Groundwater Modeling Efforts

for

Paducah Gaseous Diffusion Plant
Groundwater Flow and Contaminant Transport Model

September 21, 2006

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Overview

- 1. Background
  - – Why Model?
  - – Model Setup & Inputs
- 2. KWRRI/KRCEE Modeling Efforts
  - – Initial Model Assessment
    - Hydraulic Model
      - – Method
      - – Re-calibration
    - Transport Model
      - – Method
      - – Calibration Recommendation
  - – Pump-Treat Studies
  - – Sensitivity Analyses
    - Basis for Sensitivity Analyses
    - Sensitivity Analyses Model Runs
      - – Physical Parameters
      - – Hydraulic Parameters
      - – Transport Parameters
- 3. Planned Activities for FY 2007

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Background

- **Why have KRCEE Model**?
  - Independent verification of past model results
  - Set the stage for new modeling efforts
  - Allow freedom to conduct “what if” model runs not covered by DOE site contracts

Background

Starting point

- Obtain and Review DOE documents related to Groundwater Modeling
  - 1989 to Present
- Obtained input files for MODFLOW Models
- Conducted verification modeling to ensure Model inputs and results were same as DOE

Background

Starting point

- 24+ Documents
  - CERCLA Decision Document for Projects
  - Model Specific Documents
- Nine (9) major documents detailing substantial updates and refinements to MODFLOW Models
- First developed in 1994
  - Flow model of RGA only using MODFLOW
- Revised in 1996, 1997, 1998, and 2000
- Revisions made in 1998 included addition of transport modeling capabilities
- Latest model uses MODFLOWT for contaminant transport (HydroSolve Inc. and GeoTrans Inc)

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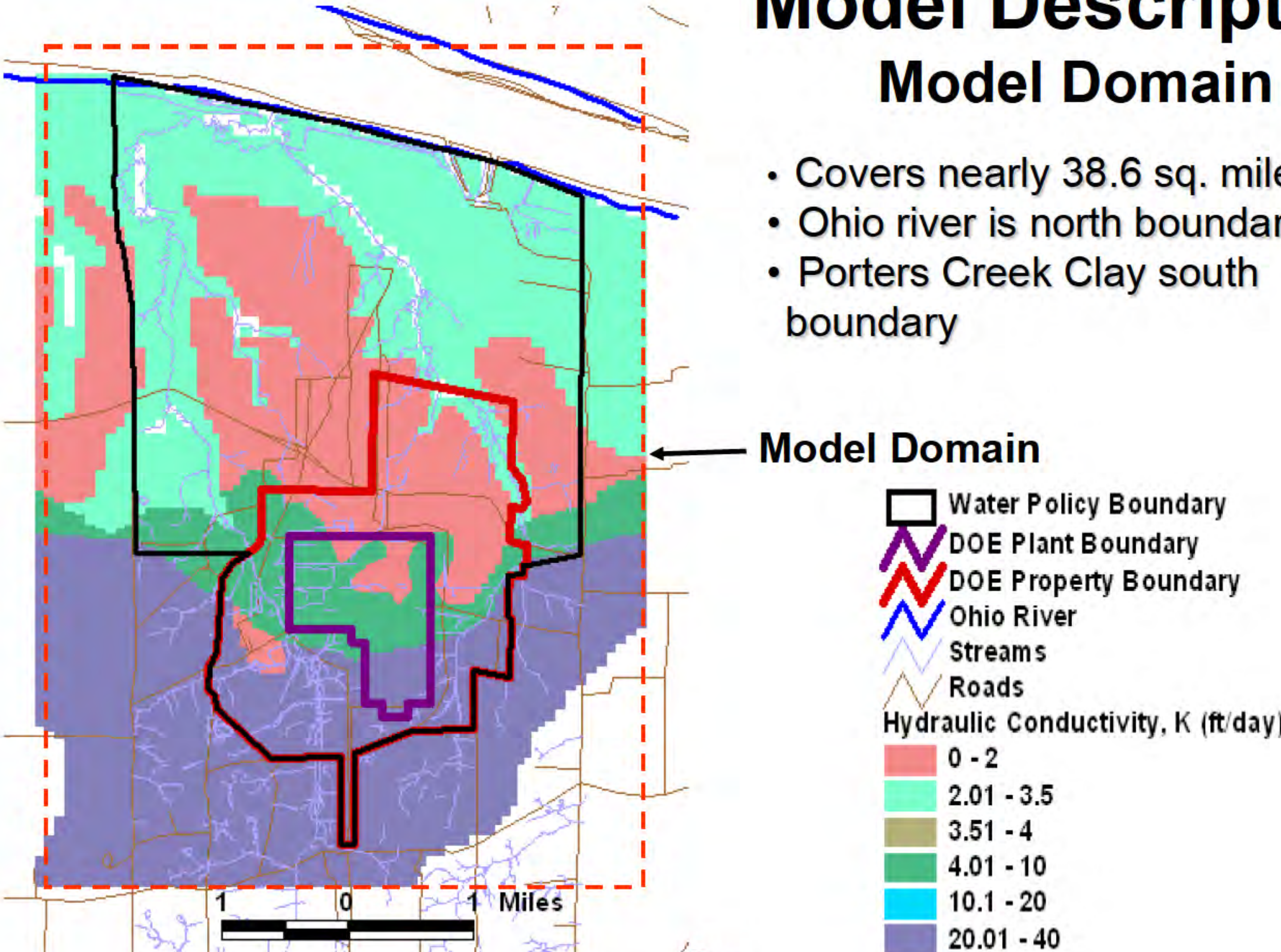
Model Description

Model Domain

- Covers nearly 38.6 sq. miles
- Ohio river is north boundary
- Porters Creek Clay south boundary



Layer 1 - K

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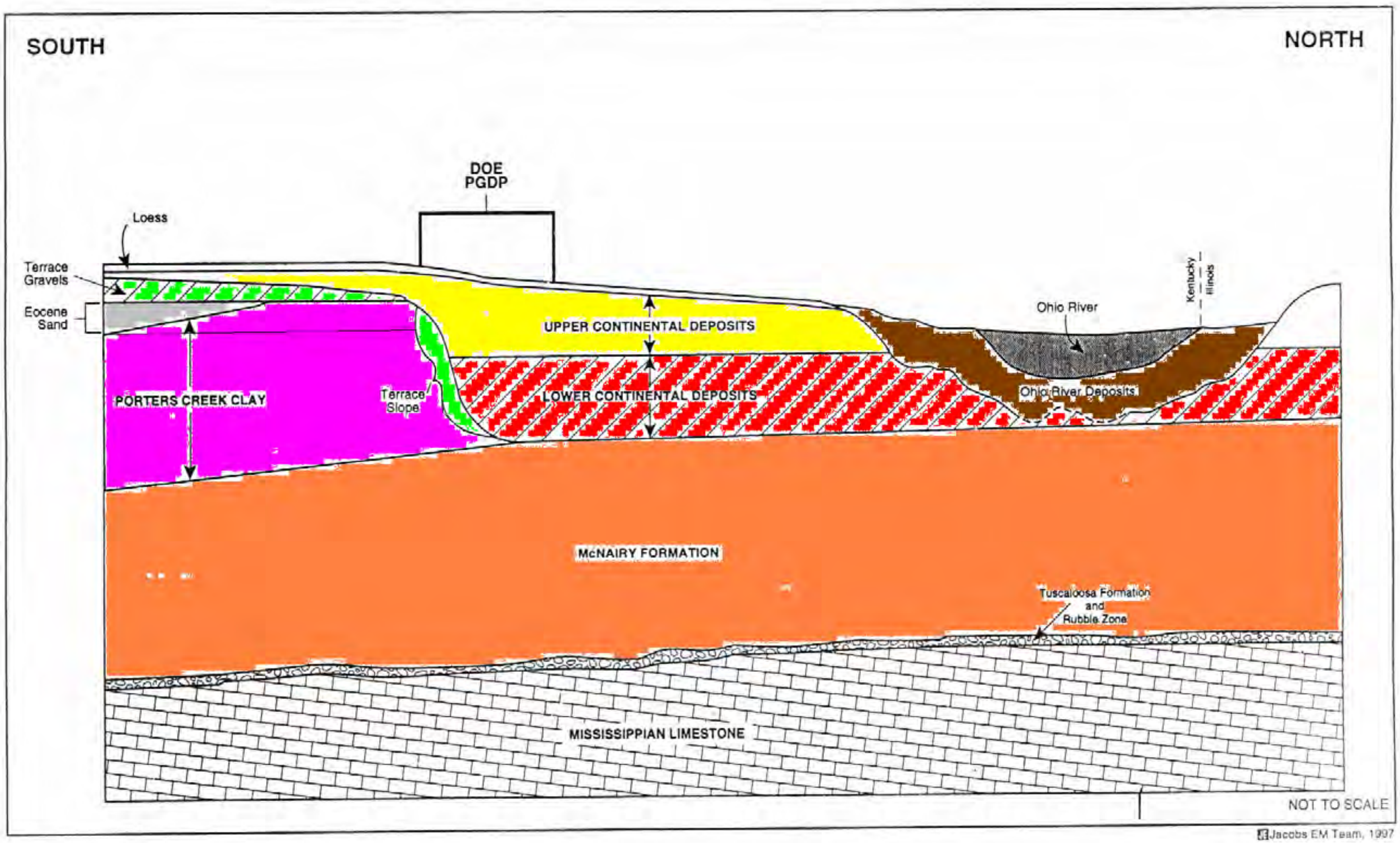
Model Description

Conceptual Geologic Model



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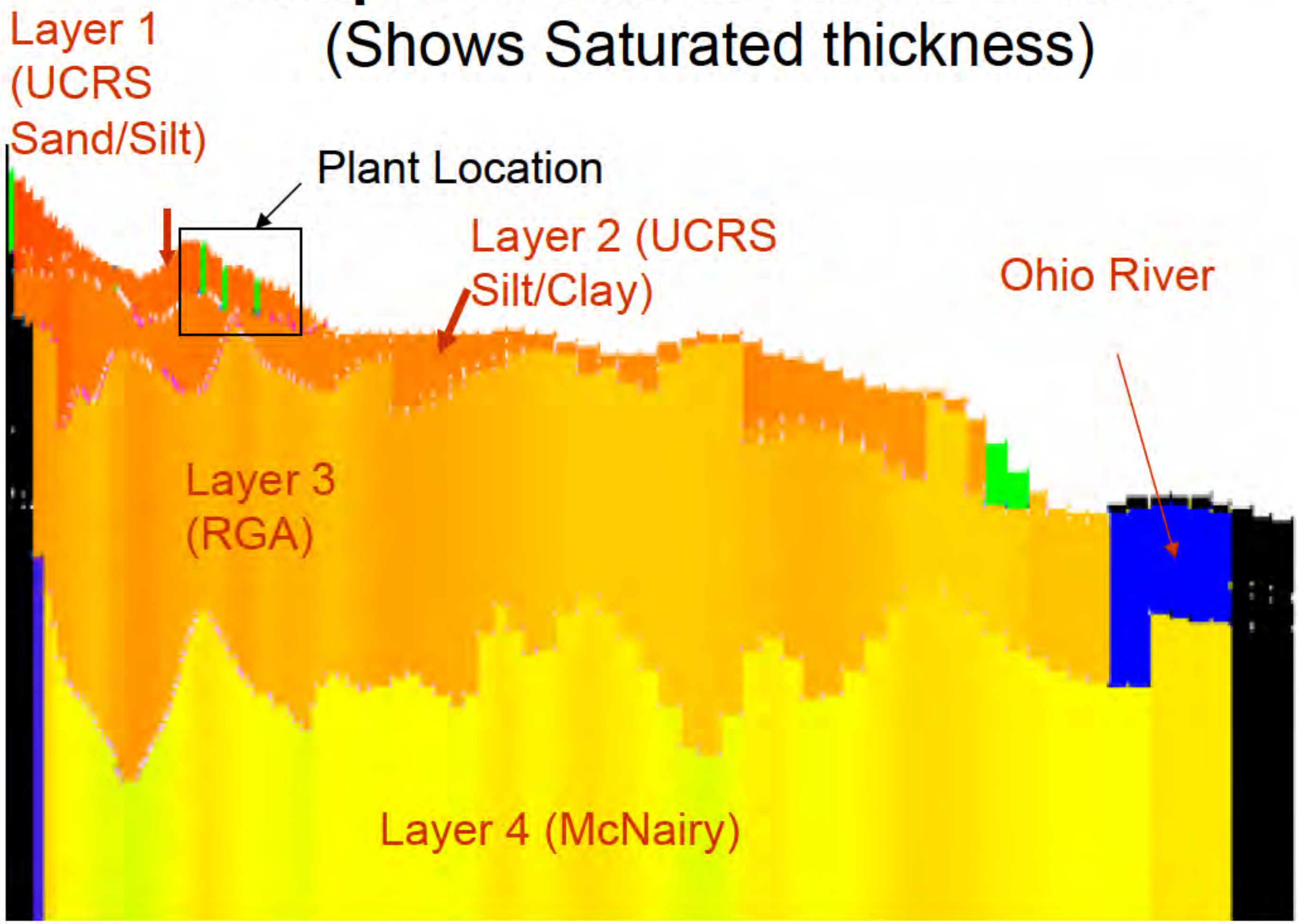
Model Description

