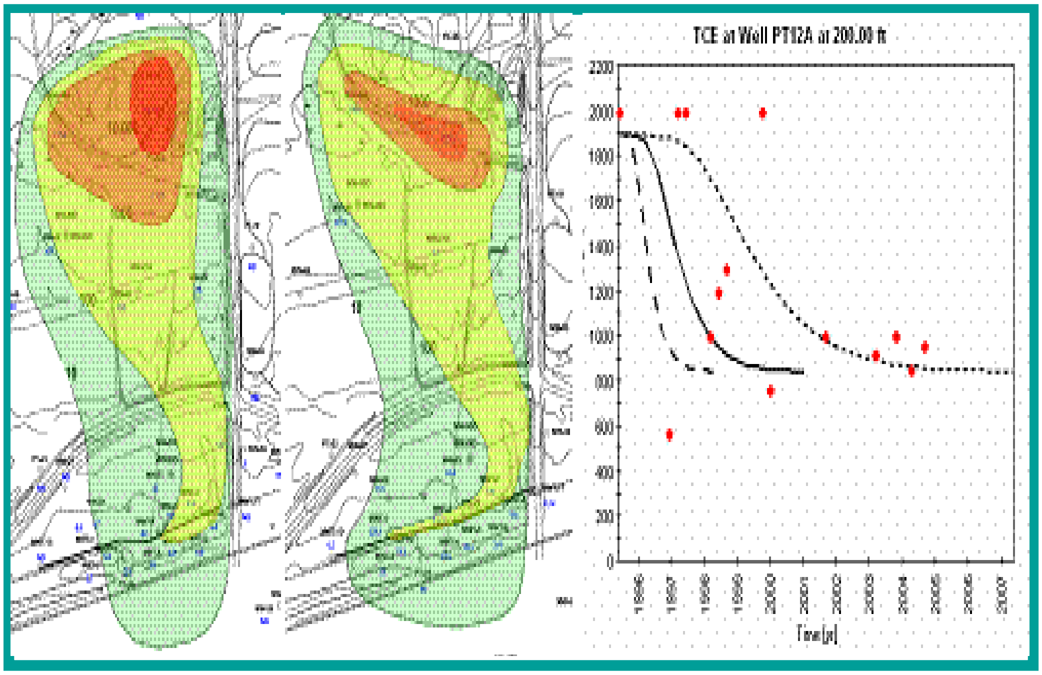
ESTCP
Cost and Performance Report

(ER-0436)



Estimating Cleanup Times Associated with Combining Source-Area Remediation with Monitored Natural Attenuation

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ENVIRONMENTAL SECURITY
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U.S. Department of Defense

COST & PERFORMANCE REPORT

Project: ER-0436

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ACRONYMS AND ABBREVIATIONS

AFB	Air Force Base
ARAR	applicable or relevant and appropriate requirements
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
DCE	Dichloroethene
DoD	Department of Defense
DOS	distance of plume stabilization
DOT	Department of Transportation
EPA	Environmental Protection Agency
ERA	engineered remedial action
ESTCP	Environmental Security Technology Certification Program
LNAPL	light non-aqueous phase liquid
MCAS	Marine Corps Air Station
MCL	maximum contaminant level
MCLG	maximum contaminant level goal
MNA	monitored natural attenuation
MODFLOW	Modular Three-Dimensional Finite-Difference Groundwater Flow Model (groundwater modeling systems)
MTBE	methyl tertiary butyl ether
NAES	Naval Air Engineering Station
NAPL	non-aqueous phase liquid
NAS	Natural Attenuation Software
NAVFAC	Naval Facilities Engineering Command
NSB	Naval Submarine Base
OU	Operating Unit
PCE	tetrachloroethene
RAO	remedial action objective
RI/FS	remedial investigation/feasibility study
RFI	RCRA Facility Investigation
RITS	Remediation Innovative Technology Seminar
RPM	remedial project manager
SDWA	Safe Drinking Water Act
SEAM3D	Sequential Electron Acceptor Model, 3D
SEDA	Seneca Army Depot Activity
SVOC	semi-volatile organic compound

ACRONYMS AND ABBREVIATIONS (continued)

TCA	trichloroethane
TCE	trichloroethene
TND	time of NAPL dissolution
TOR	time of remediation
TOS	time of plume stabilization
USGS	U.S. Geological Survey
VC	vinyl chloride
VOC	volatile organic compound

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Technical material contained in this report has been approved for public release.

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1.0 EXECUTIVE SUMMARY

Under suitable conditions, monitored natural attenuation (MNA) can be a cost-effective strategy for restoring contaminated aquifer systems either as a stand-alone technology or in combination with other engineered remedial actions. However, the Environmental Protection Agency (EPA) guidance specifically requires MNA to achieve site-specific cleanup objectives within a reasonable time frame. Thus, it is necessary to provide estimates of cleanup times whenever MNA is proposed as part of a cleanup strategy. In response, a screening tool NAS was developed for estimating time of remediation (TOR) for MNA with varying degrees of source area remediation. NAS is designed to make complex analytical and numerical solutions of the TOR problem accessible to remedial project managers (RPM) and their contractors using site-specific remediation objectives. Conventional screening tools for MNA are not designed to address source zone remediation options or simulation plume reduction.

The Natural Attenuation Software tool was co-developed by the U.S. Navy, USGS, and Virginia Tech. NAS consists of a combination of computational tools implemented in three main interactive modules to provide estimates for: (1) target source concentration required for a plume extent to contract to regulatory limits, (2) time required for contaminants in the source area to attenuate to a predetermined target source concentration, and (3) time required for a plume extent to contract to regulatory limits after source reduction. Natural attenuation processes that NAS models include are advection, dispersion, sorption, non-aqueous phase liquid (NAPL) dissolution, and biodegradation of petroleum hydrocarbons, chlorinated solvents, or any user-specified contaminants or mixtures.

The objective of this demonstration is to evaluate the NAS capability to provide reasonable estimates of MNA cleanup time frames in a variety of environments and sites throughout the United States. The tool is evaluated by using data from eight sites with long-term monitoring data that encompass diverse geologic and hydrogeochemical environments and different remediation options. The eight demonstration sites are located at Seneca Army Depot and a USGS study site in New York, Naval Air Engineering Station (NAES) Lakehurst in New Jersey, Hill Air Force Base (AFB) in Utah, Naval Submarine Base (NSB) Kings Bay in Georgia, Naval Air Station Cecil Field, Naval Air Station Pensacola in Florida and a USGS study site in Alaska.

Remedial actions at Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites must be protective of human health and the environment and comply with applicable or relevant and appropriate requirements (ARAR). Drinking water standards provide relevant and appropriate cleanup levels for ground waters that are a current or potential source of drinking water. Drinking water standards include federal maximum contaminant levels (MCL) and/or non-zero maximum contaminant level goals (MCLG) established under the Safe Drinking Water Act (SDWA), or more stringent state drinking water standards. Selection of MNA as a remedy for cleanup of hazardous substances requires that estimates of time of cleanup be made to assess its feasibility as a remedy.

