Estimating MNA Remedial Timeframes with Natural Attenuation Software (NAS)

U.S. Geological Survey
Columbia, SC

Virginia Tech
Blacksburg, VA

Purpose

- Describe the features of Natural Attenuation Software
  - A computational screening tool for assessing the effects of different source reduction strategies combined with monitored natural attenuation (MNA)
- Explain how NAS is useful to RPMs for decision making:
  - Comparing the efficacy of different remedial strategies
  - Formulating inputs for life-cycle cost estimates
- Present case studies of the application of NAS at three sites and lessons learned

Presentation Outline

- Background
- Components of Natural Attenuation Software
- Validation of Natural Attenuation Software
- Site Demonstrations
- Summary

EPA Directive on MNA (1999)

- MNA is only appropriate if site objectives can be achieved
- Time of remediation must be reasonable
- Remedial strategy using MNA will include:
  - Long-term monitoring
  - Source control
- Challenge in 1999:
  - What constitutes time of remediation (TOR)?
  - Technical guidance on implementing MNA lacking
  - Reliable, accurate computational screening tool needed

Responding to the Challenge

- In 2000, NAVFAC, US Geological Survey, and Virginia Tech collaborated to produce technical guidance for assessing MNA as a remedial strategy at US Navy sites
- Published in 2003: USGS WRIR 03-4057
  - Systematic methodology and decision-making framework for implementing MNA in conjunction with source zone remediation
  - Computational screening tool for estimating the effects of combining source zone remediation with MNA

Defining the Problem

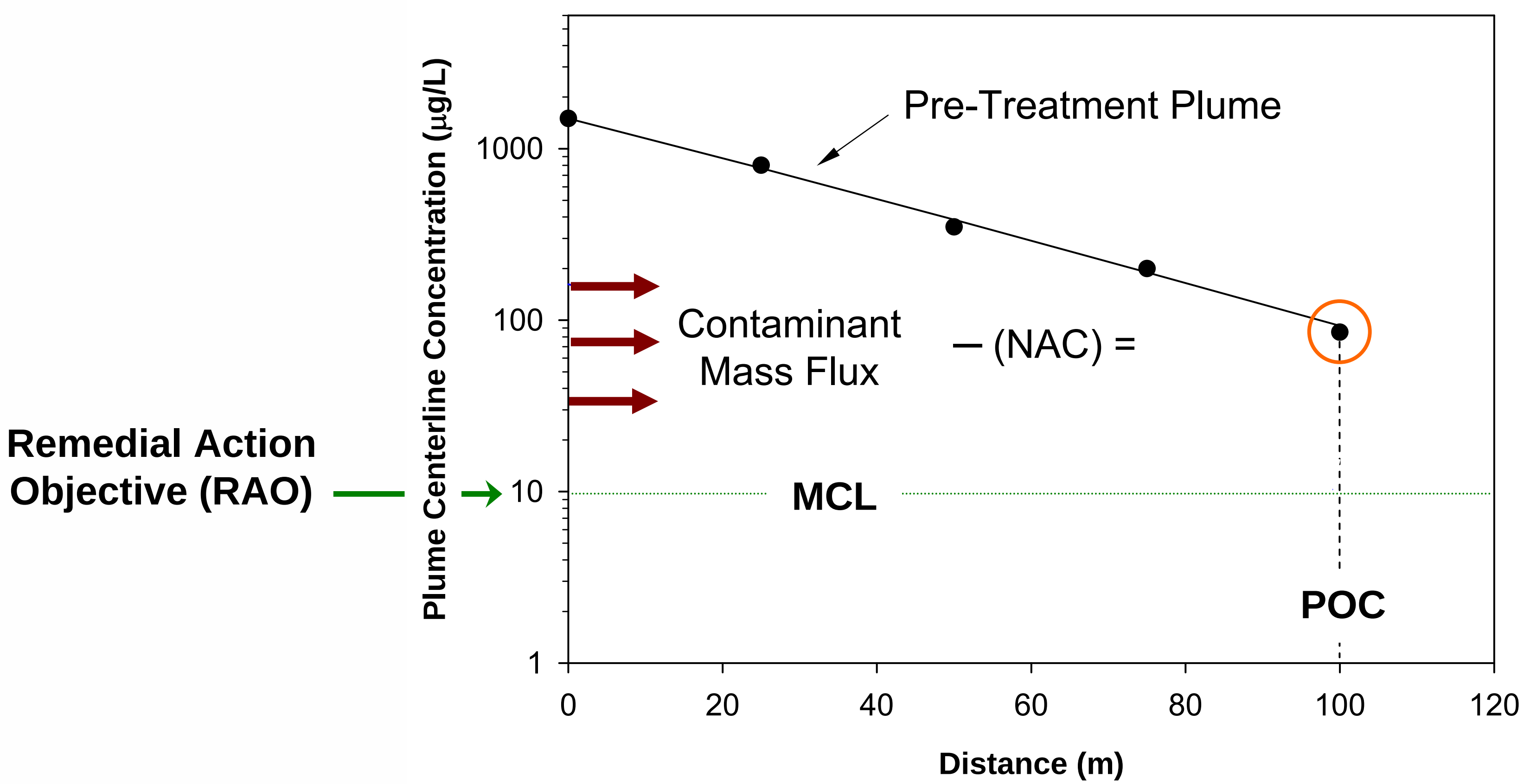
Plume reduction consists of two components to meet site-specific remedial action objectives (RAOs):

- **<u>Distance of Stabilization (DOS)</u>**
  - Reduction in plume length through reduction in source strength
  - Reduction in concentration at point of compliance (POC)
- **<u>Time of Stabilization (TOS)</u>**
  - Time required to re-stabilize contaminant plume

These components are illustrated in the following animation:

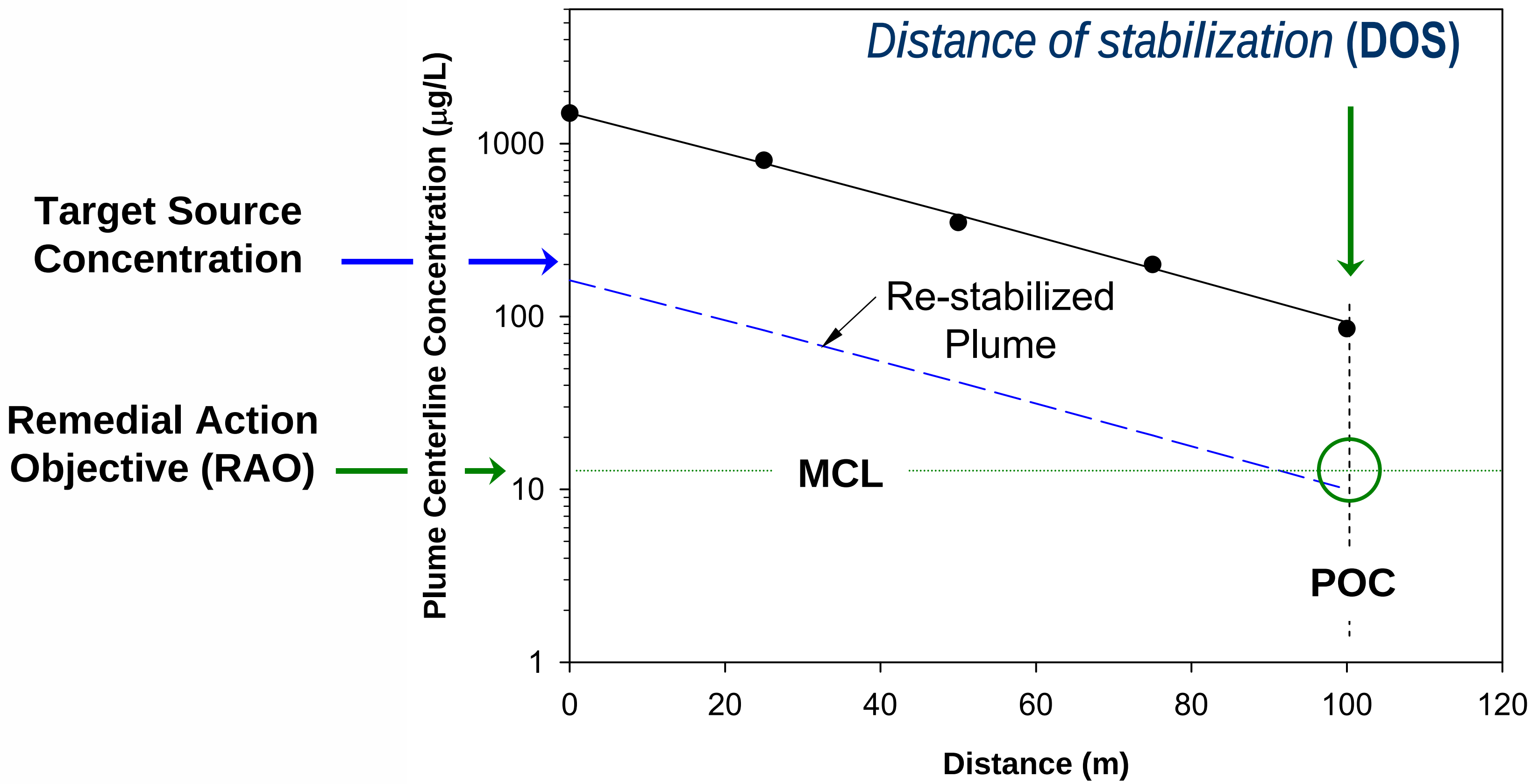
Distance of Stabilization

The ***Distance of Stabilization*** **depends on the** ***Natural Attenuation Capacity*** **(*NAC*) of the aquifer.**



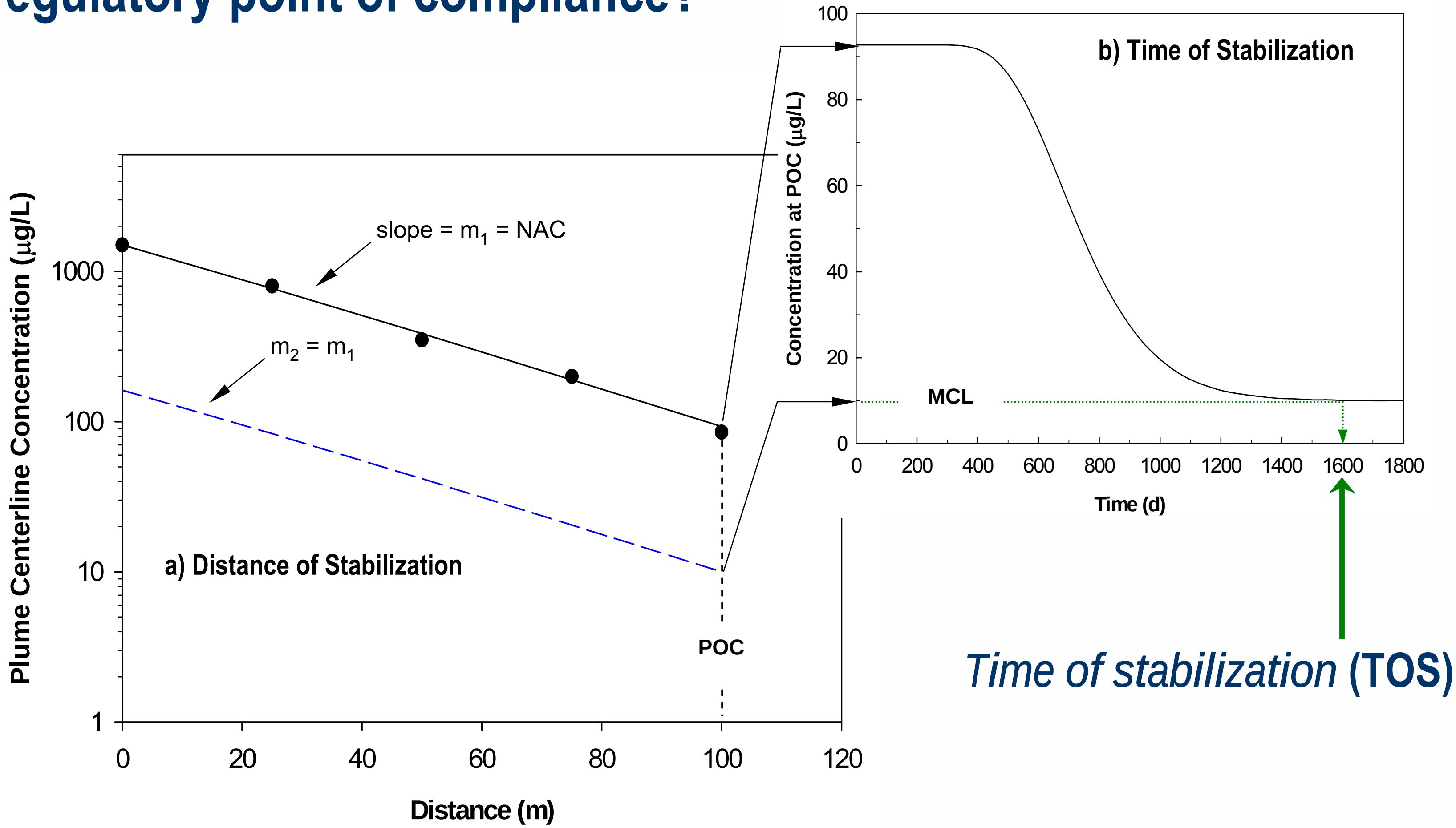
Distance of Stabilization (cont.)

For any given NAC, source remediation can reduce the mass flux of contaminants, resulting in a smaller, stable plume where concentrations meet remediation goals.



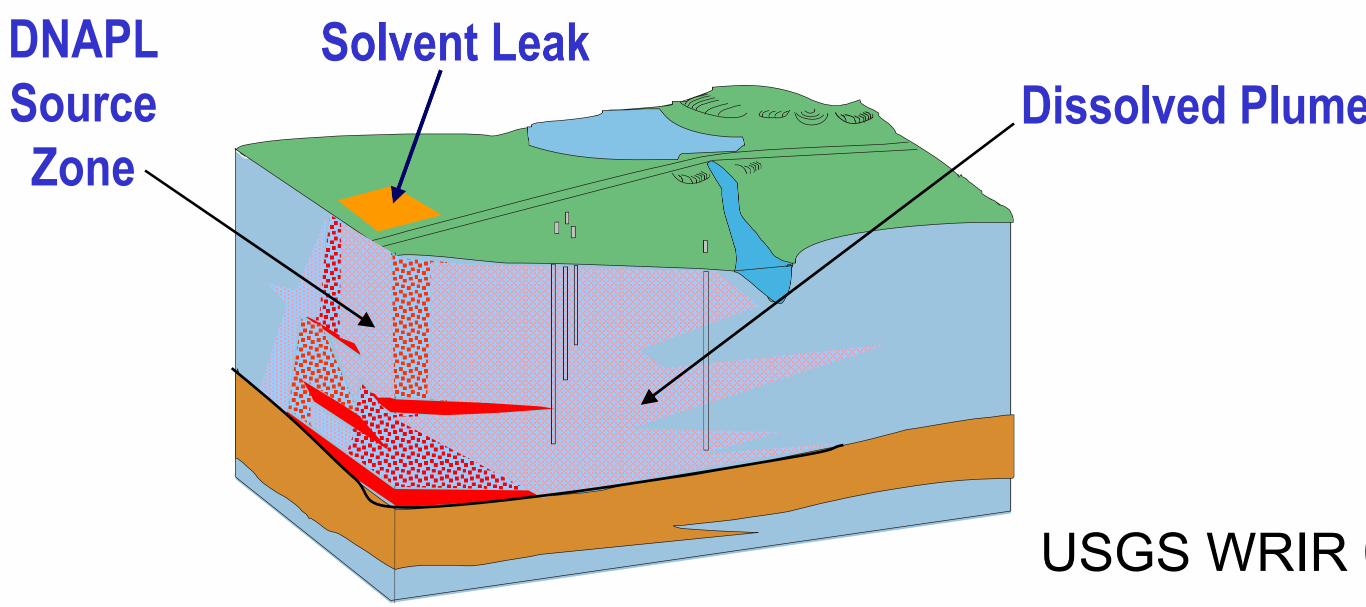
Time of Stabilization

The question often posed is *when* will the RAO be reached at the regulatory point of compliance?



Source Depletion

- **At sites where risk is deemed acceptable or source reduction is technically impracticable, it is useful to evaluate time for source zone depletion**
  - This is illustrated in the next animation:

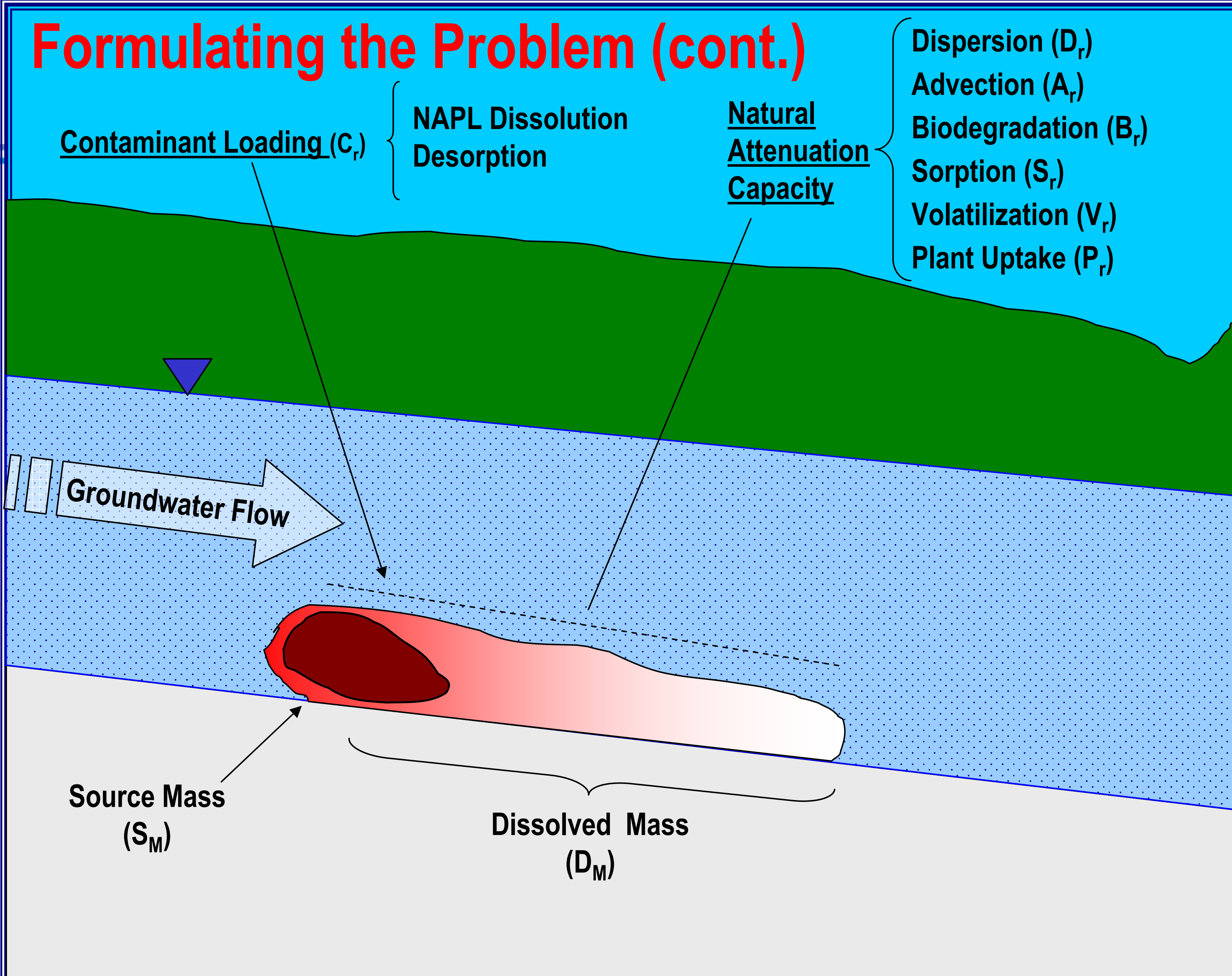


USGS WRIR 03-4057

Formulating the Problem

- Once the concepts were defined, the next question was how to formulate the problem
- MNA-based remediation strategies are based on the efficiency of the NAC of the aquifer
- NAC analogous to assimilative capacity in surface water hydrology and soil science

Formulating the Problem (cont.)