Sample MODFLOW Cross-section

(Shows Saturated thickness)



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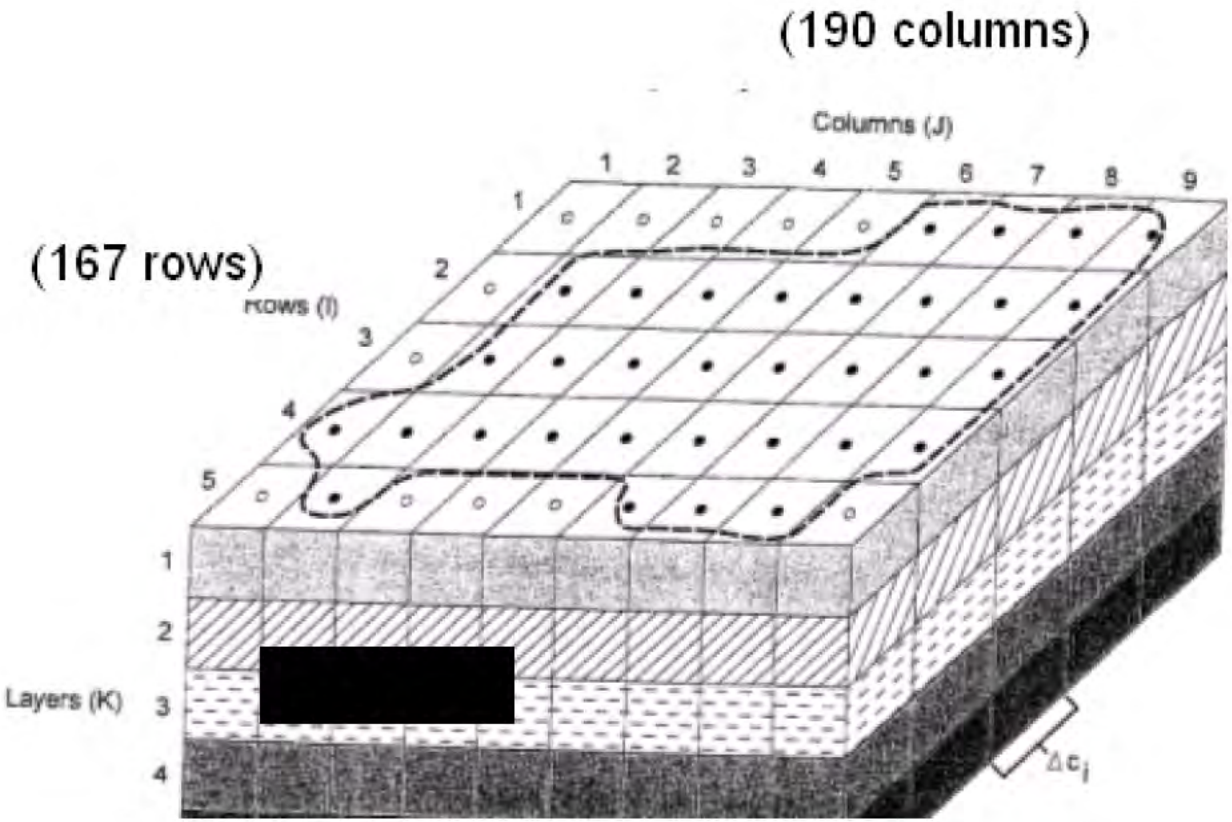
Model Description

Conceptual Model



Layer 1 - sands and silts of the Upper Continental Deposits (HU2A)

Layer 2 - silts & clays of lower portion of the Upper Continental Deposits (HU2B) & alluvial deposits near Ohio River.

Layer 3 - simulates the permeable sands and gravels of hydrogeologic units HU4 and HU5

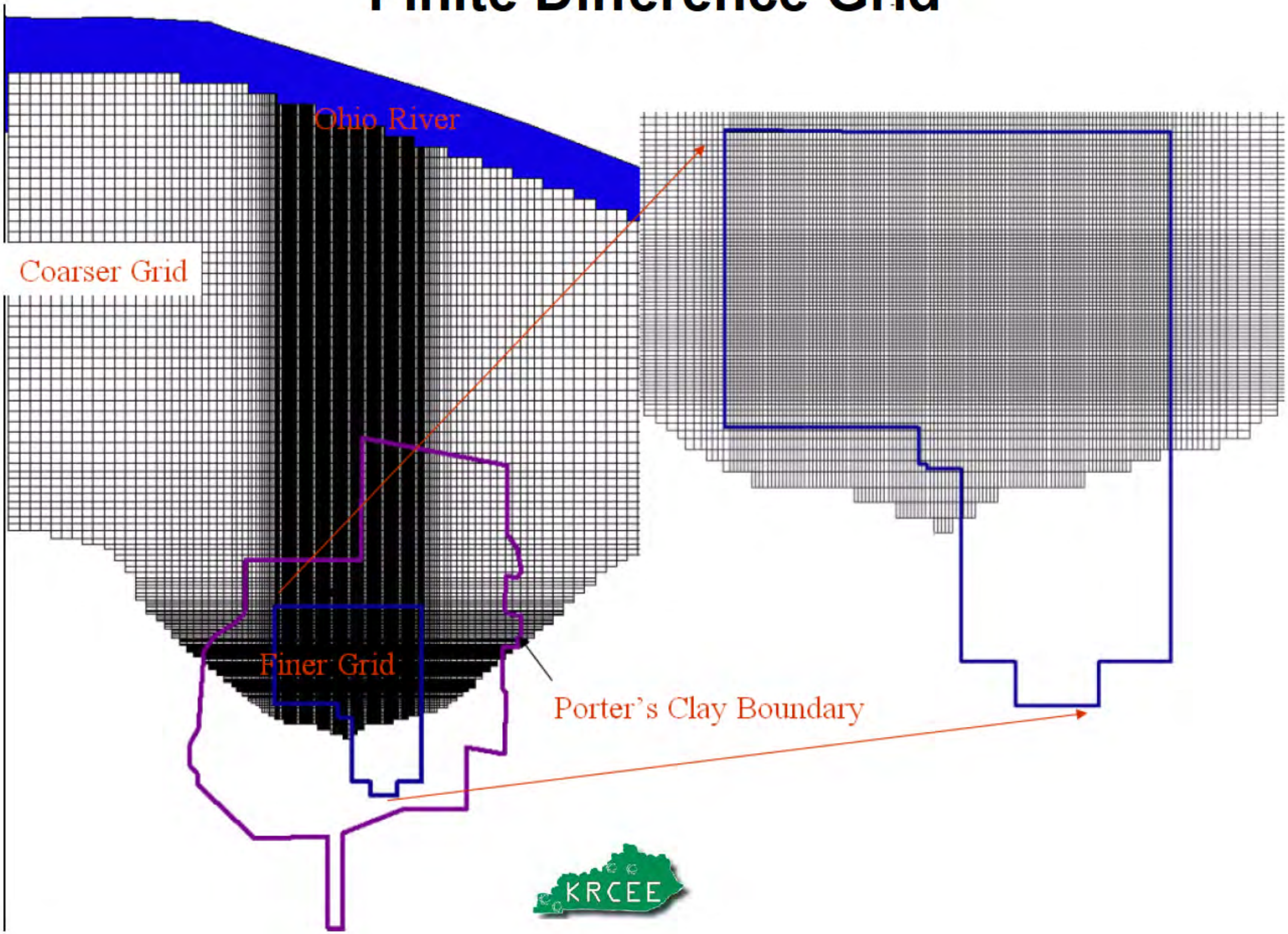
Layer 4 - simulates the McNairy Formation flow system (HU6)

Model Description

- Finite Difference Grid
  - 167 rows (about 36,000ft)
  - 190 columns (about 25,000 ft)
- Variable grid size
  - Smaller spacing in the plant vicinity
  - Column width varies from 45 – 425
  - Row height varies from 50 – 425 ft
- Total number of cells = 126,920
  - 95,215 active cells (75%)
- Two Stress Periods

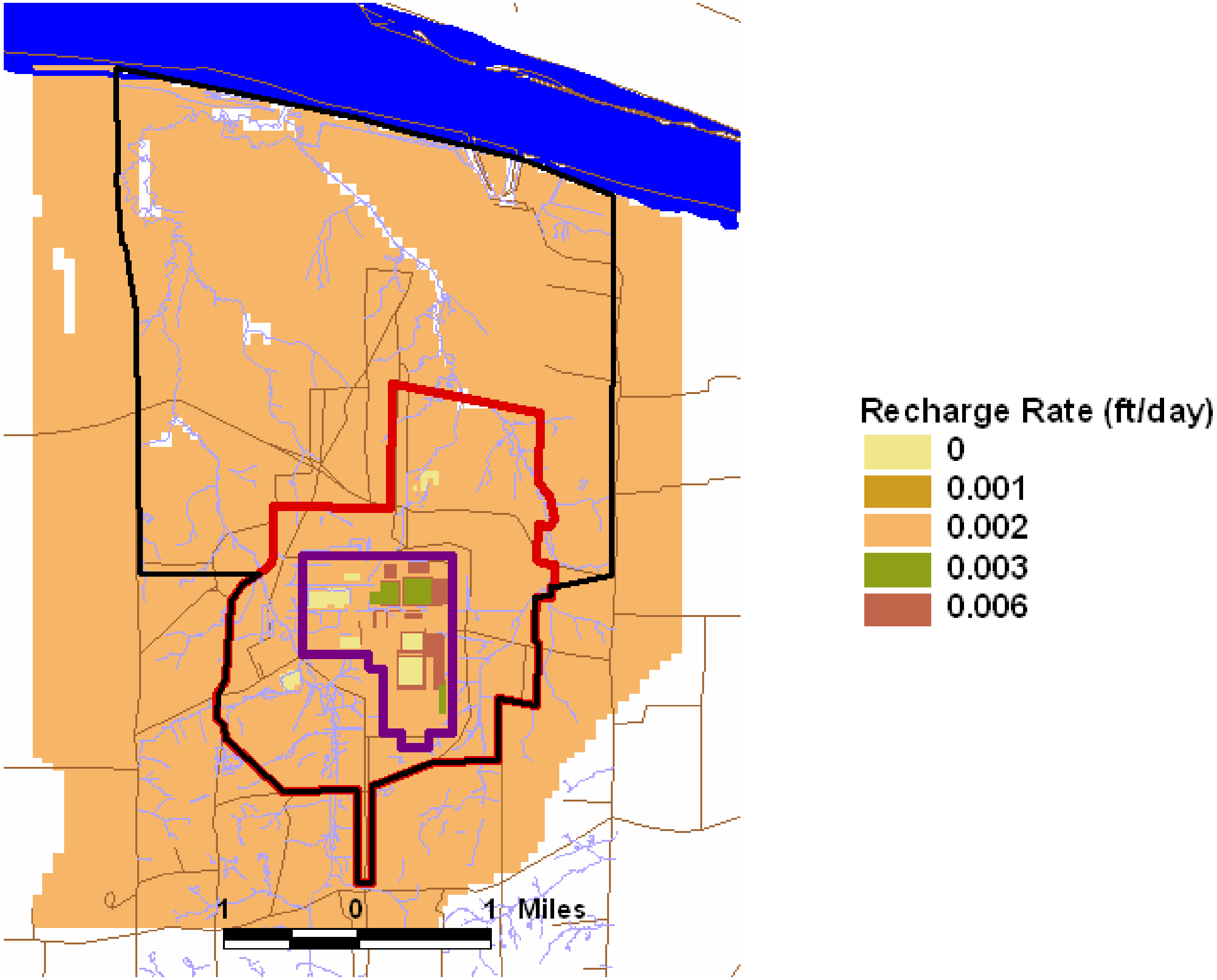
Model Description

Finite Difference Grid



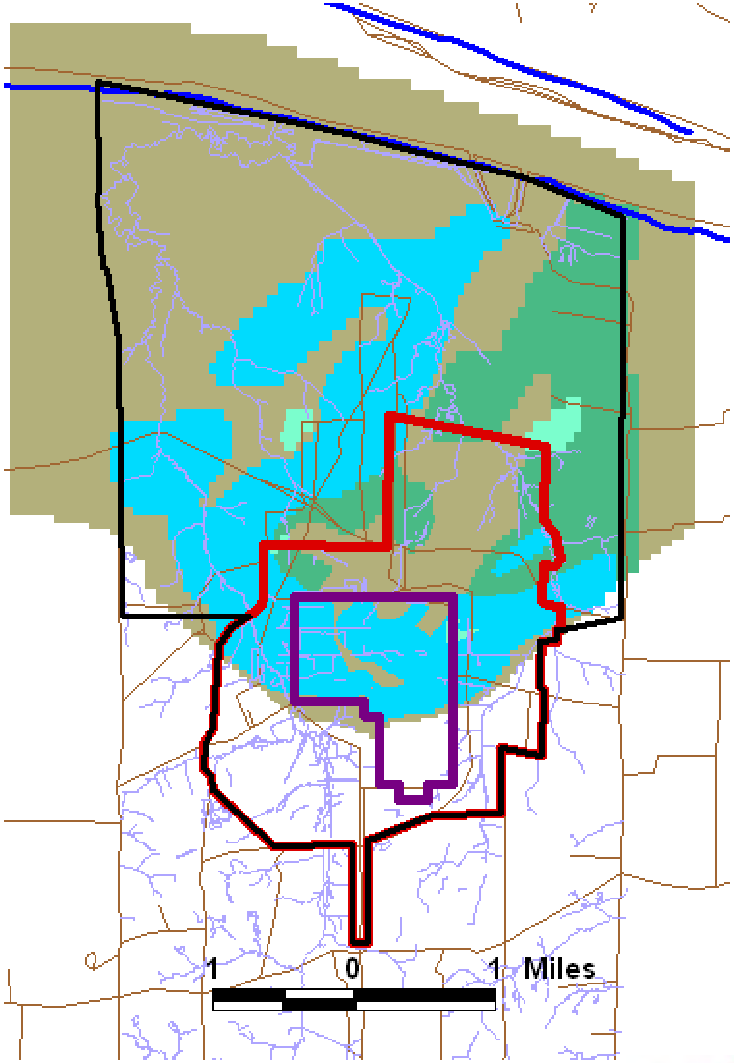
Model Description

Recharge Zones – for the first 10 year period (ft/day)



Model Description

Hydraulic Conductivity Zones for Layer 3



Hydraulic Cond. Kx (ft/day)

- 1
- 75
- 200
- 500
- 1500

Model Description

Transport Model - Model Parameters

- Soil/water partitioning coefficient (Kd)
  - The Kd value is contaminant and medium specific
  - Indicates constituent's affinity to bind with the soil
- Bulk Density
- Half life
- For TCE
  - Kd = 0.05L/kg,
  - bulk density = 1.9
  - half life = 9729.05 days (26.5 years)

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Model Description
Transport Model – Initial Concentrations

- 1000 zones of initial concentration
- Handled source(s) at C-400 as initial concentrations in RGA (secondary sources)
  - Source began depletion with model runs
  - UCRS primary sources not addressed in baseline model
- Tc99:
  - Maximum concentration at source point is about 10,700 (pCi/l).
- TCE:
  - Maximum concentration at source point is about 500,000 (µg/l).

