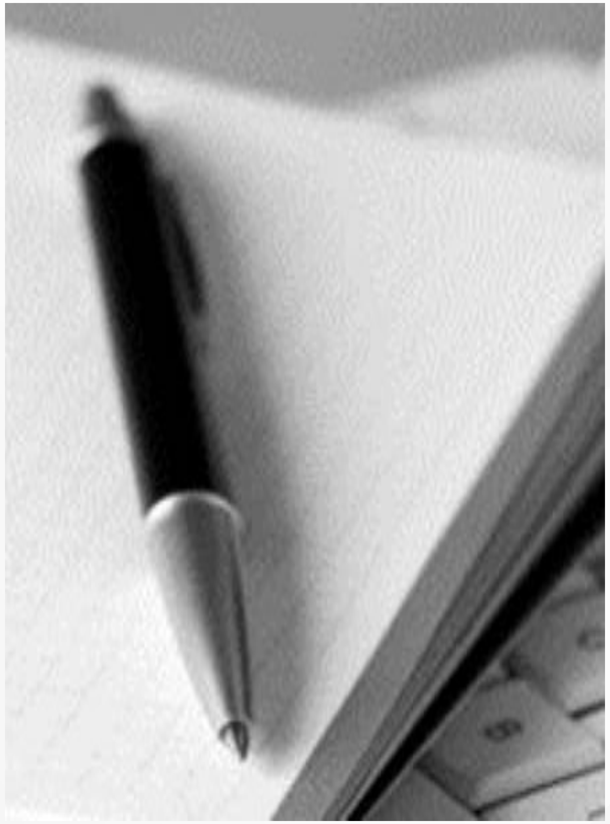
MOVING BEYOND SUBJECTIVITY –

Informed Optimization Concepts in Enhancing Groundwater Extraction and Recirculation Remedy Performance

April 28, 2021

Agenda



1 **Health and safety moment**

2 **Large plumes & complex sites**

3 **Why optimize?**

4 **Remediation hydrogeology concepts**

5 **Key metrics and methods to consider when designing/optimizing**

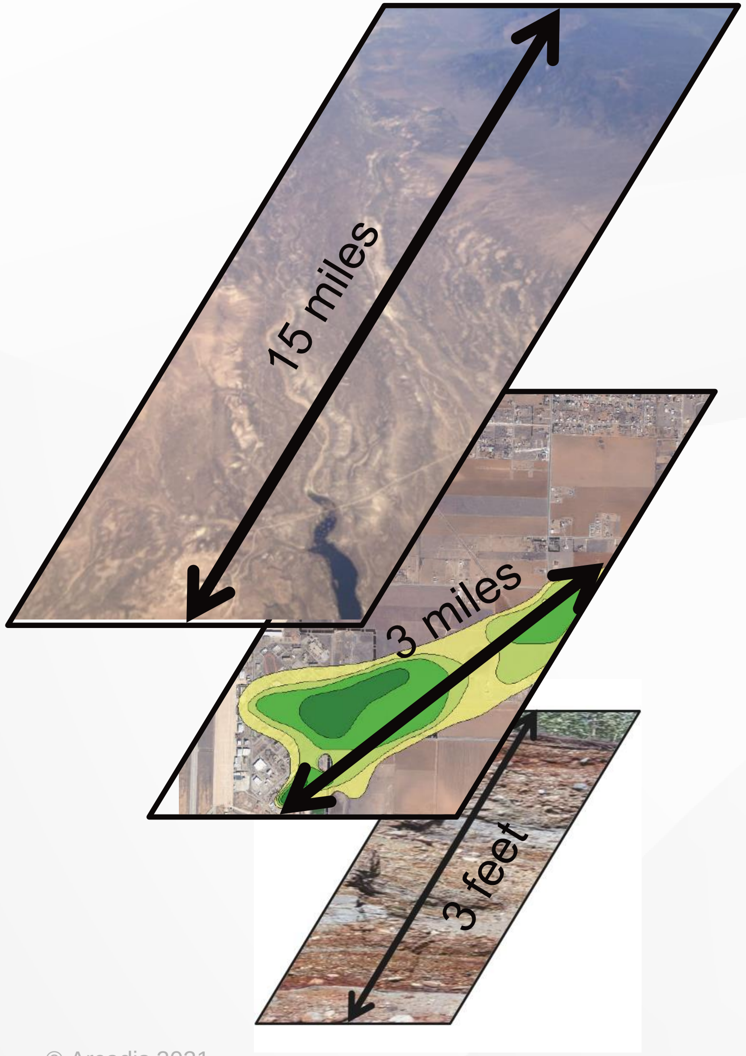
6 **Illustrative examples**

Health and Safety Moment

- 66% of all utilities struck were 3’ or less below ground surface (bgs)
- 55% of all utilities struck were 2’ or less bgs
- 33% of all utilities struck were high & medium risk utilities (gas, electric fiber) and <3’ deep
- Utility depth is critical when working above it! (sawing, digging, heavy equipment crush risk)
- Don’t Forget to look up! 10% of utility strikes are above grade – mark these too!

Can we ‘soft’ dig it…to 3 ft bgs?

Large Plume and Complex Groundwater Cleanup…



What

- New experience and insights into where contaminants move through the subsurface
- Now capable of solving the impossible – complex groundwater restoration with certainty and a feasible endpoint

Why

- Water scarcity is driving renewed focus on groundwater quality
- Forever remedies are costly and continue to threaten water supply
- Recent experience demonstrates we can cost-effectively clean up large plumes

How

- Rethinking the challenges of aquifer complexity – using the right tool for the job
- Dynamic Groundwater Recirculation (DGR^{SM}) – a remedial strategy offering "reach" and effectiveness at the large diffuse plume scale

Large/Complex Plume Challenges

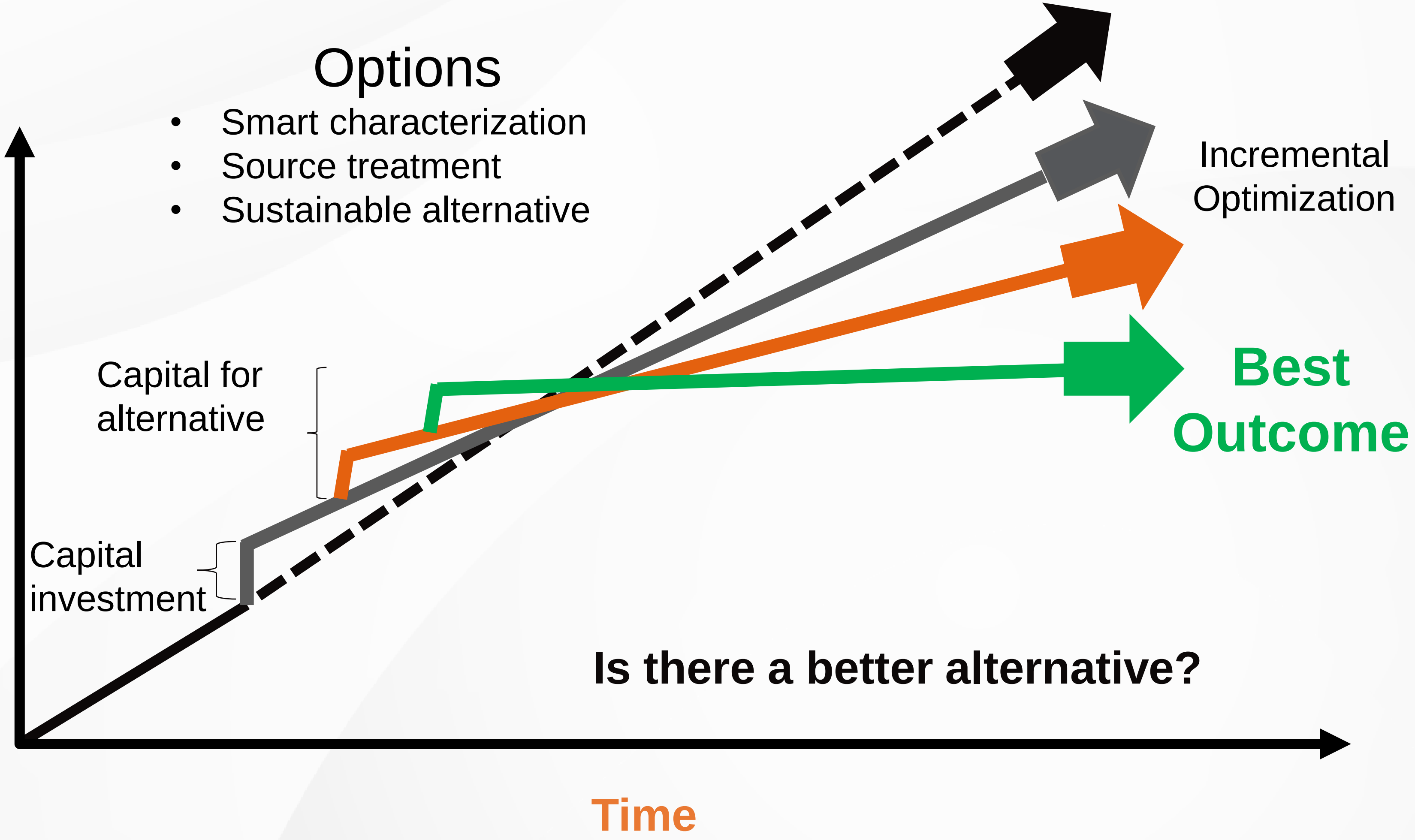
- Investigations – finding the plume
- Persistent sources
- Remedial strategies
- **Development of the Appropriate CSM**

What We've Learned

- **Smart characterization™** – separation of characterization and monitoring infrastructure
- **Mass flux** – contaminants move through small fraction of aquifer
- **Combined remedies** required
- **Big data** – re-thinking existing CSMs
- **Renewed focus on groundwater recirculation** achieves results on diffuse portions of plumes

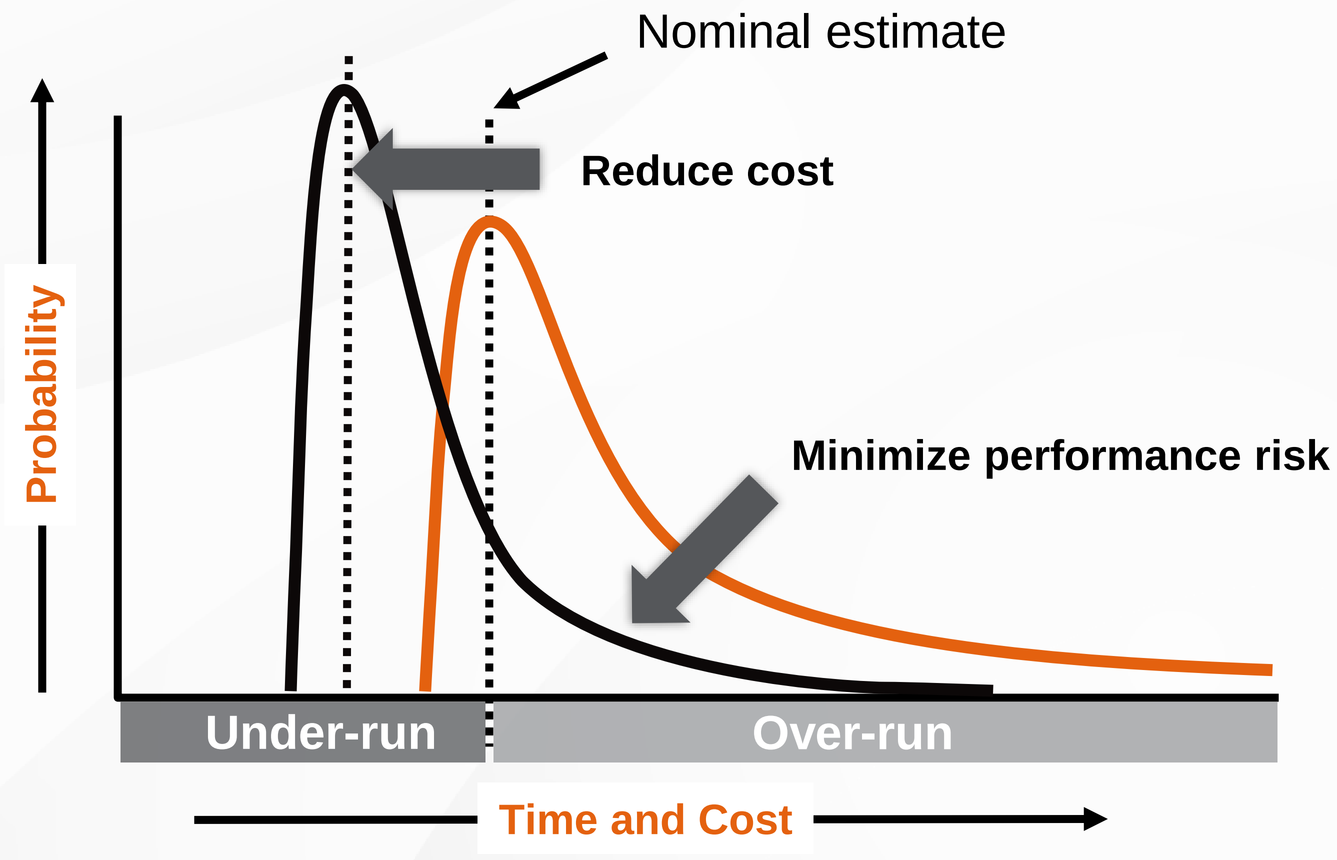
The Remedy Optimization: Business Case

Return on Investment
What investment makes sense and how do we measure success?



