Temporal and Spatial Statistical Monitoring Optimization Applications and Plan Modification Success

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ABSTRACT: Optimization of long-term monitoring (LTM) activities can improve performance and increase monitoring efficiency while simultaneously resulting in a reduction in monitoring scope and costs. Various methods for monitoring optimization and plume assessment have been presented over the past decade in literature, guidance and case studies. Quantitative optimization methods incorporate algorithms to optimize temporal sampling frequencies and spatial locations, resulting in a rigorous assessment of monitoring criteria. In addition, geospatial plume stability analysis and assessment of first-order attenuation further allow for a projection of future plume conditions to be made. Based on these algorithms, a temporal and spatial optimization approach is developed along with assessments of plume stability and first-order attenuation, providing straightforward and easily communicable metrics to all stakeholders. Results of the optimization approach utilized for several Midwest solid waste and remedial cleanup facilities illustrate successful plan modifications. Lessons learned in the optimization process include several key items based on the corresponding life-cycle stage of the facility which would allow for greater acceptance of the optimization results.

INTRODUCTION

LTM programs are established to verify that contaminants are not endangering potential receptors, and that remediation is occurring at expected rates. Monitoring programs established during site characterization, however, may not be optimal for LTM. Optimizing such programs results in a reduction in monitoring scope and costs, but maintains and clarifies the primary objectives of evaluating temporal concentration changes.

Traditionally, a reduction in the scope of monitoring is proposed based on qualitative analyses, including information such as site characteristics, contaminant concentration levels and contaminant trends. However, the use of quantitative methods in guidance and practice has grown rapidly, including algorithms to optimize temporal sampling frequencies and spatial locations. Further, the use of geospatial methods coupled with assessment of first-order attenuation allows for the projection of future plume conditions. Use of these quantitative methods in optimizing a monitoring program provides a rigorous and defensible approach to setting monitoring criteria.

Guidance. A national approach that unifies previously independent optimization efforts is outlined in *National Strategy to Expand Superfund Optimization Practices from Site Assessment to Site Completion* (USEPA, 2012). Referred to as the “Strategy,” the approach brings together freestanding optimization methods such as the triad approach, remediation system evaluations, long-term monitoring optimization (LTMO) and green remediation. A key component within the Strategy is optimization of monitoring systems, which may incorporate either temporal optimization, spatial optimization, or both. In addition, the use of three-dimensional (3-D) visualization and analysis is recommended to communicate and maintain consensus with stakeholders.

The Interstate Technology & Regulatory Council also provides a review of geospatial methods for optimization decision making in *Geospatial Analysis for Optimization at Environmental Sites* (ITRC, 2016). Geospatial methods incorporate the spatial and temporal dependence between nearby data points to optimize monitoring programs while minimizing overall information loss. These methods are applicable across all project life cycle stages (release detection, site characterization, remediation, monitoring and closure).

MATERIALS AND METHODS

Temporal Optimization. Temporal optimization algorithms often consider observed variation in historical data, along with existing trends, to assess the stability of the dataset. The premise is that sampling frequency should be based on the rate of change of constituents relative to a concentration standard. High rates of change or high levels of variation warrant more frequent sampling. Temporal optimization algorithms which accomplish this include the Cost Effective Sampling algorithm (CES) (Ridley and MacQueen, 1995) and the Modified CES algorithm (Monitoring and Remediation Optimization System - MAROS) (AFCEE, 2012).

Temporal optimization as performed in the case studies given below in the Results and Discussion section utilized the MAROS modified CES method. This provides optimal well sampling frequencies based on statistics describing the trend, variability and magnitude of contaminant concentrations as summarized on Figure 1.