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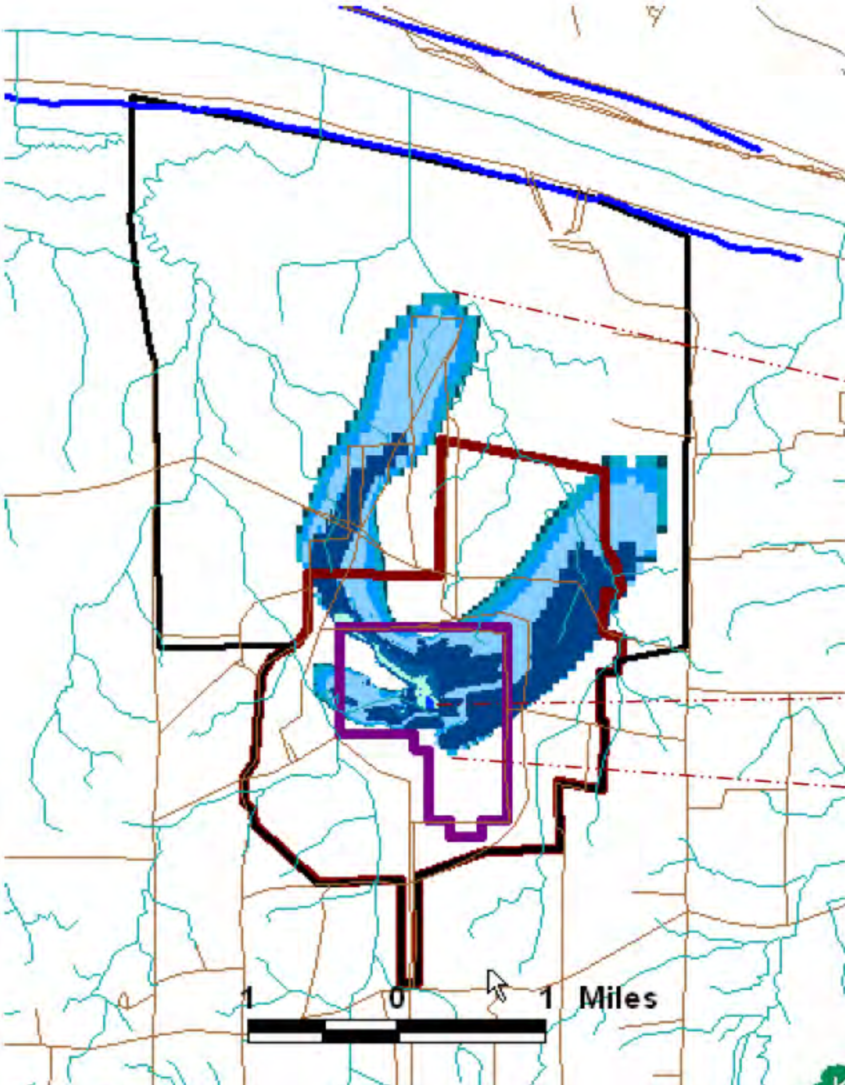
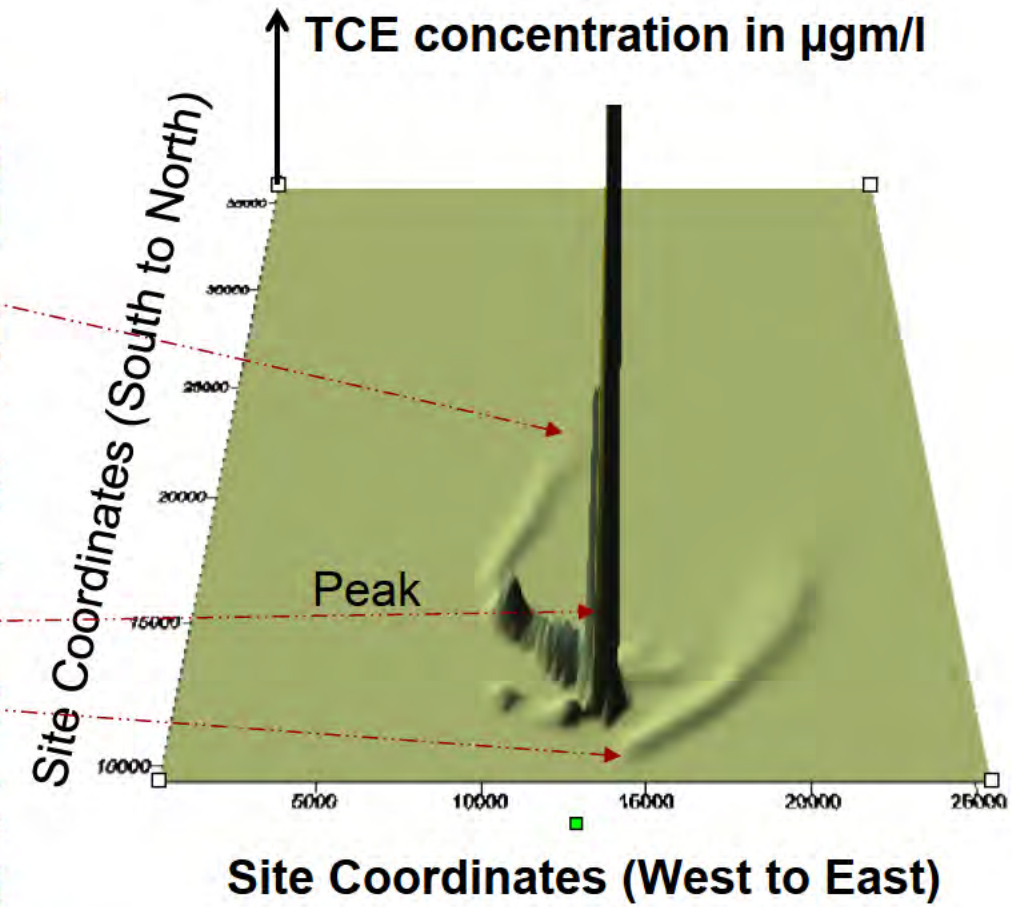
Model Description

Transport Model – Initial Concentrations





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Hydraulic Model
Verification of Model Calibration

- **Hydraulic Parameters**
  - Initial hydraulic conductivities were assigned based on lithology
  - Hydraulic conductivities (K) were adjusted based on observed heads in more than 100 monitoring wells
  - Majority of the monitoring wells penetrate to RGA – layer 3
  - A few wells go all the way to layer 4.

Hydraulic Model Verification

Measured and Computed Heads

Example from earlier report

Table 3. Summary of Model Residuals for 1998 Refined Model for the Paducah Gaseous Diffusion Plant

Name	X	Y	Layer	Observed	Computed	Residual
MW 007	10788.54	13243.04	2	361.59	362.21	-0.62
MW 043	16115.5	17847.23	3	323.56	322.64	0.92
MW 052	11295.59	13579.74	3	324.19	324.44	-0.25
MW 054	11060.36	13885.99	3	324.17	324.35	-0.18
MW 063	10751.76	14542.56	3	323.98	324.18	-0.20
MW 064	10752.13	14527.54	1	363.21	366.33	-3.12
MW 065	10752.59	14512.42	3	323.97	324.19	-0.22
MW 069	13644.25	11572.96	2	341.74	342.03	-0.29
MW 071	13614.57	11573.14	3	325.04	324.90	0.14
MW 073	12486.97	12913.31	3	324.51	324.66	-0.15
MW 075	12370.09	12805.14	2	364.92	361.56	3.36
MW 103	11735.36	10146.46	3	325.61	325.27	0.34
MW 104	11390.73	9964.42	2	349.8	351.92	-2.12
MW 106	9548.6	14638.23	3	324.36	323.91	0.45
MW 124	19866.65	14373.68	3	324	323.50	0.50
MW 125	12324.69	19786.58	3	321.71	321.54	0.17
MW 126	19868.99	14383.97	3	323.79	323.48	0.31

Hydraulic Model Verification

Measured and Computed Heads

Example from earlier report

- 100 calibration well observations
  - Nine (9) calibration wells had residuals > 2 feet different from target field head measurement
  - 4 wells in Model Layer 1 (UCRS sand/silt)
  - 2 wells in Model Layer 2 (UCRS silt/clay)
  - 1 well in Model Layer 3 (RGA)
  - 2 wells in Model Layer 4 (McNairy)

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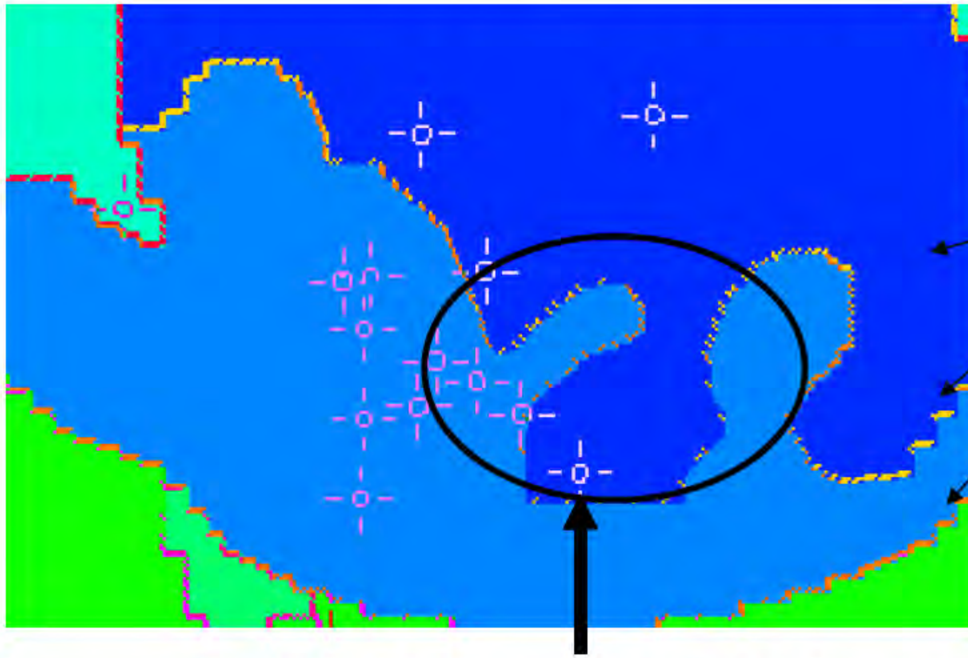
Hydraulic Model Verification
Adjusted Zone Boundary



Hydraulic conductivity zones

Revised zone near MW 157

Few such fine tunings were done in the modeling during validation

Sensitivity Analyses

Water Budget Sensitivity Analyses

(1999 – 2001) CAB and Site GW Modeling Working Group requested that additional geologic and hydrogeologic "Water Budget" data be collected to refine MODFLOW Flow & Transport Models

- Leakage from water bodies
- Areal recharge from rainfall
- River Stages

Water Budget Sensitivity Analyses

- Pumping at TVA Shawnee Plant
- Hydraulic conductivity in layer 3
- Plant shut-down
  - No outflow to Little Bayou Creek
  - Reduced outflow to Big Bayou Creek Recharge rates
  - Plant recharges (lagoons)
  - Rain recharges

Water Budget Sensitivity Analyses

- Leakage along the pipeline
  - Distributed
  - Concentrated
- Effect of Lineal elements
- Recharge from Shawnee Plant Ash Pond
- TCE (bio)degradation Rates
- Model sensitivity to simultaneous changes in multiple parameters

