Multi-objective Design of Active Remediation with Natural Attenuation Under Parameter Uncertainty

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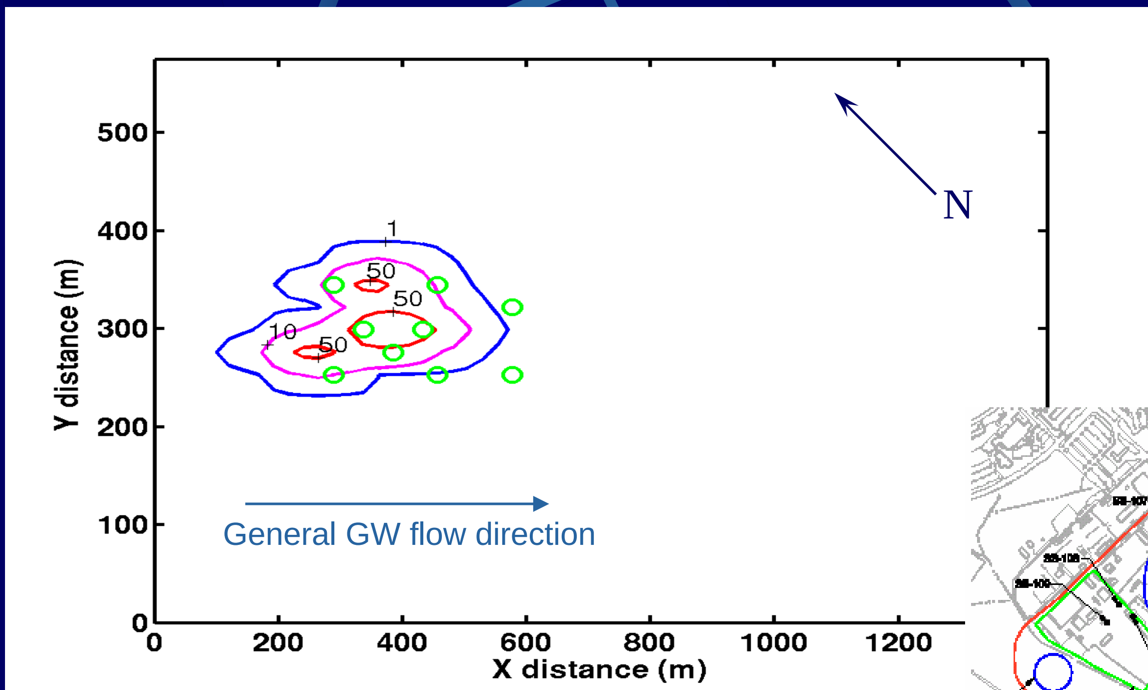
Motivation

- Need for identifying cost-effective and reliable groundwater remedial designs
- Increased use of natural attenuation (NA), often combined with active remediation
- Natural variability of and limited data on system parameters, leading to difficulty in:
  - Predicting remediation effectiveness
  - Estimating remediation costs
  - Designing remediation strategies

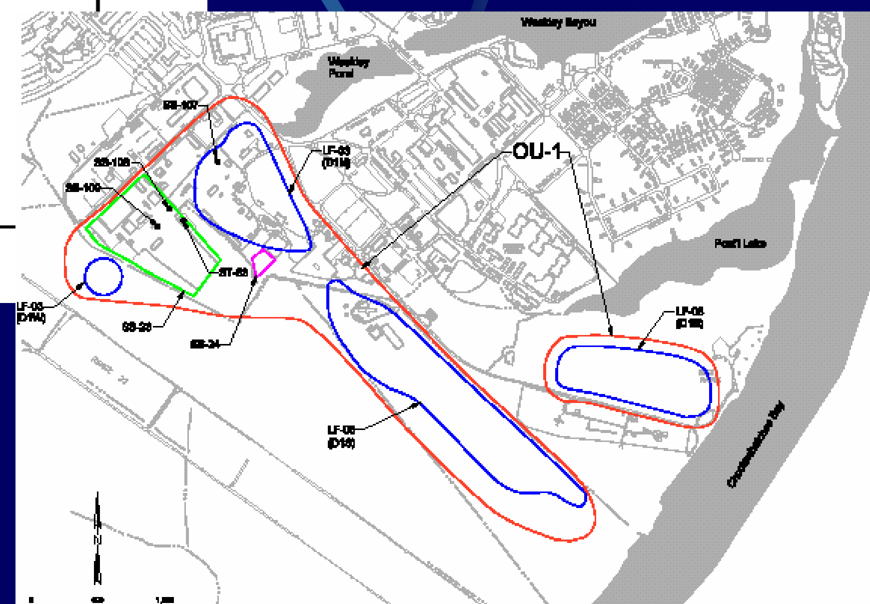
Research Objectives

- Develop and apply Enhanced Multi-Objective Robust Genetic Algorithm (EMRGA) to optimize groundwater remediation designs
- Find cost effective and reliable remediation designs while considering uncertainty
- Analyze effects of parameter uncertainty on optimal design of combined natural attenuation/active remediation systems

Study Site



- Developed study site based on OU-1 site at Eglin AFB, Florida



- NA observed at site
- Contaminants: Benzene, TCE, VOCs, PCBs

Remediation Optimization

- Use combination of active remediation and NA to reduce benzene concentrations:
  - Year 1: active remediation (pump and treat)
  - Years 2-5: natural attenuation (NA)
- Identify optimal set up extraction wells to achieve multiple remediation goals
- Account for uncertainty/heterogeneity in:
  - Hydraulic conductivity (K)
  - Hydraulic gradient (dh/dx)
  - First-order decay rate (k)

Optimization Problem

- Two conflicting objectives:
  - Minimize total active remediation costs:

$$\min Cost = Gpump + Gcarbon + Gcap,treat + Gcap,well$$

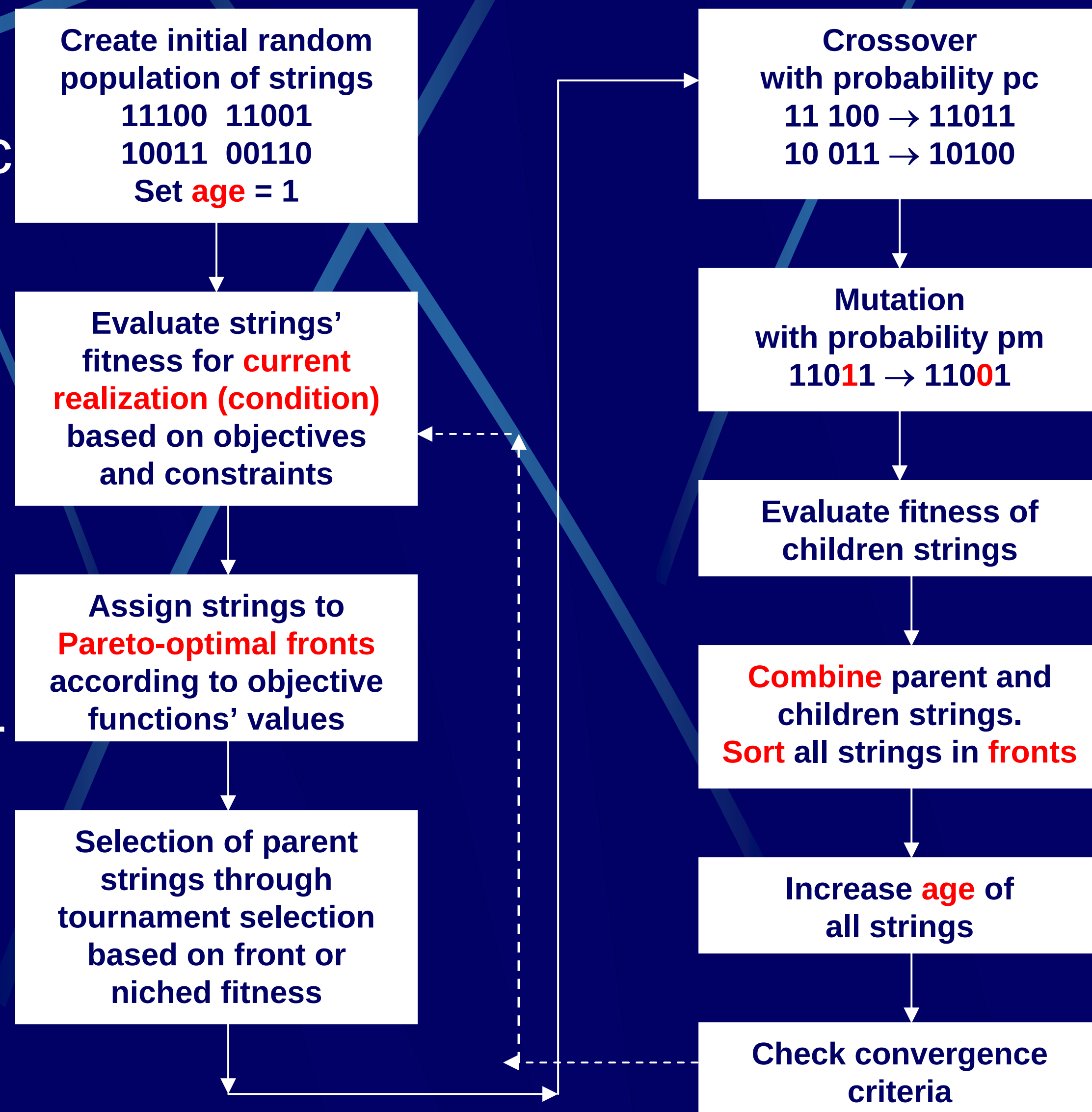
  - Minimize maximum concentration:

