Groundwater Models and Modeling Considerations

MPCA Industrial Landfill Guidance Workgroup
April 30, 2009

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The Three Legs of the Stool

1. Engineering design and construction determines source flux.
2. Operational practice determines the source strength.
3. The final leg is the placement of the above known conditions directly into the specific hydrogeologic setting of the site for purposes of quantitatively evaluating the groundwater impact potential before the activity occurs.

Note: Certain site conditions result in unreliable performance from one of the above legs, such as;

- Flooding conditions
- Geotechnical instability (e.g., seismic, karst, unstable soils)
- Unpredictable groundwater movement (e.g., karst)
GW Modeling
Key Components

• Source Characteristics
• Flow systems
  – Mixing (i.e., Advection and Dispersion)
  – Diffusion
• Geochemical Transformation
  – Attenuation
  – Retardation
• Steady State or Transient
Choosing a Model?

• What level of analysis do I need?
  – Is simpler better? ➤ Analytical vs. Numerical
  – *The level of analysis should match known field data and project objectives*

• Conceptual Site Model?
  – Unsaturated flow or saturated flow? Both?
  – Is the main flow field 1-D, 2-D, or 3-D?
  – Are there complex hydraulic interactions with boundary conditions (Sources, Streams, no-flow boundaries, etc)
Model Development Approach

From EPA 1992 (Fundamentals of Groundwater Modeling)

Models are commonly misused

Trying to represent processes by mathematical equations

Garbage in = Garbage out
Analytical Models

- Direct solution with given set of input parameters
- Allow for quick and cost effective analysis of groundwater flow systems and transport
- Usually involve a number of simplifying assumptions
  - Requires professional judgment and experience to apply to field situations
- Best used for situations where groundwater flow conditions are straightforward
Numerical Models

• Require a greater level of field data collection and site characterization

• Basic types:
  – Finite-difference, Finite-element, Boundary-element, Particle tracking models, Integrated finite-difference models

• MODFLOW and MT3D are the industry standards for numerical modeling

• Able to simulate very complex conditions that analytical models cannot handle
Select Examples of Groundwater Flow and Solute Transport Model Programs

**Analytical**
- Dilution Models
  - Summers Model
- Advection-Dispersion
  - Bioscreen
  - Biochlor
- Combination Sat-Unsat
  - SESOIL-AT123D
- Quickflow (steady state or transient hydraulic analysis)

**Numerical**
- Unsaturated
  - VLEACH
  - UNSAT-H
- Saturated
  - UTCHEM (NAPL)
  - Bioplume III
  - MODFLOW
  - MT3D
- Combination
  - SUTRA
MODFLOW

- Three-Dimensional Finite Difference Groundwater Flow Model
- Undergone rigorous peer review and regulatory accepted
- The modular structure of MODFLOW consists of a Main Program and a series of highly-independent subroutines called modules (packages)
- These packages allow for the code to simulate a wide variety of systems
- “MODFLOW is most appropriate in those situations where a relatively precise understanding of the flow system is needed to make a decision” (www.modflow.com)
MT3DMS

- Simulates solute transport utilizing the cell by cell flow files from MODFLOW
- Modular three-dimensional transport model
- Code also undergone extensive peer review and regulatory accepted
- Updated since inception in 1990 to incorporate complex solute transport processes
  - Multi-Species Reactions (biological or geochemical)
  - Dual-Domain Sorption
Analytical vs. Numerical

- Steady-State vs. Transient;
- 1-D flow field or 2-D vs. 3-D flow field;
- Source Geometry – simple vs. complex;
- Source Conceptualization – simple vs. complex; and,
- Simplified geochemical processes and reactions vs. spatially and temporally variable reaction packages.
Steady-State vs. Transient

Analytical Solution
• Can be either steady state or transient
• Can account for time-varying effects such as seasonal water-level fluctuation, transient source-strength variation, seasonal recharge loading cycles, etc.

Numerical Solution
• Can be steady state or transient
• Can be discretized into unlimited timesteps to accurately resolve the short-duration events
• Can be setup to simulate complex seasonal effects on groundwater flow field and dissolved-phase concentration distribution
• Can simulate changes in source strength over time
Steady State Considerations

• Sensitivity versus Groundwater Protection
• Most protective sites have high dilution attenuation factors
• Clay site example
1-D vs. 3-D

Analytical
• Single-layer aquifer system;
• Groundwater flow field is isotropic and homogeneous;
• Groundwater flow is restricted to only one horizontal direction;
• Results in a specified 1-D or 2-D groundwater flow velocity field.