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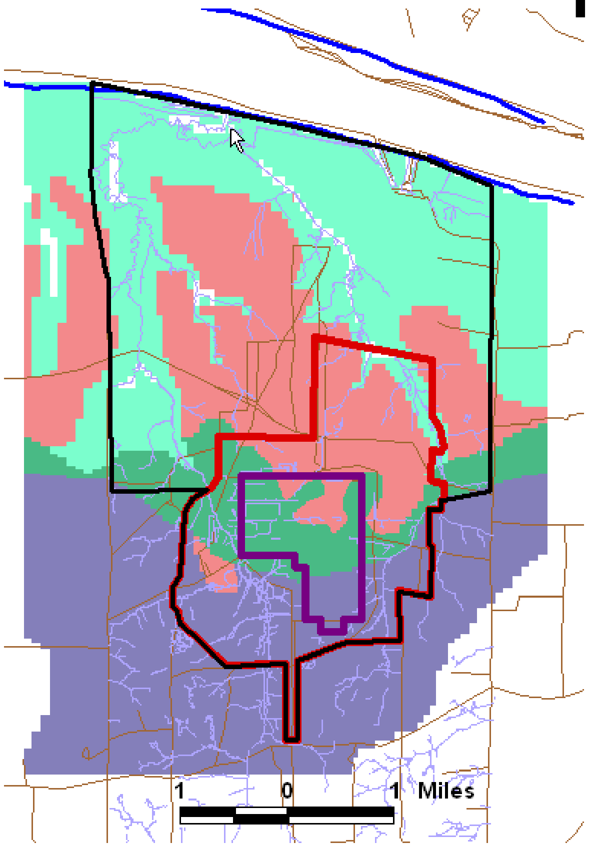
Sensitivity Analyses

- Conducted sensitivity analysis model runs to evaluate MODFLOW Flow and Transport model sensitivity to physical, hydraulic, and contaminant parameter inputs
- Prioritize collection of “Water Budget” data
- Gain confidence in model

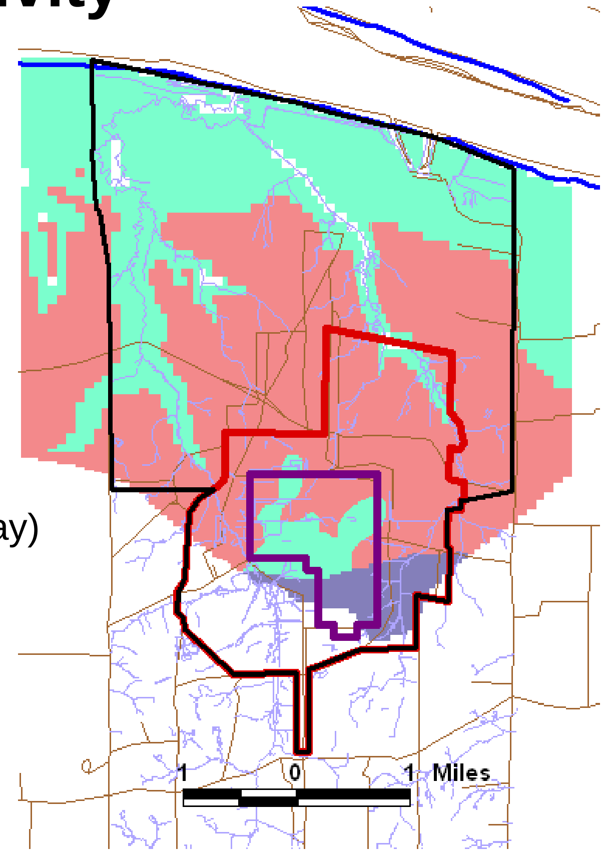
Sensitivity Studies

Hydraulic Conductivity

Layer 1



Layer 2



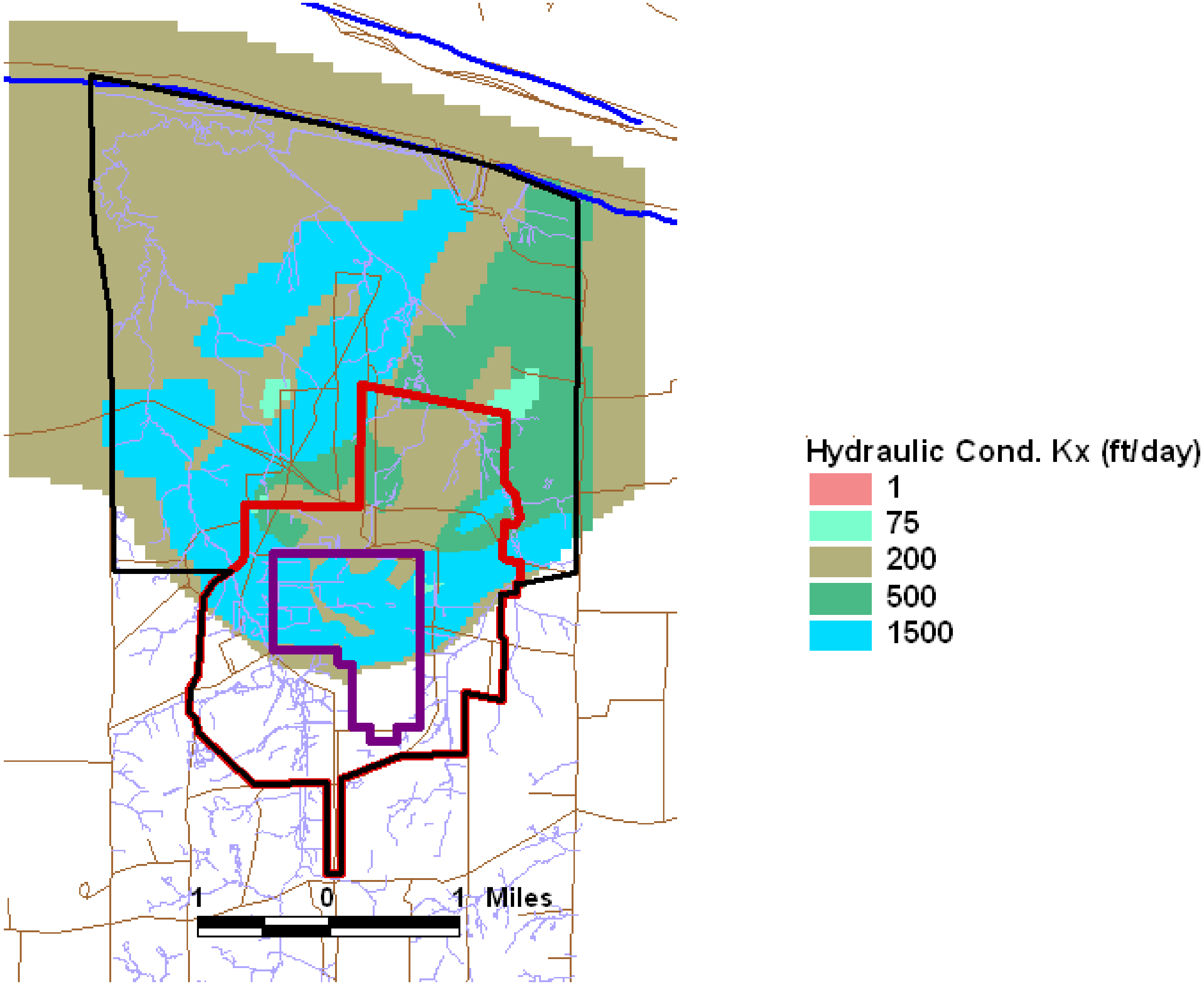
Hydraulic Conductivity (ft/day)

- 0 - 2
- 2.01 - 3.5
- 3.51 - 4
- 4.01 - 10
- 10.01 - 20
- 20.01 - 40

Although, K values in RGA are very high, the K values of the upper recharge zones are much smaller and therefore restrict rapid movement of water through the aquifer!

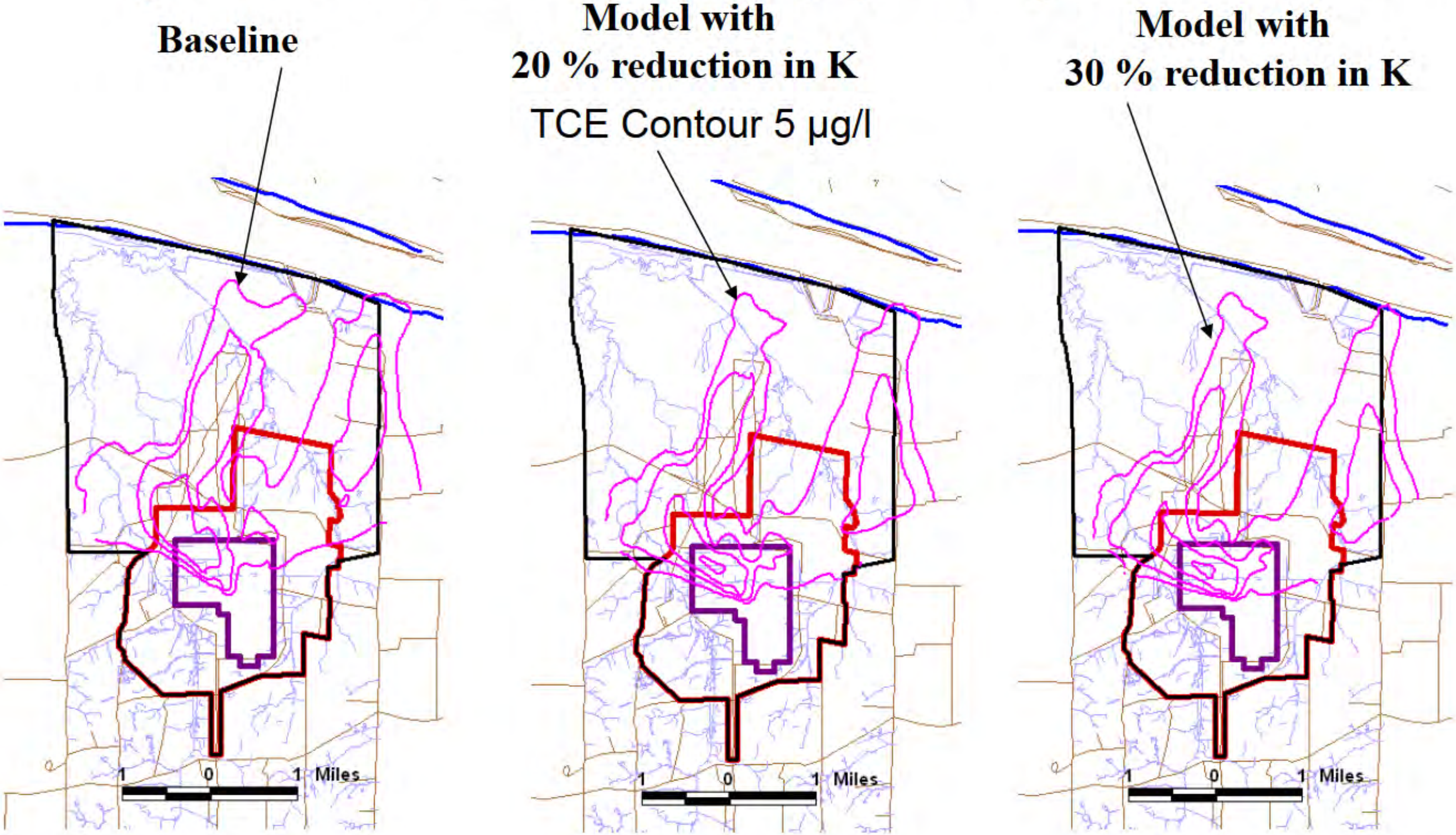
Sensitivity Studies

Hydraulic Conductivity Zones for Layer 3



Sensitivity Studies

Hydraulic Conductivity (K) – 30 year results



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Sensitivity Studies
Hydraulic Conductivity - Observations

- Significant reduction in TCE plume extent in western domain with reduction in hydraulic conductivities (K)
- Higher concentrations of plume constrained with reduced hydraulic conductivities
- No significant influence on water level contours (not shown)

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RGA Hydraulic Conductivity (K) Additional Observations

- Reduction in Hydraulic Conductivity results in following changes in model flow
  - Increased Surface Recharge (from numerical output)
  - Decreased Recharge from Bayou Creeks (from numerical output)
  - Increased outflow to Bayou creeks where they are receiving streams
  - Overall reduction in cumulative (aquifer) inflows and outflows
- Model is sensitive to changes in RGA hydraulic conductivities
- Changes to RGA hydraulic conductivities not appropriate based on evaluation

Pump and Treat Studies

- **Purpose is to evaluate effects of theoretical Pump and Treat actions on plume extents and on RGA gradients (not shown)**
- Two Time Periods
  - Time Period -1: 1997 – 2007 (10 years)
    - Steady state hydraulics
    - Time-varying TCE concentrations
    - No pumping during this period
  - Time Period -2: 2007 – (5-50 years)
    - Time-varying hydraulics and transport
    - Different pumping scenarios
  - No further release of TCE from landfills or other sources to the aquifers
- Two scenarios are presented

Pump and Treat Study
Scenario 1

Number of P & T Wells: 3
Time Period 1 (TP 1) : 10 years
Time Period 2 (TP 2) : 20 years
Number of installed wells for attaining results in this simulation @ 24

