Application of Transport Optimization Codes to Groundwater Pump and Treat Systems

Internet Training Seminar
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Today’s Presenters

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Remedial Optimization
For P&T Systems

- Remediation System Evaluation (RSE) or Remedial Process Optimization (RPO) provides a broad assessment of...
  - Goals and exit strategy
  - Below-ground performance
  - Above-ground performance
  - Monitoring and reporting
  - Potential for alternate technologies

- Pumpage optimization is a subset or a component of these more general optimization evaluations
  - Trying to determine the “best” extraction/injection strategy assuming P&T is the most appropriate technology
Presentation Outline

• What is “transport optimization”?
• Why perform transport optimization?
• General optimization process
  – Formulating problems
  – Solving problems
• Recent DOD “ESTCP” groundwater remediation optimization study
  – Project Background
  – Example: Umatilla
  – Example: Blaine
  – Lessons Learned
• Further Information
What is “Transport Optimization”? 

- Optimization algorithms coupled with existing groundwater flow and transport models that determine an “optimal” set of pumping/injection well rates & locations

Example: Minimize total pumping rate subject to:
- TCE < 5 ppb at each cell within current plume extent after 5 yr.
- TCE < 1 ppb at each cell outside current plume extent (all times)
- extraction volume equals injection volume
Why Perform Transport Optimization?

• “Hydraulic Optimization” can be too limiting for many sites (1999 EPA Demonstration project)
  – Optimization based only on ground water FLOW model
  – Focus is on containment, cannot optimize based on concentration or cleanup times
Hydraulic Optimization

Example: Minimize total pumping rate subject to:
- inward flow at plume boundary = plume containment
- extraction volume equals injection volume
Why Perform Transport Optimization?

- “Hydraulic Optimization” can be too limiting for many sites (1999 EPA Demonstration project)
  - Optimization based only on ground water FLOW model
  - Focus is on containment, cannot optimize based on concentration or cleanup times

- Transport Optimization
  - Optimization based on ground water FLOW and TRANSPORT model
  - Not just containment…considers concentrations and cleanup times
Why Perform Transport Optimization?

- Assuming a model is being used to evaluate pumping alternatives...the optimization algorithms will yield improved strategies relative to strategies determined by trial & error model simulations

- Potential benefits of improved strategies include
  - Faster cleanup
  - Lower life-cycle cost

The DoD has ~ 200 operating pump-and-treat systems for containment or containment and treatment. The total O&M cost of those sites is about 100M/yr. The optimization codes are expected to be cost effective at 25%-30% of those sites.

Studies completed by EPA and Navy indicate the majority of the p&t systems are not operating as designed, have unachievable or undefined goals, and have not been optimized since installation.
General Optimization Process

• Start with a real-life problem for which you are seeking the “best” or “optimal” solution

• **Formulate the Problem.** Develop an “optimization formulation” that describes the essential elements of the real world problem *in mathematical terms* to establish…
  – The parameters for which optimal values are to be determined
  – The criteria for determining that one solution is better than another
  – The rules for allowing some solutions and disallowing others

• **Solve the Problem.** Select and apply an appropriate methodology to search possible and allowable combinations of pumping strategies for an “optimal” solution
Formulation Components (Terminology)

- **Decision Variables**
  - What we are determining optimal values for

- **Objective Function**
  - The mathematical equation being minimized or maximized
  - Value can be computed once the value of each decision variable is specified
  - Serves as the basis for comparing one solution to another

- **Constraints**
  - Limits on values of the decision variables, or limits on other values that can be calculated once the value of each decision variable is specified
Formulation Components Example

Objective Function $\rightarrow$ Max $x^2 + y^2$

Decision Variables

Subject to:
- $-4 \leq y \leq 4$
- $-2 \leq x \leq 2$
- $2x + 3y \leq 12$
Example of Formulation Process for a Real-Life Situation

- Real-Life Problem
  - What is the optimal driving route between home to work?
Example of Formulation Process for a Real-Life Situation

- Formulation must establish...
  - The decision variables
    - Combinations of roads/turns between my house and work
  - The objective function (some possibilities)
    - Minimize distance traveled
    - Minimize travel time
    - Minimize number of traffic lights
  - The constraints (some examples)
    - Must travel on paved roads
    - No more than four traffic lights allowed
    - Cannot go wrong way on a one-way street
Mathematical Descriptions are Often Difficult…

• Example: Minimize Travel Time
  – How do you mathematically account for traffic when calculating time of travel for a selected route of travel?
    • How do you estimate speed on the interstate?
    • Does it depend on time of day?
    • Does it depend on day of the week?