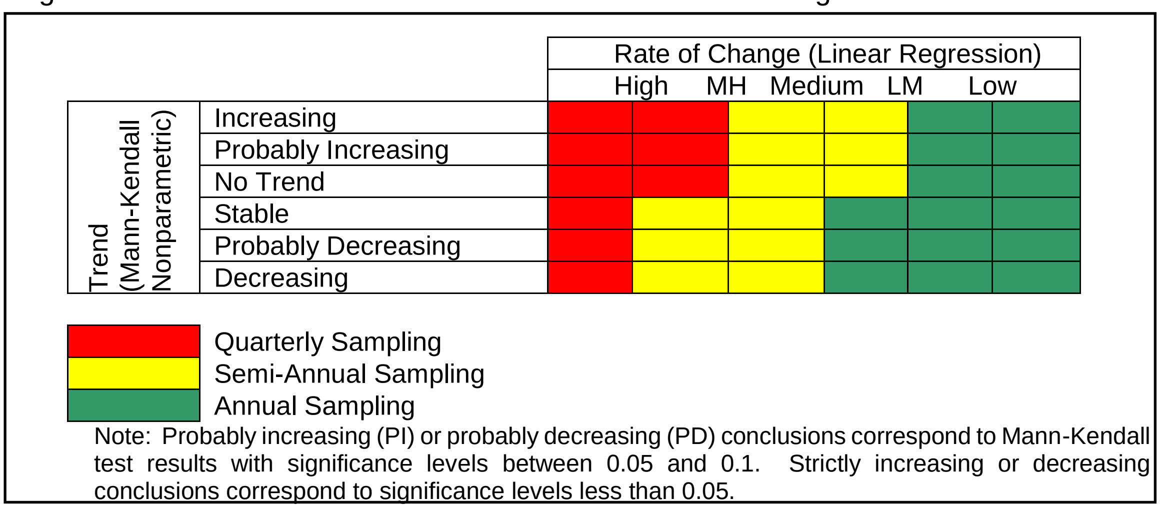


FIGURE 1. Optimal Sampling Frequency Flowchart.
(Adapted from Figure 5.1 of AFCEE, 2012.)

Spatial Optimization. Spatial optimization algorithms incorporate geostatistical evaluation to identify sampling locations that either have little impact on the historical characterization of a constituent plume, or conversely, identify areas of high uncertainty needing further delineation. Locations are redundant if nearby samples generally offer the same information. In optimizing a monitoring network, redundant and insufficient locations are assessed through the spatial correlation structure of the conceptual site model (CSM).

Strategies to spatial optimization include evaluating relative kriging weights and global kriging variance (GTS) (Cameron et al., 2011); evaluating kriging variance after well removal (Parsons Three-Tiered) (Nobel and Anthony, 2004); minimizing the maximum interpolation error (SampleOptimizer™) (Summit Envirosolutions, 2009); and estimating the difference between observed predicted concentrations relative to the surrounding well concentrations (MAROS) (AFCEE, 2012).

Concepts from the above algorithms were incorporated into a basic and straightforward approach. Monitoring locations which are qualitatively suspected of providing redundant information are removed from the data set, and data from the remaining locations are spatially interpolated. This is similar to cross-validation (i.e., one-off) procedures in geo-statistical modeling, but instead, multiple locations are simultaneously removed. Resulting concentration estimates at the removed locations are then directly compared to observed sample data. Concentration estimates which are comparable to observed data provide evidence of spatially redundant locations.

The adaptation employs a 3-D approach instead of the more common 2-D interpolation modeling. Utilizing a 3-D CSM provides not only a more realistic interpolation model for monitoring optimization, but also a highly effective communication tool among stakeholders, allowing “what-if” questions to be identified and addressed. Commercially available software (Earth Volumetric Studio™ by C Tech and GMS™ by AQUAVEO) along with custom programmed utilities are used in the analysis.

Plume Stability and First-Order Attenuation. Evaluating plume stability during optimization can greatly benefit the analysis by comprehensively characterizing plume trends. This provides clarity, particularly when concentration trend results do not agree for all individual well locations. The assessment is performed similarly to the 2-D method of plume stability analysis given by Ricker (2008), however, as with the spatial optimization analysis described above, it instead employs 3-D interpolation modeling.

Plume stability is assessed by developing 3-D interpolation models of the concentration plumes for each constituent of concern (COC) and each monitoring event over the period of interest. Based on the interpolated results, custom algorithms are used to calculate plume metrics such as average and maximum concentration, plume area and volume, and 3-D center of mass for each constituent and event. Trends in these metrics are then statistically evaluated through parametric or non-parametric trend tests.

Further, geospatial methods allowing for the estimation of plume trends, coupled with assessment of first-order attenuation, allow for the projection of future plume conditions. First-order attenuation in plume concentration is calculated following the approach given in USEPA (2011). The rate of attenuation is governed by the equation $C/C_0=e^{-kt}$, with C/C_0 being the concentration reduction, k the first-order rate constant and t the time elapsed. The first-order attenuation is estimated through regression analysis of the natural log-transformed concentrations, i.e., $ln(C) = ln(C_0)-kt$. The lower 80% confidence interval on the regression line provides measure of uncertainty in determining whether the projected concentrations will remain above a given cleanup standard.

