Hydrology of Landfill Final Covers: Modeling and Monitoring

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Research Questions:

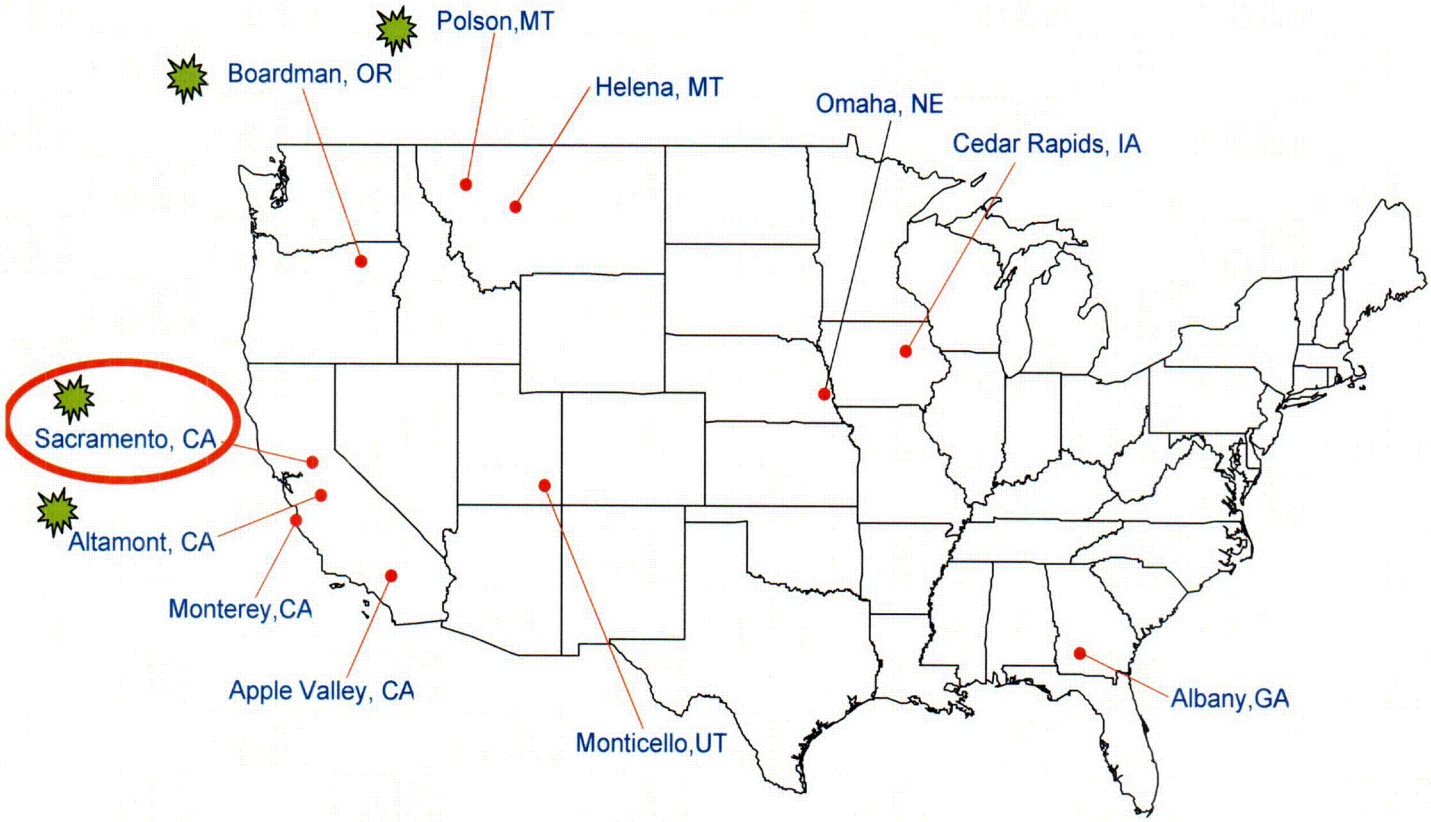
- Do common numerical models used for design/evaluation of cover hydrology provide *accurate* predictions?

- How can we improve model predictions using field monitoring data?

Model Assessment

- Must be compared with field data.
- Must use measured properties as input to the greatest extent possible.
- Must match boundary conditions.

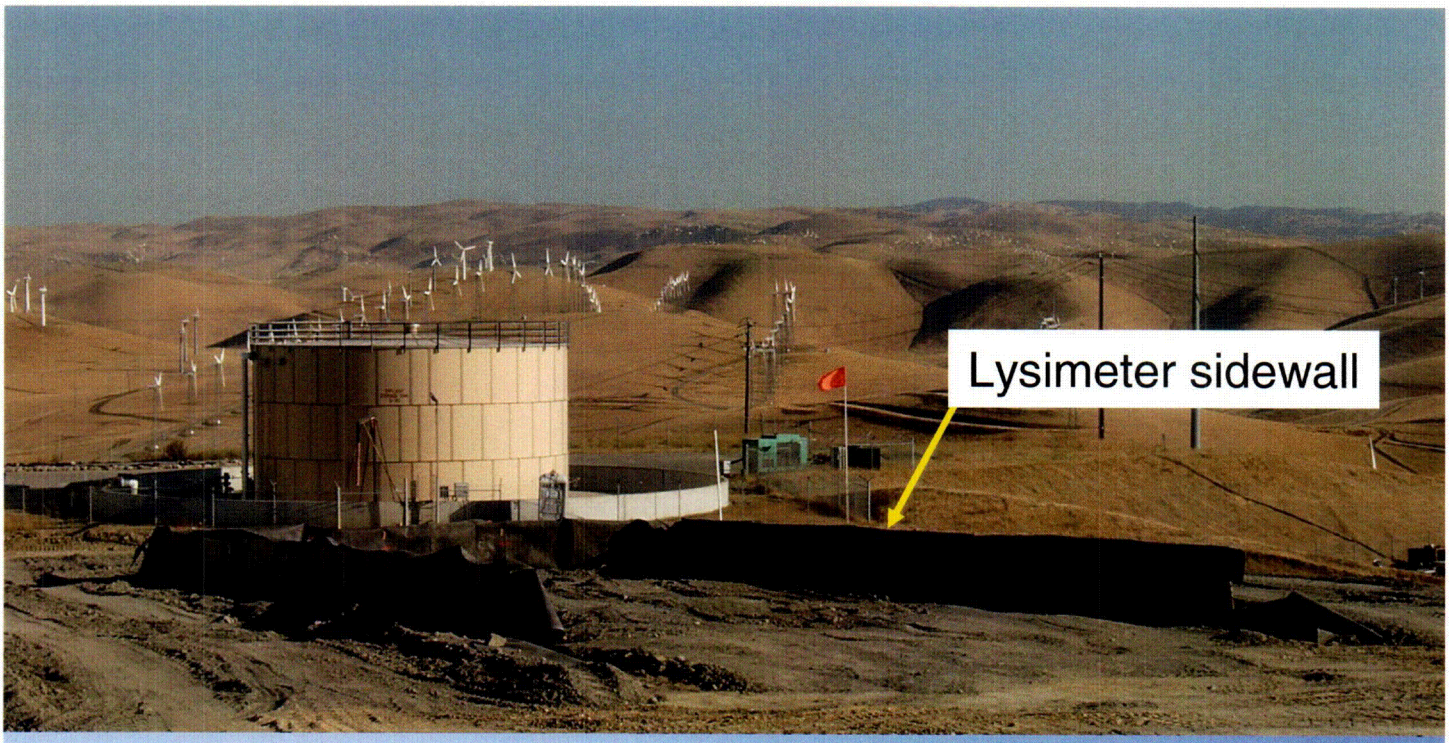
ACAP Field Sites in Modeling Study

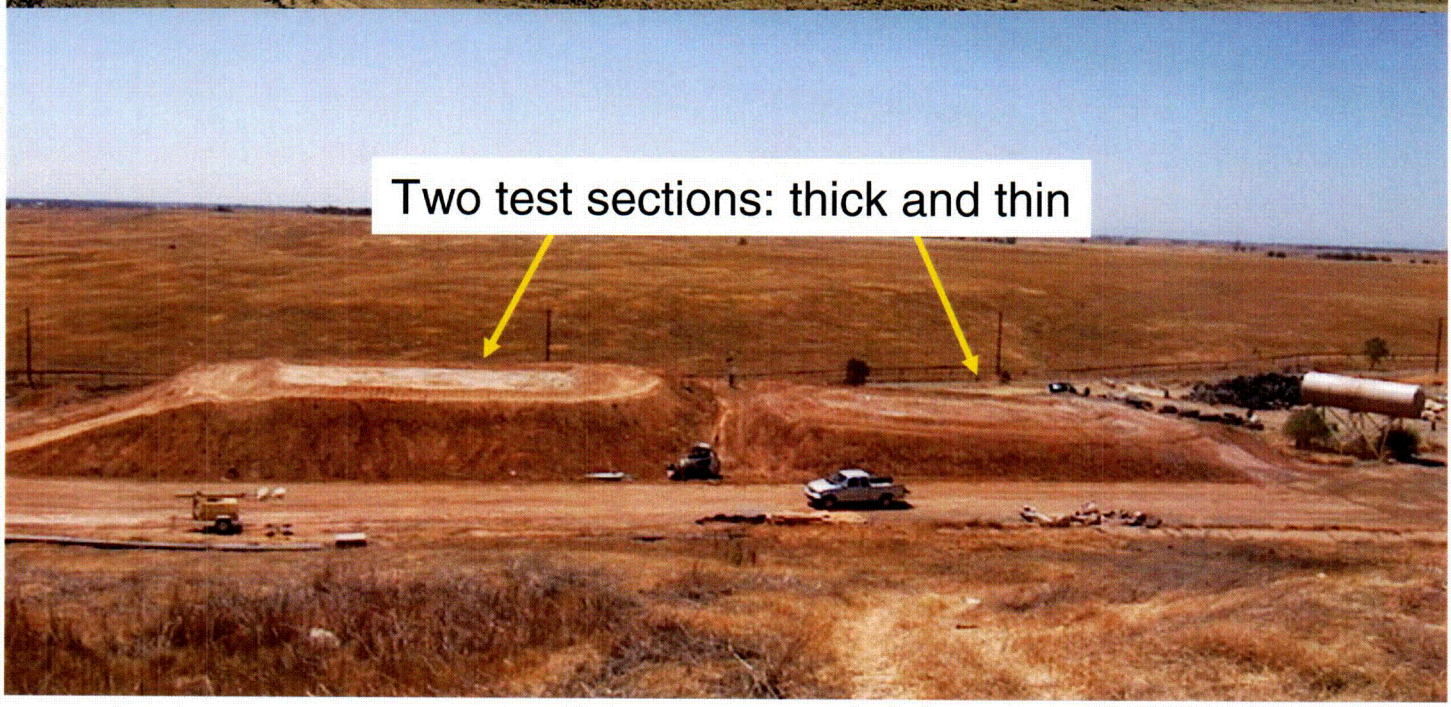


- site used in modeling study

Presentation focuses on model predictions and monitoring data from Sacramento site.

Large Instrumented Lysimeters Constructed 1999-2000





Instrumented to measure all water balance components except ET over 10 x 20 m area.

ET obtained by difference.

Hydraulic Properties and Vegetation

- Collected undisturbed soil samples during construction for hydraulic properties. Surface layer sampled annually thereafter.

- Root density and LAI of vegetation periodically; wilting point inferred from monitoring data.

Models Evaluated

- HYDRUS-2D (USDA, J. Simunek) – 2D
- LEACHM (Cornell/Flinders U., J. Hutson) – 1D
- UNSAT-H (PNNL, M. Fayer) -1D
- Vadose/W (GeoSlope, G. Newman) – 2D

All four models commonly *used in practice* for simulating cover hydrology.

Underlying Physics

- Richards' Equation for Unsaturated Flow & Root Water Uptake

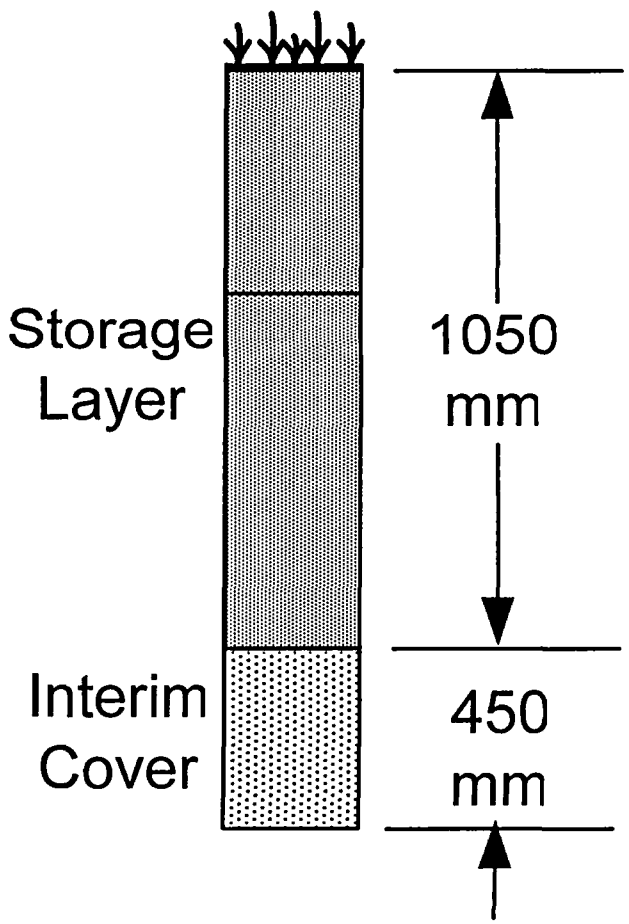
$$\frac{\partial\theta}{\partial\psi}\frac{\partial\psi}{\partial t} = -\frac{\partial}{\partial z}\left[K_T\frac{\partial\psi}{\partial z} + K_\psi + q_{vT}\right] - S(z,t)$$

Can be solved in 1-D or 2-D with existing codes, but most often in 1-D

- Boundary Conditions
  - atmospheric flux at surface (meteorology driven)
  - unit gradient or 'seepage face' at bottom, latter recommended by some for lysimeters

Sacramento Field Site

- Kiefer MSW Landfill, SE Sacramento, CA
- Semi-arid site
  - avg. precipitation (P) = 434 mm/yr
  - P/PET = 0.33
  - avg. daily temp. 3 °C (Jan) to 34 °C (Aug)
- Monolithic Cover
  - 1050 mm thick storage layer
  - 450 mm interim cover
  - broadly graded alluvium
  - Upper 150 mm highly weathered surface layer



Input Data

- Field-measured on-site meteorological data
- Field measured vegetation properties (leaf area index, or LAI, and root density distribution)
- Hydraulic properties: geometric mean K_s and α; arithmetic mean n, θ_s, θ_r

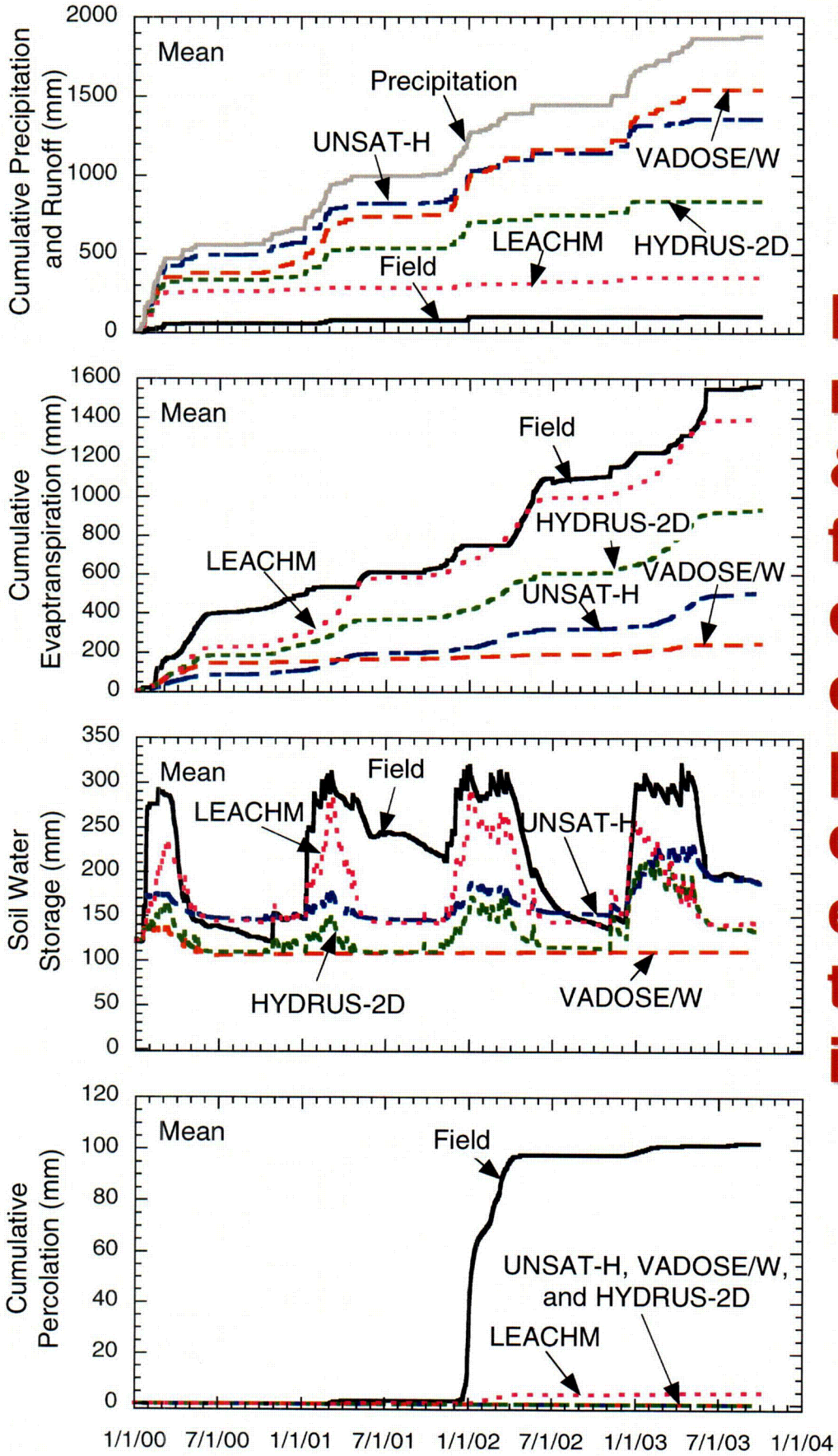
Layer	van Genuchten Parameters				Saturated Hydraulic Conductivity, K_s (cm/s)			
	θ_r	θ_s	α cm^{-1}	n	00	01	02	03
Surface (150 mm)	0.01	0.30	0.006	1.40	6.4×10^{-7}	2.6×10^{-6}	1.6×10^{-5}	2.6×10^{-5}
Storage (900 mm)	0.00	0.31	0.001	1.26	1.3×10^{-6}			
Interim (450 mm)	0.02	0.33	0.001	1.42	6.2×10^{-6}			

