, which were based on historical similar project, the FRTR unit cost guide, and from the USEPA Remediation Technology Cost Compendium report, from 2000[25]. A risk cost assessment using the @RISK 7.6 Industrial calculator was then applied to estimate future risks of each alternative. @RISK is an add-in software compatible to Microsoft Excel that helps project managers simulate potential risks in cost estimate and anticipate project uncertainties. The @Risk model helps answer two main questions: (1) What is the probability that the project will actually be delivered within this budget?; and (2) How much contingency is needed?; it then analyzes the cost estimate using PERT distributions and gives a probability of the project to reaching the base budget scenario, and how much should the cost should be adjusted to reach a certain percentage of confidence. In this project a 95% budget confidence was set in order to adjust the final cost numbers. Lastly, a Net Present Value was given based on the results from the costs obtained, using a 10% average public/semi-private investment rate, minus 3% inflation, for a 7% discount rate.

In this project a 5-point approach was used to determine social sustainability and calibrated to provide the most accurate results. Within this 5-point system, four methods were used to quantify the results. The first method used was Professor Reddy's Social Sustainability Evaluation Matrix (SSEM)[11], which uses preset social indicators to analyze and compare each technology. The SSEM matrix uses a score from 2 to -2, 2 being ideal for positive impact, 1 being improved positive impact, 0 not applicable, -1 diminished with negative impact, and -2 being unacceptable. The second method conducted a public survey which correlates the connection of social sustainability with economic and environmental sustainability. The survey was converted into a scoring system from 1 to 5, 1 being most sustainable, and 5 being least sustainable. The third method investigates the social aspect of the SimaPro model, which correlates the technology impact on human health and resources available. Lastly, the social cost of greenhouse gas emissions for all remedial options were calculated based on EPA's table from the Social Cost of Carbon for Regulatory Impact Analysis -Under Executive Order 12866[12].

The last step into the sustainability analysis is to weigh or calibrate the results by using a mathematical model approach, called the MIVES method, *Integrated Value Model for Sustainability Assessment* [19]. This method is a decision-making model that assumes an equal value of 33.33% for each of the three sustainability pillars: Environment, Economic, and Social. In addition, within each category a percentage value is established for each subcategory, based on impact. In order to calculate the weighted value, a unit function that converts qualitative into quantitative values is applied. A final sustainability index is then calculated. The calculations and percentage allocated for each category can be adjusted accordingly for specific stakeholders. Once the results from the sustainability assessment above are determined, the MIVES method applies

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[11] SSEM, Version 1, 2013

[12] Social Cost of Carbon: Technical Documentation, available directly from the EPA website: https://19january2017snapshot.epa.gov/climatechange/social-cost-carbon_.html

four steps to determine a single score result; (1) determination of tendency; a function increasing when the increasing of a value causes an increase of final index score, as usual in the case of social sustainability. A function is decreasing when a value decrease causes an increase in final index value. The latter is often applied in environmental and economic values. (2) Definition of minimum and maximum values. (3) Determination of function shape; concave, convex, linear or S-function. In this project the increasing linear function was used to weight the social sustainability, decreasing concave for environmental sustainability, and decreasing convex function for the economic sustainability. (4) Definition of a mathematical expression. Equation 1 shows the mathematical expression defined. Figure 12 shows the schematic of MIVES method and basic calculations used to determine the single final sustainability score.

$$Vind = B * \left[e^{-k*\left(\frac{|Smax-Smin|}{C}\right)^{P}} \right] \qquad \text{Equation 1}$$

$$\text{Where, } B = 1/\left[1 - e^{-k*\left(\frac{|Smax-Smin|}{C}\right)^{P}} \right] \qquad \text{Equation 2}$$

Where:

Indicator	**Tendency**	**Function**	**P**	**K**	**C**
Social	Increasing	Linear	1	0	Xmin
Environmental	Decreasing	Concave	0.8	0.8	Xmax < C < Xmax + (Xmin-Xmax)/2
Economic	Decreasing	Convex	3	0.05	Xmax + (Xmin-Xmin)/2 <C < Xmax

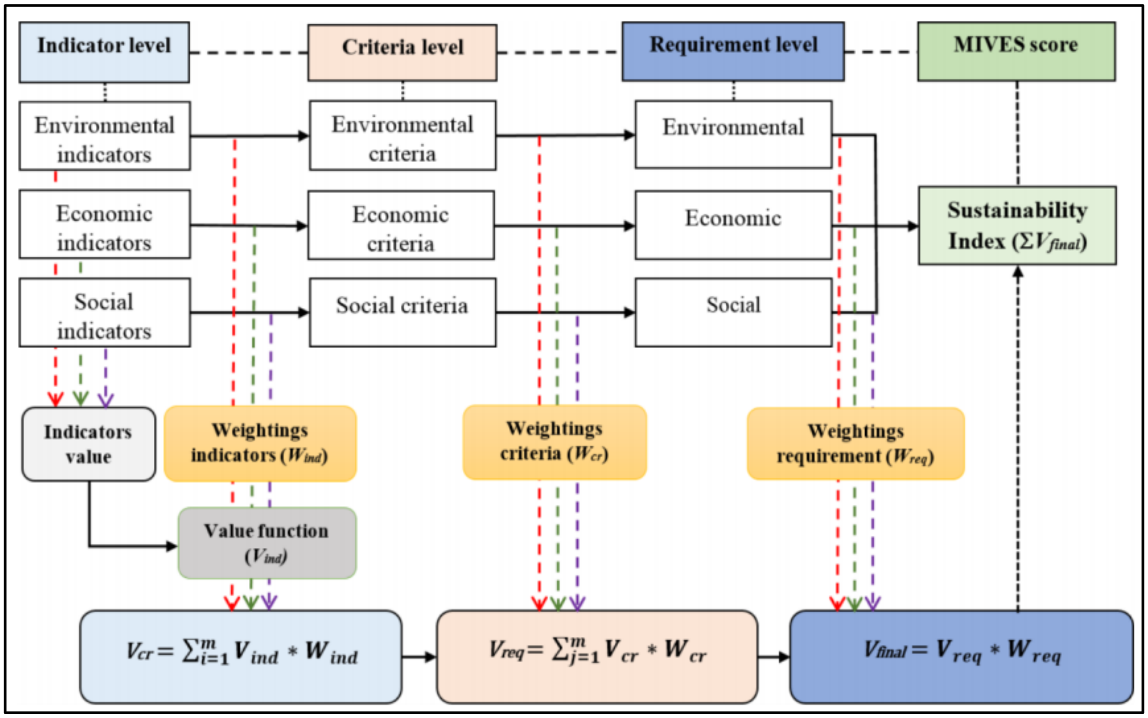


Figure 12. Schematic of MIVES methodology used in this project.

A. ENVIRONMENTAL IMPACT

When running SEFA and SiteWise for environmental impact, three areas were analyzed, the total energy consumption, greenhouse gas releases, and water consumption for each alternative. In addition, SEFA breaks down the greenhouse gases into total nitrogen oxides (NO_x) emissions, total particulate matter (PM_{10}) emissions, and total sulfur oxides (SO_x) emissions. NOx mainly impacts human health by causing respiratory conditions, which in turn causes inflammation of the airways. Environmentally, NOx can have a negative effect on vegetation, including leaf damage and reduced growth. It can make vegetation more susceptible to disease and frost damage 0]. PM_{10} are small particles that can lodge inside the lungs and find its way into bloodstreams causing a variety of health concerns, including heart and lung dysfunctions. PM_{10} also reduce visibility, and most important, it contributes to acidity increase in water bodies and acid rains, which can damage sensitive forests and farm crops[21]. The largest contributor to SO_x into the air is burning of fossil fuels. SO_x affect both human and environmental health in similar ways as NO_x and PM_{10}.[22]

The results are very similar between the two tools. Figure 13 shows the total energy used in soil and groundwater treatment options, respectively. Figure 14 shows the total greenhouse gases released for the soil and groundwater remediation option. Figure 15 shows the total water consumption from SiteWise. Lastly Figure 16 shows NOx emissions for both locations from SiteWise. While Figure 16 shows SOx emissions for both locations from SiteWise, and Figure 17 shows the particulate matter emissions for both locations from SiteWise.