$$\min(C_{\max})$$

- Constraints on:
  - Hydraulic heads: $h_j \geq h_{min} \quad \forall\ j \in 1,N$
  - Pumping rates: $Q_{\min} \leq Q_k \leq Q_{\max} \quad \forall\ k \in 1,K$

Optimization Approach

- Enhanced multi-objective robust genetic algorithm (EMRGA)
  - GW flow and contaminant transport model
  - Spatially-correlated random field generator
- Accounts for parameter uncertainty
- Evolves trade-off curves (Pareto-optimal sets)



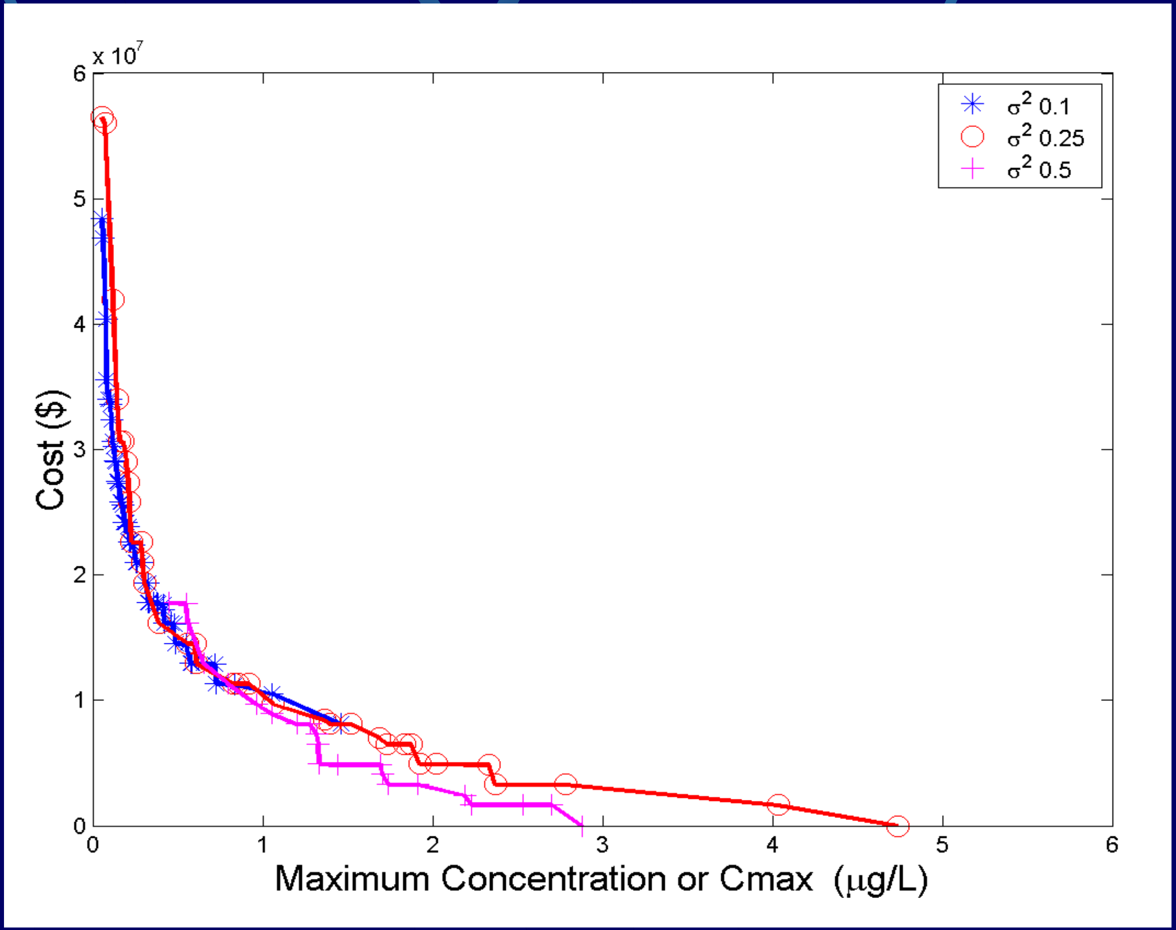
Numerical Experiments

Same average value of each parameter for all cases

Hydraulic Conductivity (*K*)	**Hydraulic Gradient (*dh/dx*)**	**Decay rate (*k*)**
$\sigma^2 = 0.1$ $\sigma^2 = 0.25$ $\sigma^2 = 0.5$	Assumed known (h_1 = 32ft, h_2 = 23 ft; dh/dx = 0.00625)	Assumed known (k = 0.001/day)
$\sigma^2 = 0.1$ $\sigma^2 = 0.5$	Low range (h_1=31 to 33 ft) Moderate (h_1=30 to 34 ft) High range (h_1=28 to 36 ft)	Assumed known (k = 0.001/day)
$\sigma^2 = 0.1$ $\sigma^2 = 0.5$	Assumed known (h_1 = 32ft, h_2 = 23 ft; dh/dx = 0.00625)	Low range (k=5e-4 to 1.5e-3) Moderate (k=1e-4 to 1e-2) High range (k=5.6e-5 to 1.8e-2)

