An Efficient Reliability-Based Approach to Aquifer Remediation Design

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Acknowledgements

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

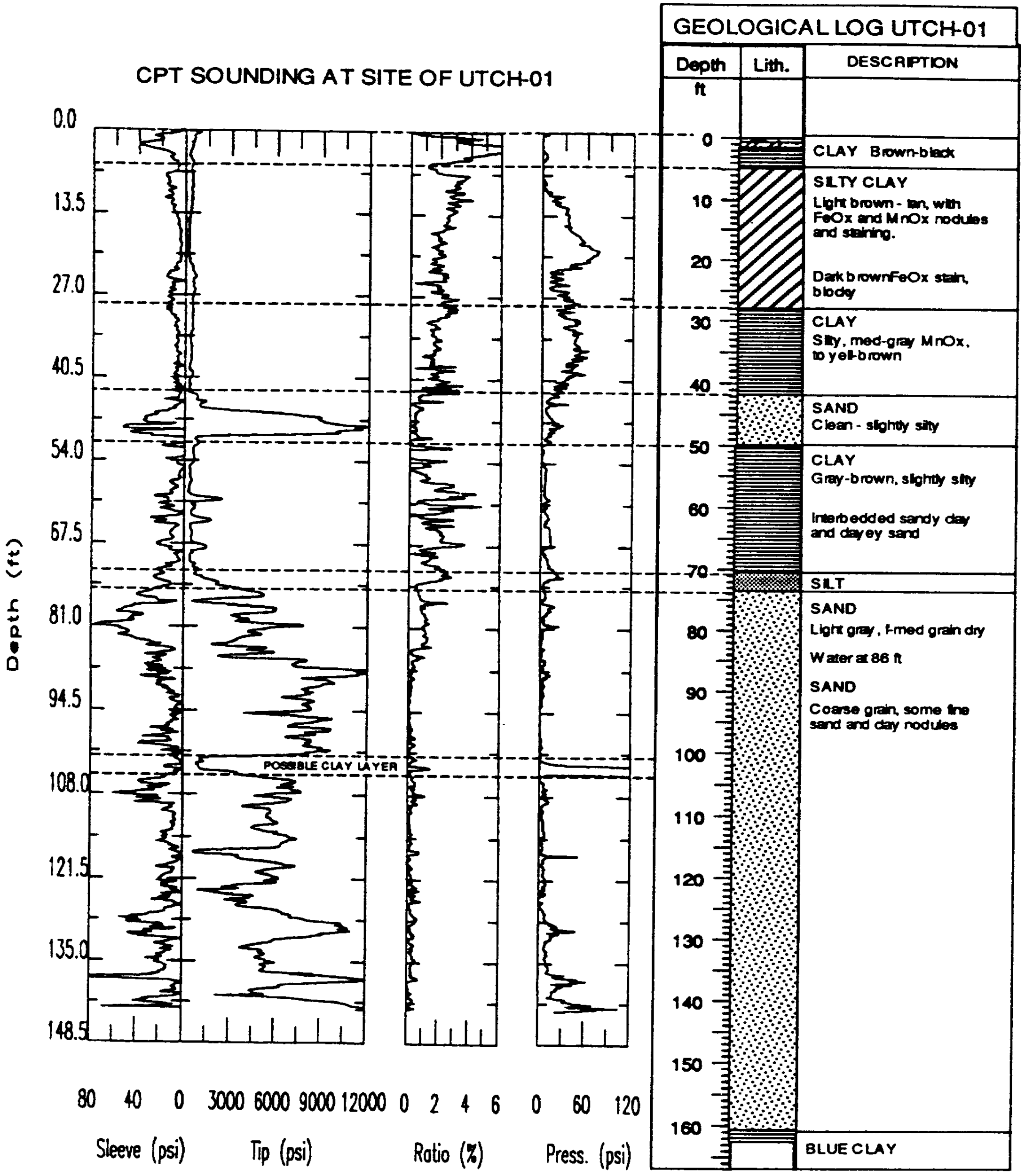
- Design of remedial strategies for contaminated soil and groundwater
  - Uncertainties in site conditions
  - Variety remedial options
  - Desire to quantify design process

Challenges

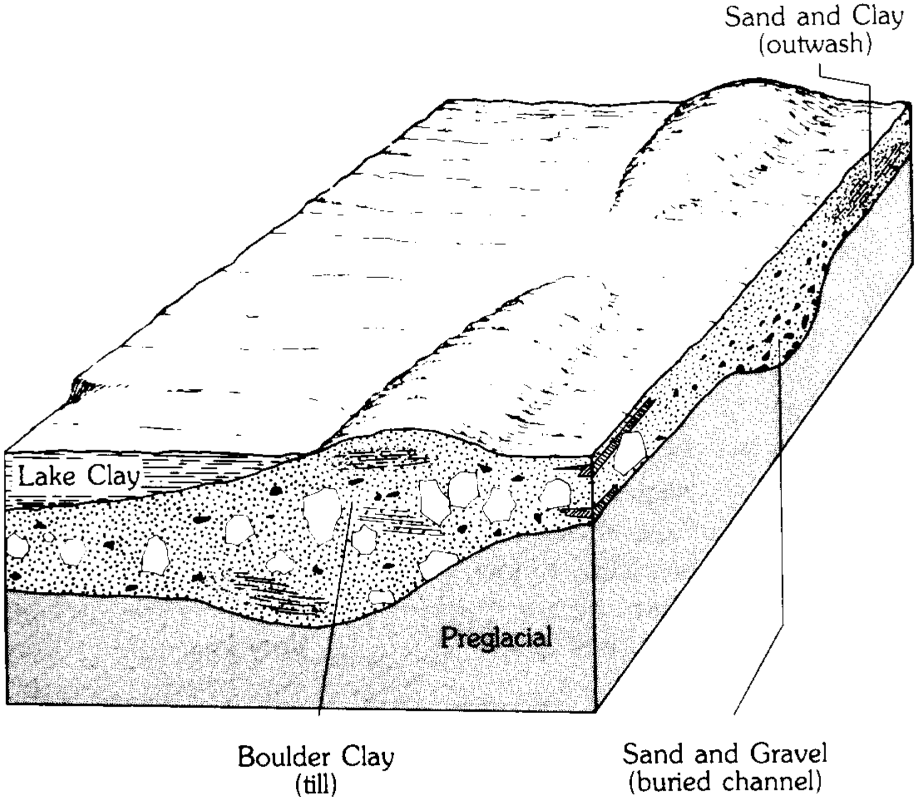
Given a contaminated site and proposed remedial activities:

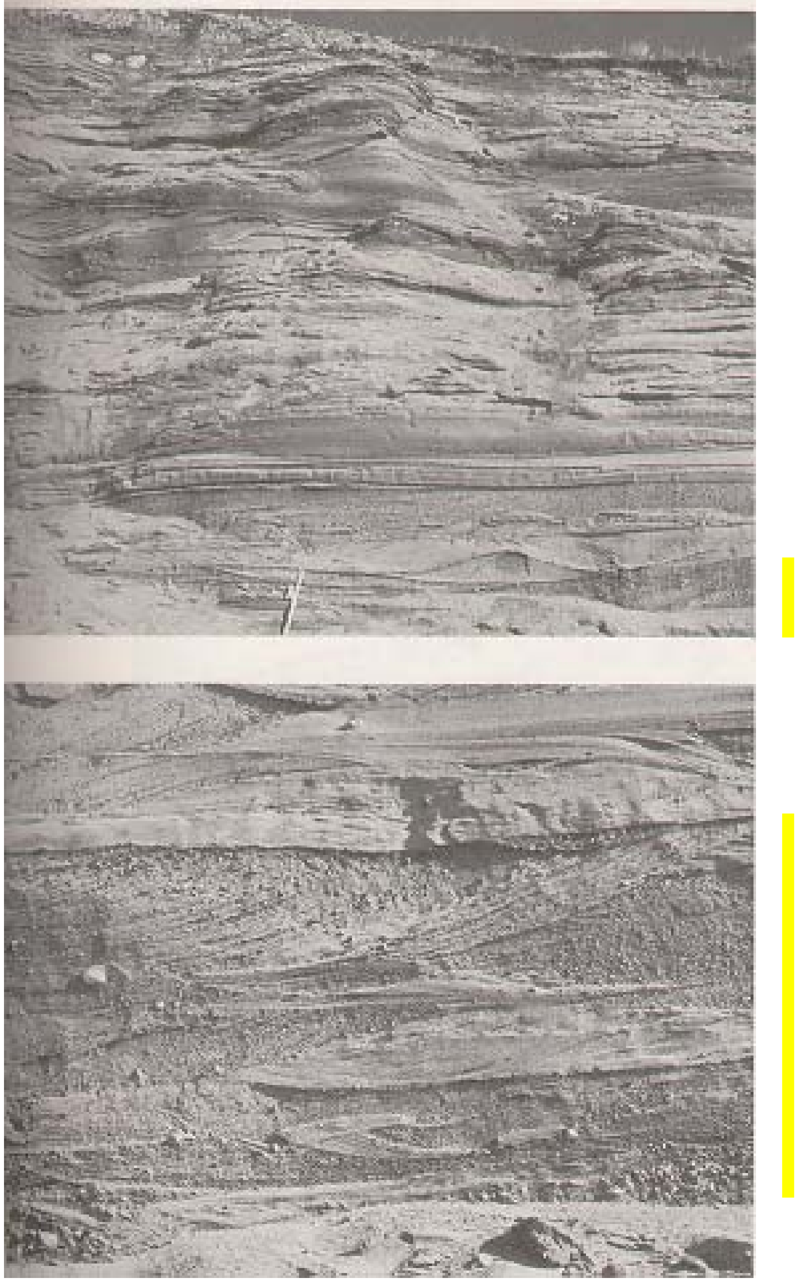
- Geology of subsurface may be complex
- Small volume of soil at a site is sampled
- Parameters of interest may vary over large ranges
- Contaminants may have complex interactions with soil and native ground water
- Clean-up schemes impose different hydrologic, chemical, or biological conditions or constraints