Boundary Conditions

- Surface: Atmospheric flux boundary
  - Infiltration
  - Evaporation (transpiration treated as sink)
  - Runoff computed as an excess quantity

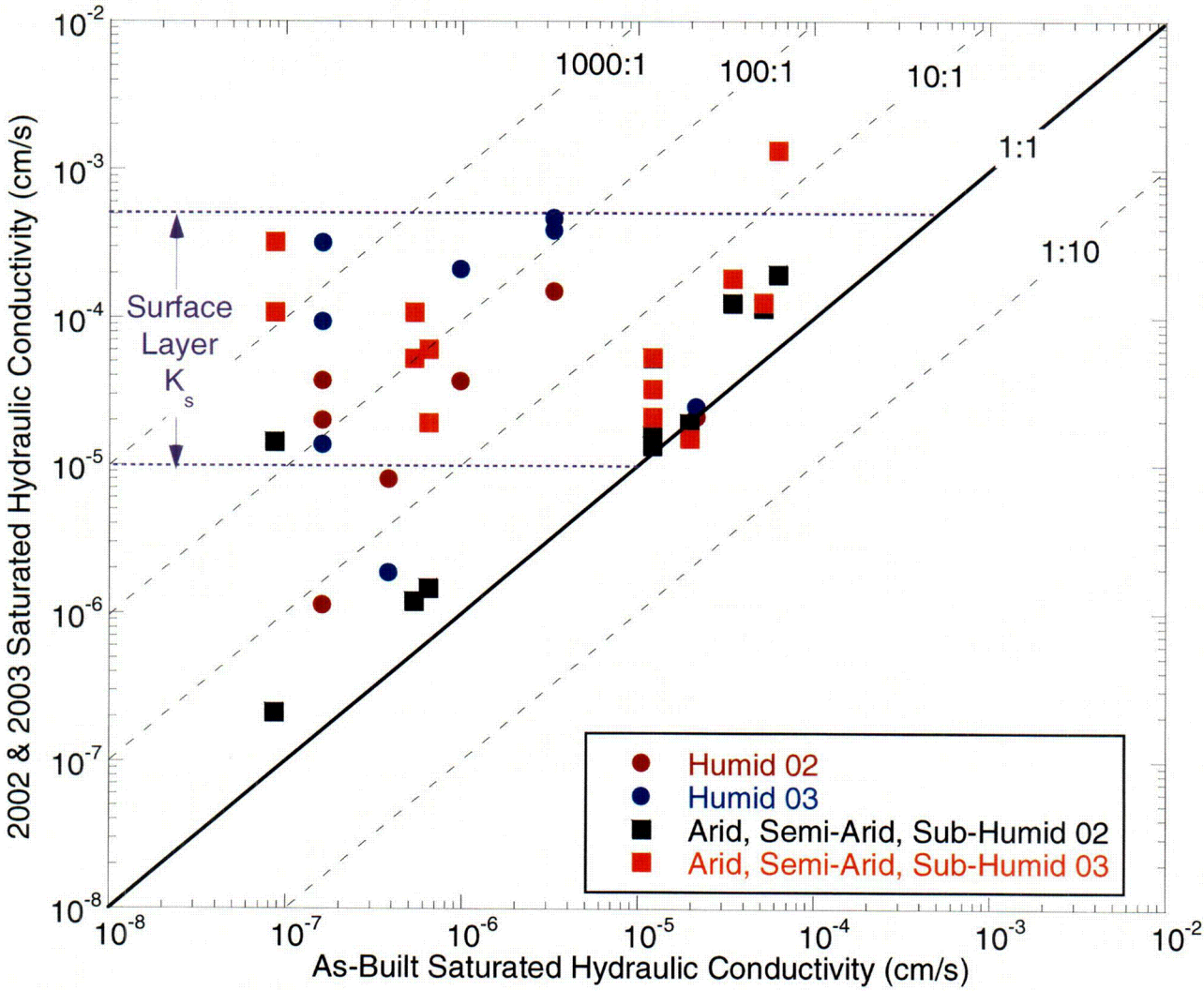
  While conceptually similar, *each model handles this boundary differently*.

- Lower Boundary - flux
  - Unit gradient: flux = K_ψ at boundary
  - Seepage face: flux = 0 unless bottom boundary is saturated, then flux = K_s
  - Appropriate boundary for lysimeter falls between unit gradient and seepage face. Capillary break should be accounted for, but flow into lysimeter drain does occur for conditions below saturation.



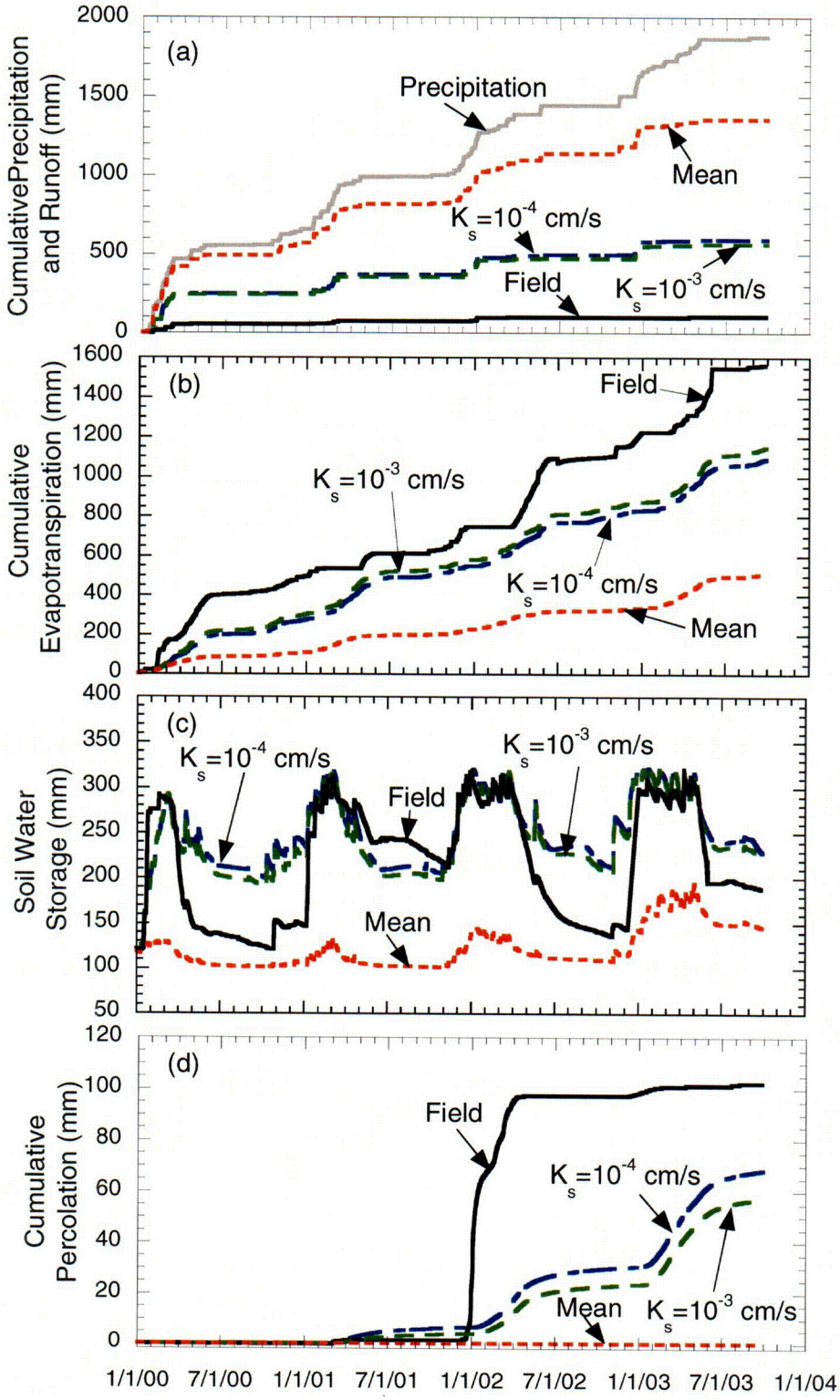
Four models & four distinctly different predictions despite essentially the same input.

Pedogenesis and Surface Layer Conductivity



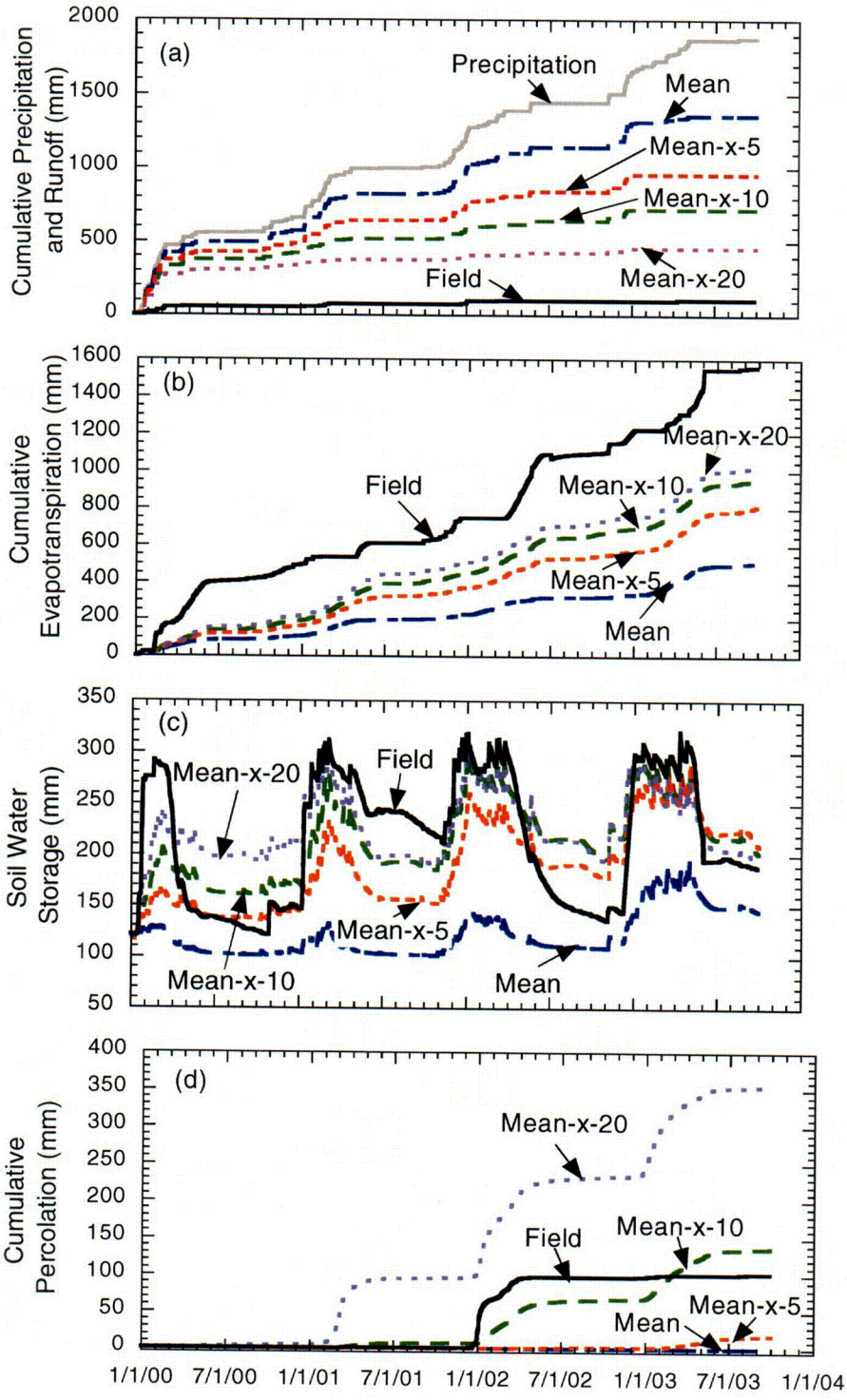
Saturated hydraulic conductivity of surface layer ranges between 10^{-5} and 10^{-3} cm/s, typically 10^{-4} cm/s.

UNSAT-H & Permeable Surface Layer



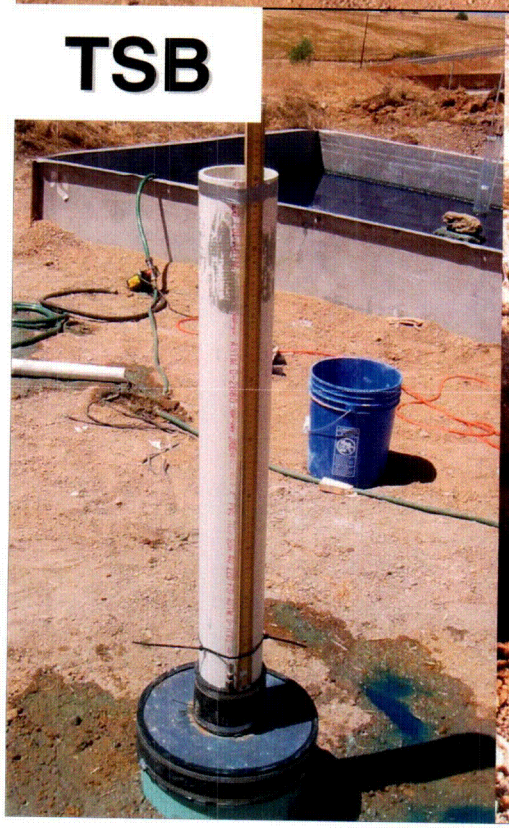
More water now enters the cover, but too much remains stored and too little drains.

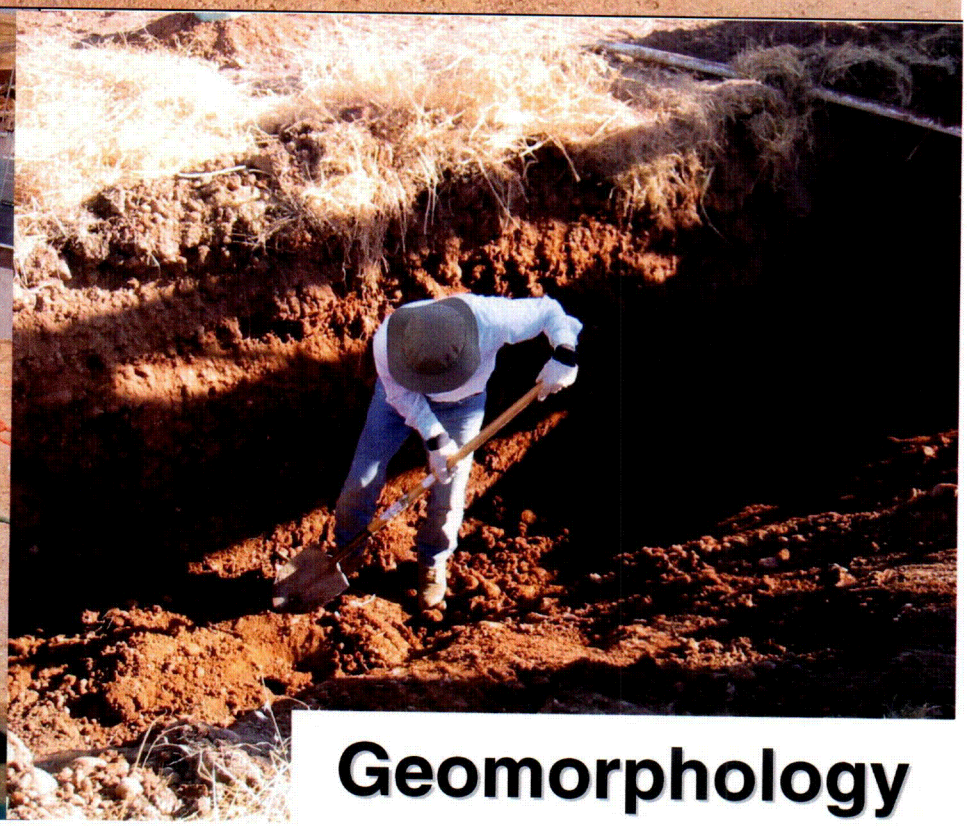
UNSAT-H & Permeable Storage Layer



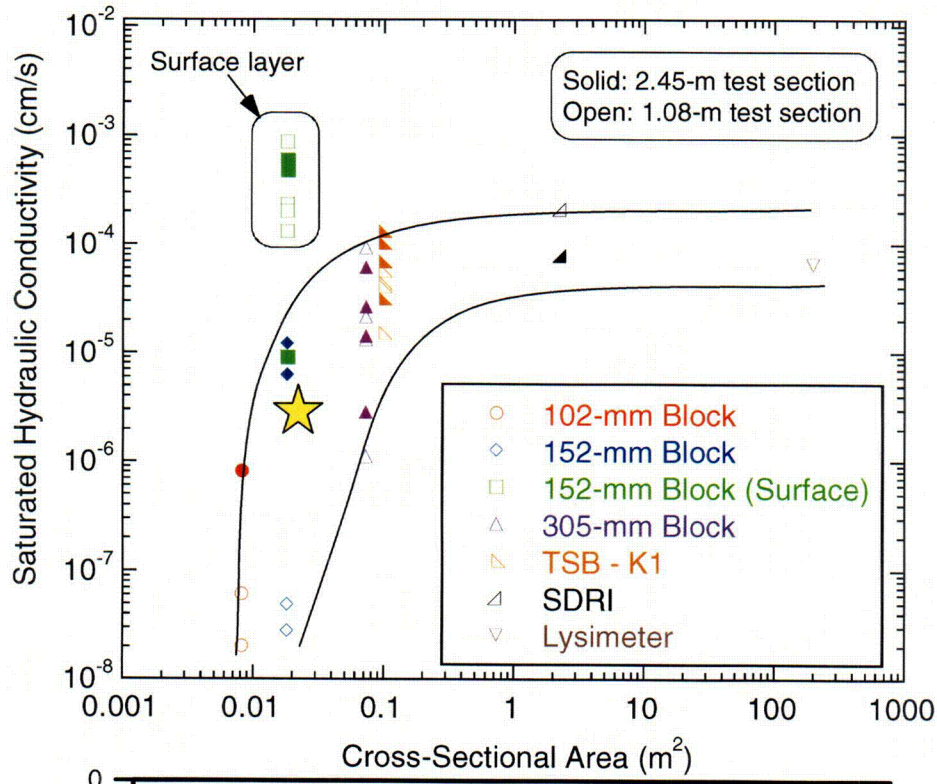
- More water now enters and drains from the cover, but too much still remains stored.