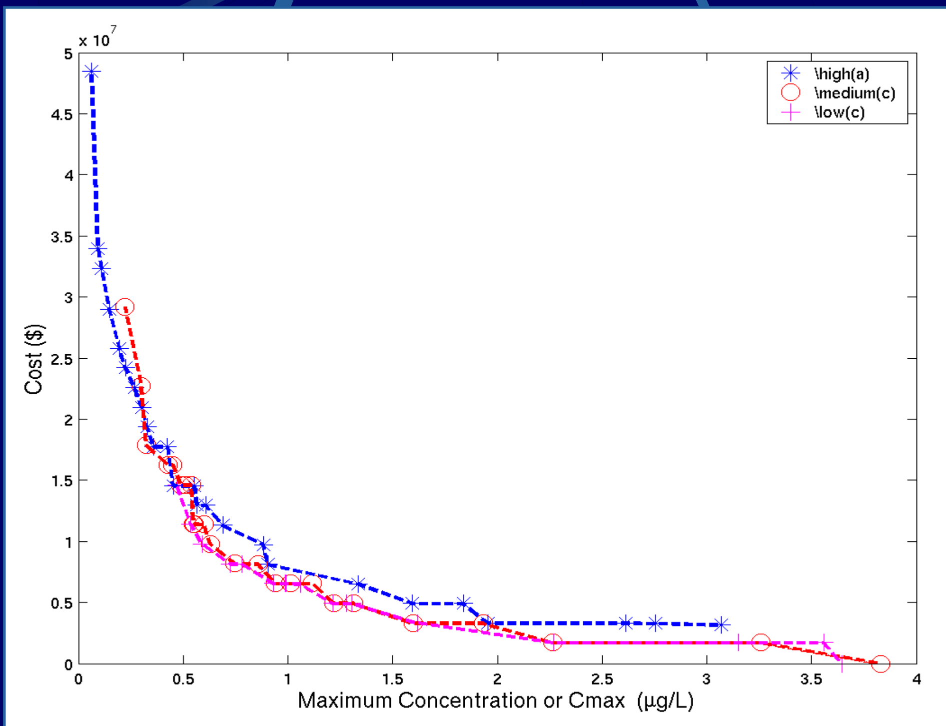
Results: Uncertainty in K

- Optimal solution represented by trade-off curve between conflicting goals
- Each point represents an optimal design