Each of these components can be summed in mass balance equations

	Advection	Dispersion	Sorption	Biodegradation	NAPL Dissolution

$$\frac{\partial C}{\partial t} = -v\frac{\partial C}{\partial x} + D\frac{\partial^2 C}{\partial x^2} - \frac{K_d \rho_b}{n}\frac{\partial C}{\partial t} - R_{bio} + R_{NAPL}$$

Goal: Solve these equations to obtain meaningful TOR estimates using a systematic, accurate, and reliable method.

Defining the Problem → **Formulating the Problem** → **Solving the Problem**

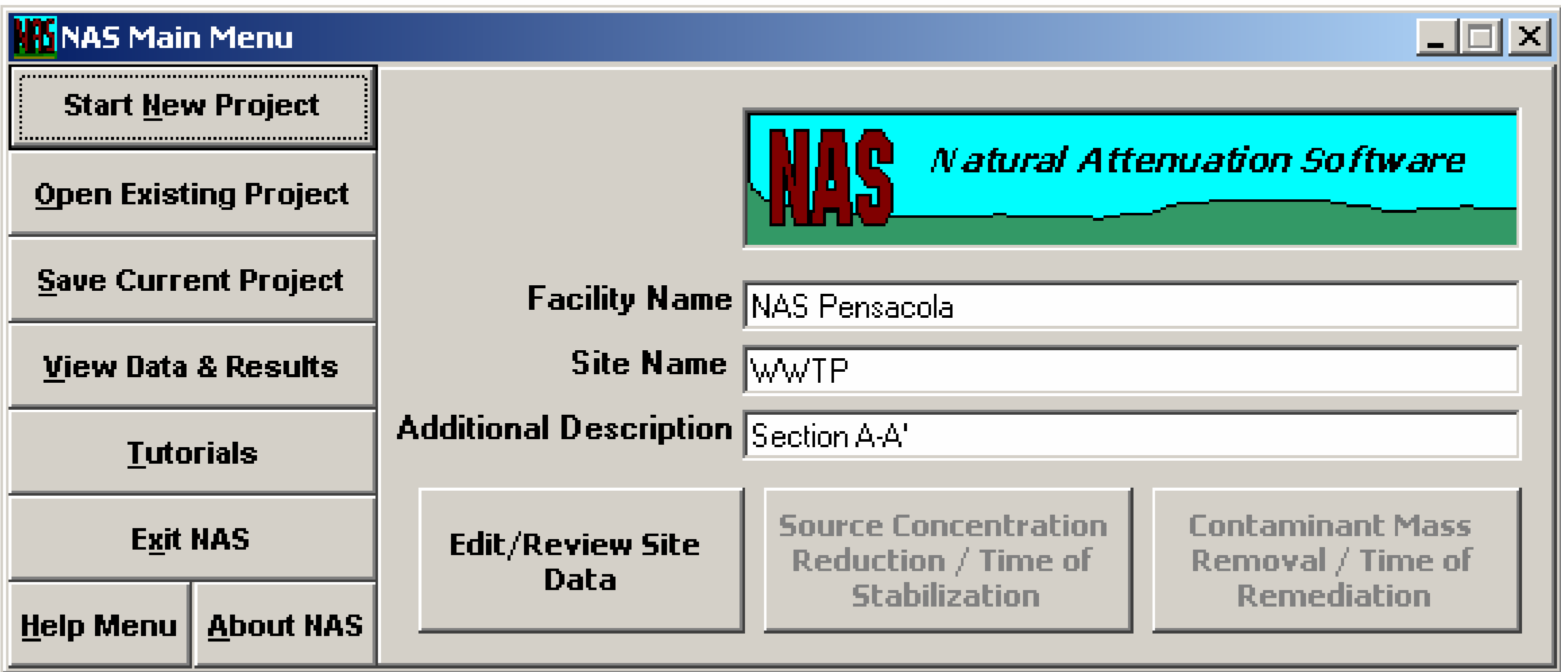
NAS

Solving the Problem

- **Natural Attenuation Software is a computational tool for evaluating the effect of source zone remediation on plume reduction and on *TOR***
  - **Screening tool for rapid and accurate solutions**
  - **Interactive software program that utilizes a Visual Basic platform**
  - **Enables the user to input site-specific data**
  - **Solutions are determined based on a site-specific RAO**
  - **Post-audit feature for evaluating in-progress sites**

NAS – Version 1

- Funded by NAVFAC (Y0817 project) under ARTT
- Developed by Virginia Tech and U.S. Geological Survey



NAS – Version 2

- Funded through NAVFAC
- Technical support from NAVFAC ESC
- Validated under the ESTCP program

NAS – End User Issues

- Who can use NAS?
  - Designed for RPMs, contractors and regulators with knowledge of natural attenuation processes
  - Modeling experience not essential
- Availability
  - Download installation program at no cost from Virginia Tech website: http:\\www.nas.cee.vt.edu
  - NAS1 approved under NMCI; NAS2 will be available via Naval Installation Restoration Information Solution (NIRIS)
- Data Requirements
  - Based on DoD field guidance documents for MNA

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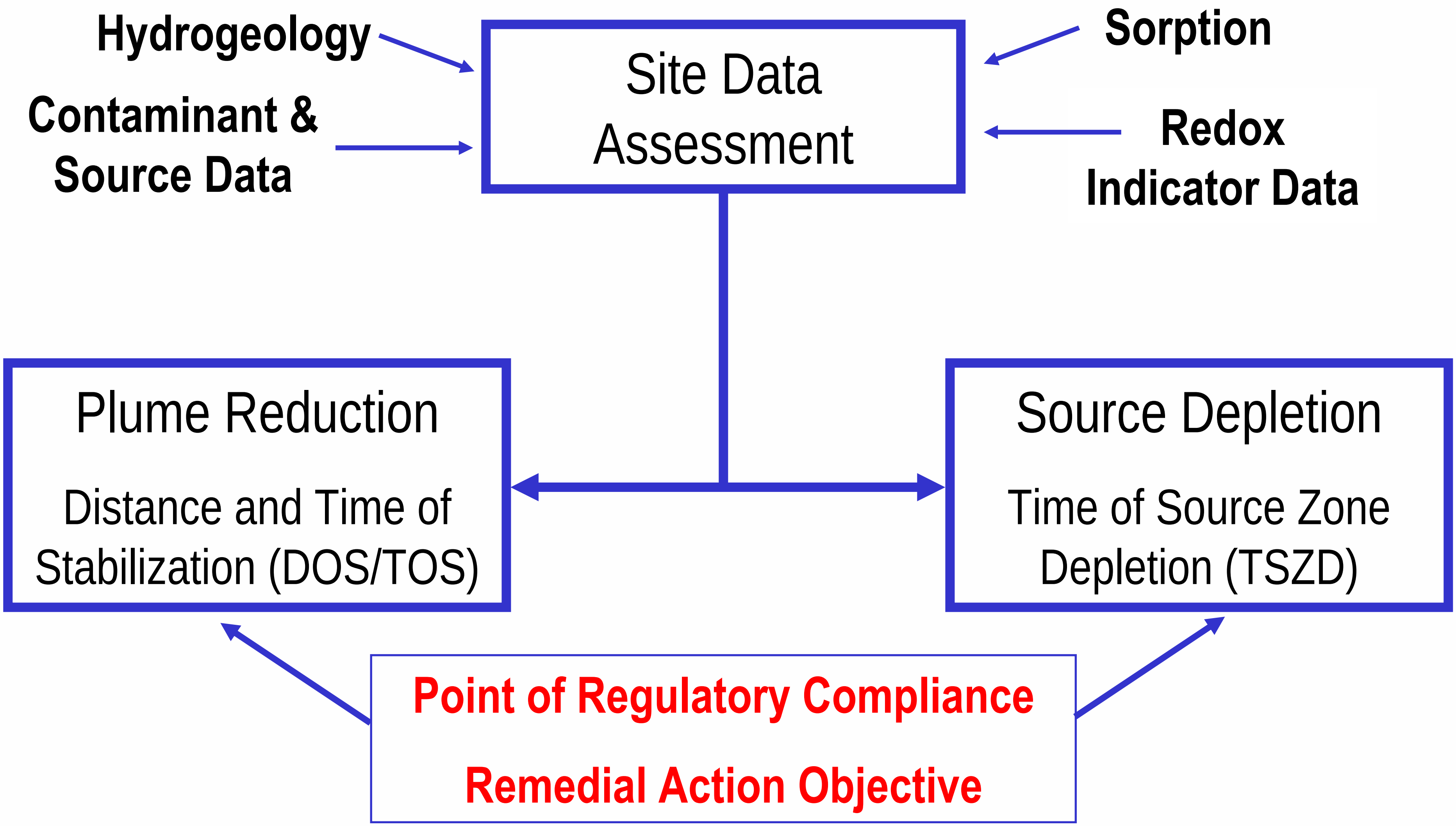
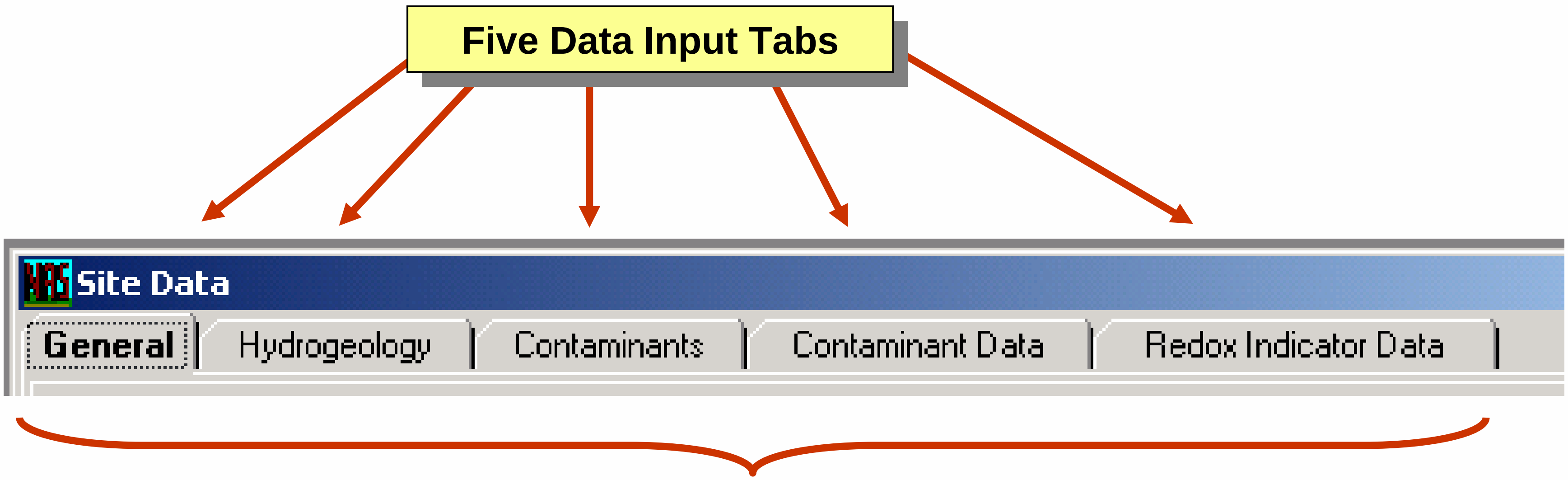
Components of NAS

- Site Data Assessment Module
- DOS/TOS Module
- Source Depletion Module
- Post-Audit Feature

NAS – Structure and Function



Site Data Assessment



- Entered sequentially
- Required before results can be viewed or TOR calculated

Hydrogeology Data Requirements

Required Data

- Hydraulic Conductivity (K)
- Hydraulic Gradient (i)
- Effective Porosity (n_e)
- Percent Organic Carbon
  - f_{oc} (input)
  - K_{oc} (NAS library)
  - R (calculated by NAS)

$$v = \frac{K}{n_e} i$$

groundwater velocity

$$v_c = \frac{v}{R}$$

contaminant velocity

Hydrogeologic Data

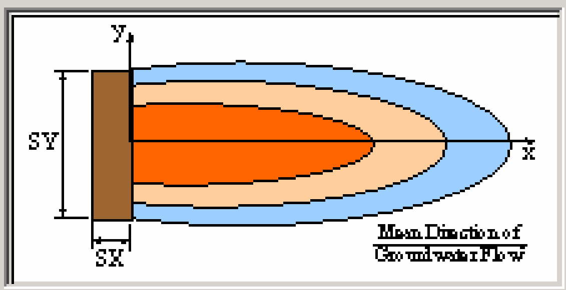
Site Data

General | **Hydrogeology** | Contaminants | Contaminant Data | Redox Indicator Data

1. Enter the following hydrogeologic and aquifer properties.

	Maximum	Average	Minimum
Hydraulic Conductivity [ft/d]	30.0	25.0	20.0
Hydraulic Gradient [ft/ft]	0.005	0.005	0.005
Weight Percent Organic Carbon [%]	0.07	0.06	0.05

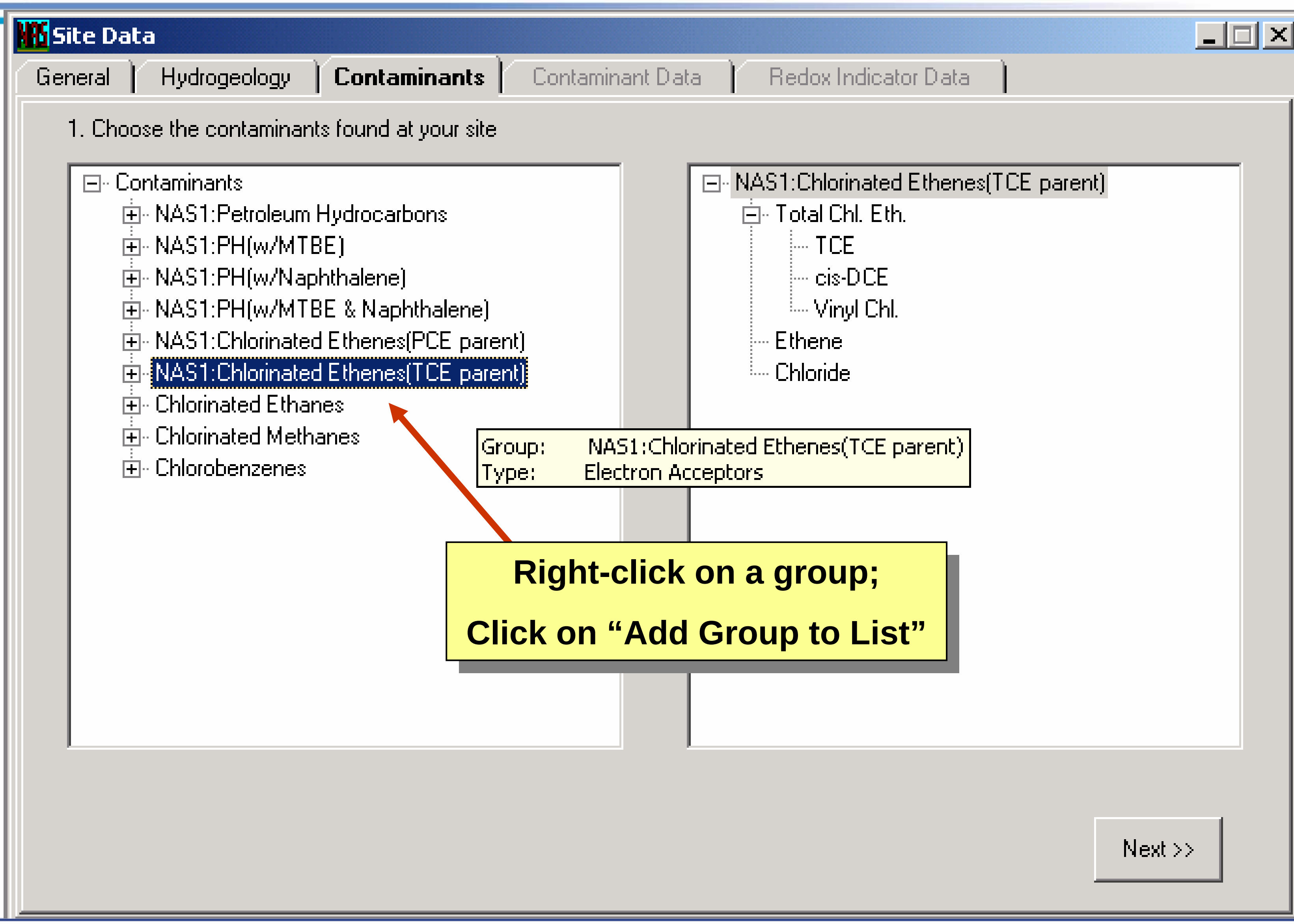
	Average
Total Porosity [ft^3/ft^3]	0.25
Effective Porosity [ft^3/ft^3]	0.25



Range of values are calculated and later used in TOR estimates

Update

Types of Contaminants



Groundwater Concentration Data Requirements

Minimum Required Data

- Data for 3 or more monitoring wells along main axis of plume
- Contaminant Concentration
  - Source compounds and biodegradation daughter products
- Redox Indicator Constituents
  - Dissolved Oxygen
  - Dissolved Iron – Fe(II)
  - Sulfate
  - Other parameters (optional)

Contaminant Data

Site Data

General | Hydrogeology | Contaminants | **Contaminant Data** | Redox Indicator Data

1. Enter the date when field measurements for contaminant concentration were collected: 12/11/1998

2. Enter the number of monitoring wells sampled for contaminant concentration along the centerline of the plume:

Currently, contaminant concentation data is reported for 7 wells.

3. Enter the well name (optional), distance downgradient of the source (required), and contaminant concentrations measured at each monitoring point.

Add DataSet | Add Well
Delete DataSet | Delete Well

Well Name	Distance [ft]	Total Chl. Eth. [µg/L]	TCE [µg/L]	cis-DCE [µg/L]	Vinyl Chl. [µg/L]
USGS5	0.0	2723.	2460.	228.	35.
IMW66	30.0	2668.	2060.	470.	138.
USGS6	73.0	1833.	802.	403.	628.
USGS1	140.0	755.	322.	166.	267.
USGS2	225.0	25.2	NS	6.5	18.7
33G12	330.0	47.9	35.7	12.2	BD
Diff Samplers	400.0	BD	BD	BD	BD

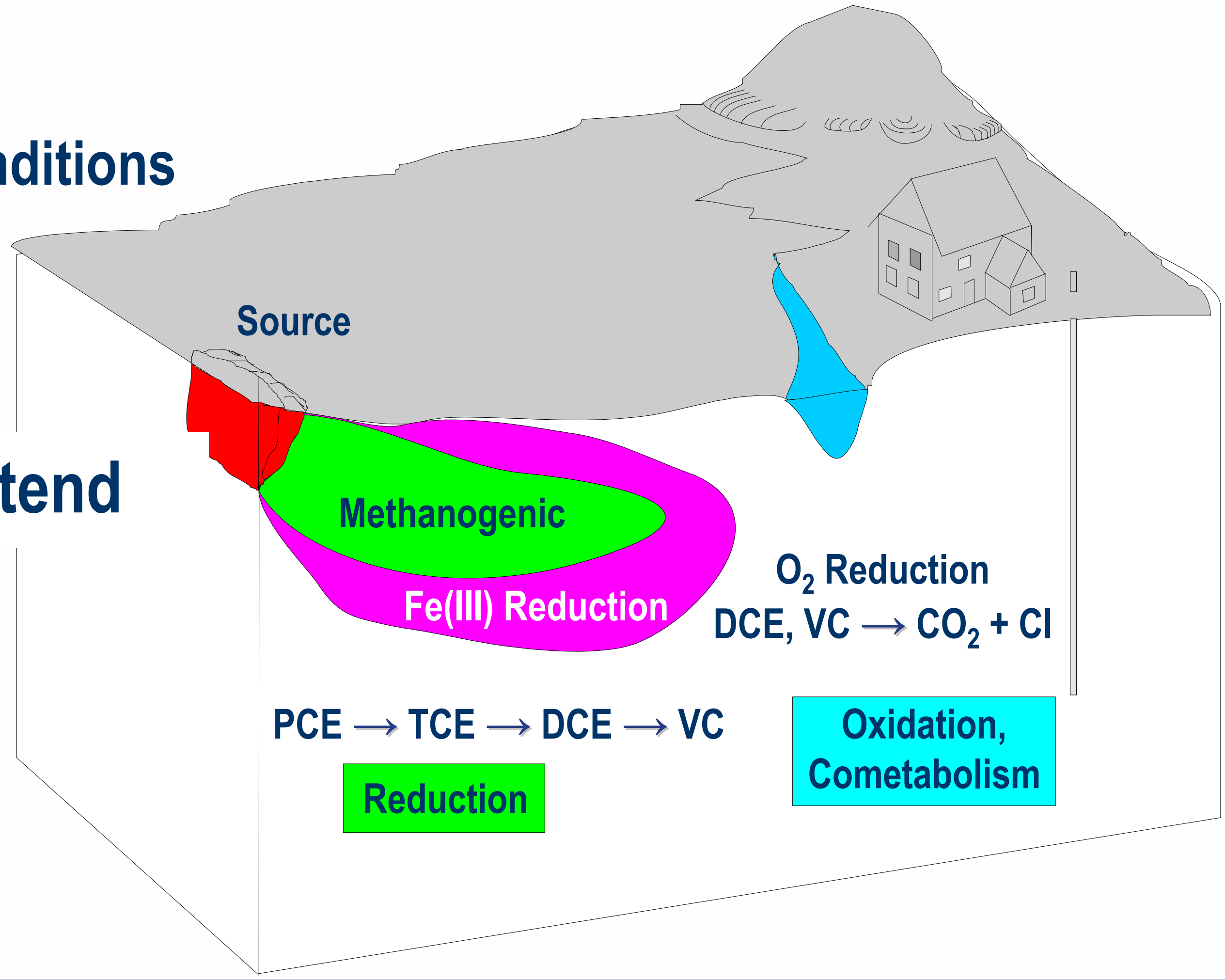
BD = Below Detect

NS = Not Sampled

Update

Why Are Redox Indicator Data Needed?