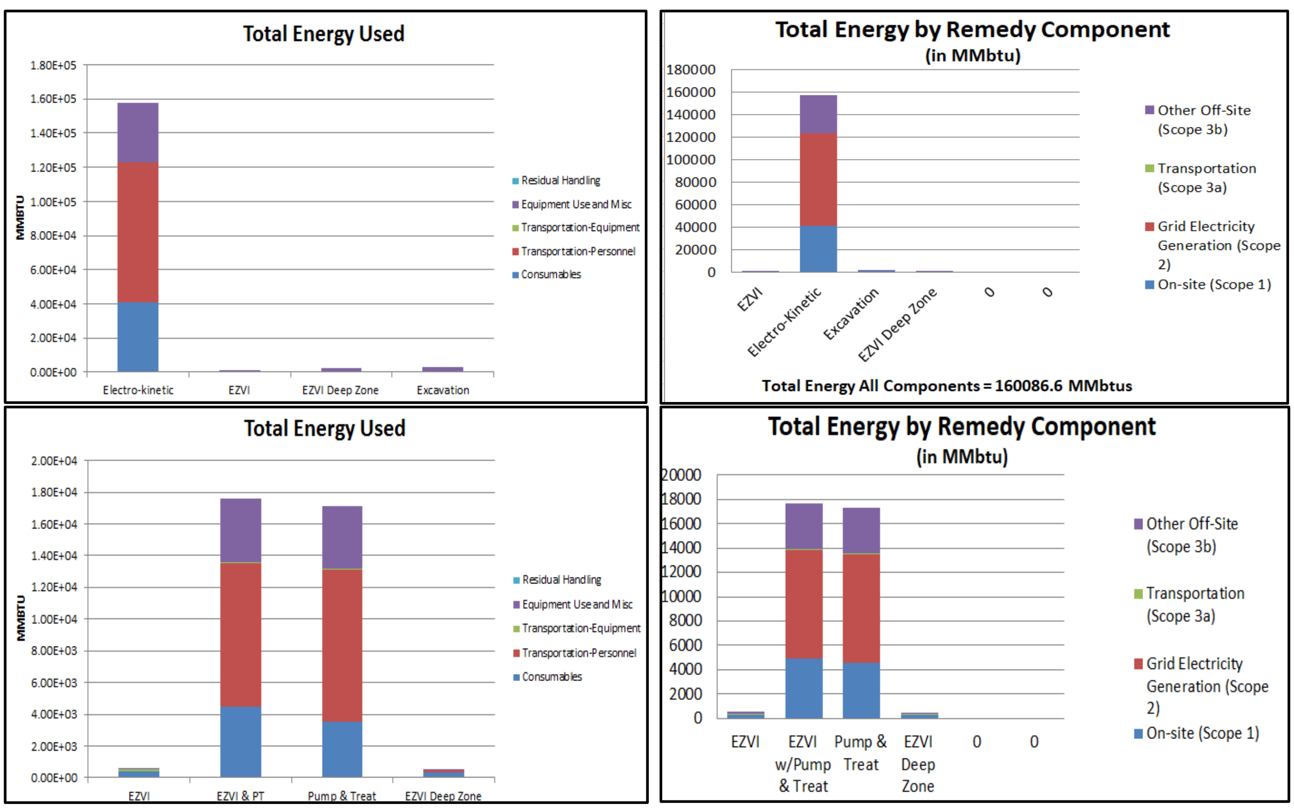


Figure 13. 13.A) SEFA total energy results for soil remediation (top left). 13.B) SiteWise total energy results for soil (top right). 13.C) SEFA total energy results for groundwater (bot. left). 13.D) SiteWise total energy results for groundwater (bot. right).

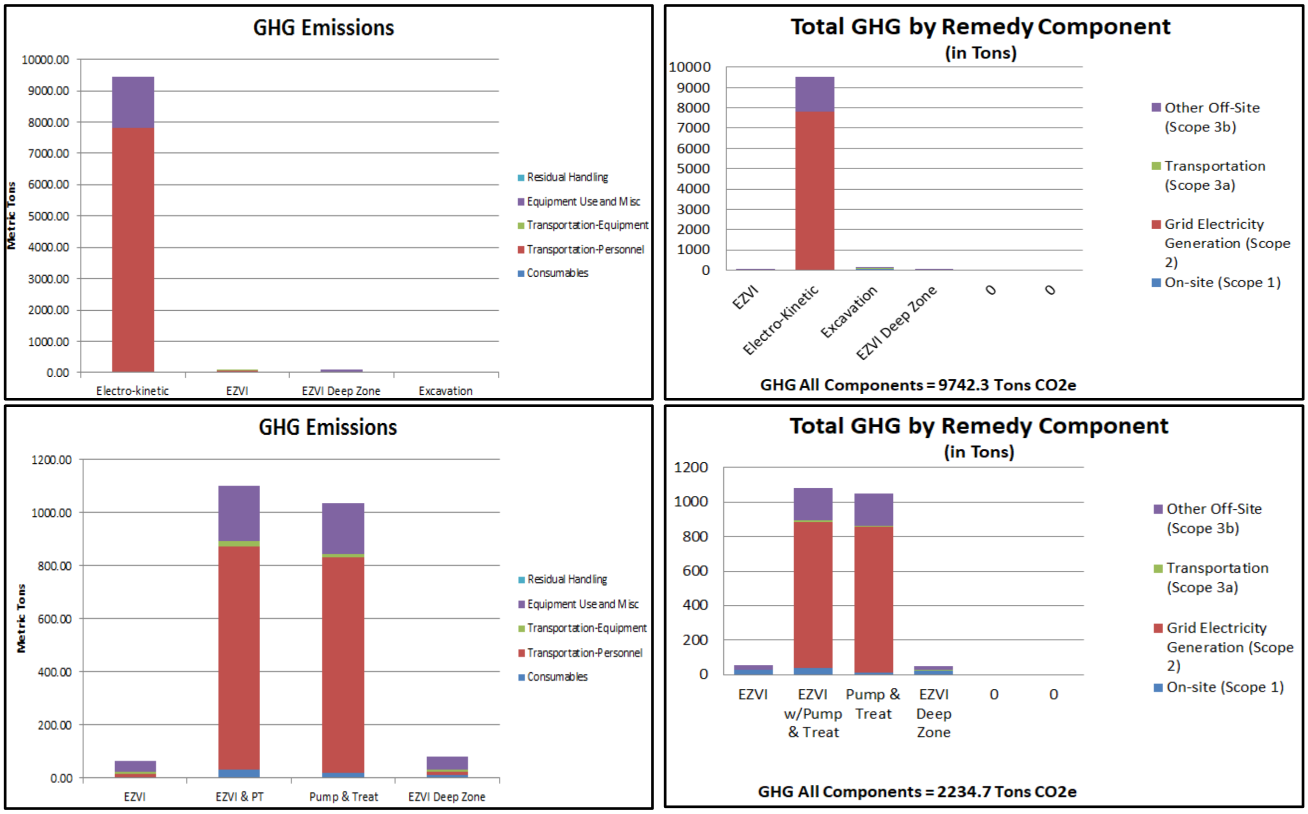


Figure 14. 14.A) SEFA total greenhouse gases release results for soil remediation (top left). 14.B) SiteWise total greenhouse gases release results for soil (top right). 14.C) SEFA total greenhouse gases released results for groundwater (bot. right). 14.D) SiteWise total greenhouse gases results for groundwater (bot. left).

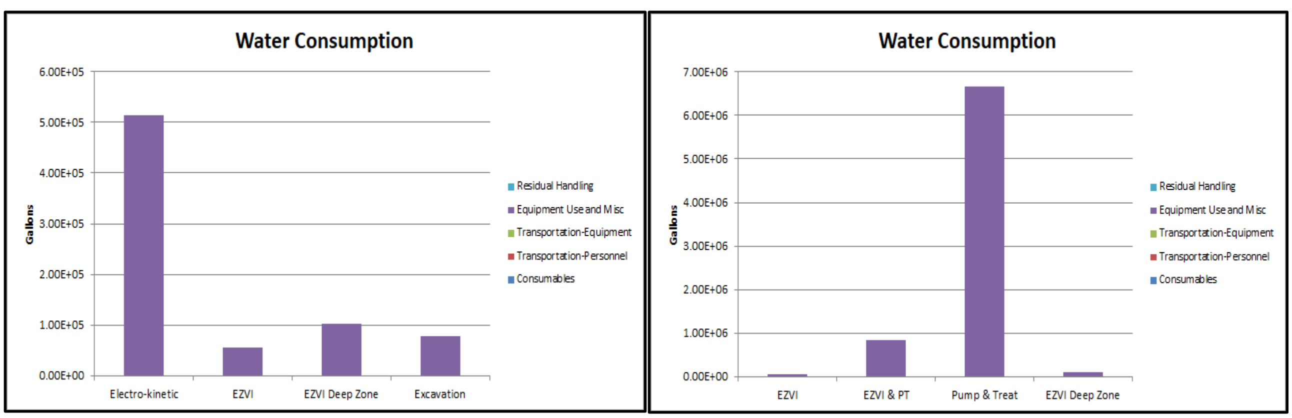
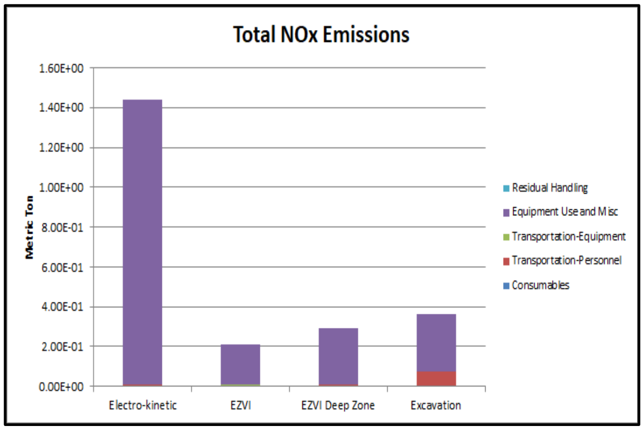
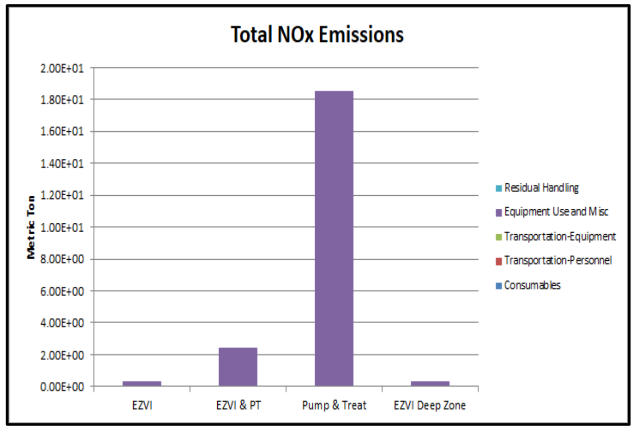
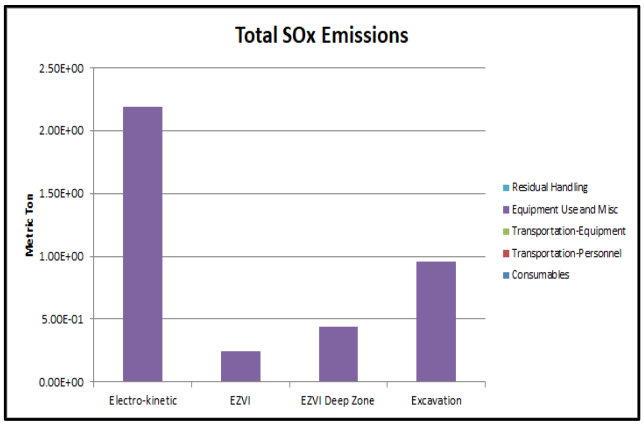