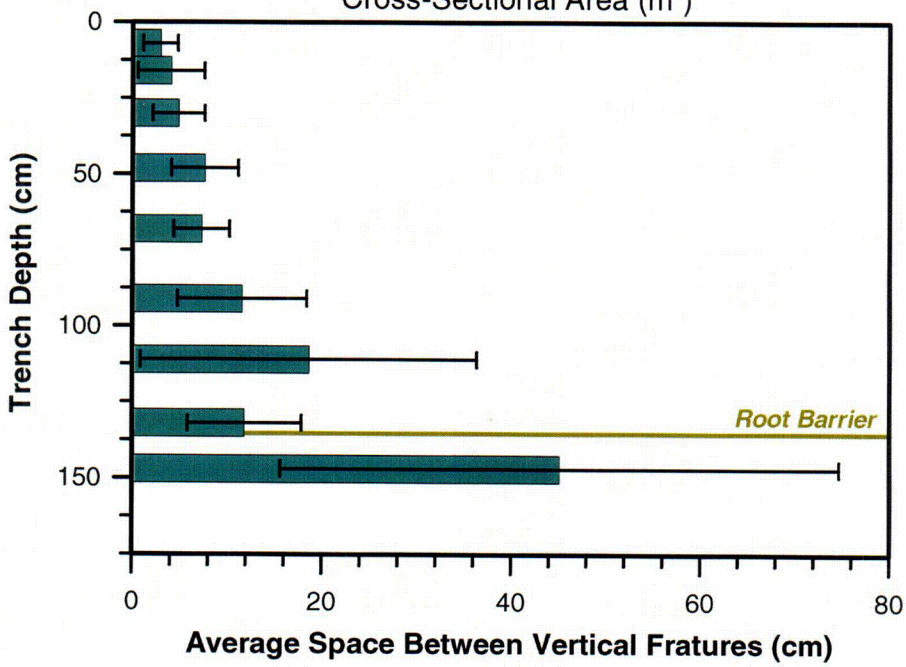
Decommissioning
August 2005





Saturated Hydraulic Conductivity - 2005





Pedogenic changes in the water retention curves also observed.

Significant Factors Identified from Analysis of Monitoring Data

- Must account for pedogenic effects on soil properties.
- Pore interaction term in K_ψ; improve storage and drainage of water using ℓ = -1 to -3.
- Match precipitation intensity to more closely simulate runoff and infiltration.
- Account for temporal changes in vegetation species and effect on water removal.
- Lower boundary far less important than suggested by others.

Summary of Observations

- Four models commonly used in practice to simulate landfill cover hydrology provided very different predictions using typical engineering data as input

- Assessing model accuracy not possible without monitoring data.

- Monitoring data and decommissioning studies led to improvements in model parameterization. Relevant to future predictions (or update predictions for a site).

- Models are an abstraction of reality and predictions depend greatly on input. Check 'reasonableness' of predictions against monitoring data if possible.

Site Characterization to Support Model Development for Contaminants in Ground Water

Robert G. Ford

U. S. Environmental Protection Agency
Ground Water & Ecosystems Restoration Division
Ada, OK

Acknowledgement: Steven Acree, Elise Striz, Bill Brandon

Advisory Committee on Nuclear Waste

Working Group Meeting on Using Monitoring to Build Model Confidence

September 19 - 20, 2006

What Controls Contaminant Transport?

- **Physical constraints:**
  - Contaminant source mass and distribution
  - Subsurface flow velocities
  - Spatial distribution of flow paths
  - Temporal variability of flow velocity & direction
- **Chemical constraints:**
  - Contaminant properties (decay rate, degradation rate, sorption affinity)
  - Aquifer sediment properties (mass distribution, sorption affinity, chemical stability)
  - Ground-water chemistry – as it affects 1) contaminant chemical speciation and 2) sediment mineral stability & sorption characteristics

This information determines accuracy of conceptual or predictive site model, which is the basis for projecting contaminant transport.

Questions to be Addressed through Site Characterization & Analysis

- What are the transport pathways within the aquifer?
- What is the rate of fluid flow along critical transport pathways?
- What processes control attenuation of the contaminant along transport pathways?
- What are the rates of attenuation & capacity of aquifer to sustain contaminant attenuation?

The data collected to address these questions also serve as the input into reactive transport models that may be employed as one of the tools to 1) assess the accuracy of the Conceptual Site Model relative to observed contaminant transport behavior, and 2) to test future projections of transport based on anticipated land-use scenarios.

Characterizing Site Hydrogeology

Characterization Goals

- Identify pathways of contaminant transport relative to compliance boundaries and risk receptors
- Establish GW monitoring network that allows collection of data to identify spatial heterogeneity and temporal variability of hydrologic and biogeochemical characteristics of aquifer
- Establish GW monitoring network that supports collection of samples that are representative of aquifer conditions (*drilling methods & materials important!*)
  - Avoid alteration of hydraulic conductivity
  - Avoid alteration of geochemistry adjacent to well screen

USEPA Monitoring Well Screening Tool

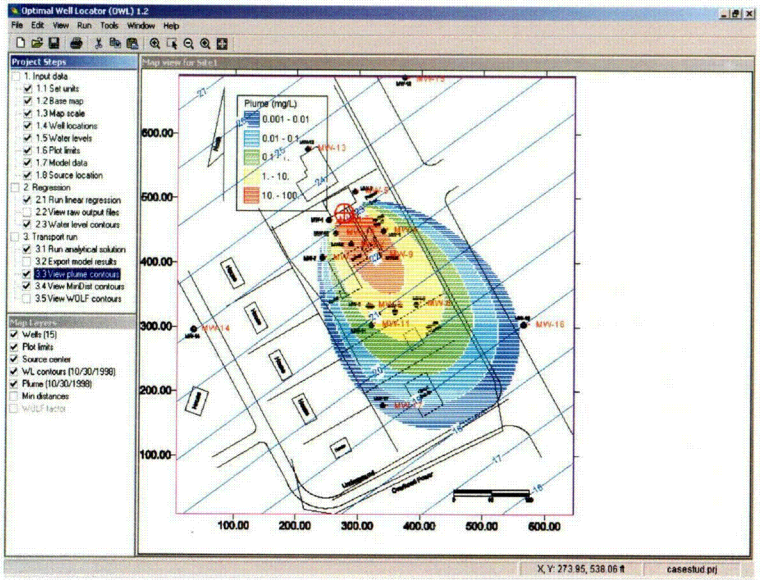
Optimal Well Locator (OWL) Version 1.2

<u>Objective</u>: To provide a simple tool for non-modelers to evaluate the ground water flow, plume migration and MW network at their site using typically collected site data.

- What is the variation in magnitude and direction of ground-water flow over time?
- How does this variation affect plume migration at the site over time?
- Are the existing monitoring wells able to intercept the plume? Where is the best place to put a new monitoring well?

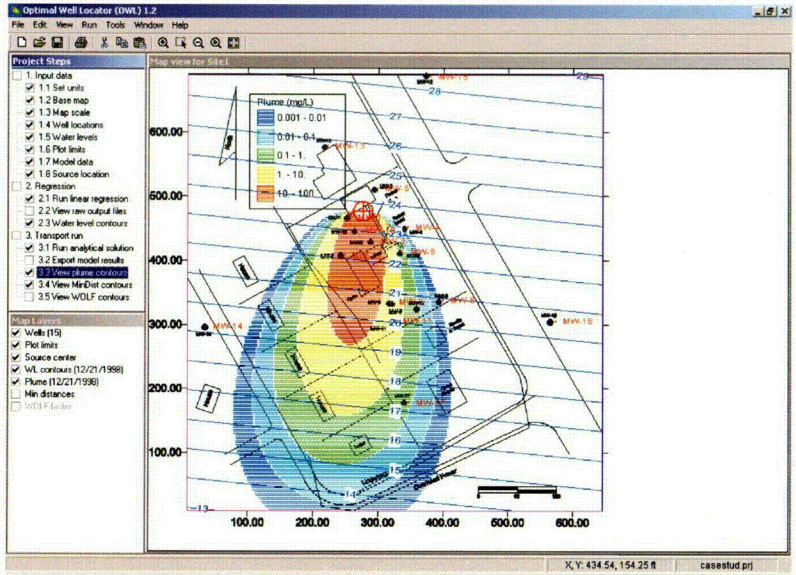
Center for Subsurface Modeling Support (CSMoS)
U.S. EPA/NRMRL/GWERD Ada, OK
http://www.epa.gov/ada/csmos/models/owl.html

Plume Migration Path 10/30/98



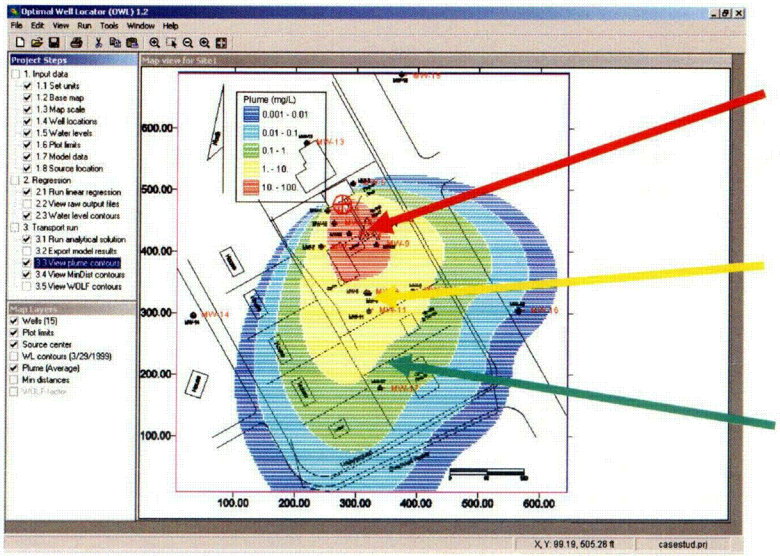
$t = 6$ years
$k = 514$ ft/yr
$\varpi = .45$
$R = 1$
No decay
$\alpha_x = 30$ ft
$\alpha_y = 3$ ft
$C_0 = 125$ mg/l

Plume Migration Path 12/21/98



Average Composite Plume (6)

$$C_{avg}(i,j) = \frac{1}{n}\sum_t C(i,j,t)$$



Red : 10-100 mg/l
Existing MW coverage good

Yellow: 1-10 mg/l
Existing MW coverage sparse

Green: 0.1-1.0 mg/l
One existing MW

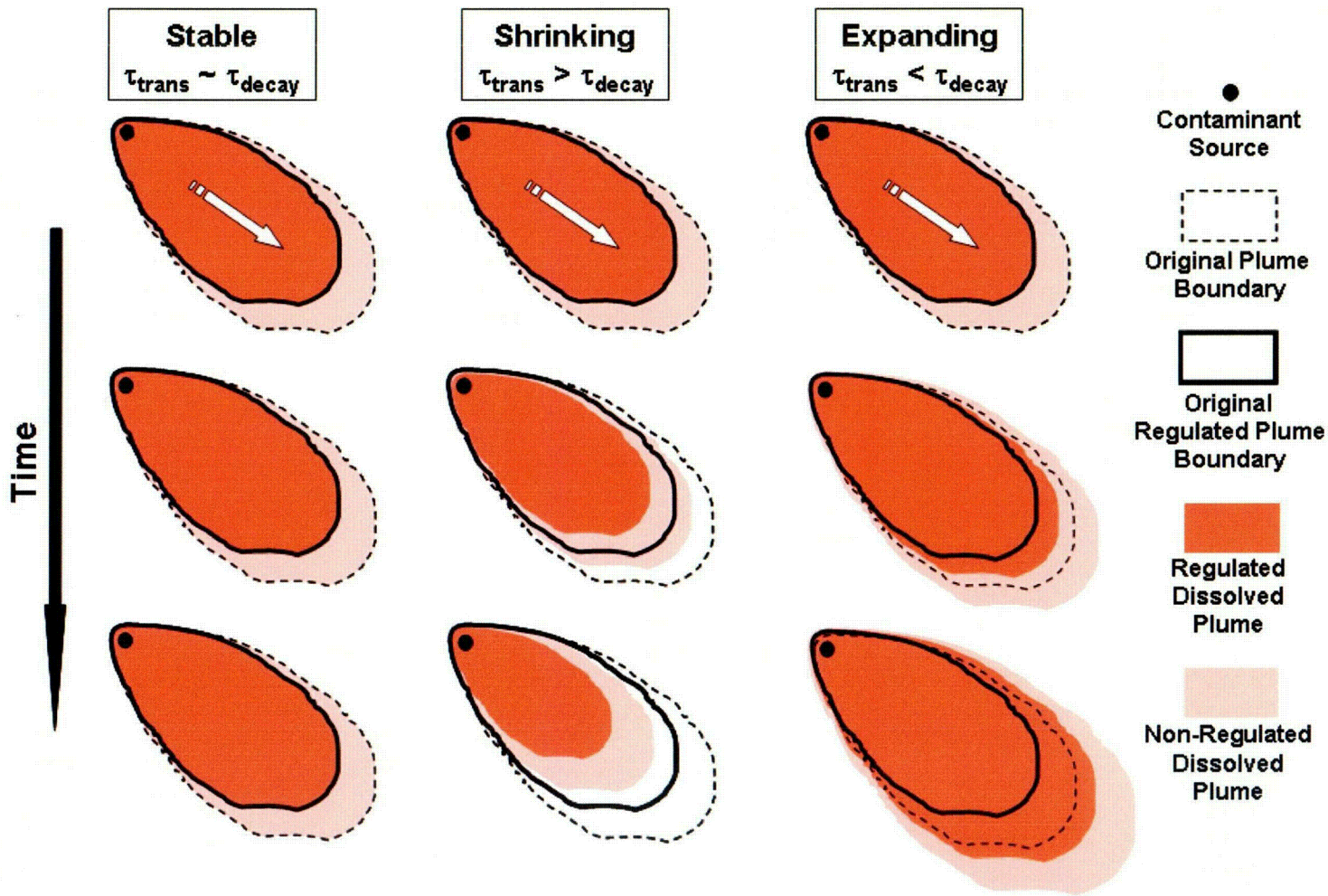
Characterizing Site Biogeochemistry

Characterization Goals

- Identify reaction mechanisms/processes that control contaminant transport
- Collect data that 1) support evaluation of Conceptual Site Model and 2) verify performance of identified transport process(es)
- Employ sample collection and analysis procedures that:
  1) maintain sample integrity
  2) characterize the factors that control contaminant degradation or partitioning between aqueous and solid matrices

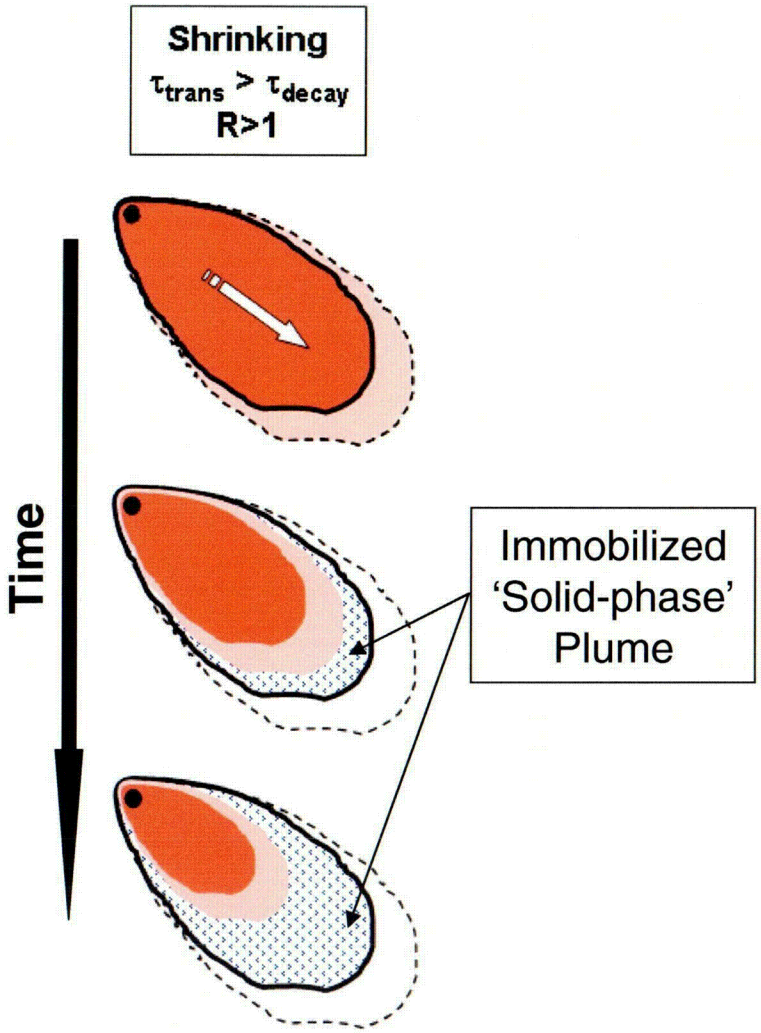
Subsurface 'Dissolved' Plume Behavior

Decaying Radionuclide - Conservative Physical Transport, Uncontrolled Source
(Regulated = exceeds Risk-based or ARAR criterion; τ = characteristic time)



Subsurface Plume Behavior

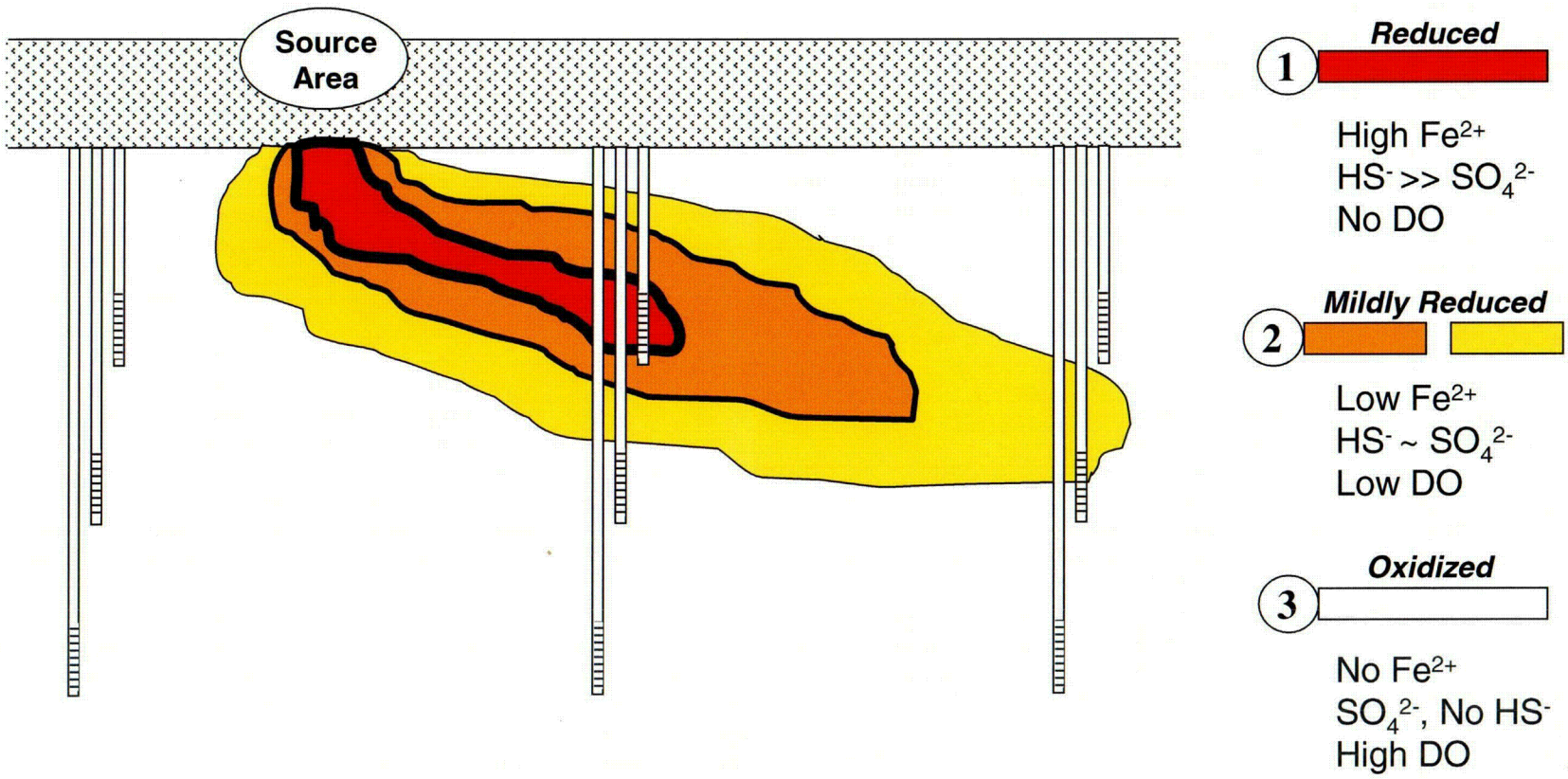
Decaying Radionuclide – Non-conservative Physical Transport, Uncontrolled Source