• Simplifications are invariably required in the formulation process

• Many alternative formulations are generally possible, each may have a different optimal solution
Solve the Formulation

- Global optimization algorithms use “heuristic” approaches to find the highest peak or lowest valley
  - Genetic algorithm
  - Simulated annealing
  - Tabu search
  - Artificial neural network

“Heuristic” refers to methods that work based on “rules of thumb” but there is no specific mathematical proof that it does work and no guarantee of optimality
Real-World Problem: Peaks and Valleys
Optimization Process: Ground Water Remediation Problems

• Preliminary Tasks
  – Understand site-specific goals and constraints
  – Verify/update flow & transport model until it is considered valid for design purposes
  – Obtain detailed information required to develop the formulations

• State formulation(s) in mathematical terms
  – Objective function
  – Constraints

• Select optimization codes/algorithms & solve formulations

• Revise formulations and solve as needed
Types of Information Collected: Ground Water Remediation Problems

- Cost components
  - One-time “capital” costs (now or in the future)
  - Annual costs
- Point of exposure, point of compliance
Point of Exposure and Point of Compliance

Point of Exposure must have concentrations below a specified limit to protect receptors at or near this location.

Point of Compliance must have concentrations below a specified limit to protect potential receptors downgradient.

Property Boundary

Regional Flow

Plume

Extraction wells
Types of Information Collected: Ground Water Remediation Problems

- Cost components
  - One-time “capital” costs (now or in the future)
  - Annual costs
- Point of exposure, point of compliance
- Containment zones

Schematic
Containment Zone defined to prevent the plume from spreading
Types of Information Collected:
Ground Water Remediation Problems

- Cost components
  - One-time “capital” costs (now or in the future)
  - Annual costs
- Point of exposure, point of compliance
- Containment zones
- Cleanup criteria and time period
- System capacity
- Pumping/injection limits
- Drawdown/water level limits

Schematic
Water Level Limit

Private Well

Land Surface

Lowest water level allowed to protect private well

Well Screen
Types of Information Collected: Ground Water Remediation Problems

- Cost components
  - One-time “capital” costs (now or in the future)
  - Annual costs
- Point of exposure, point of compliance
- Containment zones
- Cleanup criteria and time period
- System capacity
- Pumping/injection limits
- Drawdown/water level limits
- Limit on capital cost, etc.
- Other planned actions (such as source removal) that may impact future remedy performance
Formulation Components:
Ground Water Remediation Problems

− Decision Variables
  • Locations of extraction/injection wells
  • Rates at each extraction/injection well over time

− Potential objective functions (select only one unless using a multi-objective algorithm)
  • Total life-cycle cost {minimize}
  • Cleanup time {minimize}
  • Contaminant mass remaining in aquifer {minimize}
  • Contaminant mass removed from aquifer {maximize}

− Potential constraints (as many as you want…here are some examples)
  • Limits on pumping rates at specific wells or total pumping rate
  • Limits on concentrations (at specific locations/times)
  • Restrictions on well locations
  • Limits on aquifer drawdown at specific locations
  • Financial constraints such as limits on capital costs
Optimization Codes:
Ground Water Remediation Problems

• Dr. Chunmiao Zheng (University of Alabama), *Modular Groundwater Optimizer (MGO)*
  – Genetic algorithms
  – Simulated annealing
  – Tabu search

• Dr. Richard Peralta (Utah State University), *Simulation Optimization Modeling Systems (SOMOS)*
  – Genetic algorithms
  – Simulated annealing
  – Tabu search
  – Genetic algorithms coupled with artificial neural network
Modular Groundwater Optimizer (MGO)

• Simulation Components
  – MODFLOW for groundwater flow
  – MT3DMS for multi-species contaminant transport