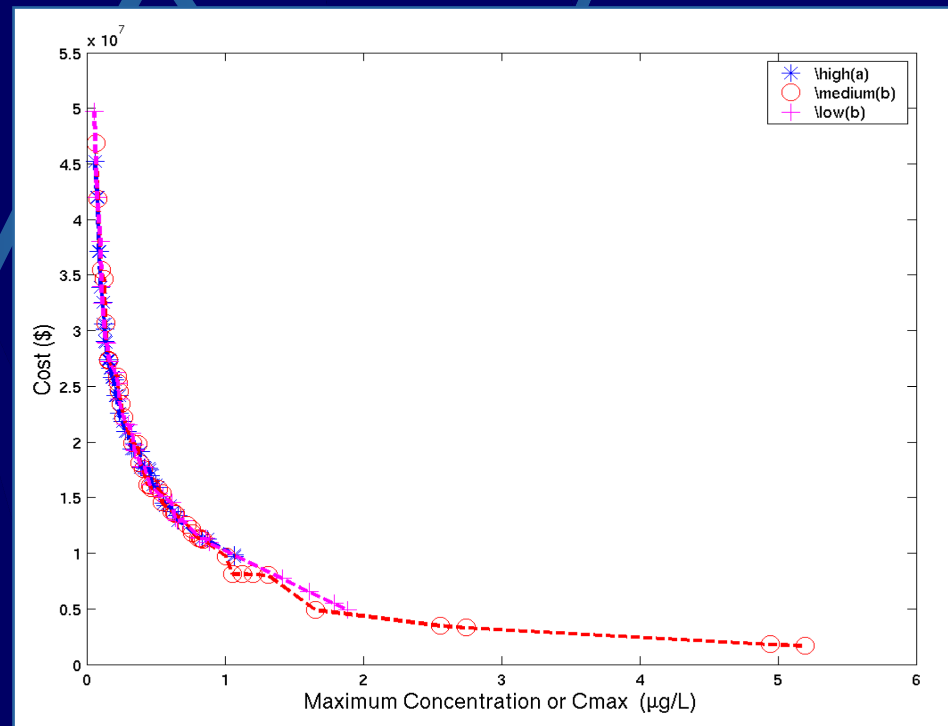


Uncertainty in dh/dx and K

High K uncertainty

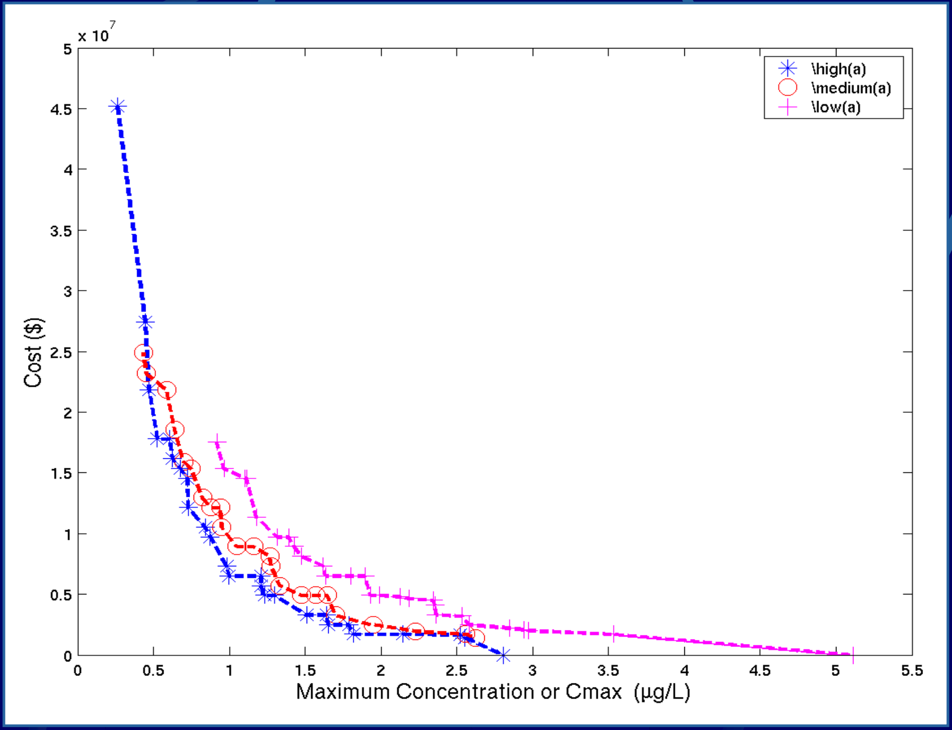


Low K uncertainty

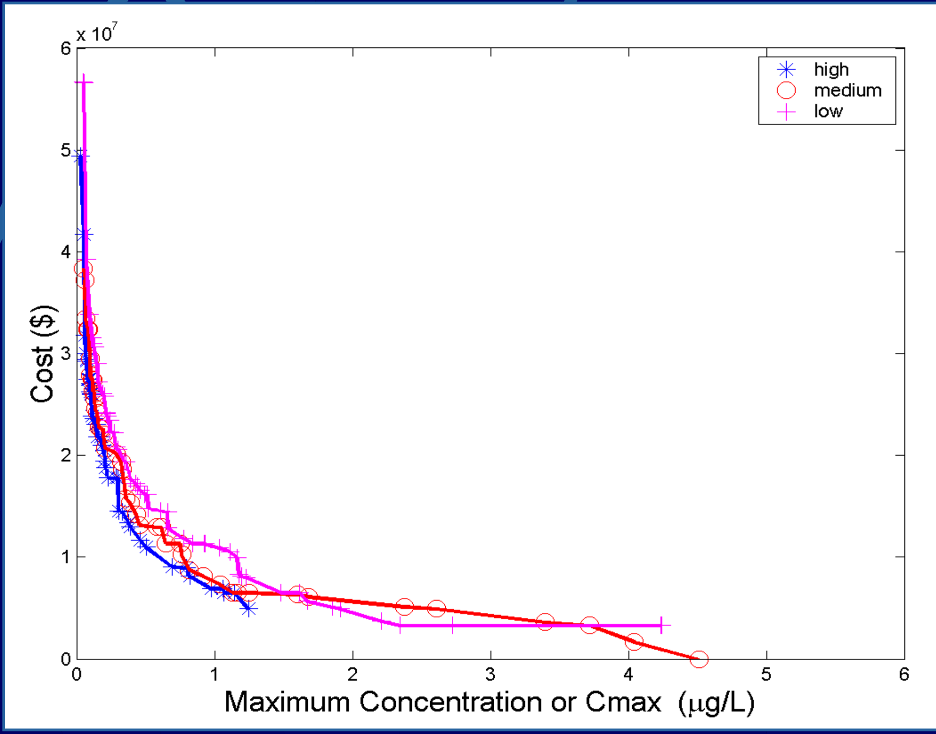


Uncertainty in k and K

High K uncertainty

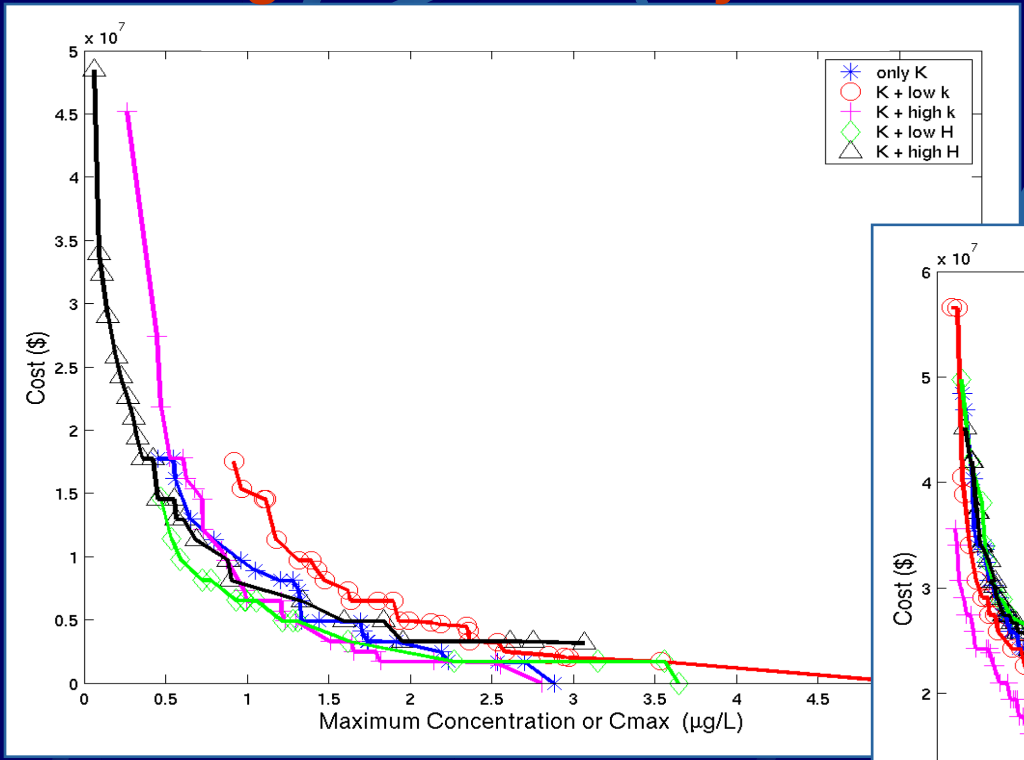


Low K uncertainty

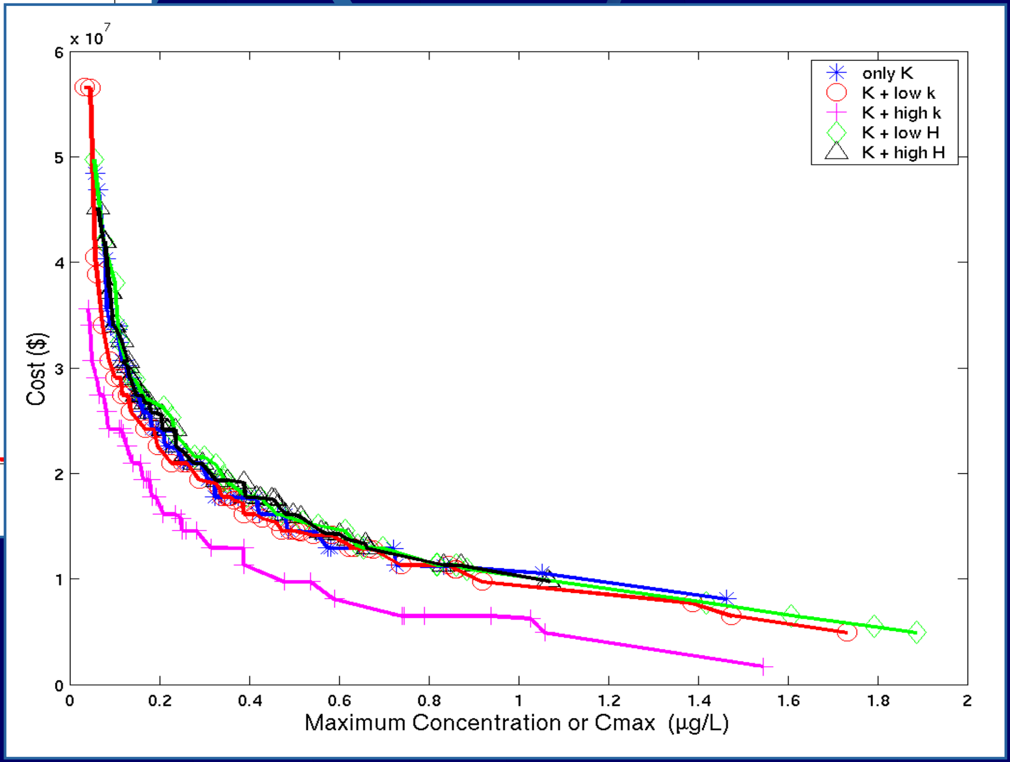


Comparison: All Cases

High K uncertainty

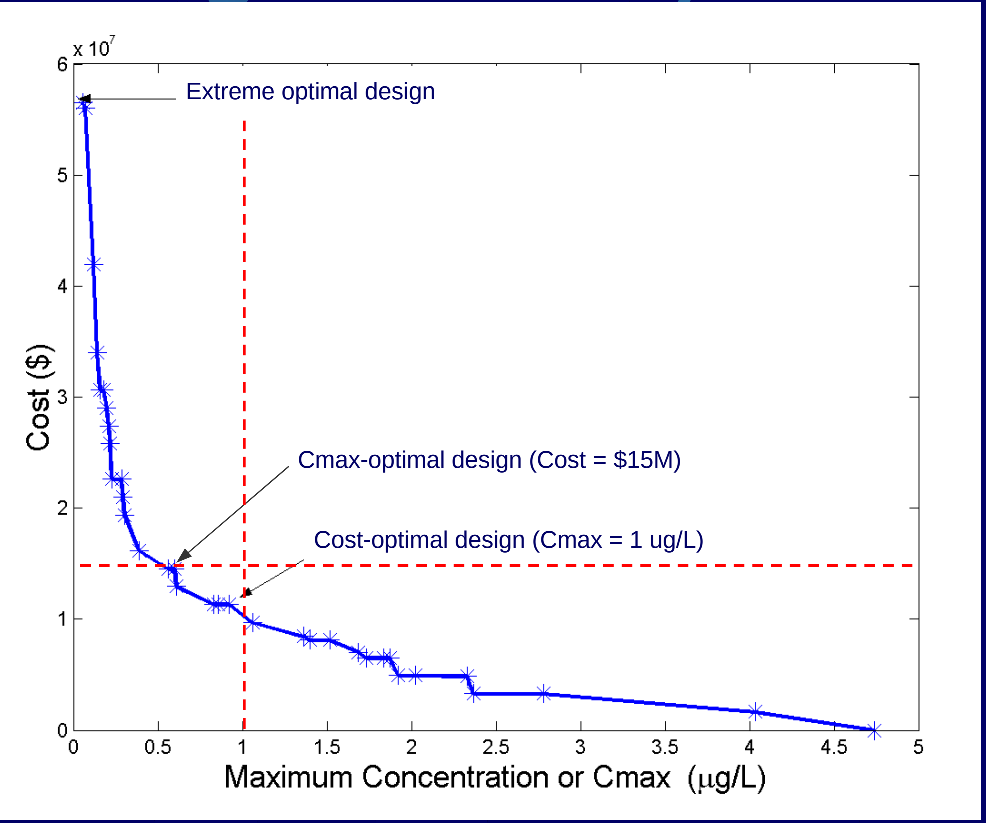


Low K uncertainty



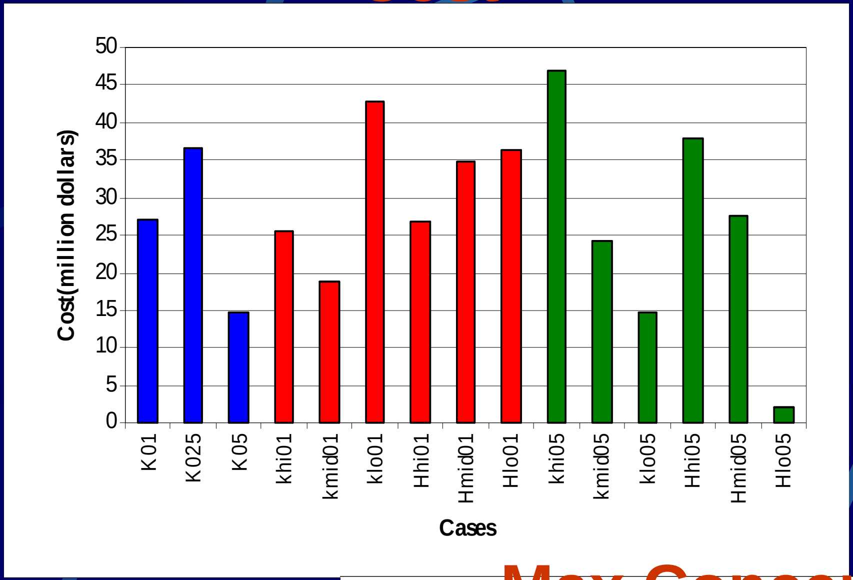