- Significant mass of non-conservative radionuclide may be accumulated onto aquifer solids
- '*Solid-phase*' plume represents contaminant mass attenuated at any point in time
- Future scenarios for evolution of '*solid-phase*' plume
  1) Declines in mass & spatial distribution due to decay
  2) Remains invariant in mass & spatial distribution
  3) Evolves to new state that serves as source for development of new dissolved plume
     - Radioactive decay produces more mobile daughter product(s)
     - Changes in ground-water chemistry cause re-mobilization

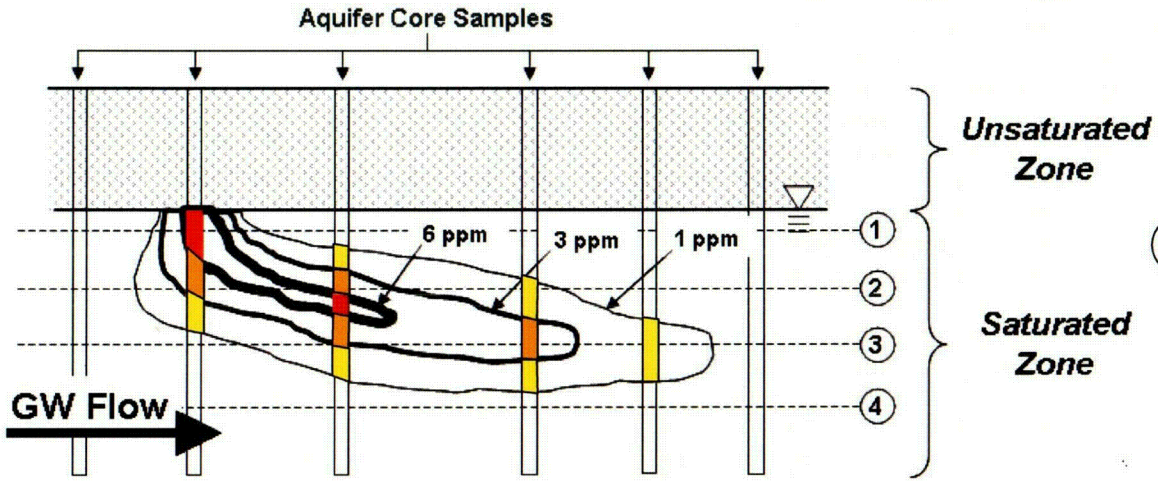
Schematic of Possible Scenario for GW Monitoring Program

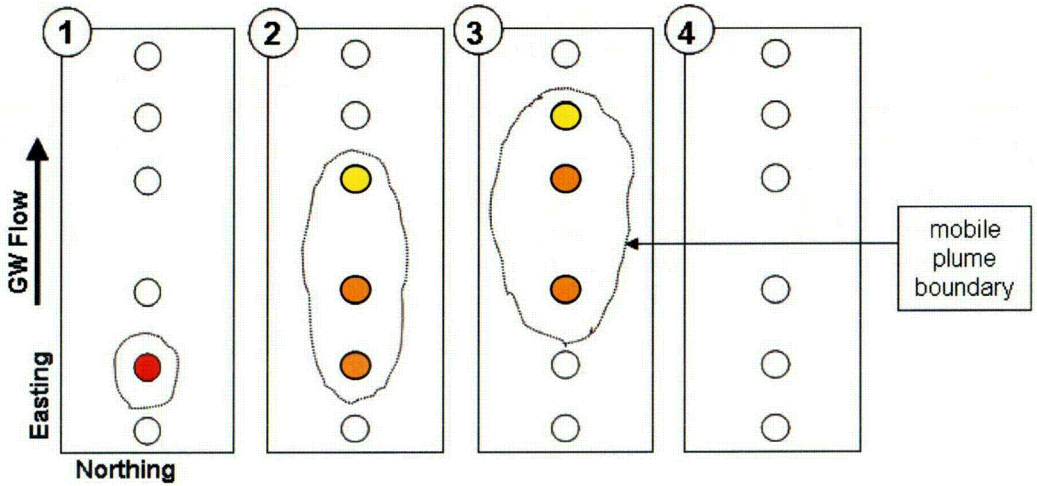
Mixed Organic-Inorganic Contaminant Plume



GW Monitoring Scenario

Sediment Redox Chemistry





1 Reduced

Reduced Fe Minerals
Sulfides
Anaerobic Microorganisms

2 Mildly Reduced

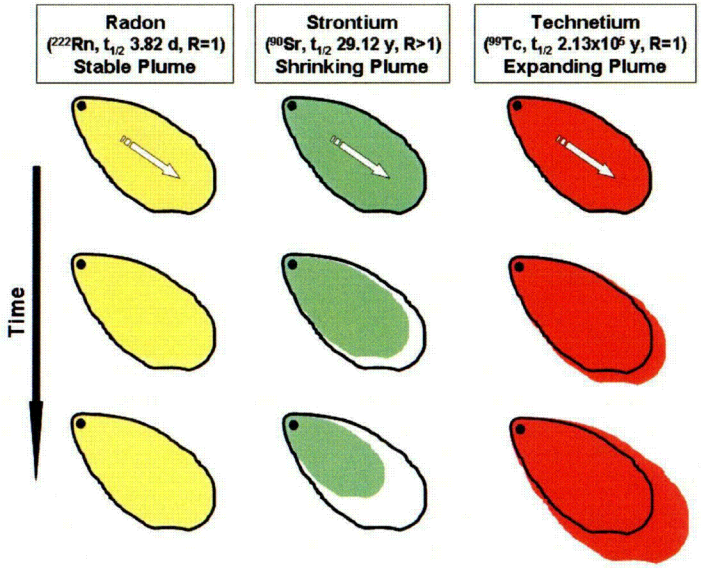
Mixed Fe(II)-Fe(III) Minerals
Carbonates-Sulfides?
Mixed Populations

3 Oxidized

Fe Oxides
No sulfides (unless native)
Aerobic Microorganisms

Importance of Proper Sample Collection to GW Compliance Monitoring

1) Proper identification of 'plume' extent for individual contaminants
   - 'plume' may contain *dissolved* and *solid* components
2) Prevent misidentification of plume geochemistry
   - Loss of viable organisms that can be cultured to determine degradation rates
   - Transformations in sediment mineralogy resulting in misleading identification of mineral(s) controlling contaminant sorption
3) Insure accuracy of estimates of sediment reactivity to engineered *in-situ* remediation technologies



Principles in Practice

Industri-Plex Superfund Site

- ***'Enhanced' MNA*** chosen as part of site remedy for restoration of GW contaminated with arsenic

EPA Region 1 – OU2

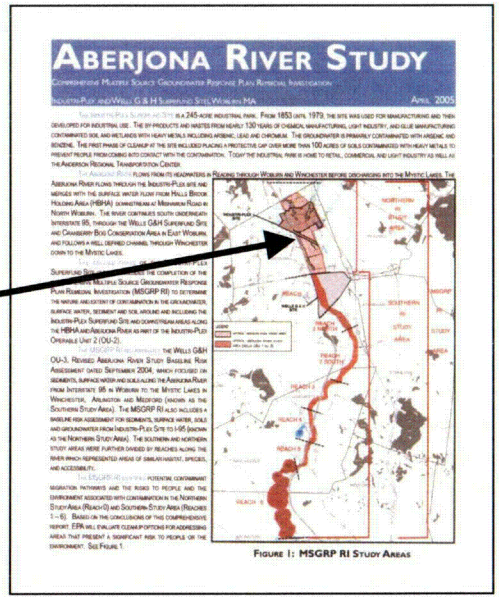
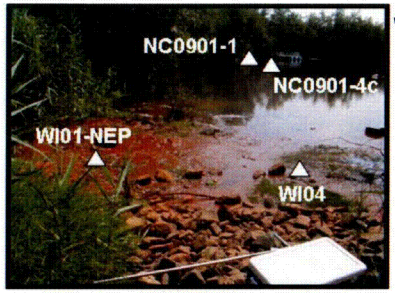
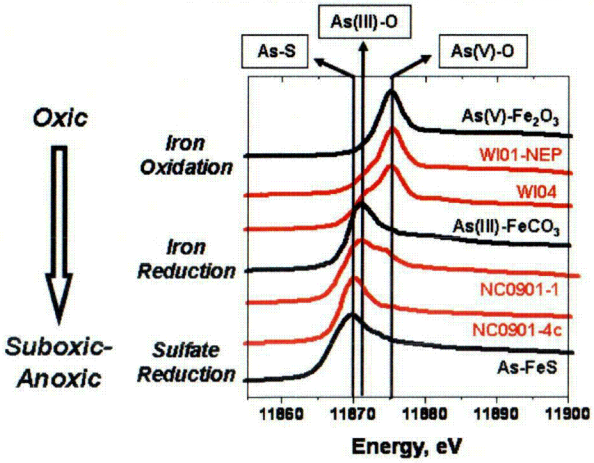

ABERJONA RIVER STUDY

FIGURE 1: MSGRP RI STUDY AREAS

http://www.epa.gov/region01/superfund/sites/industriplex/237453.pdf





Supporting Documentation

- EPA/ORD Final Report to Region 1
  http://www.epa.gov/ne/superfund/sites/industriplex/230912.pdf
- EPA/ORD Research Brief
  http://www.epa.gov/ada/download/briefs/epa_600_s05_002.pdf
- EPA/ORD Research Report
  http://www.epa.gov/ada/download/reports/600R05161/600R05161.pdf

Thanks - Questions?

EPA/ORD Documentation Relevant to GW Sampling and Preservation

- Low-Flow (Minimal Drawdown) Ground-Water Sampling Procedures, EPA/540/S-95/504 - This document is intended to provide background information on the development of low-flow sampling procedures and its application under a variety of hydrogeologic settings. It is intended to support the production of standard operating procedures for use by EPA Regional personnel and other environmental professionals engaged in ground-water sampling. (http://www.epa.gov/ada/download/issue/lwflw2a.pdf)

- Workshop on Monitoring Oxidation-Reduction Processes for Ground-water Restoration, EPA/600/R-02/002 – This document provides a current survey of the scientific basis for understanding redox behavior in subsurface systems within the framework of site characterization, selection of remedial technologies, performance monitoring of remediation efforts, and site closure. (http://www.epa.gov/ada/download/reports/epa_600_r02_002.pdf)

- Performance Monitoring of MNA Remedies for VOCs in Ground Water, EPA/600/R-04/027 - This document provides technical recommendations regarding the types of monitoring parameters and analyses useful for evaluating the effectiveness of the natural attenuation component of ground-water remedial actions. (http://www.epa.gov/ada/download/reports/600R04027/600R04027.pdf)

Toward a Modeling Mindset for Nuclear Facility Site Performance

Integrating ground-water modeling with ground-water monitoring

My message for this talk

- The concept of "model" means a lot more than just a computer simulation of flow / transport
- Today's modeling effort also includes data management, visualization, and communication
- State of the art allows near real-time data integration and visualization at reasonable cost
  - Characterization
  - Monitoring
  - Simulation
  - Communication

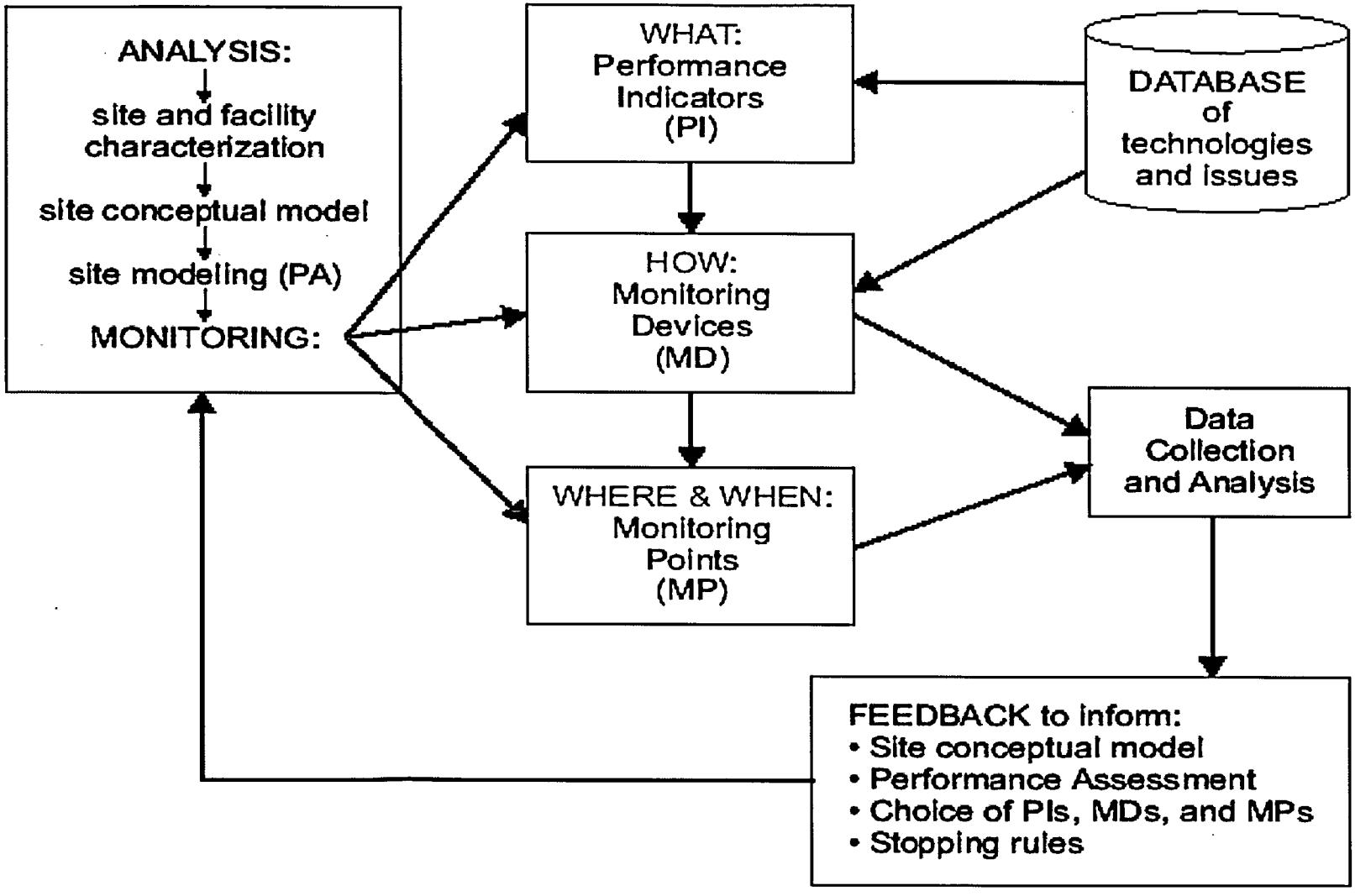
NRC Monitoring Strategy Project

- Goal of project is to provide logic and guidance for ground-water monitoring at NRC-licensed sites
- Focus has been on "Performance Confirmation Monitoring"
  - Monitoring to test the hypothesis that a site is performing within a design envelope of defined risk or is consistent with PA
  - Performance; Compliance; Detection
- Draft strategy developed
- Various presentations at NGWA, AGU, GSA meetings
- Currently in testing phase using data from DOE, DoD, and USGS sources as illustrations

For NRC Staff AES Has Presented Short Workshop Overviews of:

- Site Characterization
- Conceptual model development
  - Ground-water perspective
    - Site
    - Facility
- Performance assessment
- Geochemistry of transport
- Flow and transport modeling (Simulation)
- Data management, visualization, and analysis

Strategy Overview



Indicators of System Performance

- Chemical
  - Risk drivers - Cs, Sr …
  - Indicators – pH, H-3,
- Physical
  - Water pressures / contents – moisture profile in cap
- Interpreted
  - Spatial - bullseye on contour map
  - Non-spatial – control chart anomaly

Systems Analysis
Leads to Monitoring Requirements

- Site Characterization
  - Controls on flow and transport
    - Fractures
    - Depositional models Slide 10
    - Permeability
- Facility
  - Potential leakage or failure
  - Operating history – spills, leaks
  - SAR
- Performance assessment
  - Assumptions
  - Input data
  - Failure modes, weaknesses

Conceptual Model
many facets

- Site –
  - Physical - geology, hydrogeology
  - Chemical – controls on chemical transport
- Facility
  - Inventory
  - Likely leaks (from SAR analysis…)
    - Pathways – e.g. gravel fill around underground lines

- Characterize (puzzle pieces) - Conceptualize – Simulate - Revise

Characterization vs Monitoring

(in Site Performance Context)

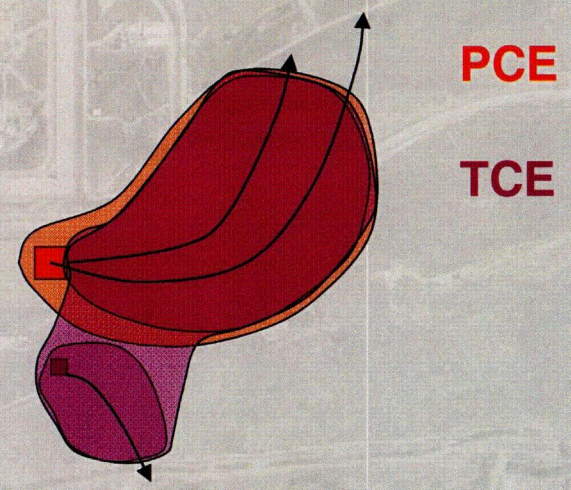
- Characterization allows development of CSM
- CSM allows modeling / simulation
- Modeling allows prediction
- Monitoring allows refinement
- Refinement allows confidence

Some things you can do with a model

- Establish separate sources or releases
  - RF overlapping plumes Slide 11
- Predict plume behavior in the future
- Communicate risk or safety factors to stakeholders
- Back-calculate from observations to improve estimates of parameters
- Evaluate alternative hypotheses
  - Congaree levee example Slide 12

Associate Source and Plume

Use probable source locations, groundwater flow paths, and daughter product distribution to delineate plume



ember 20, 2006
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A backwards look

- History of subsurface modeling
  - Water resource studies
  - Mineral resource studies
- A matter of scale
- A matter of detail
- Mining and petroleum applications – **profit related**
  - Lots of software development
- Environmental applications – **cost related**

So What is a Model?

