

US EPA ARCHIVE DOCUMENT

An Efficient Reliability-Based Approach to Aquifer Remediation Design

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- Department of Civil Engineering, Northwestern University
- Co-PIs: C.H. Dowding (Northwestern University) and T. Igusa (Johns Hopkins University)
- Colleagues and students: A.J. Graettinger (University of Alabama), J. Lee (University of Missouri-Kansas City), M.D. Fortney (Law School at Northwestern U.), D. Dethan (ERM Consulting)

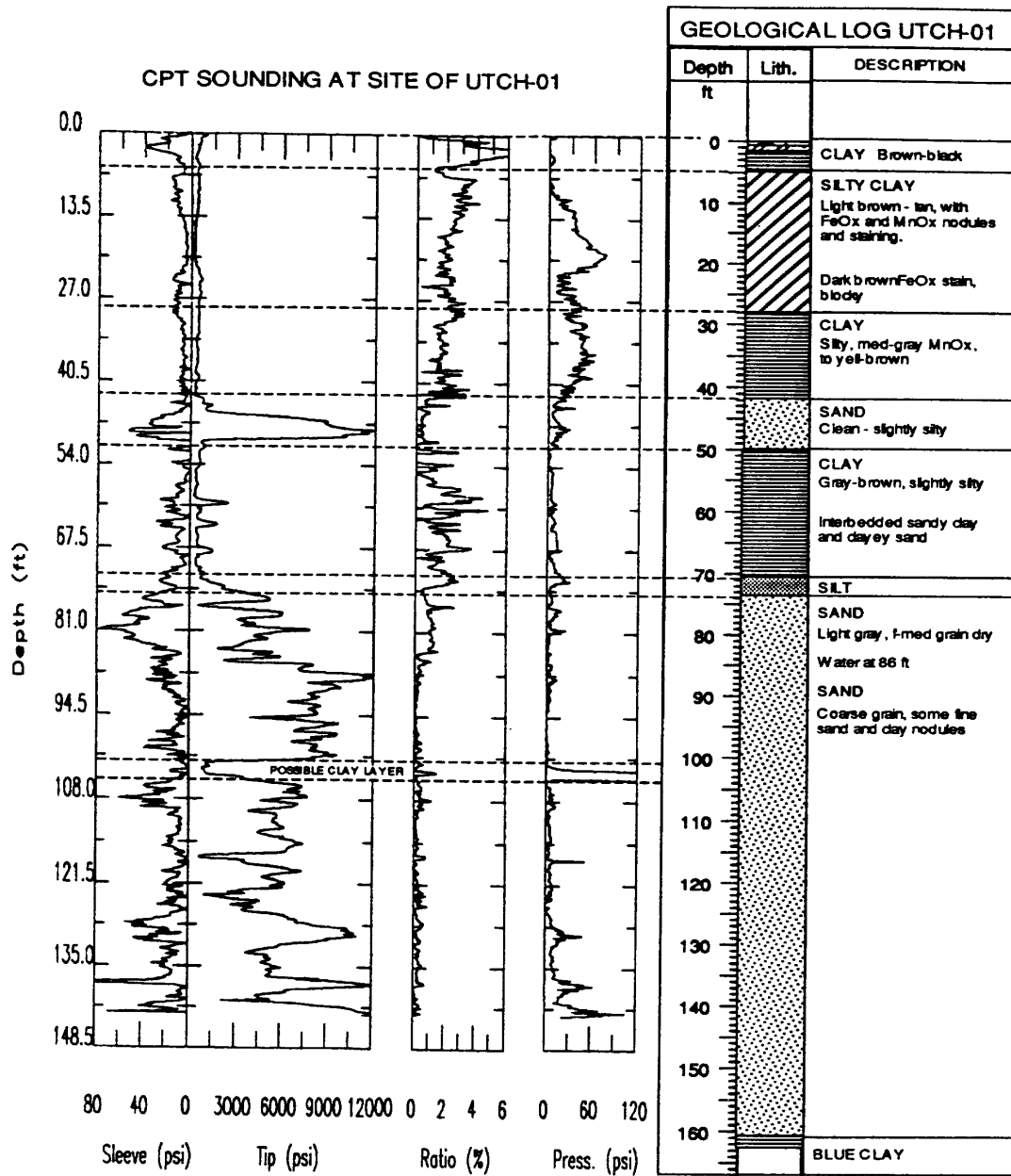
Motivating Problem

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

Challenges

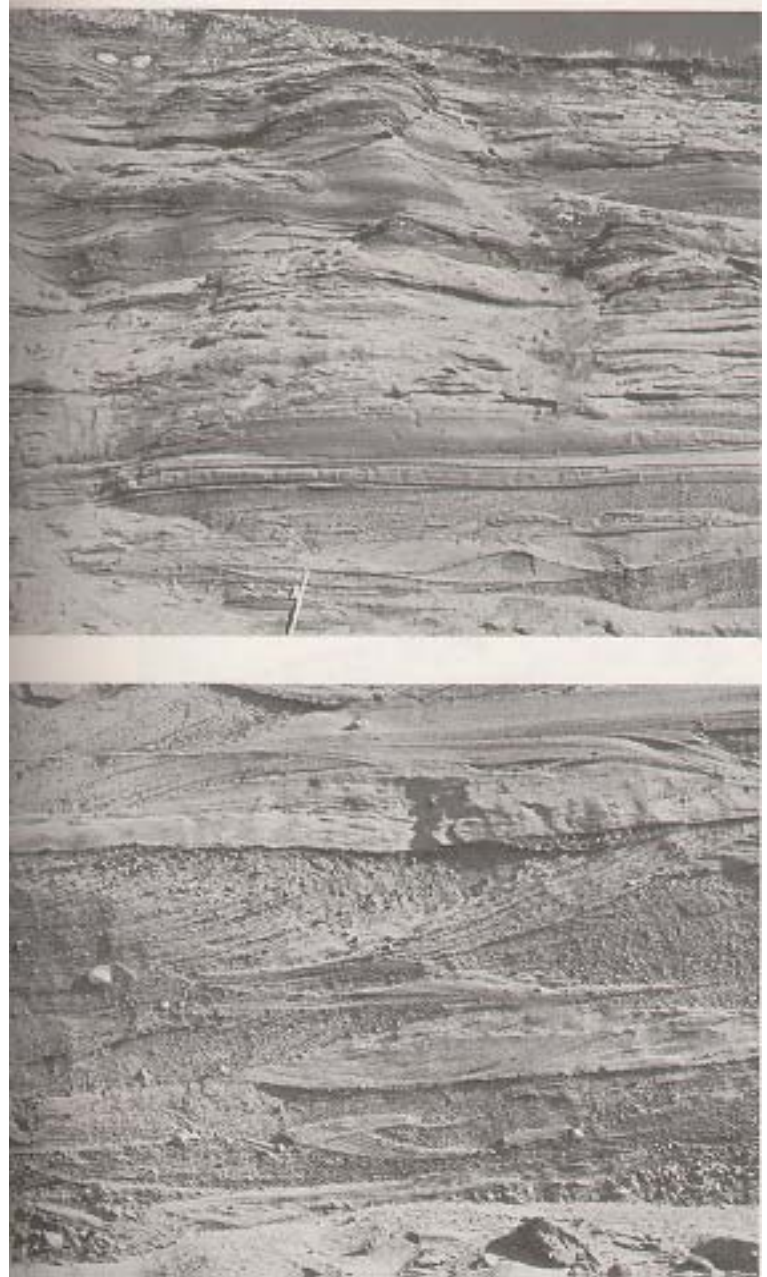
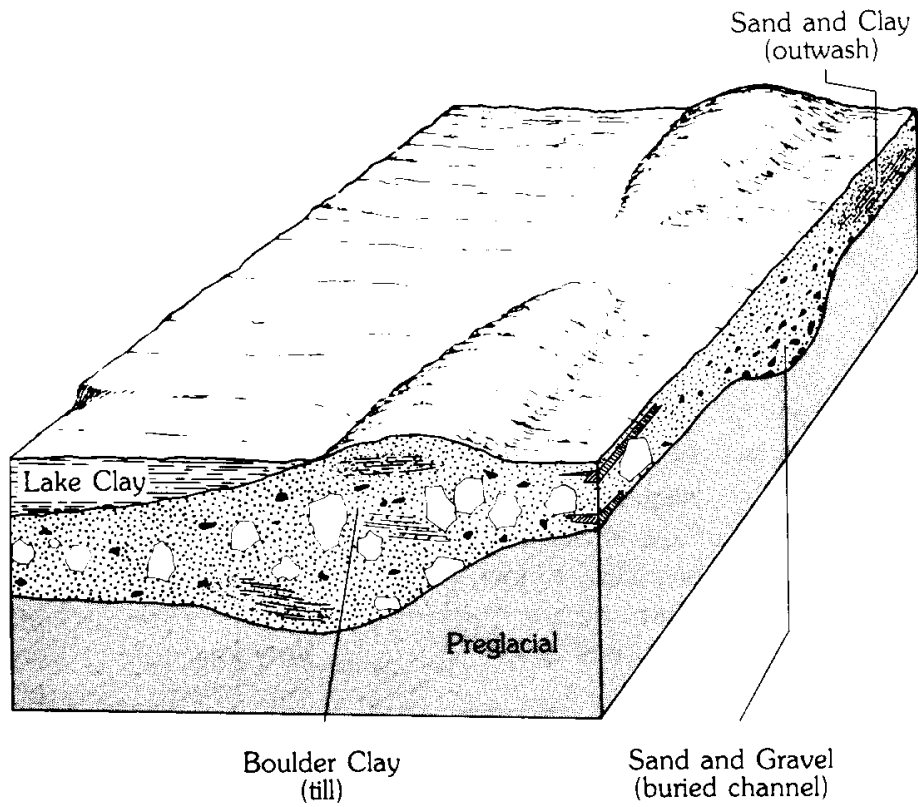
Given a contaminated site and proposed remedial activities:

- 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 cm², 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

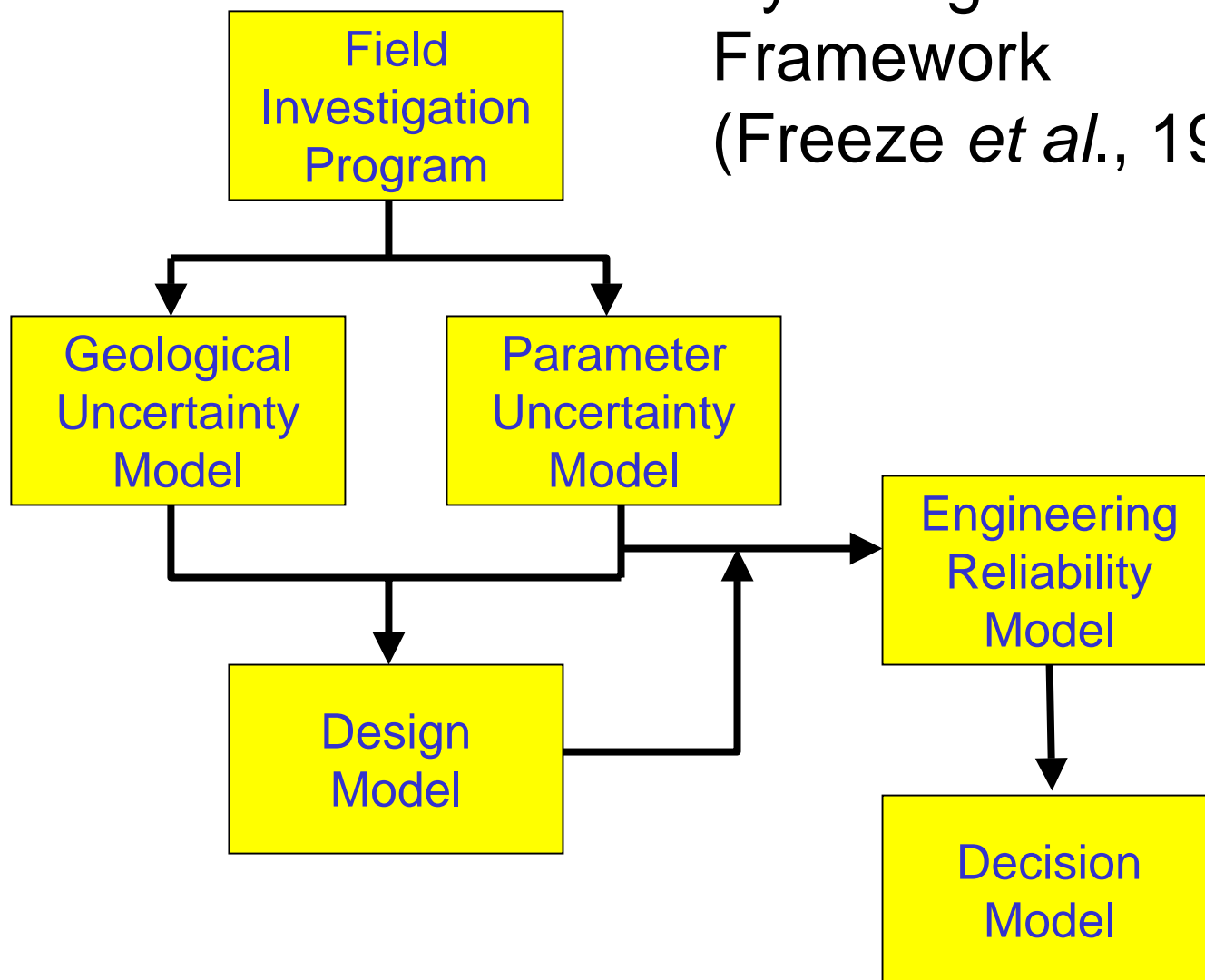
Site Characterization

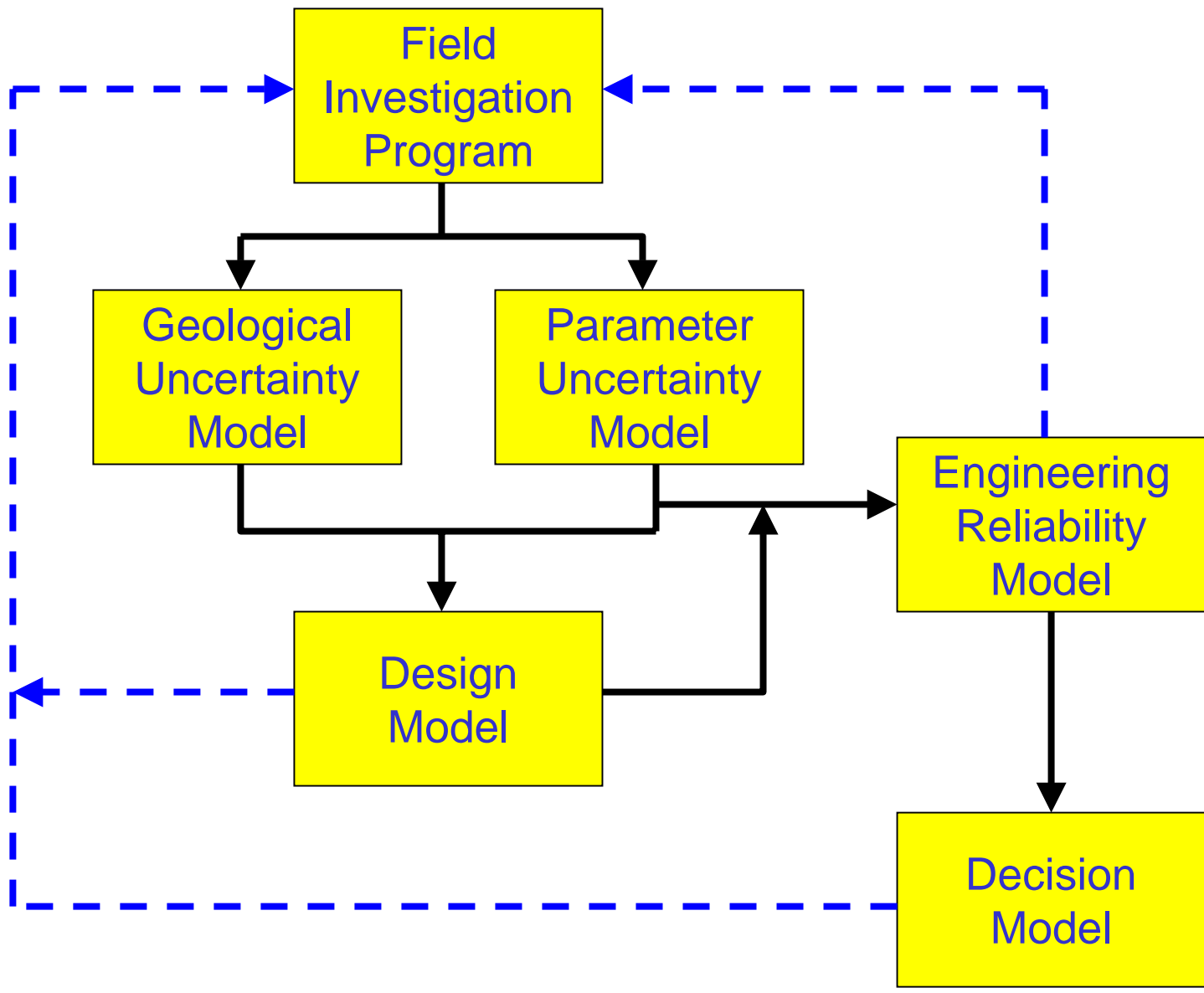
- Are there sufficient data to base the design?
- What data are required and where should these data be collected to increase confidence in the design?

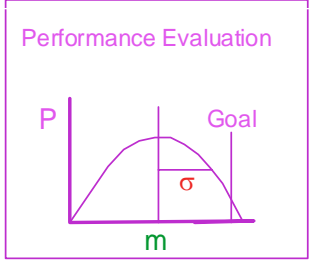
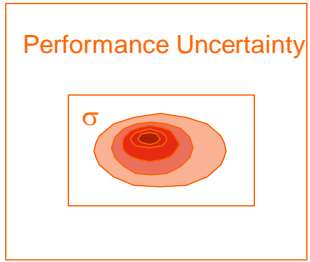
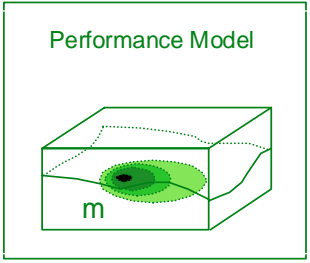
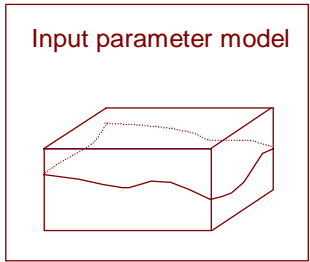
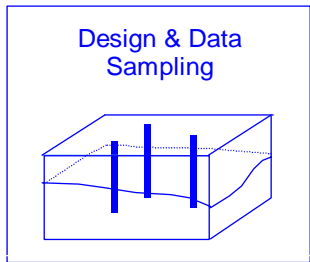
Approach

- 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)







Design and Data

Input Model

Design Model

Performance Uncertainty

Evaluation of Design and Performance Reliability

Bayesian Condition Calculation

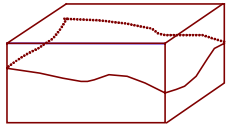
Finite Element/
MODFLOW-2000

First-Order Second Moment (FOSM)