Example Cone Penetrometer (CPT) log



CPT has an area of 10 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

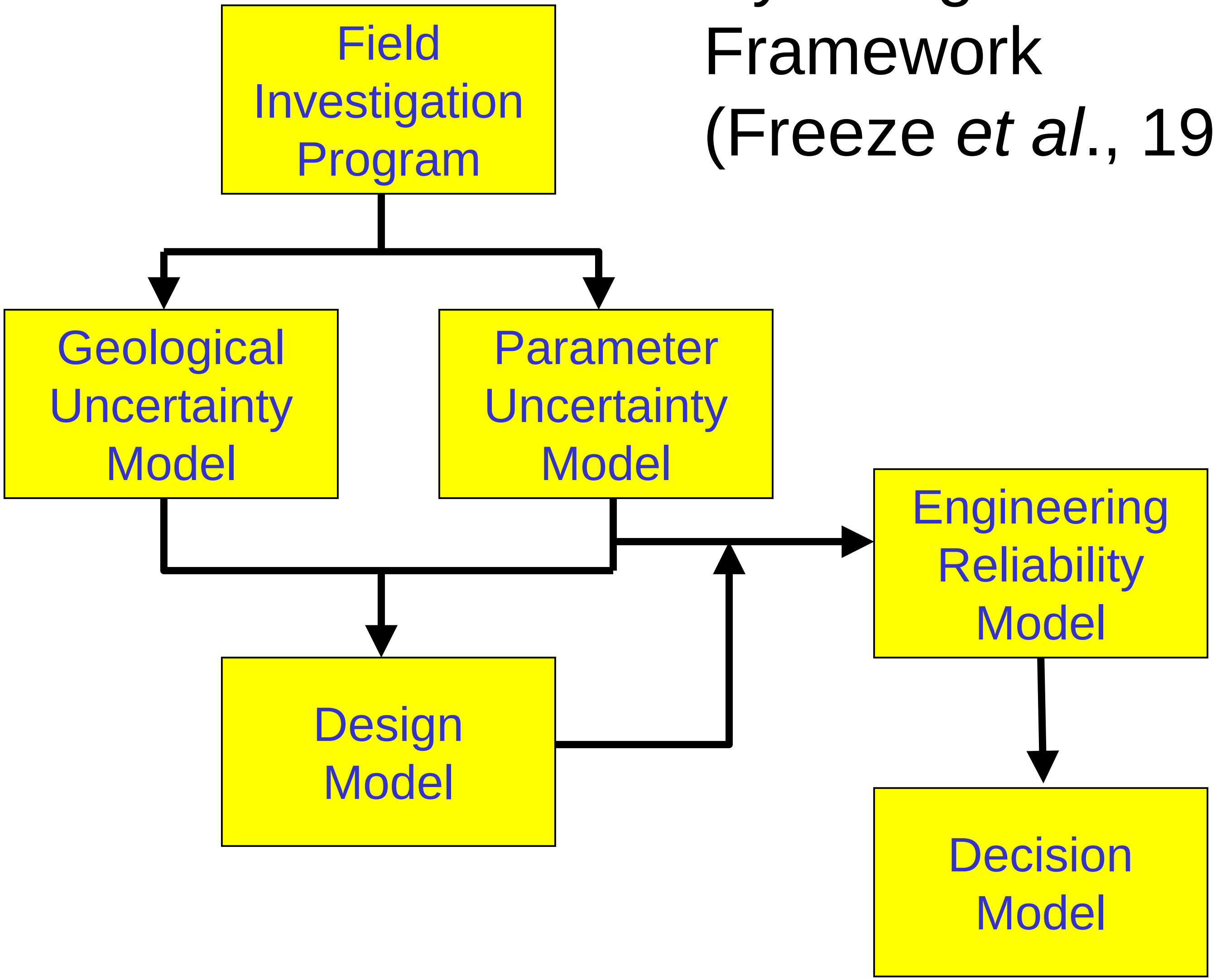
- Are there sufficient data to base the design?

- 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

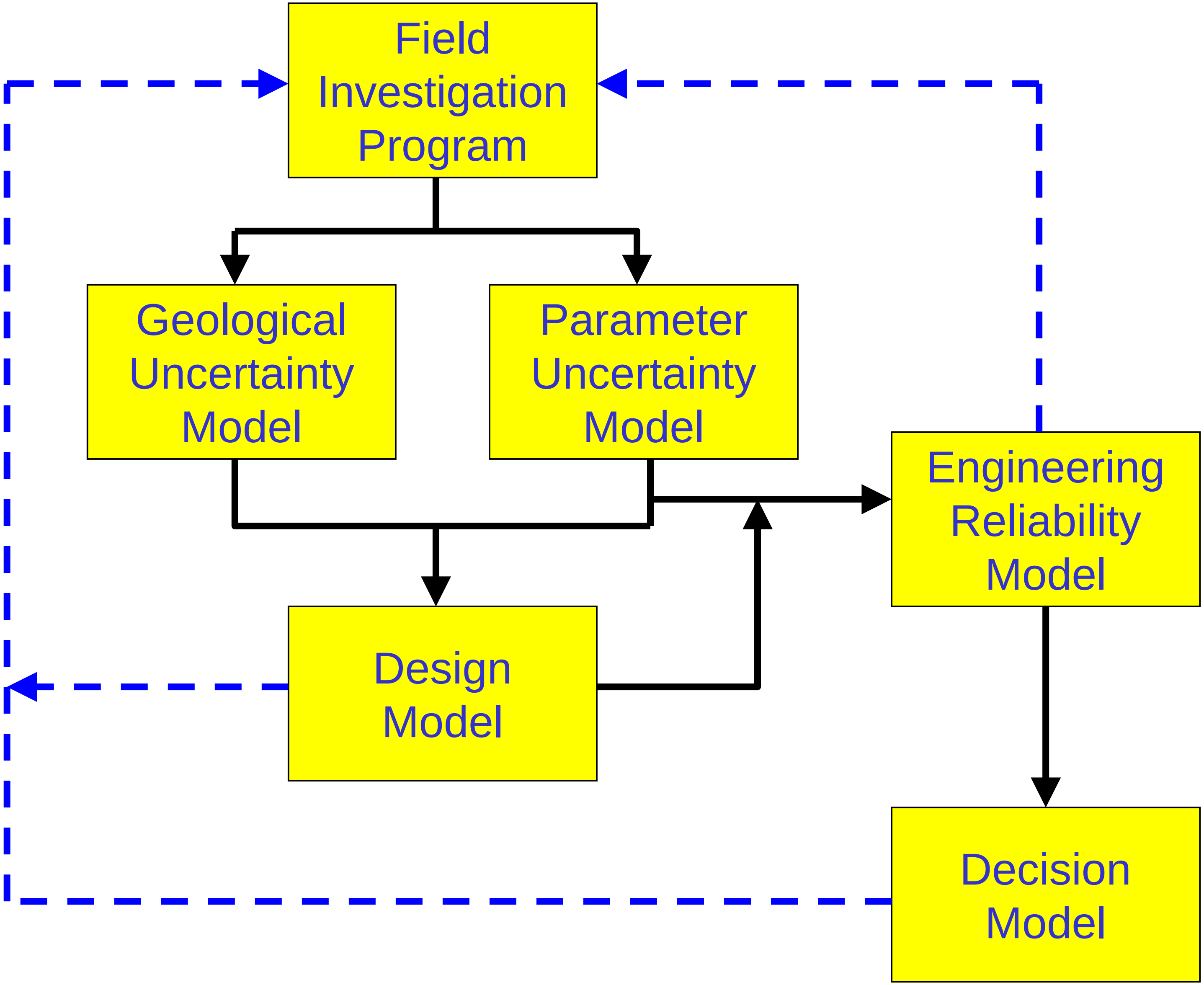
Geological Uncertainty Model

Parameter Uncertainty Model

Engineering Reliability Model

Design Model

Decision Model



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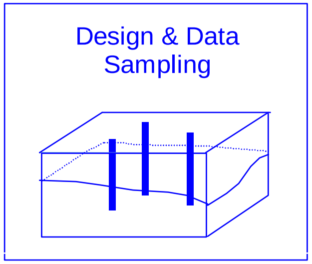
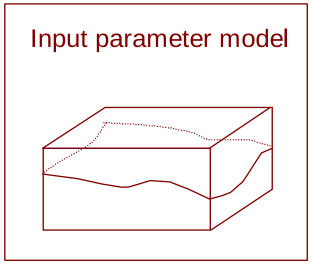
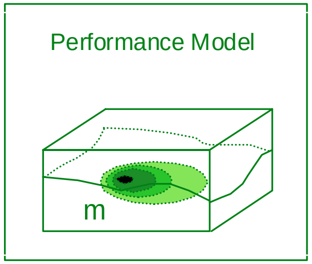