- State of practice 1990-
  - Commissioned like a work of art by a patron
  - Computer resource hog
  - Expensive
  - Once done, resting on a shelf
- State of art 2006
  - Database for all characterization data
  - Visualization for communication support
  - Dynamic use of new site data
  - Desk-top computer adequate
- State of Practice 2010+ ?
  - Could be routine practice at every facility with an environmental program

A 1986 Modeling Example

- Conceptual model
- Predictive results
- Monitoring Observations

Conceptual Model

1986 model

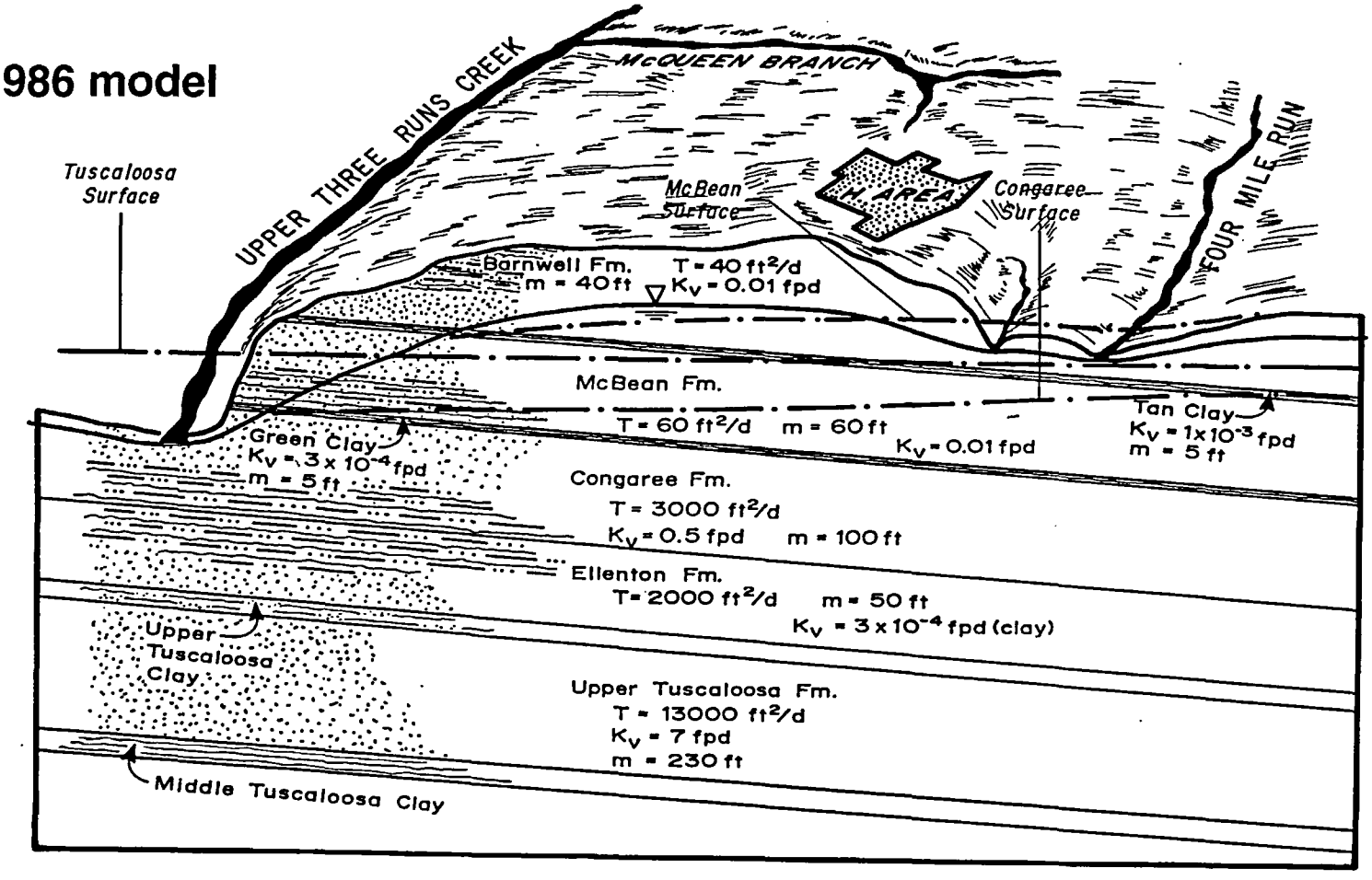


Figure 1.3 Summary of hydrogeologic conditions for the General Separations Area.

Prediction Made with Model

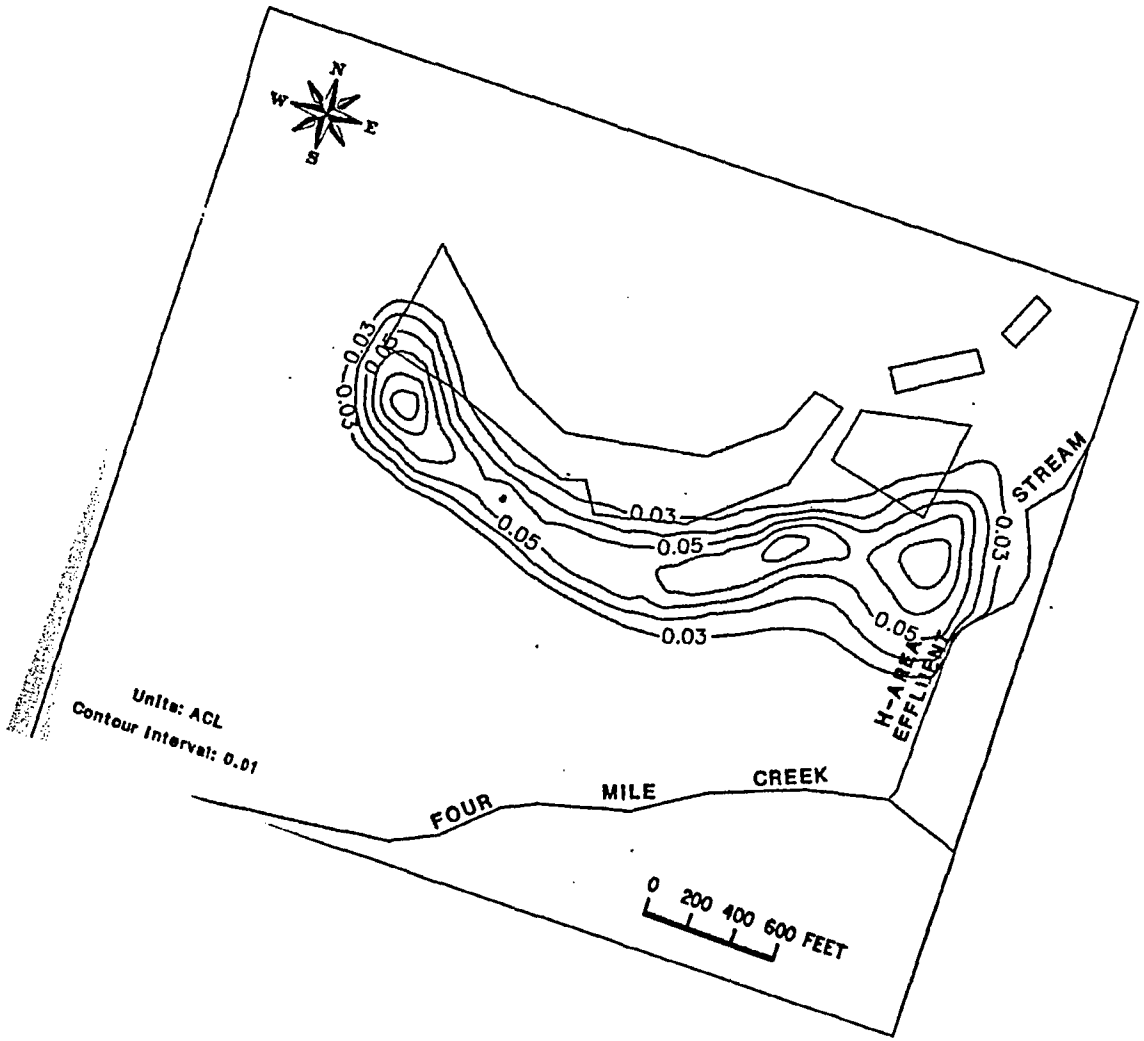
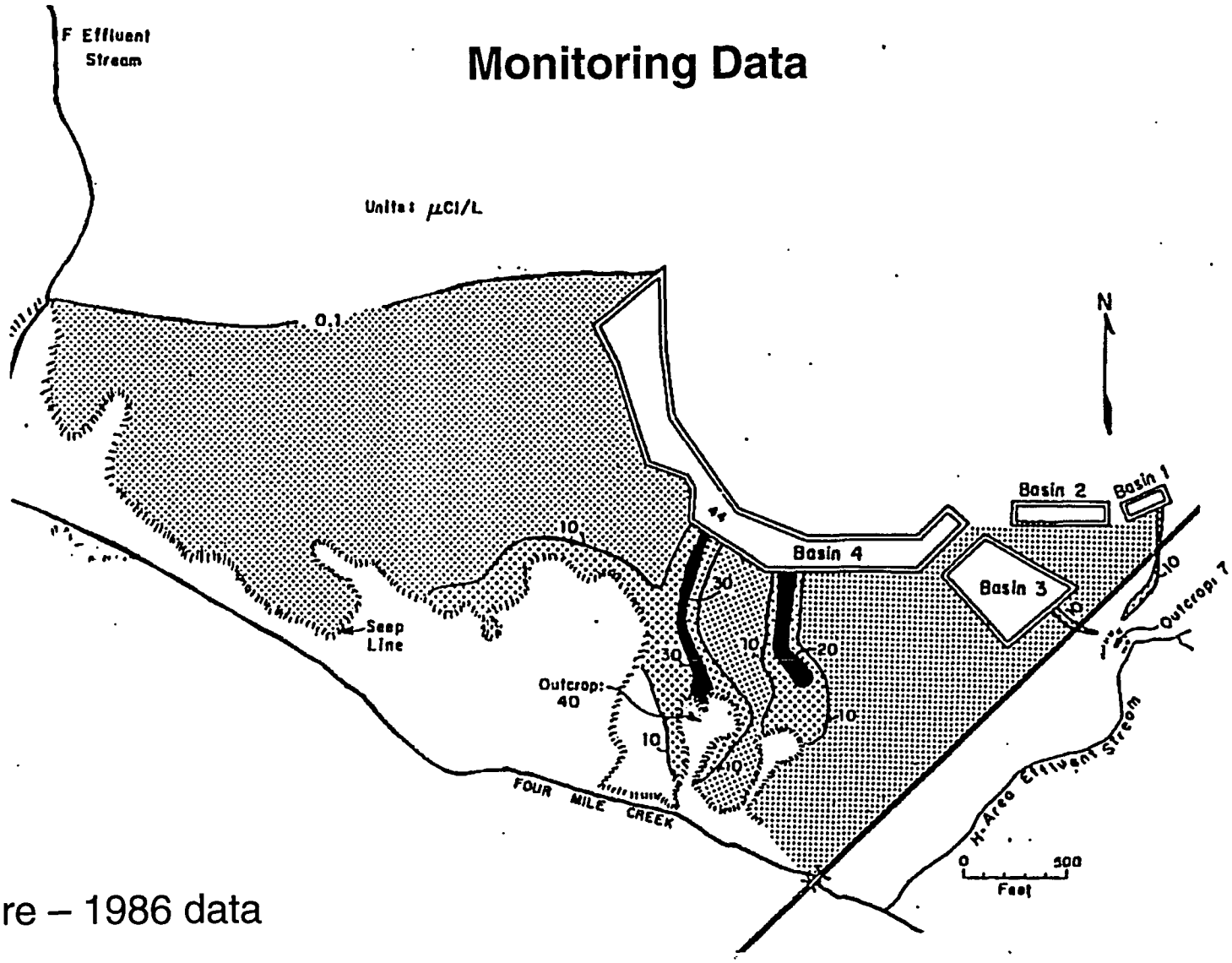


Figure 2.16 H Area Concentrations in the Barnwell aquifer at the end of 45 years of operation, R = 5.0.

Monitoring Data



Pre – 1986 data

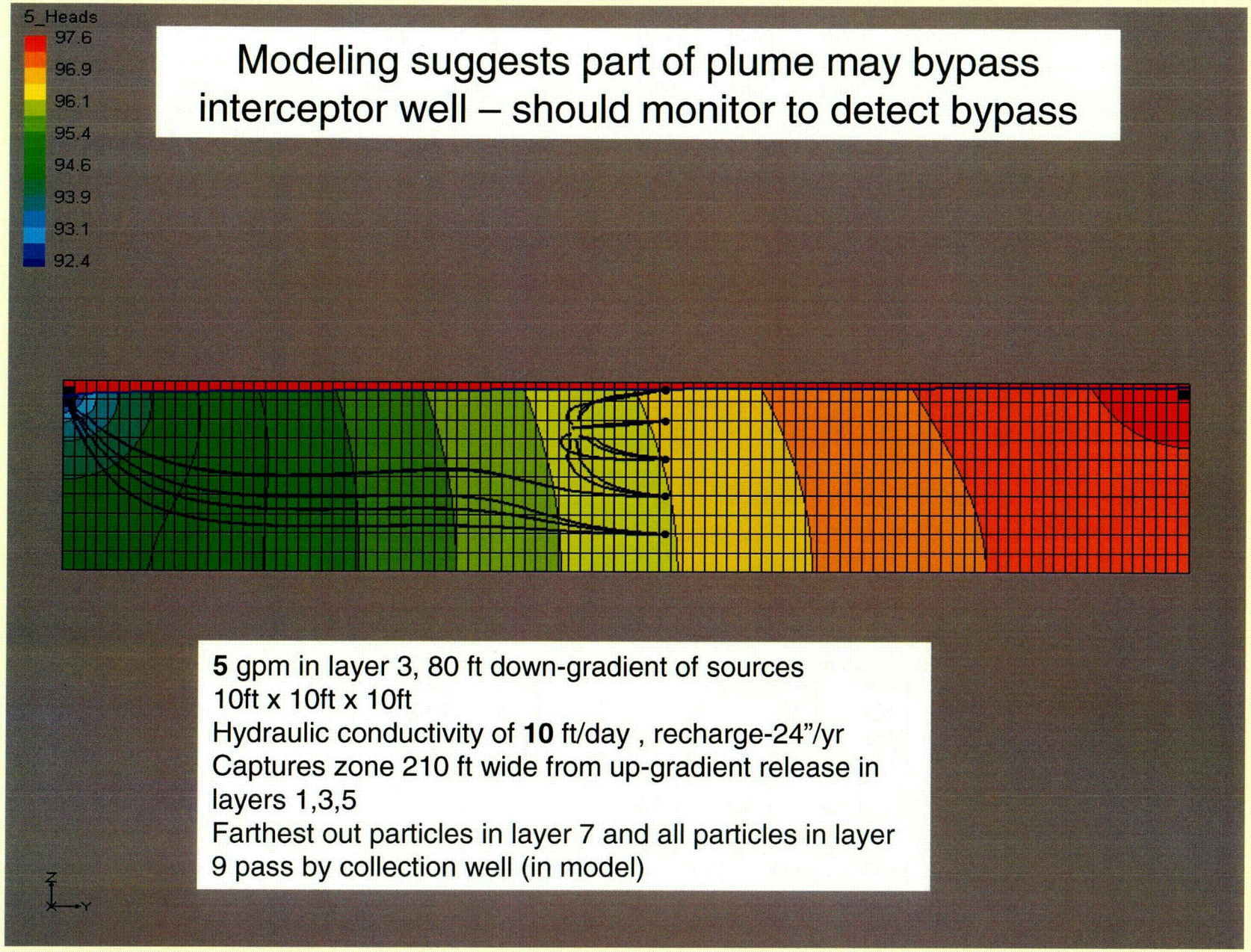
FIGURE 3. Isoconcentration Contours of Tritium in Ground Water at H-Area Seepage Basins

The Modeling-Monitoring Connection

Wang and Anderson, 1981, Introduction to Groundwater Modeling, Chapter 1, Page 1

- "Good field data are essential when using a model for predictive purposes
- An attempt to model a system with inadequate field data can also be instructive as it may serve to identify areas where detailed field data are critical to the success of the model.
- In this way, a model can help to guide data collection activities."