Reliability Index, β Analysis

Sensitivity Analysis

Sensitivity-Equation Sensitivities



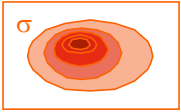
Input Component

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



First-Order Second-Moment

$$E[C] \cong g(E[u|v])$$

$$\text{Cov}(C(t_1), C(t_2)) \cong J_u(t_0, t_1) \text{Cov}(u|v) J_u^T(t_0, t_2)$$

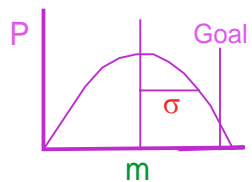
$E[C]$ = expected value for concentration

$g()$ = design model

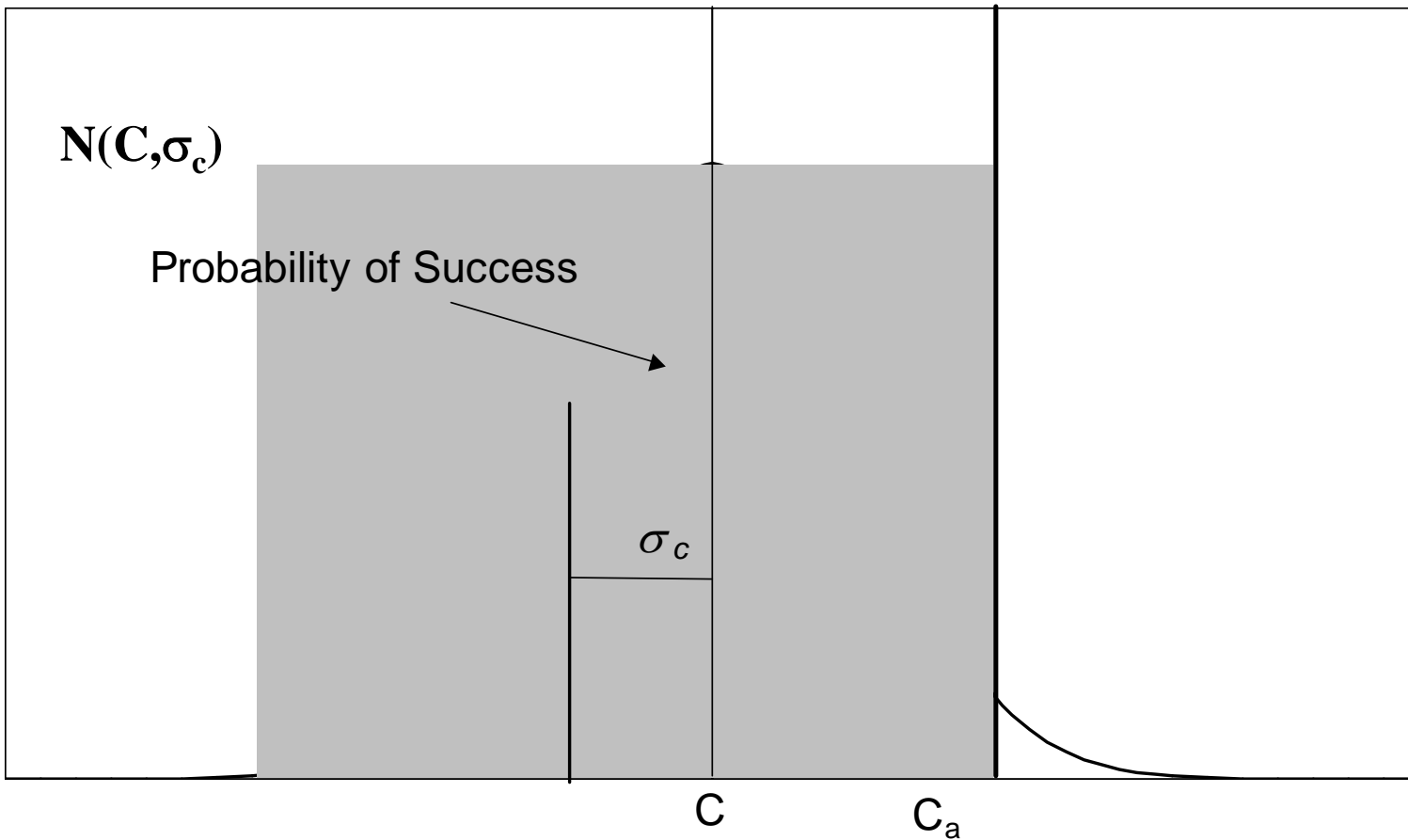
u = vector of uncertain input parameters

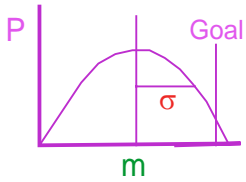
$$J_u = [\partial C_i / \partial u_j]$$

$\text{Cov}(.,.)$ = covariance matrix describing uncertainty in input parameters



Performance Evaluation





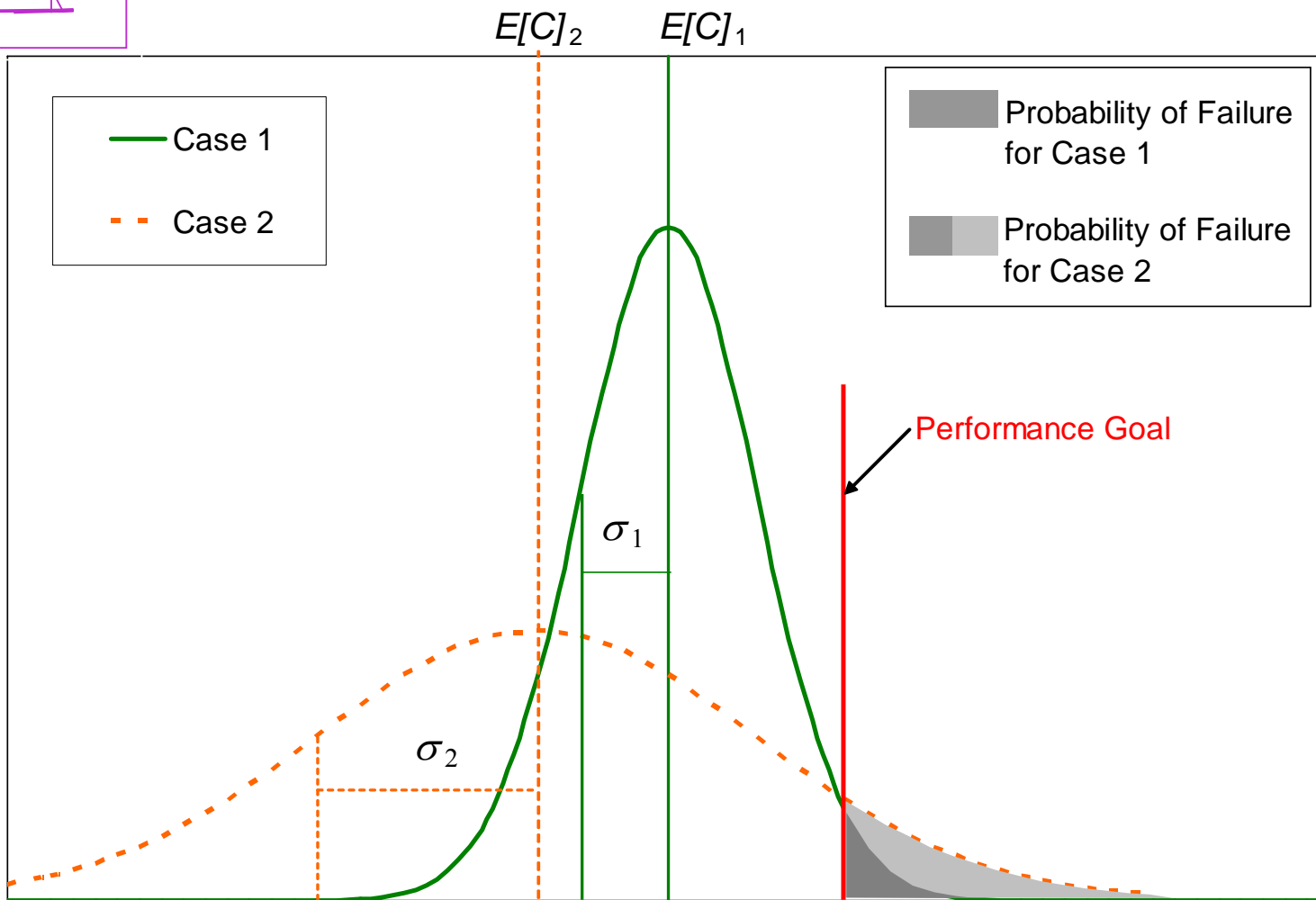
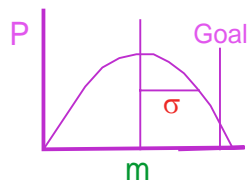
Reliability Index

- Point reliability may be determined

$$\beta = \frac{C_a - C}{\sigma_c}$$

- σ_c - the standard deviation of C = Square root of the variance of C
- Uncertainty in site input and model performance are combined in C