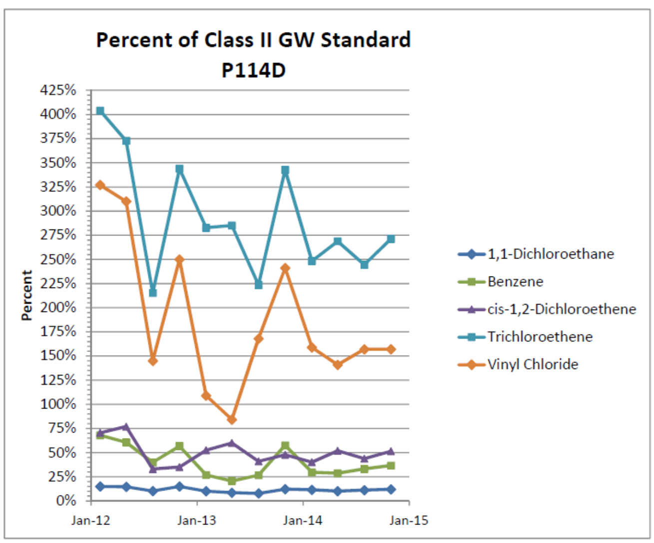
RESULTS AND DISCUSSION

Case 1 – Temporal and Spatial Optimization at a West-Central Illinois Solid Waste Facility. A monitoring network optimization study was performed at a west-central Illinois solid waste facility licensed to accept general refuse, special non-hazardous waste, and demolition debris. Elevated leachate levels in the northern area of the landfill were identified as a likely source of volatile organic compound (VOC) contamination in the Phase I and Phase II landfill areas. To control the contaminant source, an improved leachate management system was put in place, and a full network of 30 wells monitored quarterly was established in 2012. Of these 30 wells, 23 were considered for the spatial optimization study and 22 for temporal optimization.

Based on concentration comparisons to the Class II groundwater standard, COCs chosen for the optimization study included 1,1-dichloroethane (1,1-DCA), benzene, cis-1,2-dichloroethene (cis-1,2-DCE), trichloroethene (TCE) and vinyl chloride. The optimization study evaluated whether a reduction in the frequency of groundwater sample collection and/or elimination of groundwater collection at some wells in the monitoring program could be achieved.

Temporal optimization analysis determined that 101 of the 115 well/constituent pairs had either stable or decreasing trends. Further, the rates of concentration change of all trends (in units of µg/L/year) were low relative to the Class II groundwater standard. Based on these results, the modified CES algorithm would suggest a biennial (once every two years) sampling for 14 of the locations, and annual sampling for the remaining eight wells in the study.

The temporal optimization results of the highest concentration well are depicted on Figure 2. Here the conclusions from the nonparametric Mann-Kendall trend test are stable for 1,1-DCA, benzene and cis-1,2-DCE, and probably decreasing for TCE and vinyl chloride. In addition, all five constituents have a low rate of change respective to the Class II groundwater standard, resulting in a recommendation of annual sampling.



Sample Size	12
1,1-Dichloroethane	
Mann-Kendall Conclusion	S
Observed ROC (Low/Med/High)	Low
Max Concentration <0.5×GWPS?	Yes
Adjusted Events/Year	Biennial
Benzene	
Mann-Kendall Conclusion	S
Observed ROC (Low/Med/High)	Low
Max Concentration <0.5×GWPS?	No
Adjusted Events/Year	Annual
cis-1,2-Dichloroethene	
Mann-Kendall Conclusion	S
Observed ROC (Low/Med/High)	Low
Max Concentration <0.5×GWPS?	No
Adjusted Events/Year	Annual
Trichloroethene	
Mann-Kendall Conclusion	PD
Observed ROC (Low/Med/High)	Low
Max Concentration <0.5×GWPS?	No
Adjusted Events/Year	Annual
Vinyl Chloride	
Mann-Kendall Conclusion	PD
Observed ROC (Low/Med/High)	Low
Max Concentration <0.5×GWPS?	No
Adjusted Events/Year	Annual

Notes:
Mann-Kendall Trend Result Designators:
D = Decreasing; PD = Probably Decreasing; NT = No Trend;
S = Stable; PI = Probably Increasing; I = Increasing
Rate of Change (ROC) Designators:
"Low" if ROC < 0.5*GWPS per year;
"Medium" if ROC > 0.5*GWPS but < 2* GWPS per year;
"High" if ROC > 2*GWPS per year.
GWPS = Ground Water Protection Standard

FIGURE 2. Temporal Optimization Result Example.