Analysis of Optimal Designs

- For each case, analyze selected designs:
  - Extreme optimal design
  - Cost-optimal design
  - Cmax-optimal design
- Analysis through Monte-Carlo simulations
- Performance measures:
  - Cost
  - Maximum concentration
  - Reliability

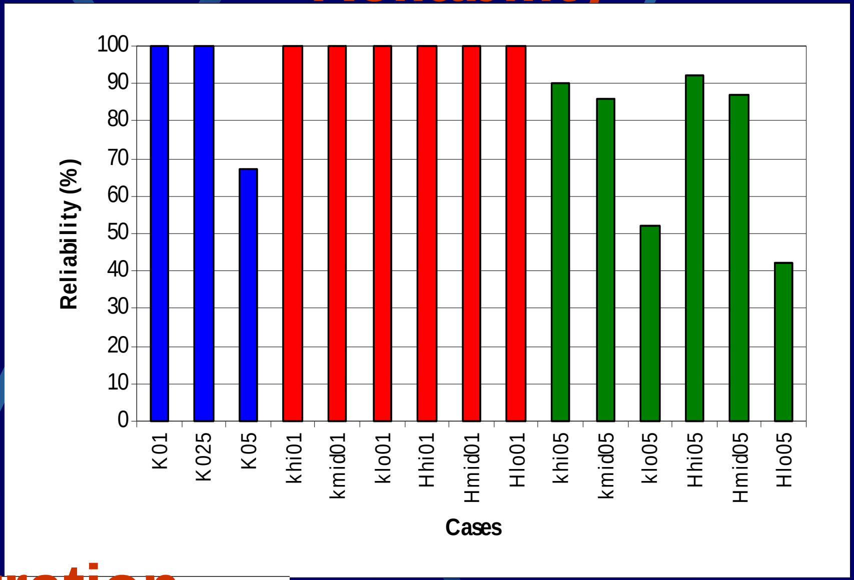


Extreme Optimal Designs

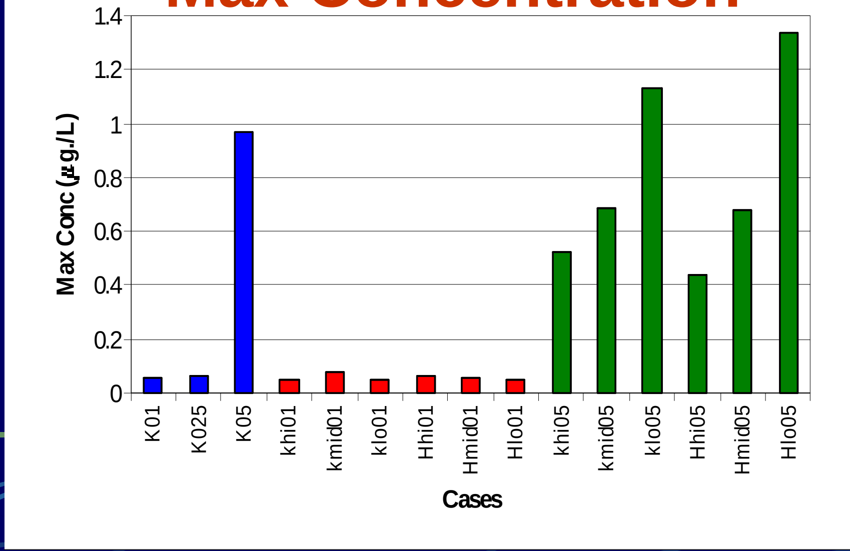
Cost



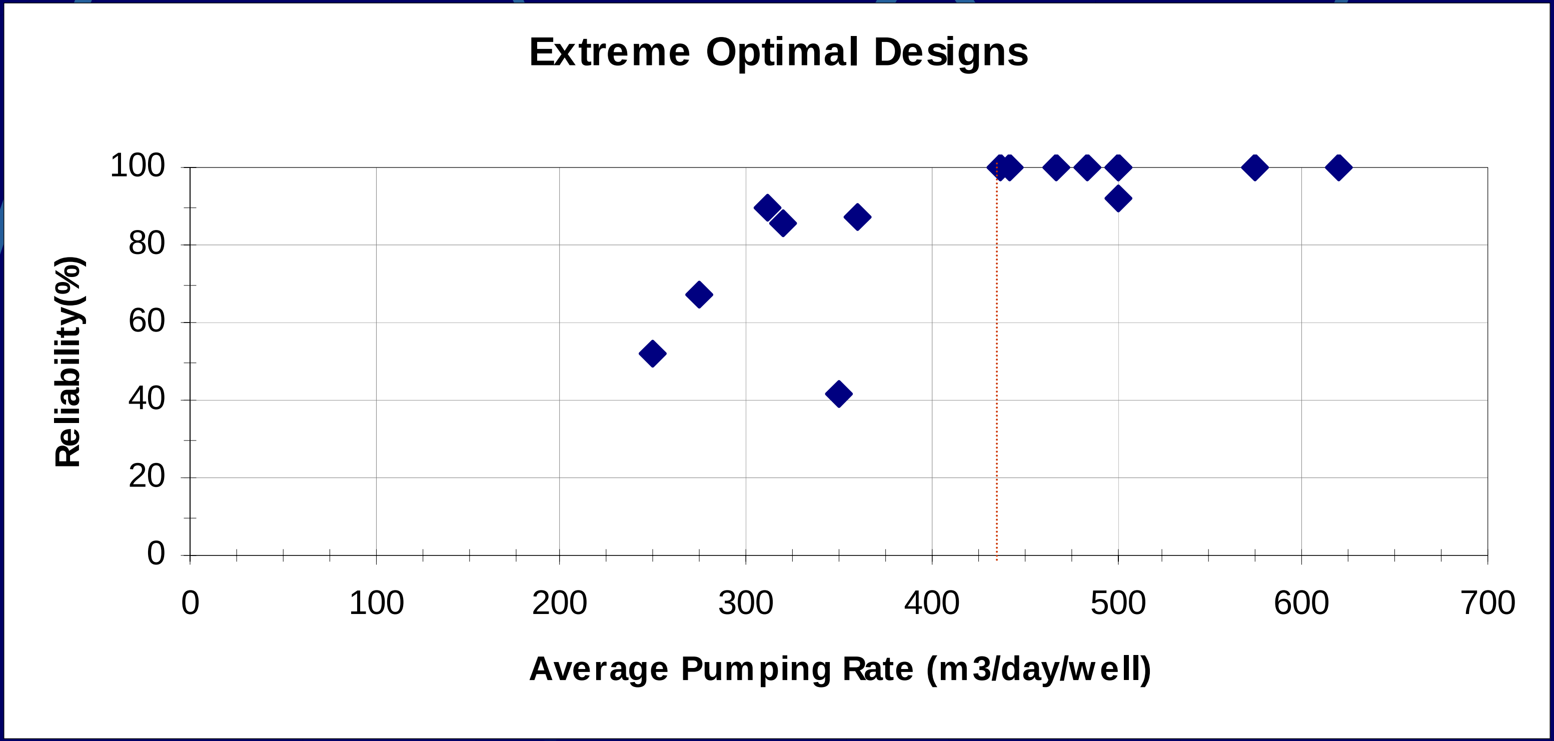
Reliability



Max Concentration



Threshold Average Pumping Rate?