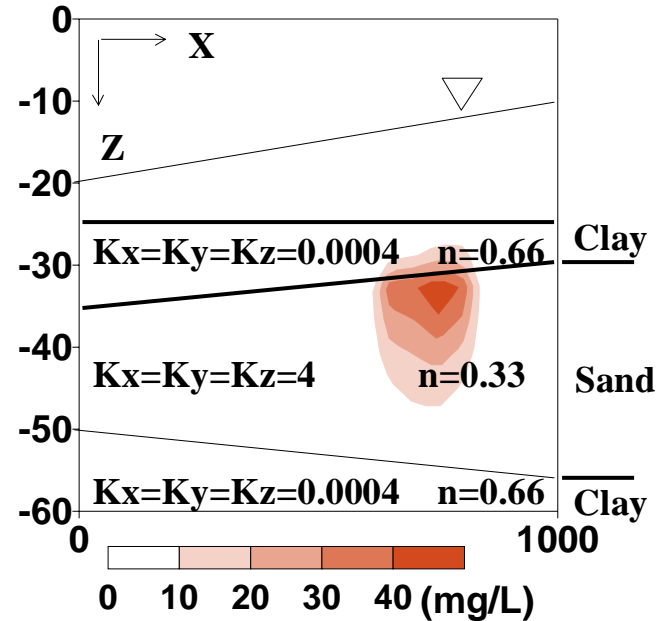
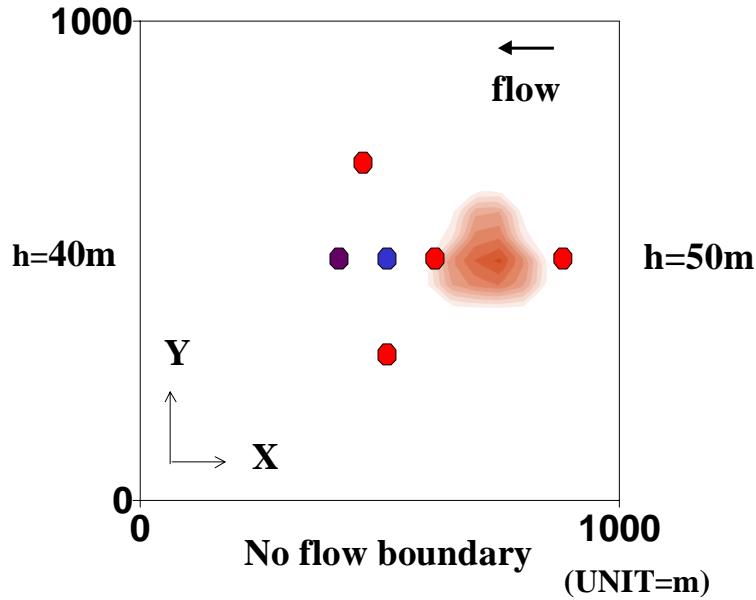
Performance Evaluation



3-D Transport Simulation

Hypothetical Model

No flow boundary



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 : $0.02 \text{ /day} \pm 0.005$

- Design parameter -

Design I : No pumping well (Natural Attenuation)

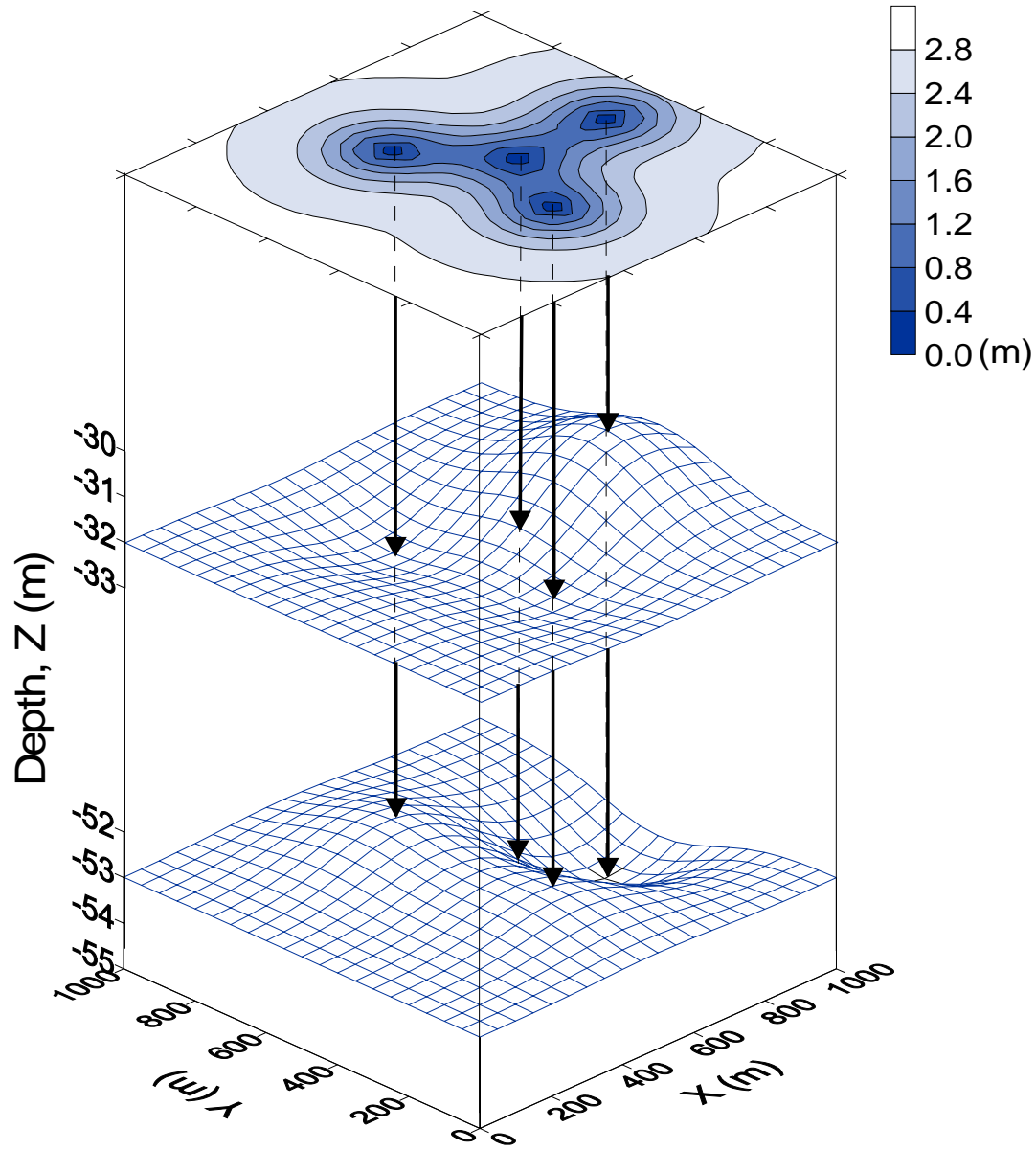
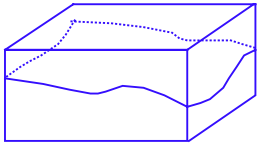
Design II : Single pumping well

(Proposed pumping rate : $300 \text{ m}^3\text{/day}$)

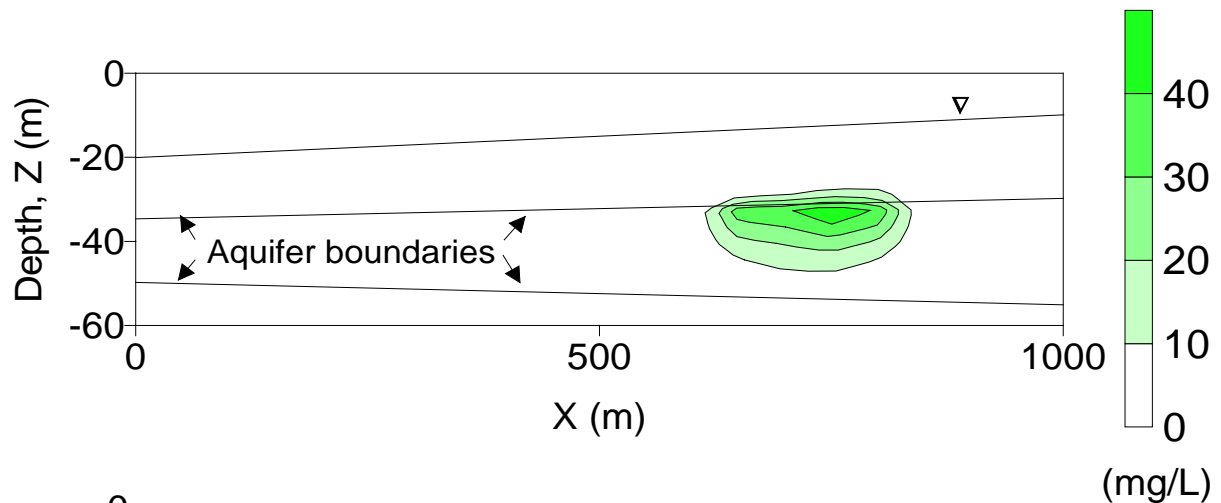
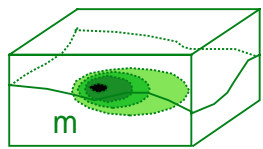
- Output parameter -