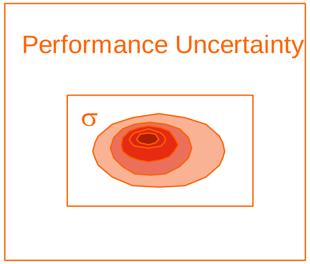
Design & Data Sampling



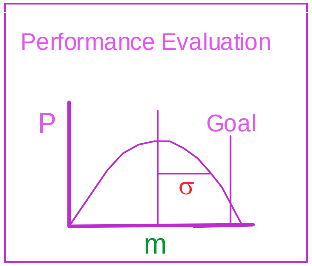
Input parameter model



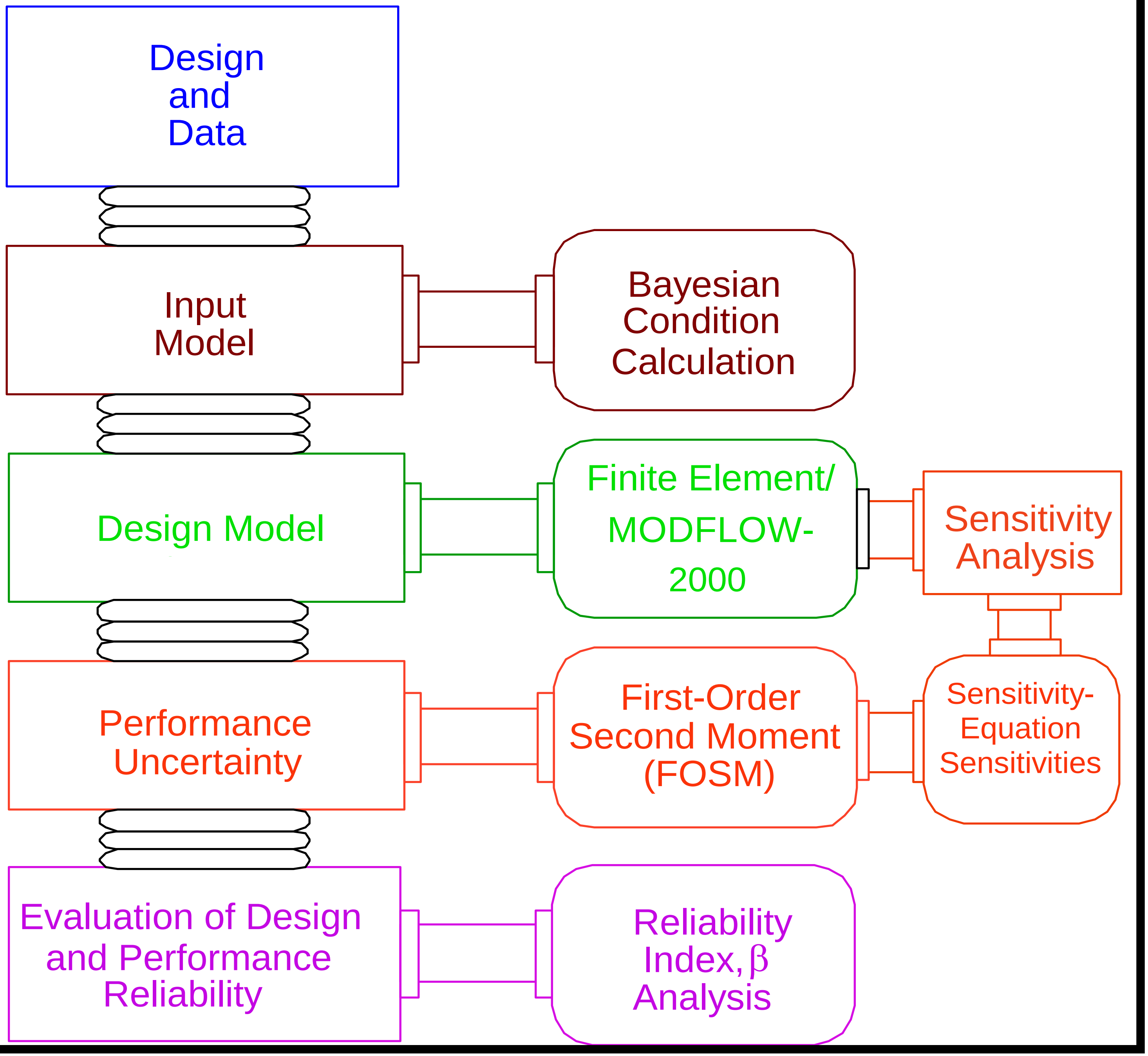
Performance Model



Performance Uncertainty



Performance Evaluation



Design and Data

Input Model

Bayesian Condition Calculation

Design Model

Finite Element/ MODFLOW-2000

Sensitivity Analysis

Performance Uncertainty

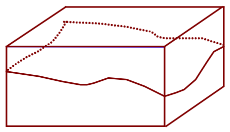
First-Order Second Moment (FOSM)

Sensitivity-Equation Sensitivities

Evaluation of Design and Performance Reliability

Reliability Index, β Analysis

Input parameter model



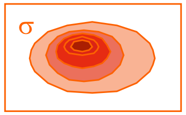
Input Component

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

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

$$Cov(u|v) = Cov(u) - Cov(v,u)\,Cov(v)^{-1}\,Cov(u,v)$$

- 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 Cov(u)

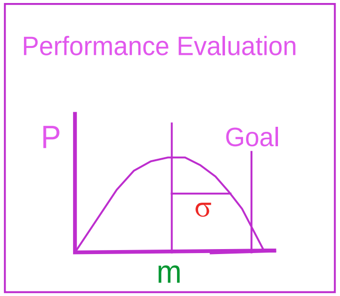


First-Order Second-Moment

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

$$Cov(C(t_1),C(t_2)) \cong J_u(t_o,t_1)\, Cov(u|v)\, J_u^T(t_o,t_2)$$

E[C] = expected value for concentration
g() = design model
u = vector of uncertain input parameters
$J_u = [\partial C_I / \partial u_J]$
Cov(.,.) = covariance matrix describing uncertainty in input parameters



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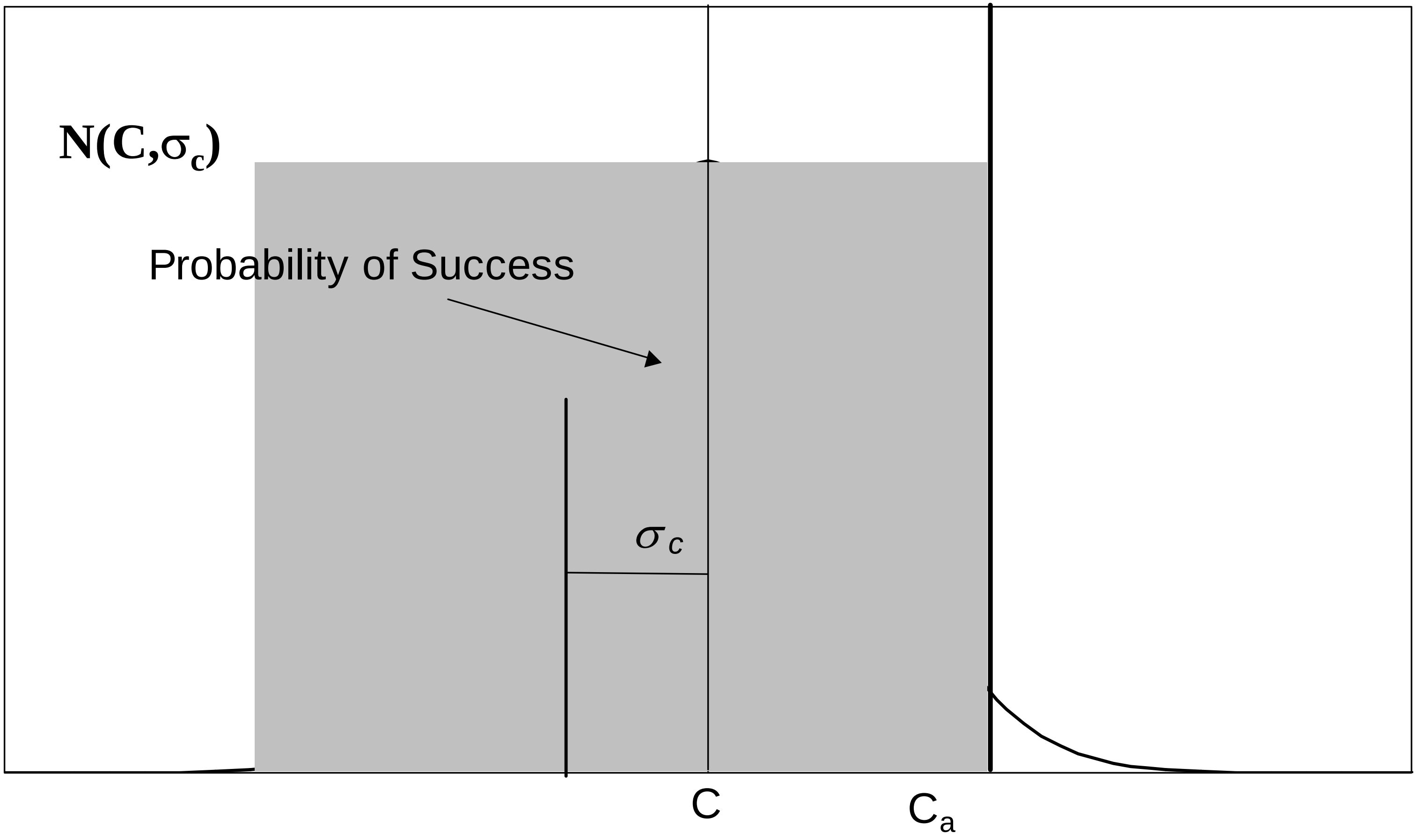
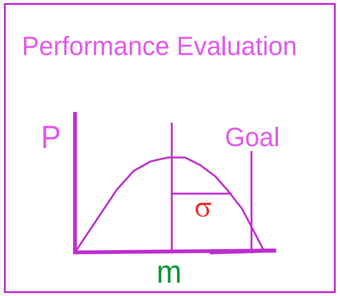