Numerical
• Unlimited number of hydrologic layers possible;
• Complex parameter distributions and multiple boundary condition types allows for simulation of anisotropic and heterogeneous flow field
• Groundwater movement is simulated in three dimensions
• Resulting groundwater velocity field can be highly complex, more accurately representing dispersive process, reducing the sensitivity of dispersivity.
A Side Note - 1-D Flow Field?
<table>
<thead>
<tr>
<th>Source Geometry</th>
<th>Analytical</th>
<th>Numerical</th>
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<tbody>
<tr>
<td></td>
<td>• Typically, a simplified source “plane”;</td>
<td>• Can be constructed to realistically represent actual source area geometry in the three spatial dimensions</td>
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<td>• Must be oriented perpendicular to 1-D groundwater flow direction, regardless of actual site groundwater flow field</td>
<td>• Independent of groundwater flow direction</td>
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Source Conceptualization

Analytical

- Typically, steady-state specified concentration only.
- Does not account for source depletion over time or other time-varying source changes.

Numerical

- Spatially and temporally-variable specified concentration or specified flux
- Can simulate changes in source over time, such as source depletion or increases in source loading.
Leachate Source Considerations

• Unlined Sites
  – HELP
  – Richards Eqn Models
  – Other

• Lined Sites
  – HELP - Defaults
  – Published Values
  – Electronic Leak Testing
Geochemical Processes

**Analytical**
- Constant retardation over entire model domain can be simulated
- Uniform, steady-state 1\textsuperscript{st}-order degradation is also possible

**Numerical**
- Spatially and temporally-variable bulk density and Kd values,
- Multiple isotherms possible
- Complex sequential-decay reactions
- Spatially and temporally-variable degradation rates possible
U.S. EPA Industrial Waste Management Evaluation Model (IWEM)

- Developed over a seven year period by U.S. EPA, twelve states, various consultants, and regulated entities.
- Goal - provide a guidance tool to evaluate and recommend the type of liner system for industrial waste based on the hydrogeological setting and leachate quality.
- IWEM is based on leachate generation modeling, groundwater fate-and-transport theory, and statistical methodology that are well accepted by hydrogeologists, engineers, and other environmental professionals working in the scientific community.
- The tier one procedure default values are representative of different hydrogeological settings found across the United States. The tier two procedure allows for state or site specific settings for geology, leachate concentrations, and engineering to be used.
Ohio EPA Study

- Evaluated IWEM using both the tier one and tier two procedures.
- Four different hydrogeological settings and three different liner options, evaluated actual leachate and waste characterization data as inputs into the model. Output compared with field data to evaluate prediction at disposal facilities in Ohio.
- IWEM is conservative, particularly with respect to certain aspects of fate-and-transport mechanisms that are difficult to model, such as contaminant attenuation in the vadose zone. These natural mechanisms may affect the mobility of potential ground water contaminants. Ohio EPA concluded that IWEM’s conservative approach significantly underestimates the ability of clay liners to contain the typical contaminant concentrations documented to occur in leachate from Ohio’s industrial waste disposal facilities.
- Accordingly, IWEM was not used to develop leachate concentration threshold levels for clay liners constructed to contain industrial waste leachate.
Ohio EPA Study (cont.)

• Ohio EPA’s evaluation of IWEM for “no liner” scenarios concluded that while the results tend to be conservative in many cases, the results are not unrealistic for the range of hydrogeologic conditions occurring in Ohio. Accordingly, the “no liner” IWEM results were used as one source of information to help develop leachate concentration threshold levels for unlined industrial waste disposal facilities.
• Links to more info”
• [http://yosemite.epa.gov/OSW/rcra.nsf/ea6e50dc6214725285256bf00063269d/7d7170e5d5214a5b852574b4005f5b35!OpenDocument](http://yosemite.epa.gov/OSW/rcra.nsf/ea6e50dc6214725285256bf00063269d/7d7170e5d5214a5b852574b4005f5b35!OpenDocument)
• User’s guide and tech manual and executable file
• [http://www.epa.gov/epawaste/nonhaz/industrial/tools/iwem/index.htm#user](http://www.epa.gov/epawaste/nonhaz/industrial/tools/iwem/index.htm#user)
• Other links:
  • [http://www.epa.state.oh.us/dsiwm/document/newsPDFs/seperation_distance.pdf](http://www.epa.state.oh.us/dsiwm/document/newsPDFs/seperation_distance.pdf)
Take-Aways

• Analytical, are typically conservative and can provide a reasonable approximation, but can’t account for complex groundwater flow conditions and source conceptualization.

• Numerical techniques allow for much more complex representation of the conceptual site model and can be calibrated to both water-level data and concentration data, yielding more accurate and realistic simulation of the fate and transport of dissolved-phase constituents.

• Combining numerical techniques with formal uncertainty analysis yields a powerful decision and management tool.
Take-Aways

• Leachate Source Flux – Critical for Lined sites.
• Steady State conditions may dramatically overestimate concentrations for declining source.
• This process is the three legged stool:
  – Engineering design and construction determines source flux
  – Operational practice determines the source strength
  – In groundwater modeling we superimpose the above into the local site specific hydrogeologic setting – to quantitatively evaluate groundwater impact potential before the activity occurs.
• With this approach are we not dealing directly with groundwater sensitivity?
• Inconsistent to then embrace a GW sensitivity matrix or decision tree that is not site specific and leaves out two legs of our stool.
Questions