Figure 15. 15.A) SiteWise total water usage results for soil remediation options (left). 15.B) SiteWise total water usage results for groundwater remediation options (right).





+Figure 16. 16.A) SiteWise total nitrogen oxides release results for soil remediation options (left). 16.B) SiteWise total nitrogen oxides release results for groundwater remediation options (right).



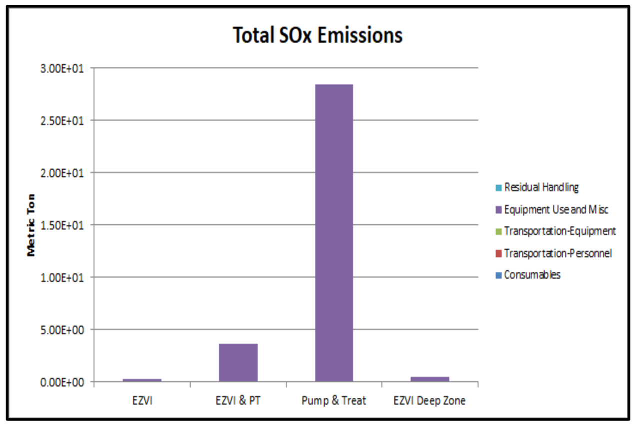
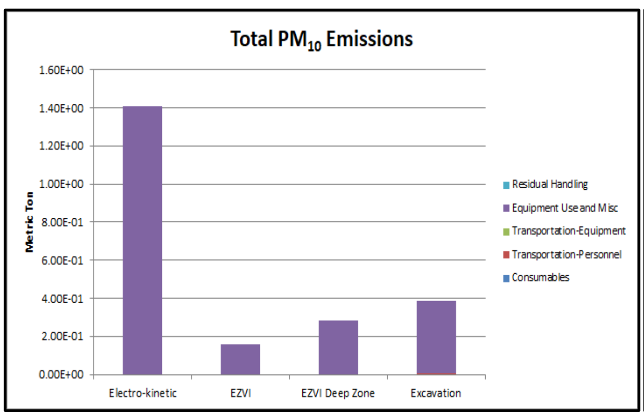


Figure 17. 17.A) SiteWise total sulfur oxides release results for soil remediation options (left). 17.B) SiteWise total sulfur oxides release results for groundwater remediation options (right).



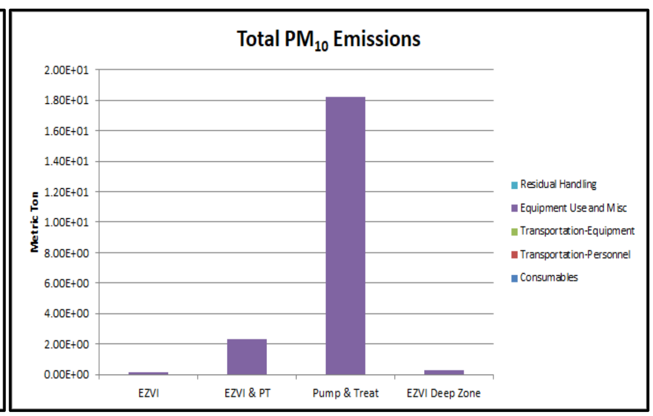


Figure 18. 18.A) SiteWise total particulate matter release results for soil remediation options (left). 18.B) SiteWise total particulate matter release results for groundwater remediation options (right).

The SimaPro model calculates a wider range of environmental issues affected, in addition it correlated these results with social impacts, including overall human health, which will be further shown in the social sustainability section. The results for the SimaPro model for each alternative are seen in Figure 19.

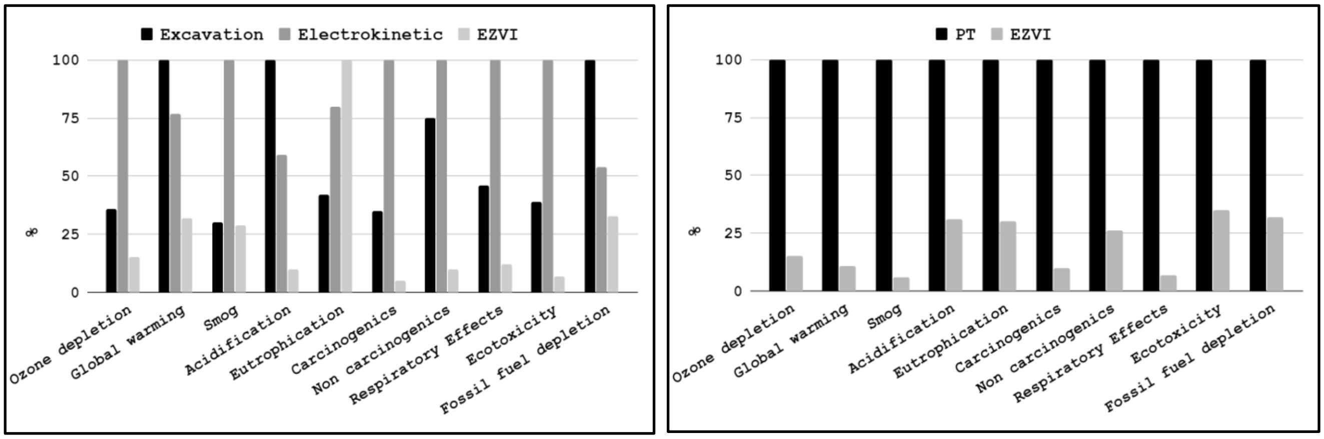


Figure 19. SimaPro V. 9.0.0 results for environmental impacts in the source area (left). SimaPro V. 9.0.0 results for environmental impacts in the deep zone area (right).

B. ECONOMIC SUSTAINABILITY AND LIFE-CYCLE COST ANALYSIS

Among the three pillars of sustainability, economic sustainability may seem the easiest to quantify, with clearer units. However, because of differences in site conditions, establishing a direct cost for in-situ options can be difficult. The first step is to establish capital and operating costs for each technology. Once these costs have been established for, the way in which these costs were developed and the way in which they are expressed may lead to quite different conclusions about the relative economic merits of the technologies. The views and options of the client on the cost of remediation options also ultimately determines which technologies will end up being used. Five main limitations for direct costs were identified, which makes it difficult to using economic models and past projects as guidelines for this one:

1. Each project is very site-specific, and conditions tend to vary greatly;
2. Different metrics are often used by technology providers, when reporting costs;
3. Variable costs are often not included in the cost provided by vendors;
4. Inconsistencies in the way costs are derived;
5. Cost is often developed by geotechnical consultants in in-situ technologies and is rarely available for general reference by other users.

