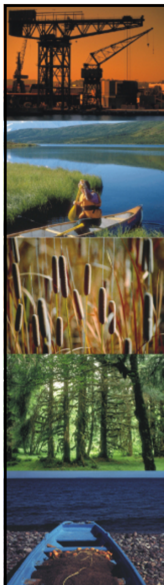

Considering Uncertainty in Remedy Design and Implementation

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engineers, scientists, economists

"Management decisions must be made even when information is imperfect. There are uncertainties associated with every decision that need to be weighed, evaluated and communicated to affected parties. Imperfect knowledge must not become an excuse for not making a decision."

National Research Council, *A Risk Management Strategy for PCB-Contaminated Sediments, (2001)*

Steps in Design Sequence

Differing degrees and types of uncertainty can enter the design sequence at any step

- Problem definition
- Alternatives creation
- Analysis among possible alternatives
- Design specification
- Design implementation
- Problem resolution and monitoring

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Why Do We Care?

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General Types of Uncertainty

Class of Uncertainty	Discriminator	Valuation	Method
Temporal (future)	Probability	Luck	Prediction
Temporal (past)	Historic Data	Correctness	Retrodiction
Structural (complexity)	Usefulness	Confidence	Modeling
Metrical (measurement)	Precision	Accuracy	Statistics
Translational (perspective)	Goals/Values	Understanding	Communications

Rowe, 1994, "Understanding Uncertainty"

Monitored Natural Recovery

- Implicitly or explicitly part of most conceptual site models (CSM)
- Implicitly or explicitly part of many remedial designs
- Active agents for remediation
  - Watershed processes
  - Biological degradation
  - Physicochemical processes

Like the Stock market, Past Performance is not Always a Guarantee of Future Trends

- Environmental media relation
  - Records from sediment, water, biota monitoring, and sediment cores
  - Quality Assurance/Quality Control (QA/QC) concerns in historic data
  - Confounding factors
- Single vs. multi-phase process
  - Multiple sources
  - Primary vs. secondary sources
  - Depositional vs. transitional sediments

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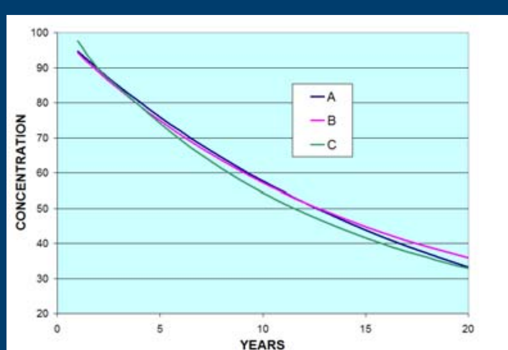
Hypothetical Rates of Natural Recovery Compared



- Three trend lines
- Trends are so close that with natural variability in environmental conditions, monitoring results would likely not distinguish a difference
- Without a more complex mechanism in the CSM, any of these trends would likely be identified as a simple exponential decay trend

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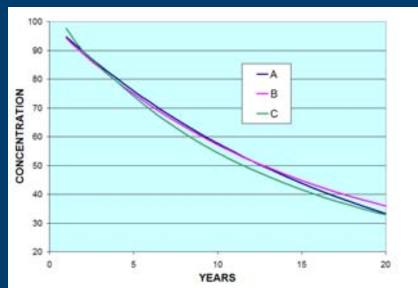
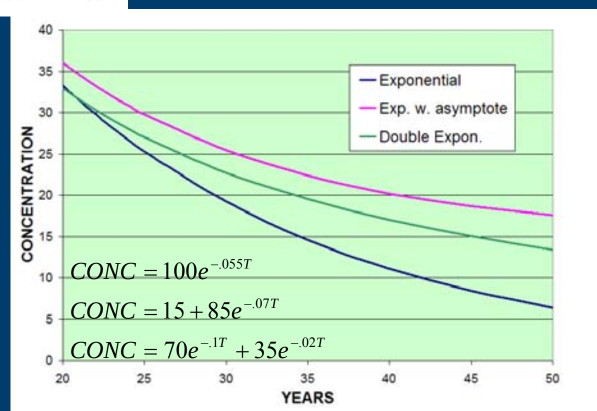