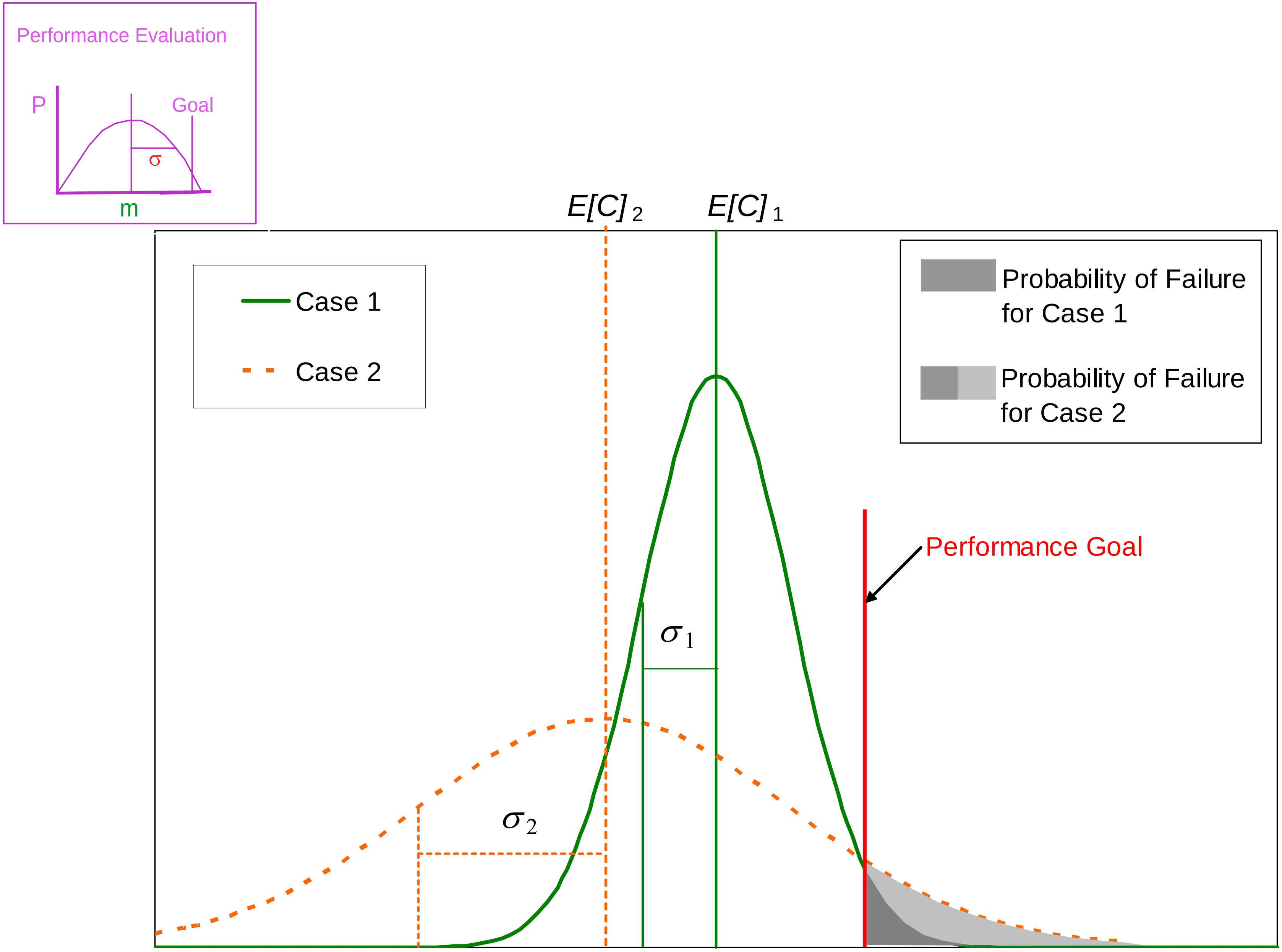


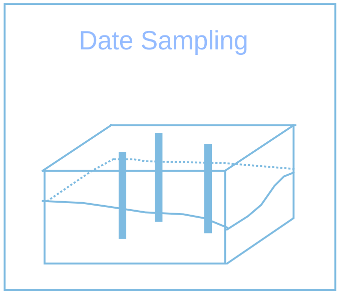
Reliability Index

- Point reliability may be determined

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

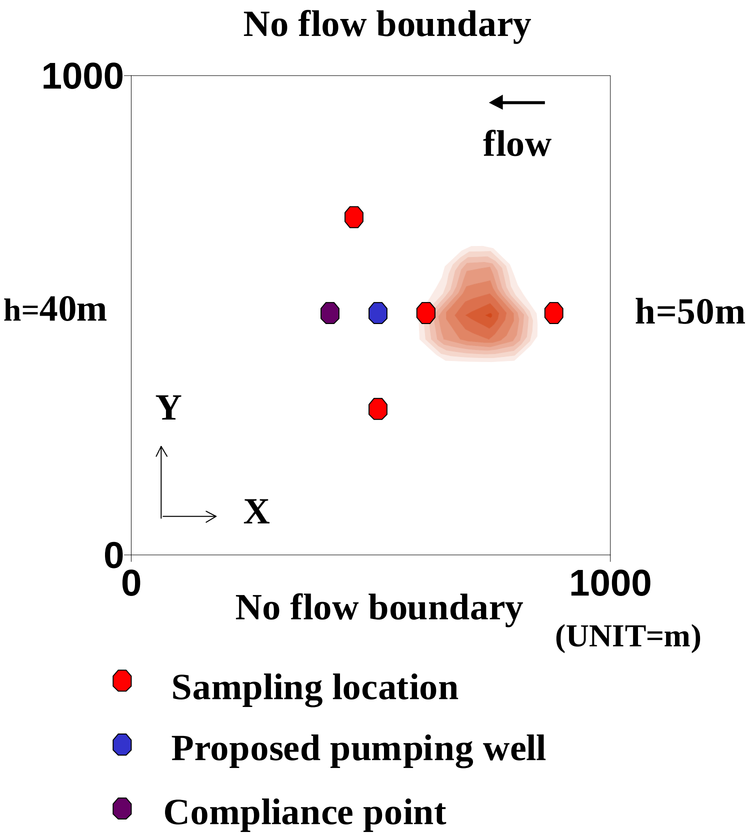
- σ_c - the standard deviation of C = Square root of the variance of C
- Uncertainty in site input and model performance are combined in C

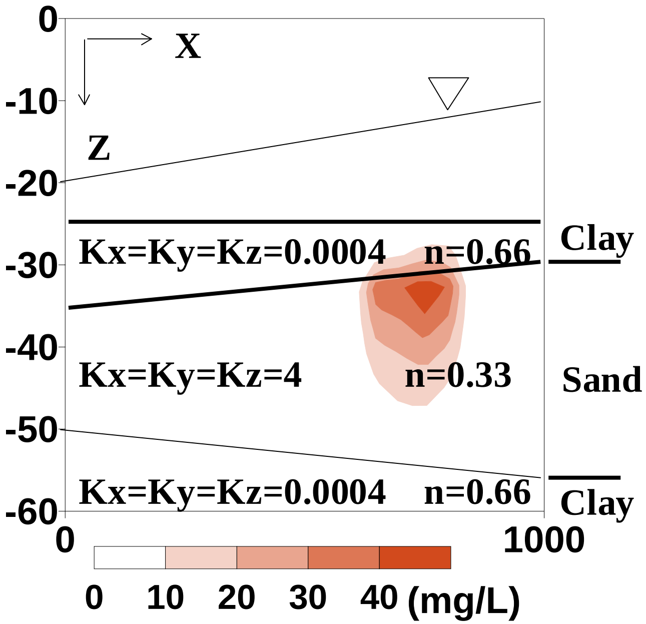

Performance Evaluation
P
Goal
σ
m
$E[C]_2$
$E[C]_1$
Case 1
Case 2
▨ Probability of Failure for Case 1
▨ Probability of Failure for Case 2
Performance Goal
σ_1
σ_2



3-D Transport Simulation

Hypothetical Model





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)

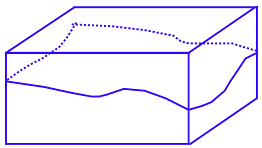
Design II : Single pumping well

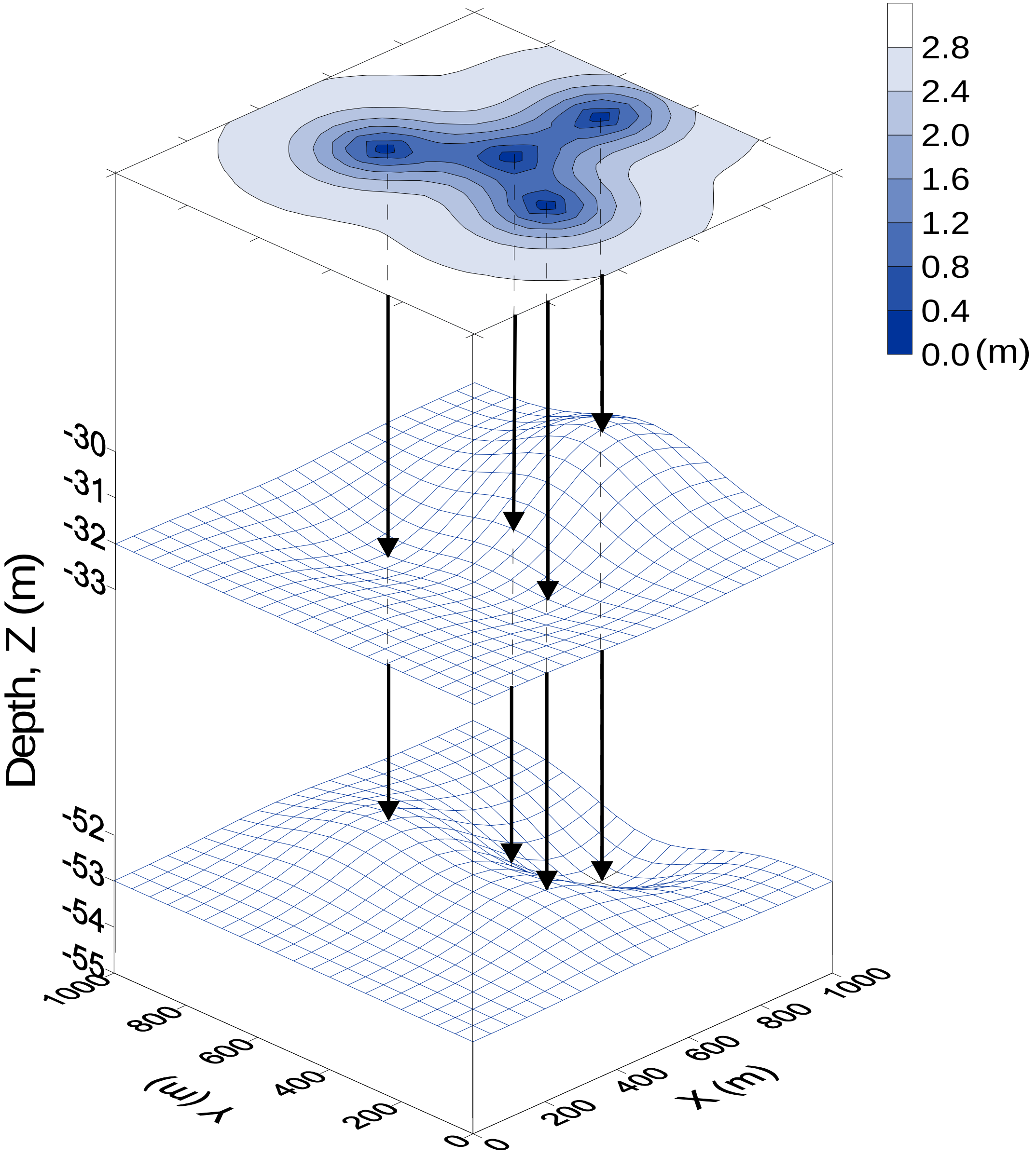
(Proposed pumping rate : 300 m^3/day)