With the limitations listed above in mind, a direct cost template was created for this project in order to make operational cost uniform across all considered technologies, using unit costs available at the FRTR.gov Reference Guide, and a USEPA guide for cleanup cost estimation, in junction with the University of Nebraska - Lincoln[23]. The results are listed in the following Table IX:

TABLE IX. DIRECT COST TABLES FOR EACH ALTERNATIVE INVESTIGATED

PUMP AND TREAT	
COST DESCRIPTION	**ITEM COST**
Modeling & remedial Design	$10,000.00
Drill and Install Two Pumping Wells - 6-in dia. Submersible 7.5 hp, 75 gpm @ 250 feet TDH with pump	$17,000.00
Pumping Equipment and Installation	$154,500.00
Setup	$5,000.00
Operations	$738,000.00
Water Disposal	$20,000.00
Permitting	$5,000.00
Decommission	$25,000.00
Final Report	$10,000.00
BASE COST	**$979,500.00**

EZVI AS PRB - DEEP ZONE	
COST DESCRIPTION	**ITEM COST**
Modeling & remedial Design	$30,000.00
Injection of EZVI in downgrading Location to Intercept COCs at 20 Locations	$354,666.00
Performance Monitoring	$269,800.00
Water Disposal	$0.00
Permitting	$5,000.00
Decommission	$15,000.00
Final Report	$10,000.00
BASE COST	**$684,466.00**

EXCAVATION	
COST DESCRIPTION	**ITEM COST**
Planning, Permitting, and Structural Analysis	$50,000.00
Install Sheet Piling	$200,000.00
Relocate Underground Utilities	$50,000.00
Sawcut, concrete removal and disposal	$3,200.00
Excavate, Load, Transport, Landfill and Stockpile	$404,600.00
Backfill and Compaction	$177,504.00
Spray HRC in open pit	$14,000.00
Concrete Paving and Professional Services	$87,660.00
Pit Dewatering and Treatment	$14,000.00
Sample and Analysis	$8,500.00
Performance Monitoring	$31,200.00
Decommission	$50,000.00
Final Report	$10,000.00
BASE COST	**$1,100,664.00**

EZVI - SOURCE AREA	
COST DESCRIPTION	**ITEM COST**
Modeling & remedial Design	$30,000.00
Injection of EZVI in Source Area at 32 Locations	$478,524.00
Performance Monitoring	$279,000.00
Water Disposal	$0.00
Permitting	$5,000.00
Decommission	$15,000.00
Final Report	$10,000.00
BASE COST	**$817,524.00**

ELECTROKINETIC	
COST DESCRIPTION	**ITEM COST**
Electrical Profiling	$2,500.00
Modeling & remedial Design	$20,000.00
Driving Equipment to Install Electrodes (3 weeks)	$75,000.00
Install vertical soil vapor and liquid contaminant wells - 20 locations	$16,000.00
Install Horizontal soil vapor and liquid contaminant wells - 11 extraction wells at 35 feet	$55,000.00
Install heat and pH sensor monitoring points in remediation area - 6 locations	$9,000.00
Install pH adjustment treatment points to delivery waters for system - estimate 4 vertical points along electrodes - 12 total	$1,200.00
Connect electrodes to rectifier, liquid piping to extraction and treatment system - sawcut, trenching, backfill and materials - estimate 600 lineal feet by 2 feet width - 5 days to complete	$15,000.00
Above ground system installation	$217,500.00
Startup	$5,000.00
Operation	$615,000.00
Waste disposal	$20,000.00
Permitting	$5,000.00
Decommission	$20,000.00
Final Report	$10,000.00
BASE COST	**$1,086,200.00**

In addition to the direct cost assessment above, another method was used to get a bigger picture of the indirect costs associated with each technology. The SiteWise model used in the environmental component of this project also populates an operational cost estimate based on energy and water usage. The results summarized in the tables below also include the risks for accident for each alternative. About 70% of these risks come from transportation of personnel and the remaining from equipment operation. For EZVI, a small percentage of the risks come from transportation of equipment.

TABLE X. SITEWISE ECONOMIC IMPACTS FOR DEEP ZONE (GROUNDWATER).

Deep Zone			
	Excavation	Electrokinetic	EZVI
Cost x $1,000,000	5.5	3.2	5.4
Labor Hours - Injury (hr.)	1.4	0.16	0.21
Accident Risk - Injury	0.135	0.02	0.027
Accident Risk -Fatality	0.00141	0.00028	0.00024

TABLE XI. SITEWISE ECONOMIC IMPACTS FOR SOURCE AREA (SOIL).

Source Area			
	PT	EZVI	EZVI + PT
Cost x $1,000,000	10	3.8	6
Labor Hours - Injury (hr.)	0.48	0.13	0.45
Accident Risk - Injury	0.06	0.017	0.057
Accident Risk -Fatality	0.00066	0.0002	0.00052

With costs at hand, the next step is to conduct a cost estimate risk, to account for uncertainties and adjustment of the direct costs calculated. The @Risk software was used to adjust these costs and the results are summarized in Tables XII and XIII.

TABLE XII. COST ESTIMATE RISK ASSESSMENT FOR DEEP ZONE (GROUNDWATER).

	PT	EZVI
Probability of meeting base case value	34.28%	29.79%
Total budget required for 95.0% confidence	$1,003,988.00	$750,610.00
Contingency required for 95.0% confidence	$24,488.00	$66,144.00
TOTAL COST	**$1,028,476.00**	**$816,754.00**

TABLE XIII. COST ESTIMATE RISK ASSESSMENT FOR SOURCE AREA (SOIL).

	EXCAV.	EKINETIC	EZVI
Probability of meeting base case value	20.17%	27.82%	31.34%
Total budget required for 95.0% confidence	$1,184,110.00	$1,186,997.00	$900,442.00
Contingency required for 95.0% confidence	$83,446.00	$100,797.00	$82,918.00
TOTAL COST	**$1,267,556.00**	**$1,287,794.00**	**$983,360.00**

Lastly, a net present value assessment was conducted using the values for direct and risk costs provided above, at a 7% discount rate. The tables below summarize this analysis.

TABLE XIV. NET PRESENT VALUE SUMMARY FOR DEEP ZONE (GROUNDWATER).

	PT	EZVI
Capital Cost ($)	$195,825.00	$415,820.00
Annual O&M Cost ($)	$750,413.00	$287,290.00
Periodic Cost ($)	$57,750.00	$31,500.00
Total Cost ($)	$1,003,988.00	$734,610.00
Total Present Value Cost at 7% Deduction ($)	**$808,565.38**	**$693,657.40**

TABLE XV. NET PRESENT VALUE SUMMARY FOR SOURCE AREA (SOIL).

	EXCAV.	EKINETIC	EZVI
Capital Cost ($)	$1,044,725.00	$463,497.00	$550,992.00
Annual O&M Cost ($)	$61,685.00	$665,750.00	$317,950.00
Periodic Cost ($)	$77,700.00	$57,750.00	$31,500.00
Total Cost ($)	$1,184,110.00	$1,186,997.00	$900,442.00
Total Present Value Cost at 7% Deduction ($)	**$1,172,161.16**	**$1,140,388.50**	**$855,240.08**

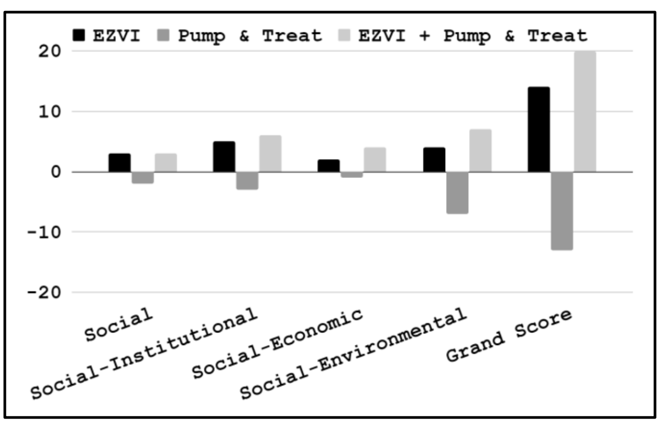
C. SOCIAL SUSTAINABILITY

Perhaps the hardest category to quantify is social sustainability. A set of social indicators needs to be identified and scored when comparing technologies available. The decision making and scoring can be quite subjective. Three main steps are followed in this project in order to assure consistent results, independent of method used. The initial step in quantifying social sustainability is to determine a set of social indicators pertinent to the project. Next is to apply the social indicators and quantify method. Lastly, is interpreting the results.

The social indicators relevant for this project are listed in Table XVI. These indicators were applied to the SSEM model as an initial screening of the selected technologies. The results for the SSEM model can be seen in Figure 20.

TABLE XVI. SOCIAL INDICATORS SUMMARY TABLE.

PART A. SOCIAL	1. Public health effects (e.g., reduced disease outbreak)
	2. Effect of the proposed remediation technology on quality-of-life during and post-installation
	3. Overall maintenance of remediation method/technology
	4. Inspirational and public education value related to tapping local resources and promoting sustainability
	5. Degree to which tangible community needs are incorporated into design
PART B. SOCIAL-INSTITUTIONAL	1. Enhancement of commercial/income-generating land uses
	2. Improvement and enhancement of market-rate housing
	3. Enhancement to local/ neighborhood
	4. Involvement and enhancement of community-based organizations
	5. Trust, voluntary organizations and local networks (also known as social capital)
PART C. SOCIAL-ECONOMIC	1. Potential increase in local job creation (e.g., to install and maintain the remediation option), if such jobs engage otherwise under-employed labor resources (i.e., not a transfer of jobs from one region or sector to another)
	2. Degree to which green/sustainable or other "new economy" businesses may be created
	3. Disruption of businesses, agricultural practices, and the local economy during construction/ active remediation phase
	4. Degree of anticipated partnership and collaboration with outside investors/institutions
	5. Potential for loss of income due to new technology availability
PART D. SOCIAL-ENVIRONMENTAL	1. Increase in “local control” of natural resources and water supply (e.g., reducing reliance on regional or imported supplies)
	2. Increased robustness, resiliency, and reliability of local water supply portfolios
	3. Degree of disruption (noise, truck traffic) from proposed installation to the surrounding neighborhoods
	4. Degree of future alteration and monitoring
	5. Degree of protection afforded to workers by proposed installation



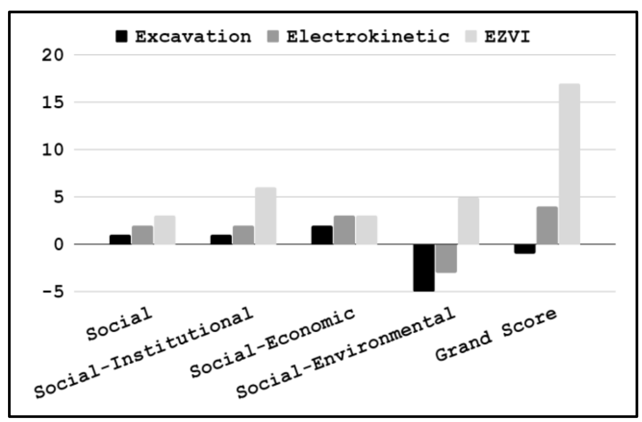


Figure 20. 20.A) SSEM results for deep zone/groundwater (left); 20.B) SSEM results for source area/soil (right).