- Rate and extent of chloroethene biodegradation depends on
  - Ambient redox conditions
  - Succession along flow path
- Redox processes tend to segregate into distinct zones



Redox Indicator Data

Site Data

General | Hydrogeology | Contaminants | Contaminant Data | **Redox Indicator Data**

1. Enter the time when the redox indicator field measurements were collected:

- ○ 12/11/1998 (Collected at the same time as contaminant data.)
- ◉ Collected at a different time than contaminant data 1 /20/1998

2. NAS requires specification of dissolved oxygen (O2), ferrous iron (Fe2) and sulfate (SO4) at all redox well locations. Indicate which additional redox indicators were measured at your site:

- ☐ Nitrate (NO3)
- ☑ Manganese(II) (MN2)
- ☑ Hydrogen Sulfide (H2S)
- ☑ Methane(CH4)
- ☑ Hydrogen (H2)

Currently, redox indicator data is reported for 4 wells.

3. Enter the well name (optional), distance downgradient of the source (required), and concentrations for indicators of redox potential measured at each monitoring point.

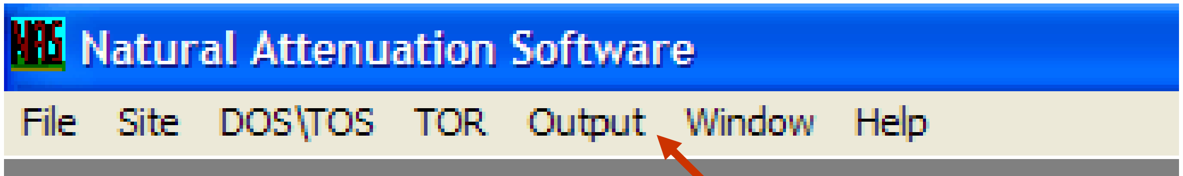
Add DataSet | Add Well | Delete DataSet | Delete Well

Well Name	Distance [ft]	Oxygen [mg/L]	Mn(II) [mg/L]	Iron(II) [mg/L]	Sulfate [mg/L]	Sulfide [mg/L]	Methane [mg/L]	Hydrogen [nM]	Redox Condition
IMW66	30.0	0.2	1.02	447.	NS	0.001	2.7	0.31	Ferrogenic
USGS1	140.0	BD	0.78	295.	NS	0.265	5.4	0.39	Ferrogenic
USGS2	225.0	BD	0.145	10.5	NS	0.053	1.7	0.85	Ferrogenic
33G12	330.0	BD	0.311	8.5	NS	0.003	0.1	0.41	Ferrogenic

Default Redox | Update

NAS assists the user to determine the distribution of redox conditions

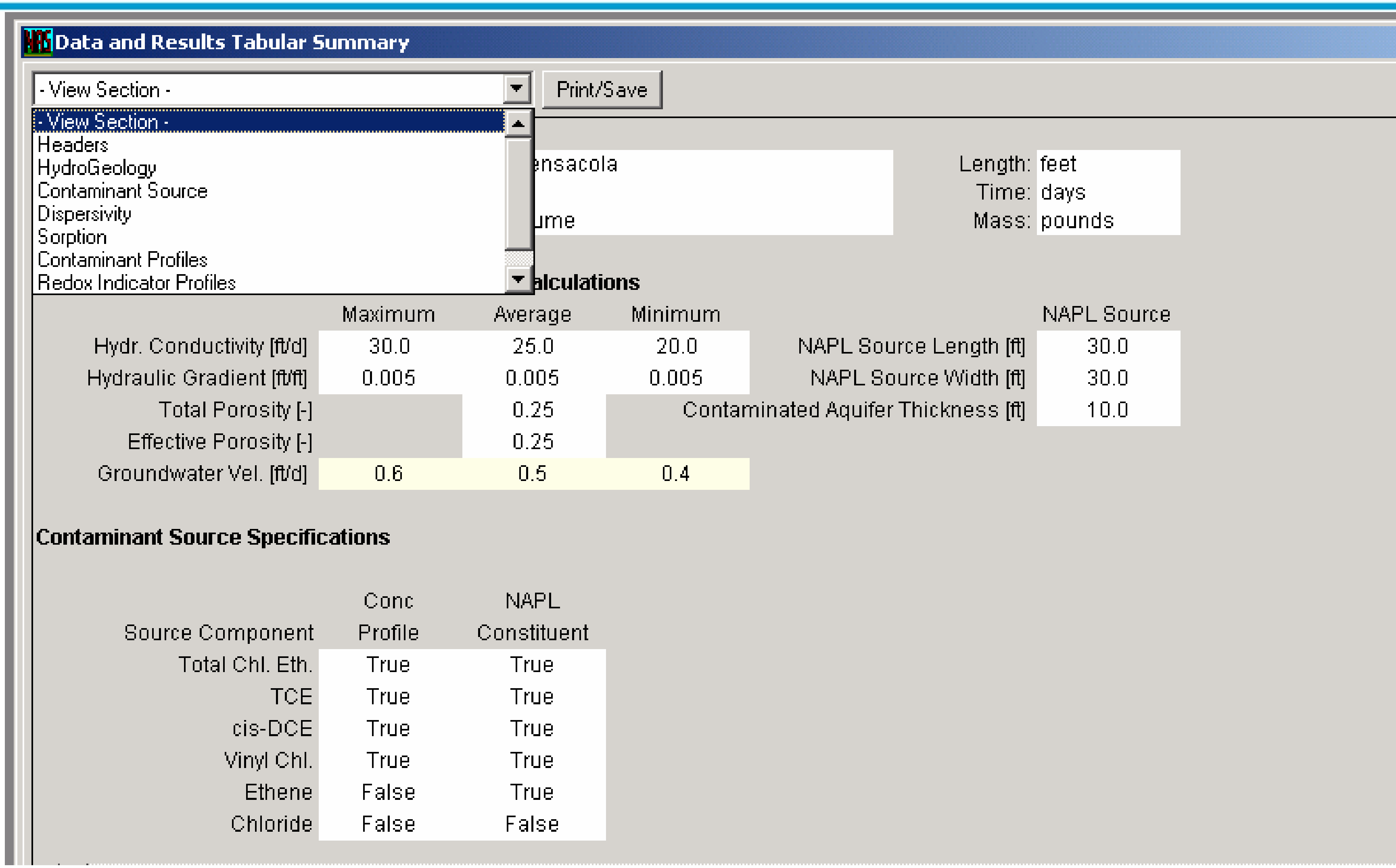
Output – Data and Results



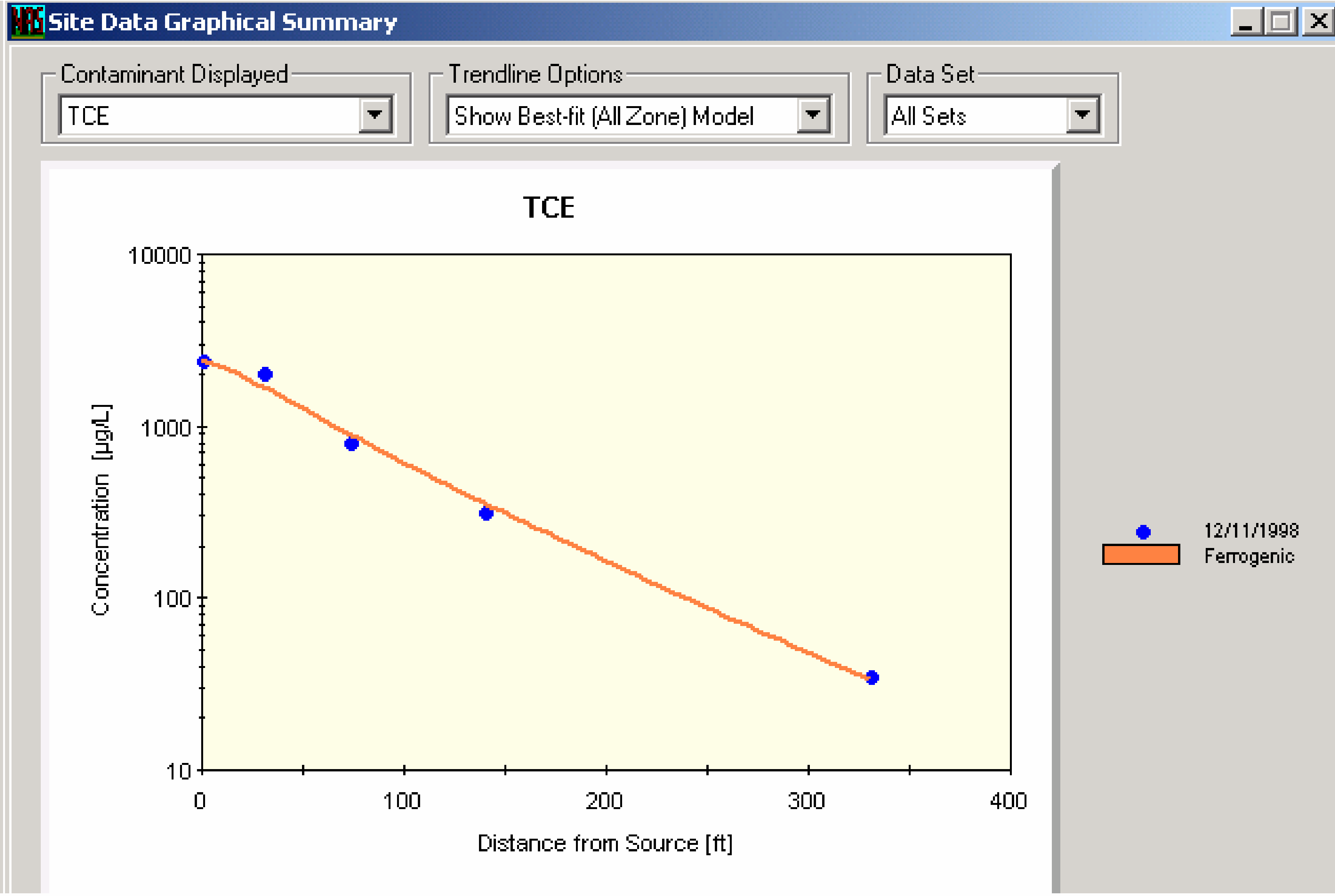
View Output:

Tables and Graphs

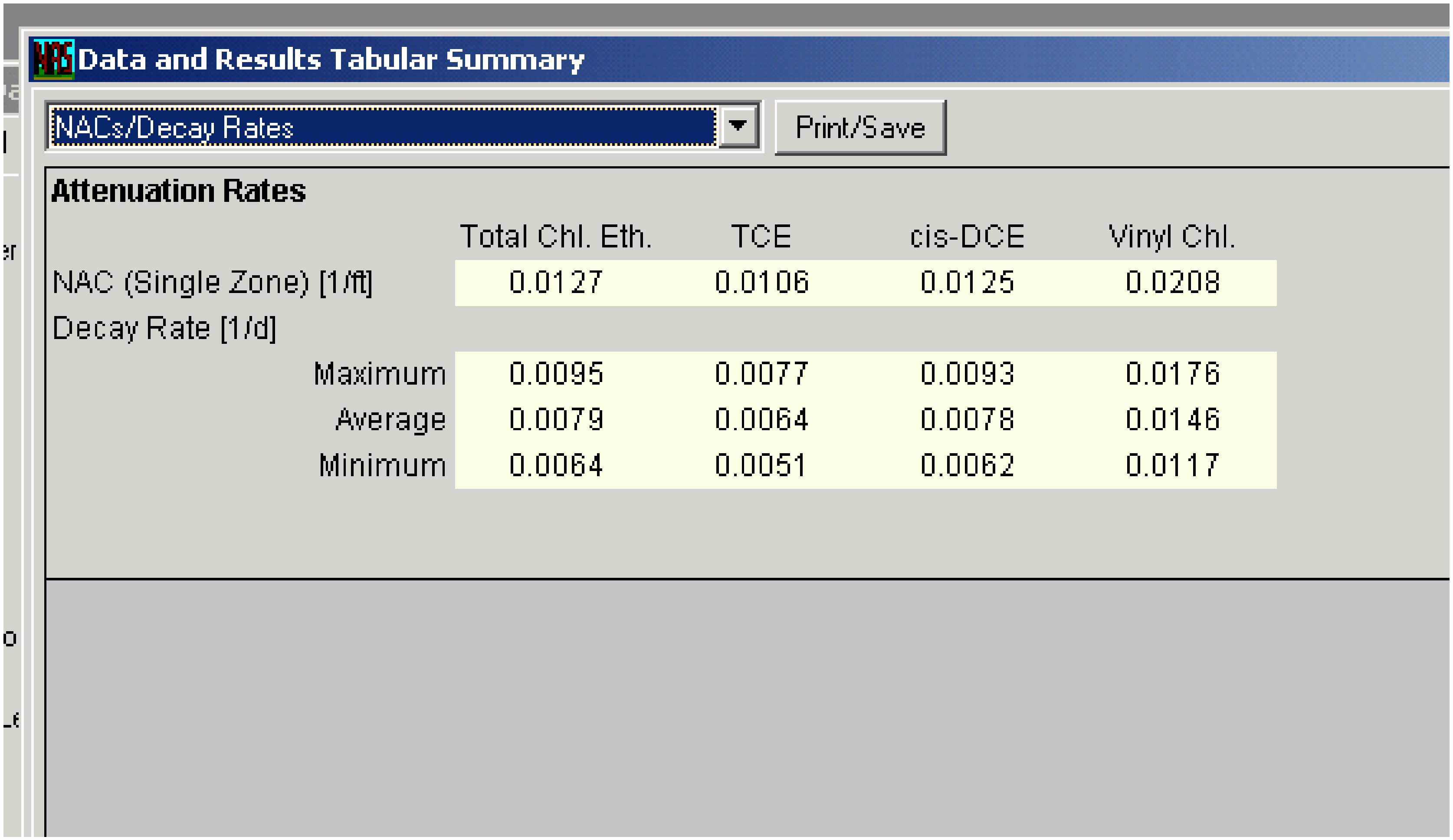
Output – Data and Results (cont.)



Output – Data and Results (cont.)



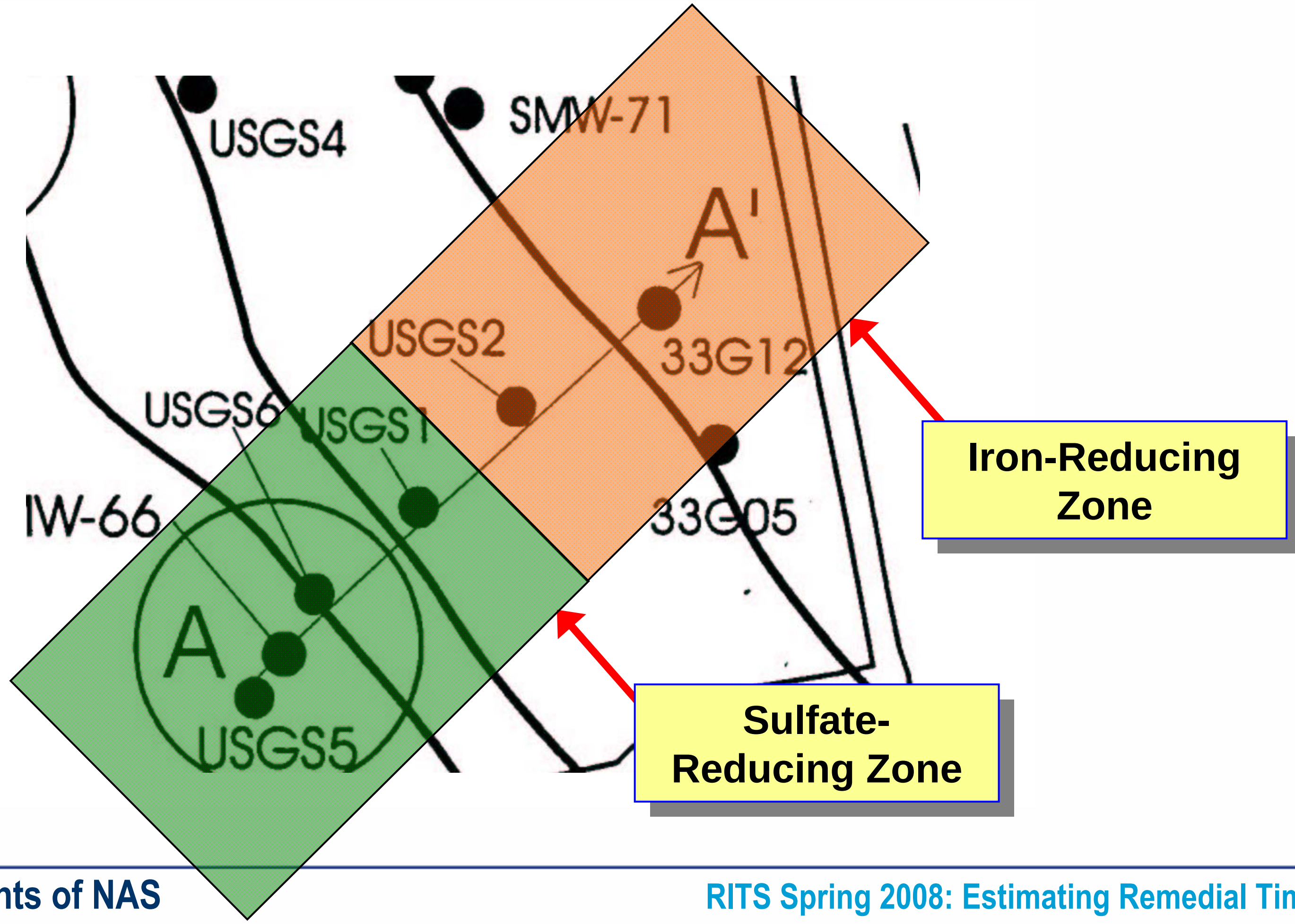
Output: Site-Specific Contaminant Degradation Rates



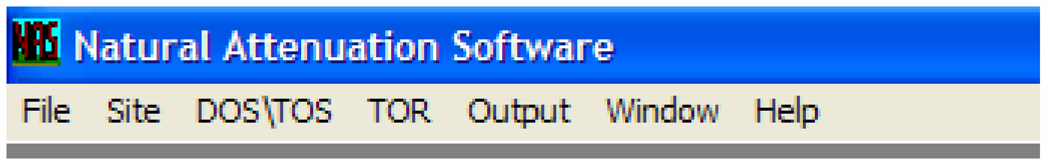
	Total Chl. Eth.	TCE	cis-DCE	Vinyl Chl.
NAC (Single Zone) [1/ft]	0.0127	0.0106	0.0125	0.0208
Decay Rate [1/d]				
Maximum	0.0095	0.0077	0.0093	0.0176
Average	0.0079	0.0064	0.0078	0.0146
Minimum	0.0064	0.0051	0.0062	0.0117

Output – Multiple Redox Zones

- At sites where distinct redox zones are evident from the data, NAS determines redox-specific decay rates