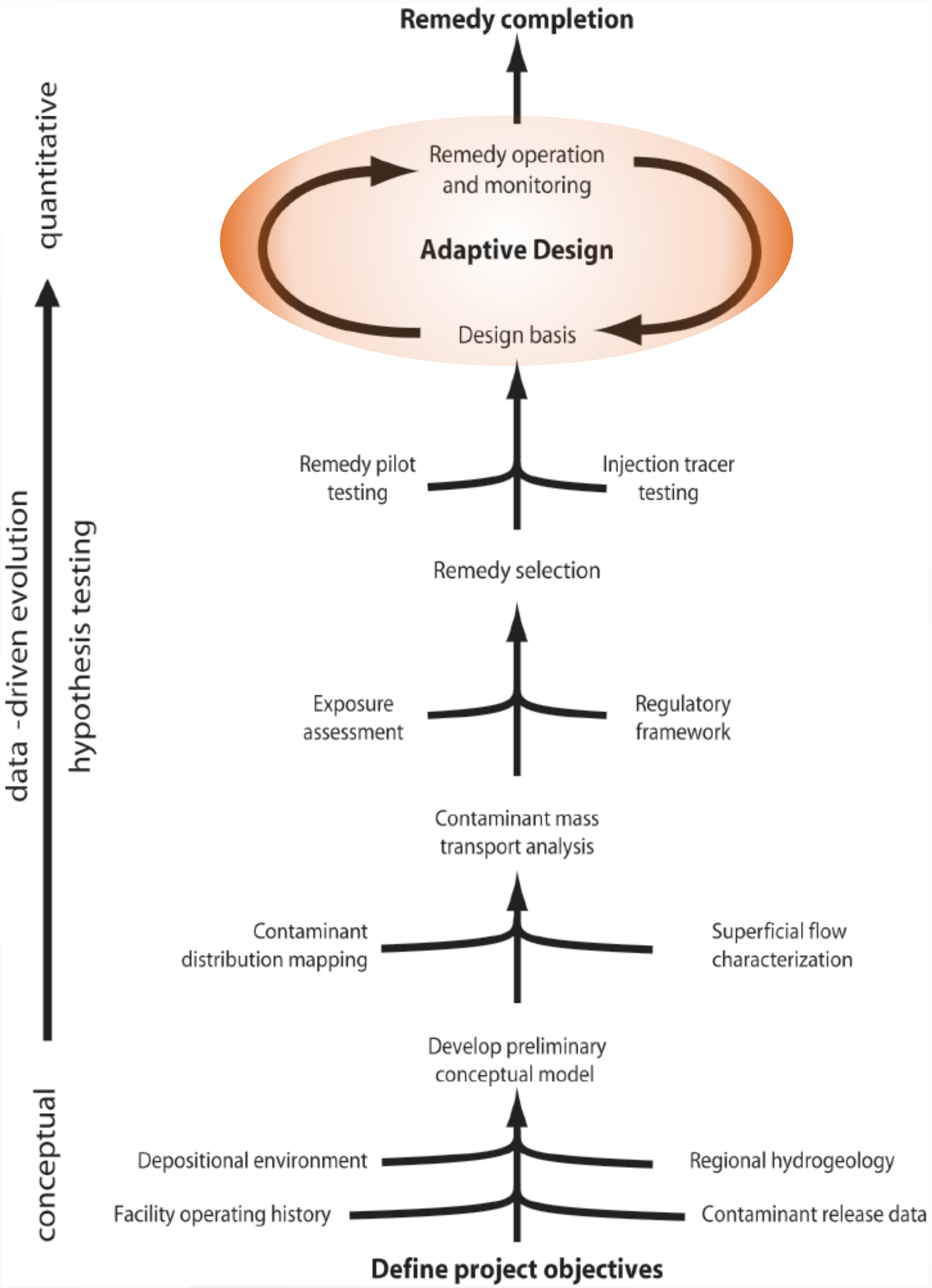
Optimization Must Improve the Remedy – Risk Profile

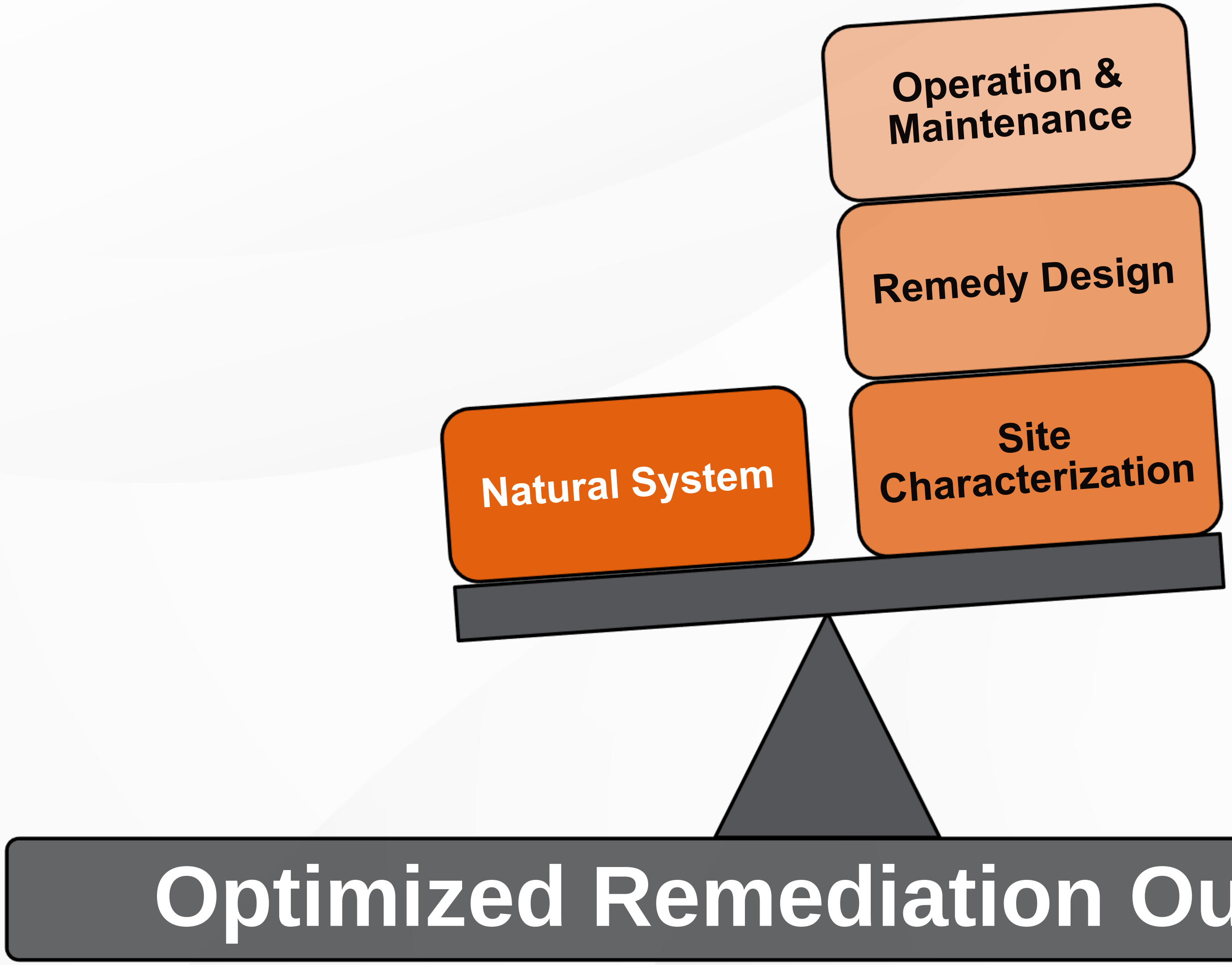
Return on Investment
What investment makes sense and how do we measure success?