Spatial redundancy was assessed by first omitting six locations from the datasets due to the observed frequency of detections and the presence of other monitoring locations in close proximity and within the same geologic strata. COC concentrations were then interpolated for each quarterly event. The average of the predicted concentrations at each of the well locations temporally omitted was then compared to the average observed sample result. The analysis illustrated that the six locations could be omitted while still maintaining concentration certainty in the plume estimation. Figure 3 depicts the 3-D groundwater interpolation model used in the optimization study, while Figure 4, Figure 5 and Figure 6 illustrate the spatial optimization results of 1,1-DCA, TCE and vinyl chloride, respectively.

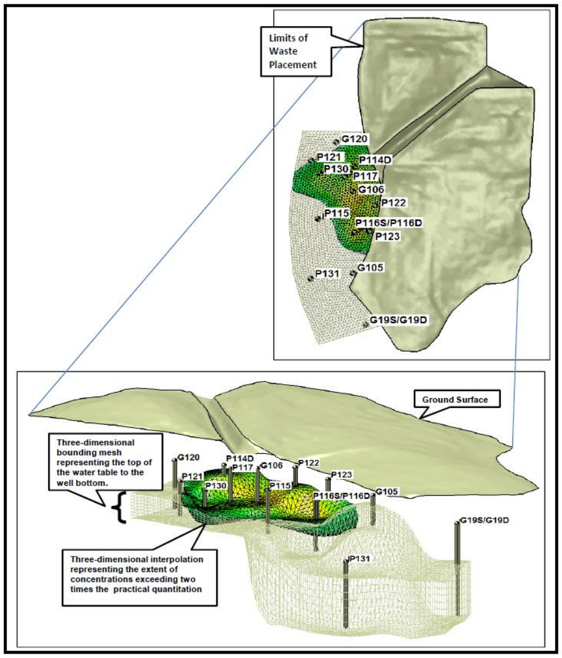


FIGURE 3. Three-Dimensional Plume Modeling.