Clean-up goal at compliance point : 10^{-3} mg/L

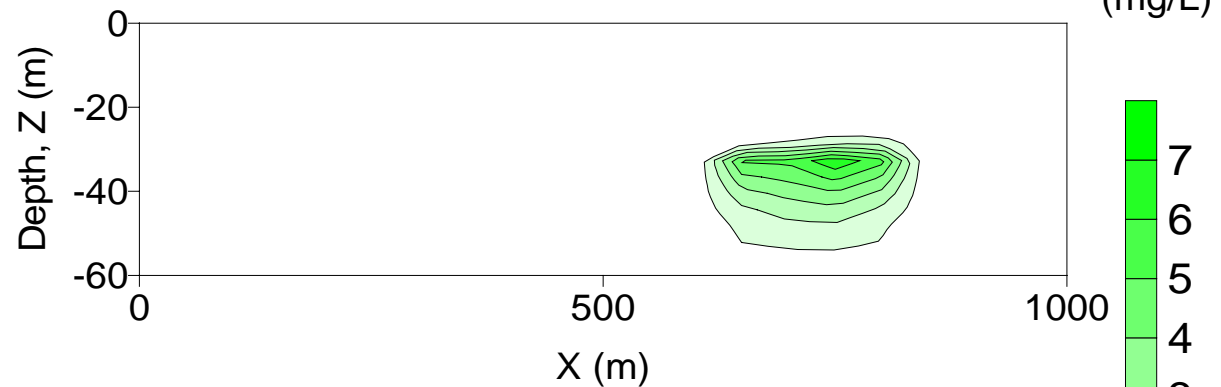
Input parameter model



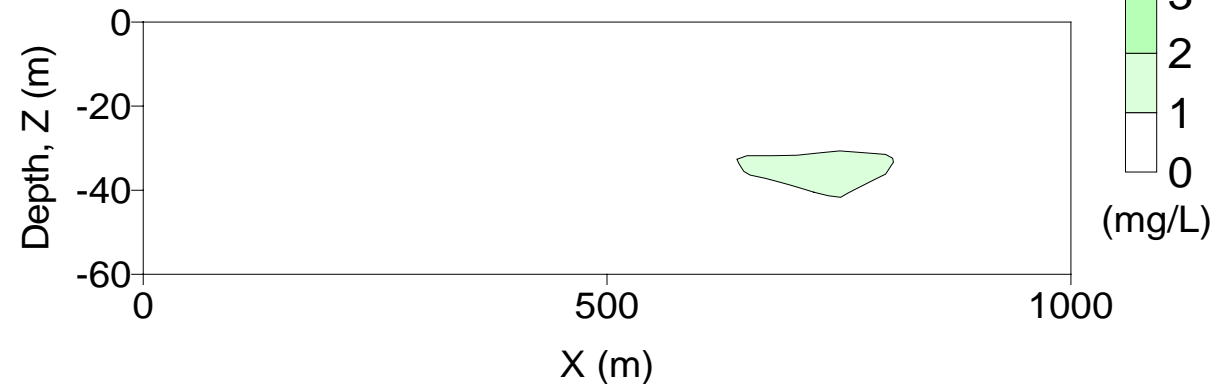
Performance Model

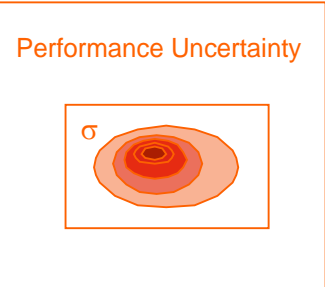


Design I
No Pumping Well

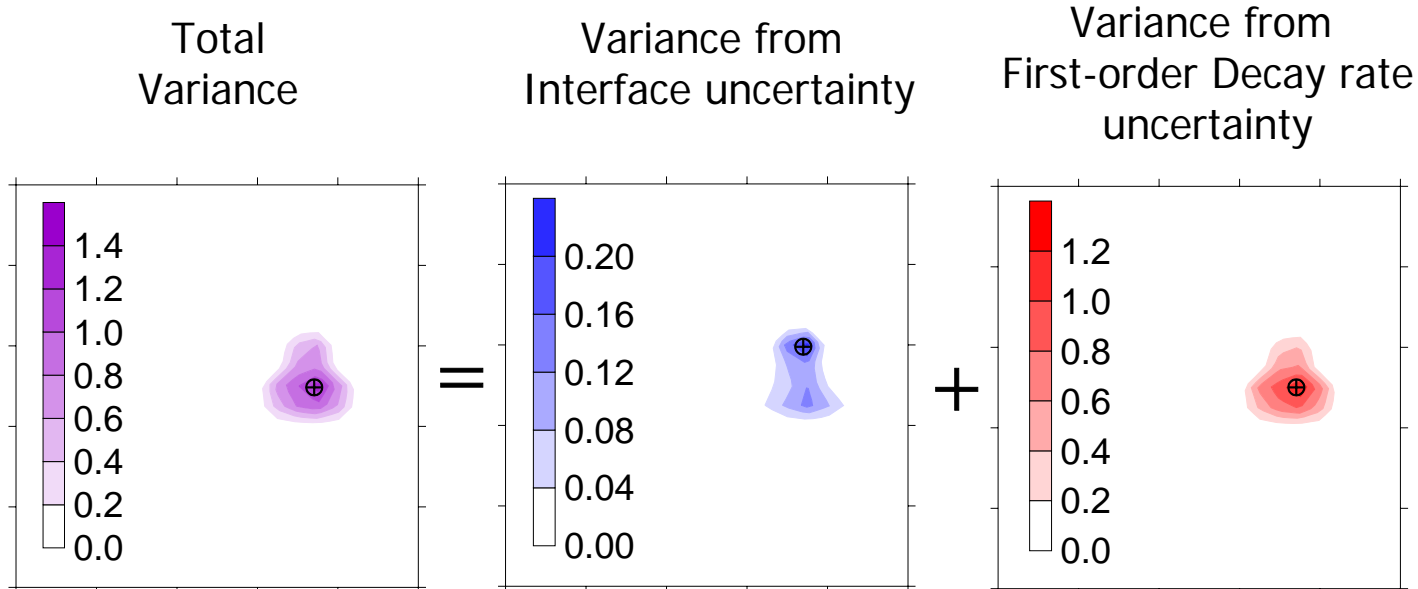


Design II
Single Pumping Well



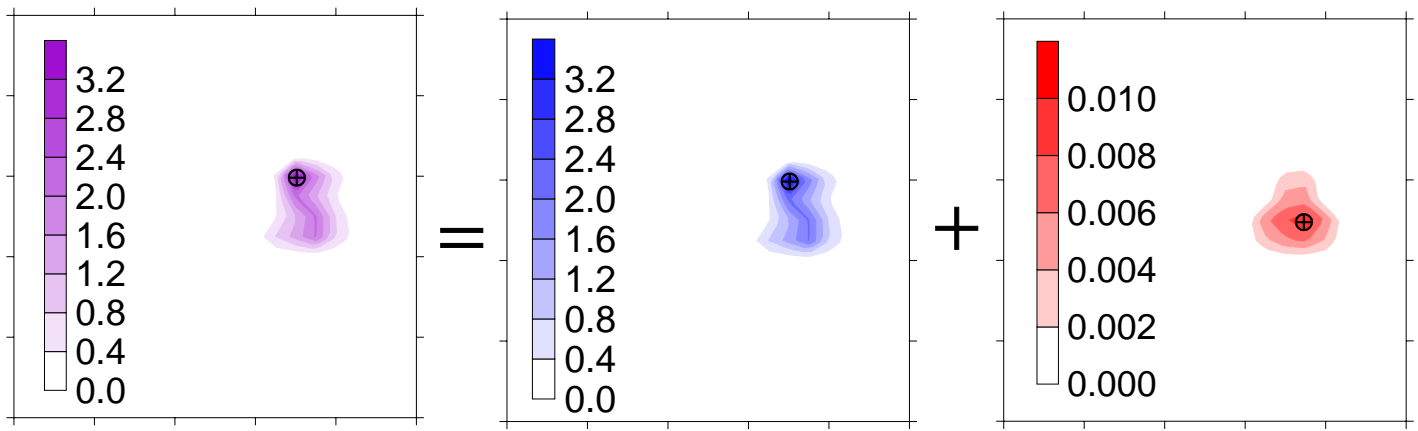


Design I
No Pumping Well

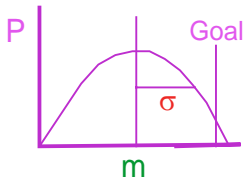


(mg²/L²)