• Optimization Components
  – Global optimization (heuristic search) techniques
    • Genetic algorithms (GA)
    • Simulated annealing (SA)
    • Tabu search (TS)
  – Integrated techniques
    • Global optimization techniques + response functions for greater computational efficiency
MGO
Program Structure

Start
Read & Prepare

Call MODFLOW and/or MT3DMS to evaluate objective function & constraints

Another simulation?
Yes

Call optimization solver Genetic Algorithms, Simulated Annealing, or Tabu Search

Another iteration?
Yes

Stop

No

No
MGO: Setup of Optimization Modeling

- Input files for MODFLOW (no modification)

- Input files for MT3DMS (no modification)

- An optimization input file specifying
  - Optimization Solver (GA, SA, TS)
  - Output options
  - Decision variables (flow rates, well locations)
  - Objective function
  - Constraints
MGO: Additional Information

• Code Compatibility
  – MODFLOW
  – MT3DMS

• Platforms that incorporates MGO
  – Groundwater Vistas
Simulation / Optimization Modeling System (SOMOS)

- Optimization Software for Managing:
  - Groundwater Flow
  - Solute Transport
  - Conjunctive Use
- SOMOS is easy-to-use Windows-based S/O modeling software
- SOMOS has a comprehensive set of heavy-duty optimizers to most efficiently address the spectrum of management optimization problems
- SOMOS significantly improves planning and management and can help optimally manage water resources systems of unlimited size
- SOMOS results from twenty years experience developing optimization models and applying them to real-world problems, including 11 pump-and-treat (PAT) systems and many large and small scale water supply problems
- SOMOS has detailed documentation, tutorials, and error checking

Developed by:
Systems Simulation / Optimization Laboratory
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Utah State University, Logan, UT 84322 – 4105
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Applications

SOMOS handles large and complex problems and has been applied to many real-world problems. Some examples are:

- Minimizing cost of TCE plume containment at Norton AFB:
  - Optimization yielded 23% cost reduction from base strategy
  - System was built, strategy was implemented and successful

- TCE contaminant plume management: Minimizing TCE mass remaining at Massachusetts Military Reservation, CS-10 plume, while preventing plume expansion
  - Optimization yielded 6% improvement from base strategy, at less cost
  - Constructed system is operating successfully

- Cache Valley sustained yield optimization problem: Maximizing sustained yield of stream-aquifer system
  - Optimal strategy showed sustainable pumping could increase 40%
  - causing management change

- Applications performed at three sites for this ESTCP project

For more applications: http://www.usurf.org/units/wdl
SOMOS Features

- Windows-based SOMOS runs in background, while user employs other programs.
- SOMOS’ spread-sheet based pre-processor, SOMOIN, simplifies input file preparation (availability depends on version).
- SOMOS’ professional design has detailed input error-checking and error messages.
- Buttons on SOMOS’ user-friendly interface speed accessing/editing I/O files, and optimizations.
- SOMOS’ flexibility allows run restarts, result merges, stepwise, sequential, and simultaneous optimization, full control over constraints and bounds in time and space.
- SOMOS’ automation allows considering multitudinous candidate wells in a run and speeds sequential running of multiple optimization actions.
- SOMOS includes a 2-D spreadsheet-based tool for mapping layered aquifer parameters, well locations and hypothetical capture zones (availability depends on version).
- SOMOS is being included within groundwater modeling packages such as Visual MODFLOW and Groundwater Vistas.
SOMOS Features (vary with version)

- **Applicability:** Any confined or unconfined aquifer system that can be modeled.
- **Simulators:** MODFLOW, MT3DMS, SEAWAT, Response Matrix, Response Surface, Artificial Neural Networks, Others.
- **12 Optimizers:** Including Simplex, Gradient Search, Branch & Bound, Outer Approximation, Genetic Algorithm (GA) linked with Tabu Search (GA-TS) and Simulated Annealing (SA) linked with Tabu Search (SA-TS).
- **Optimization Problem Types:** linear, quadratic, nonlinear, mixed integer, mixed integer nonlinear, multi-objective, stochastic (i.e. under uncertainty).
- **Controllable Variables:** ground-water pumping, gradient, cell-head, head at well casing; surface water diversion, flow, & head; aquifer/surface body seepage; contaminant concentration, mass remaining & removal; user-definable variables.
- **Management Goals:** Can optimize for 90+ distinct objective functions plus user-defined objective and multi-objective optimization.
Questions
DOD Groundwater Remediation
Optimization Study
ESTCP Demonstration Project