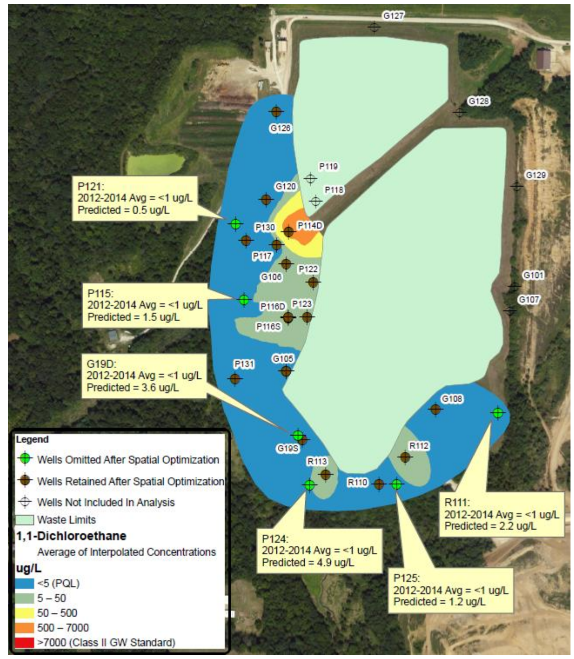


FIGURE 4. Spatial Optimization of 1,1-Dichloroethane

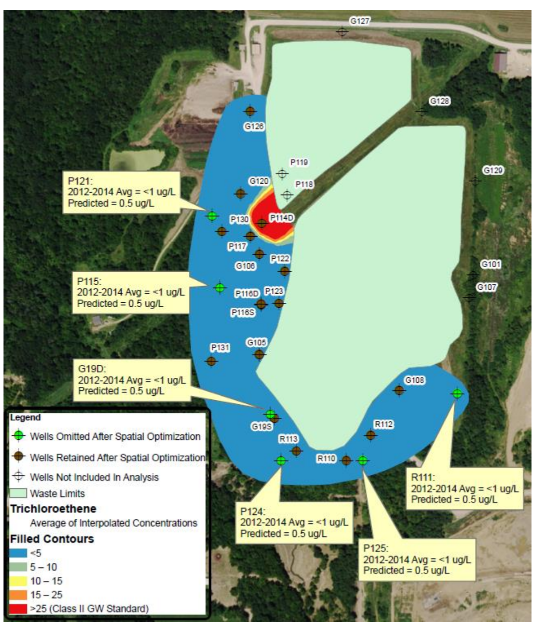


FIGURE 5. Spatial Optimization of Trichloroethene

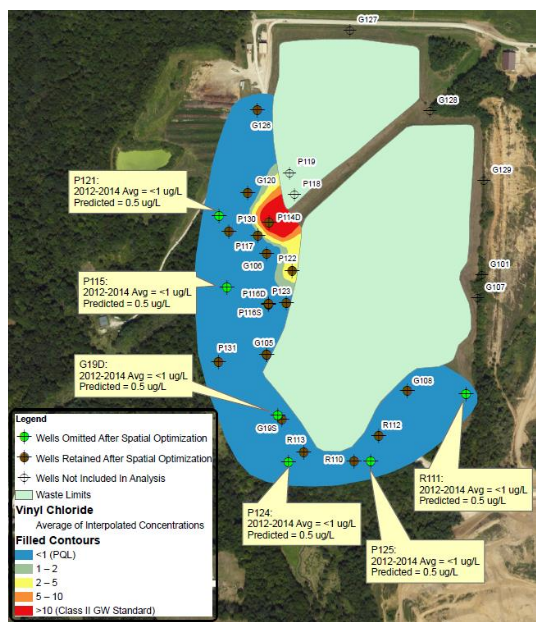


FIGURE 6. Spatial Optimization of Vinyl Chloride

In addition to the optimization results, plume stability analysis indicated very stable contaminant plume conditions with respect to plume area, volume, average concentration, dissolved mass and 3-D center of mass. Furthermore, the estimated plume maximum concentration levels are decreasing, and modeled first-order attenuation rates project the plume maximum concentration to fall below the Class II groundwater standard within 10 years for TCE, and within only a few years for vinyl chloride. Concentrations are already below the Class II standard for 1,1-DCA, benzene and cis-1,2-DCE.

Temporal optimization recommendations included moving wells within the monitoring program to either annual or biennial sampling based on the individual trend results. Agency agreement was received to move 14 wells implemented for VOC characterization to annual sampling, while maintaining a quarterly schedule on the remaining wells. While spatial optimization results indicated that six wells could be removed entirely from the monitoring network without significant loss in plume characterization, it was recommended that following four years of additional monitoring, another plume stability analysis be conducted to assess groundwater conditions. At that time, a supplemental permit application would be completed if the plume characteristics remain stable or declining, COCs continue trends towards compliance levels, and methane exceedances at gas monitoring devices and the final cover are not detected.

Case 2 – Plume Stability and First-Order Attenuation at a Solid Waste Facility in Western Iowa. A plume stability study along with the assessment of first-order attenuation in plume concentrations was performed for a closed cell at a western Iowa solid waste facility. Solid waste was accepted for the closed unit between 1972 and 2006, during which time it accepted municipal, commercial, and industrial wastes. Between 1994 and 2007, several groundwater quality assessments were performed for chlorinated VOCs (CVOCs). Assessment of corrective measures identified source control measures including final capping of unlined areas, additional leachate collection and selection of monitored natural attenuation (MNA) as a remedy. The analysis was performed to ascertain success of the MNA remedy, and characterize progress towards meeting groundwater protection standards (GWPS).

Plume stability was evaluated based on five CVOCs: 1,2-dichloropropane (1,2-DCP), cis-1,2-DCE, tetrachloroethene (PCE), TCE and vinyl chloride. Semi-annual monitoring results collected between 2008 and 2016 were interpolated for each CVOC. For illustration, the interpolation results of PCE are summarized on Figure 7 for the first semi-annual event of 2008, 2010, 2012, 2014 and 2016. Figure 7 illustrates groundwater PCE plumes on both the north and south sides of the facility.