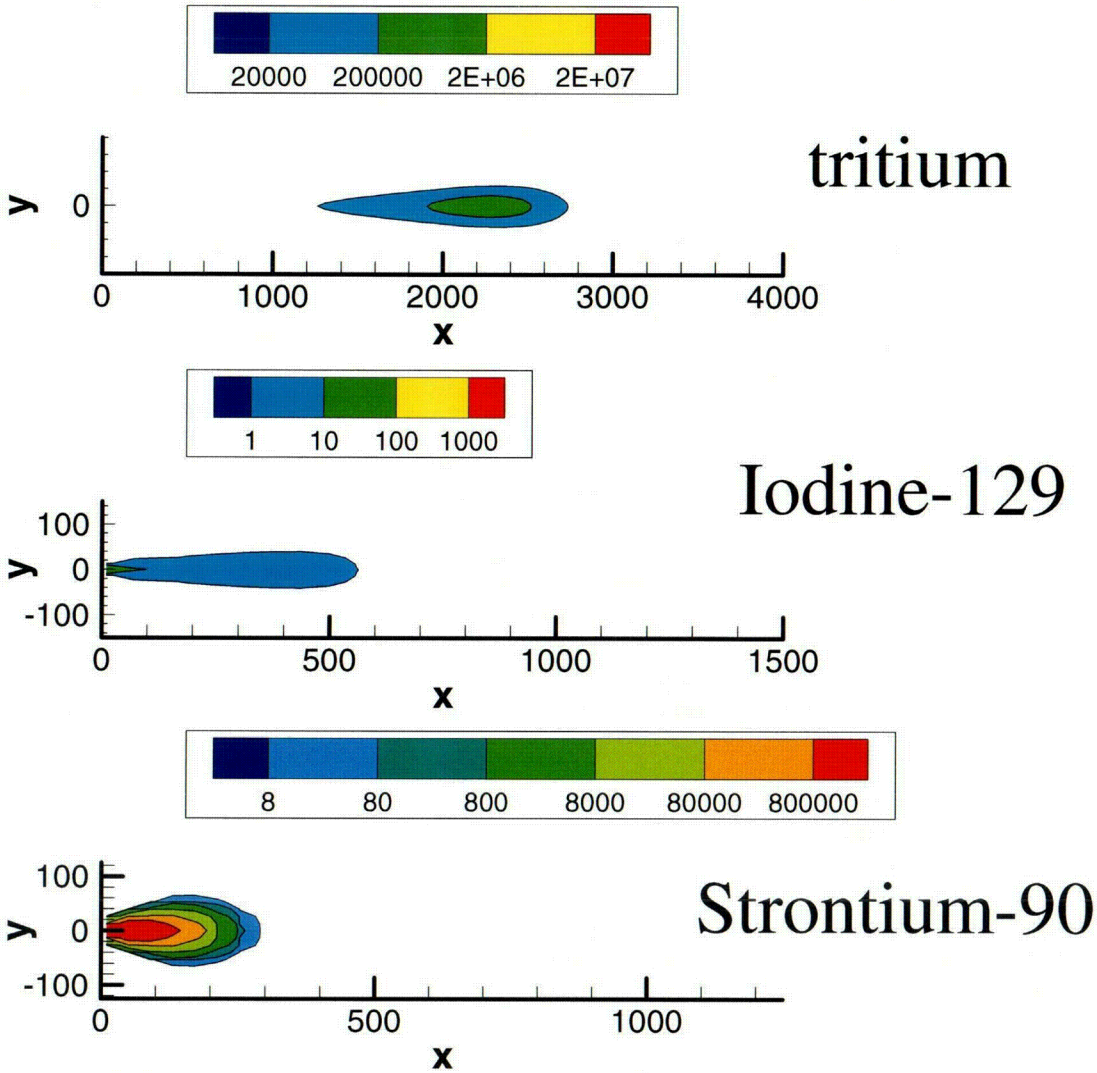
Modeling suggests part of plume may bypass interceptor well – should monitor to detect bypass



5 gpm in layer 3, 80 ft down-gradient of sources
10ft x 10ft x 10ft
Hydraulic conductivity of **10** ft/day , recharge-24"/yr
Captures zone 210 ft wide from up-gradient release in layers 1,3,5
Farthest out particles in layer 7 and all particles in layer 9 pass by collection well (in model)

Simple analytical example along flow path

Tritium could pass observation point before Sr arrives.
If H3 detected, look upgradient for others. Don't abandon wells after H3 is low.



BNL--HFBR

- 6 – 9 gallons / day of tritiated water to a "dry" vadose zone
- Installed **up-gradient and down-gradient horizontal wells** to confirm (0.6 – 1.6 meters below WT)--- (but < 5000 pCi/L when sampled)
- Relatively **fast moving aquifer** (0.3 m/day) created thin plume beneath HFBR (estimated to be about 0.3 m)
- The plume spreads downward **after emerging** from beneath the HFBR

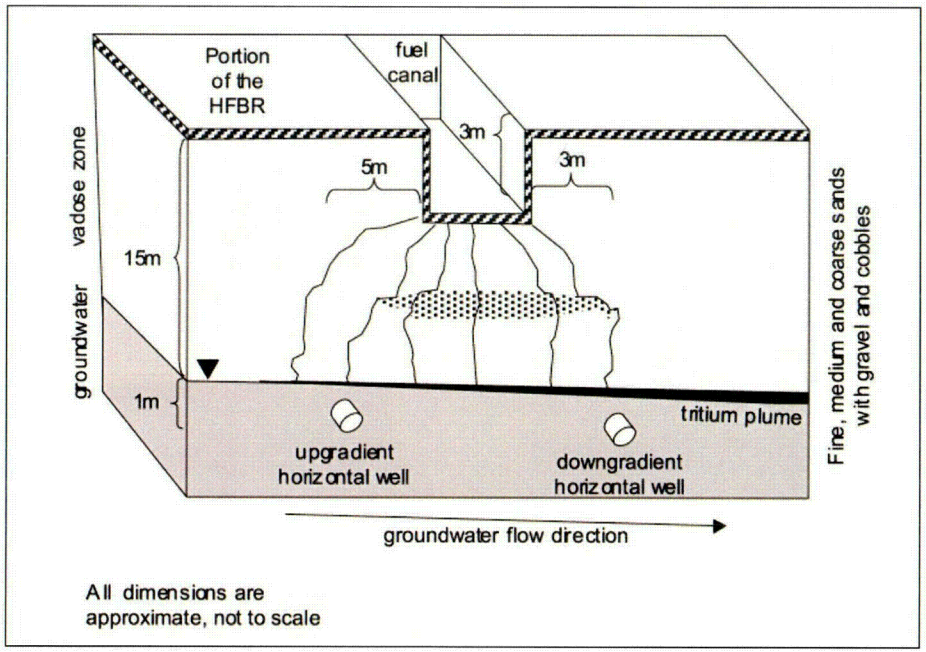


Figure 2. Detail schematic of vadose zone and shallow groundwater beneath the HFBR. Flow lines from a small continuous leak in a dry vadose zone spread out widely, especially when they encounter gravel and cobble zones.

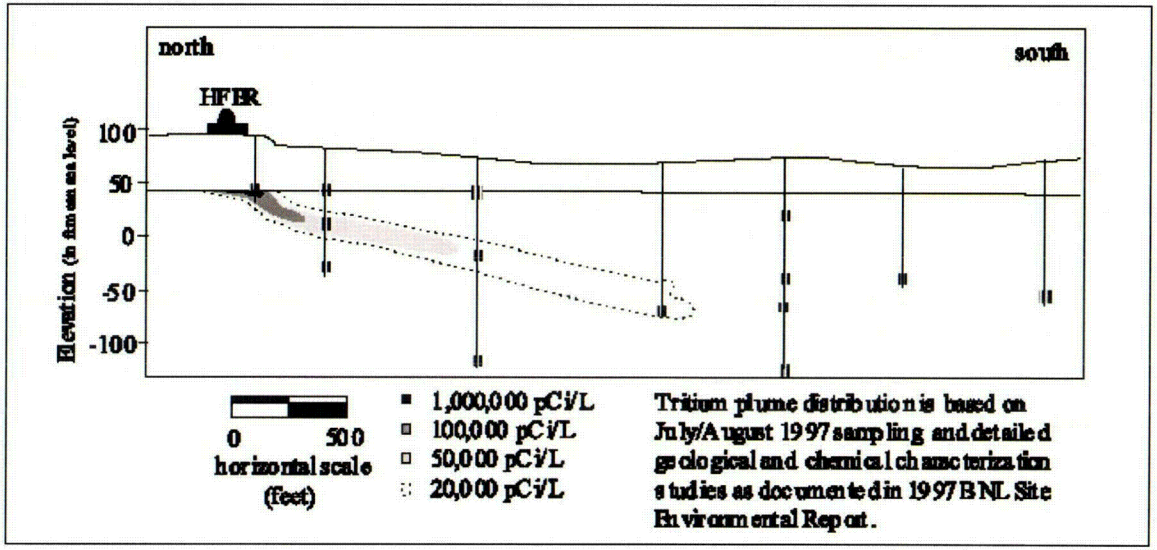
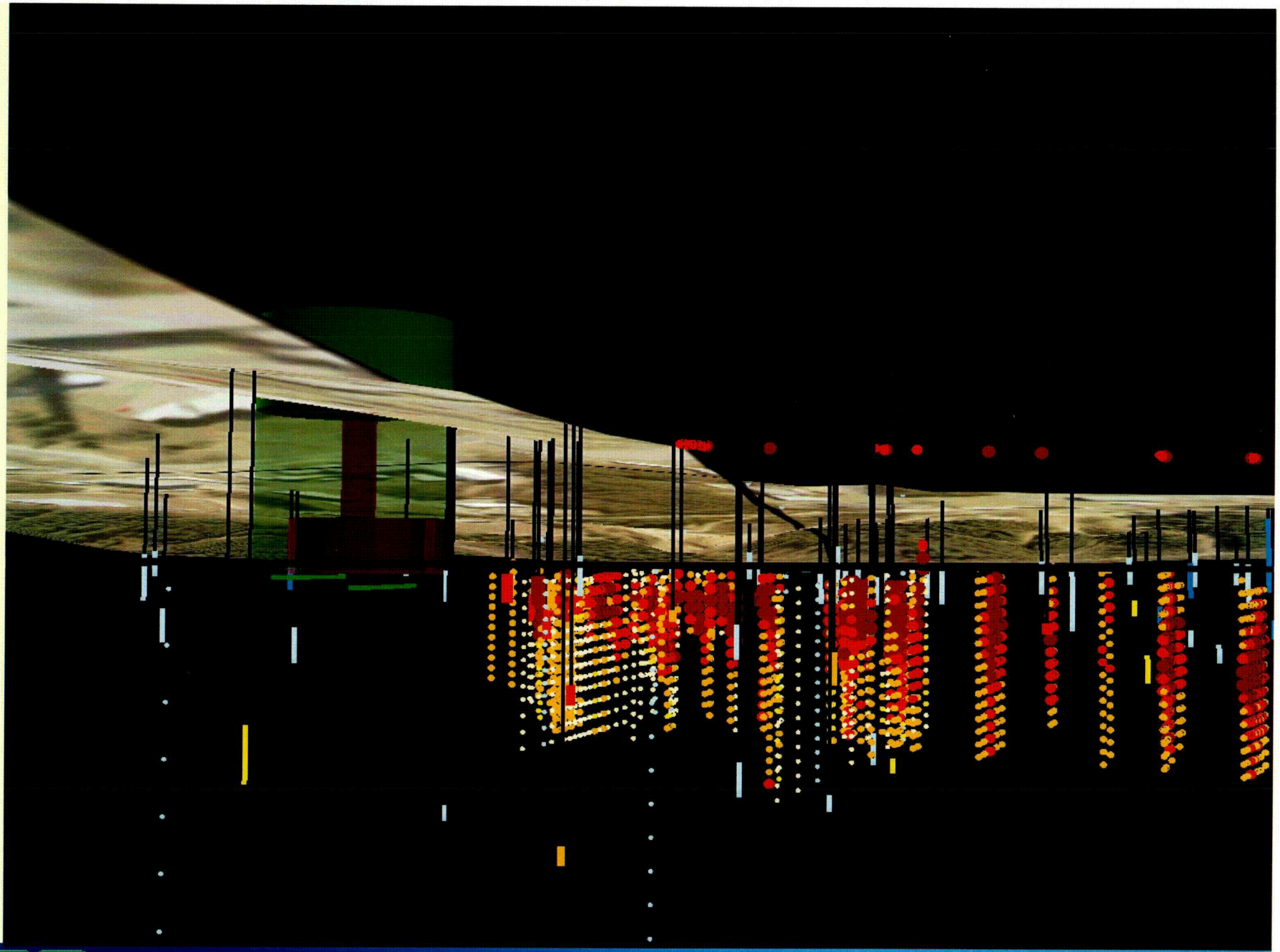


Figure 5. Observed tritium plume geometry at the HFBR.

ADVANCE



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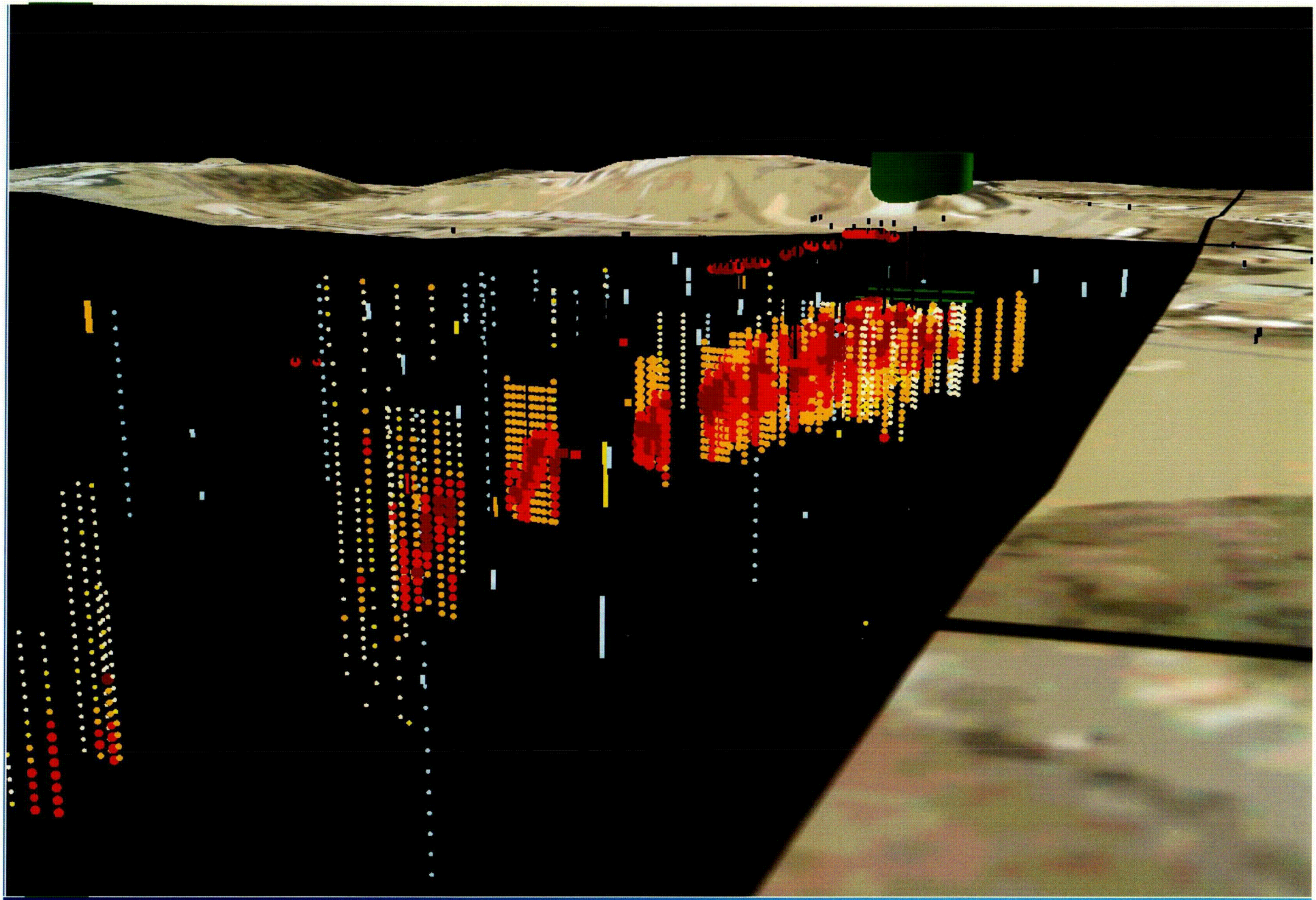
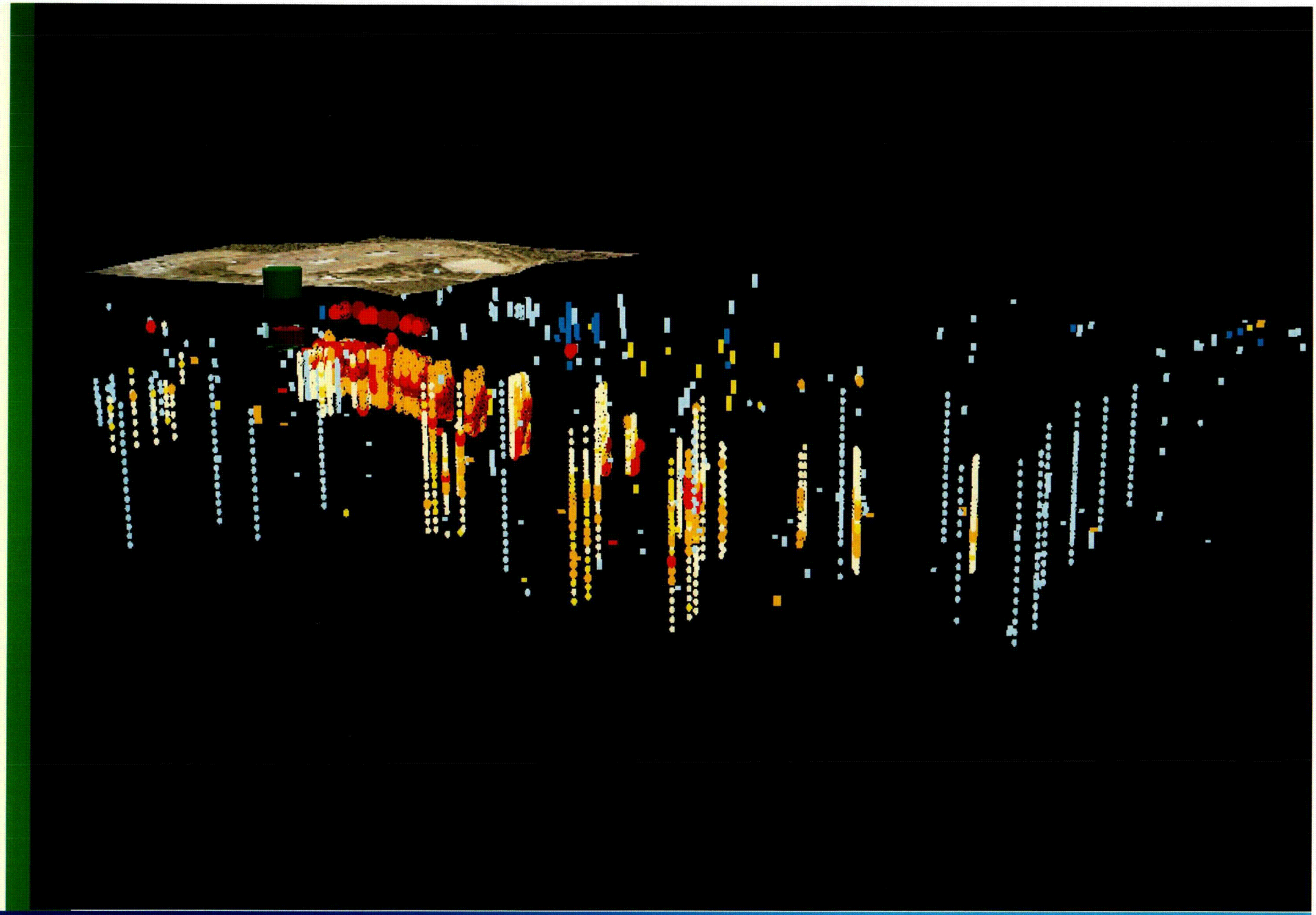
September 20, 2006
ACNW