Improve cost-effectiveness and reduce performance risk

Planning for Optimized Remediation





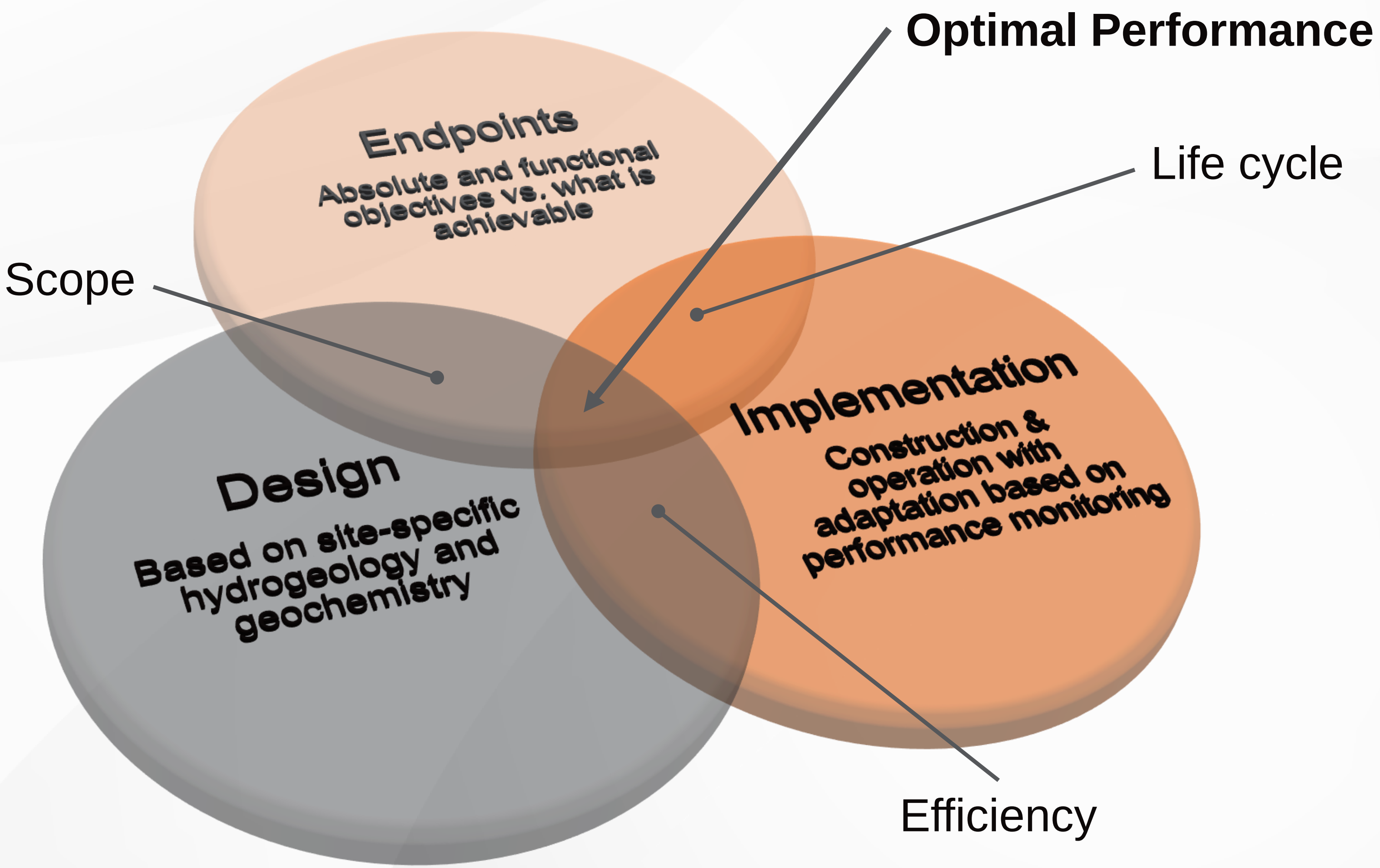
Adaptive management

Flux-based and adaptive remedies

High resolution and tested CSM

3-Compartment Model

Optimized Remediation



Evolution of Remediation Technologies

All Physical

Pump & treat SVE
Excavation Air sparging

In Situ Sustained Treatment

Biological Abiotic
Chemical ISS
Thermal

Integrated/Combined

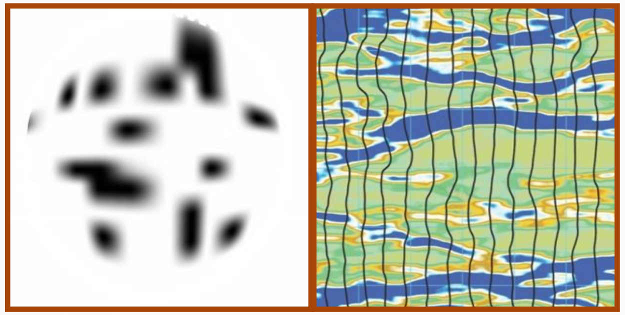
Flux-Focused Treatment
Combined Remedies, DGR^{SM}
3C Model, Improved outcomes

Mobile Mass — Mobile and Stored Mass — Focused Solutions

1970 — 1980 — 1990 — 2000 — 2010 — 2020

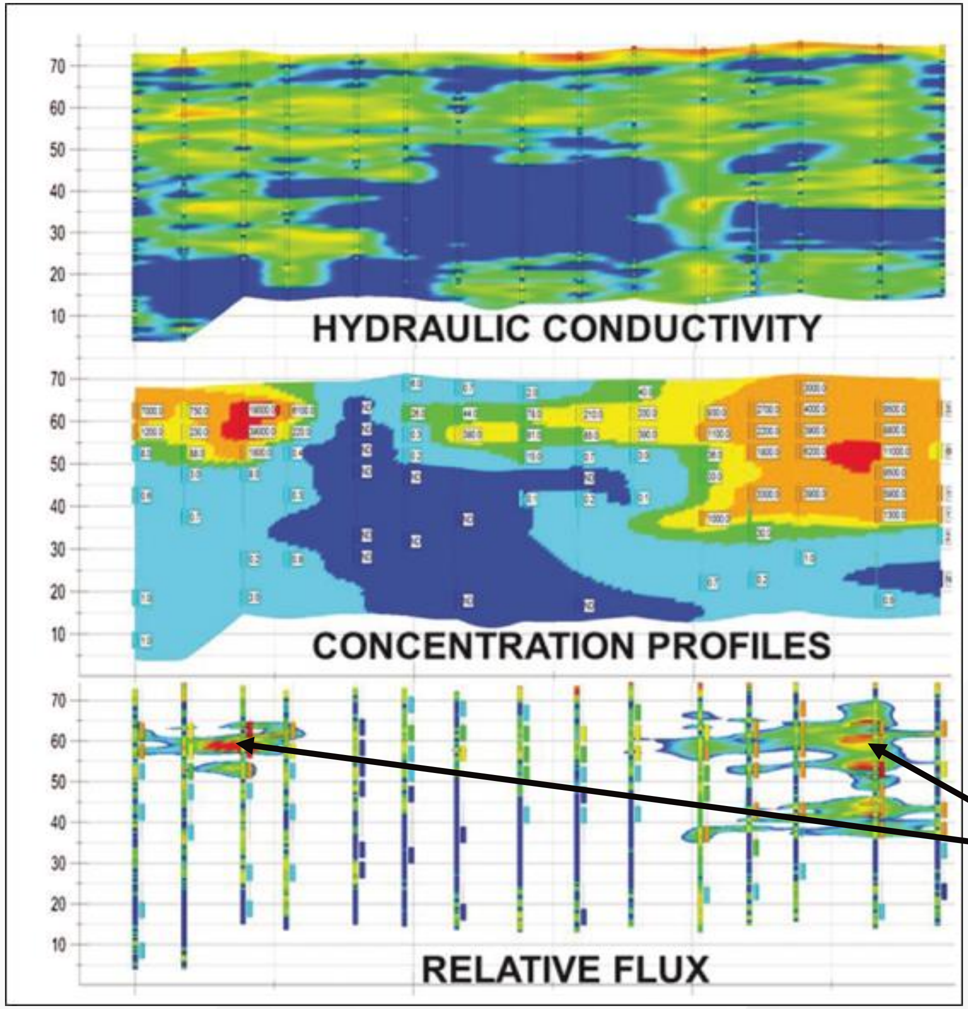
AVERAGES

→



Increased Precision of Treatments

A New CSM For Groundwater Restoration



Flux-based CSM

- Stratigraphic Flux™
- 3-Compartment Model

Hydraulic design & optimization

- Emerging contaminants
- DGR™

>90% of flux occurs
<10% of cross section

The Three-Compartment Model

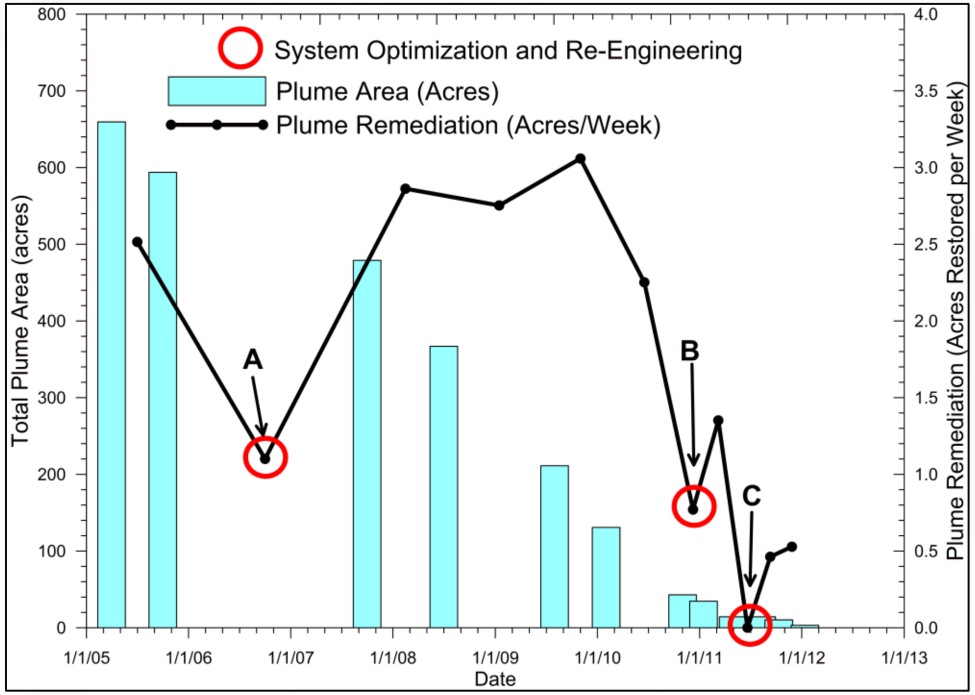
Aquifer division based on how water flows through an aquifer

Groundwater flow in an aquifer is divided based on order of magnitude contrasts in groundwater flux

- Q_{90} 90% of groundwater flows in the advection/transport zone – this is the zone where advective transport occurs
- Q_9 9% of groundwater flows in the slow advection/storage zone – this is the zone where slow advective transport occurs and diffusion affects transport
- Q_1 1% of groundwater flow is in the storage zone – this is the zone where diffusion is usually the most important process

These three zones are present in all aquifers because of contrasts in permeability.

A Data Driven Approach – Reese AFB



Site background:

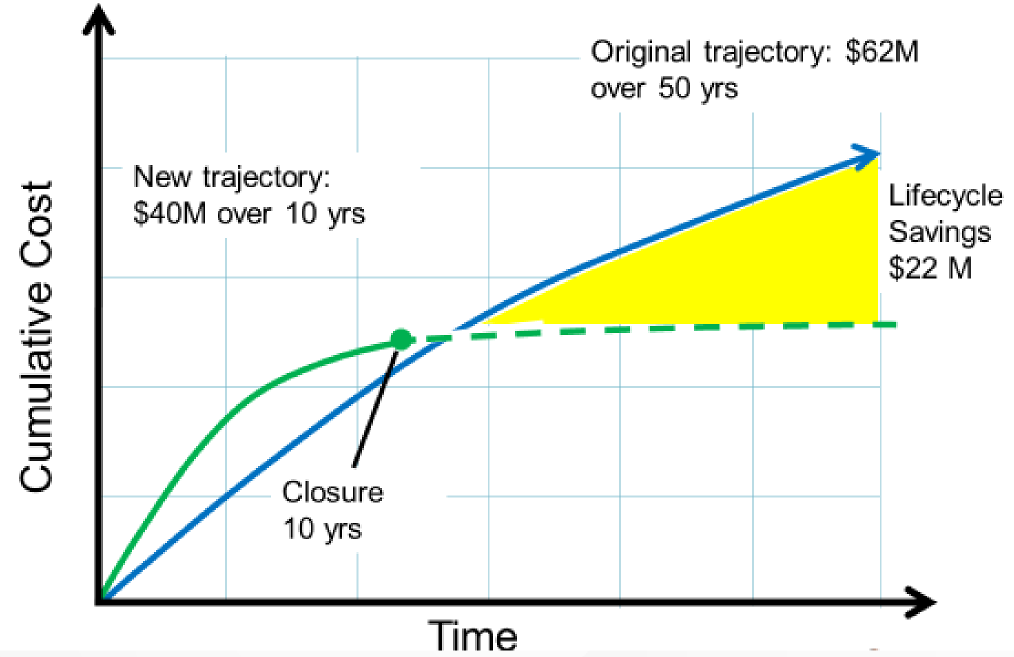
- 700-acre, 3-mile long TCE plume
- TCE plume extends to ~200 ft bgs
- 10-year contract period to MCL-based closure
- 2-3 acres per week pace of remediation

Keys to maintaining the pace of performance:

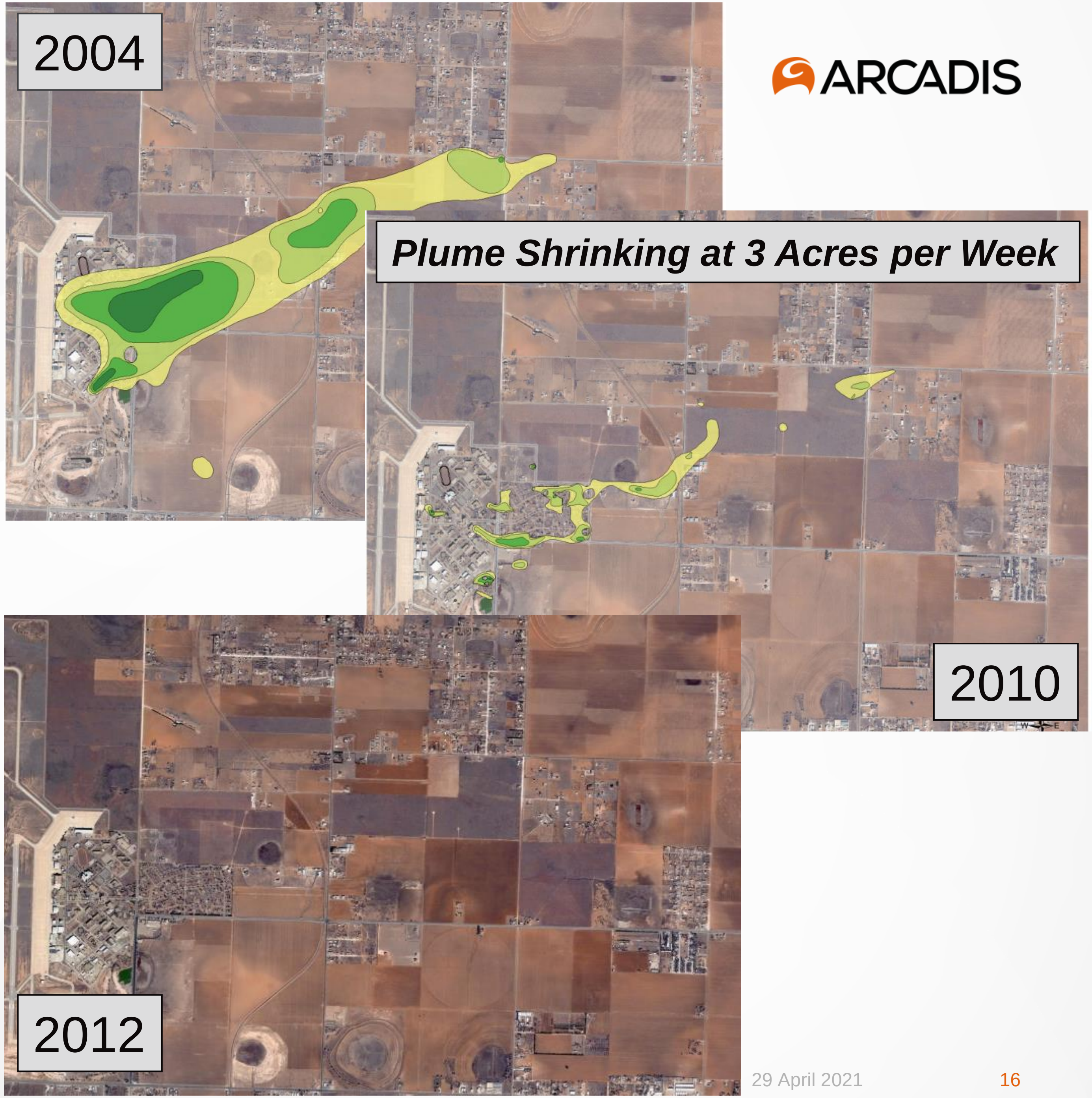
- Adaptive management
- Data driven
- Anticipate change
- Utilize remedy trains

A Data Driven Approach Works

Reese Air Force Base



DGR™ and ERD restored aquifer to potable use in 10 years



What Defines Optimal?

- Minimum Pumping for Hydraulic Containment
- Robust Capture
- Maximum Contaminant Removal
- Shortest Period of Performance
- Least Cost
- Fewest Wells
- Other

> *"Optimization is a process to streamline RAO [remedial action operation] programs by maximizing remedial effectiveness and cost efficiency"* (US Navy, 2001).

MODALL (MODular flow ALLocation)

Defining theoretical limits

Or

Assessing the limits of quantifiable effects

*For most academics, consultants, and practitioners – this has been a semantics discussion for the past 40 years because **Pathlines Analyses** have long been used to provide both answers.*

Groundwater

Issue Paper/

Capture Versus Capture Zones: Clarifying Terminology Related to Sources of Water to Wells

by Paul M. Barlow[1], Stanley A. Leake[2], and Michael N. Fienen[3]

Vol. 56, No. 5–Groundwater–September-October 2018 (pages 694–704)

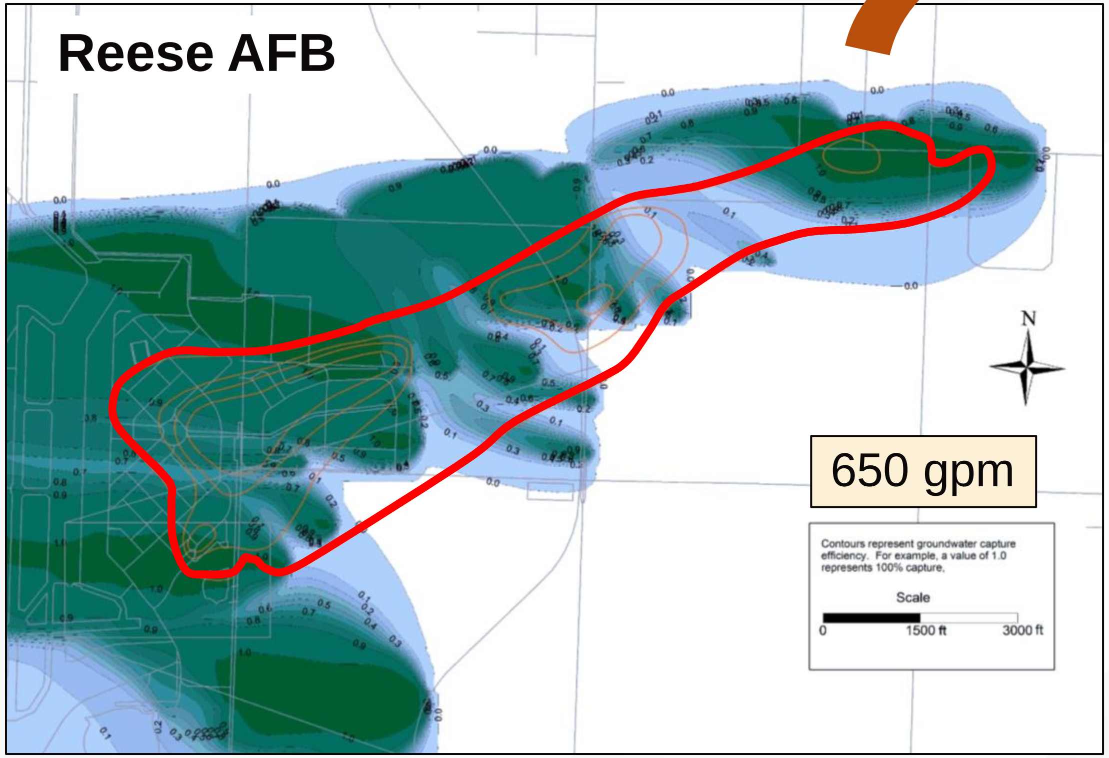
Volumetric-tracking is the best approach to assess capture

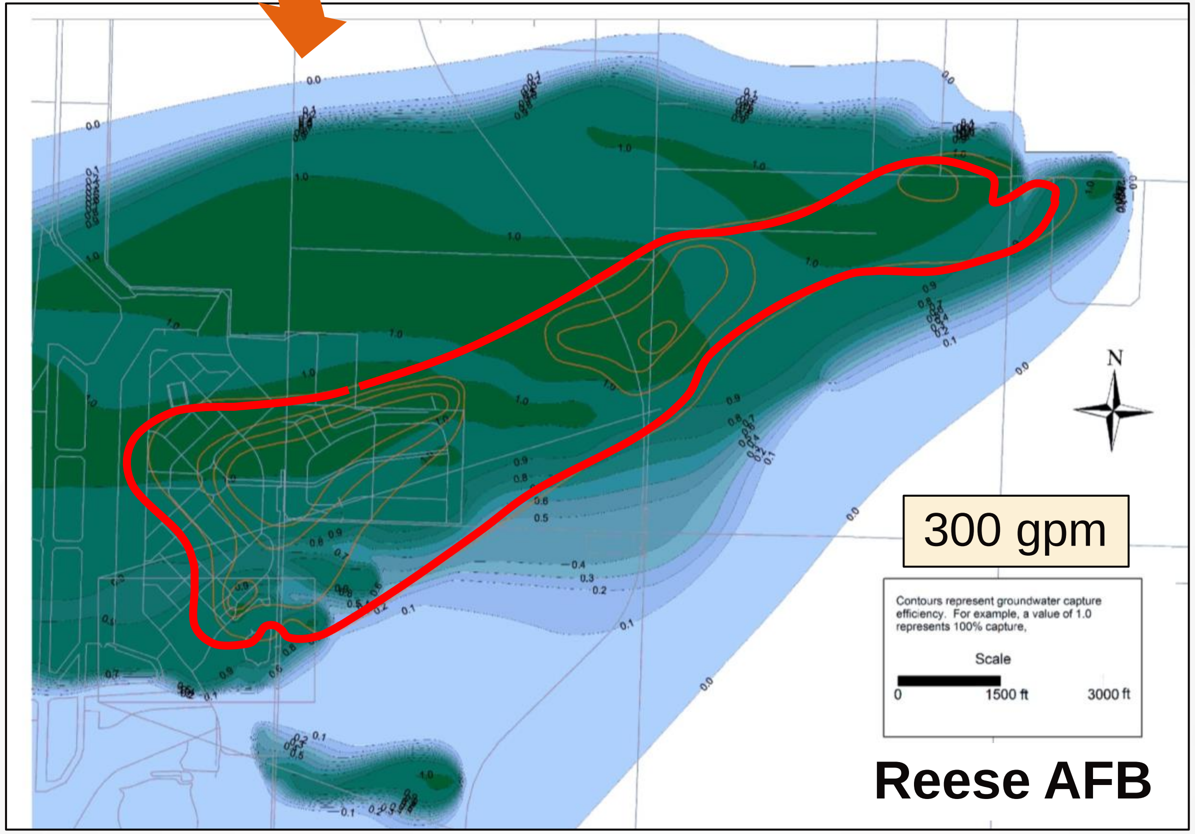
MODALL is a volumetric tracking approach to assess capture and capture zones

MODALL (Potter et al., 2008)