The analysis indicated that concentrations above the GWPS are generally bounded. High concentration areas typically were located on the western side of the facility (Figure 7). Since groundwater flows south-southeast, the plumes are not anticipated to migrate significantly in a westerly direction. Statistically decreasing trends for plume area, average and maximum concentration for each of the five CVOCs are observed with the southern plume. The center of mass trended slightly east-southeast, reflecting not necessarily a migrating plume, but instead, decreasing plume concentrations on the western side. With the northern plume, trends in the plume metrics were again decreasing, with the exception of an increasing concentration trend in the intermediate product cis-1,2-DCE. However, the maximum cis-1,2-DCE concentration remains below the GWPS.

In addition to the plume stability metrics, the first-order attenuation rates of the modeled concentrations were assessed to project future plume conditions. The results of the analysis for the southern plume are illustrated on Figure 8. Parent product PCE is currently below the GWPS, along with 1,2-DCP. TCE is following an attenuation rate that, if continued, would fall below the GWPS within the near future. The attenuation rate for intermediate product cis-1,2-DCE, if continued, would result in concentrations below the GWPS within approximately 15 years; and the rate for daughter product vinyl chloride would result in concentrations below the GWPS within 20 years. Note that attenuation rates for cis-1,2-DCE and vinyl chloride may increase once parent product TCE has been fully degraded.