Well no	Grid position in Model domain (Row, Column)	Pumping rate (ft3/day)		Pumping rate (gpm)	
		TP-1	TP-2	TP-1	TP-2
1	45,160	0	150,000	0	779.25
2	45,170	0	150,000	0	779.25
3	45,180	0	150,000	0	779.25

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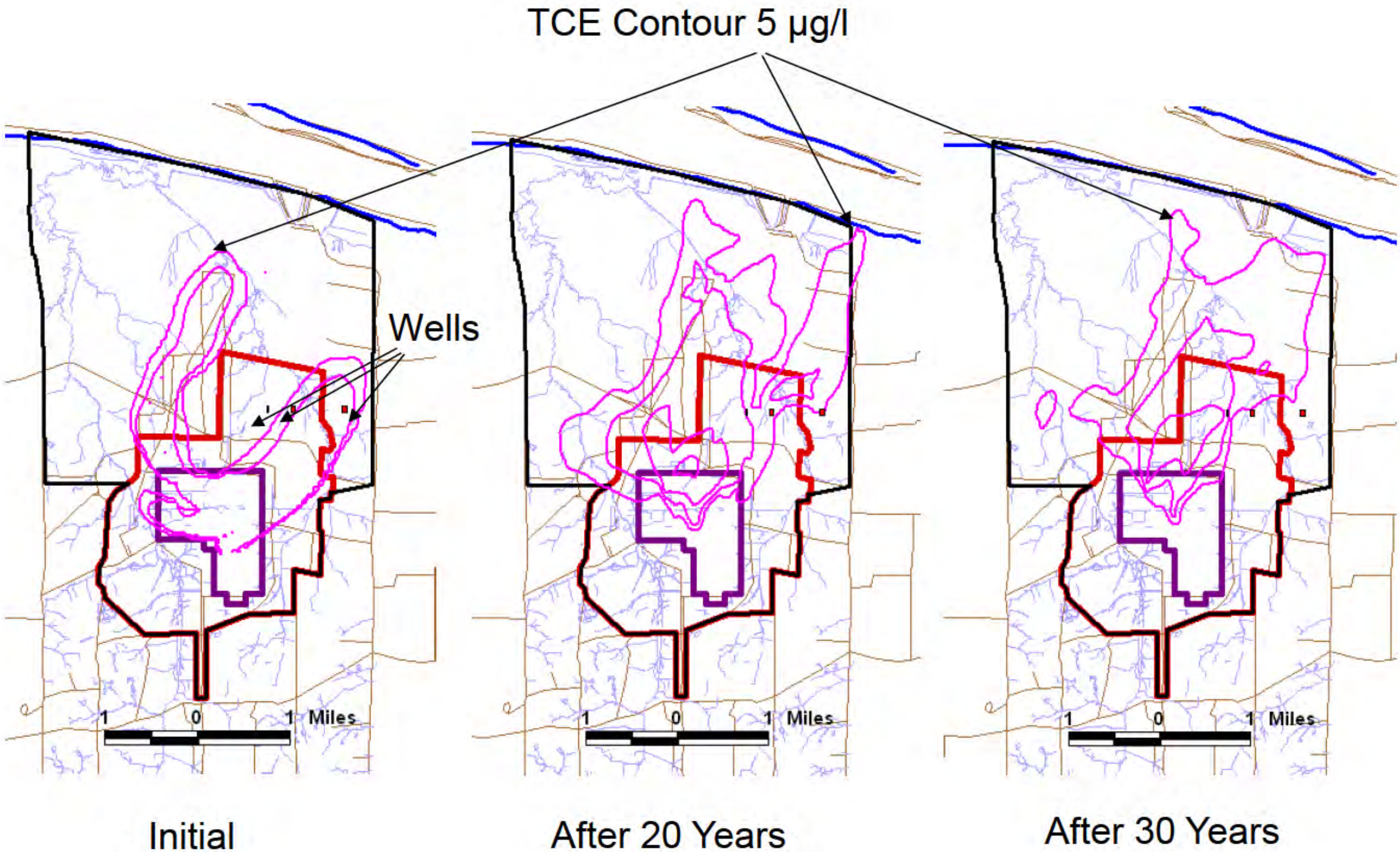
Pump and Treat

Scenario 1



Pump and Treat Study

Scenario 4

- Number of wells = 18
- TP-1 : 10 years
- TP-2 : 20 years
- Avg pump rate = 430 gpm
- Can't pump this rate?
- Rate @ 100 gpm = 64 wells to attain pump volumes in this simulation

Well no	Grid position in Model domain (Row, Column)	Pumping rate (ft3/day)		Pumping rate (gpm)	
		TP-1	TP-2	TP-1	TP-2
1	50,150	0	90,000	0	467.55
2	45,45	0	90,000	0	467.55
3	45,60	0	70,000	0	363.65
4	45,80	0	80,000	0	415.60
5	45,95	0	70,000	0	363.65
6	45,110	0	70,000	0	363.65
7	45,100	0	70,000	0	363.65
8	45,160	0	70,000	0	363.65

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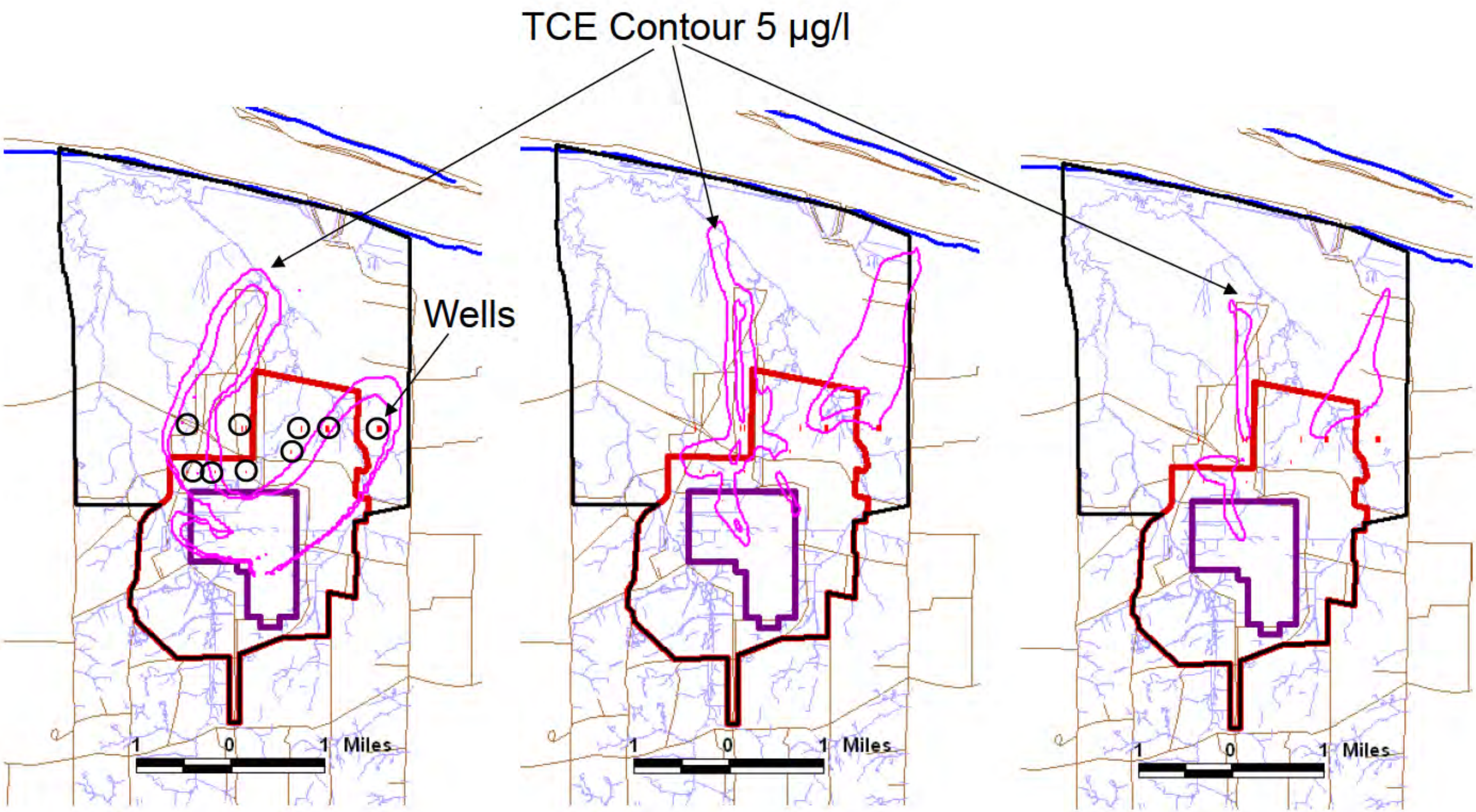
Pump and Treat Study

Scenario 4



Initial

After 20 years

After 30 years

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Pump and Treat Study

Scenario 5

- Number of pumping wells : 6
- Number of recharge wells : 2
- TP-1 : 10 years
- TP-2 : 20 years

Well no	Grid position in Model domain (Row, Column)	Pumping rate (ft3/day)		Pumping rate (gpm)	
		TP-1	TP-2	TP-1	TP-2
1	36,76	9240.6	9240.6	48	48
2	36,79	8663.1	8663.1	45	45
3	66,174	19251.3	19251.3	100	100
4	67,175	15401.1	15401.1	80	80
5	60.36	10588.2	10588.2	55	55
6	60,38	11550.8	11550.8	60	60
7	128,99	-19251.3	-19251.3	100	100
8	128,108	-19251.3	-19251.3	100	100

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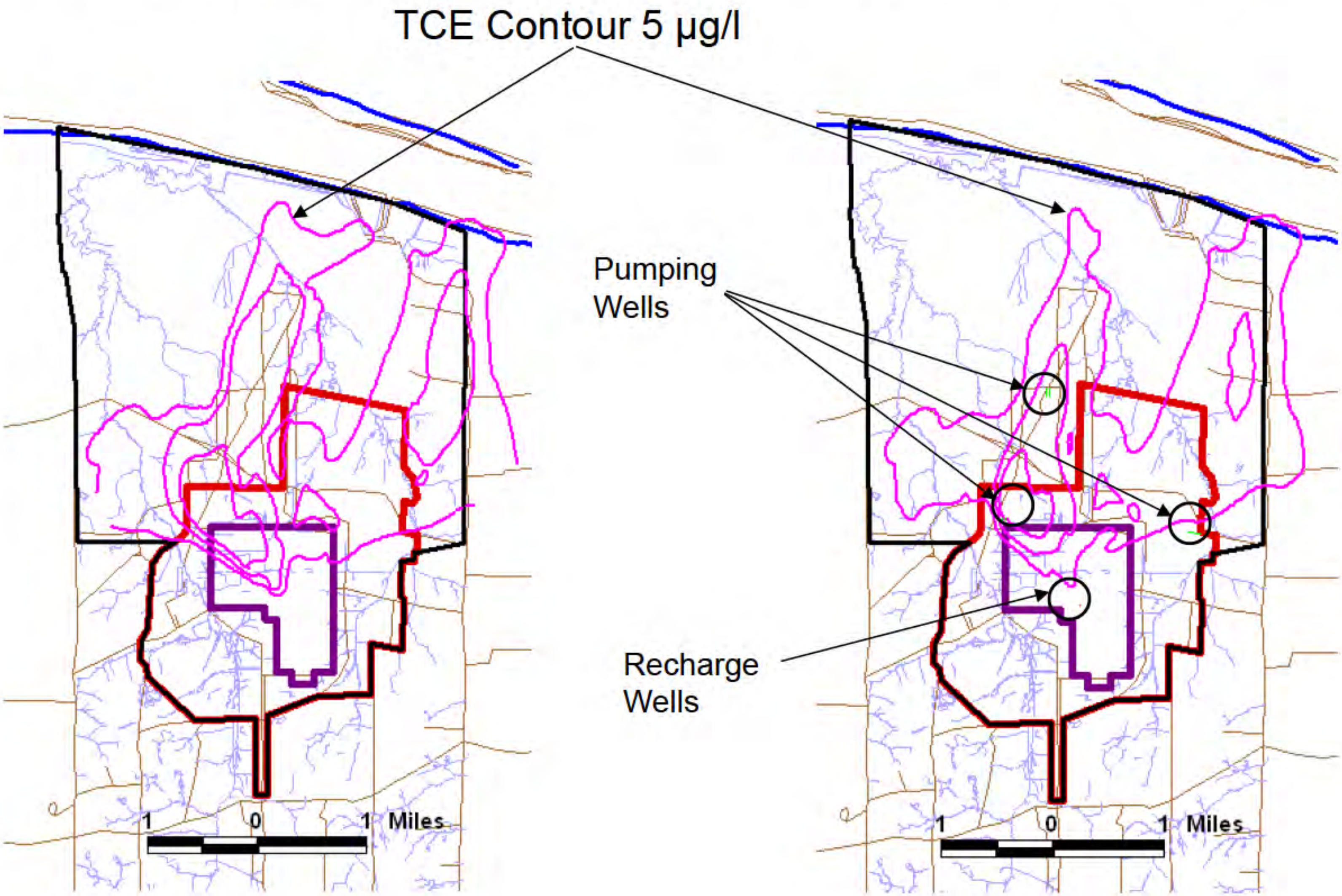
Pump and Treat Study Scenario 5