Where natural recovery rate is dependent on multiple processes, minor historical contributions can potentially produce a significant future influence



Monitored Natural Recovery Predictive Tools

- Regression analysis
- Modeling
- Realistic bounds on natural variability
- Acceptance of chance occurrence of the rare event

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Regression Analysis Methods for Monitored Natural Recovery

- Bounds of expectation
- Dealing with natural variability
  - Response to rare but expected conditions
  - Other ancillary factors
- Importance of monitoring plan
  - Expectation for various monitored media
  - Identifying reasonable time periods
  - Identifying the truly unexpected results
  - Adaptive management options identified
- Communication with stakeholders

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Capping - Potential Uncertainties

- Because material remains, the consequence of uncertainty increases
- Stability and permanence
  - Event and construction driven
  - Secondary channel impacts
- Chemical Isolation
  - Mass transfer
  - Difference between organics and metals
  - Bioturbation depths
  - Ground water, DOC, gas generation
- Habitat considerations

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Dredging - Potential Uncertainties

- Dredging releases
  - Short term and long term
- Residual concentrations
  - Certainty of mass reductions vs. uncertainty of concentration reduction
- Transport and disposal
- Dredging prism production and volume
- Material characterization for processing

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Modeling

Often the question is not if to model but what and how to model

- Hydrodynamic model with sediment and chemical transport capabilities
- Chemical mass balance/transport
- Materials processing mass balance
- Cost modeling

be aware of underlying assumptions

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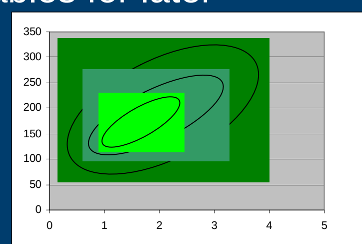
Sensitivity Analysis

(ΔOutput/Output)/(ΔInput/Input)

- Measure the effect of a variable, process or assumption over its probable range on the resulting output – **determine dominant variables**
- Can be used to screen variables for later Monte Carlo
- Usually single variable, but sometimes multiple



Monte Carlo Simulation

- Developed 50+ years ago
- Uses repetitive statistical sampling to obtain a probabilistic approximation to a solution of an equation or model
- Input parameters fixed, empirical, or probability distribution
- Simple random or Latin Hypercube or bootstrap
- Used extensively in environmental risk assessment

Guiding Principles for Monte Carlo Analysis (EPA, 1997)
Policy for Use of Probabilistic Analysis in Risk Assessments (EPA,1997)
Suppl. Guide to RAGS: The Use of Probabilistic Analysis in Risk Assessment – Part E 16

"This problem of specification of probabilities in cases where little or no information is available is as old as the theory of probability."

E.T. Jaynes, 1957
"Information Theory and Statistical Mechanics"

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Advective Transport to Evaluate a Proposed Cap

Parameter	assumed value	assumed distribution		
			mean	st.dev.
Effective Thickness	0.4 meters	normal	0.4	0.1
Cap TOC	0.80%	normal	0.008	0.002
Cap porosity	0.35	uniform	0.3 (min)	0.4 (max)
Cap Spec. Grav.	2.55	uniform	2.45 (min)	2.60 (max)
Sed. Contam. Conc.	20 mg/kg	normal	20	2.5
Log Koc	5.75	normal	5.75	0.25
Log Kdoc	4.75	regression	0	0.6
Sed. TOC	4.00%	lognormal	-1.4 (0.04)	0.2 (60%)
Sed. DOC	10 mg/l	lognormal	1 (10)	0.2 (60%)
GW velocity	2 cm/day	lognormal	0.3 (2)	0.25 (80%)

