An Efficient Reliability-Based Approach to Aquifer Remediation Design

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EPA Region 5 STAR Seminar
July 14, 2004
Acknowledgements

• U.S. Environmental Protection Agency (EPA) STAR Program through Grant R 827126-01-0
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Motivating Problem

• Design of remedial strategies for contaminated soil and groundwater
  – Uncertainties in site conditions
  – Variety remedial options
  – Desire to quantify design process
Challenges

Given a contaminated site and proposed remedial activities:

– Geology of subsurface may be complex
– Small volume of soil at a site is sampled
– Parameters of interest may vary over large ranges
– Contaminants may have complex interactions with soil and native ground water
– Clean-up schemes impose different hydrologic, chemical, or biological conditions or constraints
Example Cone Penetrometer (CPT) log

CPT has an area of 10 cm$^2$, but continuity of this layer across the site is important.
Heterogeneity at different scales
Reaction to Uncertainty

• Over design - leads to increased costs without improving performance
Reaction to Uncertainty

- **Over design** - leads to increased costs without improving performance

- **Over sampling** - increased cost without changing design
Site Characterization

• Are there sufficient data to base the design?

• What data are required and where should these data be collected to increase confidence in the design?
Approach

• Combine design model and geostatistical description of geologic setting to estimate design uncertainty
• Use design uncertainty to guide exploration
• Contrast with sampling based on budget or regulatory constraints
Hydrologic Decision Framework
(Freeze et al., 1990)

- Field Investigation Program
- Geological Uncertainty Model
- Parameter Uncertainty Model
- Design Model
- Engineering Reliability Model
- Decision Model

Hydrologic Decision Framework (Freeze et al., 1990)
Field Investigation Program

Geological Uncertainty Model

Parameter Uncertainty Model

Design Model

Engineering Reliability Model

Decision Model
Performance Evaluation

Evaluation of Design and Performance Reliability

First-Order Second Moment (FOSM)

Reliability Index, $\beta$ Analysis

Sensitivity Equation Sensitivities

Sensitivity Analysis

Finite Element/ MODFLOW-2000

Performance Uncertainty

Bayesian Condition Calculation

Design Model

Input Model

Design and Data

Input parameter model

Design & Data Sampling

Performance Model

Performance Uncertainty

$\sigma$

$\mu$

$P$

$\sigma$

$\mu$

$\beta$

Input parameter model

$\sigma$

$\mu$
Input Component

- Bayesian approach to condition input vector, $u$, to observation vector, $v$

  \[
  E[u|v] = E[u] + \text{Cov}(v,u) \text{Cov}(v)^{-1} (v - E[v])
  \]

  \[
  \text{Cov}(u|v) = \text{Cov}(u) - \text{Cov}(v,u) \text{Cov}(v)^{-1} \text{Cov}(u,v)
  \]

- Variance of $u$ is the diagonal of $\text{C}(u|v)$ matrix

- Can reduce to kriging estimate of $E[u|v]$ with appropriate priors for $E[u]$ and $\text{Cov}(u)$
First-Order Second-Moment

\[ E[C] \approx g( E[u|v] ) \]

\[ \text{Cov}(C(t_1), C(t_2)) \approx J_u(t_0, t_1) \text{Cov}(u|v) J_u^T(t_0, t_2) \]

- \( E[C] \): expected value for concentration
- \( g() \): design model
- \( u \): vector of uncertain input parameters
- \( J_u = [\partial C_i / \partial u_j] \)
- \( \text{Cov}(.,.) \): covariance matrix describing uncertainty in input parameters
Performance Evaluation

\[ N(C, \sigma_c) \]

Probability of Success

\[ \sigma_c \]

C

Ca
• Point reliability may be determined

\[ \beta = \frac{C_a - C}{\sigma_c} \]

• \( \sigma_c \) - the standard deviation of \( C = \) Square root of the variance of \( C \)

• Uncertainty in site input and model performance are combined in \( C \)
Case 1
Case 2

$E[C]_2$  $E[C]_1$

Performance Goal

Probability of Failure for Case 1
Probability of Failure for Case 2

Performance Evaluation

P
Goal
m

Case 1

- Case 2

$\sigma_1$

$\sigma_2$

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3-D Transport Simulation

Hypothetical Model

- Sampling location
- Proposed pumping well
- Compliance point

K : conductivity (m/day), n : porosity
3-D Transport Simulation

Model Conditions and parameter description

Steady state flow and transient transport

- Uncertain input parameter -
  Geologic interface elevations : 4 samples
  First-order decay rate : 0.02 /day ± 0.005

- Design parameter -
  Design I : No pumping well (Natural Attenuation)
  Design II : Single pumping well
  (Proposed pumping rate : 300 m$^3$/day)

- Output parameter -
  Clean-up goal at compliance point : $10^{-3}$ mg/L
Performance Model

Design I
No Pumping Well

Design II
Single Pumping Well

Aquifer boundaries

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Design I
No Pumping Well

Design II
Single Pumping Well

Performance Uncertainty

\( \sigma \)

Total Variance

Variance from Interface uncertainty

Variance from First-order Decay rate uncertainty

(mg²/L²)

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Reliability index indicates which design is more reliable.
Reliability index can be used to estimate probability of success

Design I

Design II

Performance Evaluation

Goal

P

σ

m

\[ \Phi(\beta) \times 100 \% \]

\[ 65.4521 \]

\[ 54.3061 \]

\[ 99.9996 \]

\[ 100.0000 \]

\[ 99.6825 \]

\[ 100.0000 \]

Time (days)

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Will directed sampling give more confidence to the remedial design?

For Design I: No pumping well (Natural Attenuation)
For Design I: No pumping well (Natural Attenuation)

Performance Evaluation

- directed sampling
- ad hoc sampling

Number of samples

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For Design II: Single pumping well

4 Sample

6 Sample

Additional Sampling

Input parameter model

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Additional sampling reduces the concentration uncertainty

For Design II: Single pumping well
For Design II: Single pumping well

Graph showing the relationship between the number of samples and the performance evaluation.

Number of samples

\( \Phi(\beta) \times 100 \) (%)
Future Work

• Approach incorporated with other design models (Dowding - NU, Graettinger - UA)
• Incorporate use of geophysical data for input (Lee - UMKC)
• Incorporate techniques into comprehensive modeling approach that includes model calibration and other uncertainty issues (Reeves - USGS)
• Test with field data and designs (All)
Bibliography (STAR + Related)


Thank you

This research is funded by
U.S. EPA - Science To Achieve Results (STAR) Program
Grant # R 827126-01-0

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