Time of Remediation Calculations



Plume Reduction

- **Distance of Stabilization**
- **Time to Stabilization**

Source Zone Depletion

Distance and Time of Stabilization

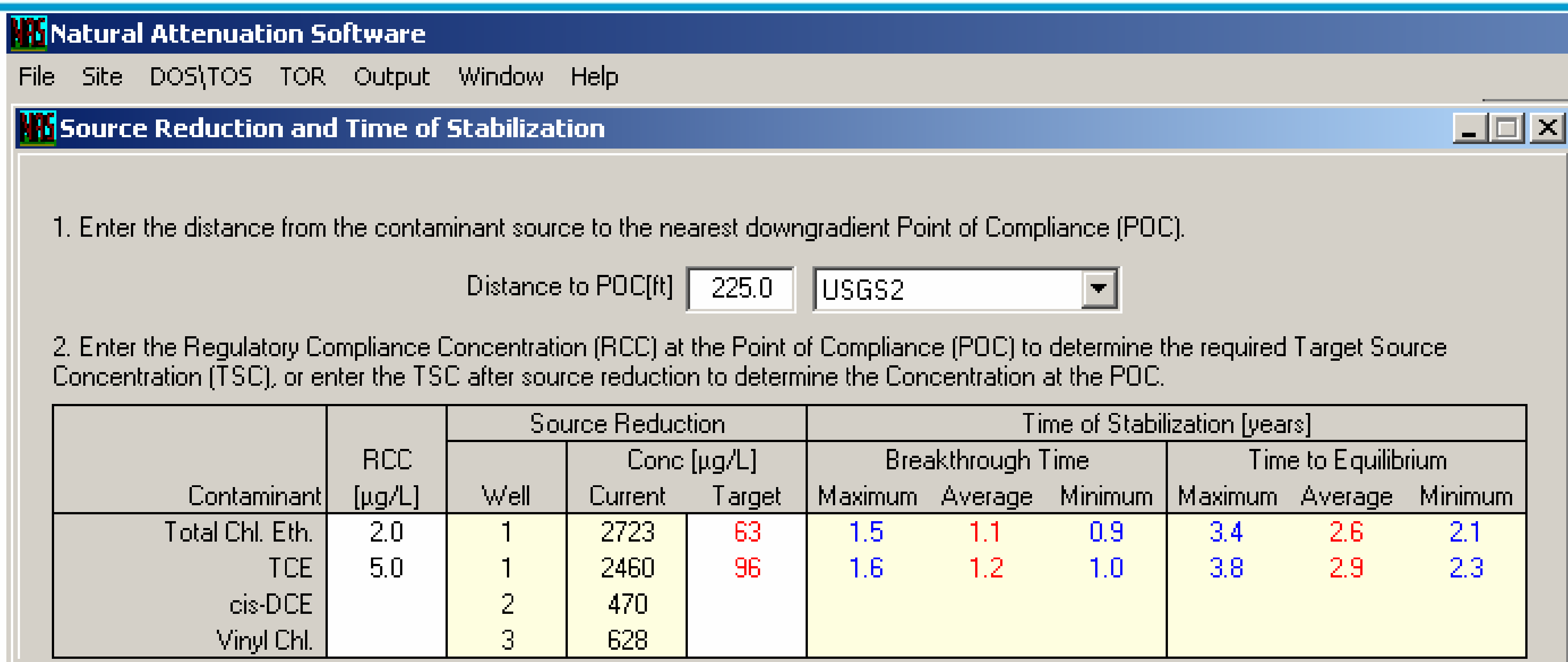
Data Requirements

- Distance to point of compliance (POC)
- Regulatory compliance concentration (RCC)
- Parameters from Site Data Assessment

Approach

- Steady-state, 2D transport (DOS)
- Transient, 2D transport (TOS)

Output – DOS/TOS



Natural Attenuation Software

File Site DOS\TOS TOR Output Window Help

Source Reduction and Time of Stabilization

1. Enter the distance from the contaminant source to the nearest downgradient Point of Compliance (POC).

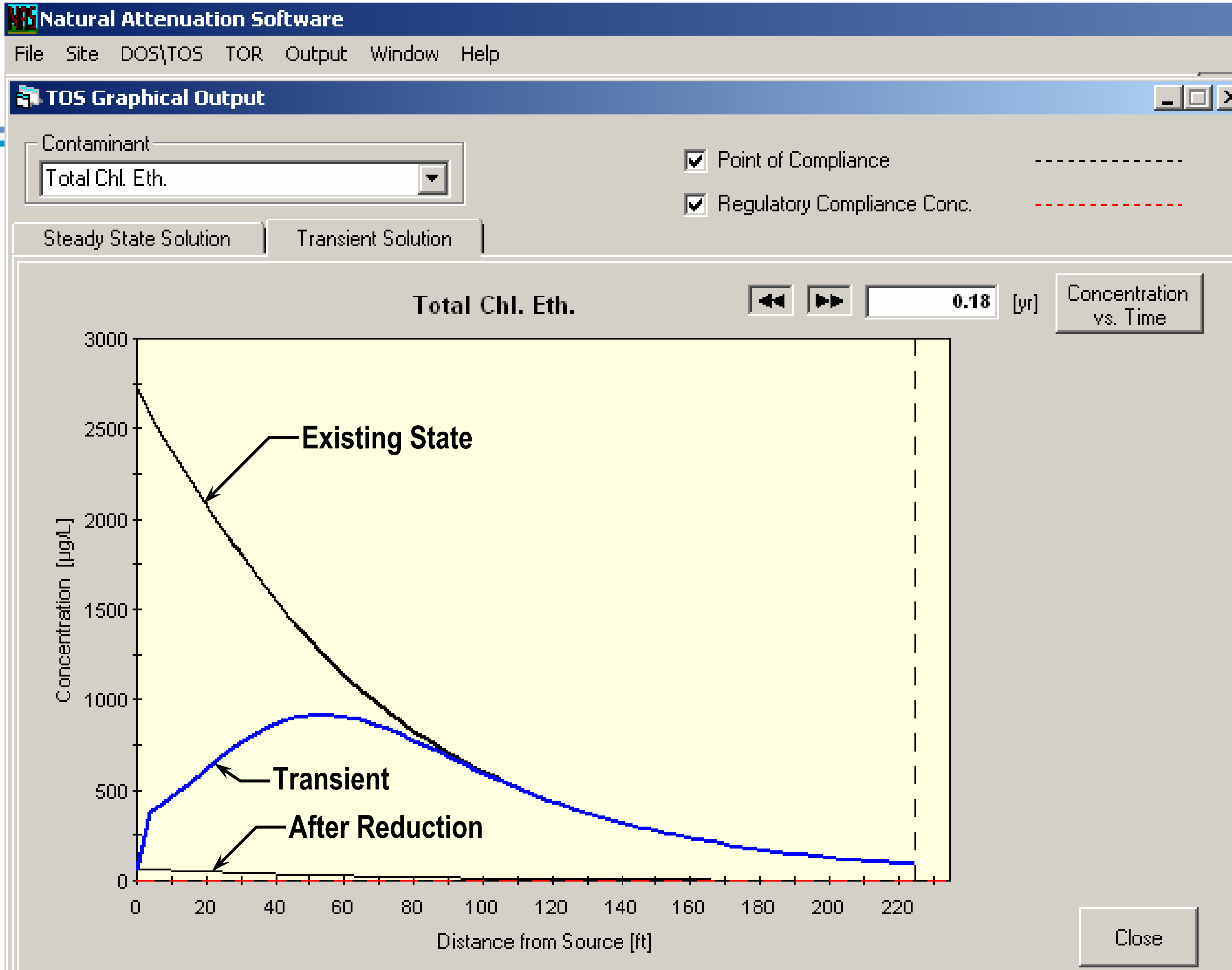
Distance to POC[ft] 225.0 USGS2

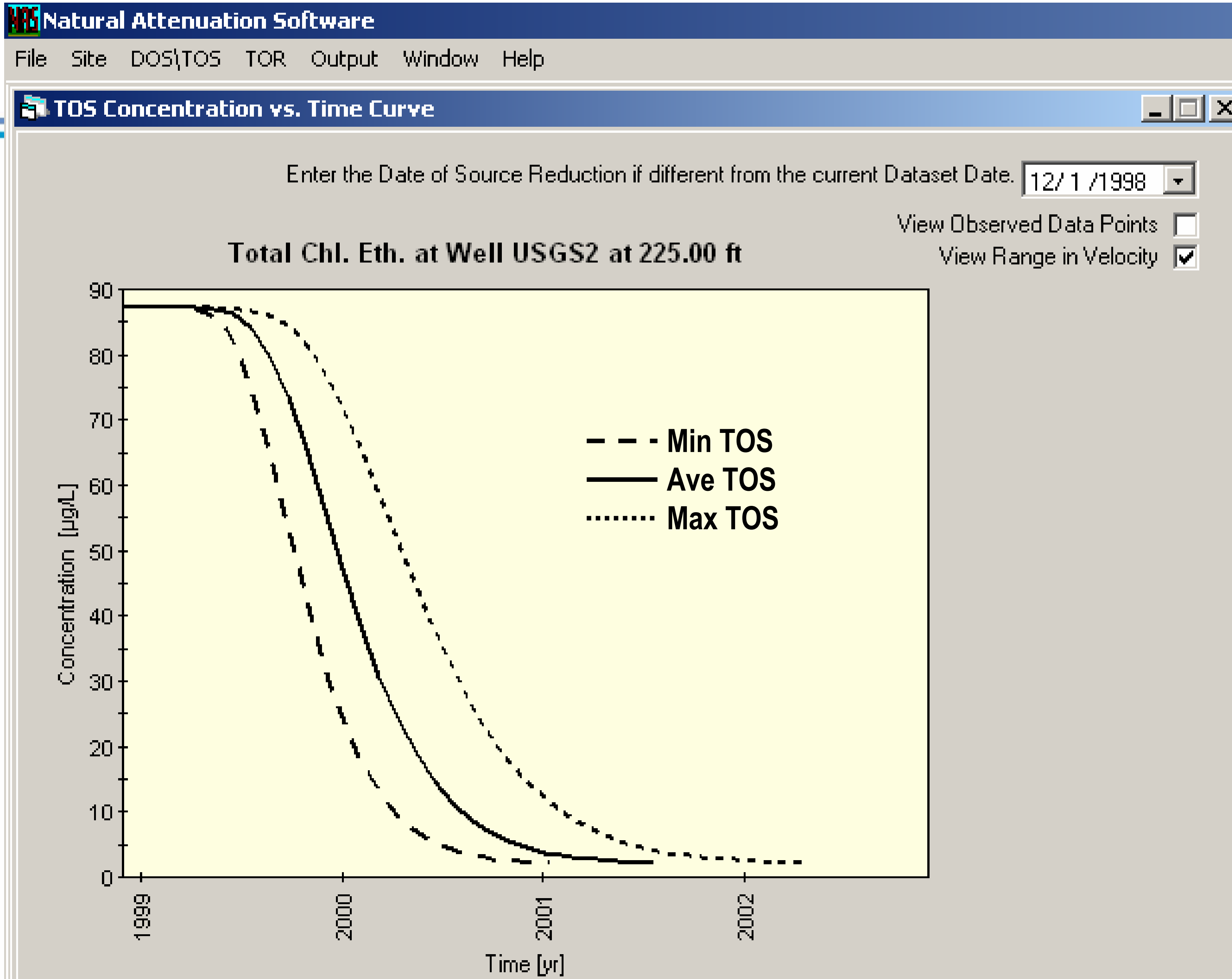
2. Enter the Regulatory Compliance Concentration (RCC) at the Point of Compliance (POC) to determine the required Target Source Concentration (TSC), or enter the TSC after source reduction to determine the Concentration at the POC.

		Source Reduction			Time of Stabilization [years]					
	RCC		Conc [µg/L]		Breakthrough Time			Time to Equilibrium		
Contaminant	[µg/L]	Well	Current	Target	Maximum	Average	Minimum	Maximum	Average	Minimum
Total Chl. Eth.	2.0	1	2723	63	1.5	1.1	0.9	3.4	2.6	2.1
TCE	5.0	1	2460	96	1.6	1.2	1.0	3.8	2.9	2.3
cis-DCE		2	470							
Vinyl Chl.		3	628							

Target C_o = post treatment source concentration

Range in time estimates for effect of source remediation to reach POC

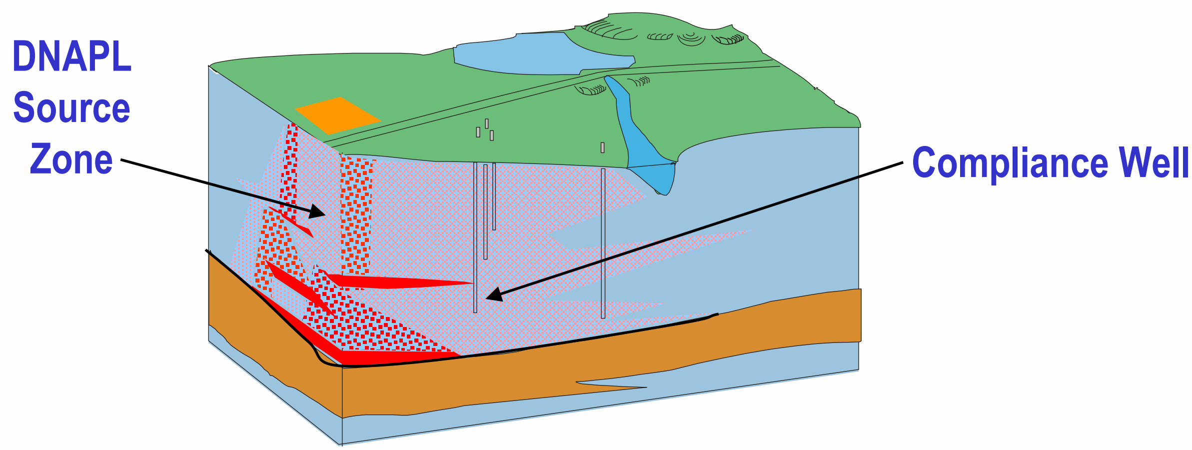

Natural Attenuation Software
File
Site
DOS\TOS
TOR
Output
Window
Help
TOS Graphical Output
Contaminant
Total Chl. Eth.
Point of Compliance
Regulatory Compliance Conc.
Steady State Solution
Transient Solution
Total Chl. Eth.
0.18
[yr]
Concentration vs. Time
Existing State
Transient
After Reduction
Concentration [µg/L]
Distance from Source [ft]
Close



Natural Attenuation Software
File Site DOS\TOS TOR Output Window Help
TOS Concentration vs. Time Curve
Enter the Date of Source Reduction if different from the current Dataset Date.
12/ 1 /1998
View Observed Data Points
View Range in Velocity
Total Chl. Eth. at Well USGS2 at 225.00 ft
Min TOS
Ave TOS
Max TOS
Concentration [µg/L]
Time [yr]
0
10
20
30
40
50
60
70
80
90
1999
2000
2001
2002

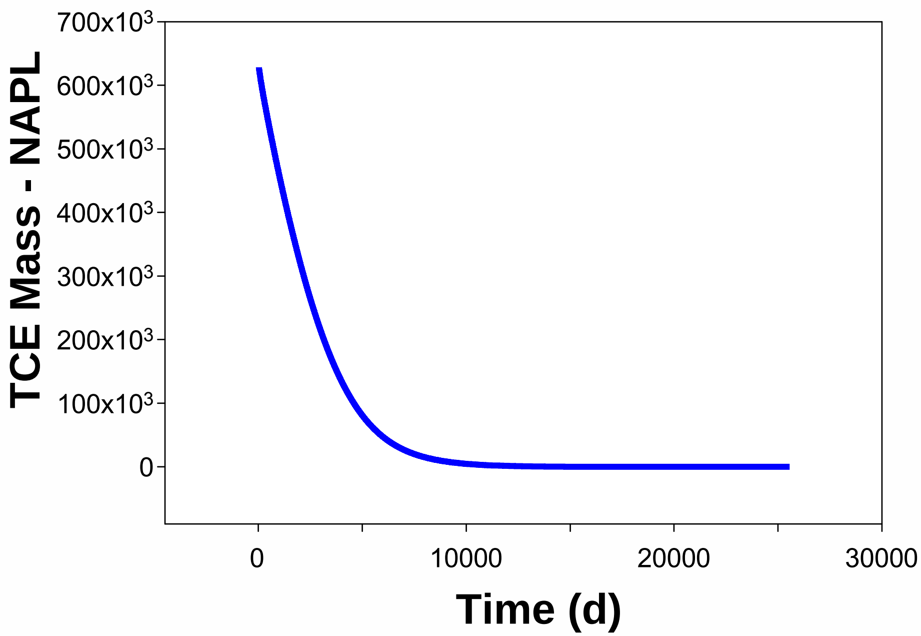
Source Depletion Model

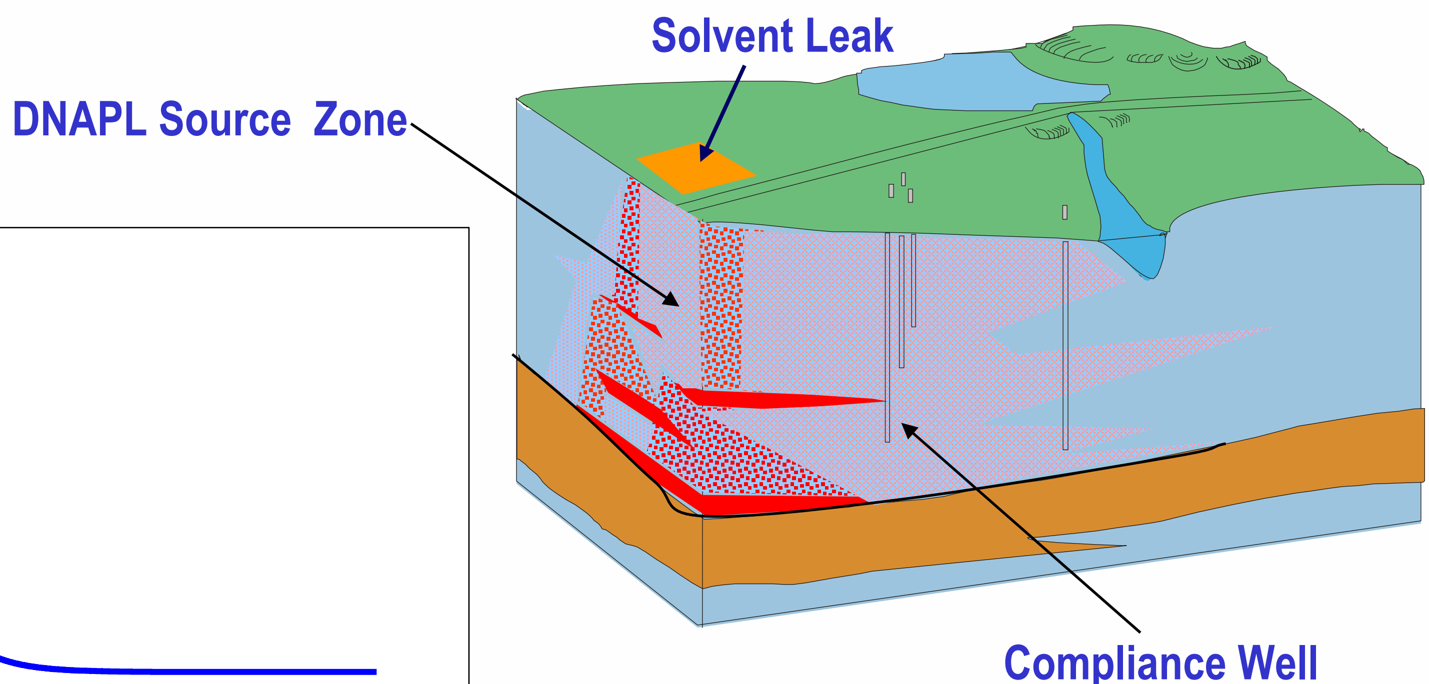
- NAS employs a mass-balance approach to the problem of source zone depletion
  - Numerical source-zone model is implemented using the code SEAM3D
  - Implements NAPL Dissolution Package – mass transfer function for multi-component mixtures



Source Depletion Model (cont.)