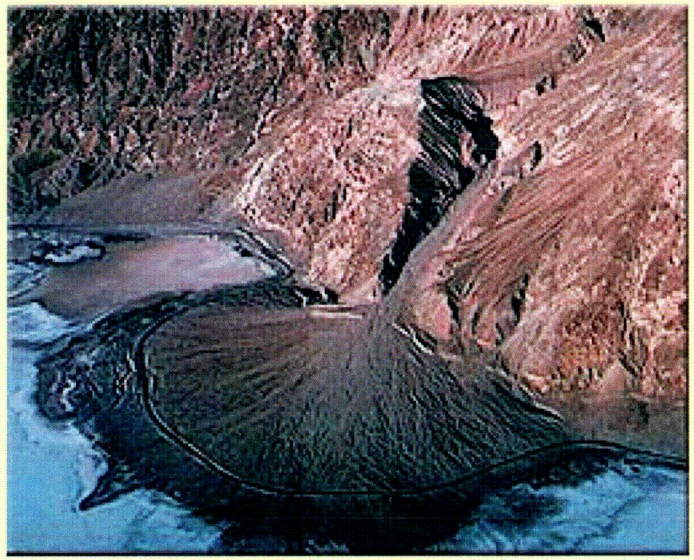


Summary

- Ground-water flow and transport models should be combined with data storage and visualization
- New monitoring data can be compared with models in near-real time
- Monitoring of performance indicators can be used to spot off-normal conditions before they become serious problems
- Currently-available software can provide powerful visualization tools for management review and stakeholder communication

Alluvial Fan Depositional Setting

Systems Analysis Leads to Monitoring Requirements



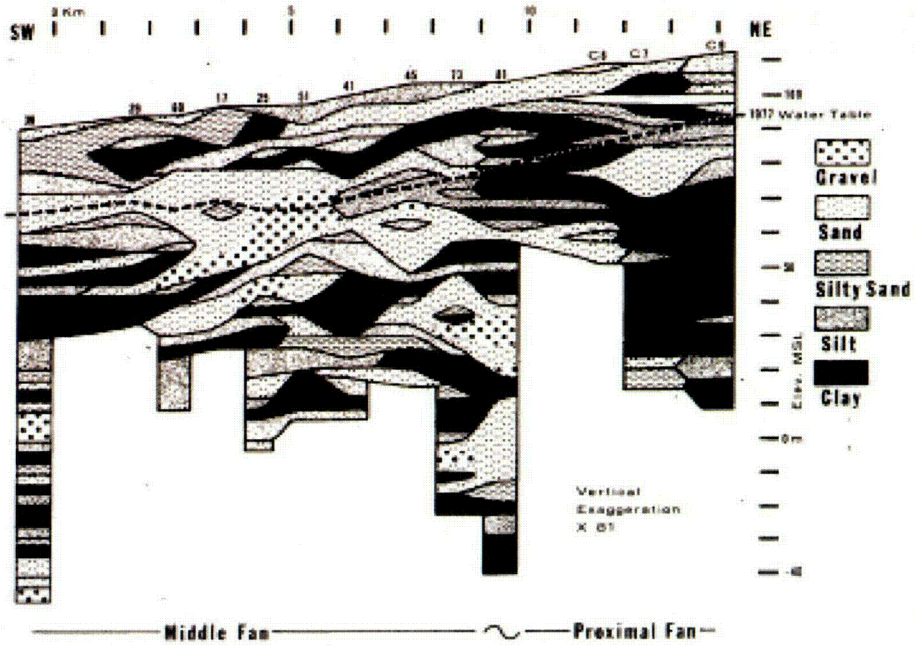


Figure 9. Downfan cross section based on Fresno (39) and Clovis (C9) municipal wells on lower proximal and upper middle Fresno fans. Cross section extends from Sec. 5, T. 13 S., R. 21 E. at C9 to Sec. 31, T. 13 S., R. 20 E. at 39.

- Revised Version 9/15/06

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Monitoring and Modeling to Improve Understanding of Contaminant-Transport Processes in an Arid Environment

B.J. Andraski, D.A. Stonestrom, C.J. Mayers, M.A. Walvoord, R.L. Michel, R.J. Baker, R.G. Striegl, and D.P. Krabbenhoft

U.S. Department of the Interior
U.S. Geological Survey

OUTLINE

- Introduction
- Environmental monitoring & modeling
  - Tritium
  - Elemental mercury (Hg^0)
- Conclusions

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INTRODUCTION

USGS Amargosa Desert Research Site (ADRS)

- Adjacent to Nation's first commercial LLRW facility (Beatty, Nevada)

Overall objective

- Improve understanding of processes controlling unsaturated-zone transport of water and mixed-waste contaminants in arid environments.

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Experimental approach

- Field-intensive research with multiple lines of data
  - Weather; ET; plants; soil & sediment properties; soil water content, potential, temperature, & gas monitoring; geology; geophysics; microbiology; ground water
  - Contaminant data
    - Tritium, radiocarbon, VOCs, elemental mercury
- Field data integrated with modeling
  - Test & refine conceptual & numerical models
- Natural & perturbed/contaminated conditions

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Amargosa Desert Research Site

- Near Death Valley Natl. Park
- Waste facility
  - Low-level radioactive, 1962-92
  - Chemical, 1970-present

- Precipitation ~100 mm/yr
- Creosote bush (*Larrea tridentata*)
- Alluvial/fluvial sediments
- Depth-to-water ~110 m

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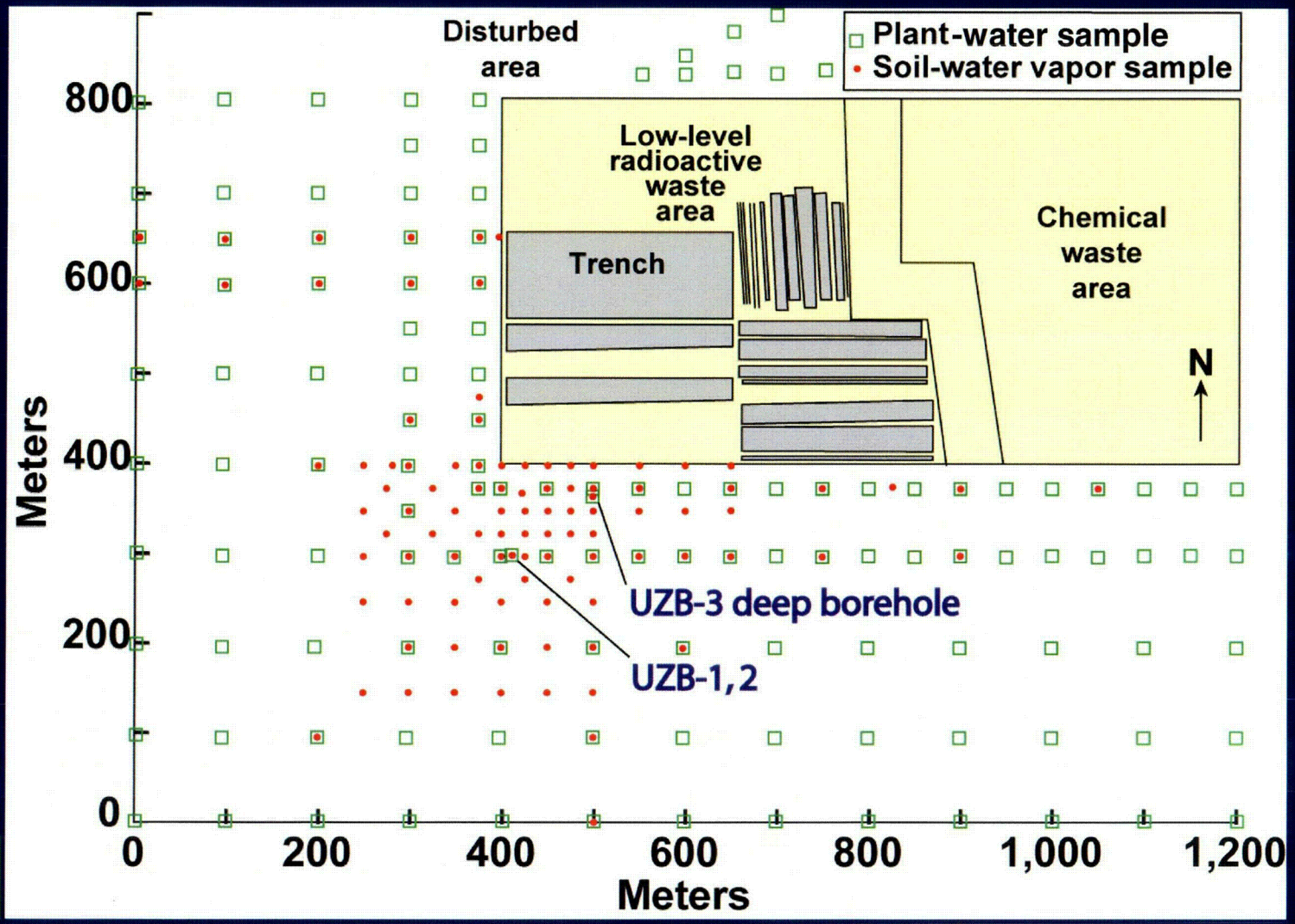
TRITIUM MONITORING — Deep UZ, Soil, Plants



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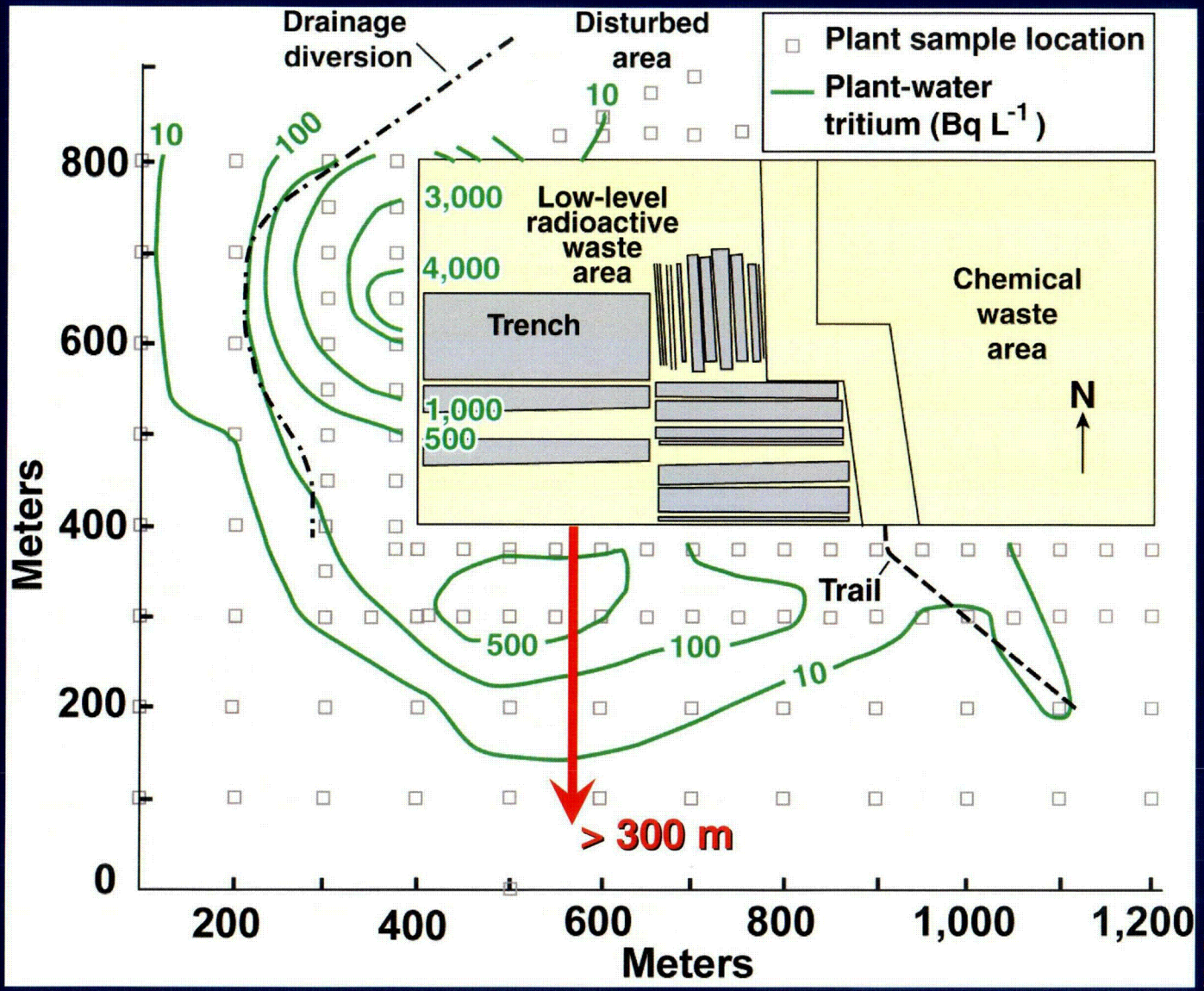
Plant Sampling & Extrapolation to Shallow-Subsurface Transport



(Andraski & others, 2003; 2005)

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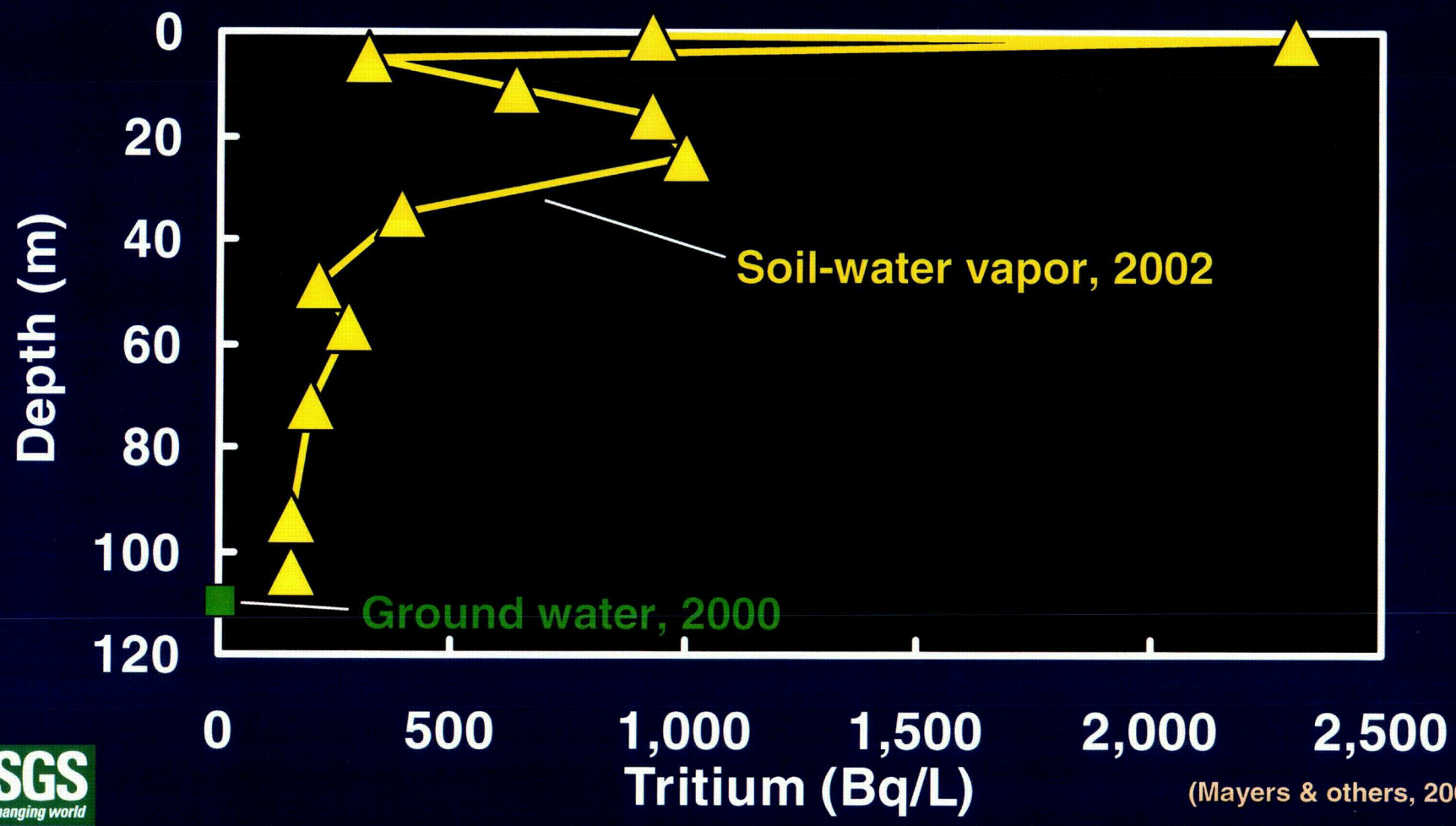
Tritium Monitoring in Deep Unsaturated Zone

UZB-3 borehole — 100 m from nearest trench



(Mayers & others, 2005)

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TRITIUM-TRANSPORT MODELING

Initial Work (Striegl & others, 1996)

- Models
  - Diffusive (Smiles & others, 1995)
  - Advective (Striegl & others, 1996)
- Results ... numerical models fell short
  - Modeled transport (~15 m) under predicted observed by ≥ 10 X
- Initial conceptual model
  - Lateral, subsurface liquid transport along preferential paths ... ???