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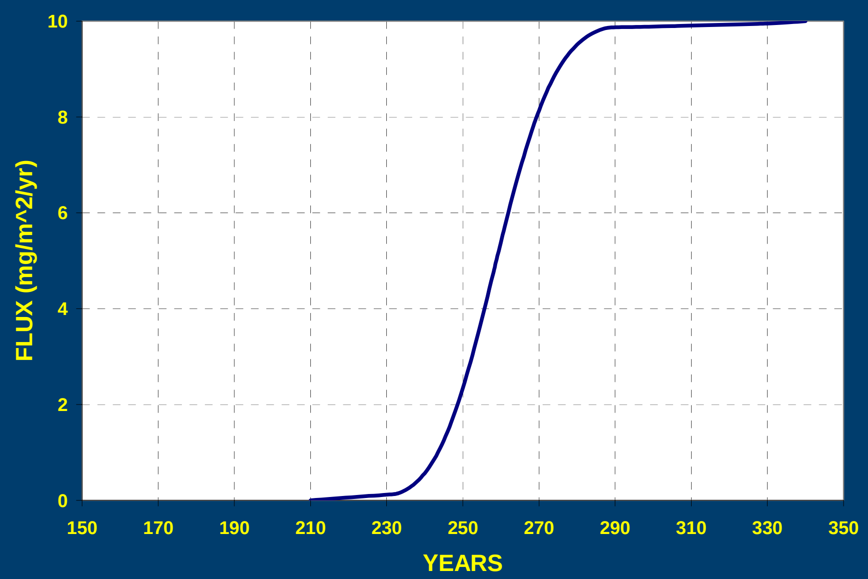
Computed Breakthrough Curve



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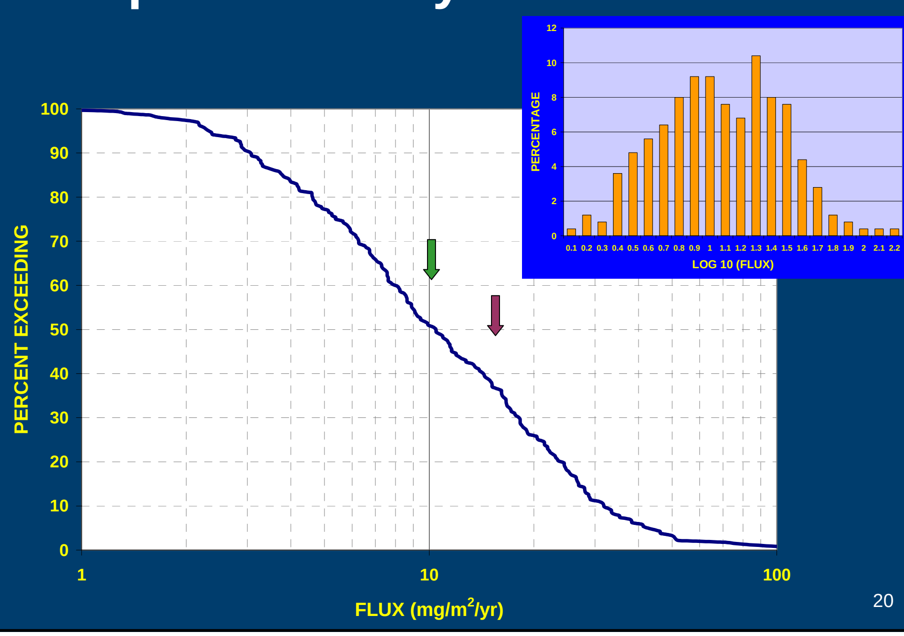
Computed Steady-State Flux



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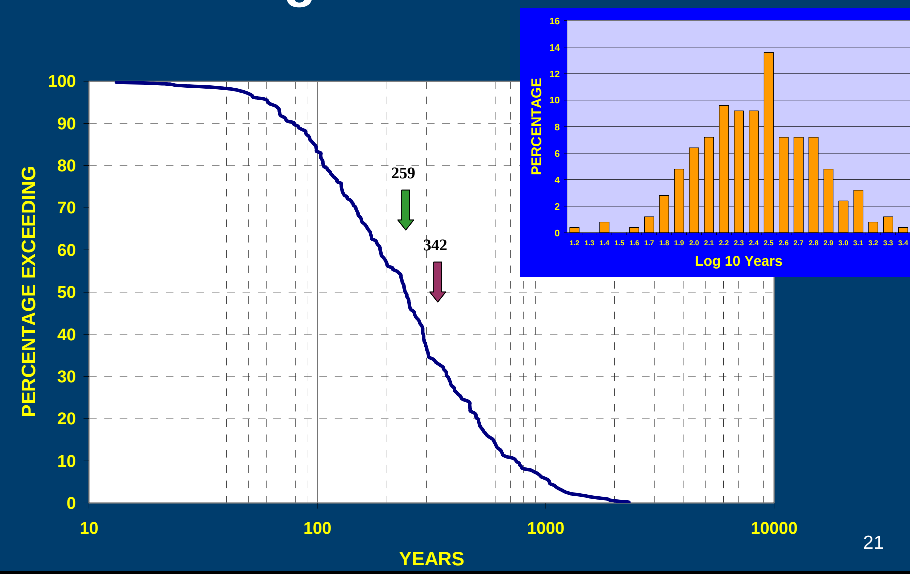
Years to Midpoint of Advective Breakthrough Curve