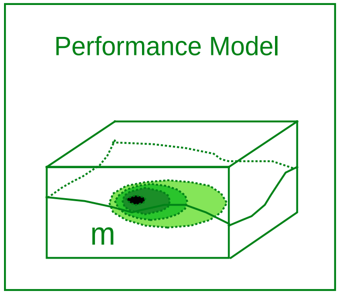
- Output parameter -

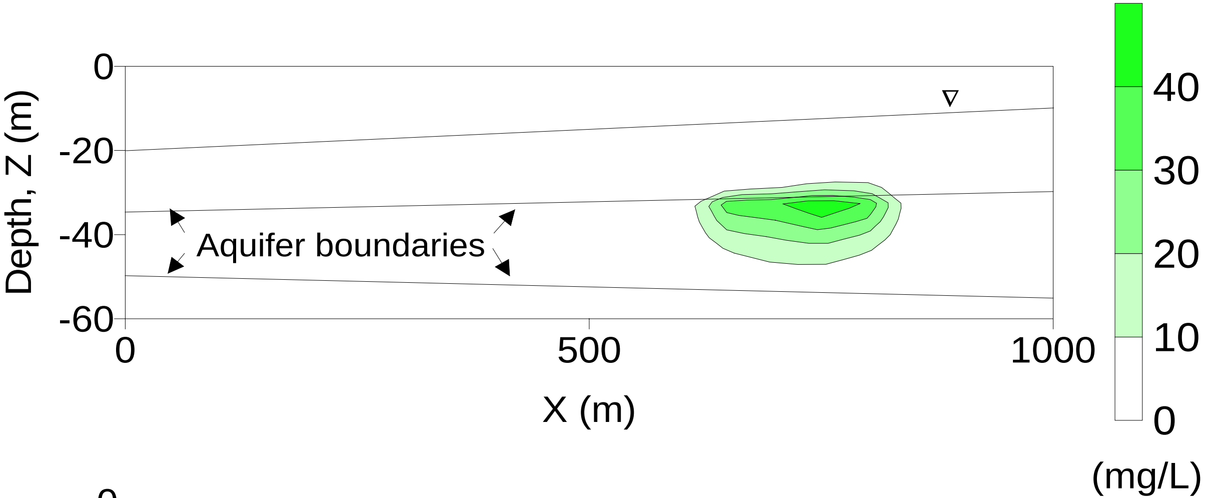
Clean-up goal at compliance point : 10^{-3} mg/L