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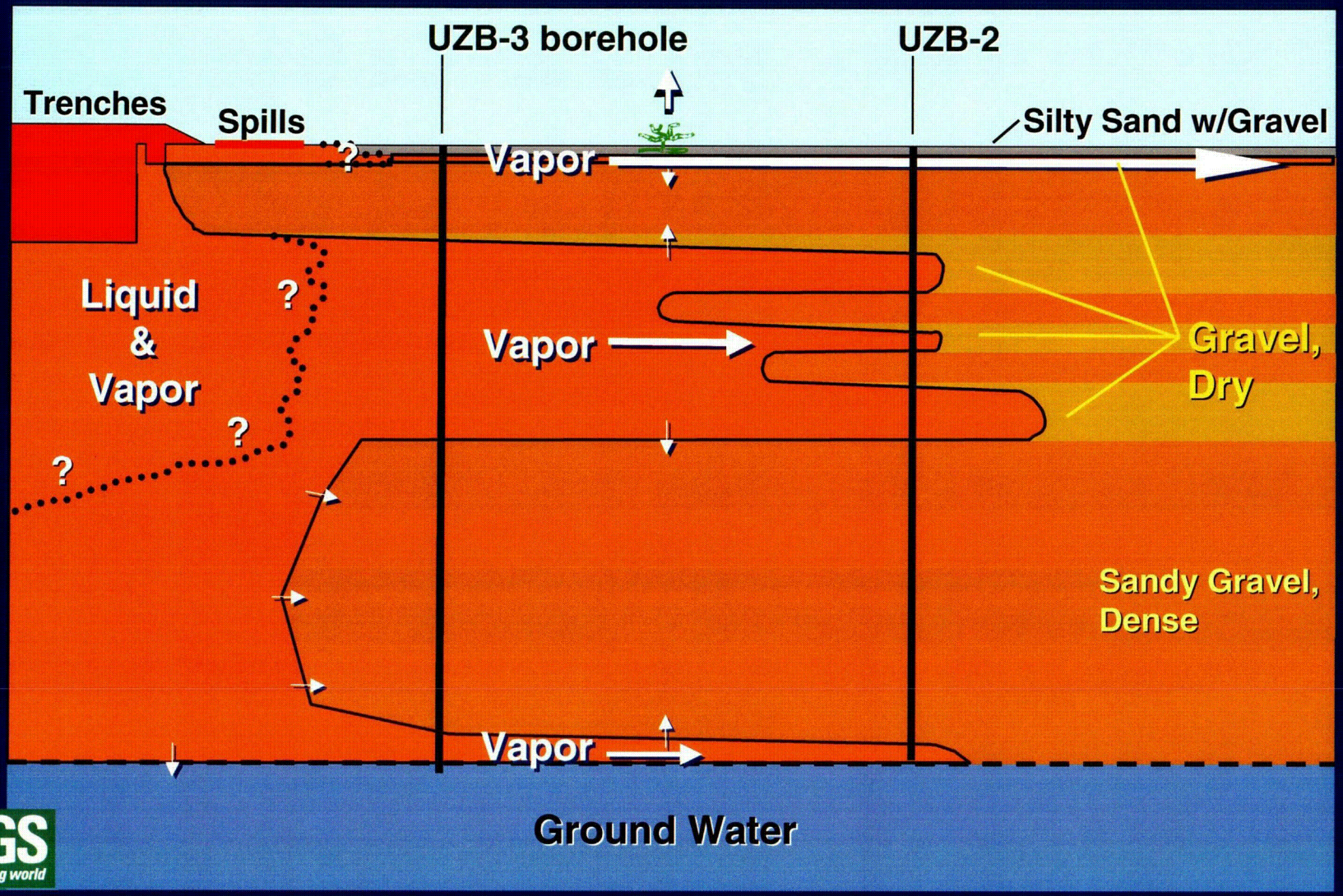
… further data collection, refined conceptual model …

Predominantly lateral, vapor-phase transport controlled by stratigraphy



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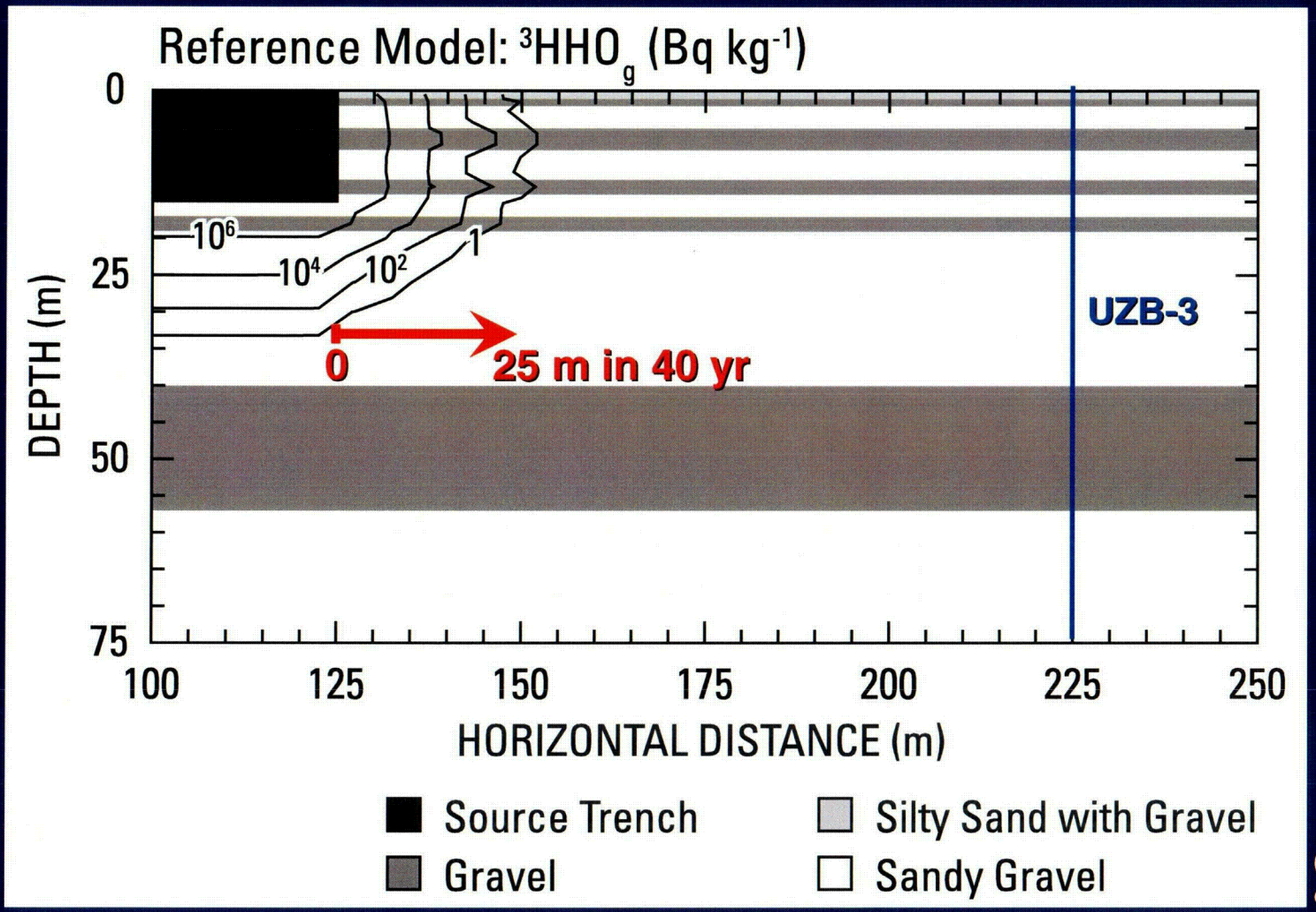
Tritium-Transport Modeling — Phase II

TOUGH2–coupled liquid-gas-heat; non-isothermal, heterogeneous domain



(Mayers & others, 2005)

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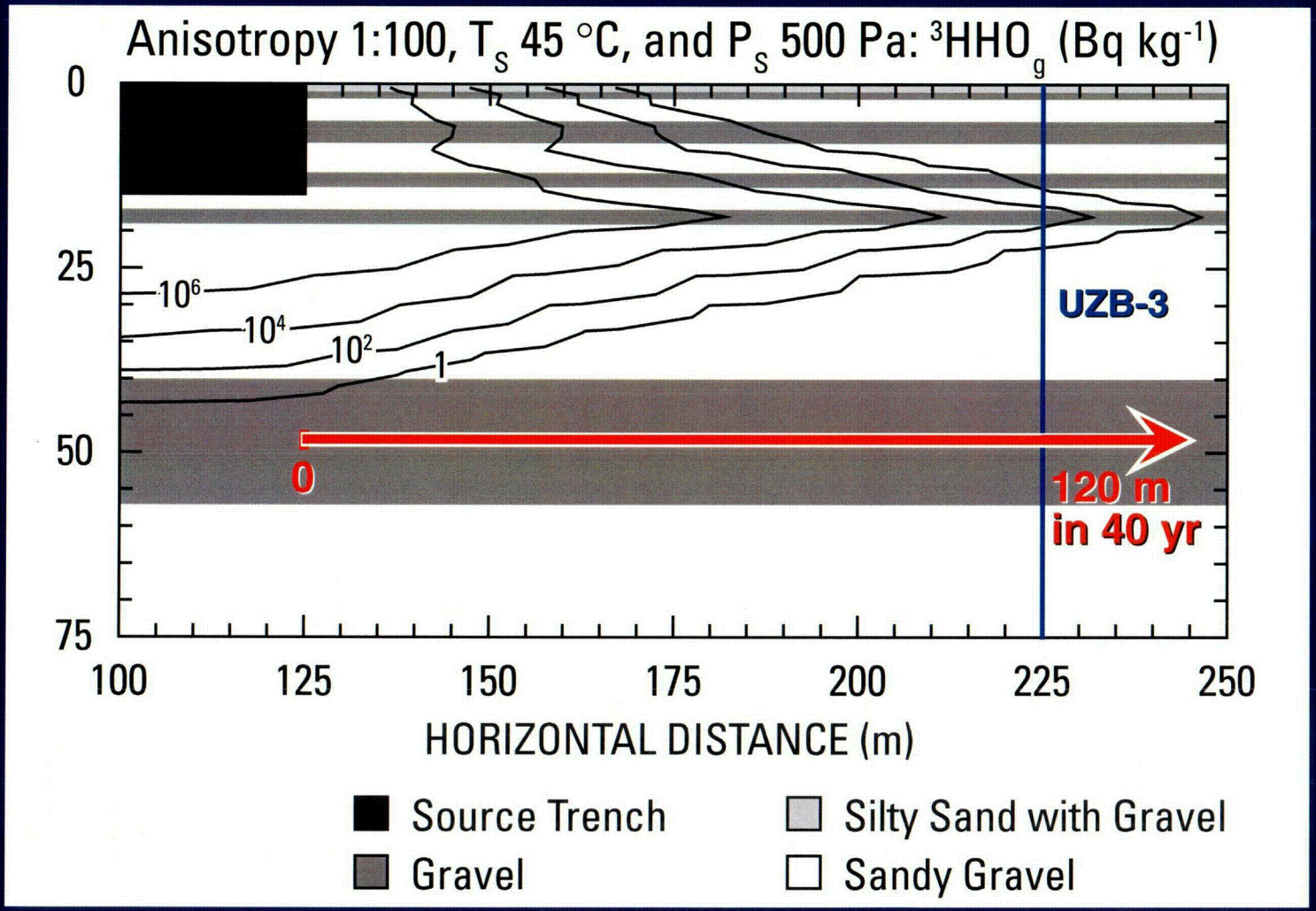
Tritium-Transport Modeling — Phase II

Effects of anisotropy, source temperature & pressure forcing



(Mayers & others, 2005)

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Tritium Transport – Summary

- Monitoring data
  - Plant-based mapping identified kilometer-sized plume
  - Tritium migrating throughout 110-m thick UZ
    - — Predominantly lateral, gas-phase transport along preferential paths
- Phase II modeling results
  - Large anisotropy & source forcing needed to enhance transport
  - Discrepancies between theory & measurements are reduced ... but not eliminated
- Other processes enhancing gas-phase transport?
  - Coupling between organic compounds & tritium?
  - Barometric pumping?

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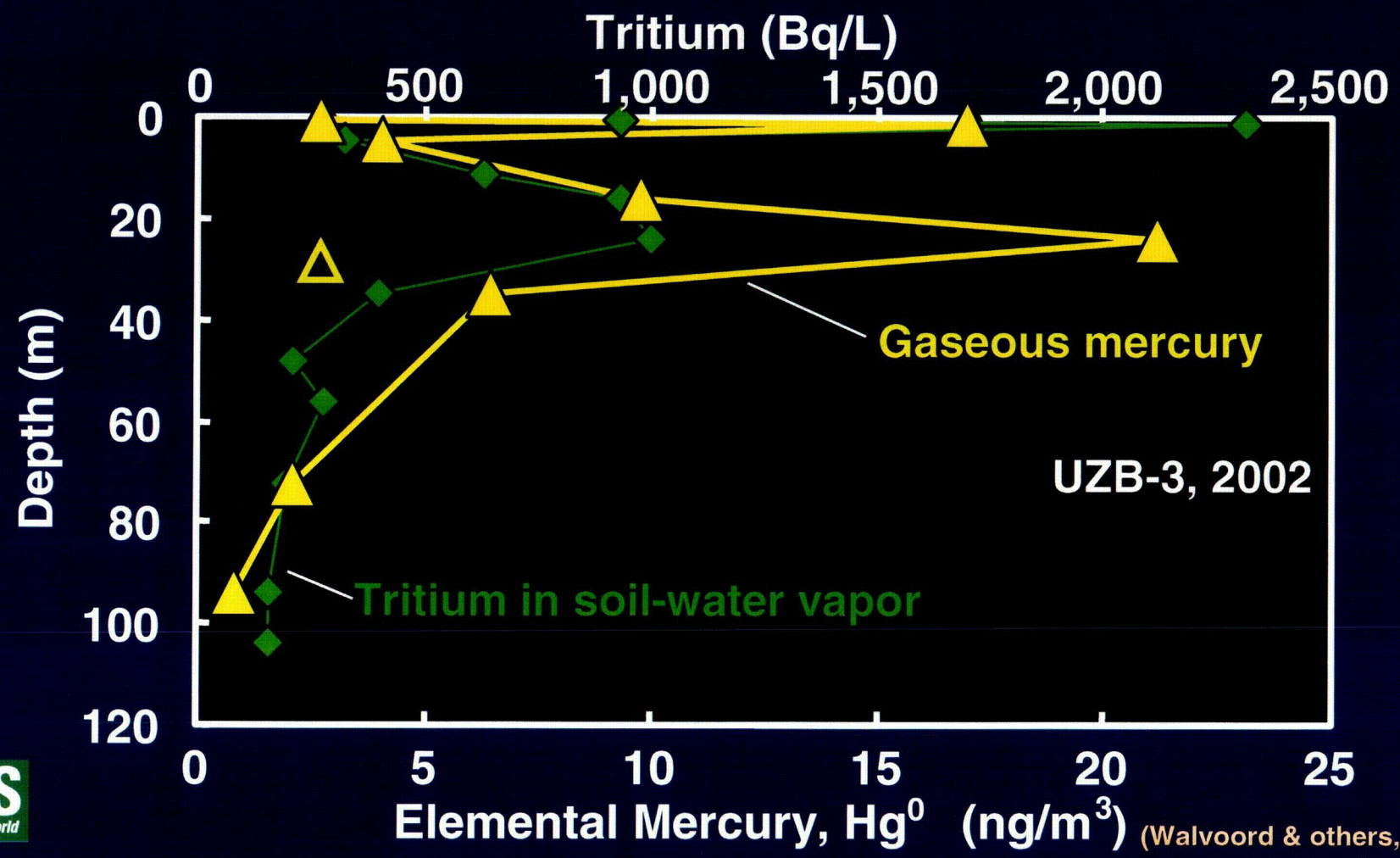
MERCURY MONITORING — Deep Unsaturated Zone

Strong correlation between mercury & tritium concentrations



(Walvoord & others, 2006)

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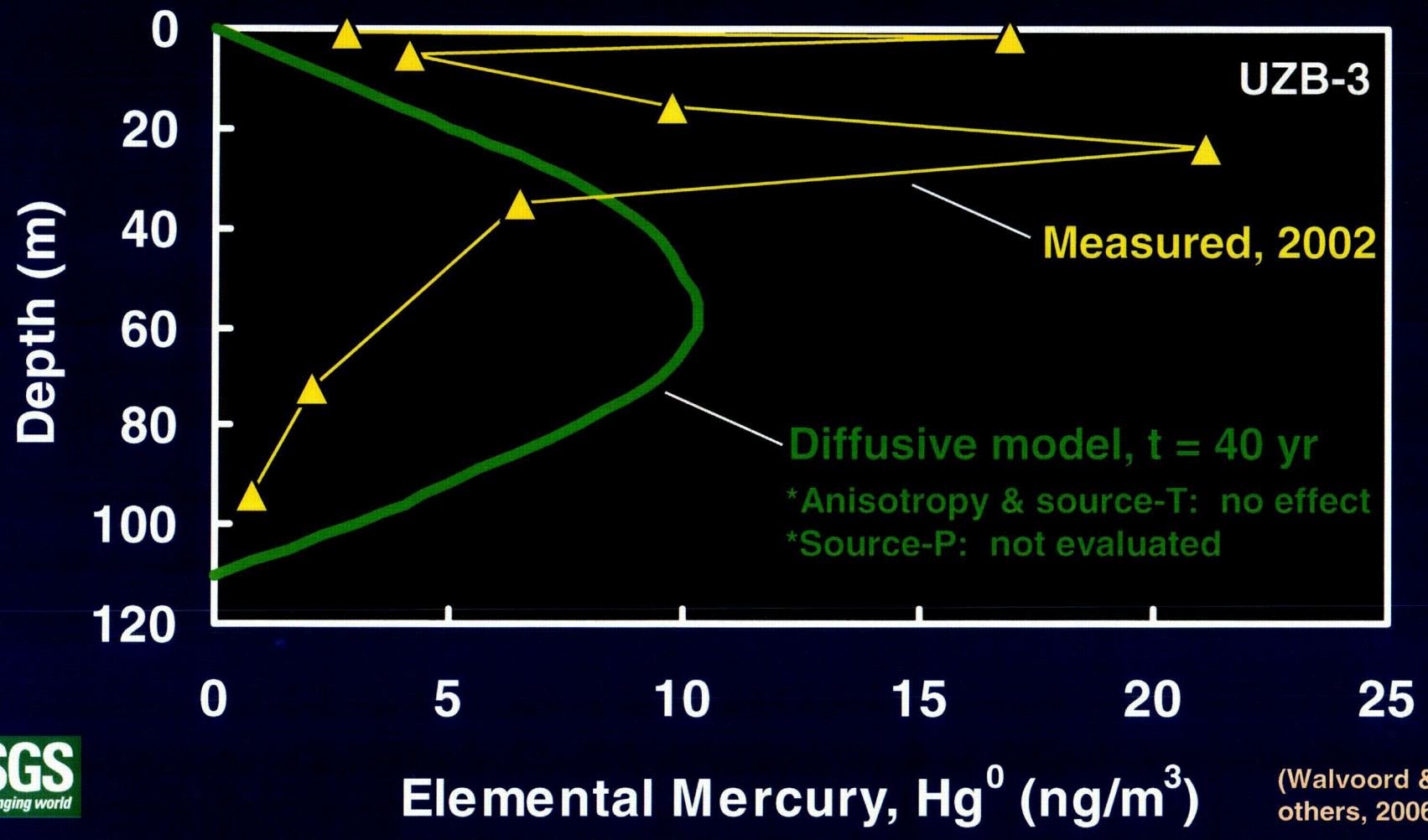
INITIAL MERCURY-TRANSPORT MODELING

FEHM–liquid-gas-heat; non-isothermal, heterogeneous domain



(Walvoord & others, 2006)

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Mercury Transport – Summary

- Monitoring Data
  - Like tritium ...
    - — Gaseous Hg^0 migrating long distances along preferential paths
  - Confirm dominance of gas-phase transport in desert soils
- Initial Modeling Results
  - Diffusive model produced a poor approximation of measured profiles
  - Unlike tritium ...
    - — Anisotropy & source-T forcing did not produce preferential-flow pattern
- Other Processes?
  - Source-pressure forcing, barometric pumping?

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CONCLUSIONS

- We CAN measure the contaminants
- We CAN map the contaminants
- But ... our present models CANNOT accurately reproduce observed extent or distribution of transport

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CONCLUSIONS — continued

- We will continue to integrate monitoring & modeling to explore questions & refine models

- Ultimately ... better process understanding is needed to develop & build confidence in UZ transport models

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Amargosa Desert Research Site

http://nevada.usgs.gov/adrs/

USGS Toxic Substances Hydrology Program

http://toxics.usgs.gov/

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