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An alternative to the computation of uncertainty by methods such as Monte Carlo analysis is to incorporate uncertainty into the design process.

Design decision can be made based on “design not to fail” techniques such as fault trees, decision trees, or failure mode and effects analysis (FMEA)

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A potential failure may be associated with a cause, mode, and effect. In the context of capping there may be either:

- **Structural Failure** - the collapse or scour of the cap or its components
- **Functional Failure** – the cap remains intact but does meet stated objectives

Not all failure modes are important; some may be inconvenient; others are critical

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Failure Mode and Effects Analysis (FMEA)

- Systematically identifies potential component failure modes and assesses the effect on the system
- Failure modes identified by case studies, lab experiments, field experience and expert opinion
- Effects, consequences, likelihood, difficulty of detection, and difficulty in correcting or compensating are rated to give a risk priority number (RPN)
- RPNs used to determine design aspects that require additional attention to prevent failure
- Can include both economic and environmental factors

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Example FMEA Matrix

Component	Failure Mode	Interaction w/ components	Effects on System	Detection Methods	Corrective Actions
Armor	channel migration	possible isolation layer exposure and sediment	possible under cutting of cap potential geomorphic impacts	visual, monitoring survey or scour pins	bank stabalization or stream modification
	navigation impact	possible isolation layer exposure	scour of islolation layer and sediment	incident reports	inspection; poss. local reconstruction
	change in basin hydrology	possible isolation layer exposure	scour of islolation layer and sediment	monitoring threshold for Q	inspection; poss. local reconstruction
	erosion of opposite bank	minimal	increase sediment transport	visual	bank stabalization or stream modification
Isolation layer	winnowing/ filter criteria	passing thru armor	long-term loss in sorptive capacity	monitoring cores through cap	additional armor/ replacement
	mixing with sediments	geotechnical instability	decrease effectivness	monitoring cores through cap	change in application geotextile additional material
Organoclay	dissolution	decrease isolation layer Kd	decrease effectivness; reintroduction	testing of core material	evaluation; possible reconstruction

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Consequence

Minimal impact
No long-term effect
Increased monitoring
Limited loss of use (water level)
Moderate short term (small breach)
Limited cap reconstruction
Shortened cap life
Significant replacement
No net risk reduction
Increase env exposure

Likelihood

Nearly impossible
Remote, but possible
Possible
Frequently observed
Reasonably probable

Detection

Easily detected
Simple visual
Routine monitoring
Increased monitoring
Specific event investigation
Extensive investigation
Extreme difficulty

Example of Capping RPNs

Component	Failure Mode	Consequence Rating	Occurance Rating	Detection Rating	Risk Priority Number
Armor	channel migration	7	3	1	21
	navigation impact	4	2	5	40
	change in basin hydrology	8	4	4	128
	erosion of opposite bank	3	7	2	42
Isolation layer	winnowing/ filter criteria	6	4	6	144
	mixing with sediments	4	3	4	48
Organoclay	dissolution	7	2	8	112

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Other Potential Means of Dealing With Uncertainty

- Site-specific knowledge based
  - Clear definition of purpose/scope/goals for decision-making
  - Evolving conceptual site model
  - Sample design and reduction
    - Geostatistic for spatial data
    - Bulk chemistry vs. bioavailable component
  - Dynamic work plans supported by field analytical methods for generation of real-time data
  - Bench scale and pilot studies
  - Feed-back for other approaches identifying needs
  - Value of information (VOI)

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Other Potential Means of Dealing With Uncertainty (continued)

- Identifying threshold levels for which additional design elements must be incorporated
- Flexibility through planned phased approach or adaptive management
- Hybrid approach, if necessary
- Experienced team – especially contractor
- Early specification of the range of observable outcomes

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