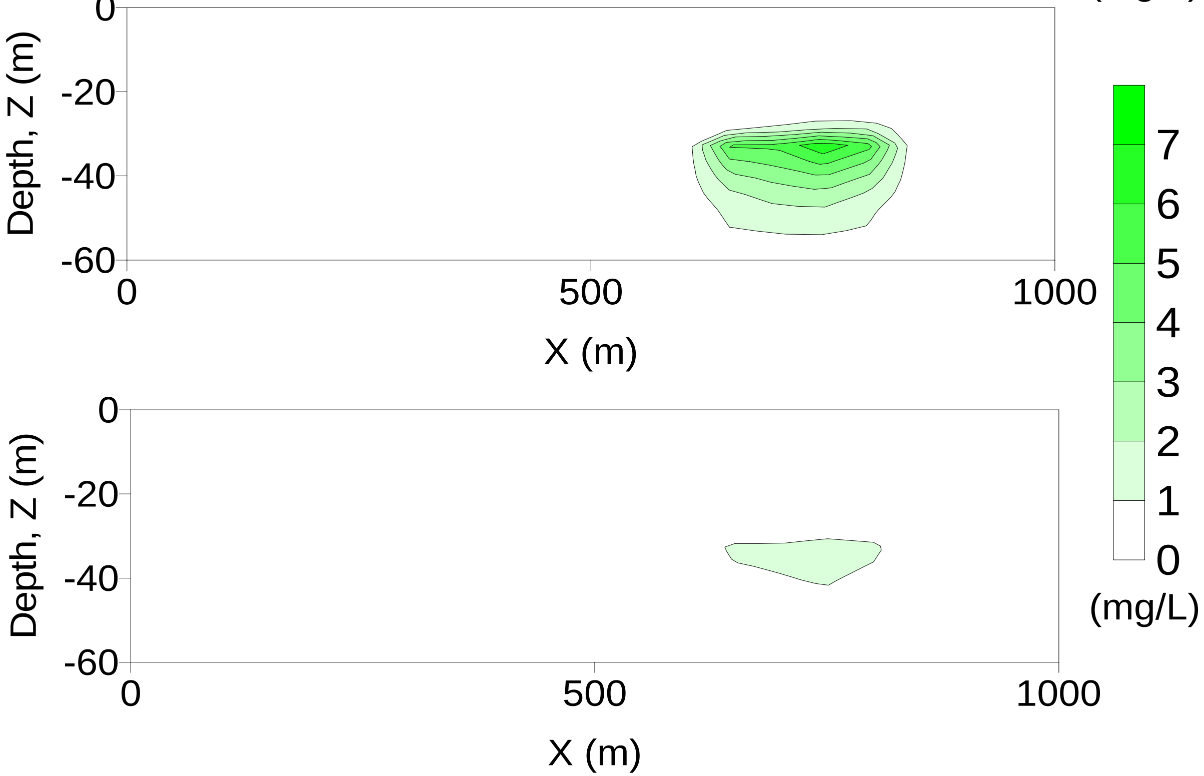
Input parameter model





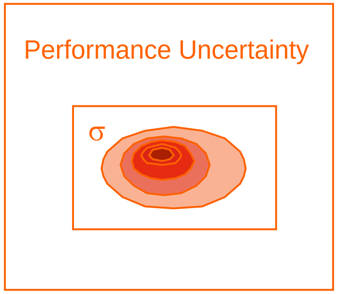






Design I
No Pumping Well

Design II
Single Pumping Well



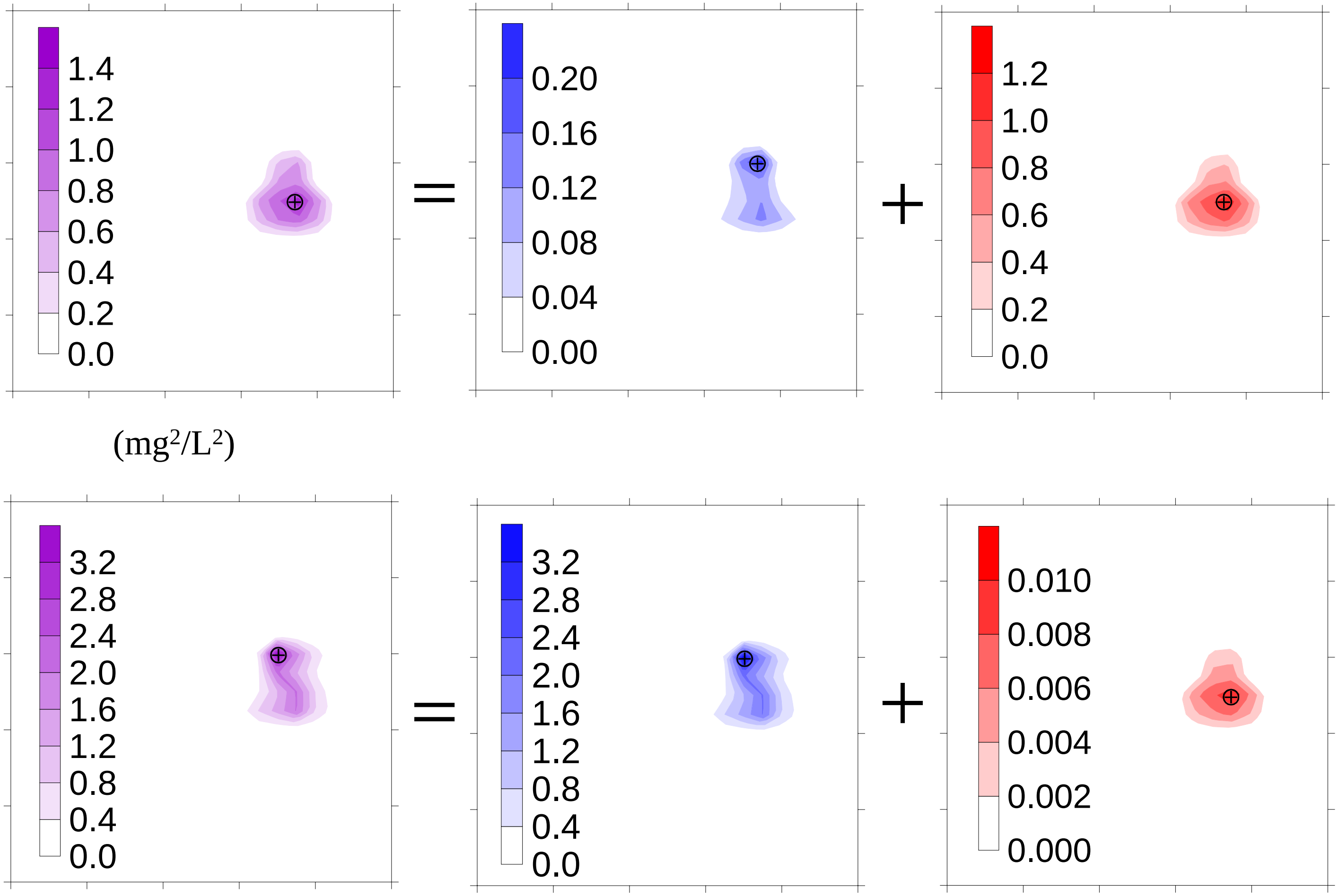
Total Variance

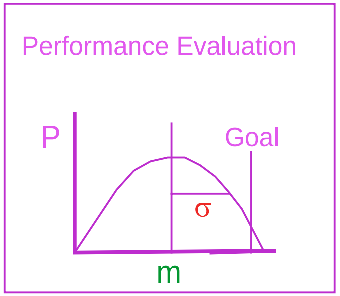
Variance from Interface uncertainty

Variance from First-order Decay rate uncertainty

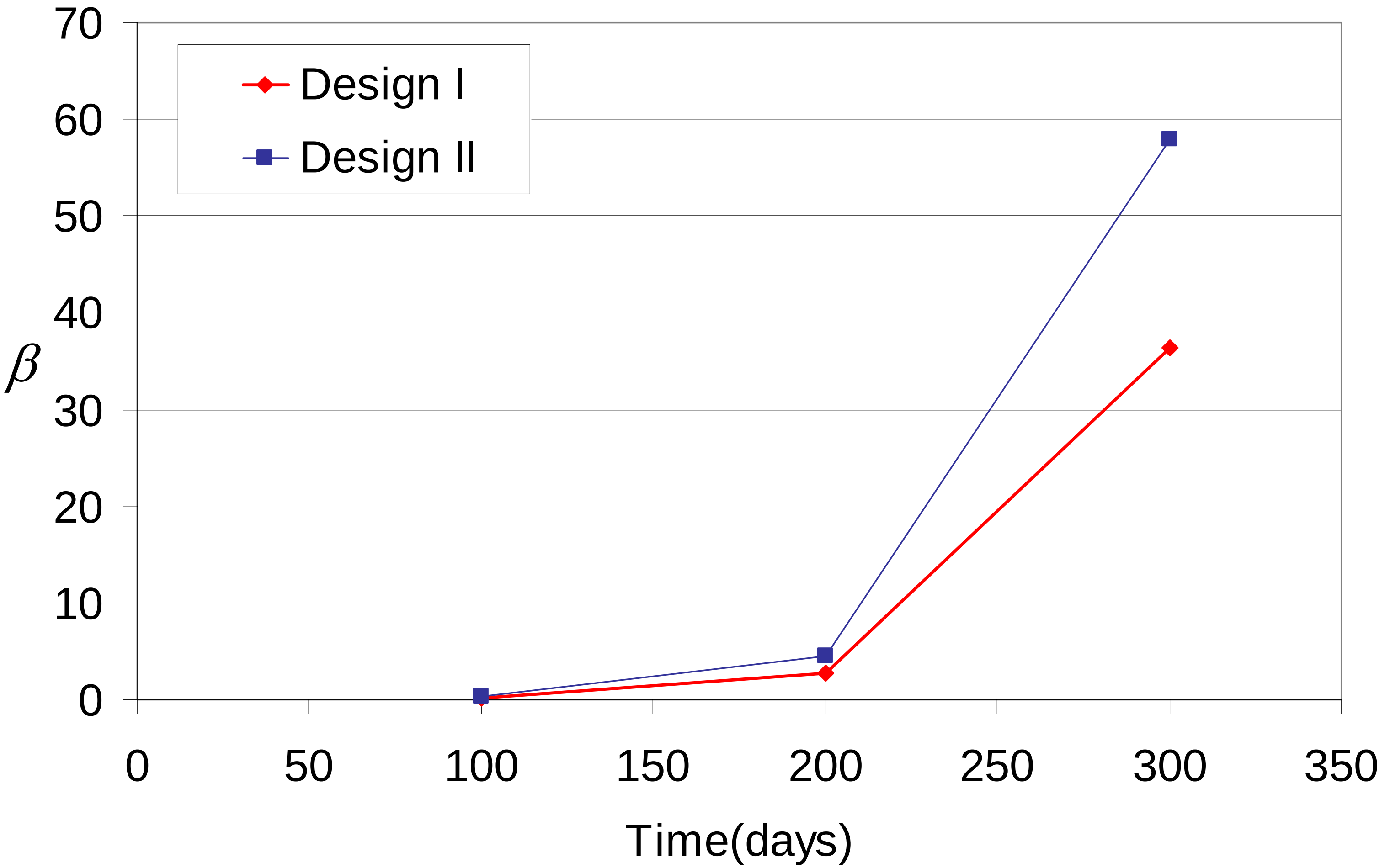
Design I
No Pumping Well

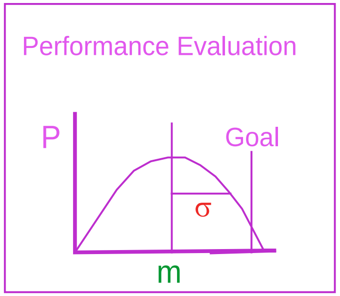
Design II
Single Pumping Well



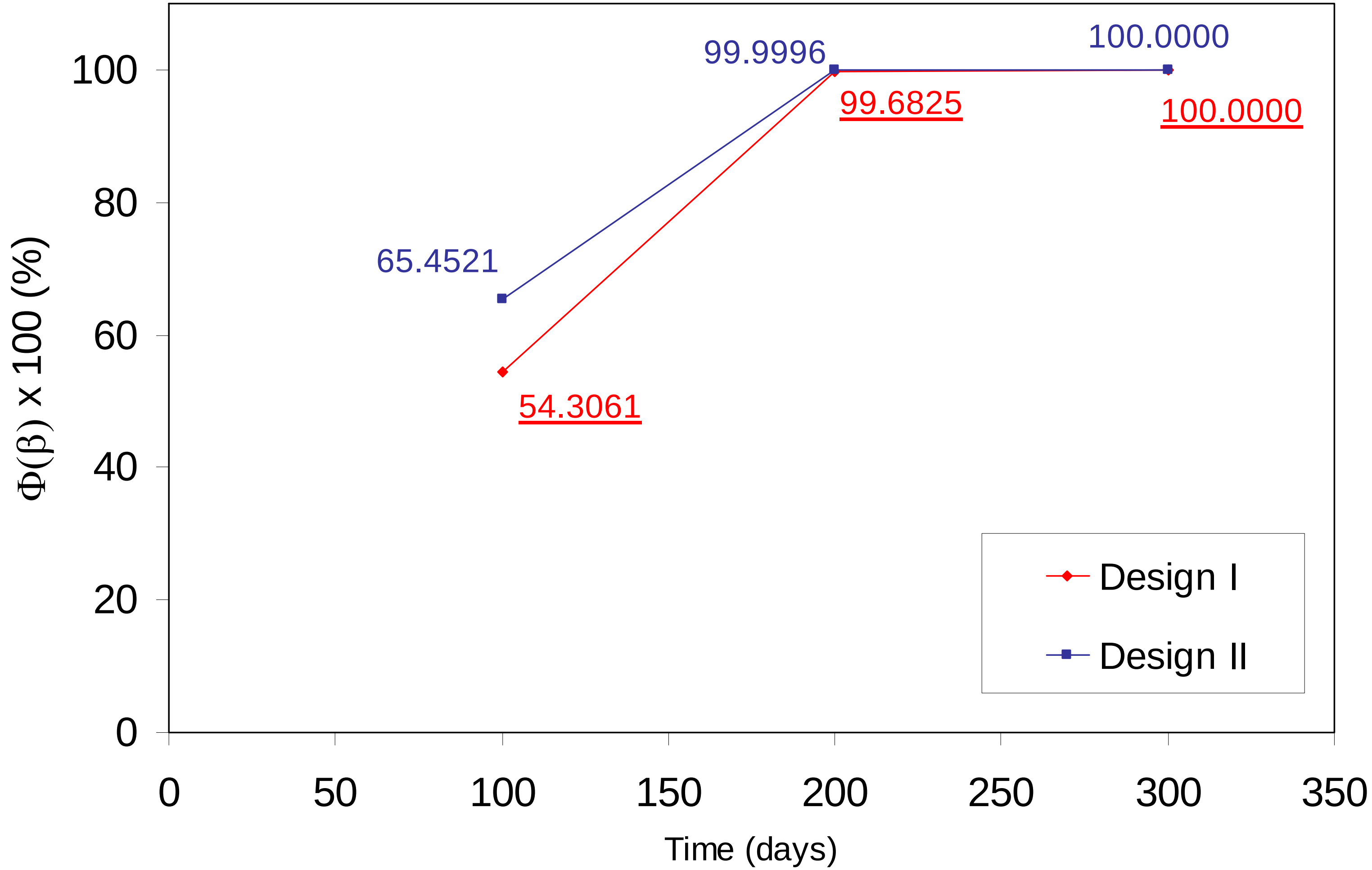


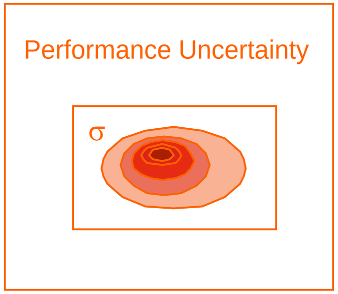
Reliability index indicates which design is more reliable