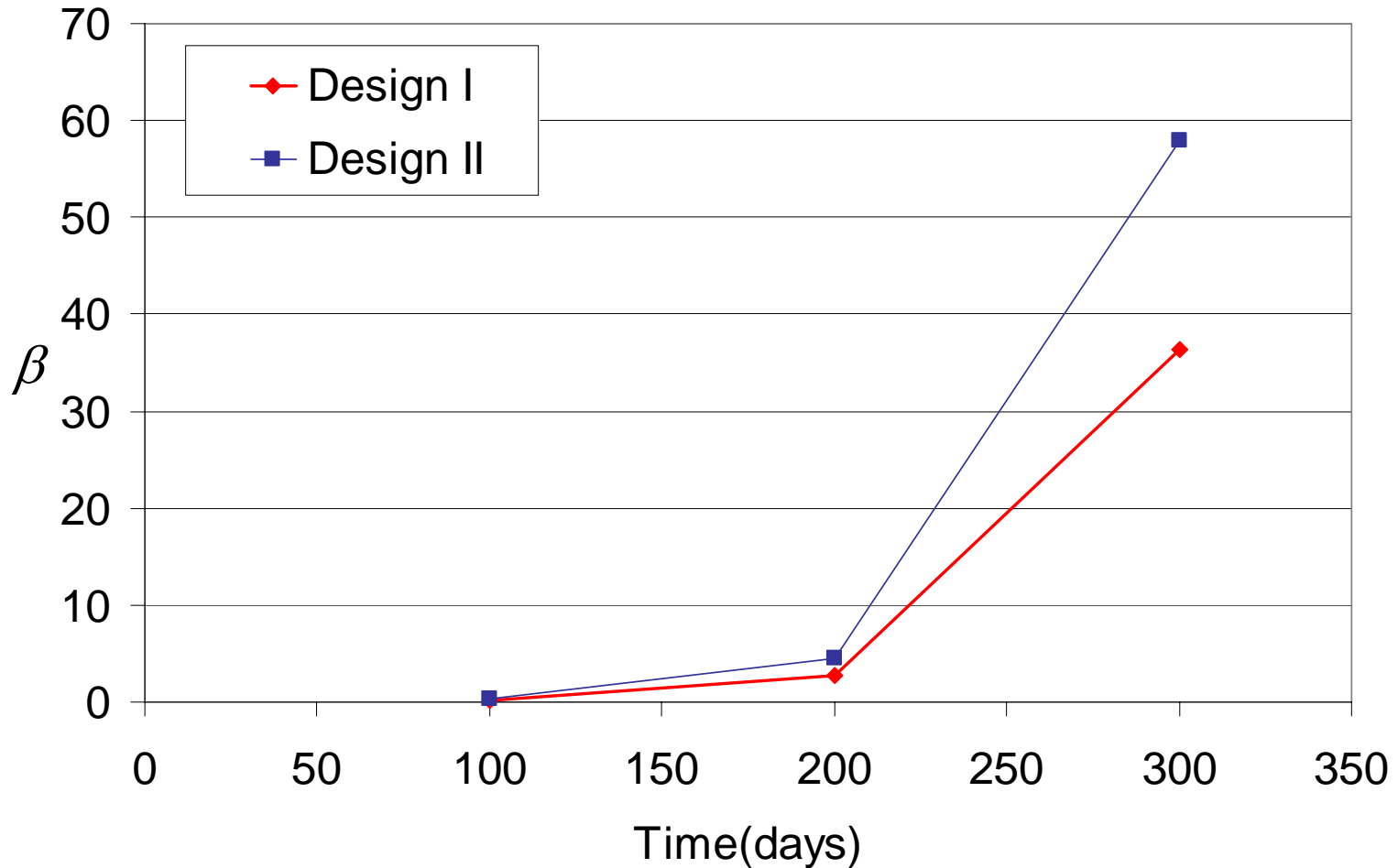
Design II
Single Pumping Well



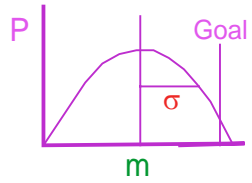
Performance Evaluation



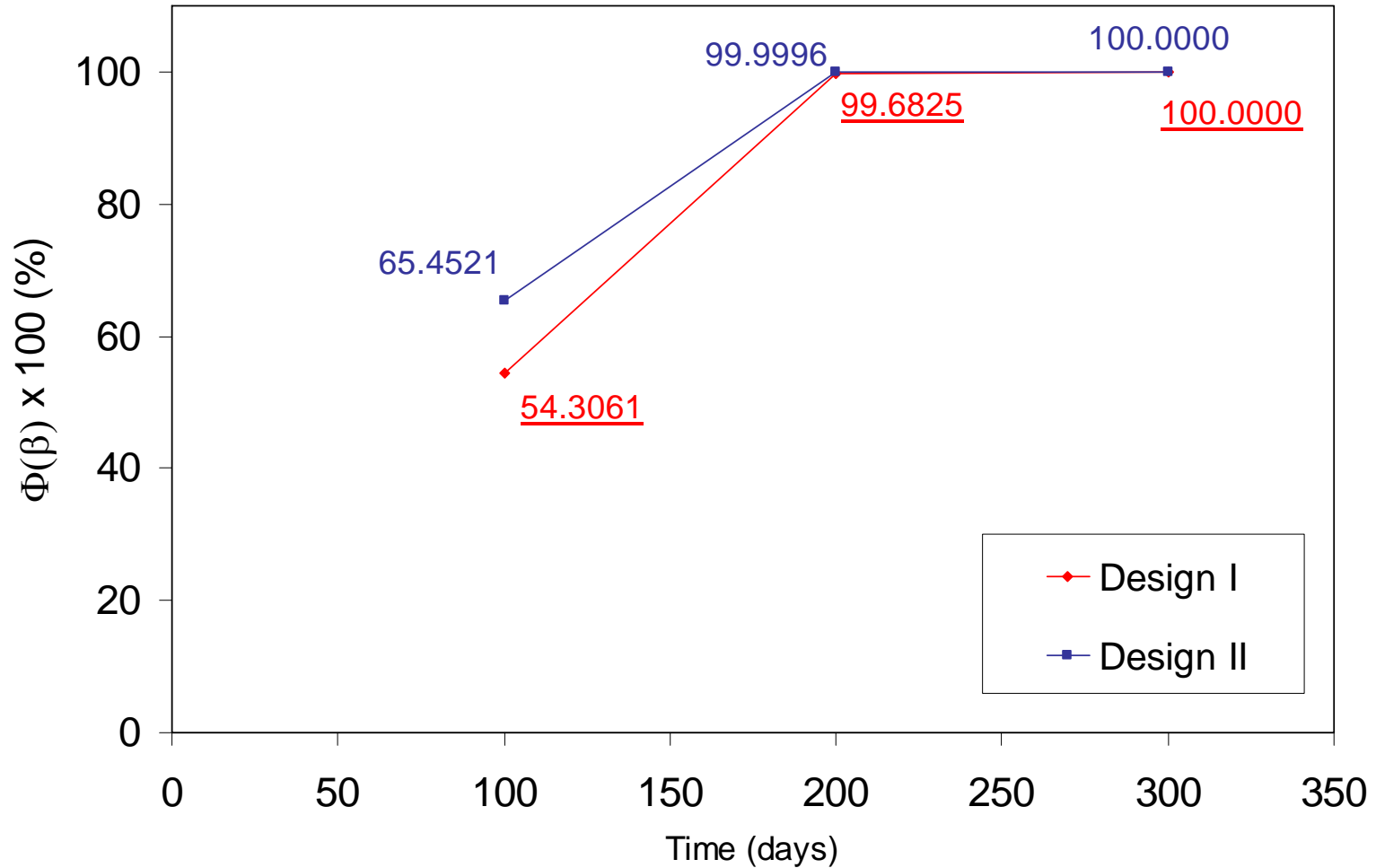
Reliability index indicates which design is more reliable

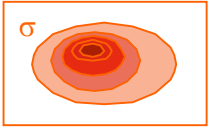


Performance Evaluation



Reliability index can be used to estimate probability of success

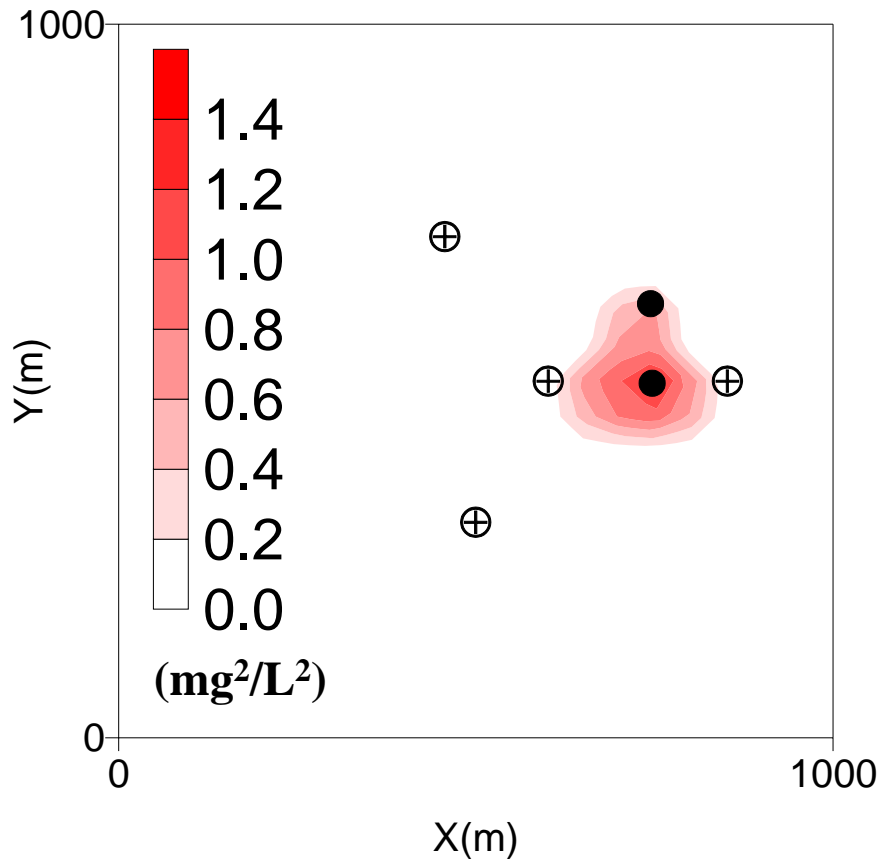




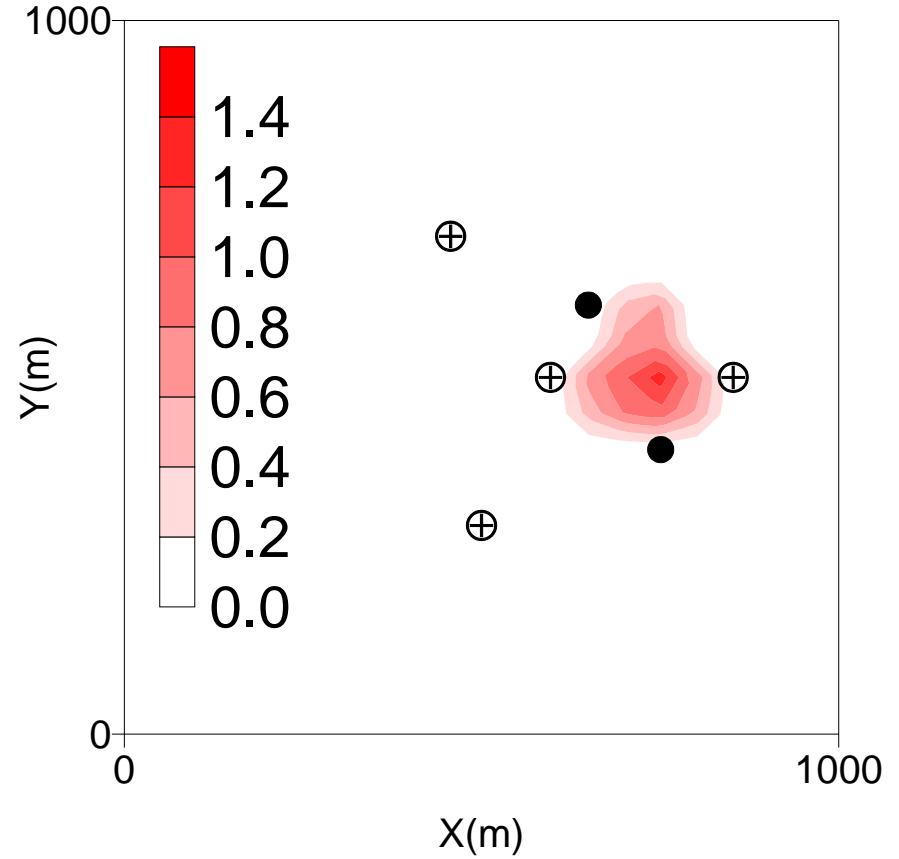
Will directed sampling give more confidence to the remedial design?