NAS was effective in predicting the time of stabilization of concentrations at downgradient monitoring wells located relatively close to the source (within 100 to 700 ft) following source remediation and a reduction in groundwater contaminant concentrations in the source zone.

Accuracy of the solution relative to the observations was impacted by dynamic behavior of the plume over time. NAS was also effective in capturing concentration time trends of natural source depletion of a multicomponent NAPL, providing a prediction that was superior to a comprehensive numerical model that was not based on source zone mass balance.

One finding of this demonstration was that NAS proved to be applicable to all eight sites, independent of hydrogeology, contaminants, characteristics of the source zone, or engineered remedial action (ERA). Therefore, the simplifying assumptions associated with the analytical solutions and the numerical source zone model do not appear to render NAS ineffective but, in fact, demonstrate the applicability and utility of NAS to a wide range of contaminated sites. In contrast, comprehensive three-dimensional numerical models constructed to simulate the complexities of a groundwater system and features of a plume subject to limited data may include unrealistic boundary conditions that do not honor the actual field conditions.

An example of an approach for combining NAS with cost to completion analysis is presented. An estimate of the life-cycle costs of monitoring associated with MNA and natural source zone depletion at NAS Cecil Field, Site 3 was developed in conjunction with NAS TOR estimates. Using the estimated TOR for trichloroethene (TCE) (43 years) and naphthalene (>69 years), the net present value for monitoring over this period of time is at least $2,333,029. In this case, additional optimization at Site 3 was recommended due to the relatively high life-cycle costs as well as the loss of efficiency associated with MNA in the source area resulting from air sparging.

An estimate of the costs to implement NAS relative to a comprehensive numerical solute transport model was presented. The analysis demonstrated that a cost savings between $94,650 and $126,030 can be realized by using the NAS modeling approach. The cost savings associated with NAS reflects a savings in labor by a factor of 5-6 and a reduction in data requirements relative to the comprehensive approach. If this same cost savings was achieved at sites (204 total) on an incremental basis over 5 years, then the cumulative 5-year cost savings to the DoD would be $20,900,000. This analysis does not factor in the additional potential cost savings to DoD at these sites by implementing an MNA-based strategy, with or without source zone reduction.

A methodology and tool for estimating the time of remediation associated with MNA allows stakeholders to make informed decisions regarding its application. In addition, budget requirements for long-term monitoring programs can be forecast based on estimates of time frames. This allows better program planning to meet the future needs of cleanup programs, and can afford RPM the ability to conduct cost benefit analyses when comparing source removal with MNA options to MNA-only strategies.

2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY DESCRIPTION AND APPLICATION

MNA is the considered use of naturally occurring contaminant degradation/dispersion/immobilization processes to reach site-specific remediation goals (EPA, 1996; 1998). In current engineering practice, the effectiveness of MNA is evaluated on a site-by-site basis by considering three lines of evidence: (1) historical monitoring data showing decreasing concentrations and/or contaminant mass over time, (2) geochemical data showing that site conditions favor contaminant transformation or immobilization, or (3) site-specific laboratory studies documenting ongoing biodegradation processes (EPA, 1998). A variety of field and laboratory methods for assessing these three lines of evidence have been developed and are currently in use (Wiedemeier et al., 1999).

In concept, estimating the length of time required for natural processes to remove a particular contaminant from a groundwater system is a mass balance problem. It requires estimates of the rate of mass flux from and depletion over time of NAPL or diffused/sorbed contaminant sources. It also requires estimates of the rates of natural attenuation processes (advection, hydrodynamic dispersion, biodegradation, sorption, plant uptake, etc.). In practice, a deterministic approach can be employed to quantify the mass balance of the aqueous phase plume and the contaminant source.

Widdowson (2004) expressed the mass balance equation of an aqueous-phase constituent in the form:

$$-v_i \frac{\partial C_l}{\partial x_i} + \frac{\partial}{\partial x}\left(D_{ij} \frac{\partial C_l}{\partial x_j} \right) + \frac{q_s}{\theta} C_l^* - R_{sin\,k,l}^{bio} + R_{source,l}^{bio} + R_{source,l}^{NAPL} = R_l \frac{\partial C_l}{\partial t} \qquad (1)$$

where C_l is the aqueous phase contaminant concentration [M L^{-3}]; x_i is distance [L]; t is time [T]; v_i is the average linear groundwater velocity [L T^{-1}]; D_{ij} is the tensor for the hydrodynamic dispersion coefficient [L^2 T^{-1}]; C_l^* is the contaminant point source concentration [M L^{-3}]; q_s is the volumetric flux of water per unit volume of aquifer [T^{-1}]; θ is the effective porosity [L^o]; R_l is the contaminant retardation factor [L^o]; $R_{sin\,k,l}^{bio}$ is a biodegradation mass loss term dependent on the mode of respiration [M L^{-3} T^{-1}]; $R_{source,l}^{bio}$ is a source term for the biogenic mass production [M L^{-3} T^{-1}]; and $R_{source,l}^{NAPL}$ is a source term due to NAPL dissolution [M L^{-3} T^{-1}].

The NAPL source term for petroleum hydrocarbons and chlorinated compounds can be represented using first-order kinetics for dissolution from a multiple-component mixture

$$R_{source,l}^{NAPL} = k^{NAPL}\left(C_l^{eq} - C_l \right) = k^{NAPL}\left(f_l C_l^{sol} - C_l \right) \qquad (2)$$

where k^{NAPL} is the NAPL dissolution rate constant [T^{-1}]; C_l^{eq} is the equilibrium contaminant concentration [M L^{-3}], represented as the product of the solubility (C_l^{sol}) of the constituent in water and the mole fraction, f_l, of NAPL constituent l. The mole fraction is a function of the mass fractions of the NAPL constituents and varies with time. The mass balance equation for each constituent in the contaminant source term is expressed as

$$\frac{dC_l^{NAPL}}{dt} = -\frac{\theta}{\rho_b} R_{source,l}^{NAPL} \tag{3}$$

where C_l^{NAPL} is the source contaminant concentration [M M^{-3}] ρ_b is the bulk density of the porous medium [M$_{solid}$ L^{-3}]

For the multicomponent NAPL problems, solutions to quantify time of remediation (TOR) using Equations (1) through (3) are achieved using numerical models. Sequential Electron Acceptor Model, 3D (SEAM3D) transport is a code designed to simulate the transport and attenuation of contaminants subject to aerobic and anaerobic biotransformations (Waddill and Widdowson, 2000). SEAM3D includes mass balance equations for a multicomponent NAPL. The rate of release for each NAPL constituent is a function of mass transport and transfer parameters (v_i and k^{NAPL}), NAPL parameters (mass, mole fraction, and geometry), and chemical properties (molecular weight and solubility) of the NAPL components.