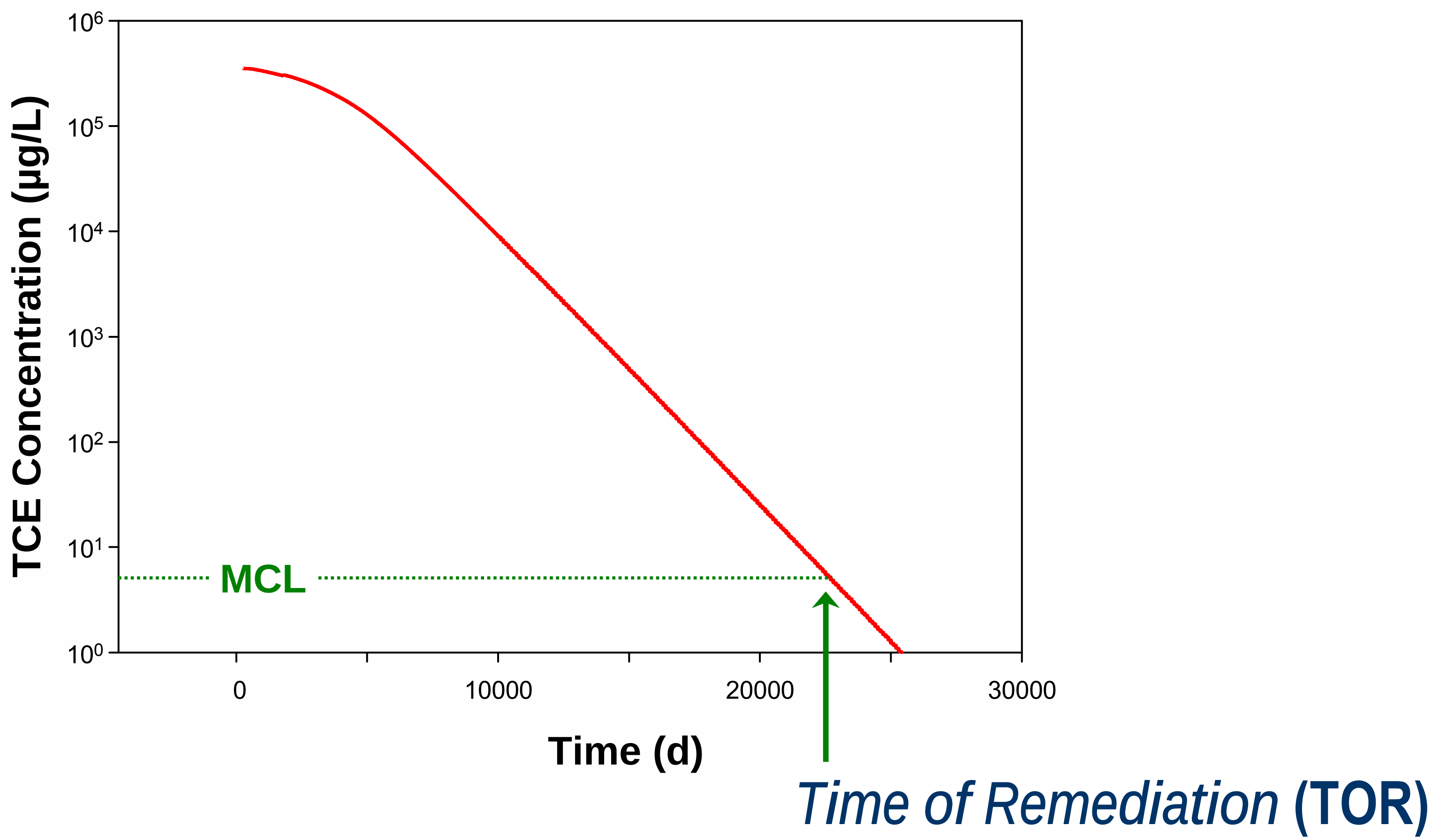
- Based on estimates of source zone mass, composition, geometry, and mass flux, NAS/SEAM3D tracks each constituent over time in both the NAPL and aqueous phases





Time of Remediation (TOR)

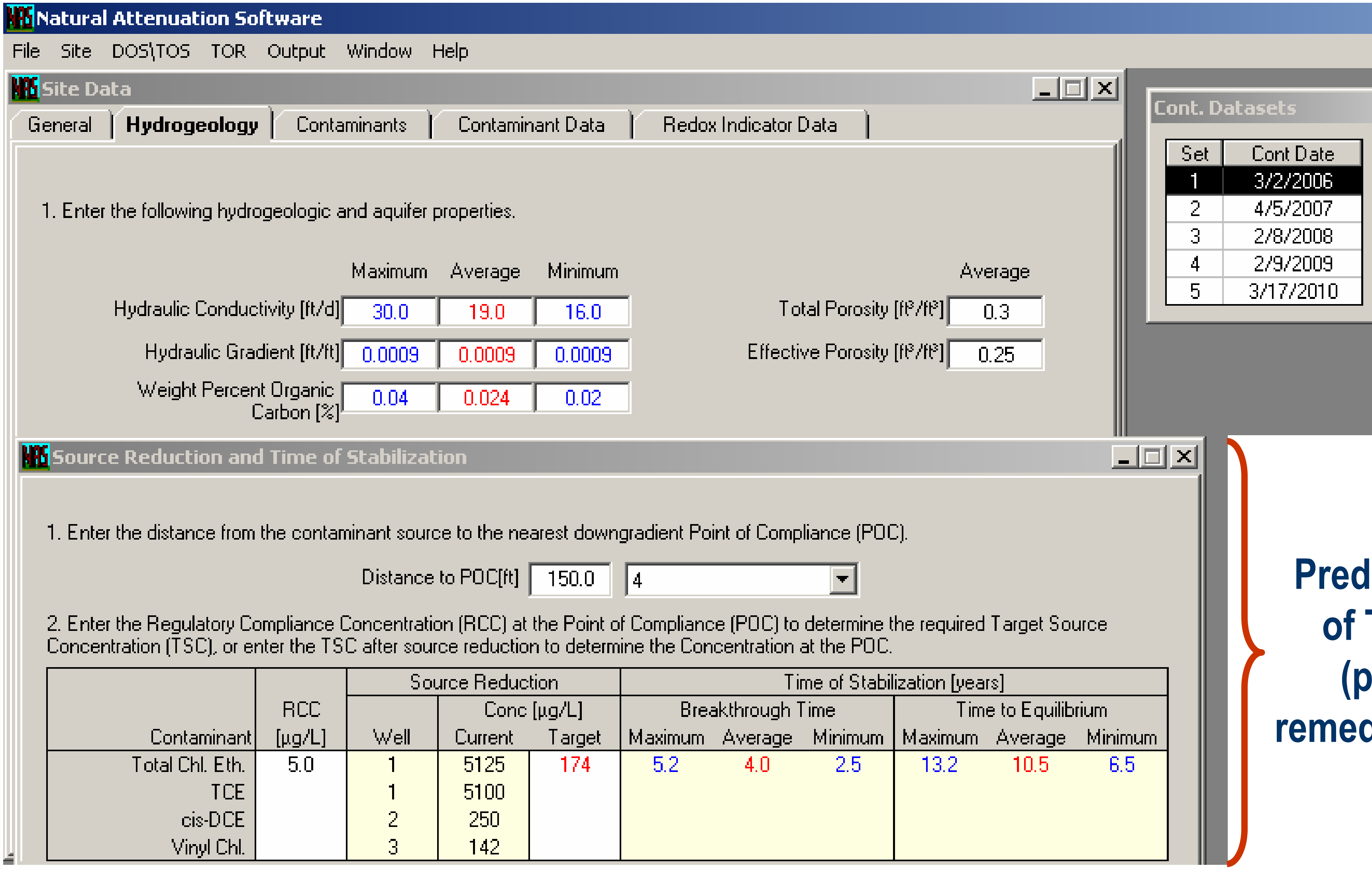
- NAS processes the results to enable the user to query the result for a TOR estimate based on RAO (e.g., MCL)



Post-Audit Data Analysis

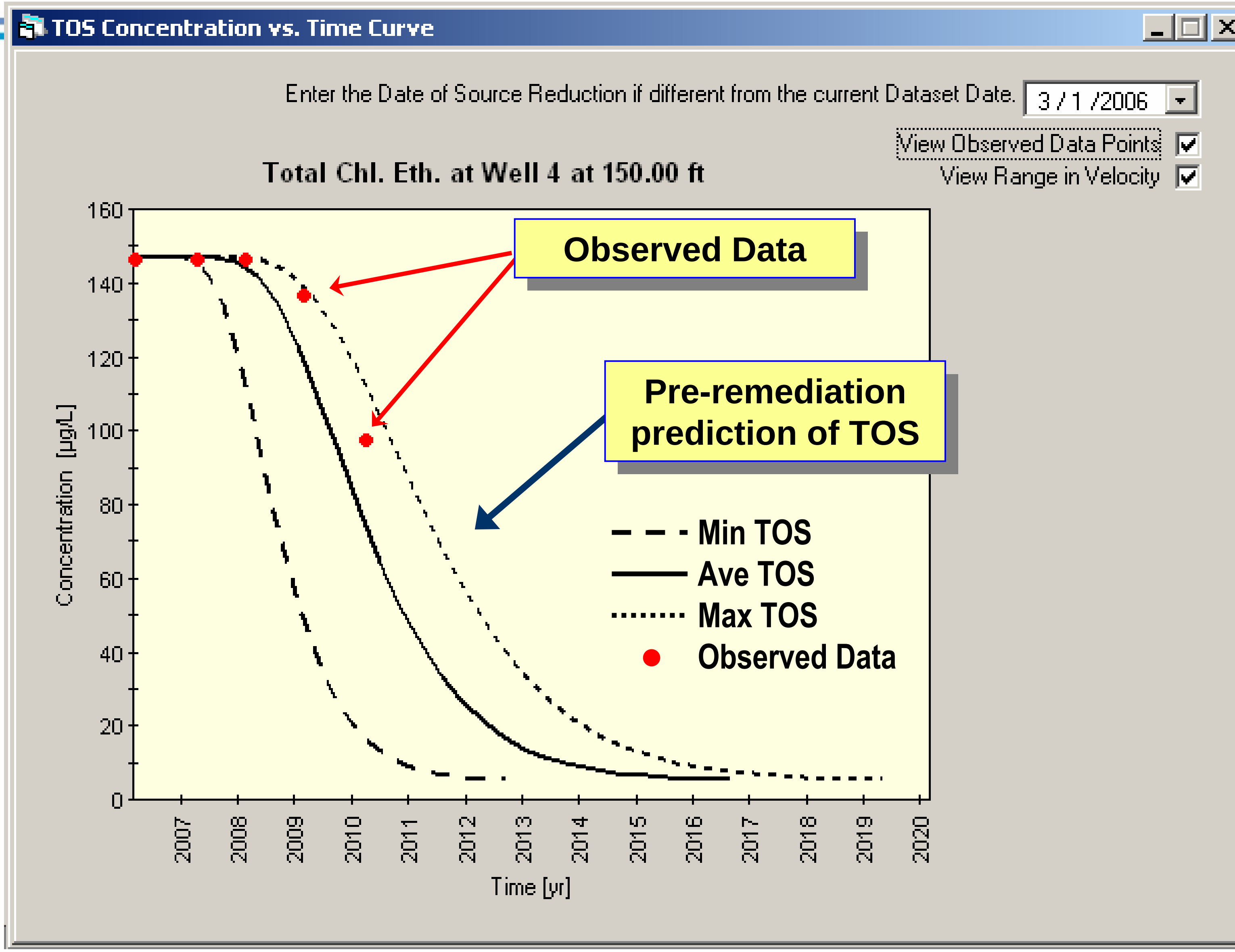
- Goal: Improve TOR estimates through comparison to long-term performance monitoring data
  - Import monitoring data for the comparison of predicted versus observed trends
  - Develop revised concentration vs. time curves

Post-Audit Data Analysis (cont.)

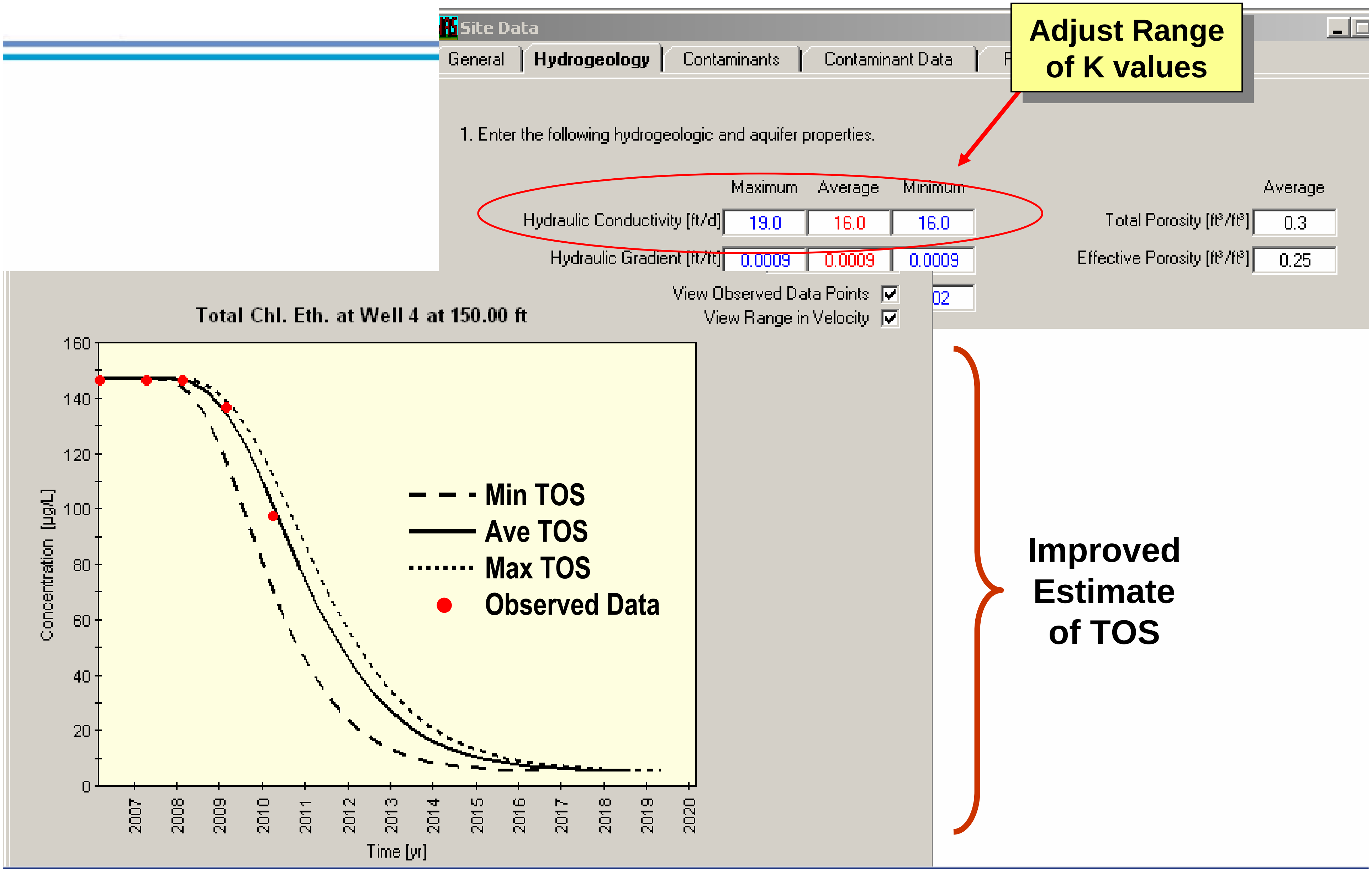


Prediction of TOS (pre-remediation)

Post-Audit Data Analysis (cont.)



Post-Audit Data Analysis (cont.)



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ESTCP Site Demonstrations

- Objective: Evaluate the capability of the NAS software to provide reasonable estimates of MNA cleanup timeframes for a variety of site conditions
- Site Selection Criteria
  - Hydrogeology
  - Geochemistry
  - Contaminant Sources
  - Remediation Technologies

ESTCP Site Demonstrations (cont.)

Facility Name	Agency	Source	Remediation	Hydrogeology
Cecil Field, FL	Navy	TCE, TCA	MNA – Air Sparging	Coastal plain sediments
NAES Lakehurst, NJ	Navy	PCE, TCE	MNA	Coastal plain sediments
NAS Pensacola, FL	Navy	DCB	Pump-Treat, MNA	Coastal plain sediments
Seneca Depot, NY	Army	TCE	MNA – Source Removal	Glaciated till and shale
Niagara Falls, NY	USGS	TCE	Pump-Treat, MNA	Fractured Dolomite
Hill AFB, UT	Air Force	TCE	MNA – Source Containment	Fluvial deposits
Fairbanks, AK	USGS	TCE	MNA – Source Removal	Alluvial sediments
NSB Kings Bay, GA	Navy	PCE	MNA – Chemical Oxidation, Vegetable Oil	Coastal plain sediments

Performance Metrics

- Accuracy – Compare NAS simulations to site data
  - Breakthrough times
  - Inflection points
- Versatility – Role of site conditions
  - Hydrogeology/Geochemistry
  - Contaminant sources
  - Remediation technologies
- Secondary Metrics
  - Reliability
  - Applicability

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- Background
- Components of Natural Attenuation Software
- Validation of Natural Attenuation Software
- Site Demonstrations
  - Site History
  - Hydrogeology
  - Plume Geochemistry
  - Remediation Approach
  - Results of NAS Application
  - Lessons Learned
- Summary

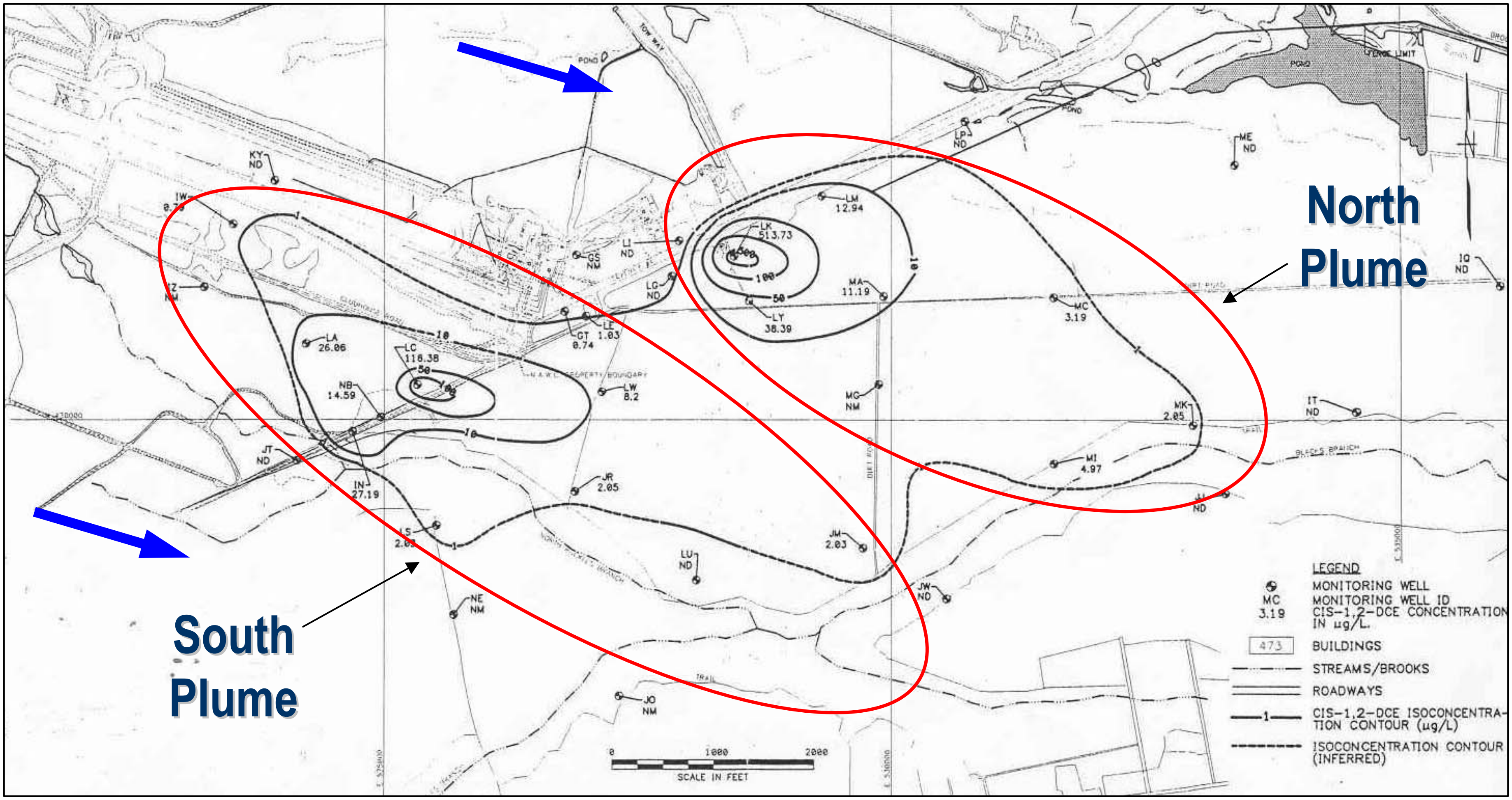
- **Natural Contaminant Source Depletion –** NAES Lakehurst, NJ
- **Source Excavation –** Seneca Army Depot, NY
- **Source Zone Chemical Oxidation –** NSB Kings Bay, GA

