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Using adaptive management to guide multiple partners in TCE remediation using a permeable reactive barrier

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Abstract
The US Department of Agriculture-Agricultural Research Service (USDA-ARS) worked together with the University of Maryland, College Park and BMT Designers and Planners (Consultant) to design a biowall to remediate the groundwater of a Superfund site located in Beltsville, MD. The US Environmental Protection Agency (US EPA) oversaw the remediation plan as per the regulations of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) program. A hybrid adaptive management strategy was employed to to guarantee the use of a science-based approach to the remediation efforts, to ensure that new information could be incorporated into the remediation plan, and to avoid the shortcomings of other remediation efforts elsewhere. Laboratory experiments and a historic-data assessment were conducted in conjunction with the monitoring plan to provide the Consultant and USDA with comprehensive feedback, to strengthen and to modify the monitoring and biowall construction plans as the requirements of the site changed. This feedback mechanism was repeated multiple times to make certain that the highest quality and most effective methods were used. The scope of the project also grew to include investigations of the soil microbial community for future structural biostimulation and bioaugmentation activities. While the biowall has reduced the concentration of trichloroethylene (TCE) to levels at or below its Maximum Contaminant Level, work is on-going to improve the functionality of the biowall and to address emerging challenges.

1. Introduction
The Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA), also known by the moniker of Superfund, was enacted by the US Congress in response to several environmental and human health disasters that had taken place during the previous decade (US EPA 2013). The Act follows the criteria of the Hazard Ranking System (HRS), a checklist which assess the relative potential threat of a site to public health and the environment, and a comments and response period to compile the National Priorities List (NPL) (US EPA 2011). Sites can be discovered and identified by anyone, including citizens, state agencies, the United States Environmental Protection Agency (US EPA), and the responsible party. The US EPA and/or the responsible party are then required to address the issue.

The project site is a former landfill that occupies approximately 1 hectare at the US Department of Agriculture-Agricultural Research Service (USDA-ARS) Beltsville Agricultural Research Center (BARC) in Beltsville, Maryland, USA. BARC was included on the NPL in 1994, and the landfill was preliminarily identified as one of several Areas of Concern (AoSs) due to its history. The landfill was used for disposal of construction debris and demolition rubble from the 1940’s to the 1980’s and was capped in 1990 adhering to existing state regulations governing such facilities (BMT Entech, Inc. 2008a, 2008b, 2009, USDA-ARS US Department of Agriculture-Agricultural Research Service (2012)). In 1998, it was formally labeled an AoC after trichloroethylene (TCE) was identified in the groundwater system.
surrounding the landfill at a concentration several orders of magnitude above the Maximum Contaminant Level (MCL) of 5 ppb (0.005 mg L$^{-1}$) and posed a potential threat to human and environmental health (US EPA 2009a, USDA-ARS US Department of Agriculture-Agricultural Research Service 2012).

The degradation products of TCE are also of great concern. The MCLs for 1, 1-dichloroethylene, cis-/trans-1, 2-dichloroethylene, and vinyl chloride are 0.007 mg L$^{-1}$, 0.07 mg L$^{-1}$, 0.1 mg L$^{-1}$, and 0.002 mg L$^{-1}$, respectively (US EPA US Environmental Protection Agency 1995, ATSDR 2006). Though no MCL for ethane exists, it is highly flammable (flashpoint = $-136.6$ °C) (Airgas 2004). The TCE plume, which is southeast of the landfill, has been estimated to be approximately 200 m long with a maximum width of approximately 140 m (BMT Entech, Inc. 2009). The surrounding area includes a wetland and an unnamed branch of Beaver Dam Creek south of the landfill.

As part of the CERCLA process, a federally-led feasibility study was carried out in the mid to late 2000’s to characterize the site, after which several action alternatives for remediation were proposed. The preferred remedy, construction of a mulch biowall, was chosen based on the study results (BMT Entech, Inc. 2009, US EPA 2009b, USDA-ARS US Department of Agriculture-Agricultural Research Service 2012), and this decision was documented in the Record of Decision (Rod) (BMT Designers and Planners 2011a). An academic institution (University of Maryland, College Park) was chosen to assist in implementation of the Record of Decision. In this instance, a research-oriented institution was selected over a more traditional consultant due to the flexibility associated with such an organization; modifications with respect to experimental questions, analytical techniques, sample size and quantity may be handled more readily and done without having to amend lengthy contracts. A collaboration of this nature also provides student training opportunities in a real-life setting.