The second step is to identify methods to compare the remediation technologies. In this project a five-approach method [24] was used to determine social sustainability and calibrated to provide the most accurate results. In this five-approach method, a point system developed. The model scores each technology on a scale from 1-5, 1 being very sustainable, 2, somewhat sustainable, 3, being neutral, 4, not very sustainable, 5, not sustainable at all. The five approaches are listed below:

1. **Social sustainability as a Distinct Objective:** this option analyses social sustainability as a standalone, parallel pillar, which does not interact with the other pillars. The usefulness of this approach is that it makes it easier and expedites the analysis of different systems applied to the same site at the same time, while the downside is a much broader definition of sustainability.

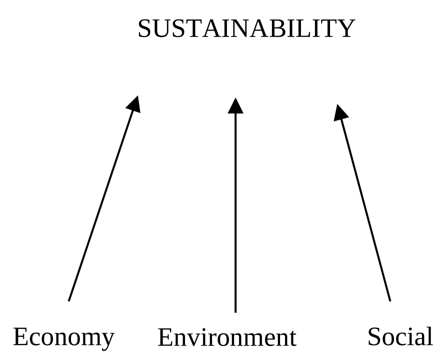


Figure 21. Social sustainability as a distinct objective.

The applied method for this approach was a public survey developed from a modified SSEM model, using the predetermined social indicators for part A and Part B, which extract the social desires of a population groups without taking into consideration other factors. Table XVII shows the combined results of the survey converted to points applied.

TABLE XVII. PUBLIC SURVEY RESULTS FOR PAR A. SOCIAL, AND PART B. SOCIAL-INSTITUTION.

	Part A					Part B					
	A-1	**A-2**	**A-3**	**A-4**	**A-5**	**B-1**	**B-2**	**B-3**	**B-4**	**B-5**	**AVG**
MNA	4	3.6	2.6	4.4	4	4.4	4.2	3	3.2	3.6	**3.7**
Excavation	2.6	4	3.2	2.8	3.6	2	2.6	3.8	4	2.5	**3.1**
Electrokinetic	2.8	2.8	3.8	2	2.8	2	2.2	3.4	2.8	2.2	**2.7**
EZVI	1.4	2.8	3.8	1.8	2.8	2.2	2.4	3.2	2.8	2.2	**2.5**
Pump & Treat	2	3	4.2	2.6	3	2.8	2.2	3.8	2.8	2.2	**2.9**

2. **Social Sustainability as a Pre-Condition for Environmental and Economic Sustainability:** In this approach the three pillars of sustainability also interact However, this approach puts a higher ranking on social capital to determine which systems will be used, and which technologies will be the most sustainable overall, with the idea the social and quality of life erosion precedes environmental deterioration and economic downfalls.

Figure 22. Social sustainability as a pre-condition objective.

One way to quantify this approach is calculating the social cost of carbon release. This method suggests that the higher the greenhouse release, the higher the costs a government unit and businesses will encounter to continue with a standard quality of life and public health. Figure 23 shows the results of the USEPA social cost analysis.

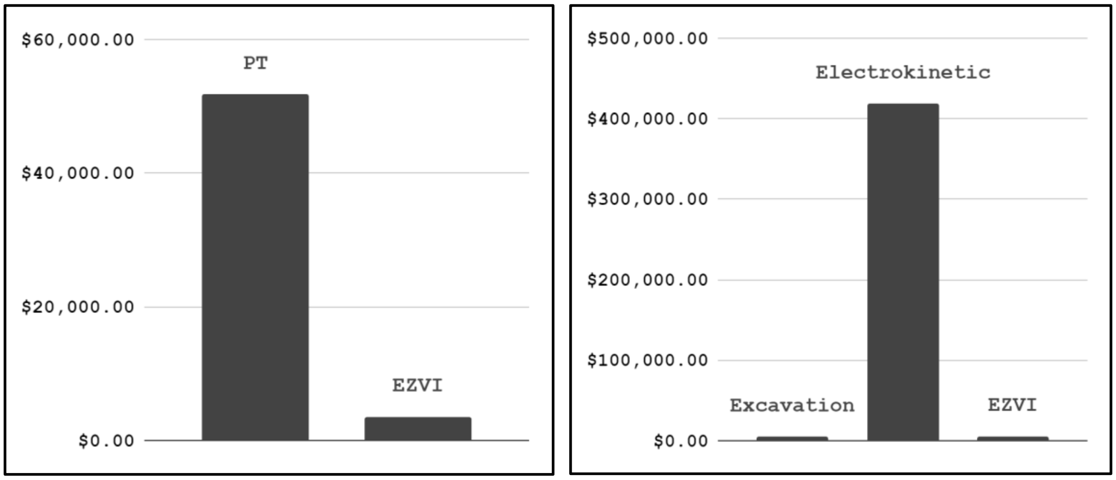


Figure 23. 23.A) Social cost of carbon release for the deep zone/groundwater (left); 23.B) Social cost of carbon release for the source area (soil).

3. **Social Sustainability as a Constraint upon Economic and Environmental Imperatives:** In this method, social, environmental and economic priorities are in competition with one another for the available resources, and a balance outcome needs to be achieved, rather than achieving all social needs. A "sustainability footprint" value is applied to the technologies analyzed. In this footprint, the rate of change in quality of life impacted by economic and environmental sustainability of each technology is considered.

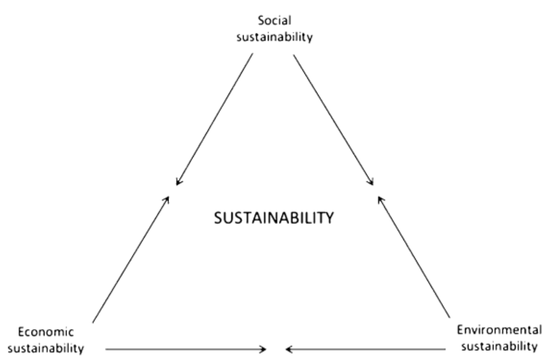


Figure 24. Social sustainability as a constrained objective.

One example is how income increase, or amount of greenhouse gases release affects the long-term health of the population. To quantify this method, the results of SiteWise, SEFA, SimaPro and overall pre-design of each alternative applied to an equivalent social indicator and given a score units for how much they affect the local area. For example, greenhouse gases and particulate matter emissions were equated to decrease in quality of life, while energy consumption were equated to the local economy. In both cases the higher values have a direct line to lower sustainability values. Table XVIII shows the framework used for this approach. Tables XIX and XX show the results for both soil and groundwater contamination.

TABLE XVIII. FRAMEWORK FOR ASSESSING SOCIAL SUSTAINABILITY AS A CONSTRAINT

COMPONENT	**SOCIAL INDICATORS**	**METHOD APPLIED**	**ASSESSED BY**
Social	Human Health	Carcinogens	SimaPro
Social	Quality of Life	GHG Emission	SiteWise
Social Institutional	Neighborhood Enhancement	GHG Social Cost	USAEPA
Social Institutional	Land Use Enhancement	Cleanup Time	Pre-design
Social Economic	Resources Used	Water Consumption	SiteWise
Social Economic	Green Economy	Energy Usage	SEFA
Social Environmental	Overall Environmental Health	Climate Change	SimaPro
Social Environmental	Local water supply condition	Acidification	SimaPro

TABLE XIX. SCORE FOR SUSTAINABILITY AS A CONSTRAINT FOR DEEP ZONE.

METHOD APPLIED	PT	EZVI	EZVI +PT
Carcinogens	3	1	2
GHG Emission	2	1	2
GHG Social Cost	2	1	2
Cleanup Time	2	1	3
Water Consumption	3	1	2
Energy Usage	3	1	2
Climate Change	2	1	2
Acidification	2	1	2
AVG SCORE	**2.38**	**1.00**	**2.13**

TABLE XX. SCORE FOR SUSTAINABILITY AS A CONSTRAINT FOR SOURCE AREA.