Site History – Areas I and J
Natural Contaminant Source Depletion – NAES Lakehurst, NJ

- Naval Air Engineering Station (NAES) Lakehurst – military operations dating back to 1915
- Primary mission – aircraft support
- In 1960s and subsequent years, typical disposal of industrial waste water into holding ponds and swales
- Contamination primarily due to the discharge of water containing TCE, hydraulic fluid, and ethylene glycol

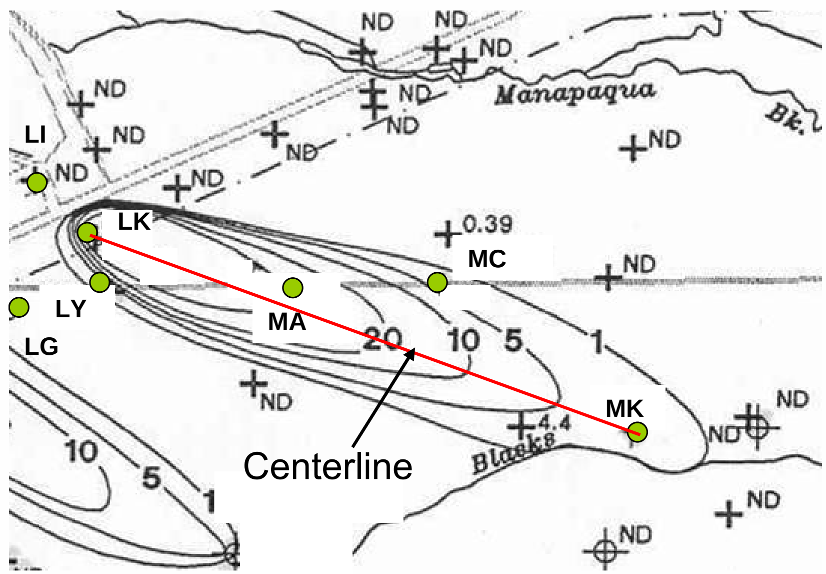
Site Map and Contaminant Plumes

- Aqueous-phase plumes are characterized as widely dispersed, varying in length from 4,000 to 5,000 ft



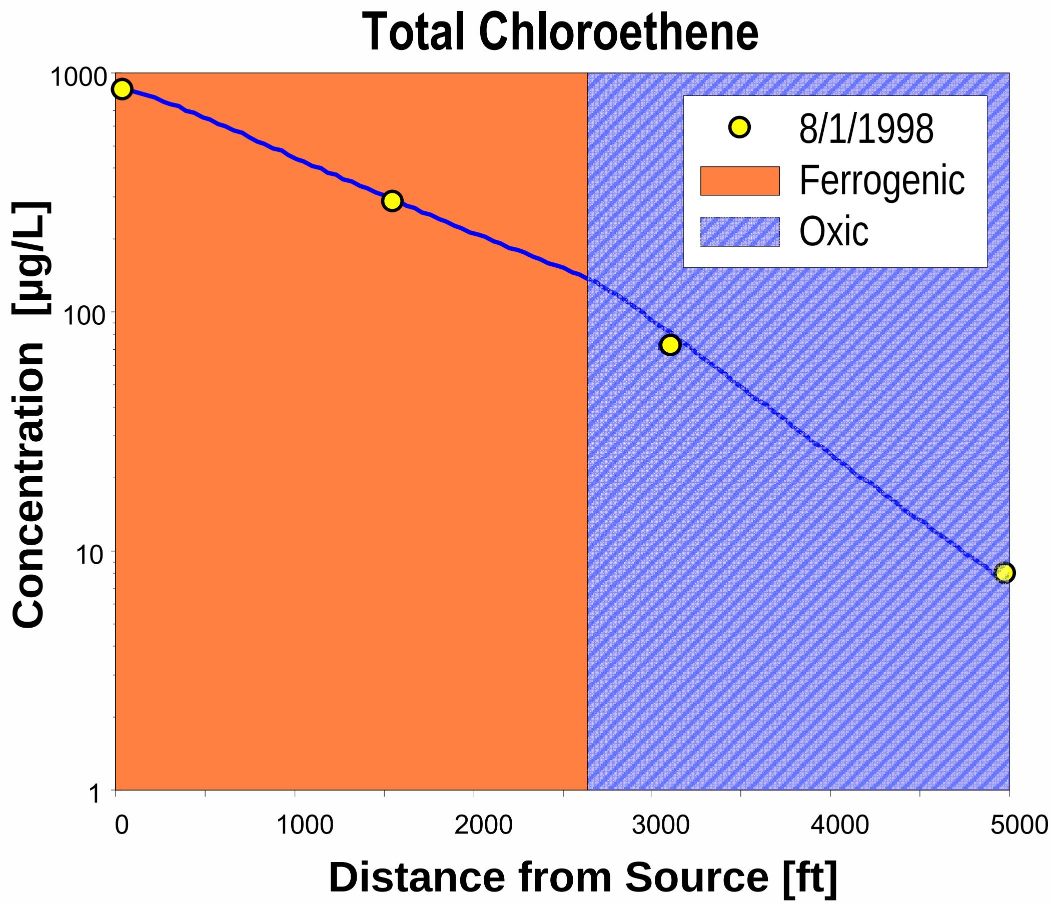
Hydrogeology

- Atlantic Coastal Plain Aquifer System
- Upper 20 to 100 ft of strata – fine to coarse grained sand
- Water table fluctuates between 7 and 11 ft bgs
- Hydraulic conductivity (K)
  - 63-99 ft/day
- Groundwater velocity
  - 0.4-0.9 ft/day



Plume Geochemistry

- Redox indicator data indicates anaerobic (iron-reducing) and aerobic zones within the north plume
- 1,2-cis-DCE: primary plume contaminant
- Source concentration (total chloroethenes) < 1,000 µg/L



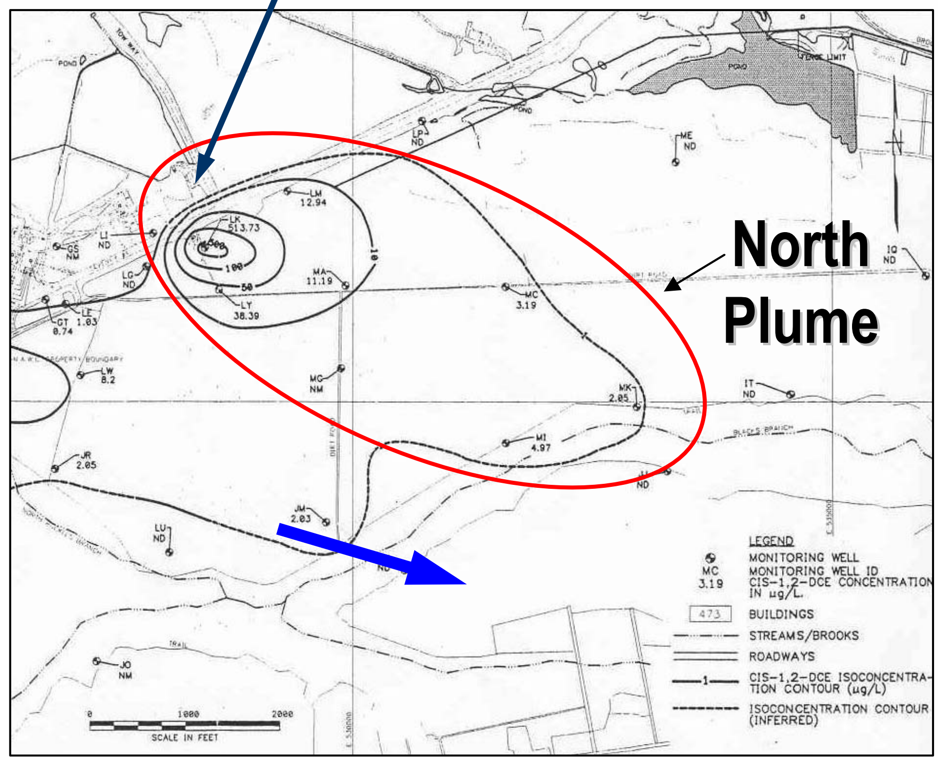
Remediation Approach

- Pump-and-treat initially proposed as the primary remedial strategy but not adopted
  - Considered ineffective
  - Concern over loss of groundwater discharge to wetlands
- The MNA remedial alternative started in 1996 following an evaluation of site data (i.e., CVOC plume, geochemistry)
- A site groundwater flow and solute transport model developed using a comprehensive numerical model to evaluate TOR
  - MODFLOW/MT3DMS

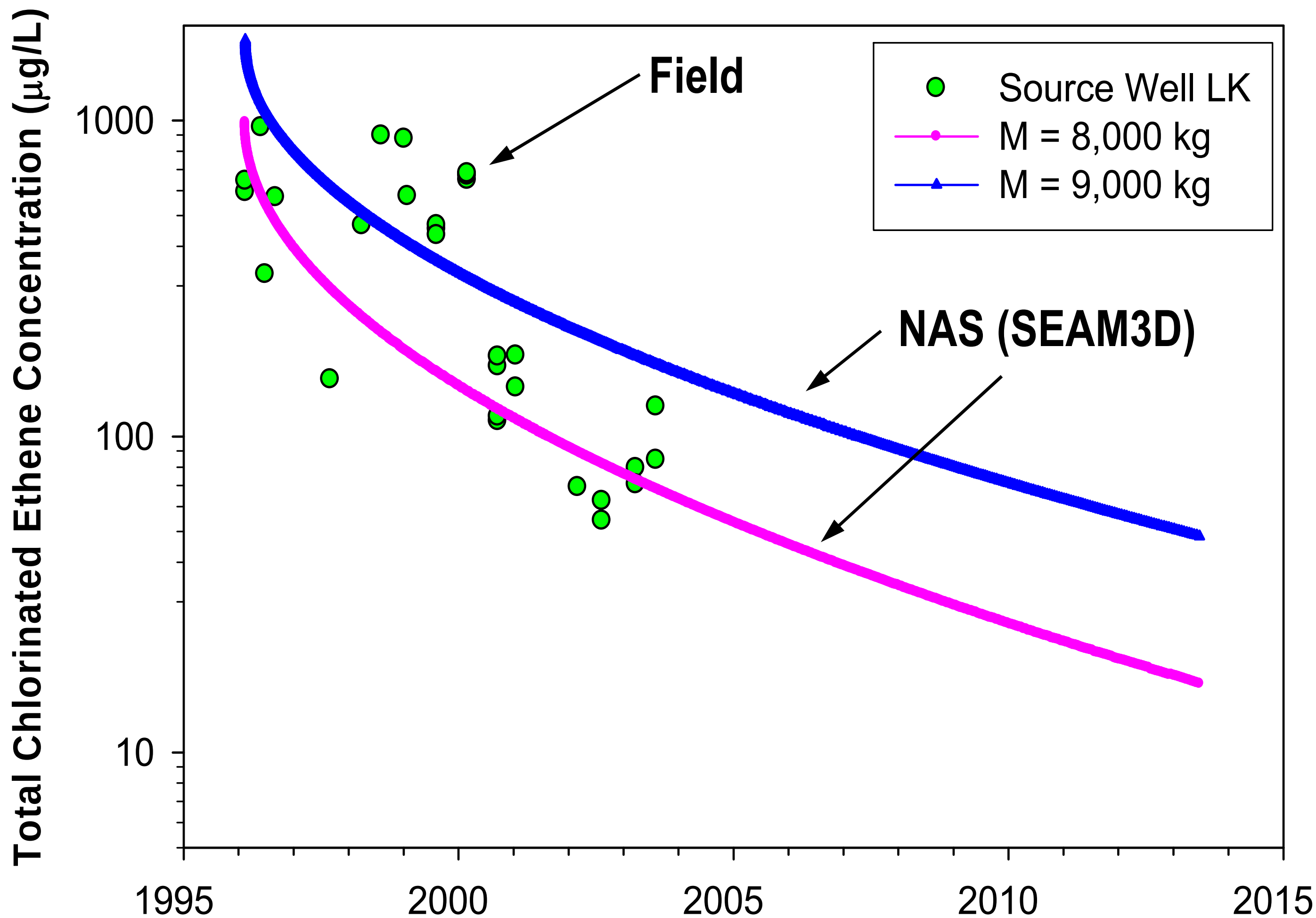
NAS Application – Source Zone Depletion

- TOR evaluated using NAS v2
- Depleting concentration at source well
- “Standard” source characterization
- NAS-based TOR estimates compared with other methods

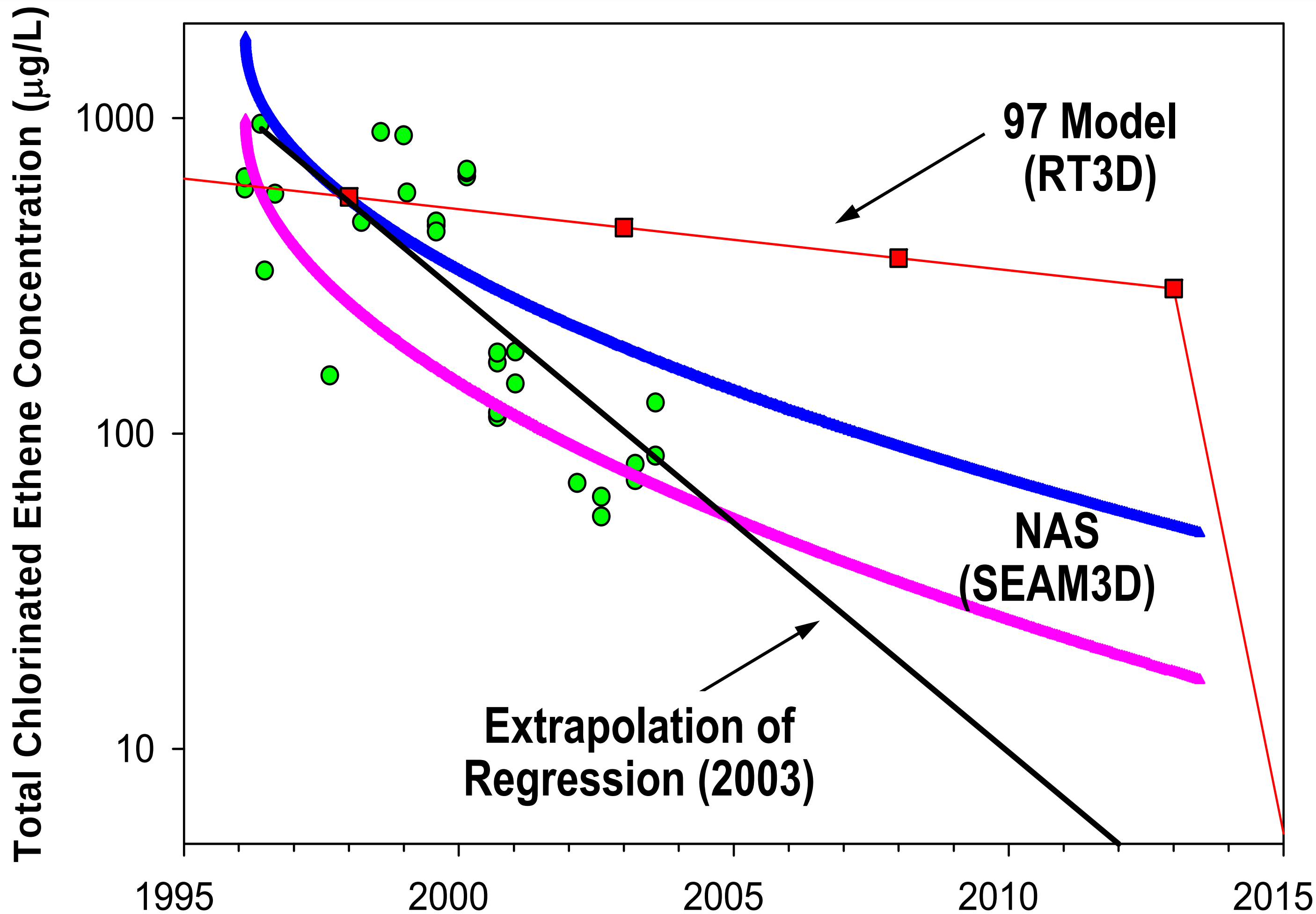
<u>NAPL source</u> simulated for north plume



Mass Estimates Constrained Using NAS



Comparison of Predictive Tools for TOR



Lessons Learned

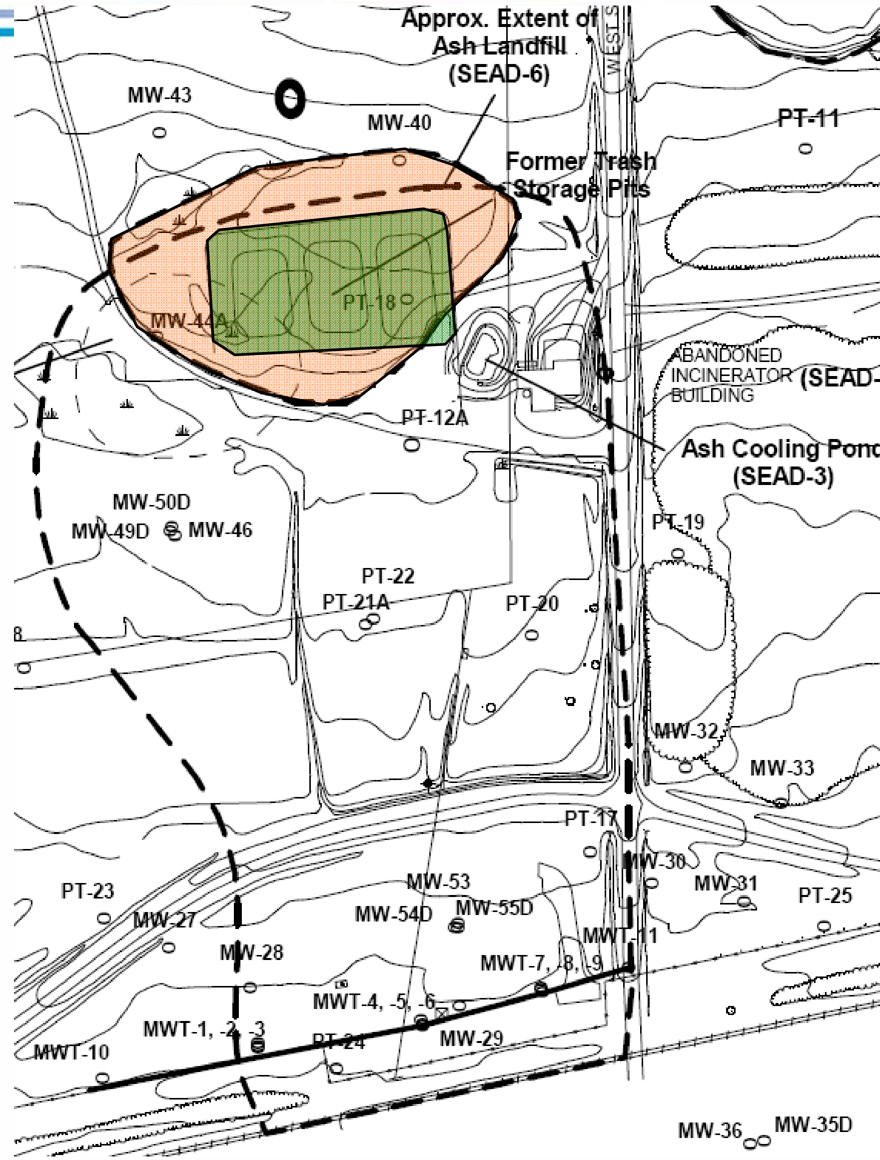
- Relative to other approaches, a mass-balance source zone model calibrated to site data (NAS) is superior to other models for calculating TOR
- This finding suggests that at some sites, knowledge of NAPL source complexities (e.g., interfacial area) is not required for a reasonably accurate estimate of TOR
- However, source characterization is key to reducing the uncertainty inherent to estimating TOR