Baseline model without any action after 30 years

Model with Six Pumping wells and Two recharge wells after 30 years

Pump and Treat Studies
Observations

- All Pump and Treat scenarios showed considerable influence on the extent of TCE plumes over time.
- The MODFLOW flow and transport models are sensitive to pumping in the RGA

Plant Shutdown Sensitivity Analyses

- Bayou and Little Bayou Creeks were modeled as "River Boundaries" in baseline model
  - Uniform depth of 2.5 ft. for all river cells
- Sensitivity Analyses assumed reduced plant inflows to **both Bayou and Little Bayou** Creeks
  - Reflected in lower stage levels to both creeks
- Assumed increases in the recharge rate within plant fence into layer 1 of the model
  - D&D expected to remove impervious infrastructure

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Plant Shutdown Sensitivity Analyses

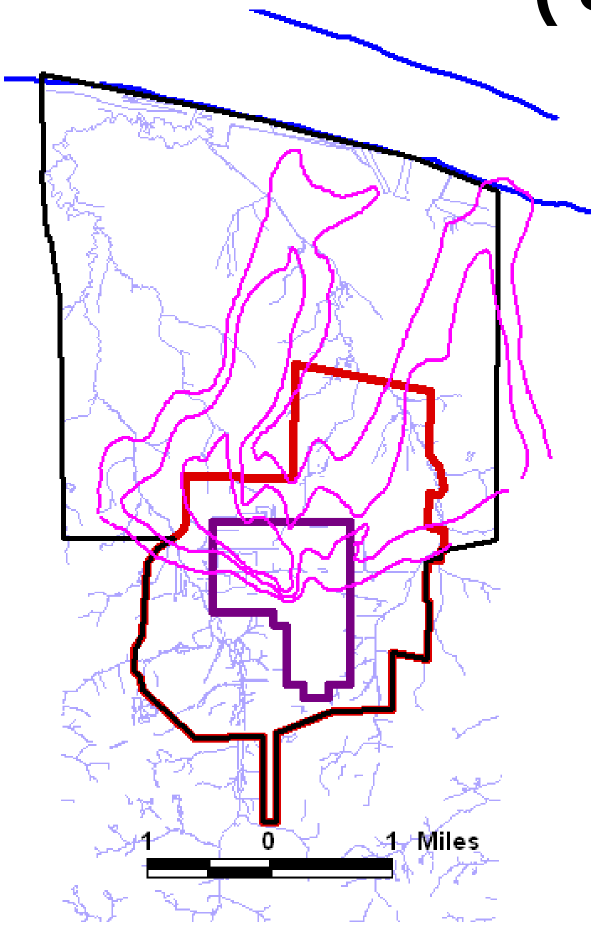
1. **Vary water depths in Big Bayou and Little Bayou Creeks**
2. **Vary recharge in plant due to D&D of infrastructure**
3. **All other parameters are maintained as per the baseline model**

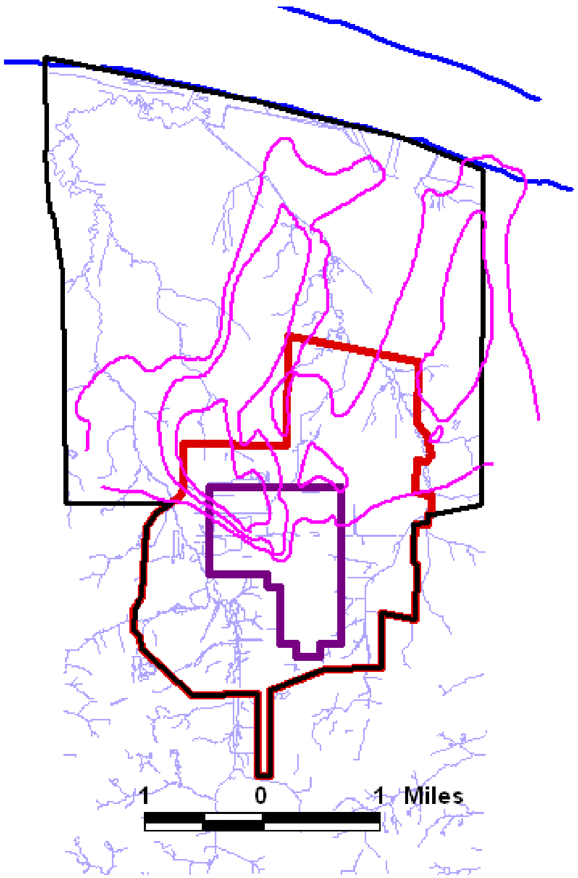
(CRSV = Creek and River Stage Variation)

- Model **CRSV** 1 :
  - ✓ reduce BBC stage to 1.25 ft (50 % reduction) and
  - ✓ maintain LBC stage at 2.5 ft as per baseline model.
- Model **CRSV** 2 :
  - ✓ maintain BBC stage to 2.5 ft as per baseline model and
  - ✓ reduce LBC stage to 1.25 ft (50 % reduction).
- Model **CRSV** 3 :
  - ✓ reduce BBC stage to 1.25 ft and
  - ✓ reduce LBC stage to 0.5 ft.
- Model **CRSV** 4 :
  - ✓ reduce BBC stage to 0.5 ft and
  - ✓ reduce LBC stage to 0.5 ft.

Plant Shutdown Scenario

(30 Years)





Baseline model
Big Bayou creek – 2.50 ft stage
Little Bayou creek – 2.50 ft stage

Model CRSV 2
Big Bayou creek – 1.25 ft stage
Little Bayou creek – 2.50 ft stage

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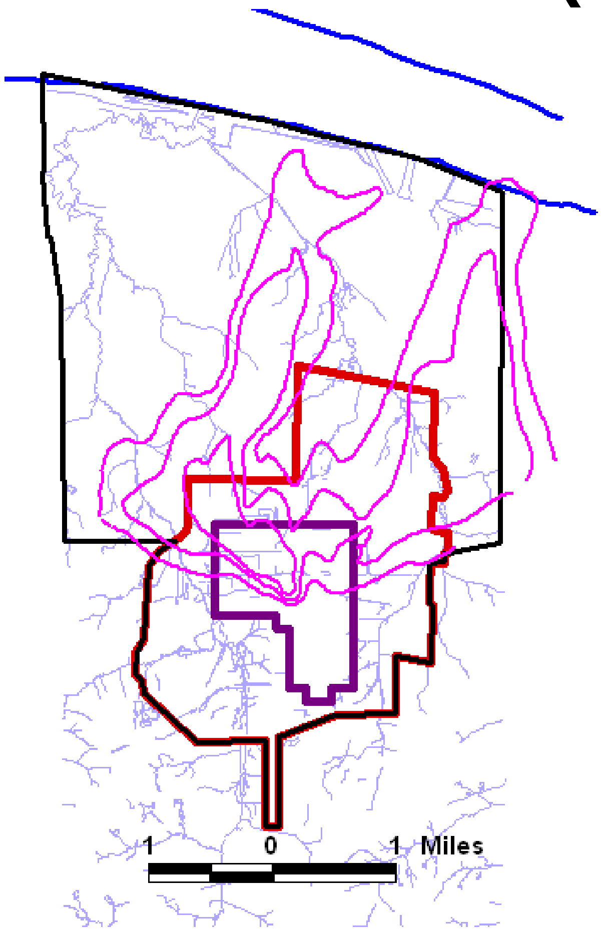
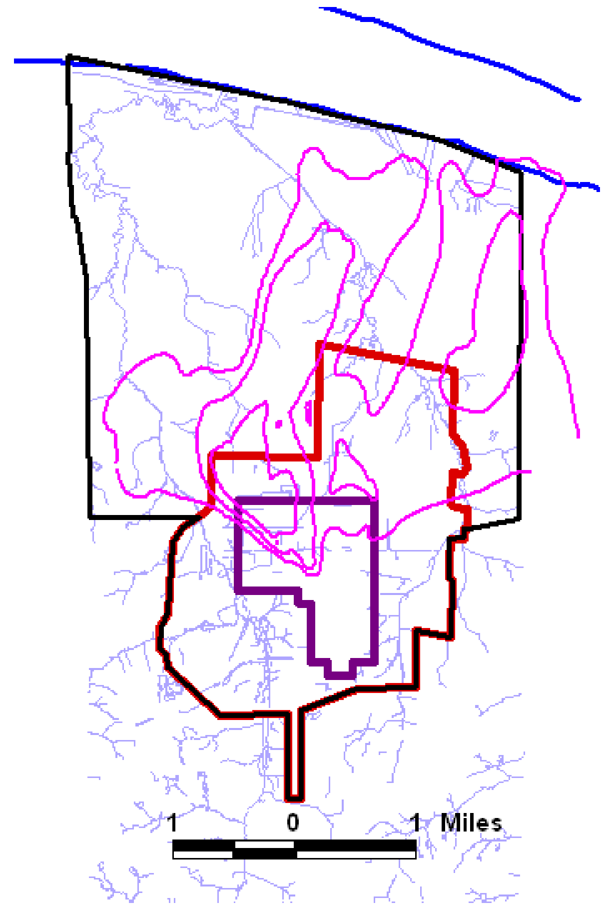
Plant Shutdown Scenario
(30 Years)



Baseline model
Big Bayou creek – 2.50 ft stage
Little Bayou creek – 2.50 ft stage



Model CRSV 2
Big Bayou creek – 2.50 ft stage
Little Bayou creek – 0.50 ft stage

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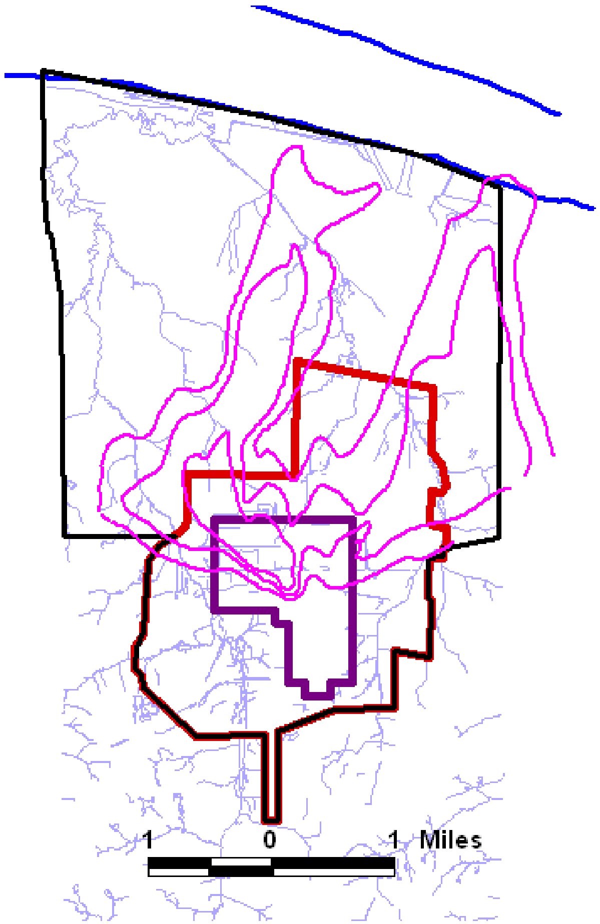
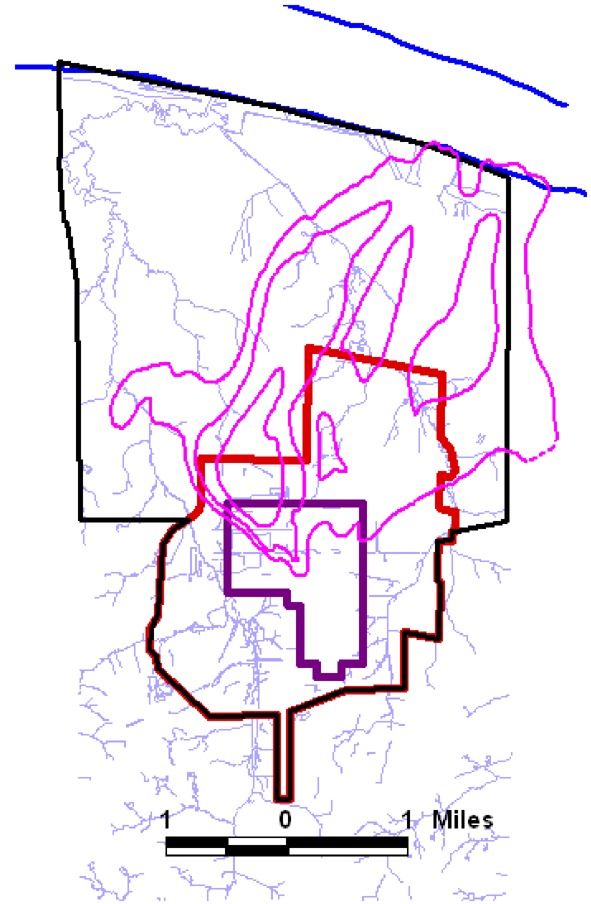
Plant Shutdown Scenario
(30 Years)



Baseline model
Big Bayou creek – 2.50 ft stage
Little Bayou creek – 2.50 ft stage