METHOD APPLIED	EXCAV	ELECTROKINETIC	EZVI
Carcinogens	2	3	1
GHG Emission	2	3	1
GHG Social Cost	1	2	1
Cleanup Time	1	2	3
Water Consumption	2	3	1
Energy Usage	1	2	1
Climate Change	2	3	1
Acidification	3	2	1
AVG SCORE	**1.75**	**2.5**	**1.25**

4. **Social Sustainability as the Causal Mechanism of Economic and Environmental Change:** In this more integrated fourth approach, the social aspects are an incentive to environmental and economic sustainability. The previous three approaches assumed that social aspects can be improved by improving environmental and economic aspects. This method suggests that environmental and economic issues are essentially social issues. Therefore, addressing areas lacking in social sustainability will eventually fix environmental and economic problems.

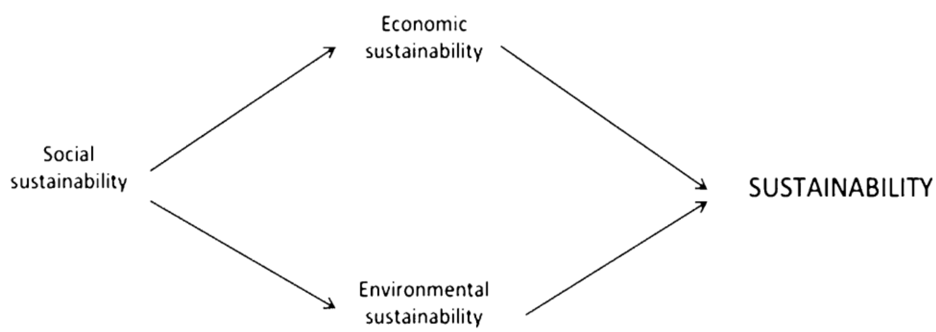


Figure 25. Social sustainability as a causal objective.

This approach is more complicated to quantify, but it can be best explained by changes in local legislations, and education and changes of social practices and consumption. One way to apply this method looking at the results for the public survey and the SSEM model for parts C and D. The results of the survey and scoring summary table are shown below:

TABLE XXI. PUBLIC SURVEY RESULTS FOR PAR C. SOCIAL-ENVIRONMENTAL, AND PART D. SOCIAL-ECONOMIC.

	Part C					Part D					
	C-1	C-2	C-3	C-4	C-5	D-1	D-2	D-3	D-4	D-5	AVG
MNA	3	2.8	3.5	3	4.2	4.2	4	4.8	3	3.6	**3.6**
Excavation	1.6	2.2	1	2.4	3.4	2.2	1.2	1	1.8	4	**2.1**
Electrokinetic	1.8	2	2.4	2.2	2.2	3	1.6	2.8	2.4	3	**2.3**
EZVI	1.8	2	2.4	2	2.2	2.8	1.6	3	2.4	2.8	**2.3**
Pump & Treat	1.6	2.4	2.2	2	2.6	3	2	2	2.8	2.8	**2.3**

5. **Social Sustainability as Place-Centered, Process-Oriented Sustainability:** The fifth method looks at social, economic, and environmental imperatives as overlapping, and more integrated, as opposed to competing and restricting.

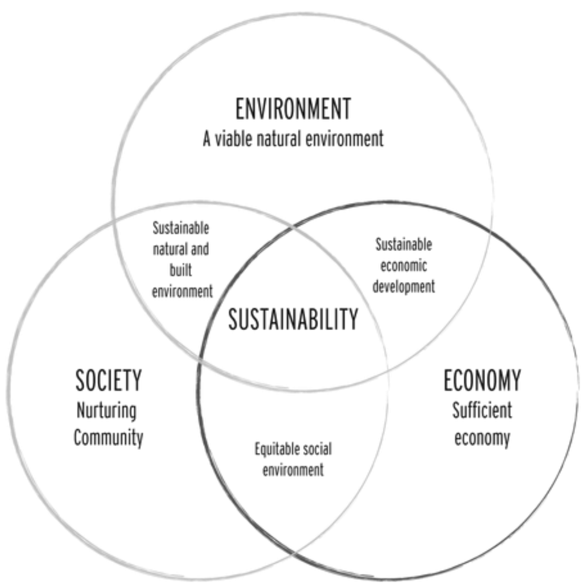


Figure 26. Social sustainability as a place-centered objective.

For this approach, a SimaPro model was developed, and compared against local government regulations, overall scores from the public survey, and other conducted models. The results for each technology are shown in Figure 27.

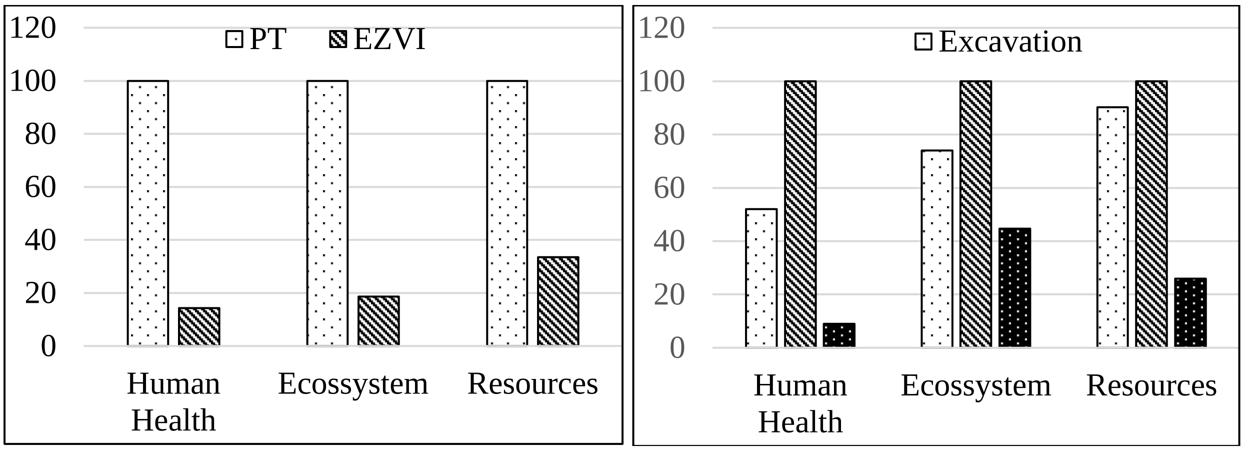


Figure 27. 27.A) SimaPro social sustainability impacts for the deep zone (left); 27.B) SimaPro social sustainability impacts for the source area (right).

VI. RESULTS AND REMEDIATION ALTERNATIVES

A. SUMMARY OF RESULTS

Once all methods and assessments were finalized, the following table summarizing all the methods and results was compiled, as seen in tables XXII and XXIII.

TABLE XXII. SUMMARY RESULTS FOR DEEP ZONE (GROUNDWATER) WITH SCORING.

Criteria	Pump and Treat	EZVI as PRB
EPA Criteria Score^	32	32
FRTR Matrix	-1	5
SEFA	Worse	Best
SiteWise Environmental	High	Lower
SiteWise Costs	Highest	Lowest
Direct Cost	$1,028,476.00	$816,754.00
Cost Risk	65.7%	70.7%
Net Present Value	$808,565.38	$693,657.40
SSEM ^	-13	14
Public Survey	2.6	2.4
Carbon Social Cost	$51,738.80	$3,450.00
SimaPro LCA	High	Low

^ *Higher score = more sustainable*

TABLE XXIII. SUMMARY RESULT FOR SOURCE AREA (SOIL) WITH SCORING.

Criteria	EZVI with Fracturing	Electrokinetics	Excavation
EPA Criteria Score^	36	28	29
FRTR Matrix	1	3	7
SEFA	Good	Worse	Good
SiteWise Environmental	Good	Worse	Good*
SiteWise Costs	High	Lower	High
Direct Cost	$900,442.00	$1,186,997.00	$1,184,110.00

Cost Risk	68.7%	72.2%	79.8%
Net Present Value	$855,240.0	$1,140,388.50	$1,172,161.16
SSEM ^	17	4	-1
Public Survey	2.4	2.5	2.6
Carbon Social Cost	$4,980.00	$418,291.60	$4,669.20
SimaPro LCA	Overall high	Highest	Low

^ *Higher score = more sustainable*

* *Result for other emissions and particulate matter are high*.

B. RESULT WEIGHTING AND CALIBRATION

The final step in assessing sustainability and deriving a single score from all results, using the MIVES methodology. Table XXIV shows the framework of the MIVES methodology including all the criteria, methods and indicators used for the overall sustainability for the remediation technology in this project. When applying the results of all assessments for each remediation alternative into the MIVES framework, considering equal 33.33% weight for social, economic and environmental impacts, the following weighted results are seen in Figure 28, the highest values signify the most sustainable option.

