Optimizing Long Term Monitoring at a BP Site Using Multi-Objective Optimization Software

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Other Project Participants

- **BP (formerly British Petroleum)**
  - Dennis Beckmann
- **Moiré, Inc.**
  - Peter Groves, Neil Kane, Tom Prudhomme
- **Delta Environmental Consultants, Inc.**
  - Jon Greetis
- **Meghna Babbar**
Outline

- Introduction and project objectives
- Site background
- Optimization process
- Results
- Conclusions
Introduction and Objective

- Long-term monitoring (LTM) costs can be substantial
- Optimization to eliminate data redundancies can help reduce costs
- Objectives:
  - Demonstrate how mathematical optimization can be used to reduce LTM costs by eliminating data redundancies.
  - Develop an optimized long-term groundwater-monitoring plan for a BP site in Michigan
    - Number and placement of monitoring wells.
Remedial Actions began in 1987 when a leaking pipeline gasket was discovered.

Catastrophic Release - estimates of the volume released are in the range of 350K gallons.

**Remediation History**

- **1987**: Remedial Actions began.
- **1989**: Groundwater Treatment / Product Skimming began.
- **1993**: Air Sparging started.
- **1993**: No LNAPL observed after 1993.
- **1999**: MNA (Maximum Net Allowable).

*118,000 gals of LNAPL recovered.*
Long-Term Monitoring Scenarios / Drivers

• Discontinuation of air sparging operation primarily based on:
  – Technical impracticability
  – Planned use of groundwater use restrictions

• Natural attenuation provides plume stability with institutional controls to address residual hydrocarbons in source area.

• 14 years of monitoring data to support plume stability assertion.
Long-Term Monitoring Scenarios / Drivers

- **MDEQ Response:**
  - MDEQ will require 30 years of post-closure monitoring
  - Costs could reach $400,000 over 30 years
- **Optimization can be used to reduce costs of monitoring by eliminating data redundancy.**
Redundancy Analyses

- **Spatial**
  - Wells that are spatially redundant provide information (usually on concentrations) that can be obtained from other nearby wells without substantially increasing errors

- **Temporal**
  - Temporal redundancy analyses identify reductions in monitoring frequencies based on redundant information from the same set of wells

- **Spatial Redundancy (BTEX) was evaluated in this case**
Define monitoring objectives and constraints

Create interpolation model using all data

Create “population” of candidate monitoring designs with different combinations of wells

Evaluate population using objectives and constraints

Apply genetic algorithm operations to create a new population

Repeat until population converges to optimal solution
Interpolation Modeling Process

- Identify key contaminants of concern (COC)
- Create spatial grid for interpolating COC concentrations
- Fit interpolation models
- Test interpolation model fit and choose model with best performance
Interpolation Model Evaluation

• To test interpolation model, use cross-validation
  – Eliminate data from well 1
  – Interpolate concentration at well 1 from data at all other wells
  – Compare interpolated concentration with measured concentration
  – Repeat for all other wells
Interpolation Modeling Results Summary

- A suite of interpolation approaches were tested
  - Ordinary kriging
  - Quantile kriging
  - Inverse distance weighting
  - Neural network for detrending in time, with quantile kriging for residual - historical data

- Quantile kriging performed best of first 3 approaches, with variograms fit to each BTEX constituent and then summed

- Detrending using historical data provided small increase in accuracy, but very large computational time increase
Interpolation Modeling Results Summary (cont’d.)

- Of the 36 wells, the following numbers of wells were predicted sufficiently accurately during cross-validation:
  - Benzene: 17 (within 5 ppb)
  - Toluene: 32 (within 100 ppb)
  - EthylBenzene: 28 (within 100 ppb)
  - Xylene: 23 (within 100 ppb)
  - BTEX: 19 (within 100 ppb)
- Benzene performs quite well, but has a much stricter acceptability threshold.
- Summing the predictions of the components of BTEX gives a small boost in accuracy over predicting it directly.
Cross-Validation Results for BTEX (summed from constituents)

Interpolation ID (Well ID) sorted by true concentration
Optimization Process

- **Create Optimization Formulation**
  - Decision Variables
  - Objective Functions
  - Constraints (none for this site)

- **Use genetic algorithms to search for monitoring designs that best meet the objective functions and constraints**
  - When more than one objective exists, find optimal tradeoffs among objectives (e.g., cost vs. errors)
Decision Variables for This Site

\[ x_i = \begin{cases} 
1 & \text{if well } i \text{ is sampled} \\
0 & \text{otherwise} 
\end{cases} \]

Optimization problem is to identify values of the \( x_i \), for \( i = 1 \) to 36 wells

\[ 2^{36} = 7 \times 10^{10} \text{ possible sampling plan designs} \]
Objective Functions for This Site

• Minimize Cost (no. of wells):

\[ \text{Minimize } \sum_{i=1}^{n} x_i \]

• Minimize maximum error between actual concentrations and those estimated with subset of K wells:

\[ \text{Minimize } \max_{K} \left\{ \text{Error} = \left| c_i^{\text{actual}} - c_i^{\text{est}(K)} \right| \right\} \]
Error Objective Functions for This Site

- **One error objective for benzene and one for BTEX**
  - Scaled by maximum acceptable error (5 ppb for benzene, 100 ppb for BTEX)

- **Locations for measuring error are important**
  - At monitoring well locations only
  - Other locations in the interpolation grid have no data support, so could only compare predictions with modeled values that have errors themselves
M-LTMO Software

- Optimization process was implemented in Multi-objective Long Term Monitoring Optimizer Software (M-LTMO) developed at University of Illinois and Moire
  - Automated interpolation model fitting and selection
  - Multiobjective optimization to find monitoring designs that best meet objectives

- For more information and a demonstration of the software, come to the Long-Term Monitoring Optimization Methods and Software Workshop Wednesday evening from 6:30-9 PM
Optimal Tradeoffs Between Errors and Sampling Levels

- Benzene
- BTEX
Benzene Concentrations for 30-Well Design

30-Well Predictions

All-Well Predictions

+ = locations that are not sampled
O = locations that are sampled
BTEX Concentrations for 30-Well Design

30-Well Predictions

All-Well Predictions

+ = locations that are not sampled
O = locations that are sampled
Benzene Concentrations for 28-Well Design

28-Well Predictions

All-Well Predictions

+ = locations that are not sampled
O = locations that are sampled
BTEX Concentrations for 28-Well Design

28-Well Predictions

All-Well Predictions

+ = locations that are not sampled
O = locations that are sampled
BTEX Cross-Validation Comparisons

![Graph showing BTEX cross-validation comparisons for different well designs. The y-axis represents the actual-predicted differences in parts per billion (ppb), while the x-axis represents the well ID numbers. The graph compares all 36 wells, 28-well design, and 30-well design.](attachment:graph.png)
Optimization Findings

• Found good predictions at all well locations using 28-30 wells
  – 17 to 22% reduction in sampling costs possible
• 28-well solution has more difficulty interpolating correctly in the southeast corner, although this area is of much less concern than the leading edge of the plume
• M-LTMO software is useful tool for identifying data redundancies
• Further testing at a New Jersey terminal site with more wells is underway