The Output from MODALL

Provides a quantitative analysis of groundwater hydraulics and inefficiencies





Potential Metrics of Performance

Total Mass

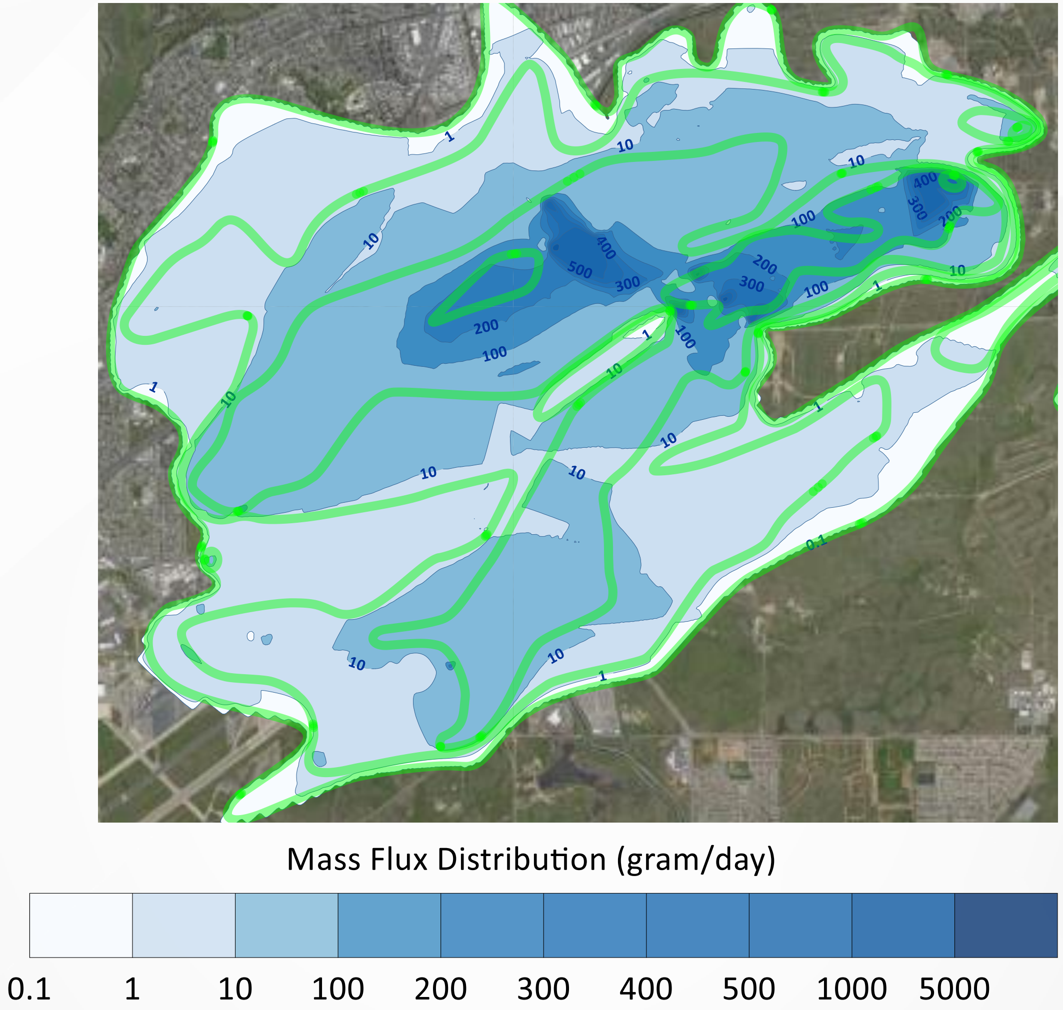
$$Total\ Mass = \sum_{i=1}^{nodes} V_i \times C_i$$

Plume Mass Capture

$$Plume\ Mass\ Capture = \sum_{i=1}^{nodes} V_i \times C_i \times \digamma_i$$

Plume Capture Function (Metric)

$$\wp = \frac{Plume\ Mass\ Captured}{Total\ Plume\ Mass} = \frac{\sum_{i=1}^{grid\ cells} V_i \times C_i \times \digamma_i}{\sum_{i=1}^{grid\ cells} V_i \times C_i}$$

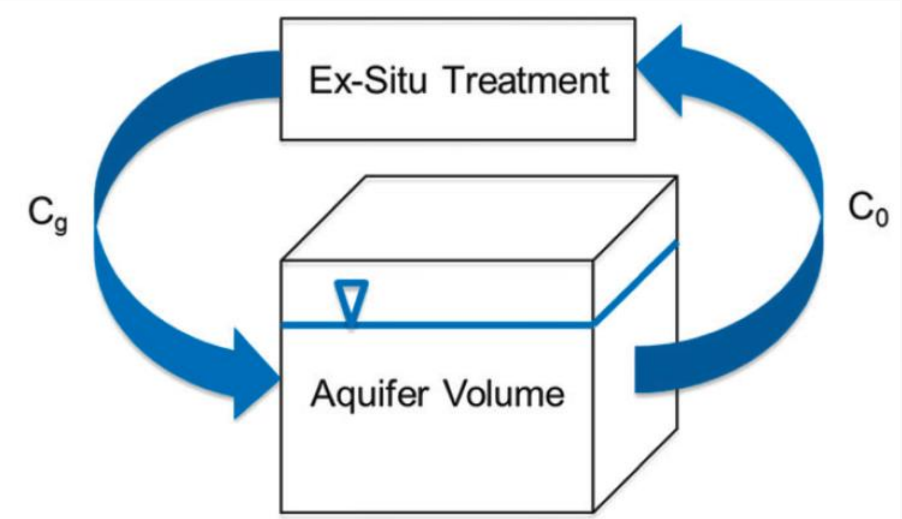


Other Metrics of Efficiency

Pore Volume = Aquifer Volume x Porosity

Complete Mix Theory

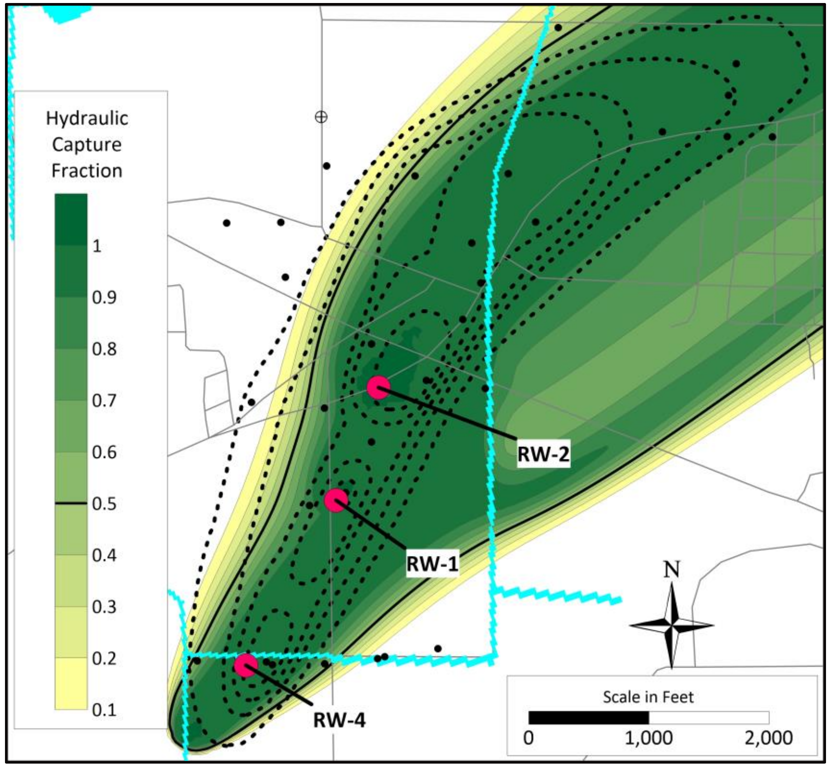
- Proven Concepts
  - Batch flush models (Gelhar and Wilson 1974; USEPA 1988, Zheng et al. 1991)
  - Well mixed, fixed volume of contaminated water flushed with equal volume of clean water, will reduce concentrations by 50%
- Volume of water contained within plume (PV)
- Pore volume flushes (NPV) required to achieve water quality goals



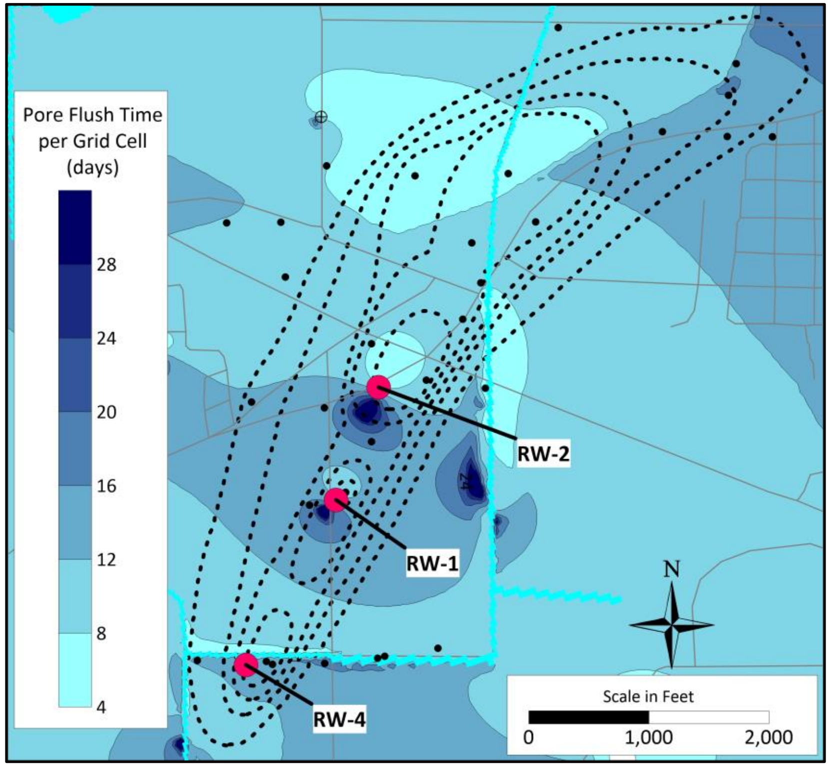
$$N_{PV} = R_f \ln\left(C_o / C_g \right)$$

What Defines Optimal?