For Design I : No pumping well (Natural Attenuation)

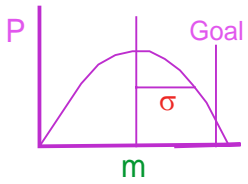
Directed Sampling



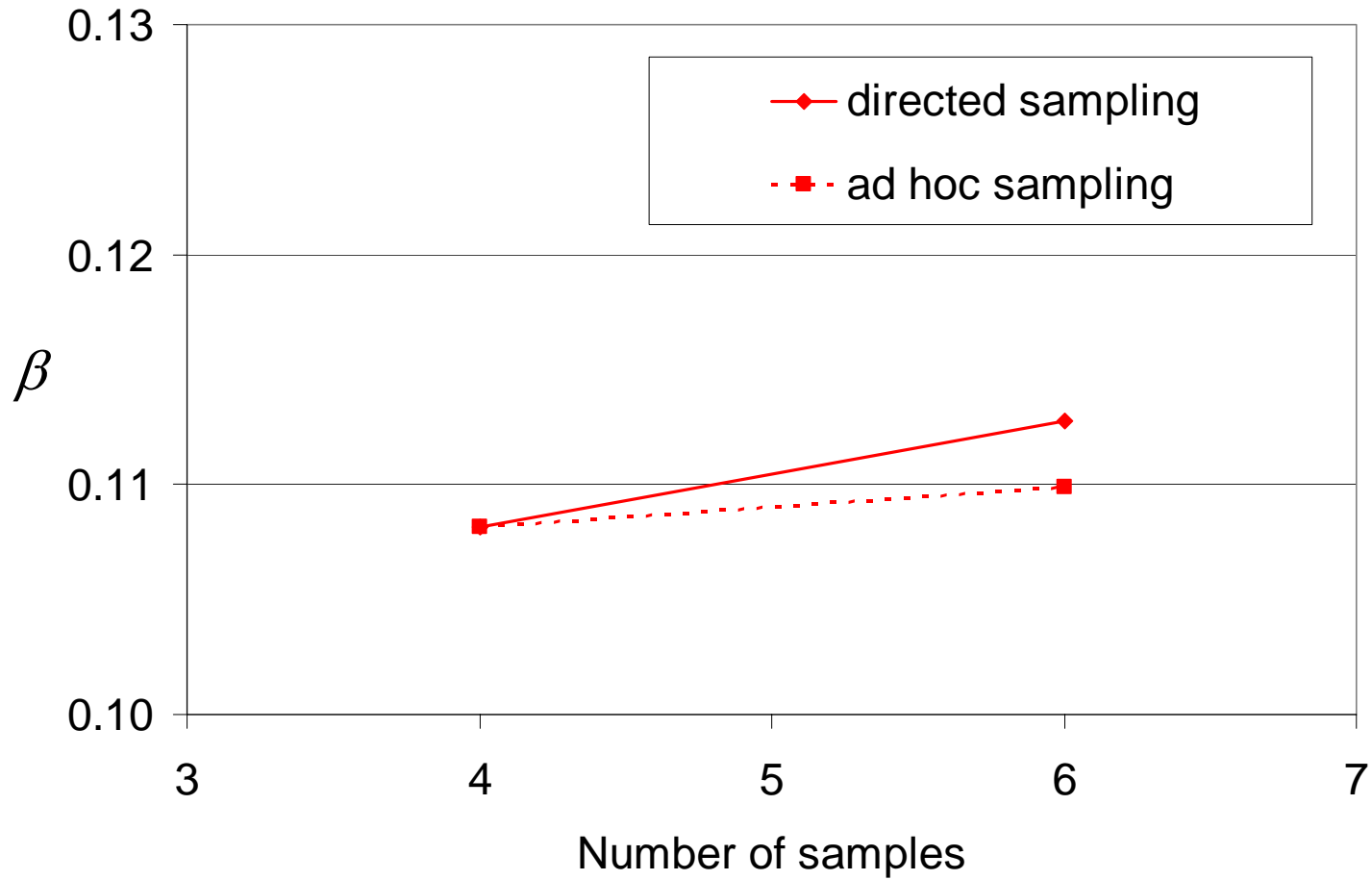
Ad hoc Sampling



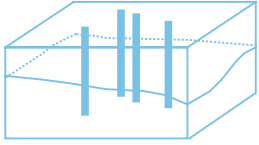
Performance Evaluation



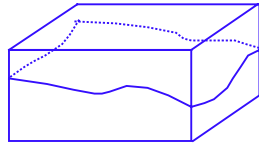
For Design I : No pumping well (Natural Attenuation)



Additional Sampling



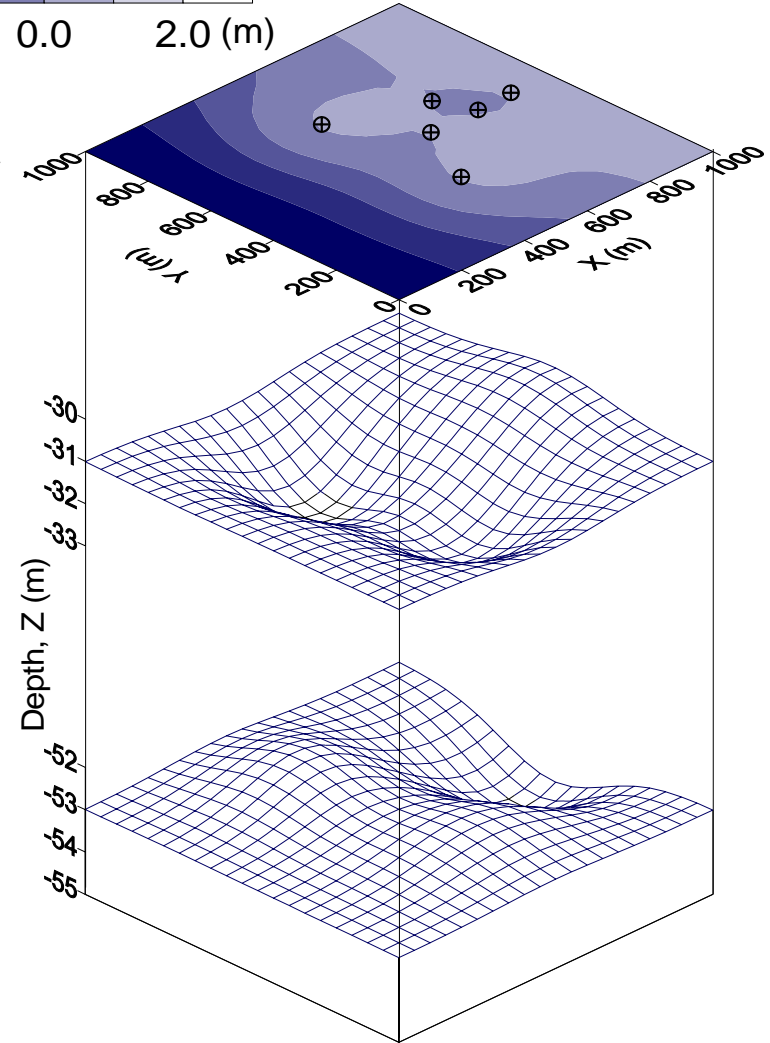
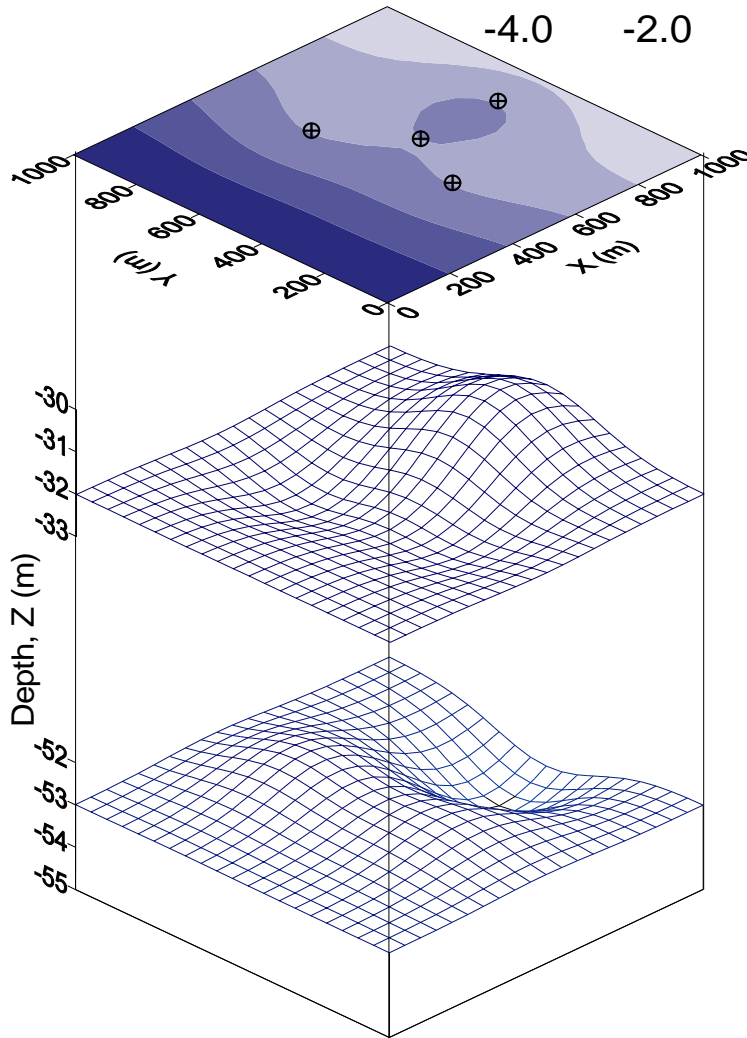
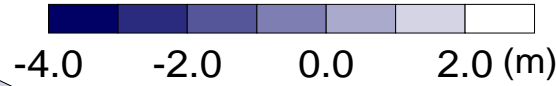
Input parameter model