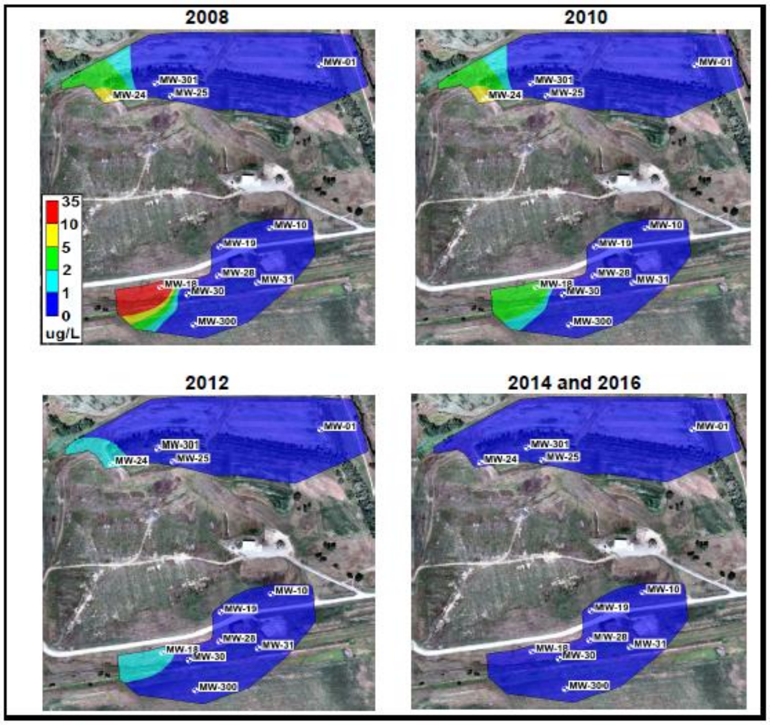


FIGURE 7. Tetrachloroethene (PCE) Interpolation Summary

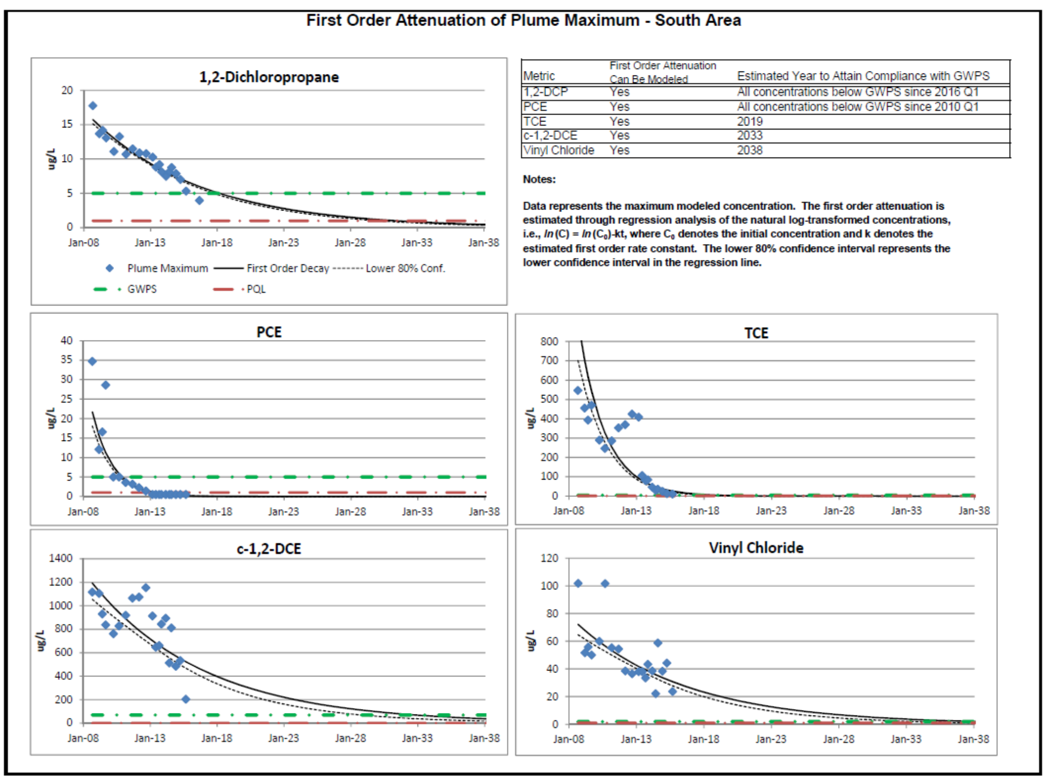


FIGURE 8. VOC and CVOC First-Order Attenuation of Plume Maximum.

Utilizing the results of the analysis, it was concluded that CVOC plume conditions are stable and decreasing, and attenuation occurring at rates consistent with expectations. Based on this, MNA was accepted by the regulatory agency to be the continued remedy.

Case 3 – Three-Dimensional Visualization and Plume Stability at a Facility in Northwestern Illinois. VOC and CVOC groundwater plumes at a solid waste facility in northwestern Illinois were 3-D modeled over a 10-year period to provide a visual assessment of progress towards remedial goals. The visual assessment was paired with the results of a plume stability study so that quantitative conclusions could be made.

The facility, which ceased accepting waste in 1992, was operated with trench and fill methodology with approximately 2,616,000 cubic yards of waste landfilled. Approximately 19,000 cubic yards of the total landfilled waste was industrial waste. Due to the detection of several VOCs, a groundwater management zone (GMZ) was established in 1997. There is a current combined network of 32 shallow and deep wells monitored quarterly. Monitoring has occurred in 24 of the 32 wells for over 20 years.

The COCs selected for the 3-D visualization and plume stability analysis were 1,1,1-trichloroethane (1,1,1-TCA), 1,1-DCA, 1,1-dichloroethene (1,1-DCE), cis-1,2-DCE, benzene, chloroethane, PCE, TCE, and vinyl chloride. The 3-D visualization in this study provided a very effective means of communicating remediation progress to key stakeholders. A time sequence was generated for each COC from the interpolated quarterly monitoring data collected between 2007 and 2017. Stakeholders had the ability to replay the time sequenced 3-D models, visually illustrating plume movement and concentration reduction. Plume stability metrics were reported for each time step. In addition, the 3-D models could be rotated, varying the viewing angle for the site. An example of the 3-D visual for cis-1,2-dichloroethene is illustrated on Figure 9.

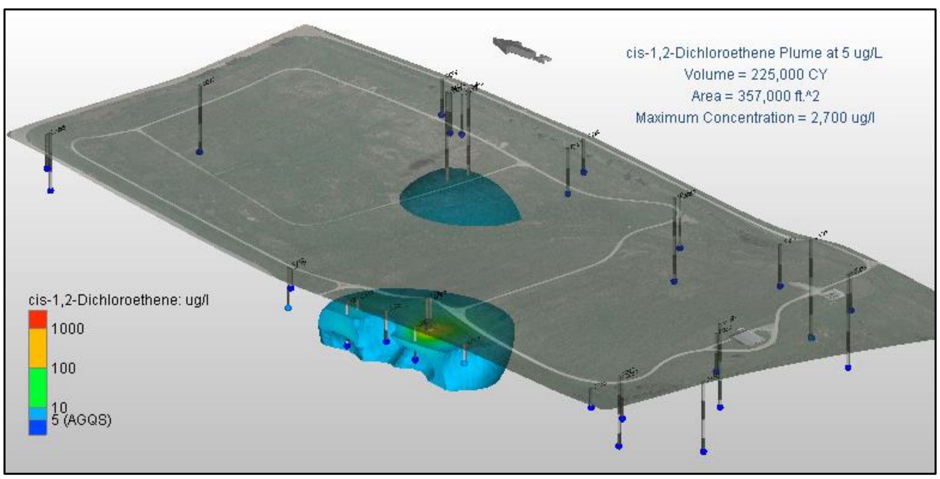


FIGURE 9. Three-Dimensional Visualization of cis-1,2-Dichloroethene Plume.