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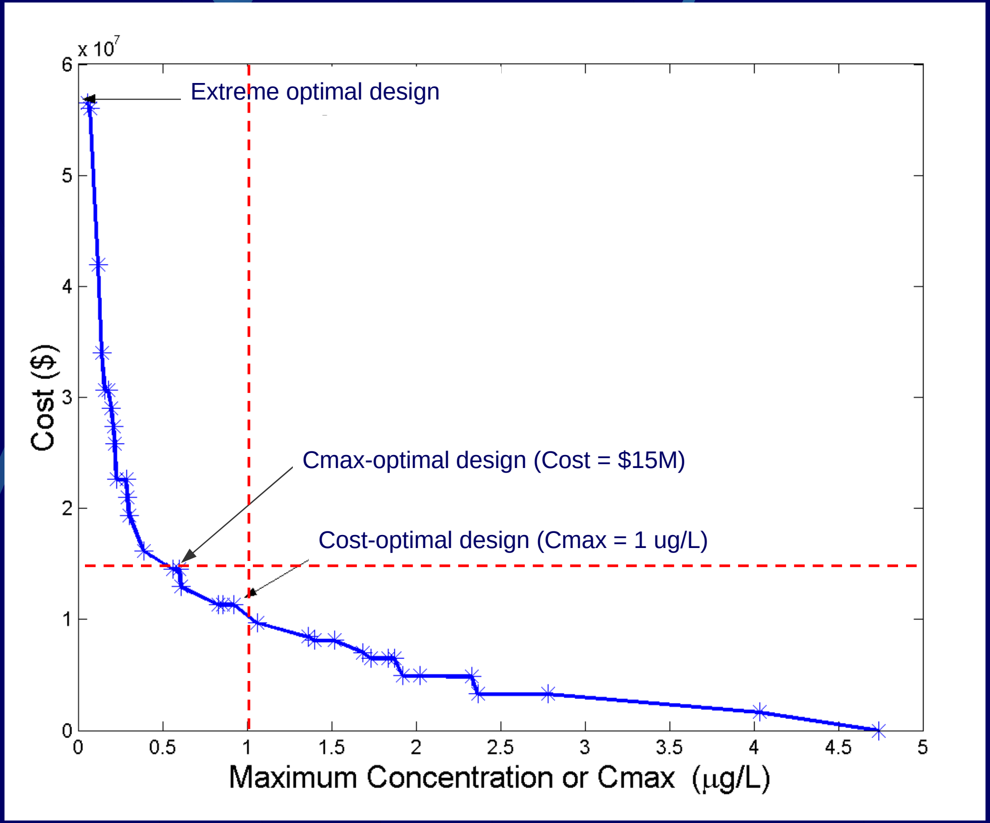
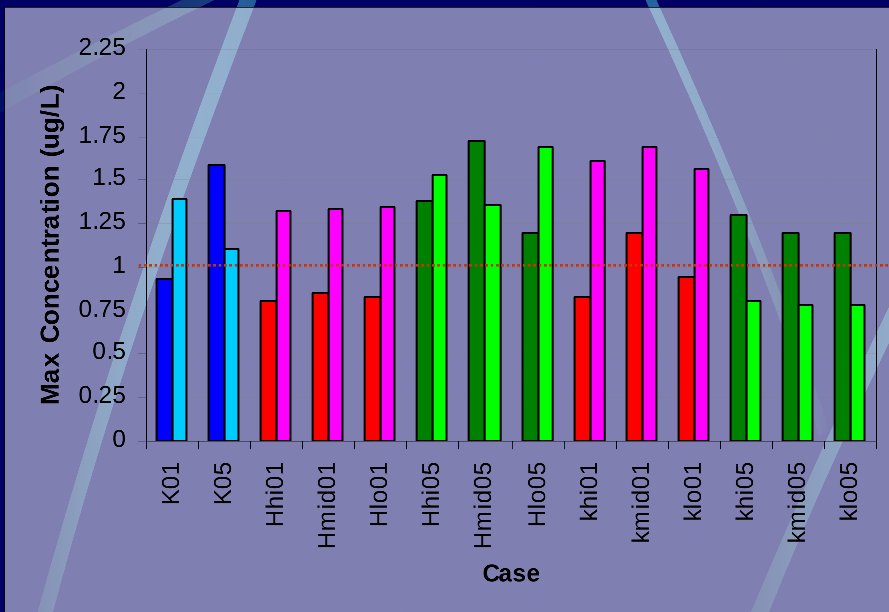