Model CRSV 3
Big Bayou creek – 1.25 ft stage
Little Bayou creek – 0.50 ft stage

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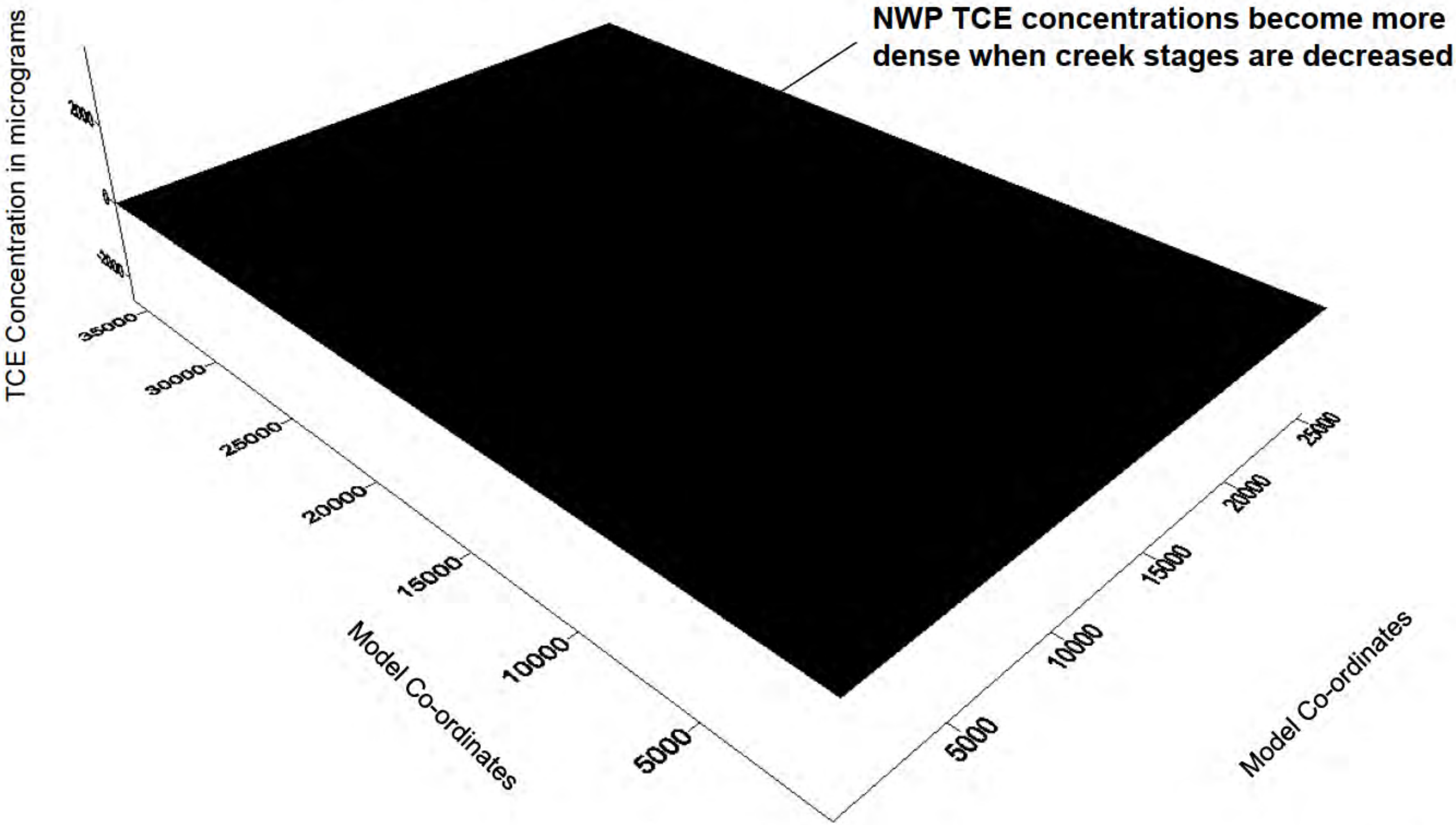
Plant Shutdown Scenario
(30 Years)
Delta Plot for Baseline and CRSV 4



Plant Shutdown Scenario
(30 Years)
Summary

- Changes to Little Bayou Creek (LBC) stage impact plume extent more than changes to Big Bayou Creek (BBC) stage
  - Hydraulic Conductivities underneath LBC are much higher than Hydraulic Conductivities underneath BBC
- Reduction of depth in LBC influences volumetric water balance considerably (not illustrated).
- Plant Shut Down will return LBC to ephemeral stream upgradient of TVA property
  - Loss of infiltrating water in upgradient portion LBC has a significant Influence on TCE Plumes
  - NWP and NEP coalesce over time as LBC stage is reduced

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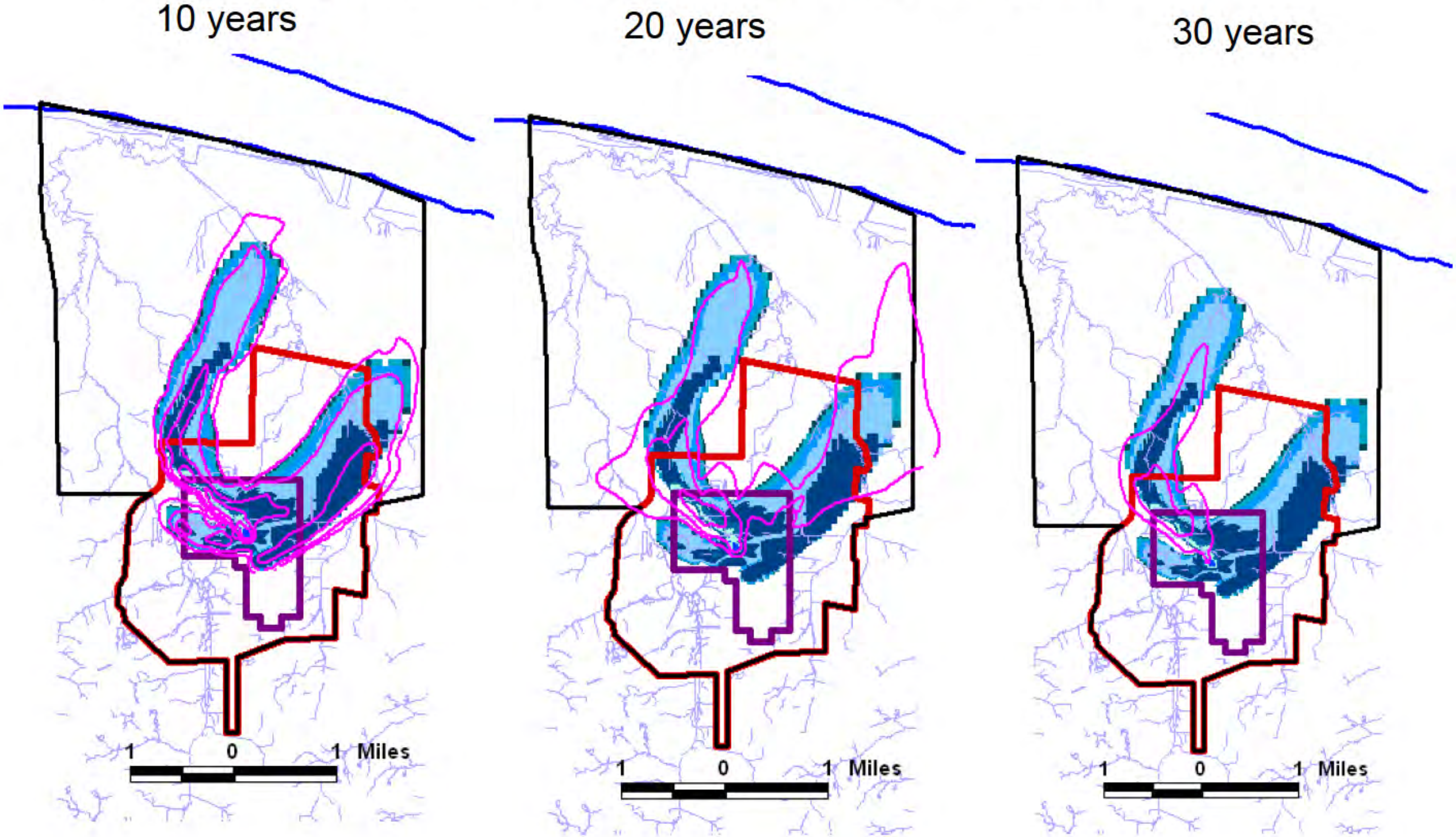
Transport Parameters
Sensitivity Analyses

Half-Life Period

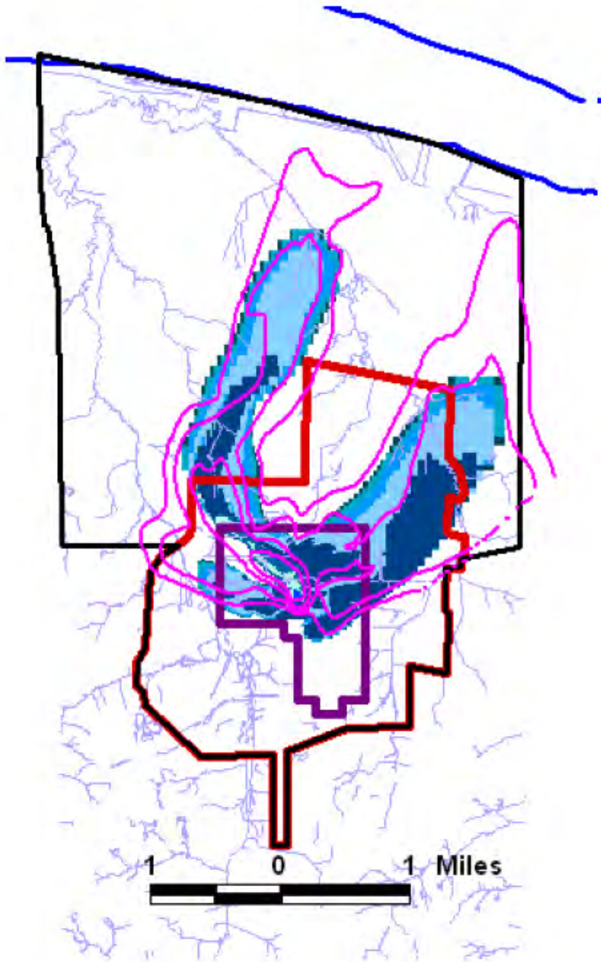
- (Bio)degradation of TCE in the PGDP transport model is handled using a Half-Life Period
  - Model uses 26.65 years or 9729.04 days
- Used across all initial concentrations
- Half-life Trials
  - 5 years, 10 years,15 years, with
  - vary half Life period in two zones
  - varying half Life period in four zones
  - varying half life period in different zones to simulate lesser (bio)degradation rates at high concentrations & sources.

Runs with 5 years Half Life

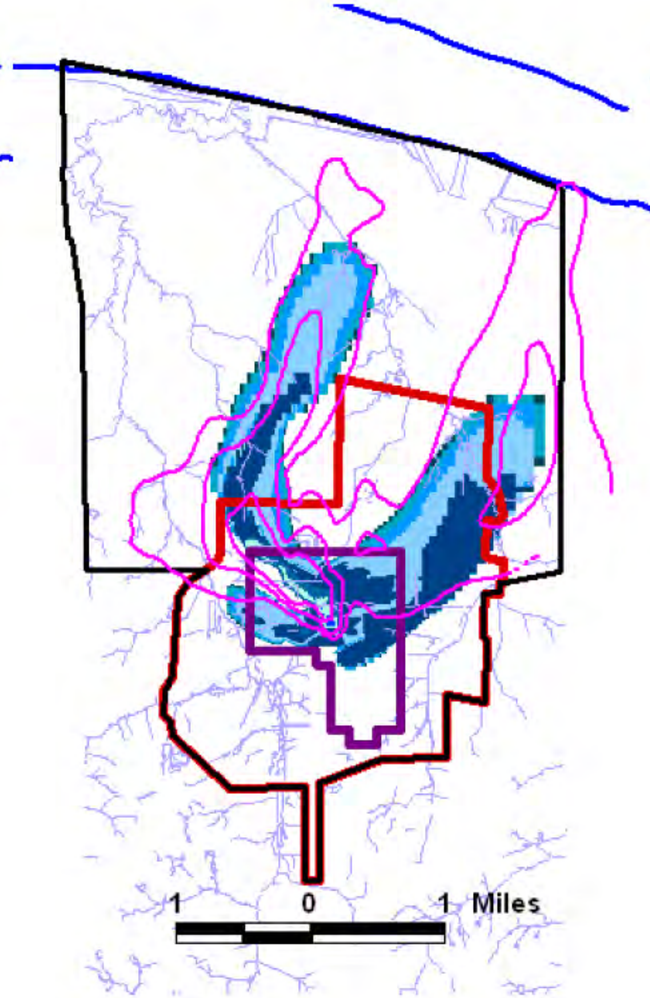
(superimposed over initial concentration plume 1997)