This approach requires an estimate of the mass of contaminant present and an estimate of the rate of ongoing natural attenuation processes acting on the contaminant. The principal technical problem, therefore, is to obtain reliable estimates of these parameters. Clearly, the reliability of any remediation time estimates will be directly linked to the reliability of the parameter estimates. In addition, determining remediation times requires the definition of an acceptable contaminant mass threshold. This threshold must be predetermined in order to make remediation time estimates.

Using solutions to Equation (1), Chapelle et al. (2003) divided the time of remediation problem into three parts: (1) distance of plume stabilization (DOS), (2) time of plume stabilization (TOS), and (3) time of NAPL dissolution (TND). Each of these issues can be addressed using particular solutions of Equation (3), which can be developed according to specific needs. NAS was developed to make use of solutions to Equation (3) in order to address these three classes of TOR problems. This software was designed to aid the user in assembling and organizing the data needed to make TOR estimates, to obtain appropriate and useful solutions of the TOR equation, and to illustrate the various uncertainties inherent in TOR estimates. No attempt has been made to make NAS applicable to all, or even most, TOR problems. Rather, NAS is designed around numerous simplifications of hydrologic, microbial, and geochemical processes that, while convenient, will introduce unacceptable error to some problems. The NAS software can be downloaded from the website http://www.nas.cee.vt.edu.

The NAS tool is designed for application to groundwater systems consisting of relatively homogeneous, saturated media such as sands and gravels. In its present form NAS is not intended for simulating solute transport in dual-domain porous media such as fractured rock aquifers and highly heterogeneous unconsolidated aquifers. However, NAS may be applicable to fractured-rock aquifer systems which can be adequately represented by an equivalent single-porosity system. NAS is designed for application to petroleum hydrocarbon and chlorinated solvent sites. Version 2 of NAS was recently updated for an expanded range of contaminant groups to provide greater flexibility for adding additional contaminants and groups.

2.2 PROCESS DESCRIPTION

First, detailed site information about hydrogeology, redox conditions, and contaminant concentrations must be entered. Table 1 provides a summary of the required site data. The goal of site data assessment is to determine site-specific, contaminant-specific degradation rates using an inverse modeling technique. NAS is primarily designed as a screening tool early in the remedial investigation/feasibility study (RI/FS) process following completion of a site investigation and characterization. If the data NAS requires is not available, then time of remediation estimates cannot and should not be made. However, another use of NAS is to reveal site data deficiencies that can be addressed during the RI/FS process and to develop monitoring strategies.

Table 1. Summary of NAS v2.2 Site Data Requirements.

Hydrogeology
Hydraulic conductivity[1]
Hydraulic gradient[1]
Fraction of organic matter[1]
Total porosity[2]
Effective porosity[2]
Average saturated thickness impacted by contamination[2]
Redox[3]
Dissolved oxygen, ferrous iron, sulfate
Optional: Nitrate, Mn(II), sulfide, methane, dissolved hydrogen
Contaminant[3]
Chlorinated ethenes: tetrachloroethene (PCE) (optional), trichloroethene (TCE), and daughter products
Petroleum hydrocarbons: benzene, toluene, ethylbenzene, xylene, methyl tertiary butyl ether (MTBE) (optional), naphthalene (optional)
Chlorinated ethanes: trichloroethane (TCA) and daughter products
Chlorinated methanes: Carbon tetrachloride and daughter products
Requirements
[1]Best estimate, maximum, minimum
[2]Best estimate
[3]Values from 3 or more wells along the solute plume flow path

Figure 1 shows a flowchart describing how the NAS software can be used to address TOR questions. After data entry, NAS estimates site-specific groundwater flow rates, biodegradation rates, and sorption properties. Based on the range of estimates, NAS then produces either analytical or numerical solutions of the TOR equation. As shown in Figure 1, one option employs analytical solutions to determine the target reduction in the source area concentration to meet site-specific remediation goals. This approach and solution addresses plume concentration issues, such as the distance of stabilization for given source-area contaminant concentrations and the time of stabilization if source-area concentrations are changed. For the distance of stabilization, NAS calculates the allowable maximum source-area concentration, based on a regulatory maximum concentration level at a given point downgradient of the source. Then, NAS estimates how long it will take for the plume to reach the lower steady-state configuration once source-area concentrations have been lowered by engineering methods. Once both the distance of stabilization and the time of stabilization are acceptable, based on site-specific regulatory criteria, MNA can become an integral component of site remediation (Figure 1).

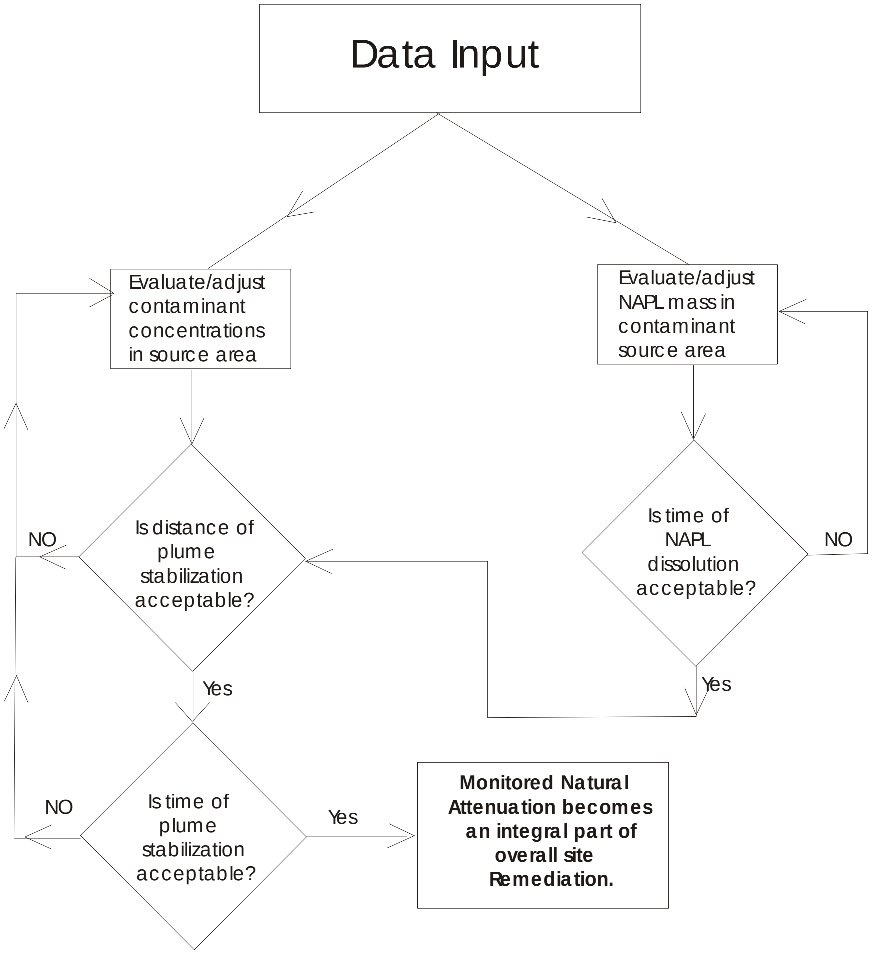


Figure 1. Flowchart Showing How the NAS Software Can Be Applied to TOR Problems.