Site History
Source Excavation – Seneca Army Depot, NY

- Seneca Army Depot Activity (SEDA) is located in the Finger Lakes region of upstate New York
- SEDA served as a disposal site for military explosives dating back to 1941
- Landfill received ash from the incineration of solid waste (1941-79)
- In the early 1980s, a chlorinated ethene plume was discovered emanating from the Ash Landfill

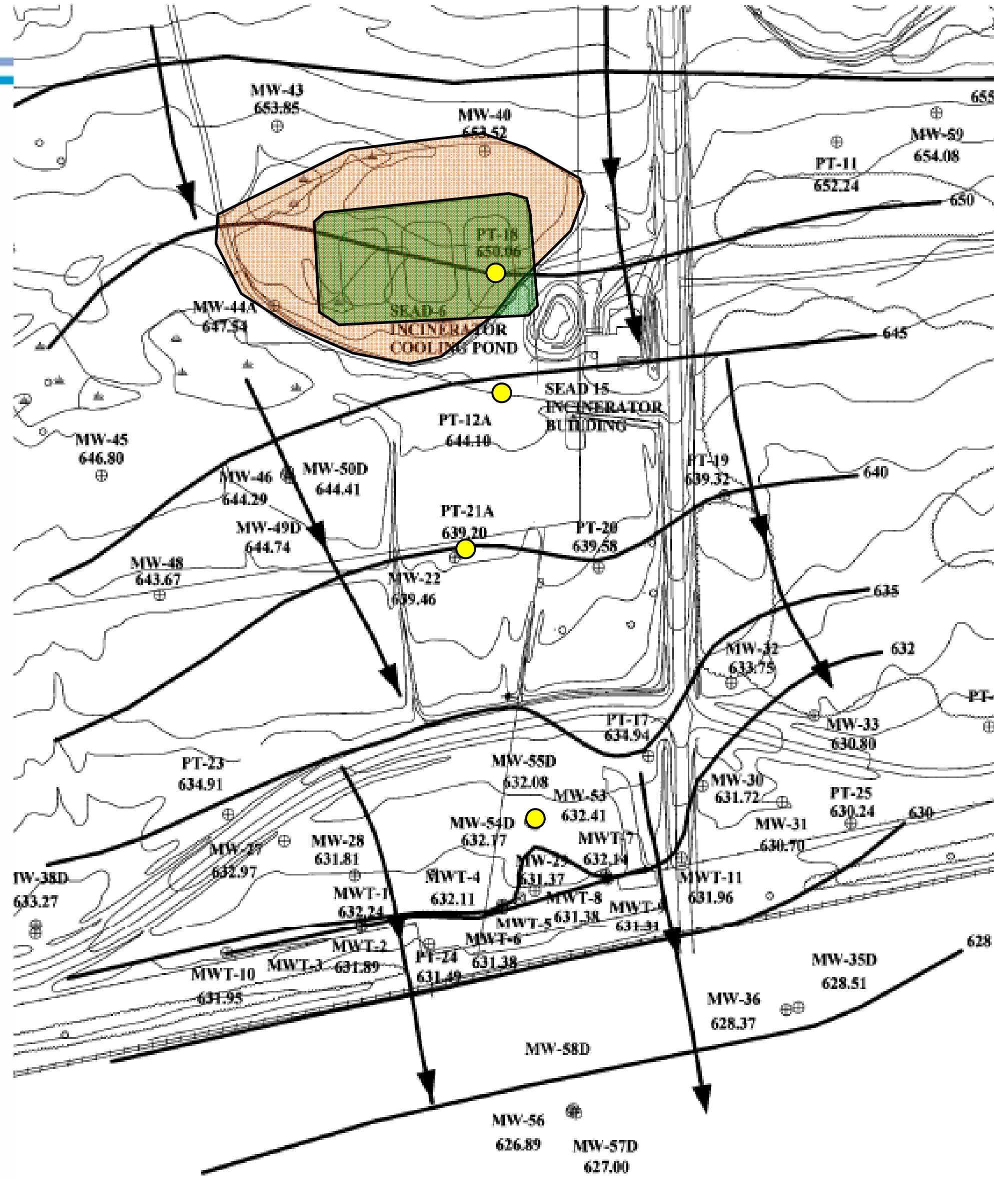
Site Map and Contaminant Plume

- Primary contaminants impacting groundwater
  - TCE
  - 1-2,cis-DCE
  - VC
- Total chloroethene concentration (source)
  - 12,000-24,000 µg/L
- 18-acre footprint

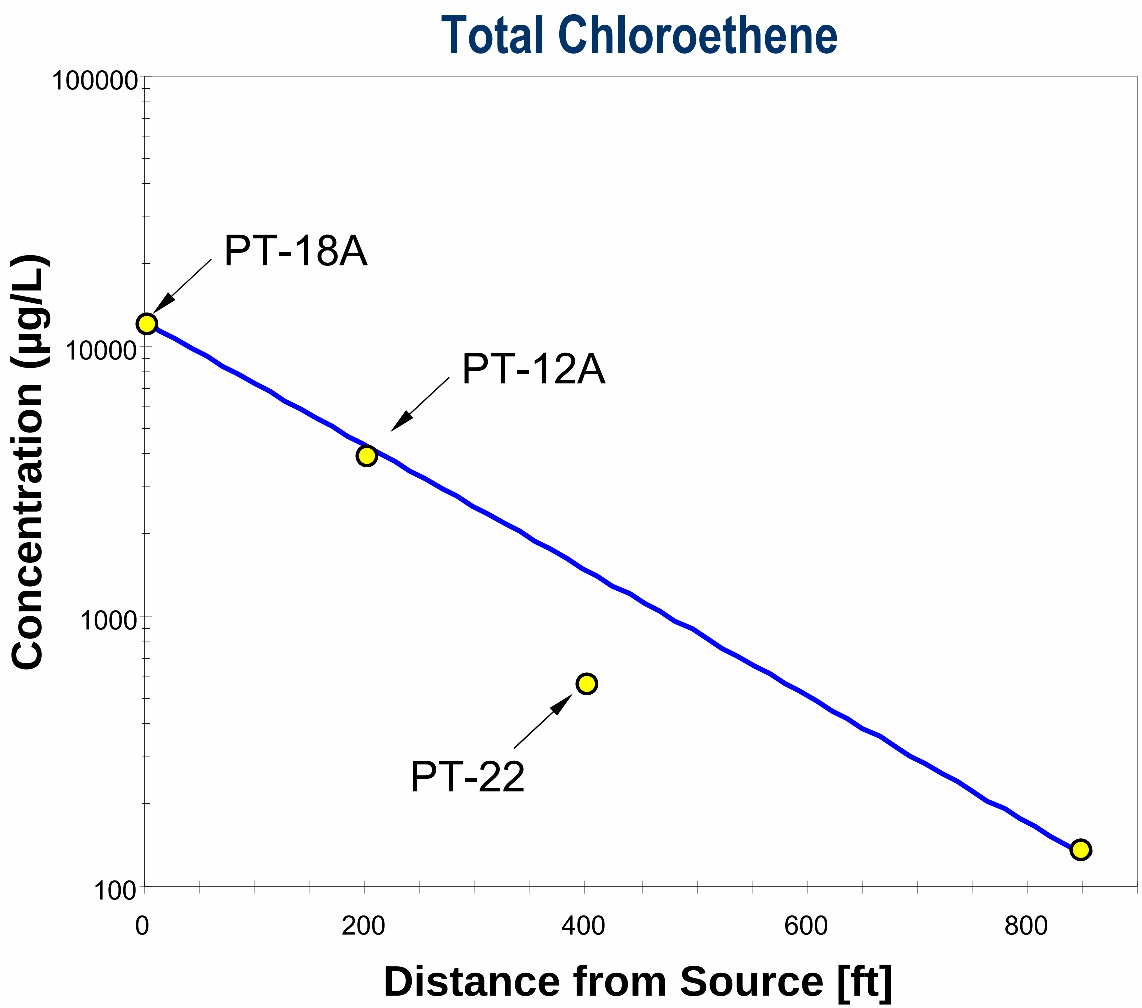


Hydrogeology

- Surficial aquifer impacted
  - Shallow, unconfined
  - Glacial till
  - Fractured weathered shale
- Hydraulic conductivity
  - 1.3 – 2.0 ft/day
- Groundwater velocity
  - 0.10 – 0.26 ft/day



Plume Geochemistry

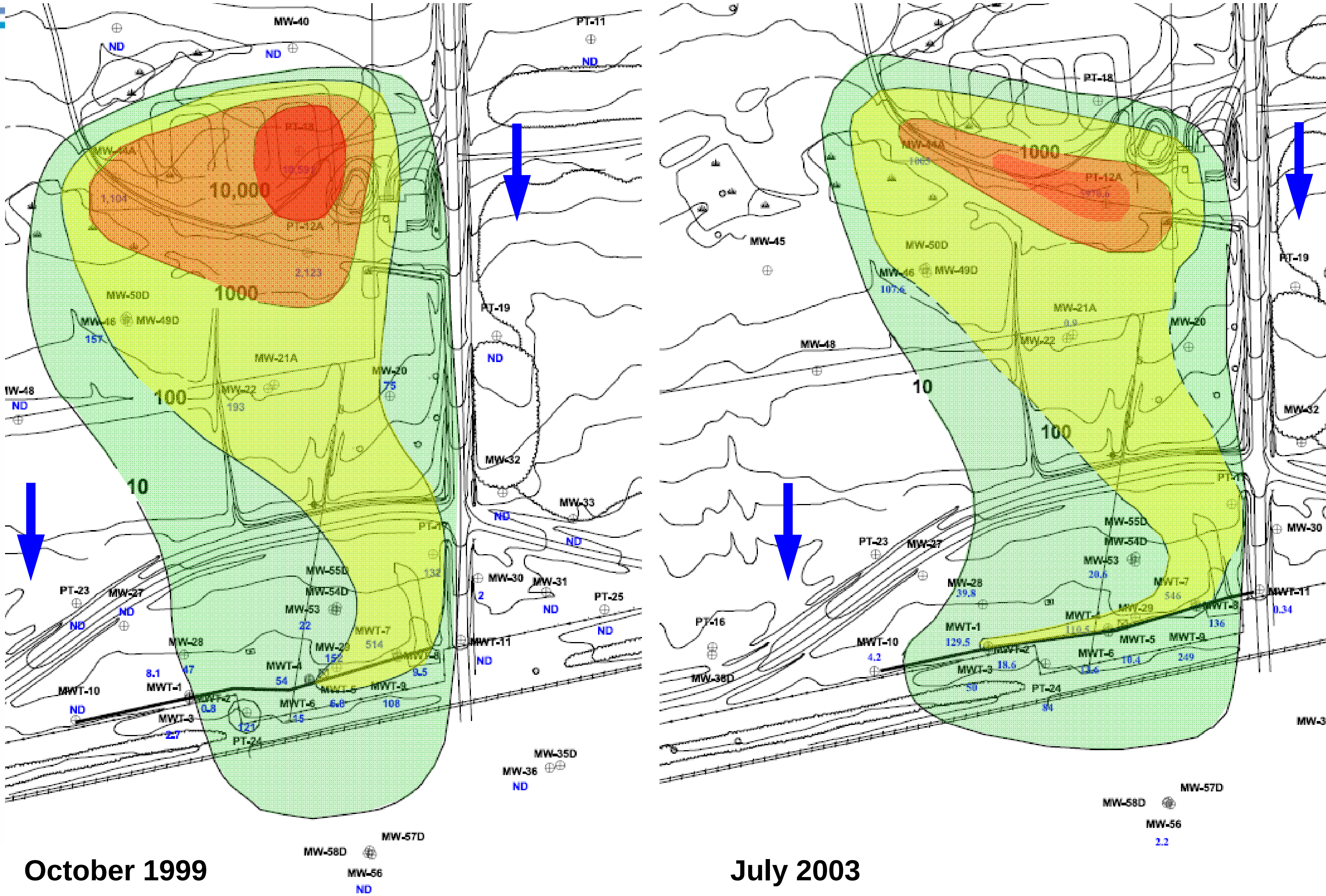


- Anaerobic system
- Single redox zone
- Sulfate-reducing conditions are present in the plume

Remediation Approach

- Source area remediation (1994-95)
  - Excavation (1.5 acre) and incineration
  - Treated soil was backfilled into excavation area
- Plume containment and remediation (1998)
  - Permeable reactive iron wall (650-ft in length)
  - Constructed at plume toe

Plume Evolution Following Source Excavation

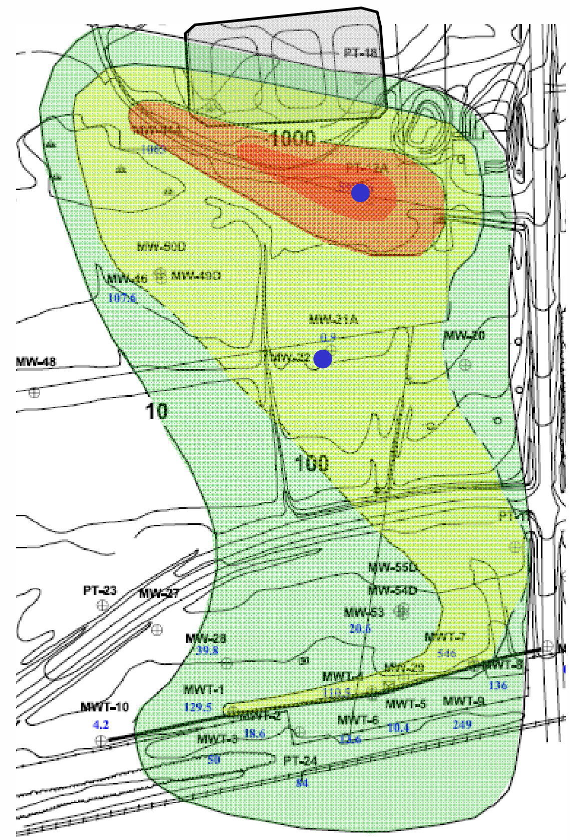


October 1999

July 2003

NAS Application – Time of Stabilization

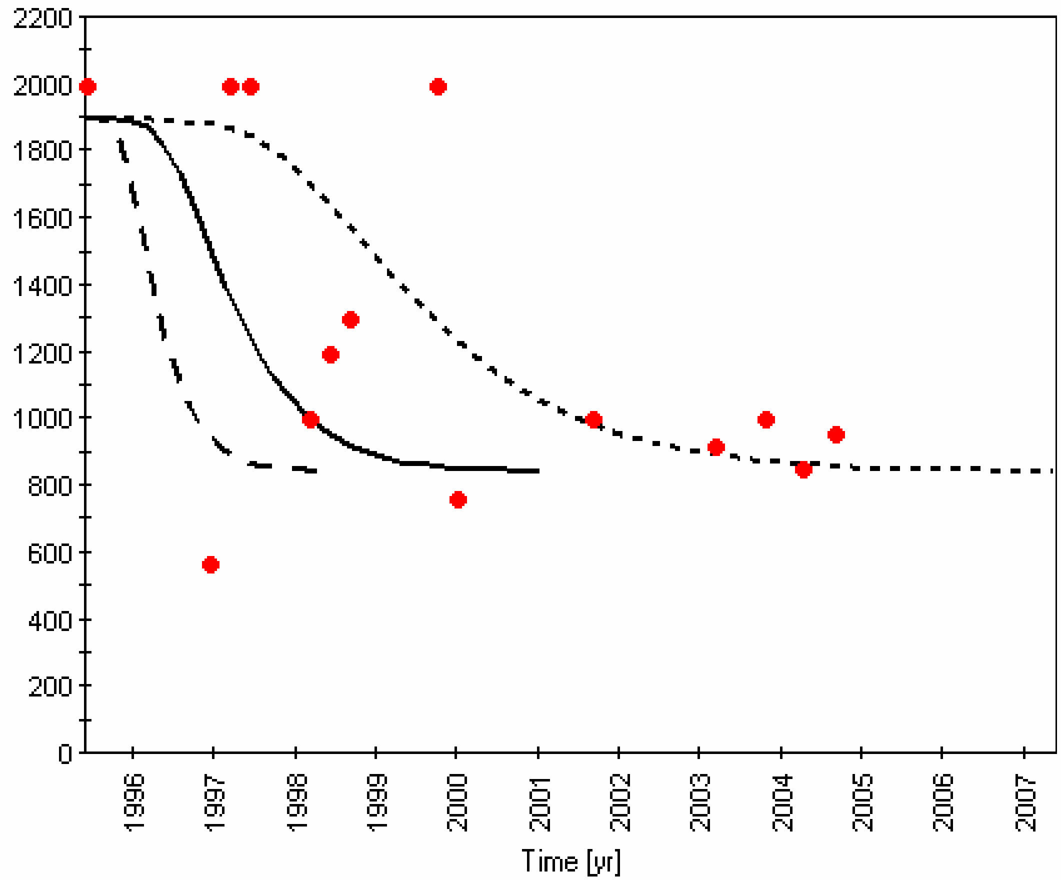
- NAS used to simulate C versus time at PT12A and PT22, located 180 and 400 ft downgradient of the source, respectively
- Observed decline in the source zone TCE concentration
  - 12,000 µg/L (pre-excavation)
  - 5,300 µg/L (post-excavation)
- Field-observed TCE concentration used as input to NAS



Results of NAS Application

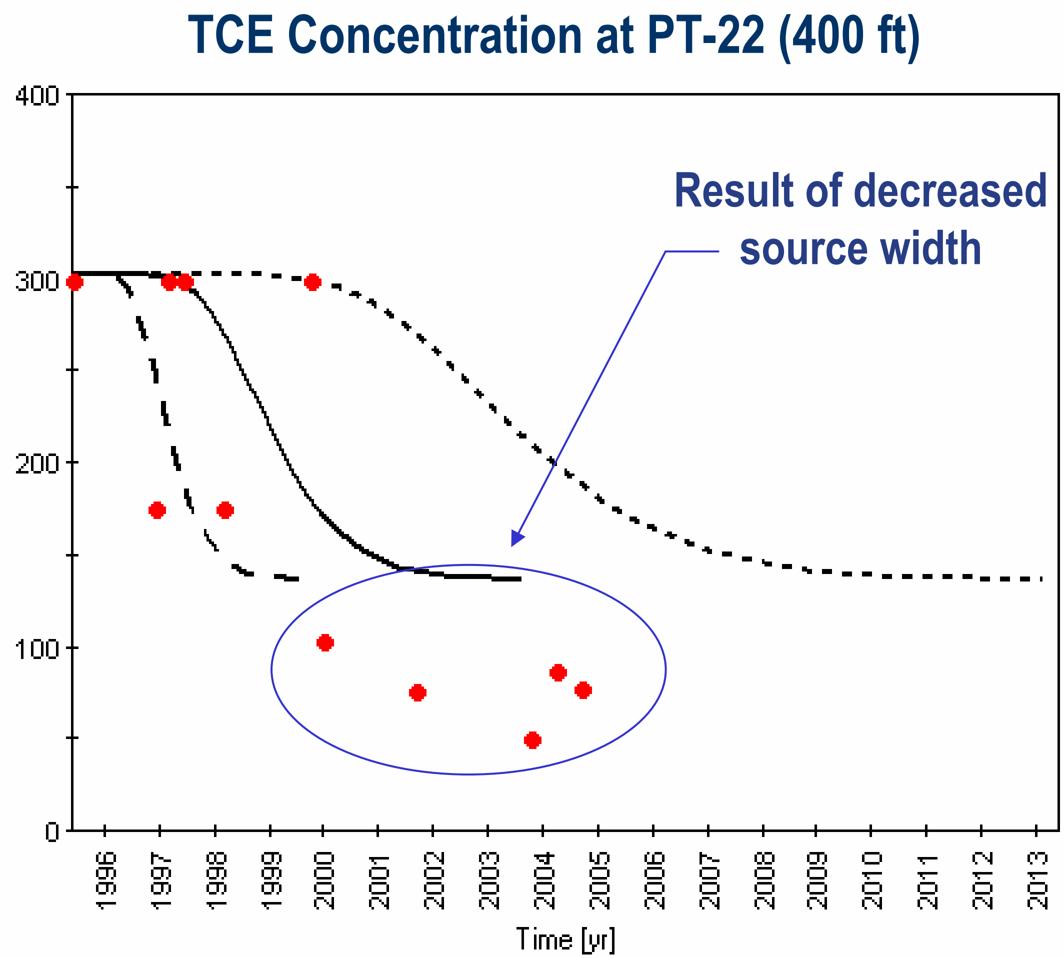
- NAS captured parts of the 10-yr trend
  - Time of stabilization
  - Equilibrium concentration
- Time fluctuations in concentrations and data gaps hinders estimation of breakthrough time

TCE Concentration at PT-12A (200 ft)



Results of NAS Application (cont.)