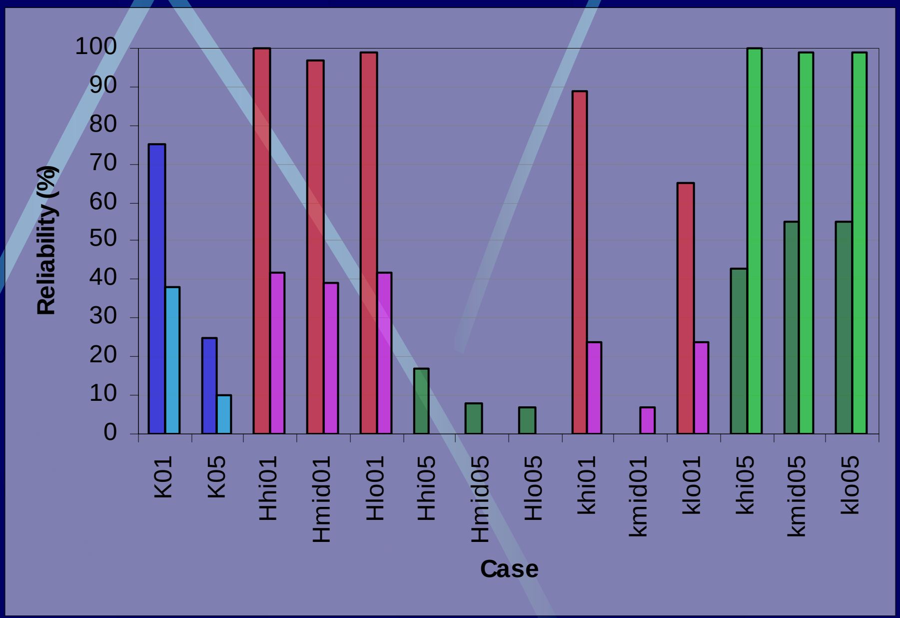
Cost-Optimal Designs

Cmax = 1 ug/L

Max Concentration



Reliability



All cases evaluated on same K uncertainty scenarios

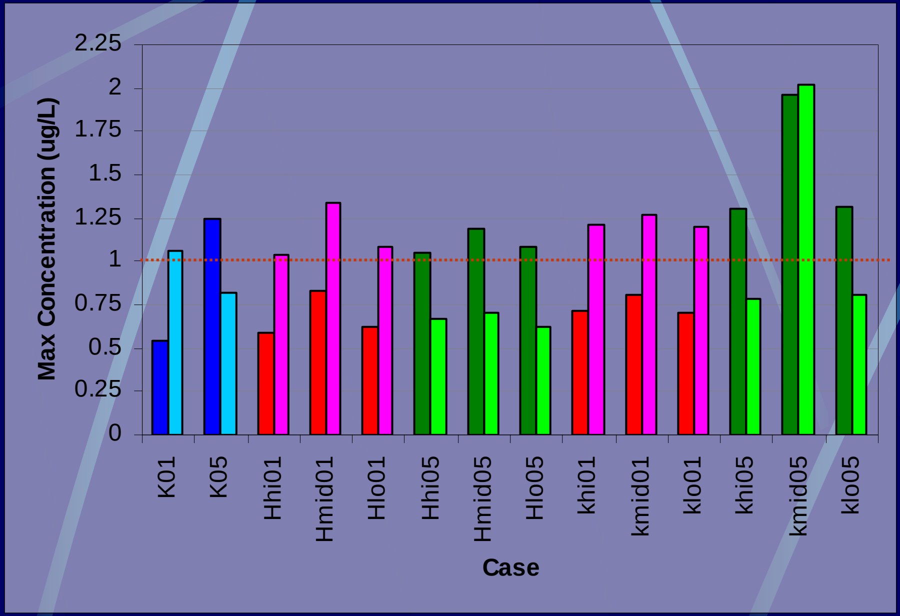
Left bars: Analyzed using low K variance ($\sigma^2 = 0.1$)

Right bars: Analyzed using high K variance ($\sigma^2 = 0.5$)

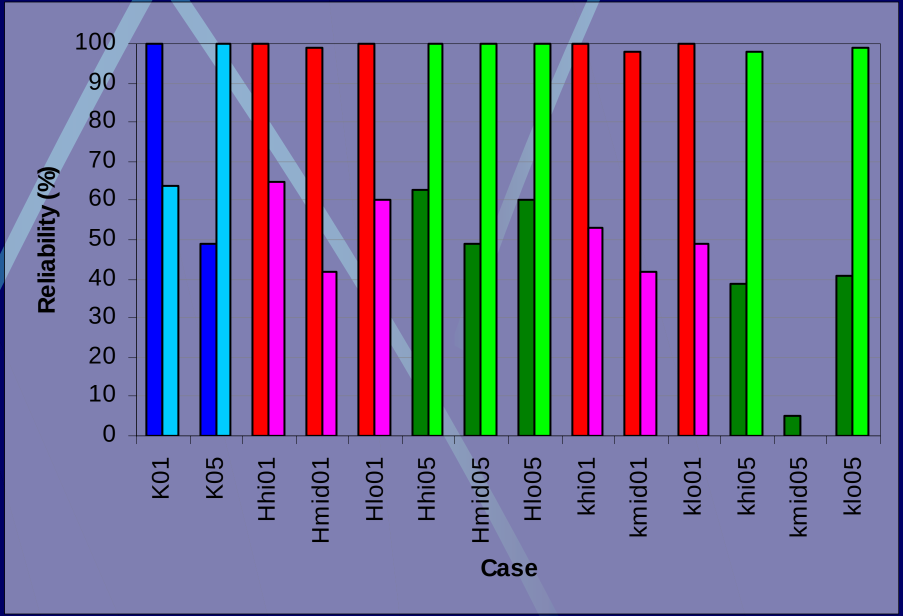
Cmax-Optimal Designs

Cost = $15M

Max Concentration



Reliability



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Conclusions

- As uncertainty and heterogeneity increases:
  - Fewer designs with lower maximum concentrations
  - Differences in trade-off curves increase
- Consider parameter uncertainty
  - Hydraulic conductivity most important
  - Multiple parameter uncertainty significant for cases with high K uncertainty
- Assuming more uncertainty/heterogeneity may not produce more robust designs
  - Quantify uncertainty and parameter variability

Acknowledgments

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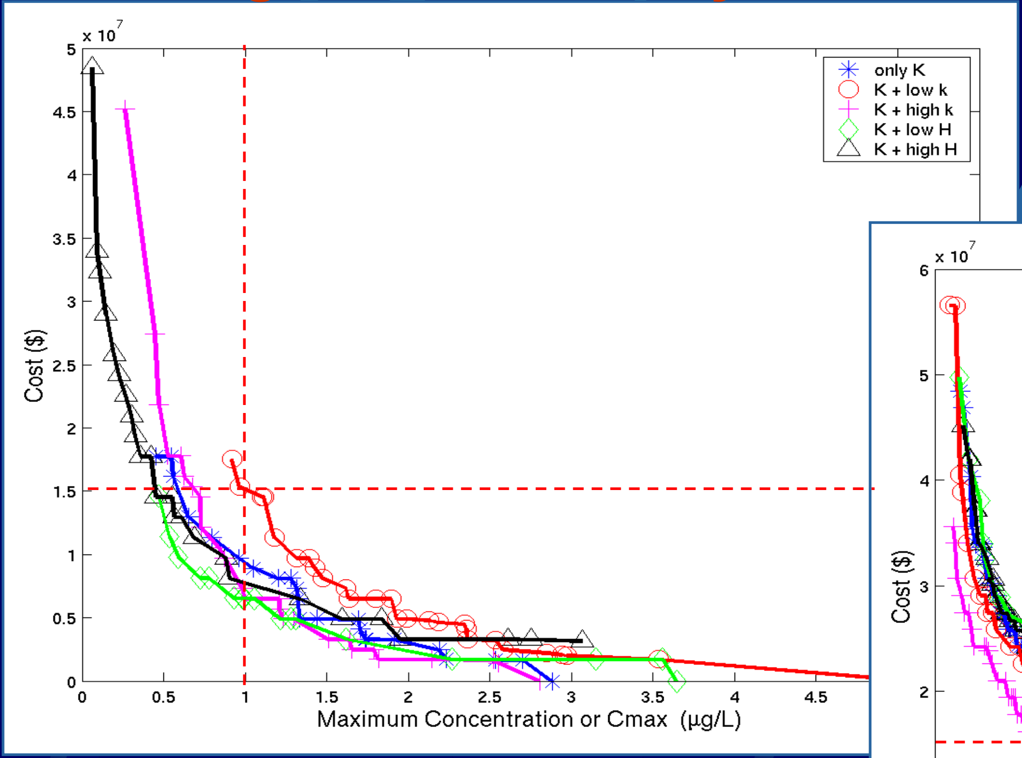
Comparison: All Cases