This paper examines the iterative management and science implementation of this trilateral collaboration to mitigate TCE and its degradation products effectively. Adaptive management is a powerful though sometimes misused tool for evaluating problems and decisions that have a high degree of complexity and uncertainty (Gregory et al 2006). Passive adaptive management relies on historical data and information to predict future site behavior followed by development of an action plan (Gregory et al 2006). During the process, new information is used to update data sets, hypotheses, and action plan(s) as needed. This routine is similar to the method followed by CERCLA to inform the selection of an action remedy. Alternatively, active adaptive management relies on experimentation to determine the best course of action; several planned alternatives are tested in series or parallel, the results are compared, and then action is taken (Gregory et al 2006). This process is more familiar to a laboratory setting.

In this project, a hybrid form of adaptive management was consciously utilized to accommodate the short- and long-term needs and missions of the partners involved and to address the reigning objectives of the project. While the principal objective was to decrease the contaminant groundwater concentrations to meet the required federal standards, the underlying or supporting, objective was to accomplish this by avoiding the shortcomings of previous remediation efforts at other sites, discussed later on, to inform the construction and monitoring of this biowall (Vogan et al 1999, FRTR Federal Remediation Technologies Roundtable 2003, Groundwater Services, Inc 2004, Wilkin et al 2005, Lu et al 2008, Phillips et al 2010, Gilbert et al 2013).

2. Methods

2.1. Assessment of historical data

USDA, the academic partner, and the consultant reviewed all previous investigative studies and all historical analytical site data related to the landfill, surrounding area, and aquifer analysis, as well as the basis for the biowall design and the preliminary monitoring plan. The focal criteria and parameters were to identify the data necessary to carry out the modeling of the contaminant fate and transport; to identify the samples required to ensure appropriate data are acquired for the modeling efforts; to ensure that the sampling locations are appropriate to gather the necessary information to track contaminant movement, degradation, and site evolution; to determine how many samples are sufficient for data quality requirements to demonstrate degradation efficacy; and to formulate a suitable monitoring schedule.

2.2. Laboratory experiments

Before construction, soil and water samples were collected from the uncontaminated portion of the study site and were used to assemble background control batch and flow-through reactors. Experiments were conducted concurrent to the historical data review to examine the physical and chemical properties of the wall components and to test the degradation and sorption capacity of a series of biowall fill materials (Niño de Guzmán et al 2018a). Parameters measured included carbon content, porosity, redox conditions, and pH. Batch reactors
containing test materials, such as mulch, compost, zero-valent iron (ZVI), and glycerol, were spiked with a TCE concentration similar to that found at the study site and were kept at the oxygen concentration and temperature of the groundwater at the landfill. Flow-through reactors were assembled consisting of the material mixtures demonstrating the greatest conversion of TCE to ethane in the batch reactors. Finally, the native soil microbial community was examined to determine if any anaerobic bacteria or communities demonstrating TCE degradation potential could be isolated and purposely introduced into the biowall materials (Niño de Guzmán et al. 2018b).

2.3. Field and biowall measurements
In accordance with the ROD, an approved groundwater monitoring program was assembled by the consultant. The sampling collection program designed by the consultant consisted of biweekly (liquid) samples from the biowall wells and biannual (liquid) samples from the biowall, transect wells, original site investigation groundwater monitoring wells, and Beaver Dam Creek. Physical parameters and inorganic and organic compounds were also measured in biowall well samples (table 1) (BMT 2014, Niño de Guzmán et al. 2018a).

Additional soil and water samples were collected from field locations identified as optimal to measure the concentration and migration of TCE and degradation products. The sampling locations up-gradient and down-gradient of the biowall are shown in figure 1. One year after the biowall was installed, samples were collected from within the structure to examine microbial migration, degradation activity, and whether contaminant equilibrium had been reached.

2.4. Meetings and communication
Quarterly meetings were held to facilitate communication between US EPA, USDA, the academic partner, and the consultant. These meetings were a forum to provide updates that generally included field monitoring test results, current research activities and preliminary results, future planned experiments, and plans for the following quarter. Frank discussions helped to avoid duplications of effort, scheduling conflicts, and miscommunication. Figure 2 illustrates the remediation project hierarchy and the most-commonly followed communication tree. More regular communication took place throughout the quarter between the USDA, the academic partner, and the consultant in the form of emails, phone calls, and site visits. The US EPA was not typically involved on a day-to-day basis and served as an overseer to ensure that the overall process was moving forward.