- Keeping all input parameters consistent with the previous simulation, the solution failed to accurately match the observed equilibrium concentration
- Consistency in the TOS estimated is noted



Lessons Learned

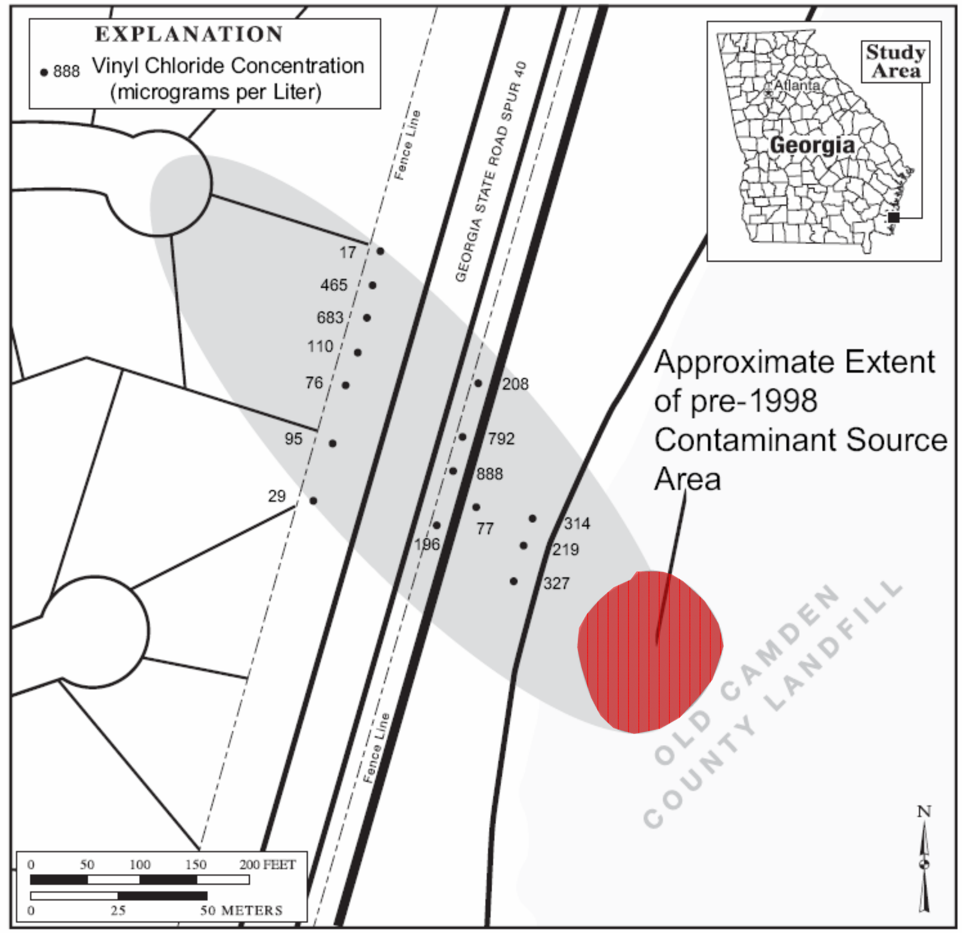
- NAS provided satisfactory performance in non-ideal hydrogeology
- Accuracy of TOS and equilibrium concentration prediction improved with proximity to source
- Decrease in the source width following remediation can reposition the plume centerline and potentially reduce the concentration at some monitoring wells
- Results demonstrate the importance of characterizing the post-remediation source zone conditions

Site History
Source Zone Chemical Oxidation – NSB Kings Bay, GA

- Naval Submarine Base (NSB) is located on the Georgia-Florida border
- Provides support for Ohio-class nuclear powered ballistic missile submarines
- Site 11: former 25-acre landfill dating back to the mid-1970s
- Chloroethene plume discovered migrating from the landfill in the 1990s

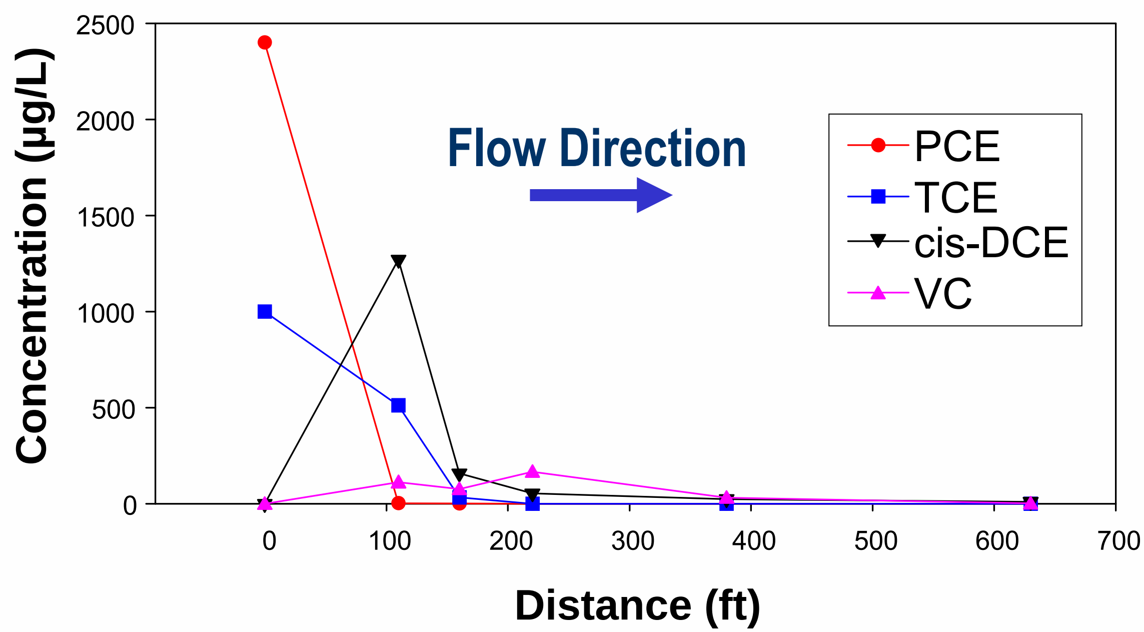
Site Map and Contaminant Plume

- PCE source concentration
  - 3,500-9,100 µg/L
- Complete transformation of chloroethenes along flow path
  - Reductive dechlorination
  - Anaerobic direct oxidation
- 3.5-acre footprint



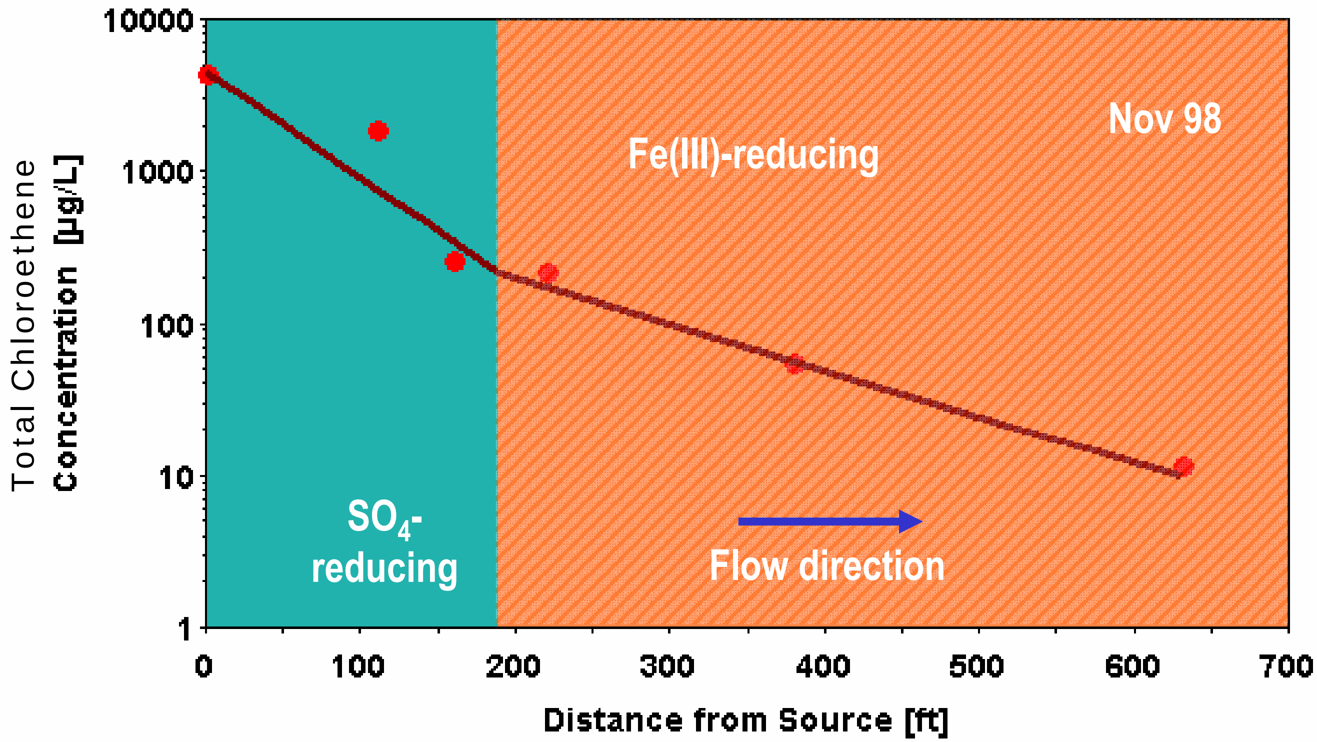
Hydrogeology

- Atlantic Coastal Plain Aquifer System
- Contamination present in a 10-ft thick strata of permeable sand located 30 to 40 ft bgs
- Hydraulic conductivity
  - 3 to 5 ft/day
- Groundwater velocity
  - 0.24 to 0.76 ft/day



Plume Geochemistry

- Anaerobic system
  - Mix of methanogenic and sulfate-reducing conditions in source
  - Iron-reducing conditions further downgradient where cis-DCE and VC concentrations > TCE/PCE

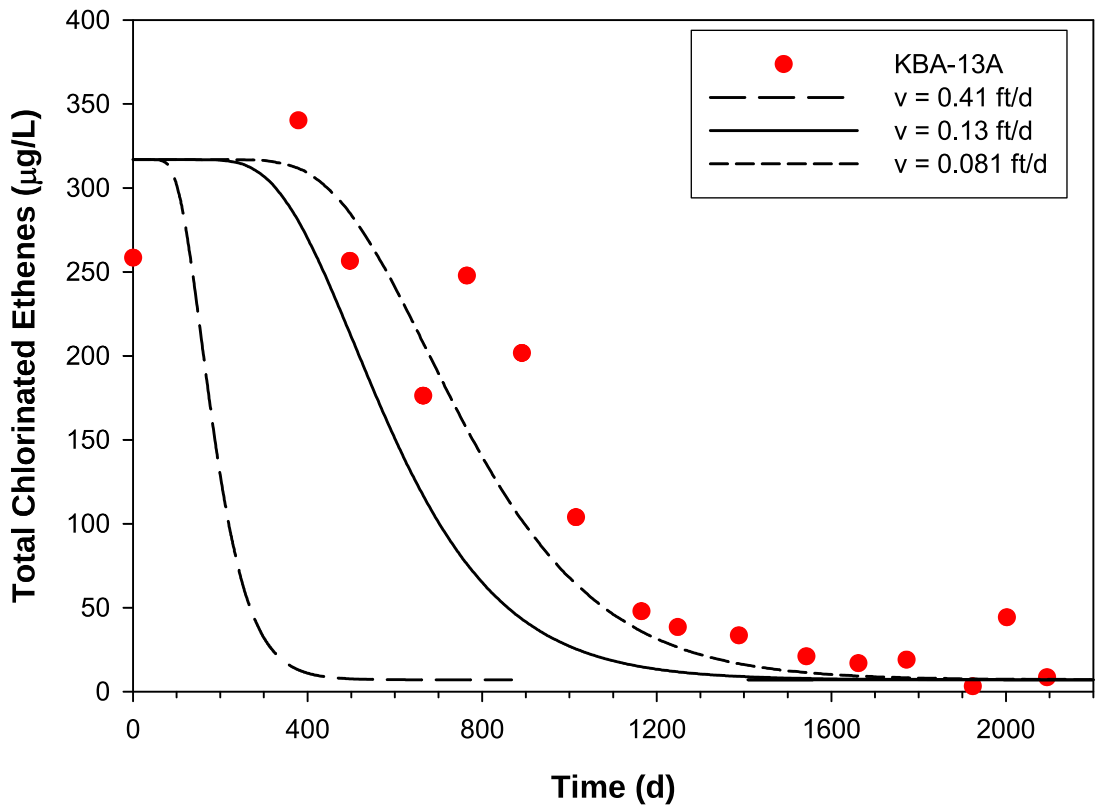


Remediation Approach

- Pumping wells installed and operated in the early 1990s to exert hydraulic control on the plume
- Source zone remediation implemented in 1998-99
  - In situ chemical oxidation using Fenton's reagent
  - Injection of vegetable oil
- The successful removal of the PCE source and subsequent plume reduction (MNA) documented over a 6-year period (Chapelle et al. 2005)

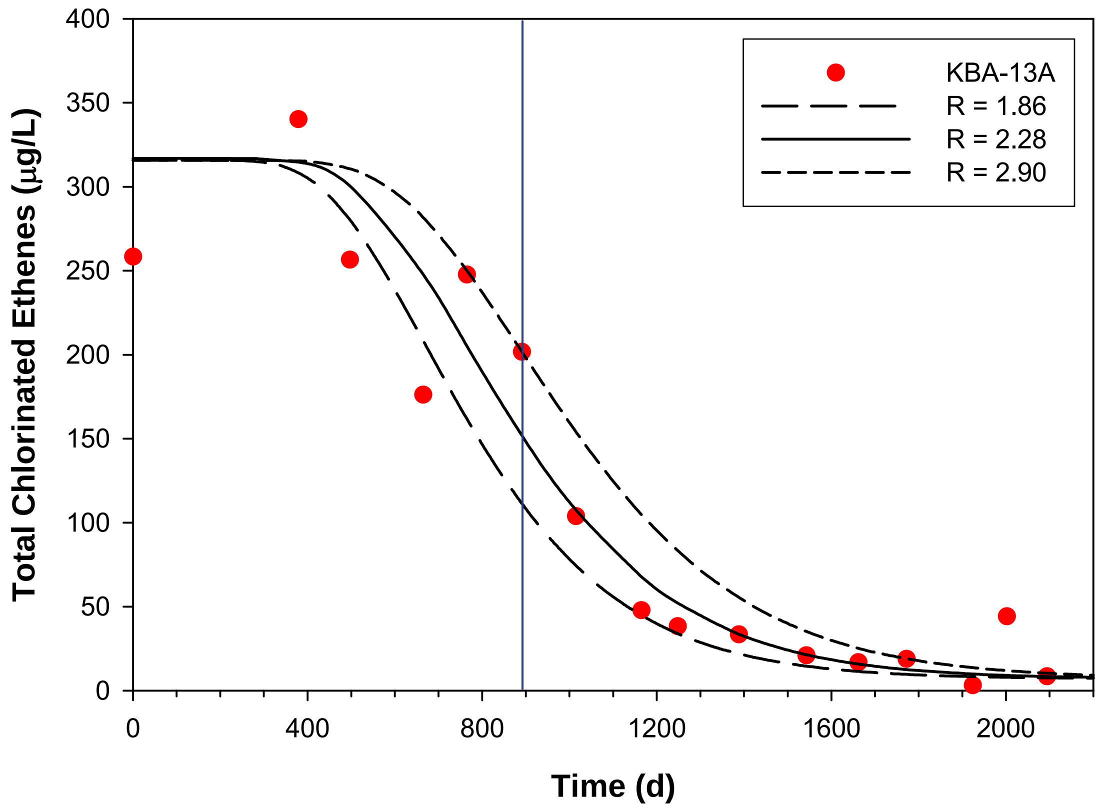
Results of NAS Application

- NAS simulation for the minimum estimated contaminant velocity reasonably matched the observed data
  - Breakthrough time
  - Time of stabilization
  - Equilibrium concentration
- Best-fit occurs for retardation factors outside a range consistent with data



Results of NAS Application

- Analysis of tracer (sulfate) data at observation wells enabled calculation of groundwater velocity (*v* = 0.18 ft/d)
- Improved estimate of *v* was not immediately available (t > 895 d)
- NAS post-audit feature was implemented to revise TOS estimate



Lessons Learned

- NAS captured the long-term trend in the observed data, showing the complete breakthrough of remediated groundwater to target concentrations (i.e., MCLs)
- Accurate results were observed at Site 11 when the groundwater velocity was derived from tracer test data
- Determining groundwater velocity and sorption parameters will result in improved accuracy of TOS following source zone remediation at all sites

Cost Savings – Kings Bay

- The RAO and considerable cost savings were realized at NSB Kings Bay, Site 11 by employing a remedial strategy of source reduction followed by MNA

Pump-and-Treat

- Capital cost = $1,920,000
- Annual costs:
  - O&M pumping system = $400,000
  - O&M treatment system = $65,000
  - Monitoring & reporting = $90,000
- Total estimated life-cycle cost[1] = $10,500,000 (30 years*)

* Note: TOR > 30 yr

Source and Plume Reduction

- Capital cost = $915,000 (est.)
  - Chem Ox = $725,000 (3 applications)
  - Veg Oil = $190,000
- Annual costs:
  - Monitoring & reporting = $55,000
- Total estimated life-cycle cost[1] = $1,270,000 (8 years)

[1]Present worth, 5% rate

NAS – A Useful Tool for Decision-Making

- Steps for reaching a decision using NAS are outlined here:
  - Characterize plume geochemistry and hydrogeology
  - Evaluate data using NAS Site Data Assessment module
  - Determine target reduction in the source concentration/mass flux for different RAO scenarios using NAS DOS module
  - Estimate costs to achieve source reduction for each case
  - Use NAS TOS or TOR module to estimate when RAO is met at point(s) of compliance
  - Estimate annual costs for monitoring over the period of performance

Presentation Outline

- Background
- Components of Natural Attenuation Software
- Validation of Natural Attenuation Software
- Site Demonstrations
- Summary

Conclusion

- NAS performance metrics were achieved through the ETSCP program
  - Accuracy
  - Versatility
- It is important to restate that application of the DOS/TOS feature was not a curve-fitting exercise
- The best matches between the observed and simulated concentrations were achieved at the monitoring wells closest to the source
  - Locations ranging from 18 to 407 ft downgradient
  - Average of 185 ft from source

Conclusion (cont.)

- NAS results demonstrated that the uncertainty in estimating plume reduction timeframes were reduced with improved site characterization of hydrogeologic parameters
  - Groundwater velocity
  - Sorption
- Application of NAS to the source zone depletion problem suggests
  - Source zone characterization (before and after remediation) are useful in improving TOR estimates
  - Complex characteristics of a NAPL source are not required

Take-Home Points

- NAS provides a framework for comparing various remediation strategies and defining remediation goals based on a selection criteria:
  - Site-specific RAOs and hydrogeology/biogeochemical data
- NAS also provides a tool for calculating life-cycle cost estimates by combining
  - Source zone remediation cost estimates and annual monitoring costs based on TOR estimates and reduction in plume size and source strength
- NAS is widely available and is designed for ease of use

Resources

- Software
  - Download installation program (version 2) at no cost from Virginia Tech website: http://www.nas.cee.vt.edu
- Other resources available at website
  - NAS Users Manual
  - Site Demonstrations
    - ESTCP Final Report
    - ESTCP Cost & Performance Report
  - USGS Publications
    - WRIR 03-4057
    - Circular Series C-1303

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