The other option is a mass-based approach to determine the target reduction in the source area NAPL or residual mass to reduce the TOR, based on site-specific remediation goals. To achieve this solution (i.e., when concentrations fall below a given user-supplied threshold), NAS uses the SEAM3D code (Waddill and Widdowson, 1998) to solve Equations (1) through (3) in conjunction with a groundwater flow code Modular Three-Dimensional Finite-Difference Groundwater Flow Model (MODFLOW). The solution provided by NAS is tailored to estimate the length of time required by a given NAPL mass to dissolve and lower contaminant concentrations at the source area. In principle, the numerical solution could then be used to estimate the distance and time of stabilization for the remaining residual concentration. Since this would significantly lengthen the amount of time required to complete a simulation, numerical simulation is not presently practical for distance and time of stabilization problems. Rather, once the target source zone concentration is determined by an analytical solution and the numerical solution is completed (time required to reach this target calculation), the analytical solution for the time of stabilization can be implemented (Figure 1). Thus, the estimated total TOR to reach compliance at a distance downgradient of the source (e.g., plume toe) is the sum of the two solutions.

2.3 PREVIOUS TESTING OF THE TECHNOLOGY

Prior application of NAS has been documented in Chapelle et al. (2003) using limited data sets from two sites: NSB Kings Bay, Georgia (chlorinated ethenes) and Marine Corps Air Station (MCAS) Beaufort, South Carolina (petroleum hydrocarbons). Although these two sites have different contaminant plumes, they share two key characteristics: (1) high-quality, long-term groundwater monitoring data and (2) long-term decline in contaminant concentrations in source-area monitoring wells following source remediation. Mendez et al. (2004) presented the application of NAS at the MCAS Beaufort, South Carolina to simulate the depletion of benzene concentrations at a source-area monitoring well, based on estimates of ground water velocity and light non-aqueous phase liquid (LNAPL) mass, composition, and dimensions.

2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

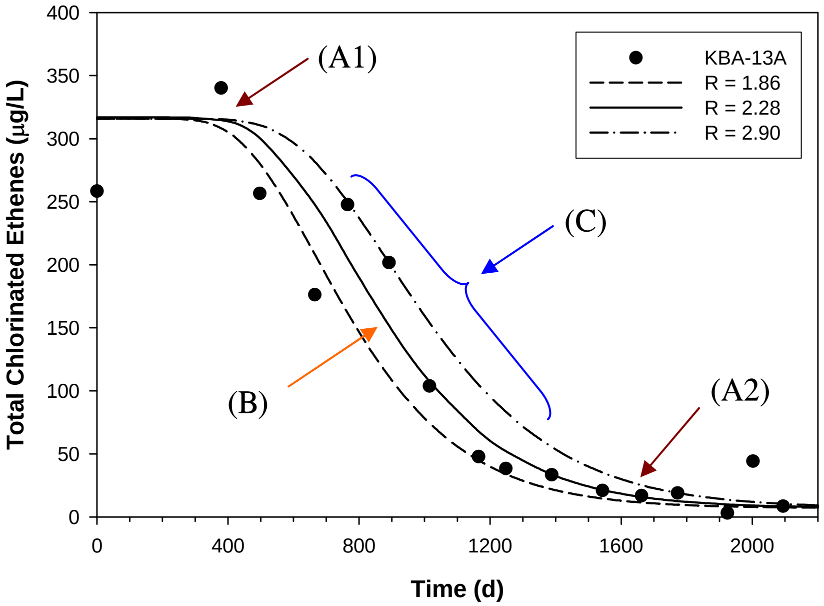
NAS offers several advantages relative to comprehensive groundwater modeling of sites. Even when NAS estimates TOR using the SEAM3D NAPL dissolution option, the user is not required to specify numerical parameters (e.g., grid spacing) or any spatial input parameters. Because NAS includes a simple self-calibrating analytical model, the amount of time and effort required is much less than for a site model for groundwater flow and solute transport. However, at the sites with complex hydrogeology and patterns of groundwater flow, comprehensive groundwater modeling offers greater capabilities relative to NAS. While hydrogeology and flow patterns obviously play a large role, an accurate and complete characterization of the source area is essential to effective remediation of the source zone (National Research Council, 2004). Likewise, any mathematical model may not be accurate if the source term is estimated based on limited information. Modeling tools, including NAS, are useful in developing and refining site conceptual models of the aqueous plume and source zones and in exposing site characterization deficiencies.

3.0 DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

The objective of the demonstration is to assess the performance of NAS as a computational tool for estimating remediation time frames following source zone remediation. To achieve this objective, NAS was implemented to simulate contaminant concentrations at chlorinated solvents sites that represent a range of conditions. NAS is designed to calibrate an analytical solution to steady-state plume contaminant concentration data first, then implement analytical and numerical solutions to simulate the transient response of plume concentrations due to source-zone treatment, depletion, or some combination of the above.

Several metrics were used to evaluate TOR estimates: (1) inflection points of contaminant concentration profiles, (2) time of breakthrough, (3) slopes of contaminant concentration profiles, and (4) contaminant concentration profiles for different NAPL components over time. The first three metrics (inflection points, time of breakthrough, and slopes of contaminant concentration profiles) are demonstrated in Figure 2, which depicts total chlorinated ethene concentration changes at a location downgradient of the source following treatment for one site application (NSB Kings Bay, Georgia).



A1, A2 = inflection points
B = Located at time of breakthrough
C = Slope of the concentration decline.

Figure 2. Observed and NAS-Predicted Total Chlorinated Ethene Concentrations
(using tracer-derived ground water velocity and the range of retardation factors, including the case (R = 2.28) where error is minimized).

Point A1 represents the time at which the impact of source remediation is first observed at a downgradient monitoring well. This point of inflection is identified at the time where a consistent decline of contaminant concentration is observed. The second inflection point, A2 corresponds to the time required to reach a new steady-state concentration at a specific location within the solute plume. Point B corresponds to the time of breakthrough where 50% of the net decrease in concentration is observed. The slope, C, is the rate of decline in the concentration between points A1 and A2. Performance objectives based on these metrics are summarized in Table 2.

Table 2. Performance Objectives.

Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)	Actual Performance Objective Met?
Quantitative	Inflection points of concentration-time data	The predicted inflection point (A1 and A2, Figure 2) of the concentration-time curve should coincide with the observed inflection point within one year.	Yes[1,5,7,8]; Inconclusive[4]
Quantitative	Time of breakthrough	The predicted time of breakthrough (B, Figure 2) of the concentration-time curve should coincide with the observed breakthrough within 2 years.	Yes[5,8]; Inconclusive[1,4,7]
Qualitative	Slope of concentration-time curve following first inflection point	The predicted slope of the inflection point of the concentration-time curve (slope C, Figure 2) should be similar to the observed slope.	Yes[4,5,7,8]; Inconclusive[1]
Qualitative	Predicted/Observed contaminant-concentration profiles for different components of NAPL	NAS will be assessed for how accurately it predicts that the more soluble NAPL components are removed sooner than the less soluble components.	Yes[3,6]; Inconclusive[2]

[1] Seneca Army Depot, New York
[2] USGS Study Site, New York
[3] Naval Air Engineering Station (NAES) Lakehurst, New Jersey
[4] Hill AFB, Utah
[5] NSB Kings Bay, Georgia
[6] Naval Air Station Cecil Field, Florida
[7] Naval Air Station Pensacola, Florida
[8] USGS Study Site, Arkansas

3.2 SELECTION OF TEST SITES

As a group, the criteria and requirements for site selection were (1) differing hydrogeologic conditions and (2) various methods of source remediation. Individually, the requirements for sites were (1) high-quality data sets and (2) long-term decline in contaminant groundwater concentrations following source remediation. Although NAS is ideally suited for sites that have wells near the source and along the center line of the plume coupled with relatively simple hydrogeologic conditions, it was viewed as useful to select some sites with non-ideal conditions. The notion was not to set up the demonstration for failure but to test the limits of the software and assess how robust the solutions are in relation to the performance objectives. For example, at some sites the monitoring infrastructure and sample data resulting from characterization efforts were not specifically aimed at demonstrating MNA lines of evidence or lacked the detail for a comprehensive modeling effort. The conceptual models at some sites were not consistent with a simple homogeneous, unconsolidated aquifer, as the site data was indicative of more complex hydrogeologic conditions. Therefore, some sites selected for the demonstration exhibited a few non-ideal characteristics.

Desired site characteristics included:

- Five years of annual monitoring data that includes the geochemical and contaminant chemistry, and water levels
- Appropriate geochemical data that allows for assessment of the plume status in an electron acceptor distribution framework
- Groundwater velocities exceeding 5 ft/year
- Darcy flow (i.e., not conduit flow such as Karst)
- Unidirectional groundwater flow fields and boundary conditions that can be reasonably simulated by the analytical code.

Data sets from the selected sites demonstrated either natural depletion of source zones over time or a declining trend in contaminant concentration at downgradient wells following a source-area ERA. Allowance was made for noise in the data and/or variation indicative of sampling or other issues that cannot be sufficiently incorporated into the solution. Candidate sites were screened based on the availability of redox indicator data collected in accordance with EPA/DoD protocols for MNA (EPA, 1998). Minimally, dissolved oxygen, sulfate, and ferrous iron data were necessary. Groundwater velocities and travel times had to be sufficient to measure changes over time relative to the period of time for which monitoring data has been collected. Because the software is not designed to handle conduit flow, sites with hydrogeologic conditions that can best be described as complex fractured bedrock and/or Karst with solution channels were not considered. Finally, local groundwater flow pattern along the length of the contaminant plume could not be significantly impacted by pumping wells or natural sources and sinks.

3.3 TEST SITE, FACILITY HISTORY, AND CHARACTERISTICS

The eight sites selected for demonstrations (Table 3) met the global criteria as reflected in the range of locations, hydrogeologic settings, and remediation options. The histories of the individual sites are described in detail in the Final Report. In general, the sites can be characterized as former or active landfills or unlined waste disposal facilities. The hydrogeology at both sites located in New York was characterized as non-ideal in which the flow systems were dominated by fractured flow. However, previous site investigations have provided reasonable justification for incorporating Darcian flow in the site conceptual models. Uniform groundwater flow field was a common characteristic at all sites with the exception of two cases—the pump-and-treat site and Hill AFB. At the latter, the presence of the barrier wall impeded flow, resulting in a nonuniform horizontal hydraulic gradient. Furthermore, the contaminant plume is present within two formations, which results in a change in hydrogeologic parameters along the flowpath.

Each site also met the two requirements for data quality and declining concentration time trends. Chlorinated ethenes were a common contaminant to the sites, which included, but were not limited to, PCE, TCE, dichloroethene (DCE) and vinyl chloride (VC). Chlorinated benzenes were present at both sites located in Florida.

Table 3. Summary of Demonstration Sites.

Facility	Site	Hydrogeology	Source Zone ERA
Seneca Army Depot, NY	Ash Landfill	Glacial till and weathered shale	Excavation
USGS Study Site, NY	Textron	Fractured dolomite	Pump-and-treat
NAES Lakehurst, NJ	Sites I & J	Fine to coarse quartz sand	Natural depletion
Hill AFB, UT	Operating Unit 2 (OU2)	Fluvial fine sand and silt and interbedded clay layers	Containment (barrier wall)
NSB Kings Bay, GA	Site 11	Medium sand (marine)	Chemical oxidation (Fenten's)
Naval Air Station Cecil Field, FL	Site 3	Fine to medium quartz sand & interbedded clay and sandy clay layers	Air sparging
Naval Air Station Pensacola, FL	WWTP	Fine to medium quartz sand (marine and fluvial)	Oxygen release compound
USGS Study Site, AK	Alaska Department of Transportation (DOT)	Highly permeable alluvium	Excavation

3.4 PHYSICAL SETUP AND OPERATION

Physical setup and operation of NAS is described in Section 2.2, Process Description. For the site demonstrations, NAS was implemented in a predictive fashion using the site-specific ranges in hydrogeologic, sorption, and geochemical (redox) parameters. A comparison of the observed data (long-term performance monitoring) to the range in simulated concentration versus time proceeded without calibration or adjustment of parameters.

3.5 SAMPLING/MONITORING PROCEDURES

Not applicable to the demonstration.

3.6 ANALYTICAL PROCEDURES

Not applicable to the demonstration.

4.0 PERFORMANCE ASSESSMENT

4.1 PERFORMANCE CRITERIA

All eight site demonstrations are described in detail in the Final Report to ESTCP (2006). Below is a summary of the simulation results in comparison to the observed data.

Time of stabilization estimates were compared to observed data at monitoring wells located downgradient of the source at distances ranging from 140 to 716 ft from the source without adjustment of input parameters (i.e., direct comparison of observed versus simulated with no calibration). Applications of NAS at both at the Seneca Army Depot Activity (SEDA) Ash Landfill and Hill AFB OU2 (Figures 3 and 4, respectively) demonstrate that fluctuations over time in the magnitude and direction of the hydraulic gradient will impact the position of the plume centerline and will contribute to concentration variability relative to the ideal solution.

The response in TCE concentration at two monitoring wells at the SEDA Ash Landfill is shown in Figure 3 following source excavation. Data gaps in the mid-1990s and the time fluctuation in concentrations hinder the accurate estimation of the observed breakthrough time. The breakthrough and inflection points are difficult to judge from the data but, in general, a reasonable fit was obtained at both wells. For both wells, the TOS estimates are consistent with the observed data. The likely cause of data variability is the reduction in the source volume through excavation combined with fluctuations in the direction of the horizontal hydraulic gradient with time. The non-ideal response can also be attributed in part to variability in the groundwater flow path through the weathered shale and till.