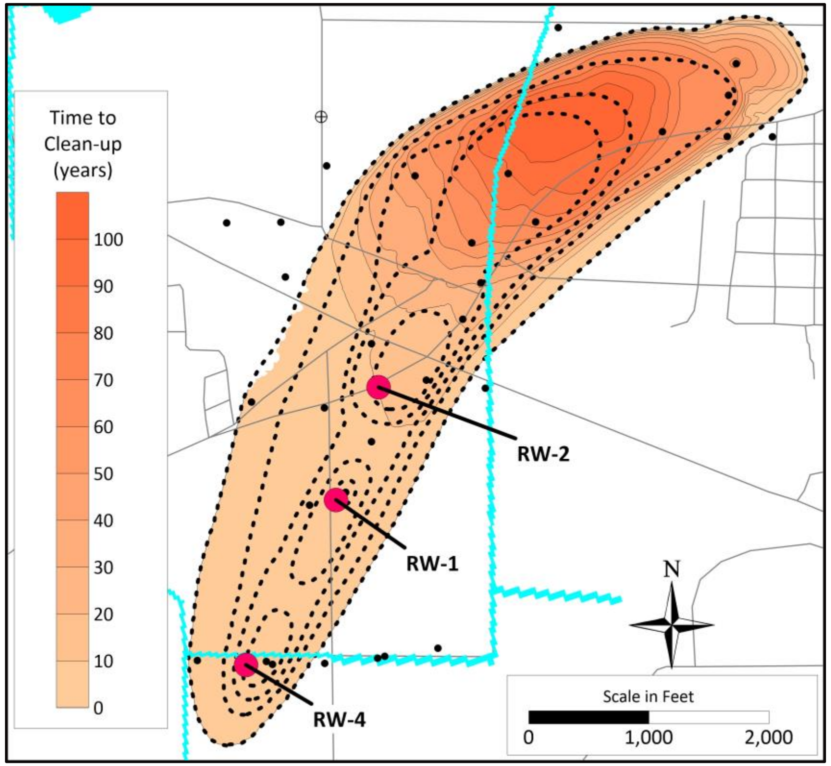
Hydraulic Capture



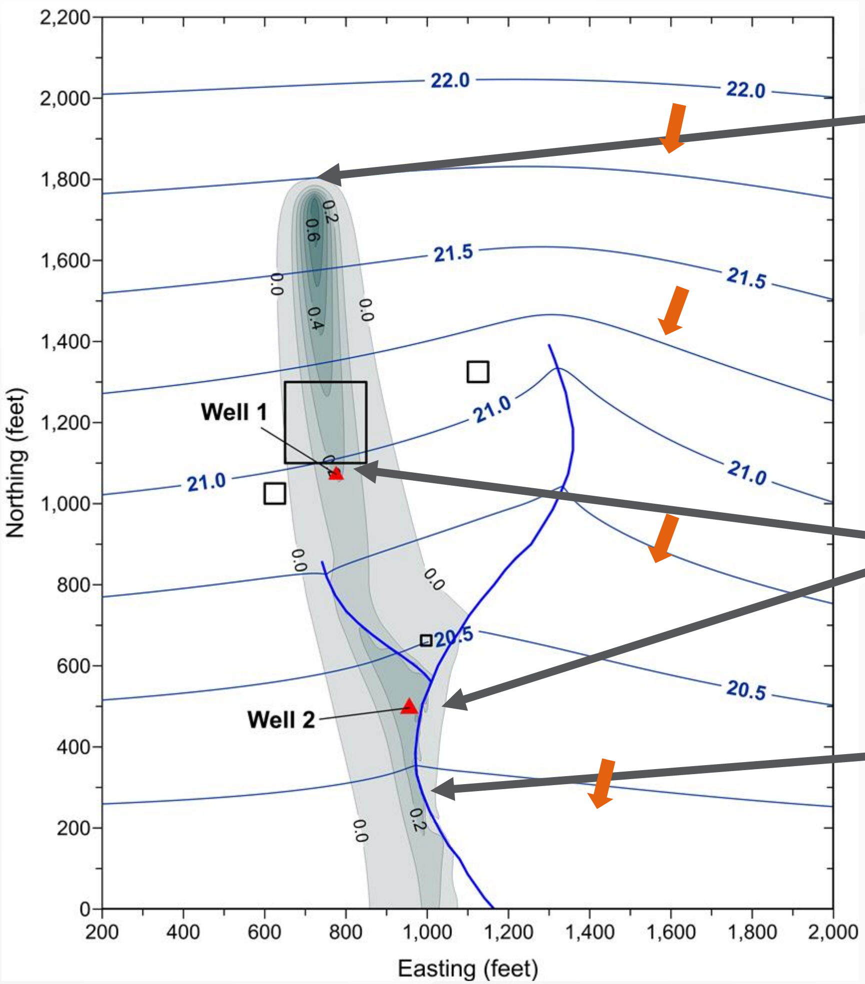
Pore Volume Exchange Rate



Estimated Time to Cleanup



Hydraulic-Based Remedy Design/Optimization



Dissolved Contaminant Release

Ambient Groundwater Flow Direction

Extraction Wells

Branched Stream

Plume Capture Function

$$\wp = \frac{\mathit{Plume\ Mass\ Captured}}{\mathit{Total\ Plume\ Mass}}$$

$$= \frac{\sum_{i=1}^{grid\ cells} V_i \times C_i \times \mathfrak{F}_i}{\sum_{i=1}^{grid\ cells} V_i \times C_i}$$

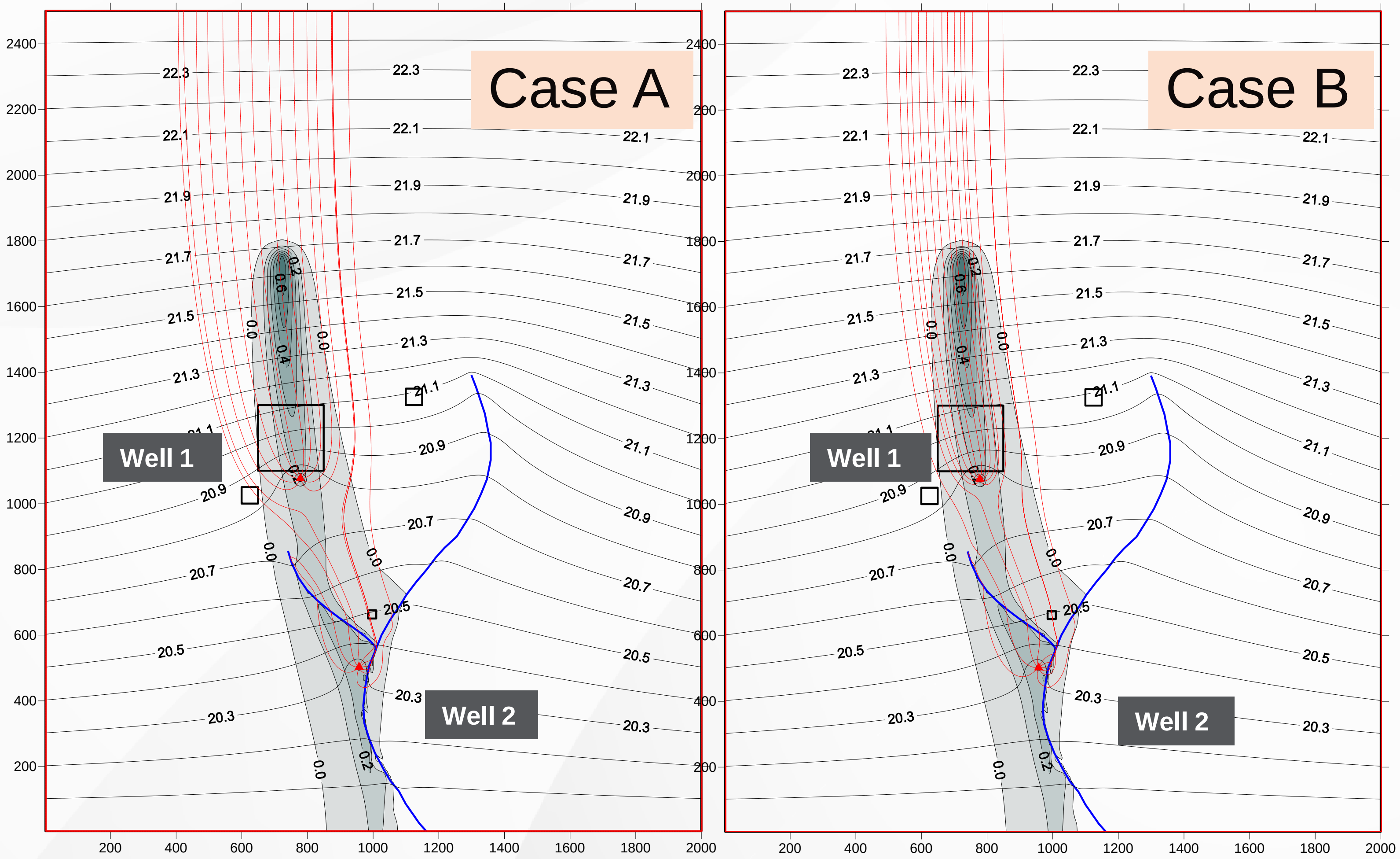
Constraints

$0 \leq Q_1 \leq 20\ gpm$

$0 \leq Q_2 \leq 20\ gpm$

$Q_1 + Q_2 = 20\ gpm$

Do pathlines identify which combination of pumping rates is better?