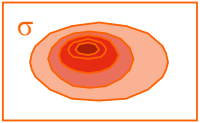
For Design II : Single pumping well

4 Sample

6 Sample



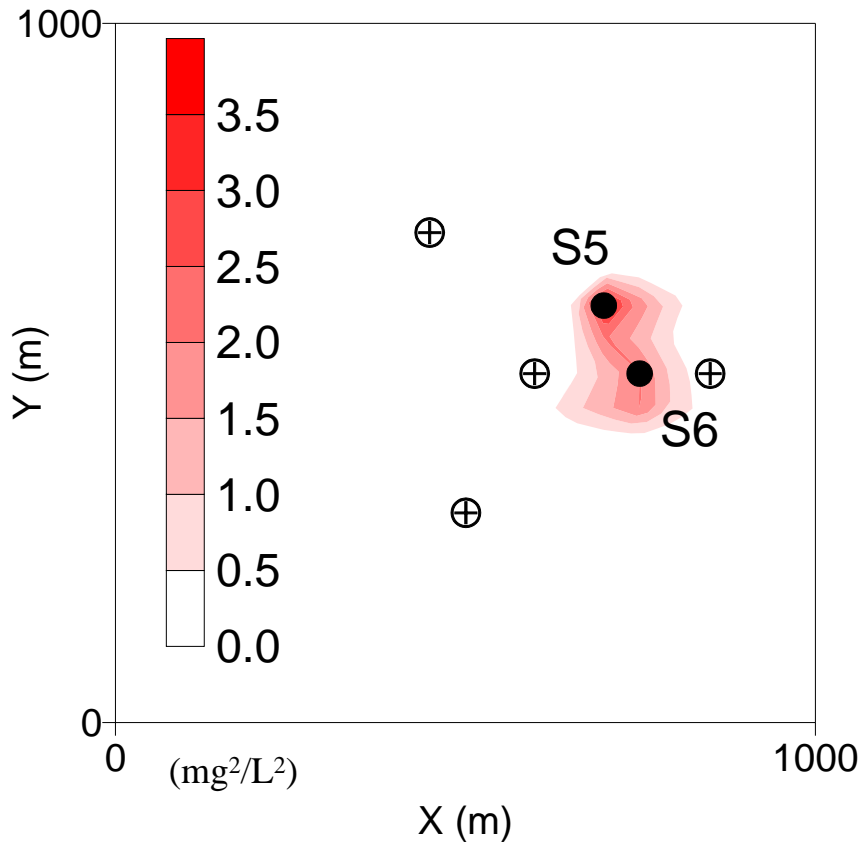
Performance Uncertainty



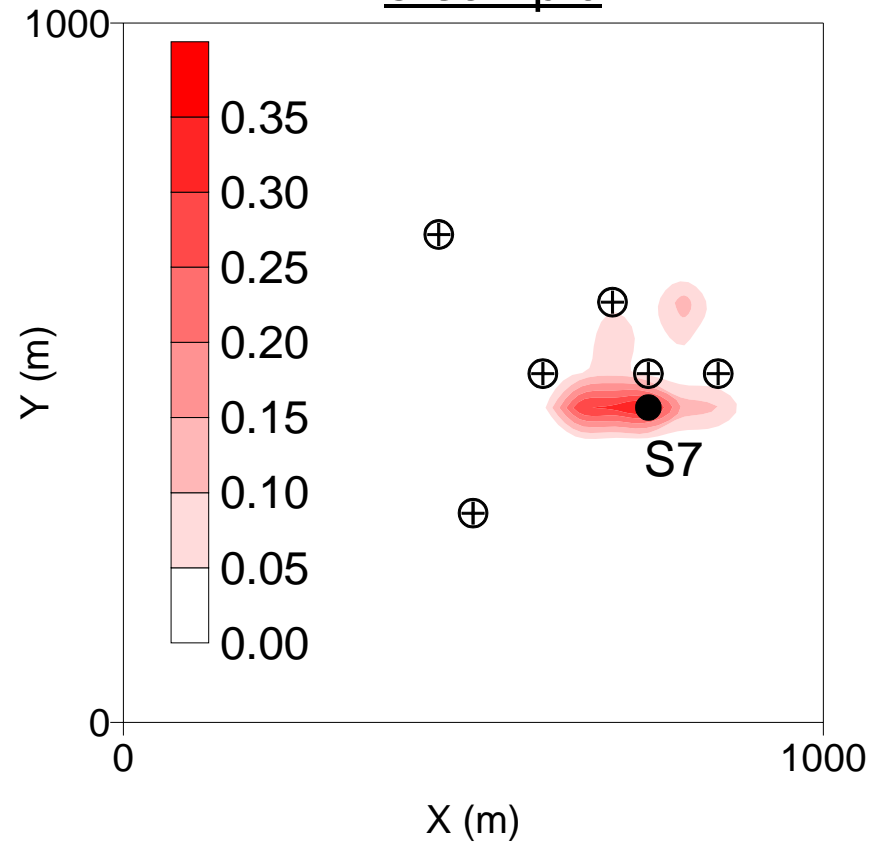
Additional sampling reduces the concentration uncertainty

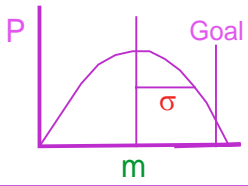
For Design II : Single pumping well

4 Sample

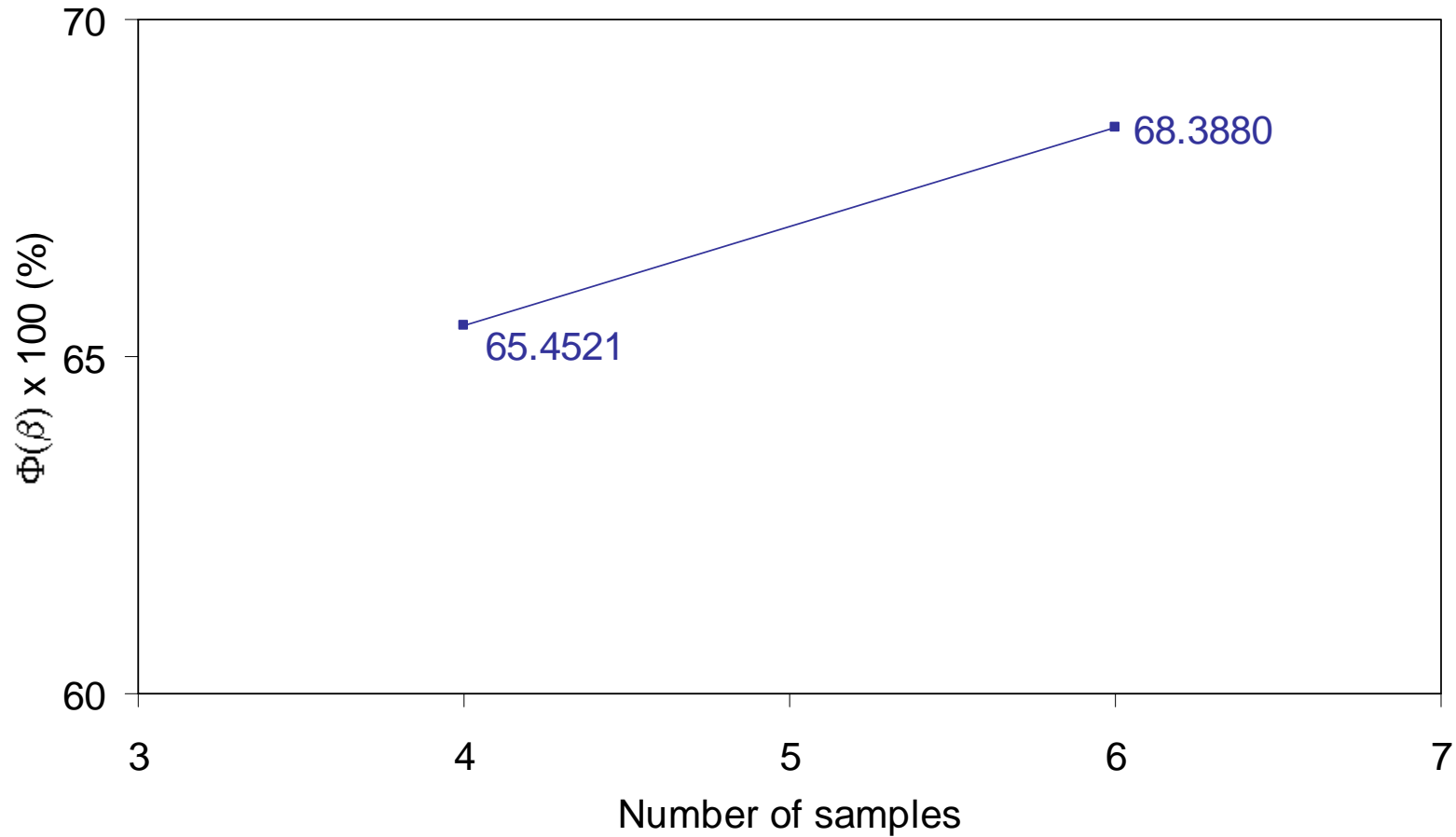


6 Sample





For Design II : Single pumping well



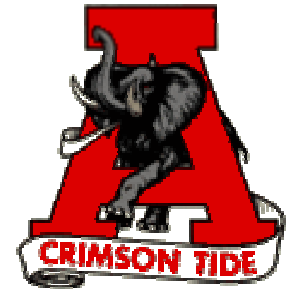
Future Work

- 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)

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