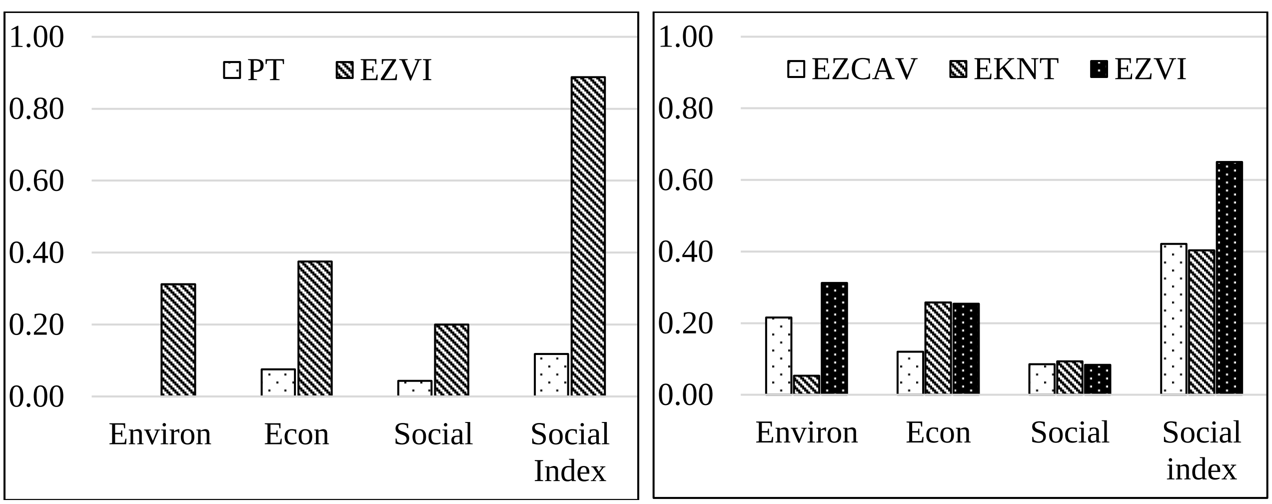


Figure 28. 28.A) MIVES weighted sustainability result for the deep zone/groundwater (left); 28.B) MIVES weighted sustainability result for the source area/soil (right).

TABLE XXIV. FRAMEWORK FOR MIVES MODEL.

Requirement	Weightage -W requirement (%)	Criteria	W criteria (%)	Indicators	W indicator (%)
Environmental	**33.33%**	**Air**	**25%**	Global Warming (SimaPro)	**14.30%**
				Ozone depletion (SimaPro)	**14.30%**
				Smog Formation (SimaPro)	**14.30%**
				Total Greenhouse Gas Emission (SEFA)	**14.30%**
				Total Particulate Emission (SiteWise)	**14.30%**
				Total NOx Emission (SiteWise)	**14.30%**
				Total Sox Emission (SiteWise)	**14.30%**
		Water Usage and Impacts	**25%**	Water Usage (SiteWise)	**50.00%**
				Acidification (SimaPro)	**25.00%**
				Eutrophication (SimaPro)	**25.00%**
		Land & Ecosystems	**25%**	Natural resource/Fossil Fuel depletion (SimaPro)	**50.00%**
				Ecotoxicity (SimaPro)	**50.00%**
		Energy	**25%**	Energy use (manufacturing/construction, operation, etc.)	**33.33%**
				Energy used for Transportation of Equipment	**33.33%**
				Energy used for Transportation of Personnel	**33.33%**
Economic	**33.33%**	**Direct Cost**	**25%**	Design	**20.00%**
				Equipment, Setup and Installation	**20.00%**
				Operations	**20.00%**
				Waste treatment and/or disposal	**20.00%**
				SiteWise Operation Cost	**20.00%**
		Maintenance & Monitoring Costs	**25%**	Monitoring	**30.00%**
				Maintenance	**30.00%**
				Permit	**15.00%**
				Decommission	**15.00%**
				Final Report	**10.00%**
		Indirect Costs	**25%**	Net Present Value	**20.00%**
				Lost Labor	**20.00%**
				Risk of Injury	**20.00%**

				Risk of Fatality	**20.00%**
				Cost Estimate Risk	**20.00%**
Social	**33.33%**	**Social Costs**	**25%**	Social Cost of CO2	**100.00%**
		Public Survey	**40%**	Social-Individual	**25.00%**
				Social-Institutional	**25.00%**
				Social-Economic	**25.00%**
				Social-Environmental	**25.00%**
		SSEM	**20%**	Social-Individual	**25.00%**
				Social-Institutional	**25.00%**
				Social-Economic	**25.00%**
				Social-Environmental	**25.00%**
		Econon/Envirn Conversions	**10%**	Environmental and Economic Impacts on Community	**100.00%**
		SimaPro Model	**30%**	Human health - Cancer	**33.33%**
				Human health - Noncancer	**33.33%**
				Respiratory Effects	**33.33%**

C. DESIGN ALTERNATIVE

With all the results at hand, the remedial conceptual design was selected based on the sustainability qualities, comprehensiveness of the approach and the potential financial burden on the stakeholders. The remedial approaches are separated in two geographical areas source area (soil) and deep zone (groundwater).

Soil/ Source Area Design - The source area is located on the soybean oil extraction processing plant near the silos. The focus of remedial design is to remediate COCs in the unsaturated and saturated soil and shallow groundwater near the area where the suspected release occurred.

EZVI with fracturing was selected. In terms of environmental sustainability, EZVI consumes much less energy and has lower greenhouse gas release effect. When costs are compared EZVI also has lower overall cost, including social cost of greenhouse gas release. The social sustainability is more comparable, when looked at individual results. However, the weighted results show EZVI still being more sustainable.

The conceptual plan and scope of work includes the following phases:

1. Initiate the collection of data to establish a baseline of current site conditions.
2. Conduct a pilot study to calibrate the conceptual design according to response to the testing.
3. Inject EZVI to facilitate remediation in source area:
   a. 27 locations to establish 10 feet radius.
   b. 5 locations to establish 5 feet radius.
   c. Injects at 2.5 feet intervals starting top of impacted soils (10 feet estimated) and approximately 15 feet into groundwater to est. 35 feet - depths will vary based on baseline profile.
4. Improve ROI by propagating a fracture - 25 to 75 psi.
5. Setup groundwater model to measure progress from remediation strategy.
6. Deliver 46 gallons of emulsified mixture per interval as:10% nZVI, 51% Water, 39% Vegetable Oil.
7. Injections of EZVI immediately followed by 154 gallons per interval of 2% emulsified vegetable oil.
8. EZVI remedial performance monitoring, assessment, and reporting.

Figure 29 shows the EZVI injection point locations.

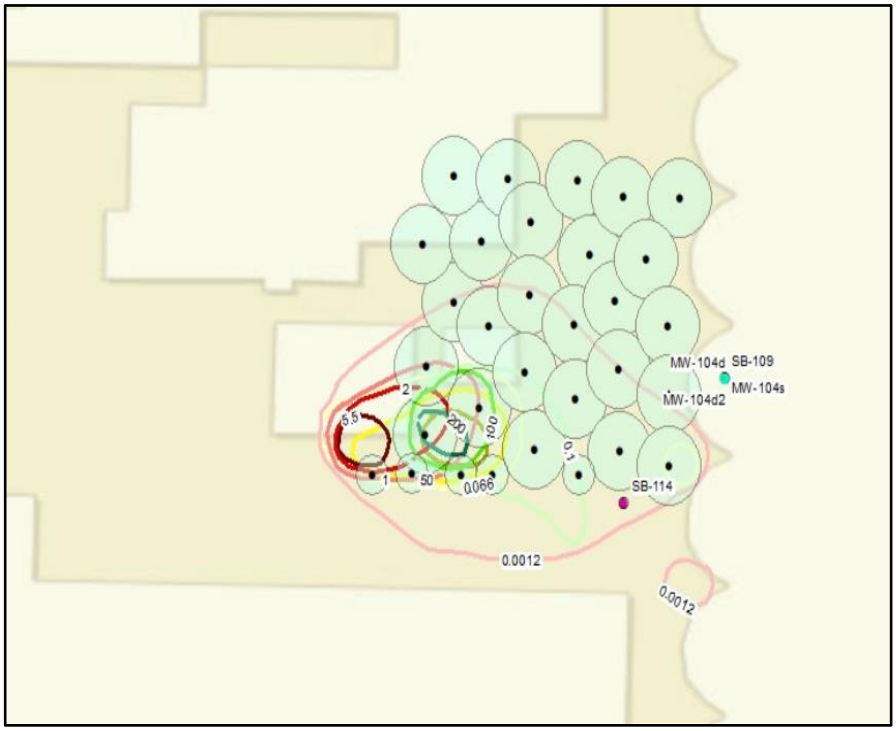


Figure 29. EZVI injection point locations at the source area.

<u>Remedial Plan Implementation of Source Area</u> - The initial phases of remedial strategy are to verify site conditions and further define any uncertainties from the conceptual plan. This phase of verification will be performed through baseline monitoring, pilot study, conceptual design refinement, development of a groundwater model and implementation of the remedial plan. The progression of the remedial plan will proceed in the following manner:

1. Baseline Monitoring.
2. Verifying site conditions:
    a. Distribution of COCs in soil and groundwater.
    b. Collect samples and analyze for abiotic and biotic enhancers.
    c. Hydraulic properties in areas of proposed injections.

3. Pilot Study.

4. Propagation of fractures and injection intervals were conceptually developed based on empirical data. Pilot testing will be performed to identify and complement the empirical model and verify site conditions by injecting EZVI at three locations at varying intervals of 1, 2.5, and 4 feet while amending soils:

   a. Verifying delivery parameters.

   b. Setting groundwater model to measure progress and contaminant transport characteristics.

5. Revise parameters of conceptual plan.

6. Implement full scale source remediation plan.

Source Area Monitoring - Performance monitoring is an integral part of the remedial strategy. Its purpose is to validate the selected remedial approach, measure progress and alert the professional of any required modifications. Performance shall be conducted in the following manner:

1. Setup Monitoring Strategy:

   a. Install 6 monitoring wells: 3 in remediation, 1 upgradient as background, and 2 downgradient to measure EZVI effects.