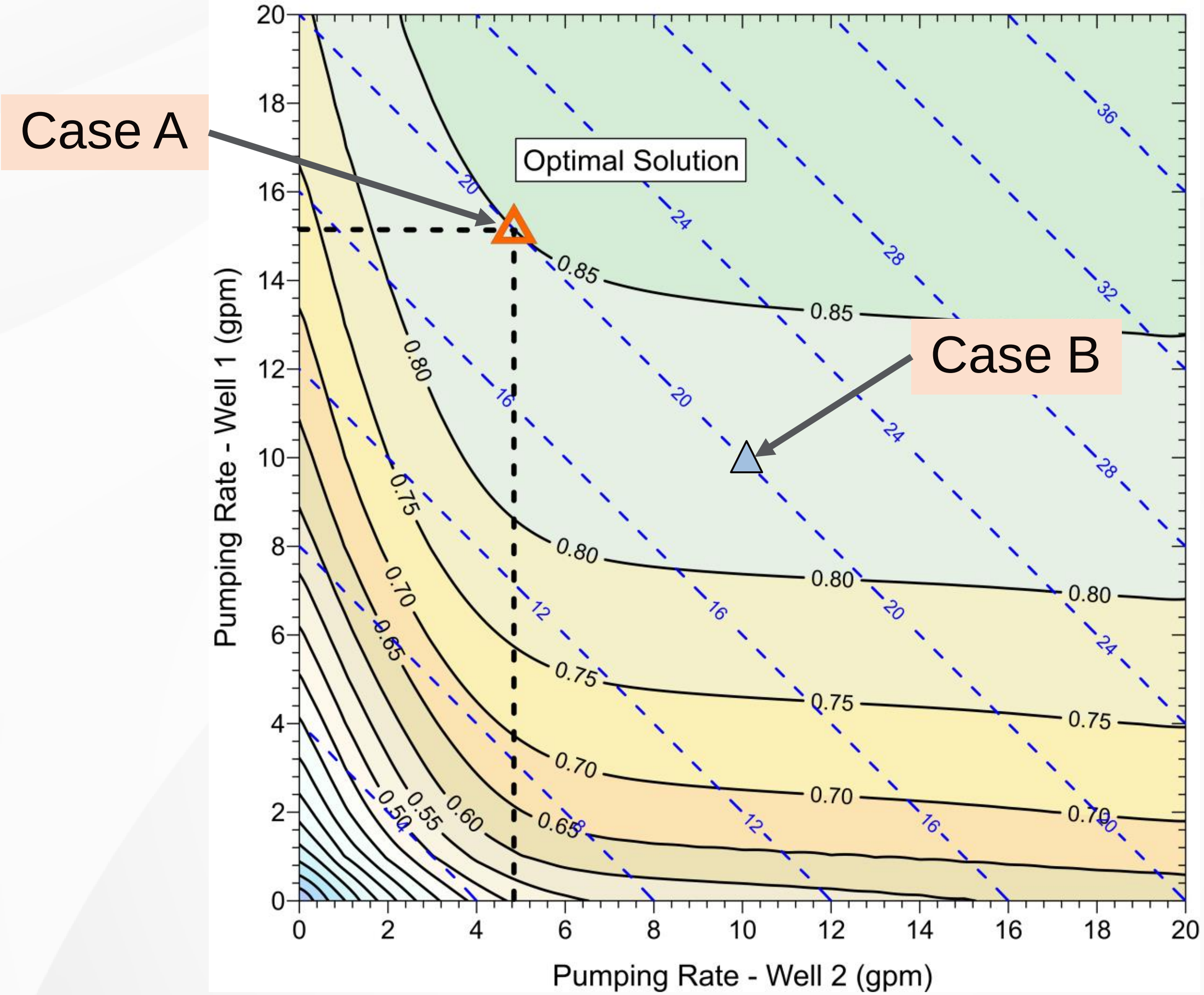


Hypothetical Example

Understanding the challenge

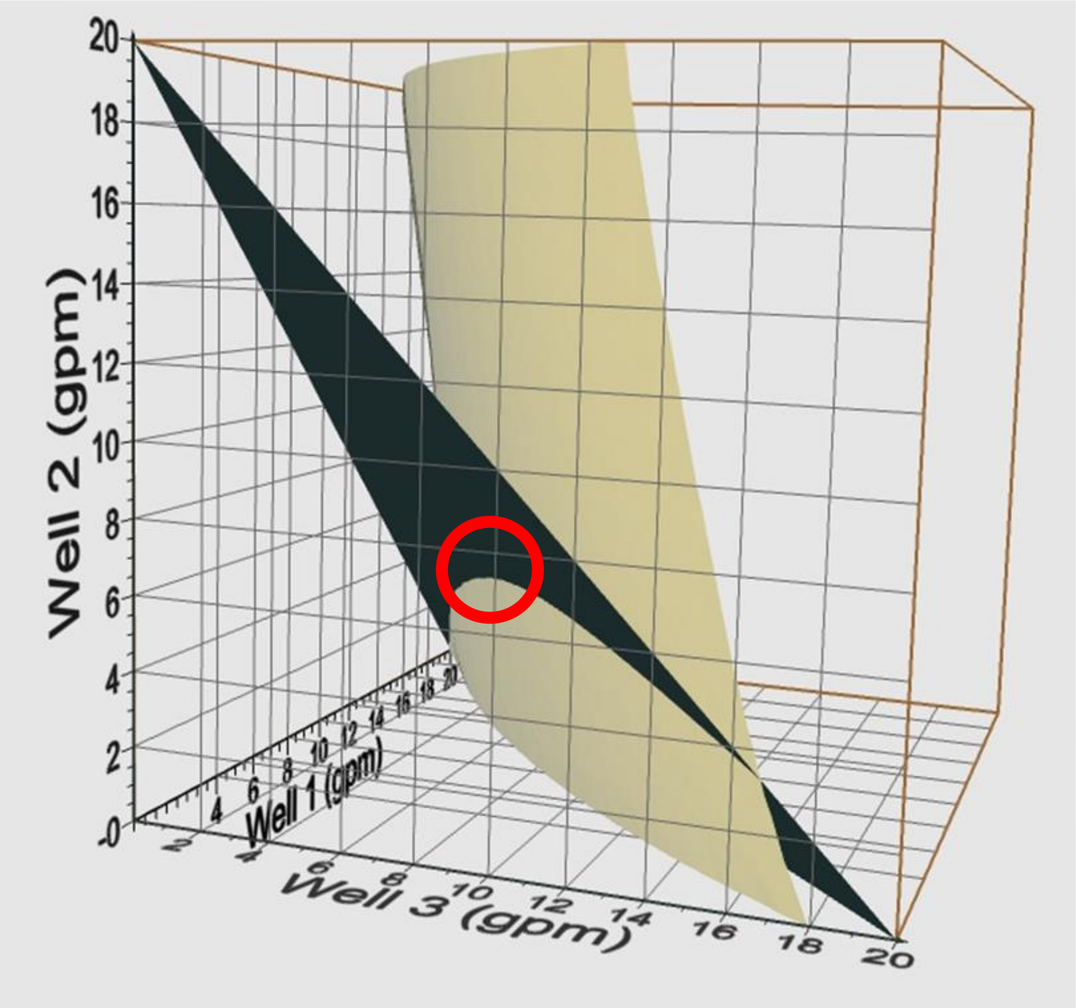
and

Finding the optimal solution amongst the possibilities



Hypothetical Example

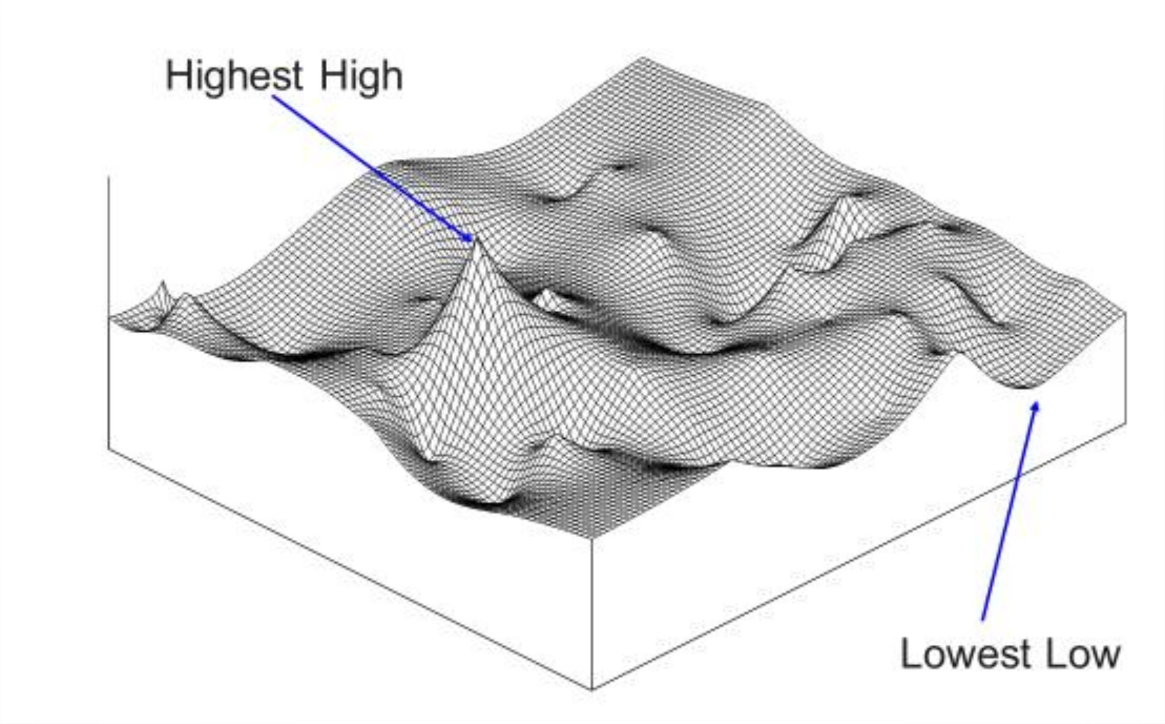
With more than 3 wells – the problem can't be shown graphically, and we need different tools to explore the possibilities



We need a logical approach to efficiently sift through the possibilities

Probabilistic Search Algorithms

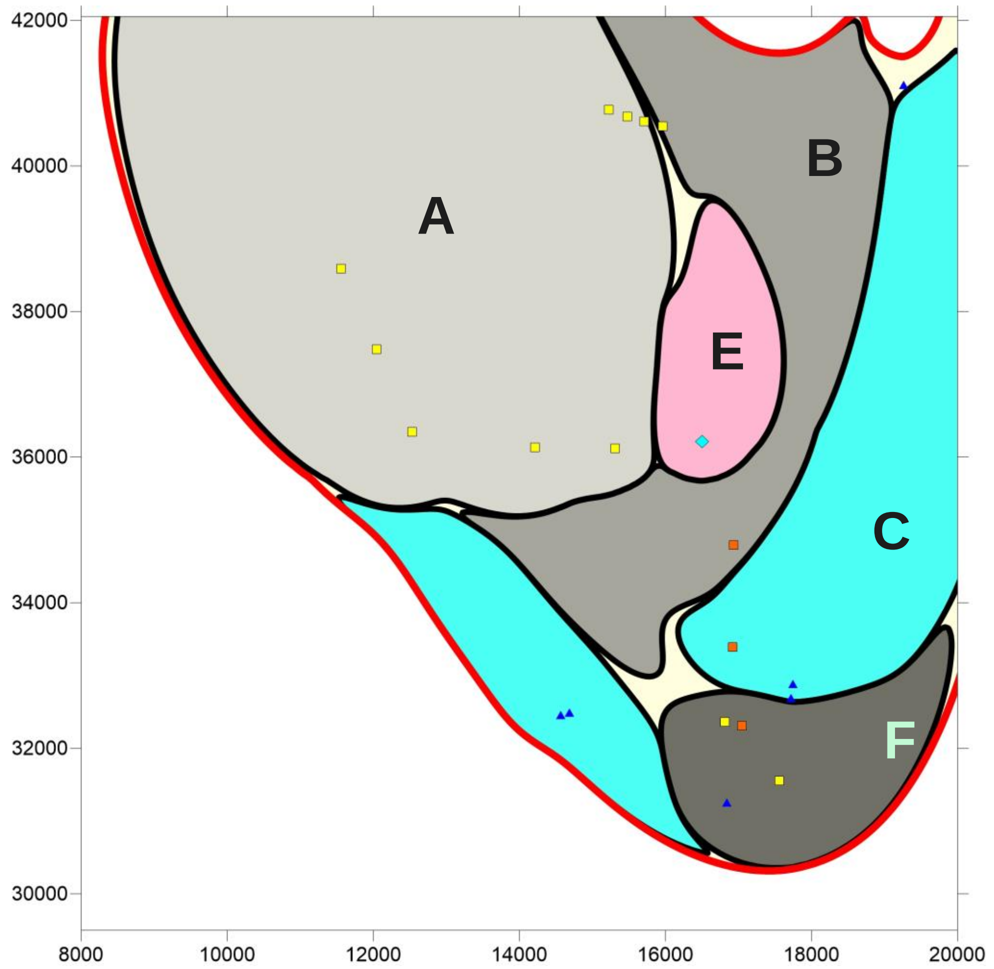
- Simulated Annealing (SA)
  - Slow but effective
- Very Fast Simulated Re-Annealing (VFSR)
  - Fast and efficient
- LIPO – Lipschitz Optimization
  - Faster and efficient



Real World: Local Solution vs. Global Solution

Capture assessment of multiple well fields

- Large VOCs plume
- ~4 miles long – 2 miles wide
- Up to 1,000 ft deep
- Sole source water supply aquifer with approximately 250,000 people living above the plume



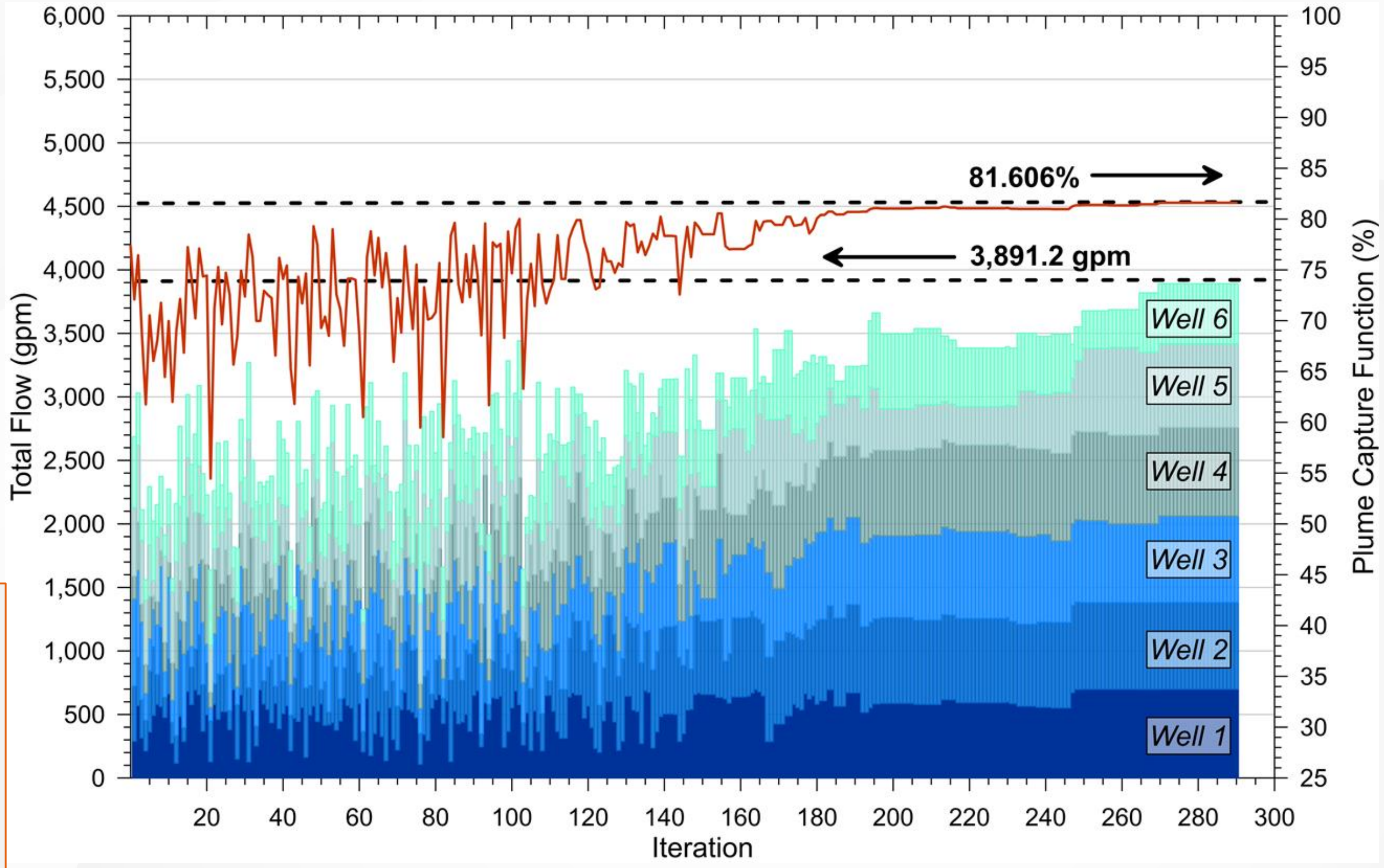
Assessment of extraction wells in "Zone A"