Reliability index can be used to estimate probability of success

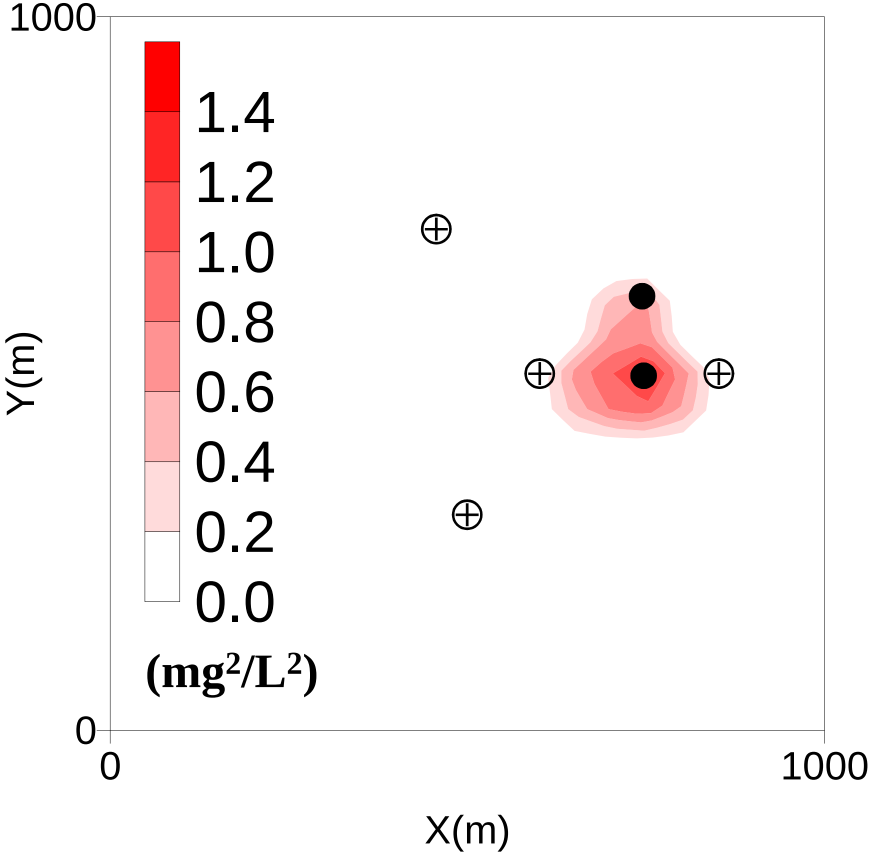




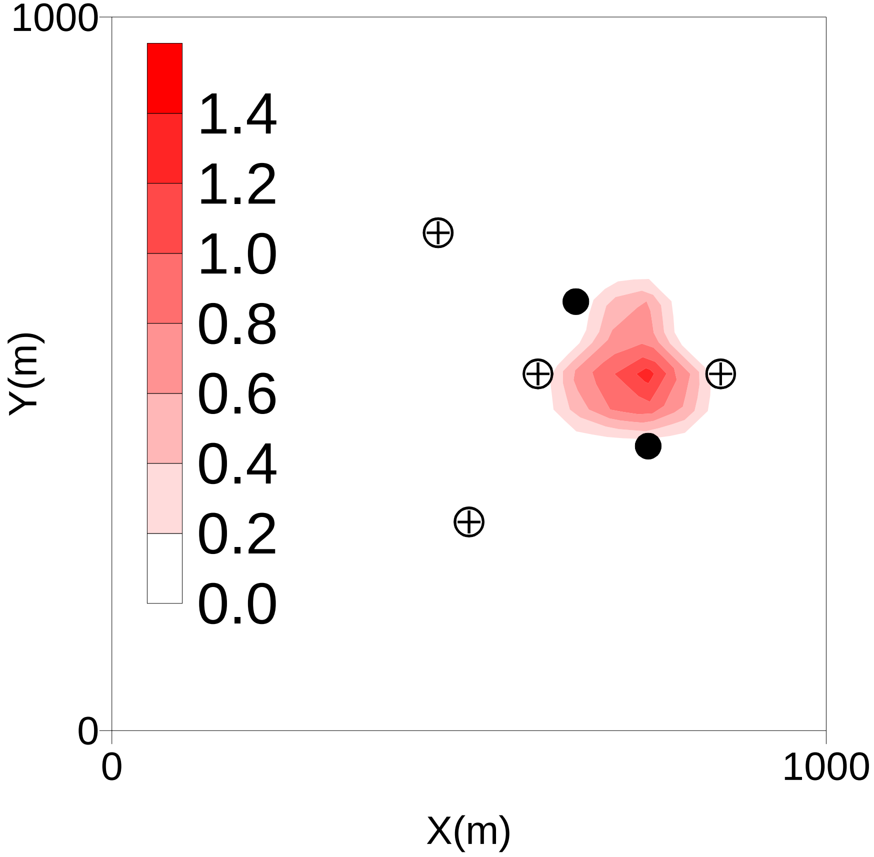
Will directed sampling give more confidence to the remedial design?

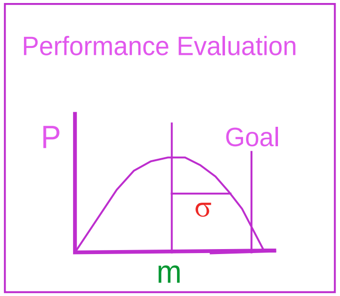
For Design I : No pumping well (Natural Attenuation)

Directed Sampling



Ad hoc Sampling





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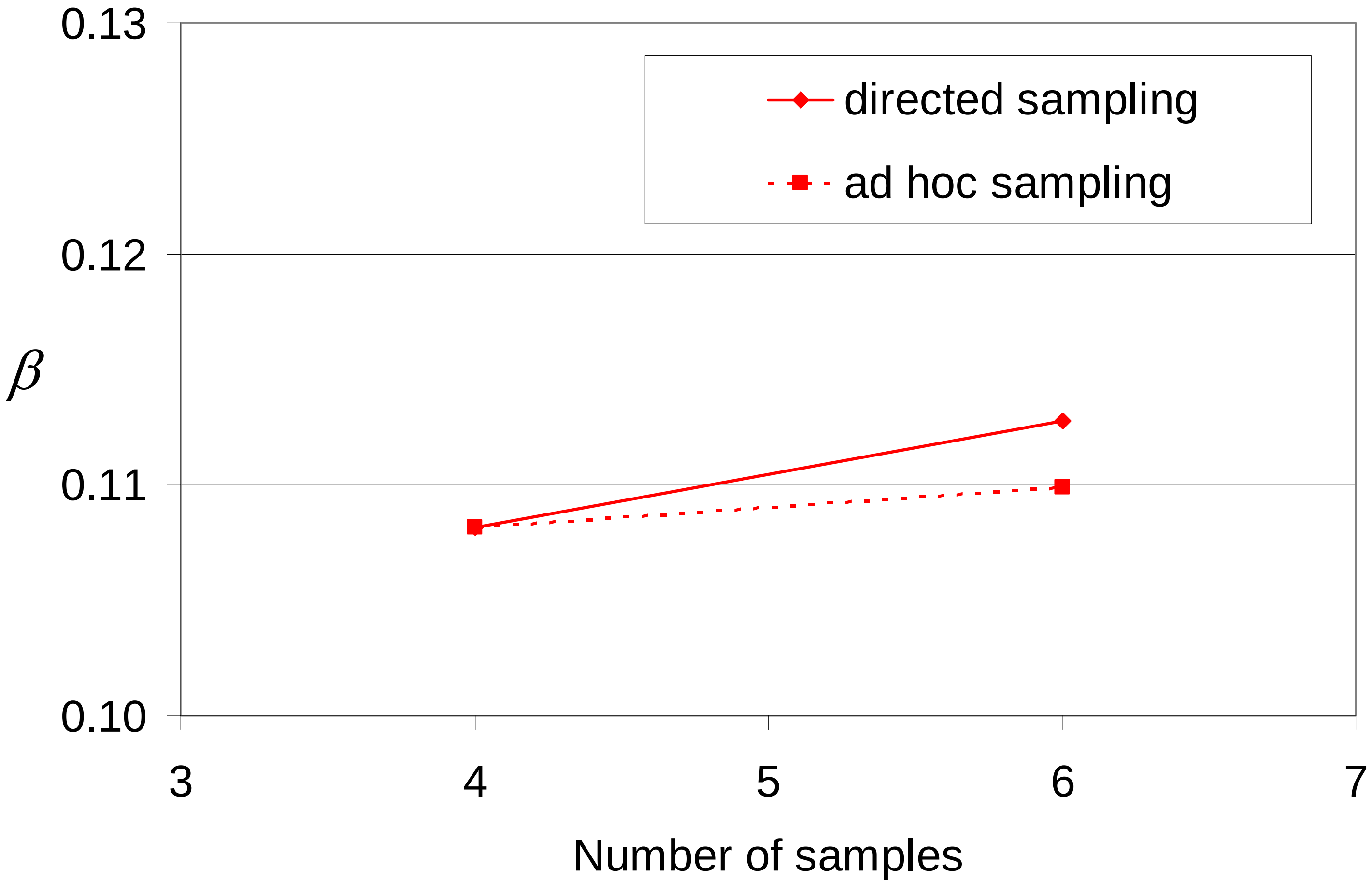
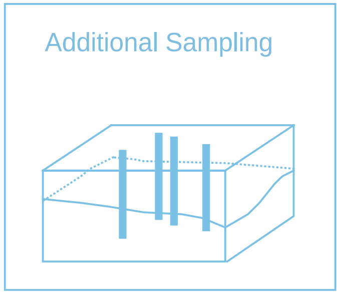
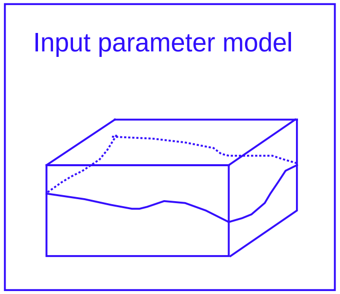