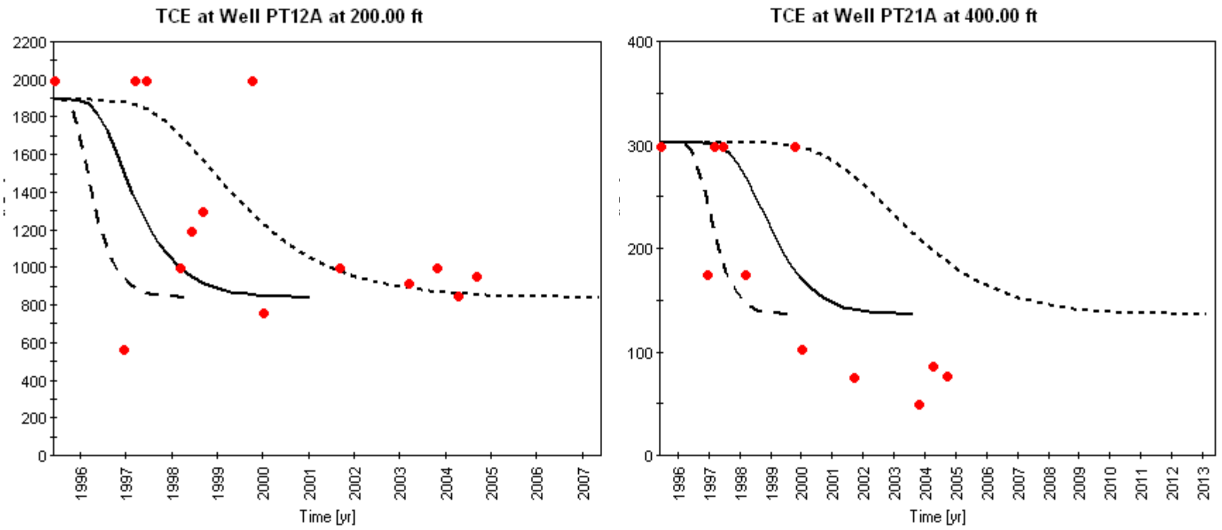


Figure 3. Observed and NAS-Simulated TCE Concentration Versus Time at Downgradient Wells
(based on the observed source concentration reduction at the SEDA Ash Landfill).

Analytical solutions used in NAS are based on the assumption that the hydrostratigraphic unit is homogeneous so that contaminant velocities do not vary along the entire length of the plume. At this site (OU2) the plume is located in two different aquifer systems. In this application, parameters are calculated based on the parameters of the two separate formations. Figure 4 shows that simulations based on the range of parameters derived from the formation closest to the containment wall resulted in the closest match with the observed data at both wells. Although NAS was not designed to simulate the effects of a containment wall on concentrations, these results suggest that NAS is useful in simulating the plume changes over time.

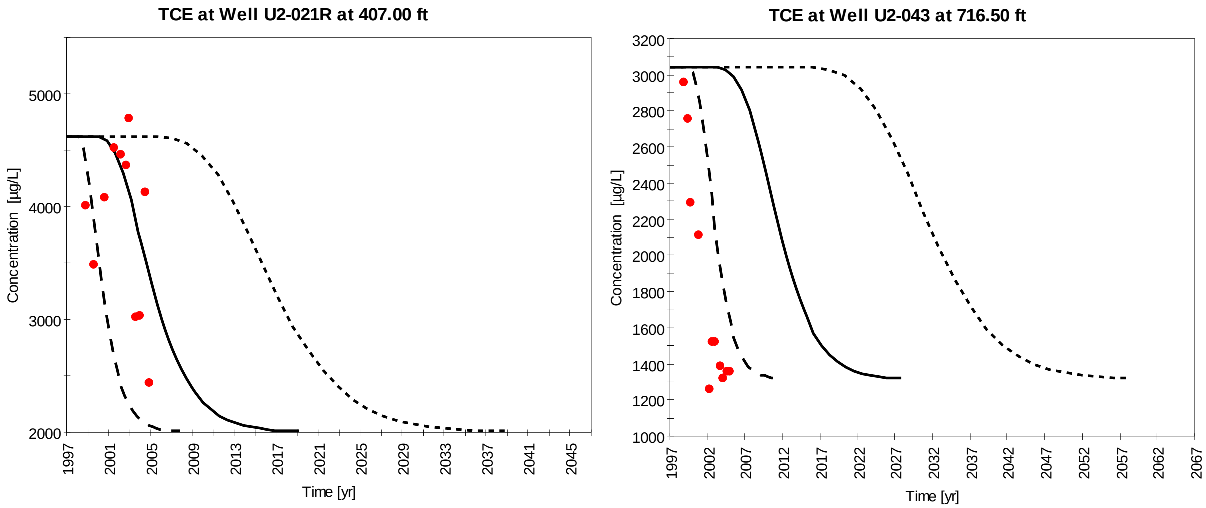


Figure 4. TCE Concentration Versus Time at Wells Downgradient of the Slurry Wall at Hill AFB OU2

(Contaminant velocity range is based on hydrogeological parameters derived from the near-source hydrostratigraphic unit and a site-averaged hydraulic gradient.)

A third application (Figure 2) utilized a tracer-based value of the groundwater velocity. A pulse of sulfate was observed in several observation wells resulting from the use of Fenton's reagent in the source zone and subsequent transport with the natural gradient. The results using a tracer-based velocity estimate showed improved agreement between the observed and calculated concentration trend when compared to the initial estimates.

The NAS Cecil Field, Site 3 demonstration illustrates the fourth performance objective involving the multi-component NAPL dissolution concept and estimates for TND in the source area. Figure 5 depicts concentration versus time curves for six NAPL components relative to historical data, using a range of groundwater velocities. The analysis suggests that the volatile organic compound (VOC) concentration trends during the early stages of NAPL dissolution appear to be most sensitive to estimates of mass. During these periods the more soluble compounds elute early and a more pronounced peak is observed in the plume concentrations. Because the observed data more closely follows the average estimate (5000 kg) of mass for both VOC and semi-volatile organic compounds (SVOC), this value was used to estimate the TND. The potential range of transport velocities predicts a range of values of TND that encompasses the observed data. The results demonstrate that the SEAM3D NAPL package is robust and capable of simulating the differing concentration changes over time, depending on the solubility and other physical-chemical properties of the NAPL components. This also illustrates the combined effect of source remediation with MNA.