- Goal of project
  - Demonstrate application of “transport optimization” at real world sites
  - Evaluate the benefits and costs of using optimization algorithms versus the traditional trial-and-error modeling approach
  - Make transport optimization technology more accessible
    - Training
    - Code availability
Project Setup

- “Transport optimization” applied at 3 sites
  - Umatilla Chemical Depot, Oregon
  - Tooele Army Depot, Utah
  - Former Blaine Naval Ammunition Depot, Nebraska

- At each site, three different optimization formulations were developed

- Each formulation was solved (over a fixed time period) by…
  - two groups applying the coupled simulation-optimization approach
  - one group running the contaminant transport model using trial-&-error (to serve as a scientific control)

- Use of two groups provided greater confidence in results, a comparison of code performance, and more insight into the “beyond the code” efforts required to solve the problems
Project Team

- ESTCP and EPA provided funding, USACE also provided support

- Diverse project management team
  - NFESC - Karla Harre, Laura Yeh
  - EPA-TIO - Kathy Yager
  - USACE - Dave Becker
  - GeoTrans, Inc. - Rob Greenwald, Yan Zhang
  - University of Illinois - Dr. Barbara Minsker

- Transport optimization modelers
  - Utah State University - Dr. Richard Peralta (SOMOS)
  - University of Alabama - Dr. Chunmiao Zheng (MGO)
### Demonstration Sites

<table>
<thead>
<tr>
<th>Site Name</th>
<th>Pump rate (gpm) and Cost ($/yr)</th>
<th># Existing Wells</th>
<th>Contaminants</th>
<th>Groundwater Model Info.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Umatilla Army Depot</td>
<td>1300/$430K (operating)</td>
<td>3 ext. 3 inj.</td>
<td>RDX/TNT</td>
<td>5 layers 10 min runs</td>
</tr>
<tr>
<td>Toodle Army Depot</td>
<td>5000/$1M (operating)</td>
<td>15 ext. 13 inj.</td>
<td>TCE</td>
<td>4 layers 10 min runs</td>
</tr>
<tr>
<td>Former Blaine NAD</td>
<td>4000/$2M (in preliminary design)</td>
<td>17 ext. (planned)</td>
<td>TCE*/TNT</td>
<td>6 layers 2 hr runs</td>
</tr>
</tbody>
</table>

* TCE simulated is combined plume of TCE, PCE, TCA, DCE, and RDX
Formulation Process For Each Site

• Perform site visit and review site data
  – Understand the real-life situation
  – Explore real-life objectives and constraints with the installations
  – Initial discussion of how to convert real life situation into mathematical description

• Review site groundwater flow and transport model
  – Receive assurance from installation that they consider the model predictions acceptable for use for remediation design purposes
  – Important because the transport model provides the mathematical relationship between the decision variable values (the pumping locations/rates) and terms in the constraints/objective function
Formulation Process For Each Site

• Develop 3 “optimization formulations” based on further interaction with the installations
  – Select an “objective function” to be minimized (or maximized)
  – Specify a set of constraints to be satisfied

• Worked with installation to establish final mathematical representations of key problem components, such as…
  – Cost coefficients (e.g., cost of new well, cost to treat each gpm, etc.)
  – Nature of the relationships between the decision variables and other terms in the objective function and/or constraints (e.g., is the cost to treat each gpm constant, or does it change based on flow rate and/or contaminant concentrations?)
## Optimization Formulations

<table>
<thead>
<tr>
<th>Site Name</th>
<th>Objective Function</th>
<th>Major Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Umatilla</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| Form. 1   | Min life-cycle cost | 1. Current treatment capacity  
2. Cleanup of RDX and TNT |
| Form. 2   | Min life-cycle cost | 1. Increased treatment capacity  
2. Cleanup of RDX and TNT |
| Form. 3   | Min total mass remaining in layer 1 | 1. Cleanup of RDX and TNT |
| **Tooele** |                     |                   |
| Form. 1   | Min total cost     | 1. POE concentration limit |
| Form. 2   | Min total cost     | 1. POE/POC concentration limits |
| Form. 3   | Min total cost     | 1. POE/POC concentration Limits  
2. Declining source term  
3. Cleanup (< 50ppb) |
| **Blaine** |                     |                   |
| Form. 1   | Min life-cycle cost | 1. Plume containment  
2. Cleanup of TCE and TNT |
| Form. 2   | Min life-cycle cost w/ 2400gpm extracted water diversion | 1. Plume containment  
2. Cleanup of TCE and TNT |
| Form. 3   | Min maximum total pumping | 1. Plume containment |