Plume stability analysis for the VOCs resulted generally in either decreasing trends or no significant trends for the spatial metrics (average and maximum concentration, plume area and plume volume). For CVOCS, the most prominent metric trends are seen for intermediate product cis-1,2-DCE, with decreasing trends of all spatial metrics observed during the previous five years. Daughter product vinyl chloride has generally inconclusive trends, but has a possible southward migration in 3-D mass. Results of the plume stability analysis are illustrated on Figure 10 for CVOC total volume.

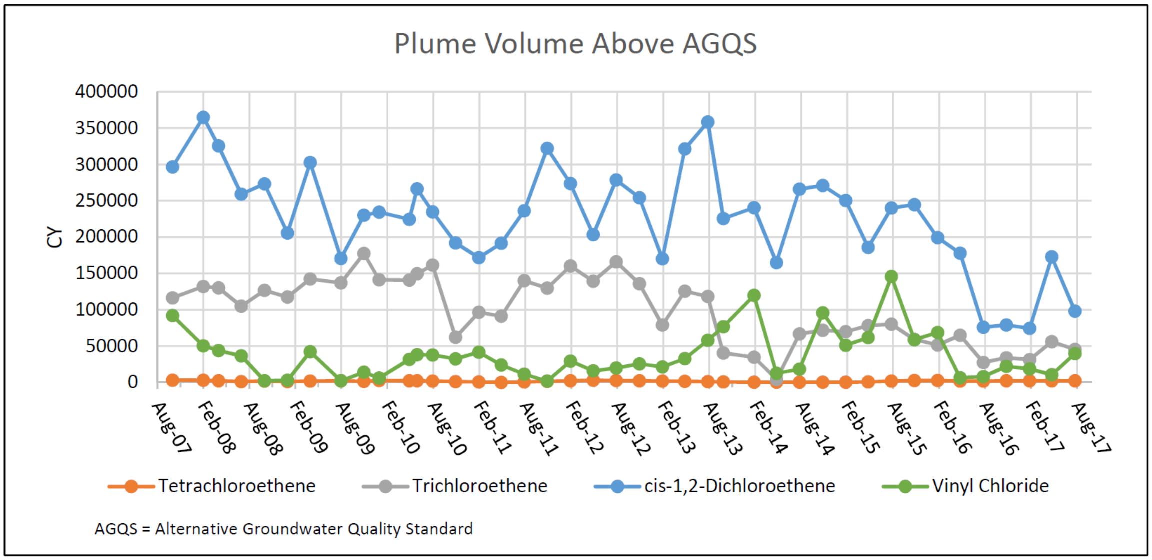


FIGURE 10. CVOC Plume Stability Trend of Total Volume.

The combined 3-D time sequenced visualizations and plume stability analysis provided a highly effective tool to stakeholders in communicating overall plume trends for the previous 10-year period along with the current plume conditions. As a result of the analysis, approval was received for eight wells which had initially been established to characterize organic impacts and are currently monitored quarterly to be moved to semi-annual sampling.

CONCLUSIONS

Quantitative monitoring optimization methods provide a rigorous platform to assess both insufficiency and redundancy in monitoring programs. Coupled with techniques of plume stability analysis and estimation of first-order attenuation, they are very effective in communicating plume trends and projecting future plume conditions. An extremely important component in communicating optimization and plume stability results is in the development of 3-D visualization tools. Interactive 3-D visualizations allow key stakeholders to easily conceptualize important aspects of current and projected site conditions, along with proposed monitoring changes.

While optimization methods are applicable during all project life-cycle stages (release detection, site characterization, remediation, monitoring and closure), they are particularly effective in LTM when reviewing programs initially designed during site characterization. LTM allows for an assessment of locations which may no longer be contributing significant information to the monitoring program.

A significant factor in the acceptance of proposed plan modifications is clear communication of optimization results and the methods of analysis utilized to reach conclusions. Visualization and easily understood metrics in combination with personal demonstration of key concepts accelerate this process.

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