2. Quarterly Monitoring:

   a. 6 newly installed and 4 downgradient monitoring wells to analyze for Total VOCs, dissolved methane, TOC, inorganics - dissolved nitrates, nitrites, sulfate, phosphorus, chlorides, iron, etc.

b. Field measurements of standard geochemistry parameters (i.e.- ORP, conductivity, temperature, DO, $CO2$, pH, depth to water.

c. Compile and submit for review a brief quarterly report.

3. Annual Monitoring – Shall include collection of the same data as in the quarterly monitoring and the following:

a. Comprehensive monitoring and sampling of all ADM monitoring wells for total VOCs and field measurement parameters.

b. Soil profile sample analysis at 3 locations for the following: COCs. abiotic enhancers, biotic enhancers and nutrients.

c. The annual report includes results of contaminant modeling assessment and compare to remedial goals and the feasibility of closure.

Groundwater/ Deep Zone Design - The deep zone area is located approximately 1,900 feet downgradient from the source area and vertically in a range of 20 to 30 feet above the sand/Dakota Sandstone formation. It is in this area where higher dissolved concentrations were detected, and in this area, EZVI with pressure injections was selected. Similarly, to the source area, EZVI is lowest in greenhouse effects and costs. As a bonus, EZVI is consistent with US EPA's green remediation policy. However, EZVI is patented and developed by NASA and usage of this technology could be limited. Remedial Conceptual Design Includes:

1. Initiate the collection of data to establish a baseline of current site conditions.
2. Conduct a pilot study to calibrate the conceptual design according to response to the testing.

3. Setup and calibrate groundwater fate and transport model to assess the need to implement the proposed in situ conceptual remedial plan.
4. Inject EZVI to facilitate remediation in deep zone:
    a. 20 locations to establish 10 feet radius in sink area of highest concentrations (estimated 200 feet by 35 feet.)
    b. Injects at 2.5 feet intervals starting at based of sandstone sand interface and up estimate 25 feet.
5. Verify 10 feet radius.
6. Deliver 46 gallons of the emulsified mixture per interval as 10% nZVI, 51% water, 39% vegetable oil.
7. EZVI injections immediately followed by 154 gallons per interval of 2% emulsified vegetable oil.
8. EZVI remedial performance monitoring, assessment, and reporting.

Figure 30 shows the EZVI injection location for the deep zone, as PRB.

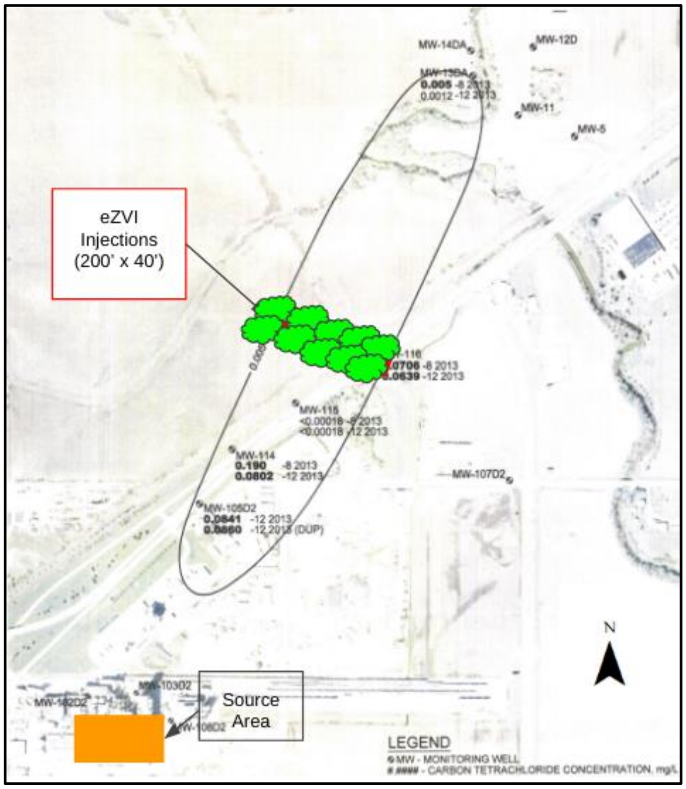


Figure 30. Injection location for EZVI in the deep zone area.

Remedial Plan Implementation for the Deep Zone - The initial phases of remedial strategy are to verify site conditions and further define any uncertainties from the conceptual plan. This phase of verification will be performed through baseline monitoring, pilot study, conceptual design refinement, development of a groundwater model and implementation of a modified remedial plan. The progression of the remedial plan will proceed in the following manner:

1. Baseline Monitoring:
    a. Verifying site conditions.
    b. Distribution of COCs in soil and groundwater.
    c. Collect samples and analyze for abiotic and biotic enhancers.
    d. Hydraulic properties in areas of proposed injections.

2. Setting up groundwater model to measure progress and contaminant transport characteristics:
    a. Calibrate model to site conditions.
    b. Evaluate contaminant fate and transport.
    c. Compare values to groundwater cleanup criteria.
    d. Determine need for in situ remediation.
    e. If values are below active remedial action requirements - implement annual monitoring program according to conceptual model results.
3. If required, conduct a pilot study:
    a. Inject EZVI at two locations varying intervals of 2.5 and 4 feet.
    b. Verify delivery parameters.
4. Revise parameters of conceptual plan.
5. Implement full scale source remediation plan.

Deep Zone Monitoring - For the deep zone, performance monitoring shall be performed similarly to the source area remedial strategy, which is to validate the selected remedial approach, measure progress and alert the professional of any required modifications. Performance monitoring shall be implemented if in situ remediation is necessary and conducted in the following manner:

1. Setting up Monitoring Strategy:
    a. Install 6 monitoring wells at 3 locations nested (middle and deep zones) to measure EZVI effects in area of injections, downgradient, cross-gradient.
2. Quarterly Monitoring:

a. 6 newly installed and 4 downgradient monitoring wells to analyze for total VOCs, dissolved methane, TOC, inorganics - dissolved nitrates, nitrites, sulfate, phosphorus, chlorides, iron, etc.

b. Field measurements of standard geochemistry parameters (i.e.- ORP, conductivity, temperature, DO, CO2, pH, depth to water).

c. Compile and submit for review a brief quarterly report.

3. Annual Monitoring – Shall include collection of the same data as in the quarterly monitoring and the following:

a. Comprehensive monitoring and sampling of all ADM monitoring wells for total VOCs and field measurement parameters.

b. Soil profile sample analysis at 3 locations for COCs, abiotic enhancers, biotic enhancers and nutrients.

c. Annual report - Include results of contaminant modeling assessment and compare to remedial goals and the feasibility of closure.

VII. CONCLUSION

This project reviewed available ADM facility documents and identified contaminants in soils and groundwater which exceed Nebraska State cleanup criteria. The contaminants were detected both on and off the ADM facility, showing a migration from the property boundaries primarily in a northerly direction, moving both horizontally and vertically to the underlying Dakota Sandstone formation. The on- and off-site distribution of COCs (carbon tetrachloride, chloroform, ethylene dibromide, and methylene chloride) are distinguished by “Source Area and Deep Zone”. A design plan was developed for the remedial approach through the development of a conceptual site model and sustainable scoring of viable remedial alternatives. Each area includes the potential for implementing in situ EZVI treatment technology.

Prior to implementing the remedial strategy for each location, a process of baseline confirmatory sampling of site conditions, pilot testing, development of a groundwater model and refinement of the remedial approach was examined. Furthermore, each remedial alternative for sustainability analysis was put through a series of models, survey, cost assessments, and scoring methods in order to come up with a uniform comparison of these alternatives for both contaminated areas. The results show the EZVI alternative being superior for this project in all three aspects of sustainability, and weighted factors, than other more conventional, technologies widely used.

Lastly, the electrokinetic remediation has the highest impact for the source area, and pump and treat for the deep zone. That is mostly due to the length of operation, equipment energy usage, and the amount of emissions released into the air.

A. FURTHER CONSIDERATIONS

This design study can be improved with the following strategies:

- Expansion of the public survey to include a wider population of residents.
- Cost-benefit ratios can be obtained by conducting a full assessment of the economic costs of MNA and using that to compare against the design alternatives.
- Investigation of alternative use of ZVI and PRB methods.
- Refine local costs of energy and water consumption, as well as local transportation costs to landfill.
- Investigate indirect and hidden costs of each alternative, including license costs, local geotechnical application costs, and training.
- Redefine LCA boundaries to include raw material of equipment.
- Redefine weightage components to encompass different stakeholders.
- Include education and public perception of fracking.
- It is important to note that, some of the results in this study are subject to different interpretations. A database with historical projects could help eliminate some of these variations.

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VITA

NAME:	Danielle da Silva
EDUCATION:	B.S., Civil Engineering, University of Illinois at Chicago, 2017
	M.S., Civil Engineering, University of Illinois at Chicago, expected 2019
PROFESSIONAL:	Engineer in Training, 2017
	Civil Engineer I, Ciorba Group, Inc., 2017-2019
MEMBERSHIPS:	Board member of Engineers Without Borders, Student Chapter at UIC, 2017