- 6 Well system
- Each well can operate
  0 < Q < 750 gpm
- The treatment capacity is 5,000 gpm
- Infiltration of treated water

You can't capture more than 81.6 % of the plume,

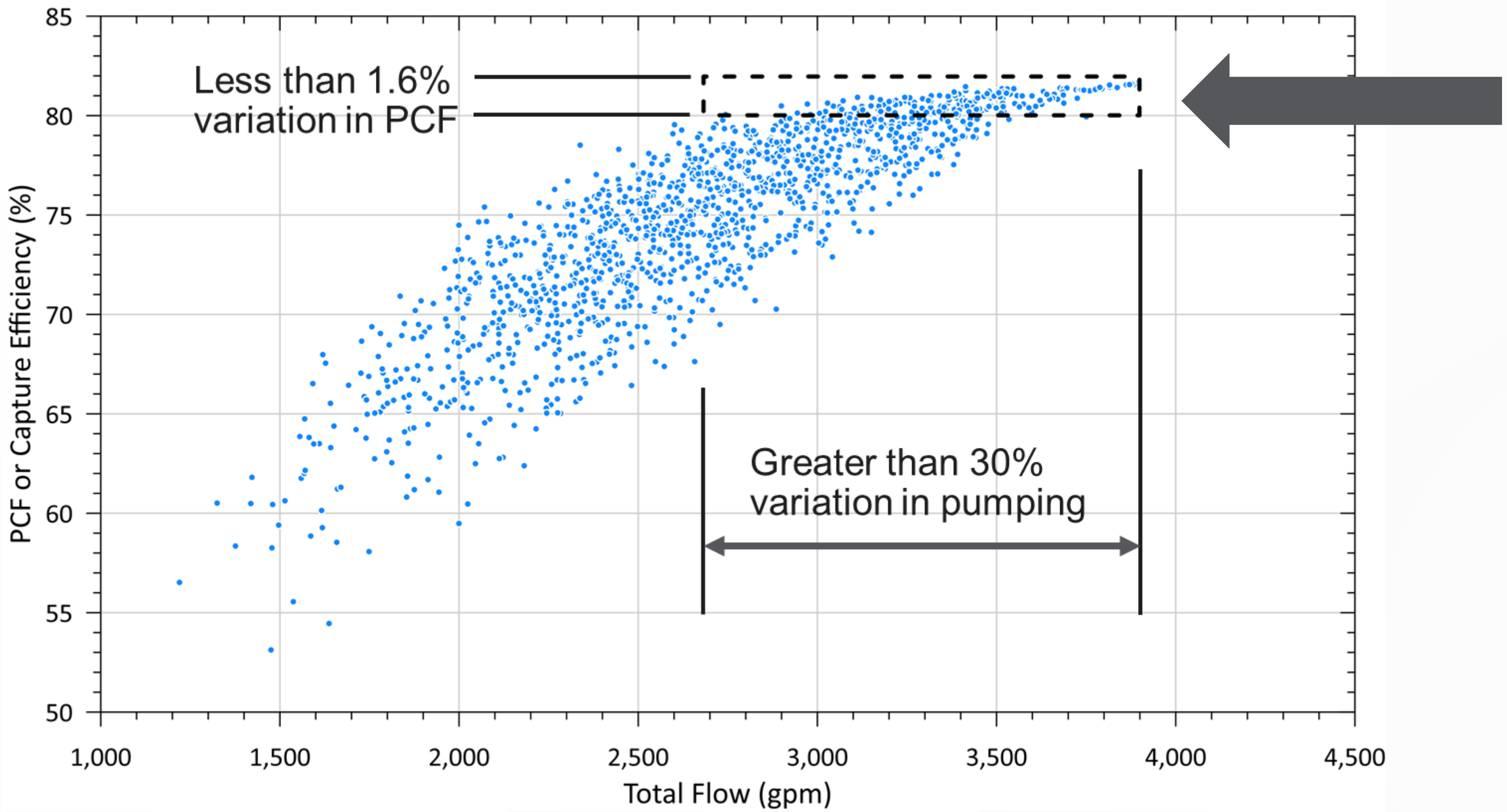
and

Pumping more than 3,900 gpm is not beneficial



Optimization of Plume Capture Function

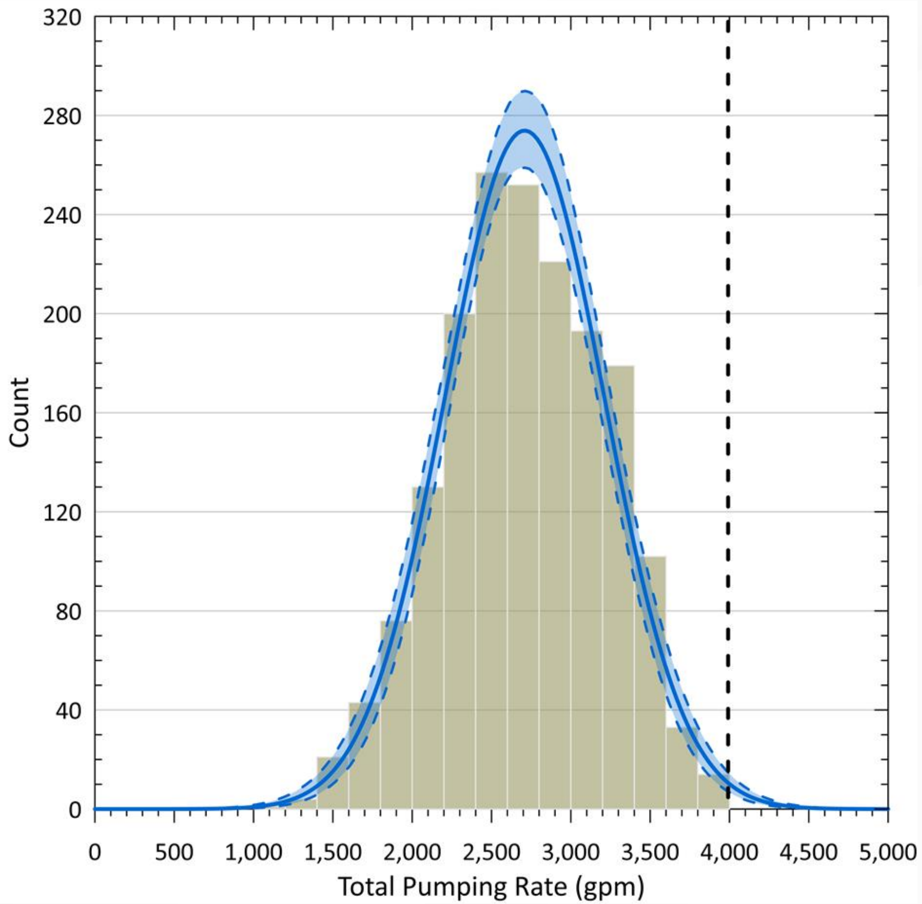
Operational options to pump water from Zone A . . . .



There a range in outcomes which provide similar levels of performance

Scatter Plot of All Flow Estimates vs. Plume Capture Function

Robust pumping configuration defined – with certainty



Total Pumping Rate of All Optimization Estimates

The optimal solution is also a robust solution

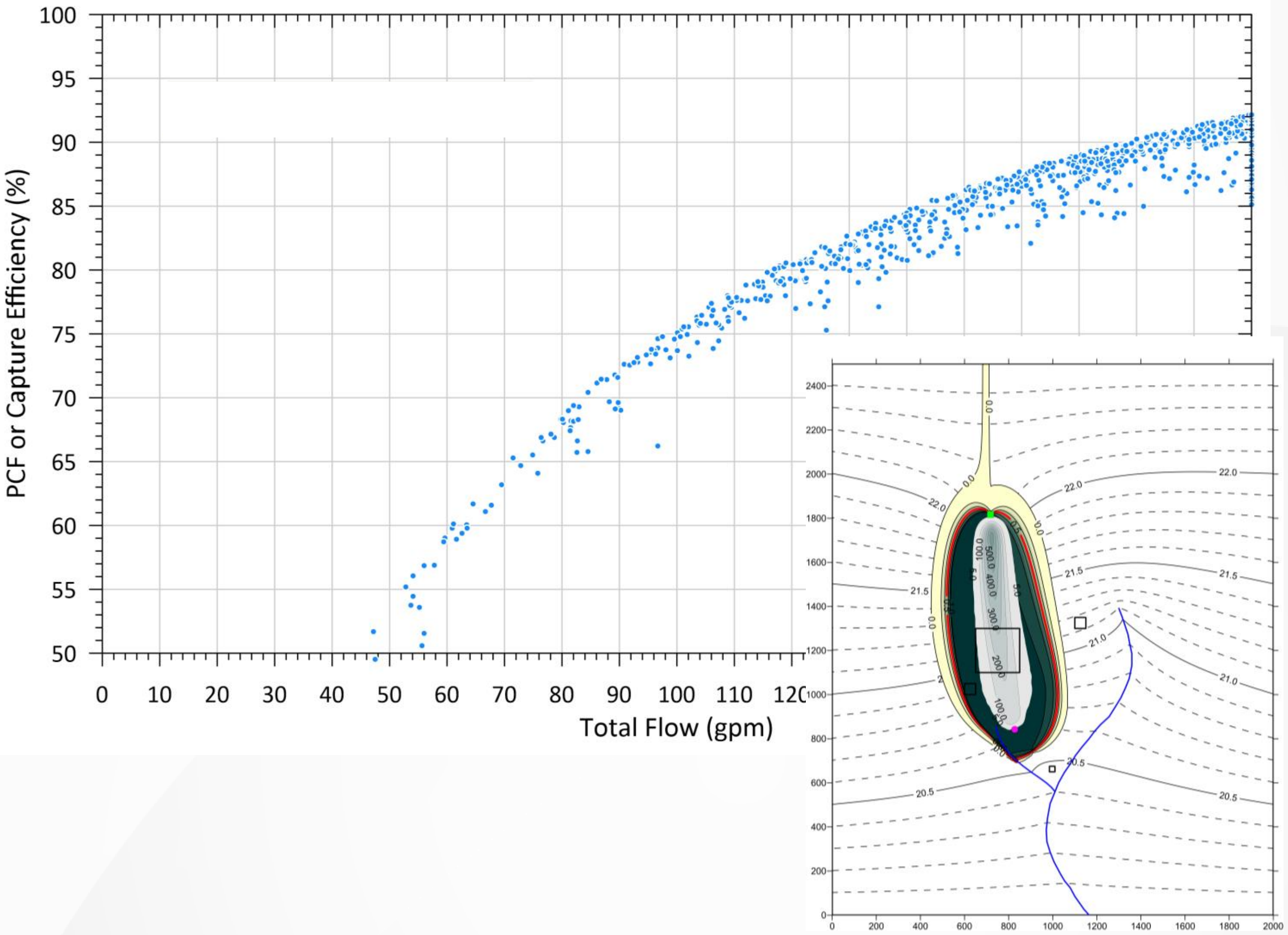
Pumping more than 3,900 gpm provides no benefit – globally and at each well

How often should we do this?

Summary

An objective design and optimization framework that…

- Helps to answer “Where and how much?”
- Leverages remediation hydrogeologic principles
- Focuses on mobile contaminant mass
- Reduces bias by applying mass flux-based metric



An improved framework for hydraulic-based system design and optimization for groundwater restoration

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Q&A

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