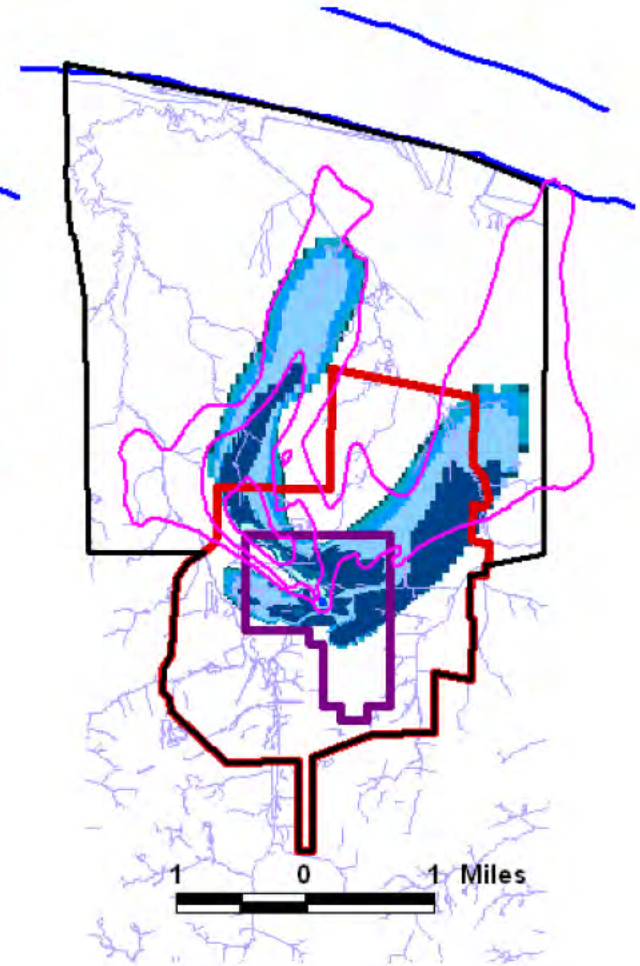
Runs with 10 years Half Life



10 years

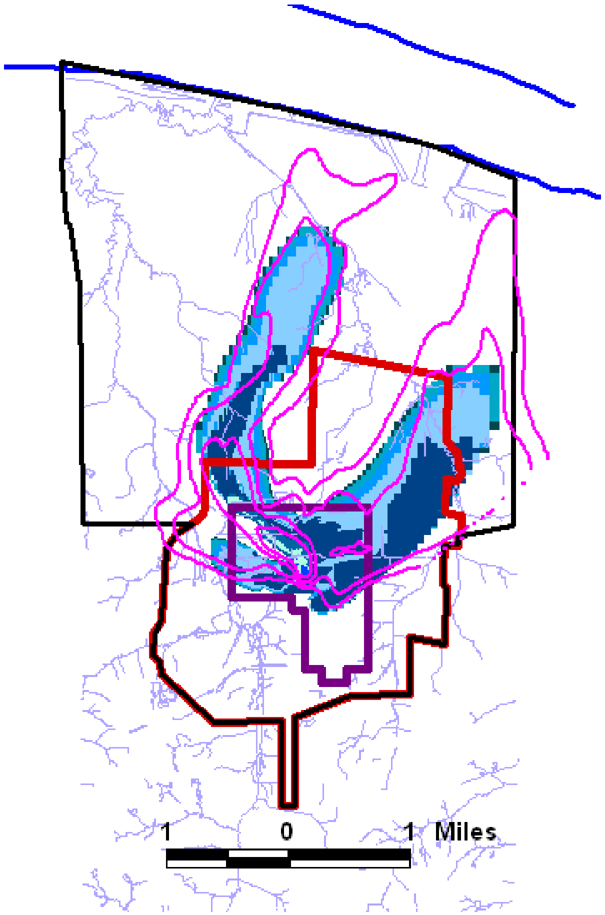


20 years

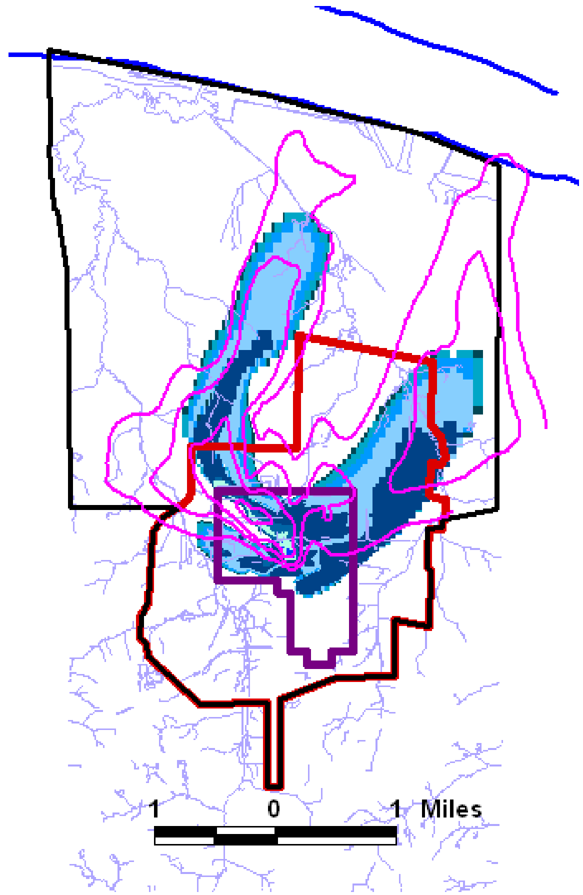


30 years

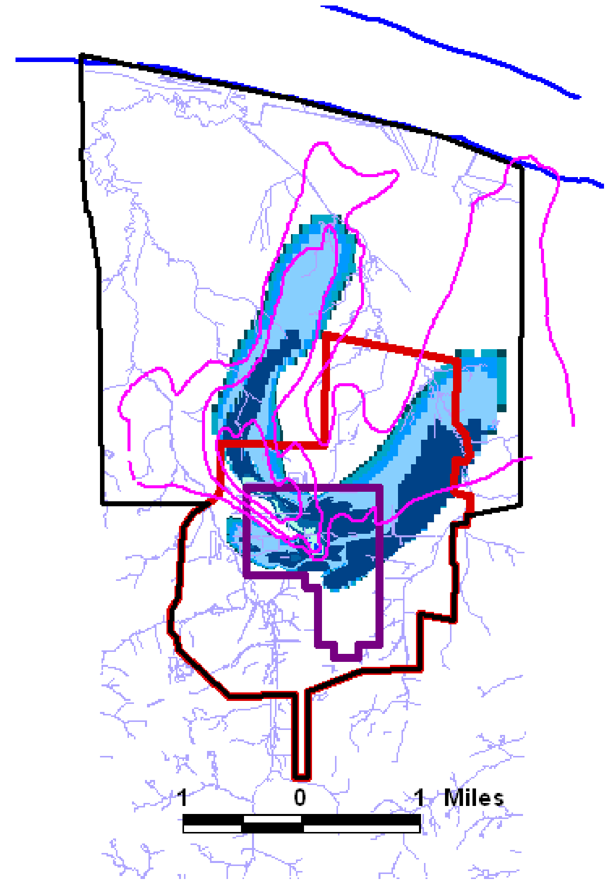
Runs with 15 years Half Life



10 years



20 years



30 years

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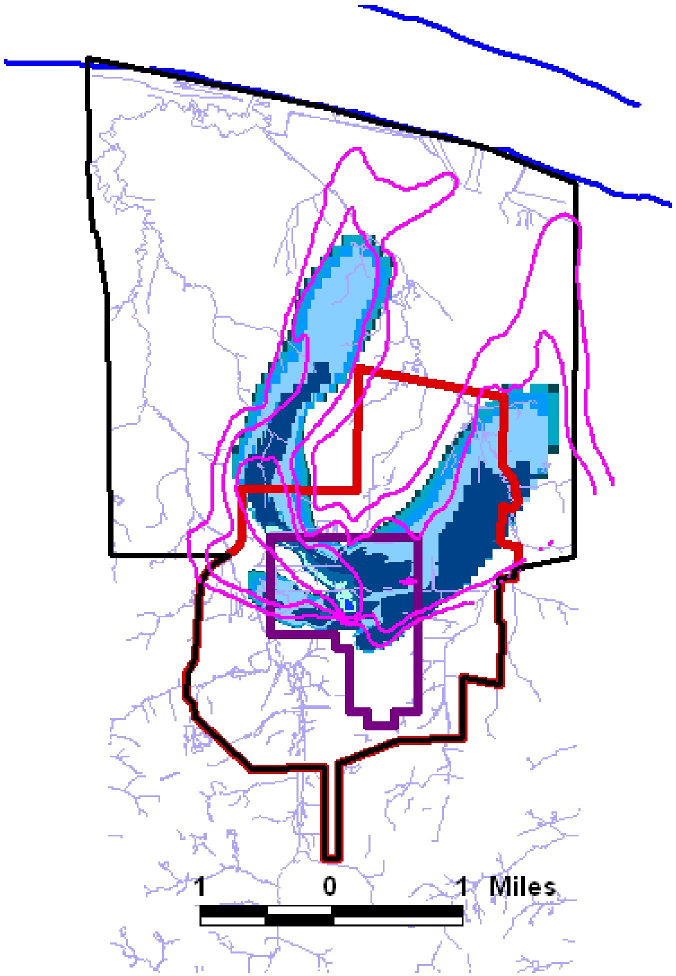
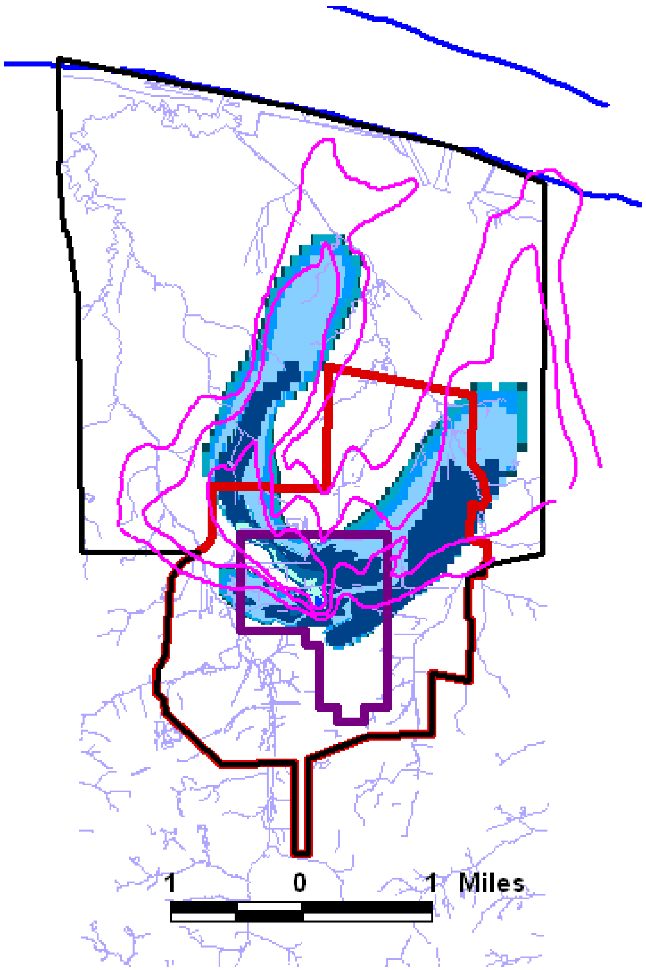
Runs with 26.65 years Half Life Period



10 years



30 years

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Half-life Sensitivity Analyses Observations

- Varying Half-life parameter results in significant temporal variations in TCE plume extent
- Model is very sensitive to TCE Half-life
- Half-life parameter needs to be further evaluation/refinement so that “future” scenario model runs accurately predict nature and extent of plume

KRCEE

Summary and Conclusions

- **KRCEE evaluation efforts provided an extensive knowledge-base about MODFLOW & MODFLOW T model suitability for present and future applications**

- **The model is sensitive to:**
  - Hydraulic conductivity (K) values in layer 3 (RGA)
    - K values in RGA appear to be accurate based on
      - pump test inputs,
      - assignment of K's to zones based on like lithologies, and
      - model results that are reasonable
  - Transport Model is highly sensitive to changes in model half-life parameter that is used for quantifying (bio)degradation rates
  - Water level changes in Little Bayou Creek
    - Indicates that plant shut down will influence future TCE plume configurations

KRCEE

Summary and Conclusions

- **Model is relatively insensitive to:**
  - Rainfall (recharge) fluctuations (not shown)
  - Point and diffuse recharge rates (not shown)
  - Pumping at Shawnee Plant (not shown)
  - Leakage of lagoons and pipeline (not shown)
  - Changes in Ohio River stage caused by Olmsted Lock and Dam (not shown)
  - Highly conductive lineal features on plume configurations (not shown)

- **Potential Future Model Refinements**
  - NWP water level data west of Security area
  - NWP water level data for distal Dissolved Phase Plume
  - Differentiation of RGA relative to lithology
  - Identification and quantification of degradation rates
  - Identification and quantification degradation zones
  - Model runs that reflect potential impacts from all source zones
    - Primary (UCRS)
    - Secondary (RGA)

KRCEE

KRCEE Future Activities

- Update flow and transport models based on recently collected field data
  - Including SW Plume, BG, and C-400 data
- Re-Calibrate the flow model based on the latest Lithologic data
  - PGDP & KRCEE
- Recalibration of transport model based on 2005 TCE & 99Tc data
- Evaluation of Army Corps of Engineers (ACOE) FEMWATER finite element model (setup & data)
- Comparison testing of ACOE FEMWATER finite element model and PGDP finite difference model
- Model integration with optimization tools
- Re-runs of sensitivity analyses reflecting UCRS primary source inputs to RGA

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