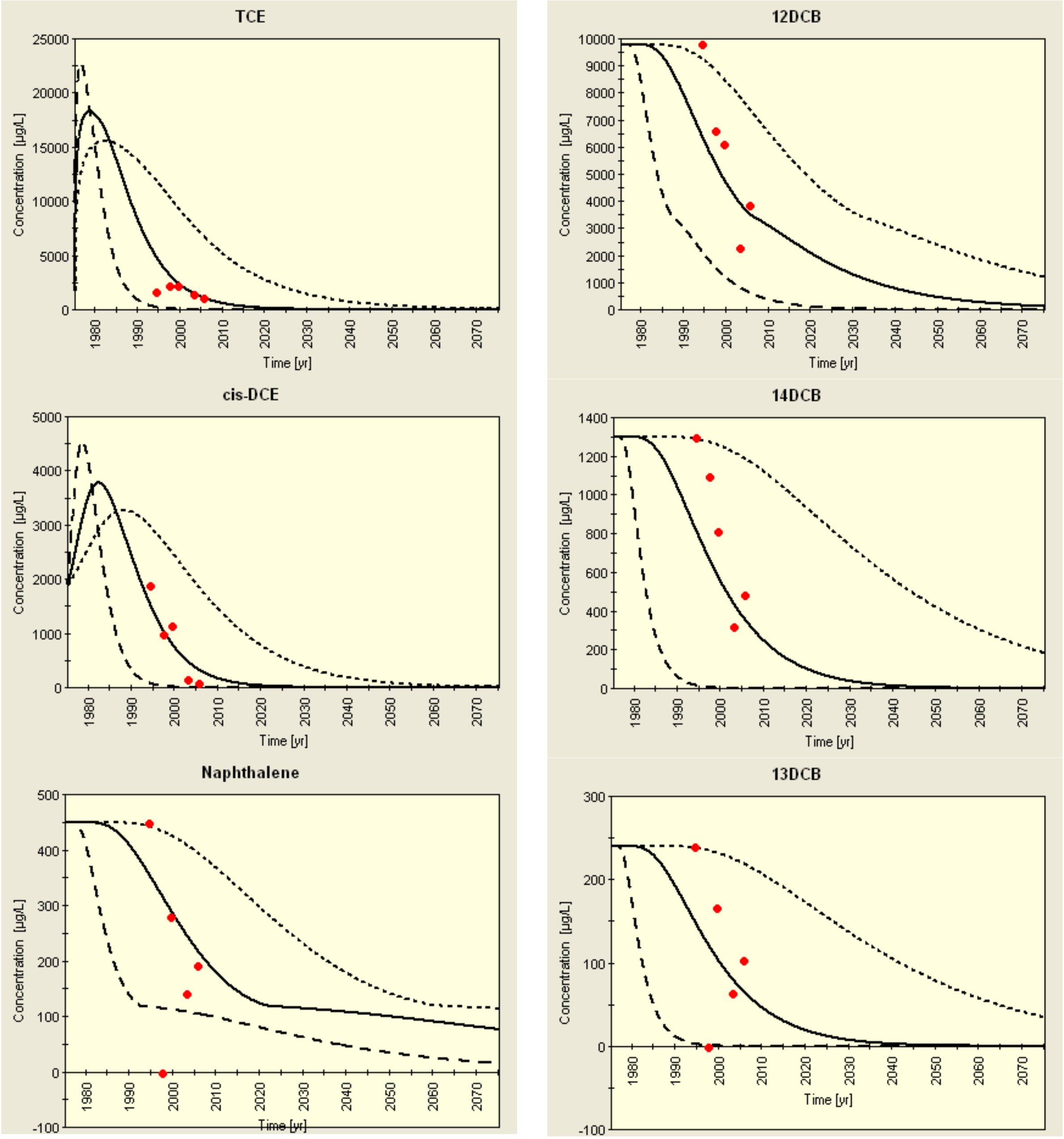


Figure 5. Observed Versus NAS-Simulated Concentrations at a Source-Zone Monitoring Well for Six NAPL Compounds Using a Range of Velocity Estimates.

4.2 PERFORMANCE CONFORMATION METHODS

Performance criteria and actual performance of NAS are summarized in Table 4.

Table 4. Performance and Performance Confirmation Methods.

Performance Criteria	Expected Performance Metric (pre-demonstration)	Performance Confirmation Method	Actual (post-demonstration)
Primary Criteria (Performance Objectives) (Quantitative)			
Inflection point of concentration-time curve	The predicted inflection point (point A1, Fig. 2) of the concentration-time curve should coincide with the observed inflection point within one year.	Concentration-time curves at least one mid-plume well, and preferably several, over time	In general, better performance noted at wells closer to source relative to further downgradient wells
Time of breakthrough	The predicted time of breakthrough (point B, Fig. 2) of the concentration-time curve should coincide with the observed breakthrough within two years.	Concentration-time curves at least one mid-plume well, and preferably several, over time	NAS captured velocity uncertainty in time of breakthrough. Performance was superior at sites where flow velocity is constrained through independent data.
Primary Criteria (Performance Objectives) (Qualitative)			
Slope of concentration-time curve following inflection point	The predicted slope of the inflection point of the concentration-time curve (slope C, Figure 2) should be similar to the observed slope.	Concentration-time curves at least one mid-plume well, and preferably several, over time	Greater data variability due to fluctuations in hydraulic gradient or other factors downgradient wells
Predicted/observed contaminant-concentration profiles for different components of NAPL	More soluble components of NAPL should be removed sooner than less soluble components relative to overall NAPL composition.	Concentration-time curves at near-source well, and preferably several, over time	Adequate performance for the data time windows (10-years) considered.

4.3 DATA ASSESSMENT

Section 4.1, Performance Criteria, contains a detailed assessment of the NAS results. The following summarizes the findings with respect to accuracy, versatility, reliability, and applicability.

- Overall, the performance of NAS was satisfactory in matching the inflection points and time of breakthrough for the five sites where TOS was evaluated.
- Using the field-measured source concentration following remediation and the site-specific estimated contaminant velocities, the best match between the observed and simulated concentrations was achieved at the monitoring wells closest to the source.

- Less accurate results were observed in some cases at wells further downgradient at monitoring wells due to time fluctuations in the direction and magnitude of the groundwater velocity.
- NAS was capable of simulating the dissolution and dissipation of individual NAPL components at the three sites where TND simulations were performed.
- The hydrogeology of the sites did not appear to be a factor in the performance of NAS at any of the eight applications.
- The mode of source remediation was not a factor in the performance of NAS.
- No significant reliability problems were encountered in the implementation of NAS version 2.2.0 at any of the eight sites.
- The results of this demonstration strongly suggest that, because NAS is based on sound science, it can serve as an effective tool for decision making, data analysis, and cost optimization at a wide range of contaminated sites and is not limited to a small subset of "simple sites" because of its simplicity.

4.4 TECHNOLOGY COMPARISON

The demonstration of NAS at NAES Lakehurst, New Jersey, Sites I & J provided a comparison of technologies; in this case with a comprehensive numerical solute transport model constructed using the code RT3D and also using a regression analysis with extrapolation forward to determine TOR. NAS was employed to predict the decline in aqueous concentration resulting from the dissolution of the NAPL source at a nearby downgradient monitoring well. Because the composition and location of the source could not be well-defined during the monitoring program, two hypothetical source compositions were modeled using NAS: (1) single-composite NAPL source (total chlorinated ethenes) and (2) multiconstituent NAPL. The comparison is provided for the first case only.