High K uncertainty



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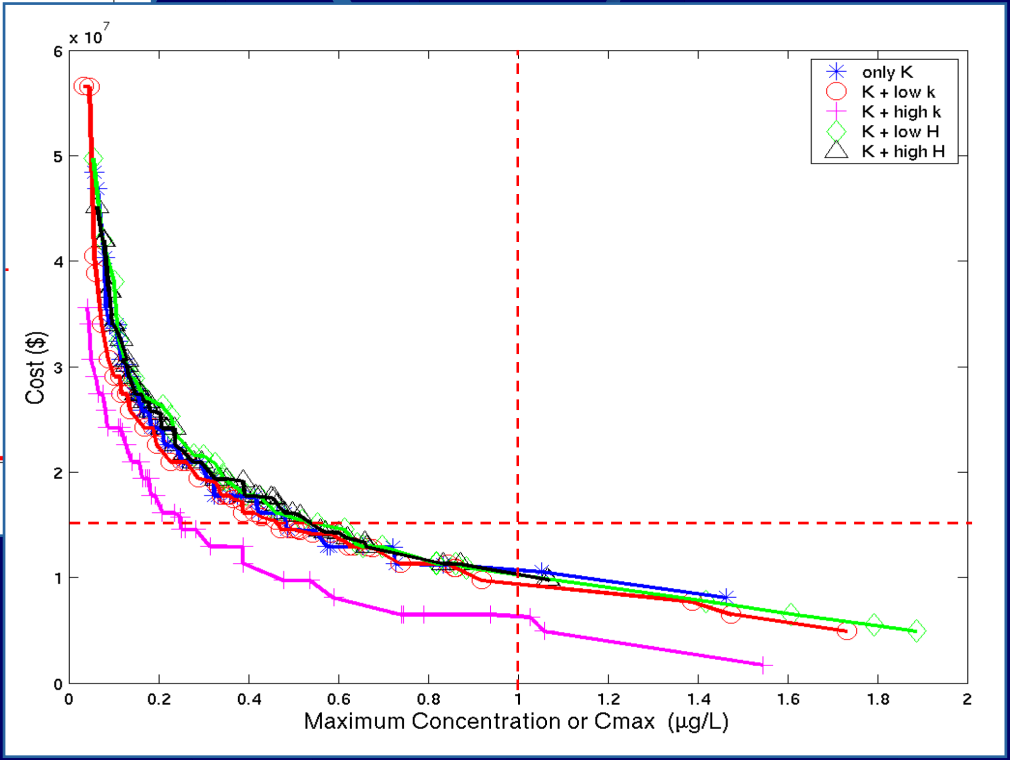
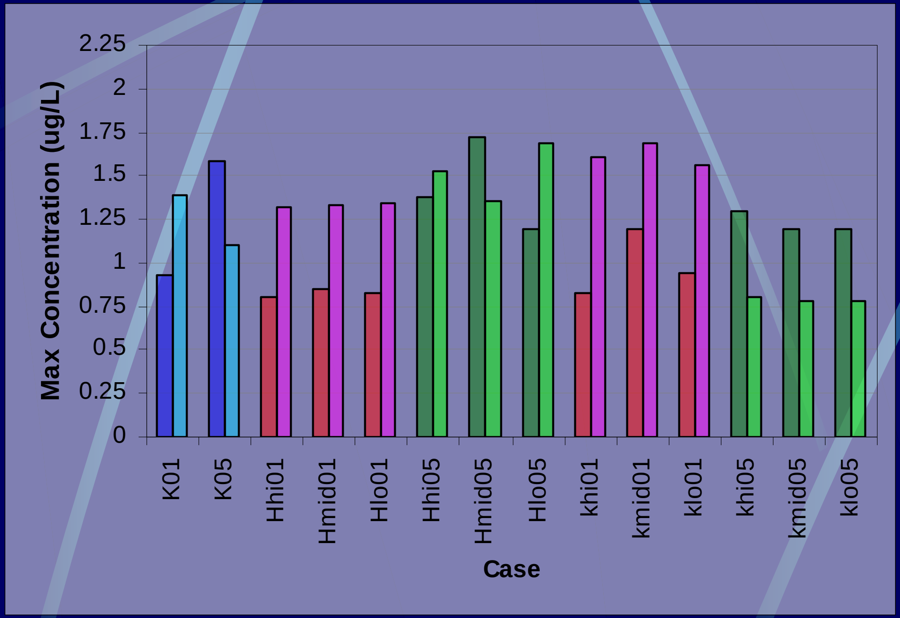
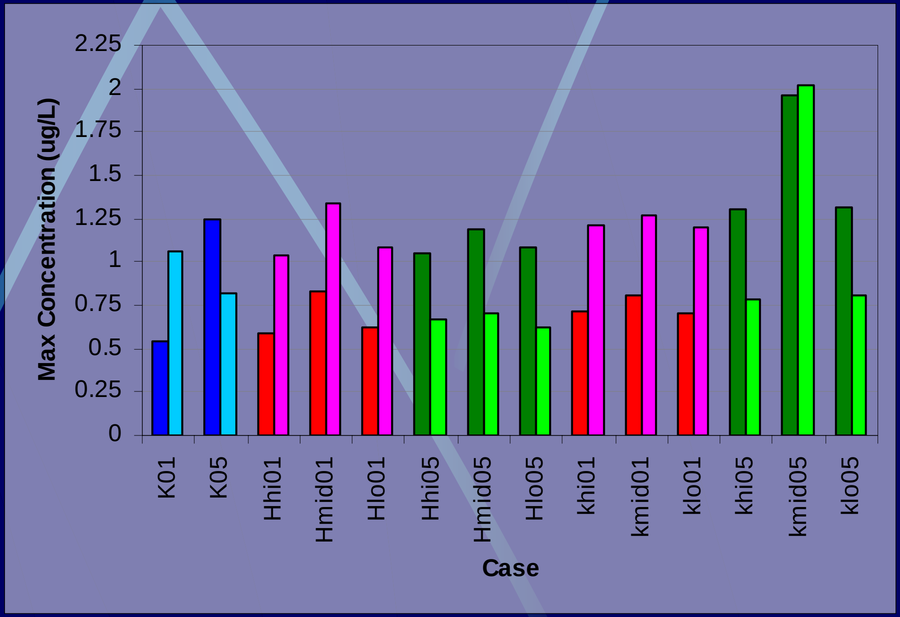


Clean-up Levels of Designs

Cost-Optimal (Cmax = 1 ug/L)



Cmax-Optimal (Cost = $15M)



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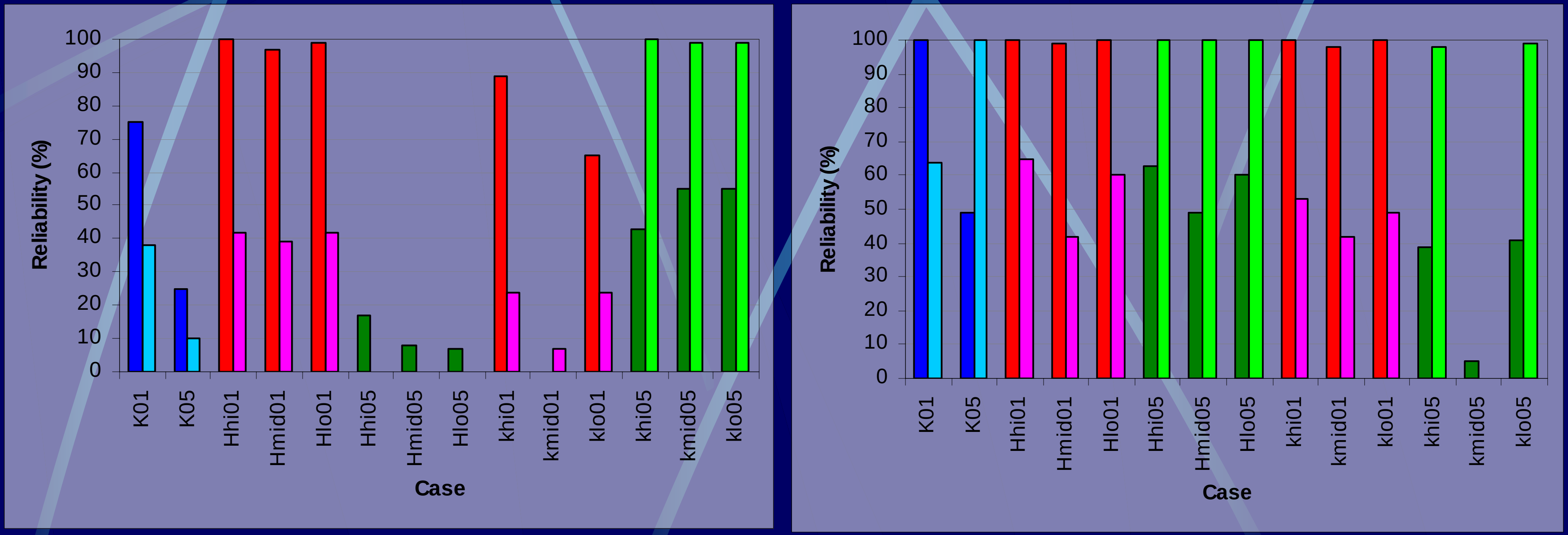
Reliability of Designs

Cost-Optimal (Cmax = 1 ug/L) **Cmax-Optimal (Cost = $15M)**



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