POE = Point of Exposure;  POC = Point of Compliance
Example: Umatilla

• Goal: cleanup 2 constituents
  – RDX: 2.1 ug/L
  – TNT: 2.8 ug/L

• Current system
  – System capacity: 2 GAC units @ 1300 gpm
    • 3 extraction wells
    • 3 infiltration basins
  – Expect cleanup in 17 years
Umatilla Objective Function: Formulation 1

• Minimize Total Cost Until Cleanup

\[
\text{Total Cost} = \text{CCW} + \text{CCB} + \text{CCG} + \text{FCL} + \text{FCE} + \text{VCE} + \text{VCG} + \text{VCS}
\]

• CCW: Capital Costs of new Wells
• CCB: Capital Costs of new Recharge Basins
• CCG: Capital Costs of new GAC units
• FCL: Fixed Costs of Labor
• FCE: Fixed Costs of Electricity
• VCE: Variable Costs of Electricity
• VCG: Variable Costs of changing GAC units
• VCS: Variable Costs of Sampling

future costs are discounted to yield Net Present Value
Umatilla: Cost Terms

- Up-Front costs
  - New well and piping: $75K
  - Put EW-2 in service: $25K
  - New recharge basin: $25K
  - New GAC unit (325 gpm): $150K

- Fixed Annual Costs (each year until cleanup)
  - Labor (fixed): $237K/yr
  - Electric (fixed): $3.6k/yr

- Variable Costs Depending on Solution (complicated)
  - Electric based on pump rate at specific wells
  - GAC changeout based on influent concentration
  - Sampling costs due to plume area
Example of Actual Details – Cost Term VCE

- VCE: Variable Cost of Electricity over system life-cycle

\[ VCE = \sum_{i=1}^{ny} \sum_{j=1}^{nwel} (CW_{ij} \times IW_{ij})^d \]

Where

\[ CW_{ij} = 0.01(Q_{ij}) \text{ for } 0 \text{ gpm} < Q_{ij} \leq 400 \text{ gpm} \]
\[ CW_{ij} = 0.025(Q_{ij}) - 6 \text{ for } 400 \text{ gpm} < Q_{ij} \leq 1000 \text{ gpm} \]

\( ny \) is the elapsed time when cleanup occurs
\( nwel \) is the total number of extraction wells
\( CW_{ij} \) is the electrical cost of well \( j \) in year \( i \). Costs differ for wells depending on the extraction rates \( Q_{ij} \)
\( IW_{ij} \) is a flag indicator; 1 if the well \( j \) is on in year \( i \), 0 otherwise
\( d \) indicates application of the discount function to yield Net Present Value (NPV)
Umatilla Constraints: Formulation 1

- Cleanup must be achieved within 20 years

- Current treatment capacity, 1300 gpm

- Limits on extraction rates imposed by hydrogeology of the site
  - Zone 1, maximum rate at well $\leq 400$ gpm
  - Zone 2, maximum rate at well $\leq 1000$ gpm

- Concentration buffer zone
  - Prohibits concentrations from exceeding the cleanup levels outside a specified area

- Balance of extraction and injection rates
Umatilla Results: Formulation 1

<table>
<thead>
<tr>
<th></th>
<th>Transport Optimization Algorithms</th>
<th>Trial-&amp;-Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objective Function Value</td>
<td>$1.66M</td>
<td>$1.66M</td>
</tr>
<tr>
<td># new wells</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td># new recharge basins</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td># new GAC units</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>RDX Cleanup (yrs)</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>TNT cleanup (yrs)</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

Improvement using transport optimization: ~26%

Results Summary
Umatilla – Formulation 1 Results

All groups added new wells in this region… USU & UA used wells only in this region.