Table 1. Summary of monitoring analyses.

| Wells                        | Physical parameters | Geochemical parameters | Chemical parameters |
|------------------------------|---------------------|------------------------|---------------------|
| Biowall Wells (BW)           | Dissolved Oxygen    | CaCO₃, Alkalinity      | VOCs                |
|                              | Redox Potential     | Total Ferrous Iron     | Total Iron          |
|                              | Temperature pH      | Dissolved Ferrous Iron | Dissolved Iron      |
|                              | pH                  | Total Organic Carbon   | Methane             |
|                              | Salinity            | Ethane                 | Ethene              |
|                              | Turbidity           |                        |                     |
|                              | Specific Conductivity|                        |                     |
|                              | Dissolved Oxygen    |                        |                     |
|                              | Redox Potential     |                        |                     |
|                              | Temperature pH      |                        |                     |
| Transect Wells (TW)          | pH                  | None                   | VOCs                |
|                              | Salinity            |                        |                     |
|                              | Turbidity           |                        |                     |
|                              | Specific Conductivity|                        |                     |
| Remedial Investigation Wells (MW) | Dissolved Oxygen | None                   | VOCs                |
|                              | Temperature pH      |                        |                     |
|                              | Dissolved Oxygen    |                        |                     |
|                              | Redox Potential     |                        |                     |
|                              | Temperature pH      |                        |                     |
| Surface Water                | pH                  | None                   | VOCs                |
|                              | Salinity            |                        |                     |
|                              | Turbidity           |                        |                     |
|                              | Specific Conductivity|                        |                     |
2.5. Reports
The consultant prepared and distributed draft quarterly monitoring reports summarizing the monitoring activities, sample test results, current biowall conditions, and general recommendations made during the last meeting. These documents were distributed at least two weeks before the quarterly meeting to give all the parties a chance to comment and to critique the materials. Yearly reports were compiled from these quarterly documents and formally submitted to the US EPA.

3. Results and discussion

3.1. Assessment of historical data
The first available groundwater and soils datasets came from a 1997 baseline groundwater sampling operation conducted by the consulting engineers and were used to assess groundwater quality, flow patterns, and hydraulic characteristics (Entech, Inc. (1998a)). A 1998 site screening study provided a second dataset, where samples were taken from four existing monitoring wells (circa 1985), nine Geoprobe® locations, and surface water/sediments were collected from an additional five locations (Entech, Inc (1998b), 2003). A remedial investigation study in 2002 included a soil gas survey that was used to determine the extent of contamination, to identify TCE and other VOC hot spots, and to guide subsequent borings and well installation (Entech, Inc 2003, BMT Entech, Inc. 2008c). Hydraulic conductivity data for the aquifer were estimated from slug tests conducted between 2004 and 2012 (Entech, Inc 2003, BMT Entech, Inc. 2008b, BMT Designers and Planners (2011b)). In 2005, nine upstream and downstream monitoring wells were installed to measure VOC concentrations annually. In addition, groundwater potentiometric mapping and groundwater flow analyses were conducted (BMT Entech, Inc. 2008c, BMT Designers and Planners 2011a).

Although a more consistent groundwater sampling schedule was adopted in 2005, the lengthy time between collections and the limited analyte scope precluded in-depth analyses of changes in geochemistry, hydraulics, or VOC concentrations. Furthermore, sand screens at the base of the monitoring wells which prevent well-screen clogging and wear and tear on sampling pumps may have caused underestimation or exclusion of certain sediment-bound analytes in the groundwater samples (e.g. iron, ion species, minerals) (Menheer and Brigham 1997, Vail 2013). This is problematic because metal concentration data are of particular interest as...
Table 2. Summary of the Beaverdam Road Landfill remediation action plan options (USDA-ARS, 2009, BMT Entech, Inc., 2008a; BMT Designers and Planners 2011b).

| Plan | Description |
|------|-------------|
| 1    | 'No action'. |
| 2    | 'Land use controls and monitoring': use signs and fencing to enforce no-trespassing, with annual groundwater monitoring to ensure contamination is not getting worse or moving beyond the property boundaries. |
| 3    | 'Monitored natural attenuation, land use controls, and monitoring': In addition to the actions of Plan 2 (above), groundwater samples are periodically taken and analyzed to determine the extent of natural attenuation at the site. |
| 4    | 'Groundwater treatment via a much bioiwall permeable reactive barrier and land use controls': build a structure approximately 0.5 to 0.9 m wide, 8 to 11 m deep, and 300 m long and implement land use controls from Plan 2. |
| 5    | 'Extraction, on-site treatment, recharge, and land use controls': install extraction wells and pumps to extract groundwater. Send groundwater through a treatment system and use to recharge the aquifer. |

certain types of iron in the soil and groundwater can promote the reduction of TCE (Davison and Seed 1983, Lee and Batchelor 2002a, 2002b, 2003, Elsner et al 2004, He et al 2008, Liang et al 2009). All these data and assessments were used by the collaborators throughout the adaptive management process.