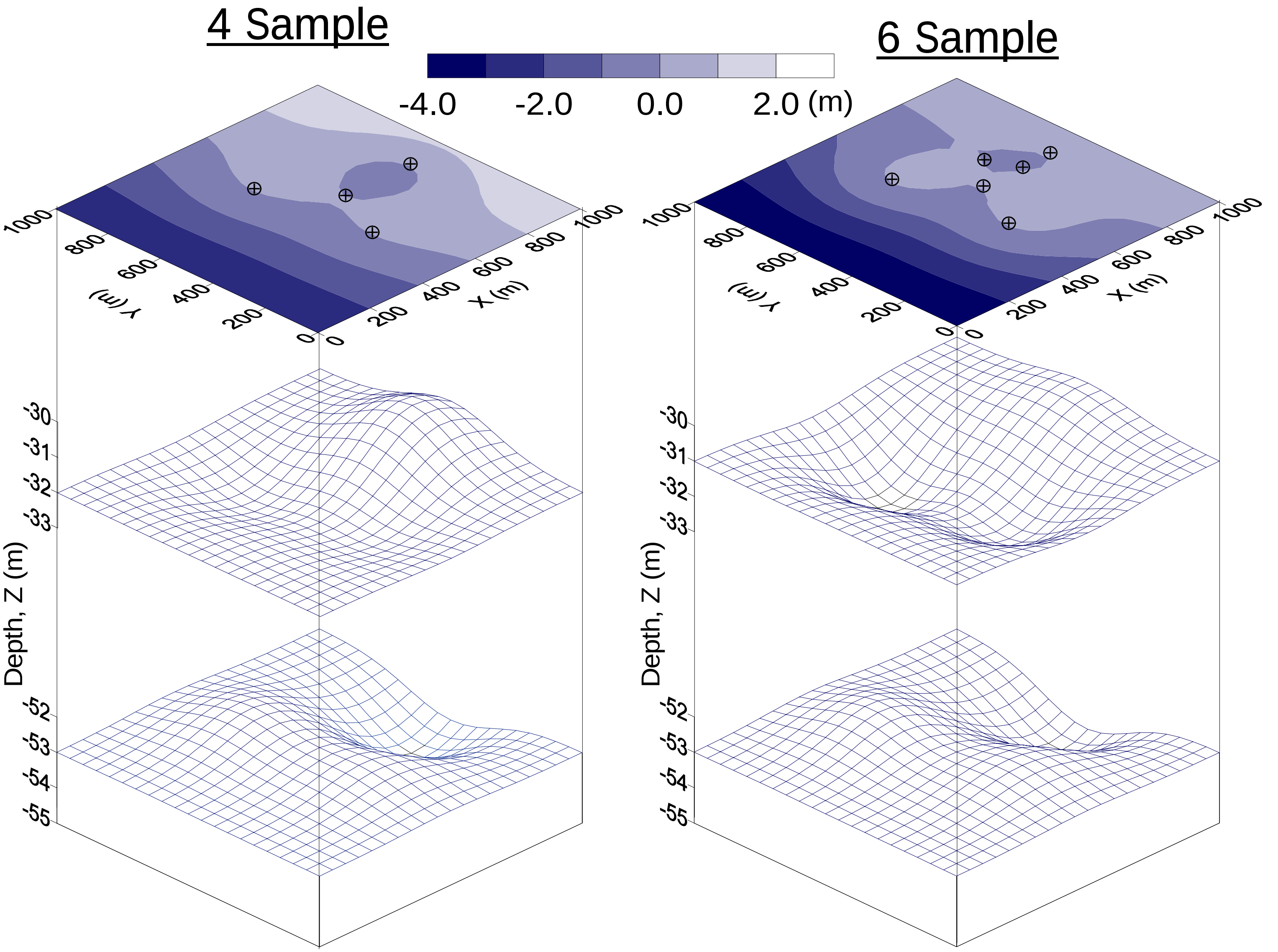


Additional Sampling



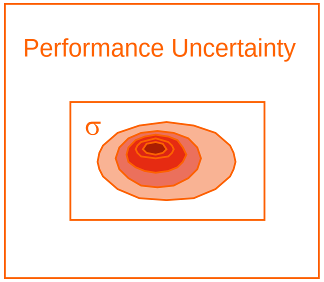
Input parameter model

For Design II : Single pumping well



4 Sample

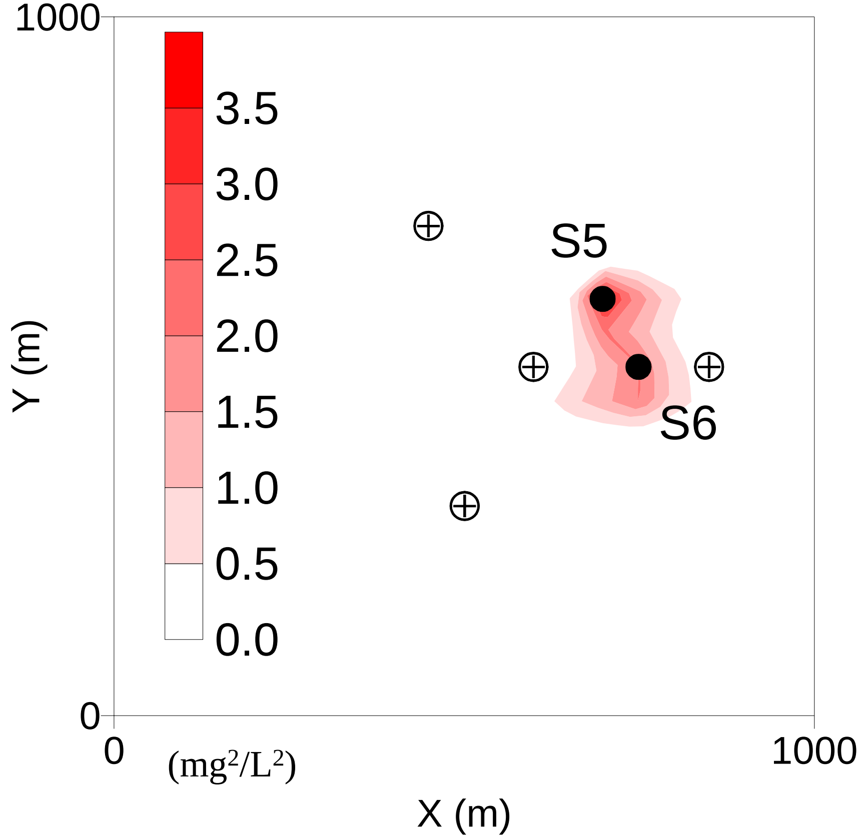
6 Sample



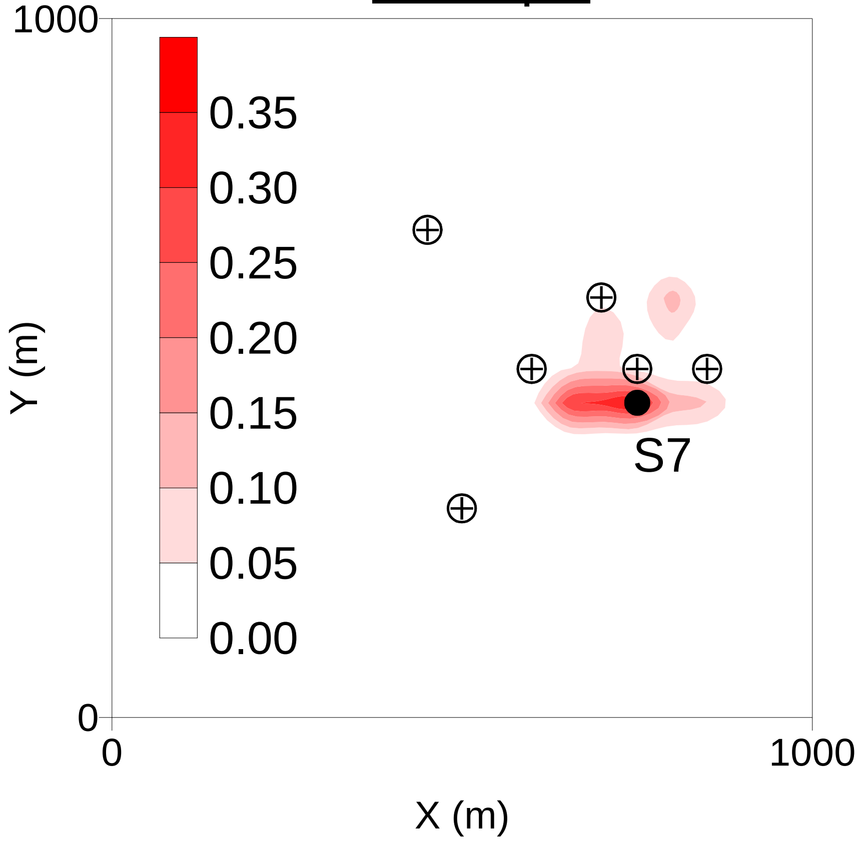
Additional sampling reduces the concentration uncertainty

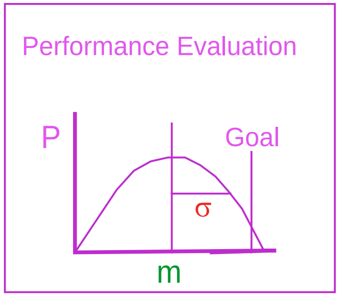
For Design II : Single pumping well

4 Sample

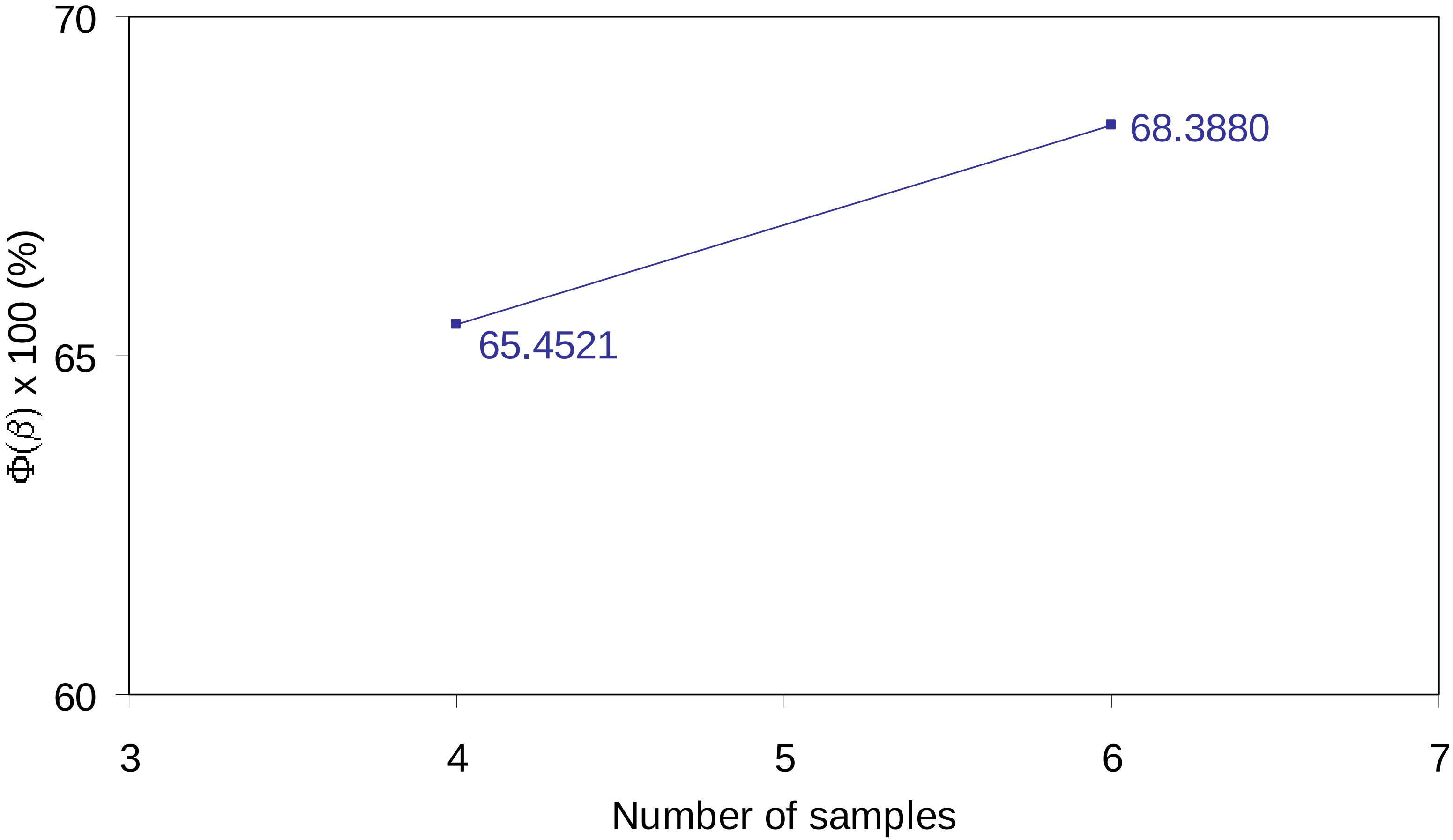


6 Sample





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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