Existing well EW-4 Only selected by the trial & error group.
Umatilla Results: Formulation 1

- RDX results for an “optimal solution”

Result w/optimization:
RDX
RDX Plume in Layer 1, 2002

2.1 ug/L
5.0 ug/L
10 ug/L
15 ug/L
20 ug/L
25 ug/L
30 ug/L
RDX Plume in Layer 1, 2004

EW-1

EW-3
RDX Plume in Layer 1, 2005

- EW-1
- EW-3

Concentration levels:
- 2.1 ug/L
- 5.0 ug/L
- 10 ug/L
- 15 ug/L
- 20 ug/L
- 25 ug/L
- 30 ug/L
RDX Plume in Layer 1, 2006

2.1 ug/L
5.0 ug/L
10 ug/L
15 ug/L
20 ug/L
25 ug/L
30 ug/L

EW-3
EW-5
Umatilla Results: Formulation 1

- TNT results for an “optimal solution”

Result w/optimization:
TN9T
TNT Plume in Layer 1, 2002

- 2.8 ug/L
- 5.0 ug/L
- 10 ug/L
- 15 ug/L
- 20 ug/L
- 25 ug/L
- 30 ug/L
TNT Plume in Layer 1, 2003

[Graph showing TNT plume concentrations]

- 2.8 ug/L
- 5.0 ug/L
- 10 ug/L
- 15 ug/L
- 20 ug/L
- 25 ug/L
- 30 ug/L

EW-1

EW-3
TNT Plume in Layer 1, 2004

EW-1

EW-3
TNT Plume in Layer 1, 2005

- EW-1
- EW-3
TNT Plume in Layer 1, 2006

- 2.8 ug/L
- 5.0 ug/L
- 10 ug/L
- 15 ug/L
- 20 ug/L
- 25 ug/L
- 30 ug/L
Example: Blaine

- Primary Contaminants:
  - VOCs
    - TCE
    - 1,1,1-TCA
    - PCE
    - 1,1-DCE
  - Explosives
    - TNT
    - RDX

Only 2 constituents simulated for optimization:
1. TNT
2. TCE (represents TCE, TCA, PCE, DCE, and RDX)

- FS Recommended Design (Hydraulic Containment)
  - 12 deep wells @ 4,050 gpm
  - 5 shallow wells @ 18 gpm
  - Expect cleanup up to 60 years
Site Location With TCE Distribution in Upper Semi-Confined Aquifer

Hastings East Industrial Park
Explosives Disposal Area
Yard Dump
Bomb And Minge Complex
Commingled Plumes in Model Layer 1, 8/30/2002
Blaine Objective Function: Formulation 1

- Minimize Total Cost Until Cleanup

Total Cost = CCE + CCT + CCD + FCM + FCS + VCE + VCT + VCD

- CCE: Capital cost of new extraction wells
- CCT: Capital cost of treatment
- CCD: Capital cost of discharge
- FCM: Fixed cost of management
- FCS: Fixed cost of sampling
- VCE: Variable cost of electricity
- VCT: Variable cost of treatment
- VCD: Variable cost of discharge

future costs are discounted to yield Net Present Value
Blaine: Cost Terms

• Up-Front Costs
  – New extraction well: $400K
  – Capital Treatment: $1.0K/gpm
  – Capital Discharge: $1.5K/gpm

• Fixed Annual Costs (each year until cleanup)
  – Fixed O&M: $115K/yr
  – Sampling: $300K/yr

• Variable Costs
  – Electric: $0.046K/gpm/yr
  – Treatment: $0.283K/gpm/yr
  – Discharge: $0.066K/gpm/yr
Blaine Constraints: Formulation 1

- Cleanup within 30 years
- Containment limits to prevent plume spreading
- Limits on extraction well rates
  - Well screens one model layer: 350 gpm
  - Well screens two model layers: 700 gpm
  - Well screens three model layers: 1050 gpm
- Restricted areas where no wells allowed
- Remediation wells not allowed in same cells as irrigation wells
- No dry cells allowed
## Blaine Results: Formulation 1