3.2. Remedial selection and biowall technology

The feasibility study step in the CERCLA process identified and considered several remediation action plan alternatives which are summarized in table 2. The alternatives proposed by the consultant were based on the feasibility study and included several different approaches, each with increasing costs, intensity, and disruption to the area. Each of the remedial alternatives included a cost and health risk assessment (BMT Entech Inc. 2008b, BMT Designers and Planners 2011a). Nine criteria were used in the selection process (BMT Entech, Inc. 2009): overall protection of human health and the environment; compliance with Applicable or Relevant and Appropriate Requirements (ARARs) (meets laws and regulations set by CERCLA); long-term effectiveness and permanence of the action; reduction of toxicity, mobility, or volume of contaminants through treatment; short-term effectiveness; ability of the plan to be implemented; cost; acceptance by the state; and acceptance by the community. The biowall (Plan 4) was selected because mitigation was needed to decrease potential risk from the contaminants, and it was more cost-effective and easier to maintain than extraction (Plan 5). This decision was summarized in the Record of Decision (BMT Designers and Planners 2011a).

Biowall technology is not a new remediation method for groundwater contamination. Over the last two decades, reactive barriers have been used extensively by the US Air Force, industry, and other entities to remediate a range of groundwater contaminants (Vogan et al 1999, NATO/CCMS North Atlantic Treaty Organization/Committee on the Challenges of Modern Society 2001), FRTR Federal Remediation Technologies Roundtable (2003), Parsons Infrastructure and Technology Group, Inc. 2008, Phillips et al 2010). Biowalls are a low-maintenance, green technology and are often a cost-effective remediation option. While biowalls do not address the contaminant source, they are designed to manage the contaminants of concern as they are released from the source and migrate through the subsurface. Thus, the biowall provides a large, reactive-surface area so that as groundwater passes through the structure, the released contaminants are sorbed and/or degraded (figure 3).

Longevity and robustness, however, are essential to the effectiveness of the biowall especially if the contaminant source lifetime and emission rate are unknown. Therefore, to ensure that a biowall remains low maintenance and economical, several factors need to be considered in implementation, including the types of materials used and their degradation, the ratio of organic-to-inorganic material, degradation kinetics of the contaminant, water geochemistry, microbial community, hydraulic characteristics (i.e., porosity and flow), and structural dimensions which, in this case, were determined using transport modeling (Tratnyek et al 1997, Vogan et al 1999, FRTR Federal Remediation Technologies Roundtable (2003), Groundwater Services, Inc. 2004, Ahmad et al 2007, Phillips et al 2010, Eroto et al 2011). Finally, another key aspect of this biowall was to attempt to utilize the native soil microbial population, specifically, those previously identified to degrade TCE.

3.3. Using adaptive management in biowall implementation and management

In addition to overseeing the installation of the engineered structure in July 2013, the consultant was also responsible for establishing a monitoring program to evaluate the biowall. Monitoring is required to assess the extent of transport, infiltration, and remediation of the site contaminants. An extensive literature review of similar remediation installations was conducted by the university partner to establish a scientifically rigorous program that would improve upon previous assessments of remediation activities (Michaelson 2012). It was
revealed that the final evaluation of some of the remediation efforts was based on insufficient or inappropriate sampling frequency based on flow rate, no established baseline, or poor sample collection protocol. Additionally, the university partner identified that in some instances the final remediation design had insufficient residence time and leakage around the structure (Vogan et al 1999, FRTR Federal Remediation Technologies Roundtable (2003), Groundwater Services, Inc. 2004, Wilkin et al 2005, Lu et al 2008, Gilbert et al 2013). While it is not possible to understand fully the limitations or other constraints placed on those studies, in hindsight, many of these issues could have been resolved with continued scrutiny of the monitoring program employed to judge performance. The remediation efforts may still have been successful, but the protocol implemented to gauge success was faulty and not necessarily designed to measure success.