<table>
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<tbody>
<tr>
<td><strong>Objective Function Value</strong></td>
<td>$45.28M</td>
<td>$40.82M</td>
</tr>
<tr>
<td><strong># New Extraction Wells</strong></td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td><strong>Elapsed Years Until Cleanup for TCE</strong></td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td><strong>Elapsed Years Until Cleanup for TNT</strong></td>
<td>30</td>
<td>29</td>
</tr>
</tbody>
</table>

Improvement using transport optimization: ~10 - 20%
Blaine Results: Formulation 1

- Optimization result from all three groups

Optimization Results:
TCE Layer 3
Transport Optimization Group 1

Transport Optimization Group 2

TCE Concentration in Layer 3, 8/31/2023

Trial-and-Error Group
Findings/Lessons Learned

• Transport optimization algorithms
  – Can be applied at real-world sites

  – Provided improved solutions compared to trial-&-error
    (representative improvement was 20%)

  – Found “outside of the box” solutions
    • Pumping only within TNT plume at Umatilla
    • Pumping less in early time periods and installed new wells later at
      Blaine

  – Are estimated to cost $40-120K per site to apply ($0-40K more
    than trial-&-error design)
    • Range varies with site complexity, model size, and number of
      contaminants
Typical Costs Estimated for A Transport Optimization Analysis

<table>
<thead>
<tr>
<th>Costs Associated With Basic Items*</th>
<th>Low Cost</th>
<th>Typical Cost</th>
<th>High Cost</th>
<th>Expected Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site visit and/or transfer information</td>
<td>$2,500</td>
<td>$5,000</td>
<td>$10,000</td>
<td>1-2 months</td>
</tr>
<tr>
<td>Develop 3 optimization formulations</td>
<td>$5,000</td>
<td>$10,000</td>
<td>$15,000</td>
<td>1-2 months</td>
</tr>
<tr>
<td>Solve optimization formulations</td>
<td>$25,000</td>
<td>$40,000</td>
<td>$60,000</td>
<td>2-4 months</td>
</tr>
<tr>
<td>Prepare report and/or present results</td>
<td>$5,000</td>
<td>$15,000</td>
<td>$25,000</td>
<td>1 month</td>
</tr>
<tr>
<td>Project management</td>
<td>$2,500</td>
<td>$5,000</td>
<td>$10,000</td>
<td>NA</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$40,000</strong></td>
<td><strong>$75,000</strong></td>
<td><strong>$120,000</strong></td>
<td><strong>5-9 months</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Costs Associated With Optional Items</th>
<th>Low Cost</th>
<th>Typical Cost</th>
<th>High Cost</th>
<th>Expected Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Update and improve simulation models</td>
<td>0</td>
<td>$20,000</td>
<td>$50,000</td>
<td>Add 1-3 months</td>
</tr>
<tr>
<td>Up to 3 additional formulations</td>
<td>$15,000</td>
<td>$25,000</td>
<td>$40,000</td>
<td>Add 2-3 months</td>
</tr>
<tr>
<td>Additional constituent simulated</td>
<td>$10,000</td>
<td>$20,000</td>
<td>$30,000</td>
<td>Add 1-2 months</td>
</tr>
<tr>
<td>Transport simulation 1 hr longer</td>
<td>$10,000</td>
<td>$20,000</td>
<td>$30,000</td>
<td>Add 1-2 months</td>
</tr>
</tbody>
</table>

* Assumes 1-2 constituents, and simulation time of 2 hours or less
Findings/Lessons Learned

• Transport optimization algorithms
  – Allow thousands more simulations
    • For example, 39 trial-&-error runs vs. ~5000 runs with the MGO
      transport optimization code for one formulation
  – Can assist sites in screening alternative strategies (e.g., aggressive
    pumping vs. containment only)
  – Have potential application during both the design and operation of
    P&T systems
  – Require development of optimization formulations, which helps
    the project team understand and quantify objectives and constraints
Technology Transfer Activities

• Project Website
  (http://www.frtr.gov/optimization/simulation/transport/general.html)
  – Optimization codes and documentations
  – Final project report
  – Modeling files for each demonstration site
  – Sample optimization code input and output files for Blaine
  – Powerpoint animations illustrating results for Each group

• Training
  – 2-day workshop - 2004

• Case Study / Site Follow-Up
  – Through summer 2004
Questions
Thank You

After viewing the links to additional resources, please complete our online feedback form.

Links to Additional Resources