CERCLA requires an efficacy assessment review every five years and a minimum 30-year commitment of groundwater monitoring to assure public safety. The in-depth historical assessment and concurrent laboratory experiments married passive and active adaptive management styles and allowed the partners to avoid previous shortcomings during the implementation of the ROD. The outcomes of the experiments and assessments were discussed during the quarterly meetings and were incorporated into the biowall design and/or monitoring plan. However, the partners determined that it was not appropriate to wait for the first five-year review to suggest changes to the monitoring plan or to initiate planning for future structural modifications based on the outcome of the scientific experiments (i.e., bioaugmentation, biostimulation, ZVI injection). Thus, refinements took place during the first 5-year period, in anticipation of the first review.

The decision points to either maintain the status quo or initiate a change in either the monitoring plan or biowall structure occurred during the institutional meetings and were vetted in subsequent emails and reports with data. Several intertwining points were deliberated prior to a decision: (1) the stability of the analytical parameter under consideration for change based on literature and historical site data; (2) using this information, how the change would affect the contaminant concentrations relative to the MCLs; and (3) the feasibility of the desired change from economic, structural, and practical perspectives. Specific changes are discussed below.

3.4. Changes to the biowall design
To determine the biowall fill material appropriate for achieving the site remediation goals, the academic partner conducted experiments investigating the type and mixture ratios of mulch and compost based on an extensive literature review (Niño de Guzmán et al 2018a). ZVI and glycerol were also considered for their potential to improve TCE degradation; ZVI has been extensively studied in this capacity while the use of glycerol as a carbon
source in this role has not been widely studied (Gillham and O’Hannesin 1994, Wilkin et al 2005, Kouznetsova et al 2007, Atashgah et al 2016). These experiments were run in parallel so that the responses could be compared directly. Results showed that extra carbon and ZVI enhanced TCE disappearance, however, the quantity of iron filings needed to affect a change was impractically large. The findings were compiled and discussed with the partners. Based on these discussions, the consultant chose a mixture of 40% mulch generated partially from the trees and brush cleared to install the wall and 30% compost generated at the BARC compost research facility which provided the extra carbon and was readily accessible. The remainder of the wall consisted of concrete-grade sand and small gravel which facilitated flow and provided structural stability.

Transect wells were not a part of the original biowall design but were added after assessing historical data. Following numerous discussions, the partners agreed that the locations of some downstream monitoring wells were not ideally situated to capture groundwater exiting the biowall. Thus, new transect wells were installed to monitor the migration of the plume hotspot as it moves through the biowall and the filtered groundwater as it exits the downstream side. Of the six wells, four were located upstream of the biowall, one of which was installed on the leading edge, while the two remaining wells were located on the lagging edge and 0.36 m downstream. The inclusion of the additional monitoring groundwater wells has been invaluable for determining background analyte concentrations and will be a crucial component for high-quality, long-term data analysis in subsequent years as evidenced elsewhere (FRTR Federal Remediation Technologies Roundtable (2003), Groundwater Services, Inc. 2004, Lu et al 2008, Gilbert et al 2013).

3.5. Updates to the field testing and monitoring plan
It was important to employ site-tailored questions and analyses to ensure that site remediation is successful. This baseline assessment was a critical step and provided the needed information for the biowall design and the restructuring of the monitoring plan. From this assessment, criteria were established to evaluate the success of the biowall, including contaminant movement, retention, and/or degradation and to consider the evolution of the site. The sampling number, schedule, and locations were also examined and adjusted to accommodate the needs of the modeling exercises. As a result, the sampling regime of the monitoring wells was changed from annually to quarterly beginning in 2014.

Since the installation of the biowall in 2013, the consultant has compiled quarterly reports of the data from the sampling activities. The initial reports, prior to biowall installation, were an exhaustive list of physical, geochemical, and chemical parameters measured in each sample to establish an extensive baseline. After a year, the partners observed that some of the parameters were quite stable and could be measured less frequently, while others provided superfluous information and could be eliminated from the list of analyses, reducing analytical costs. For example, nitrate and nitrite were removed from the analyte list one year after the biowall was installed because they were not detected in any of the biowall well samples. Sulphide analysis was also discontinued based on the likelihood that iron (II) sulphide formation was occurring inside the biowall, a precipitate unable to be captured in the collected water samples. On the other hand, methane, ethane, and ethene were added to the analyte list of the transect wells after the fourth quarter sampling event to improve monitoring of full degradation and methanogenesis. This type of data and analysis review provided savings financially and in human capital and allowed the partners to focus on efforts which could provide more fruitful analyses.

3.6. Adaptive management and microbial populations
Since installation of the biowall, TCE levels have decreased approximately 90% in the groundwater that passed through the structure, although levels of certain degradation products have increased. For instance, from March 2014 to September 2016, the vinyl chloride concentrations downstream of the biowall increased from 13 μg l⁻¹ to approximately 20 μg l⁻¹ while the ethylene concentrations at the same locations increased from not detected to approximately 5 μg l⁻¹ (Niño de Guzmán et al 2018a). The presence of ethylene is auspicious as it is the fully dechlorinated, non-toxic final degradation product, while the buildup of vinyl chloride is of concern due to its known toxicity. To combat the growing concentration of vinyl chloride strategically, field sampling and laboratory analyses have continued; the data are being used to inform the next generation of experiments to investigate and promote vinyl chloride degradation, among other objectives. Nonetheless, the hazard quotient of the site has decreased 88% (Niño de Guzmán et al 2018a).

In addition to determining the composition of the biowall, the batch reactor experiments explored potential remedies to future degradation issues (addition of ZVI and/or glycerol) and insight into potential interaction concerns. The addition of ZVI shavings instigated sufficient reducing conditions to decrease but not completely prohibit vinyl chloride formation. However, ZVI shavings in concert with glycerol actually increased vinyl chloride production (Niño de Guzmán et al 2018a). As previously mentioned, the impetus for including glycerol in these experiments was to explore its use as an easily accessible source of carbohydrates for the microbial population, to encourage their proliferation inside the biowall material and the biotic degradation of TCE. In the
course of field sampling, the group discovered that the biowall material was aging faster than anticipated, possibly due to a combination of microbial activity and natural decay. Unfortunately, due to its effect on the production of vinyl chloride when coupled with iron, glycerol was found not to be the best material to use as a 'sacrificial' carbohydrate-rich substance to slow the biological degradation of the biowall. This suggests that a different carbohydrate-containing material should be investigated.

Groundwater and soil samples were collected before and after biowall installation as well as from the biowall structure after one year later to monitor and to catalog the microbial community. Next generation DNA sequencing was employed to index the different bacteria present in high, moderate, and no contamination zones; nested PCR assays were used to specifically search for members of the *Dehalococcoides* genus, able to completely dechlorinate TCE (Niño de Guzmán *et al* 2018b). PCR assays were also used to search for the presence of three different functional genes previously found necessary for the dehalogenation of chlorinated ethenes (Holmes *et al* 2006, Fung *et al* 2007). The goal is to consider individuals or communities discovered in the samples for bioaugmentation of the biowall to increase the degradation capability and longevity of the structure. Additional feasibility experiments are underway to examine this issue as well as the effects of ZVI exposure on the indigenous microbial community.

4. Conclusions

As part of the Superfund program, the Beaver Dam Road Landfill remediation project required USDA, UMD, and the Consultant to work in concert for the successful implementation of the US EPA action plan. The approach taken by the team facilitated capture of the broadest remedial scope, while the use of adaptive management ensured that the action and monitoring plans remained organized and flexible. Communication between entities, though less formal, allowed for more free-flowing, frank dialogue. It is important to note that aside from their designated roles, the USDA research organization and the Consultant provided invaluable professional and real world insight necessary to design experiments and to advise the UMD graduate students. This type of communication experience is often not available in a university environment either through the classroom or research projects.

The detailed historic data assessment in conjunction with the laboratory experiments to inform the final biowall design and monitoring plan has enabled this project to overcome or avoid several common pitfalls uncovered during the extensive literature review. From these modifications, it is with confidence that the biowall is successfully lowering the groundwater TCE concentration to the MCL downstream of the structure. Additionally, it is clear that new challenges are emerging as the site and structure continue to mature; this is an on-going investigation and area of research. Data assessment and research continue to evolve to address this dynamic system and are consistently used to inform future decisions concerning biowall adjustments and the monitoring regime. The major project changes in the beginning, i.e., monitoring well placement and chemical analyses, were the result of the impartial evaluation of historic and present data. The extension of the project from the original scope to include microbial community analysis is expected to generate results that will provide insight into structural biostimulation activities and the maturation of the site and structure.

The scope of this project is unique, and the use of a hybrid adaptive management method as a way to facilitate a constructive collaboration process is recommended in other similarly large projects to take advantage of the distinctive synergy that can be created though each participant area of expertise. As new information becomes available and technological advancements in the engineering and scientific fields are made, we anticipate that further refinements to the monitoring plan will be implemented.

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