Using NAS and calibrating to the first 5 years of data only, the single compound assumption yielded a best fit to the observed data using a source mass of 8,000 kg and a mass fraction of 0.05 (Figure 6). Unlike SEAM3D, which employs a mass balance approach to the source term, depleting sources in RT3D must be manipulated by the model users through the implementation of the model input (e.g., time-varying boundary condition). Source mass depletion must be calculated outside of RT3D (typically, in a spreadsheet) so that TOR is based on an assumed starting mass and model-simulated mass flux for the rate of depletion. The model user must make assumptions about the relationship between source mass and contaminant concentrations in groundwater (e.g., directly correlated) for implementation of the site model. The failure to capture the time trend using this approach is evident in the RT3D results (Figure 6). The simple data extrapolation method was employed using the complete data set. The inherent assumption with this approach is that source decay (i.e., groundwater concentration decline) is first order and will continue to decay at the same rate. A comparison with the source mass-balance approach suggests that a first-order solution may oversimplify the problem, resulting in overly optimistic estimates of TOR.

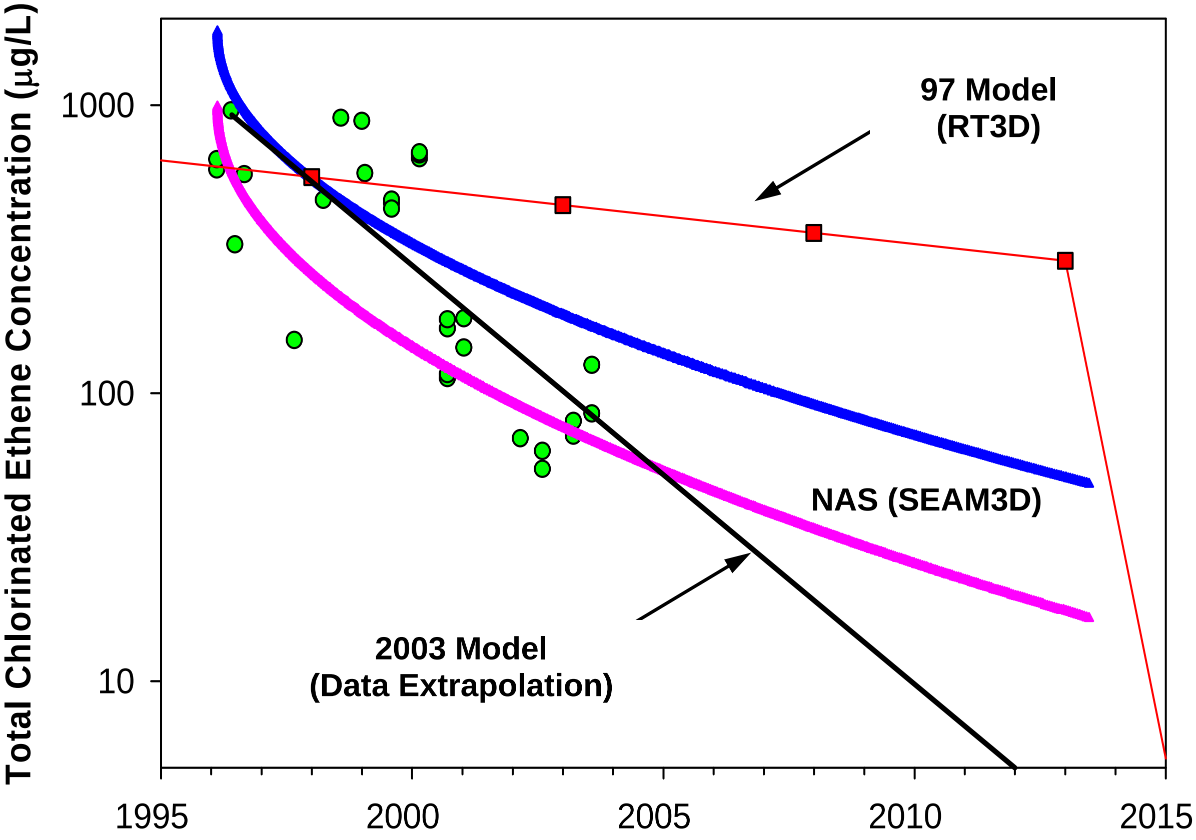


Figure 6. Observed Concentrations of Total Chlorinated Ethenes for Single-Component Source Models Using NAS and RT3D
(A first-order regression model is also shown.)

5.0 COST ASSESSMENT

5.1 COST REPORTING

The NAS software is used to estimate the time in which remedial objectives will be met. Once this time frame is established, the cost to monitor the site can be estimated. Typical costs associated with a long-term performance monitoring program include the cost of sampling and analysis of wells and an annual report compiling the progress of remediation for the site. Often, long-term monitoring programs incorporate more frequent sampling at the beginning of the monitoring program and a less frequent sampling as trends become established and seasonal impacts are understood. At sites where source remediation is combined with MNA, the cost of implementing source ERA is included. For this demonstration, the estimated cost was determined to sample the number of wells at the NAS Cecil Field site until the estimated time to reach remedial objectives was met. The basis for the cost estimate is summarized in Table 5.

NAS may be used as part of an RI/FS and in a postaudit analysis of a site where MNA with or without source remediation is the selected remedy. Under both of these scenarios the time and cost to build a comprehensive flow and transport numerical model can require significant effort including the additional cost associated with required field data. For this demonstration the estimated cost to implement NAS was determined and compared to the estimated cost associated with implementing a comprehensive flow and transport model to evaluate MNA. The analysis compares the cost of using the two technologies early in the RI/FS with the same data availability.

Table 5. Basis for Cost Estimates.

Cost Factor	Variables
Number of wells in sampling program	Optimized sampling program?
Frequency of sampling	Optimized sampling program?
Sample collection	Geographic labor rates and well characteristics
Field and laboratory analysis	Fixed base laboratory and field portable kits
Time to meet remedial objectives	Estimated within a range by NAS
Source zone removal	Yes/no?
Annual reporting	Geographic labor rates

5.2 COST ANALYSIS

5.2.1 Life-Cycle Cost Analysis

An estimate of the life-cycle costs of monitoring associated with TND for the current MNA remedy at NAS Cecil Field, Site 3 was developed in conjunction with NAS TOR estimates. The present cost of semi-annual monitoring for VOC, SVOC, and geochemical parameters at 11 monitoring wells is shown in Table 6. The cost of preparing an annual report is $100,000. The net present value of long term monitoring at Site 3 is estimated in Table 6 using both the estimated TND for TCE (43 years) and naphthalene (>69 years) to achieve NFA criteria. The net present value for monitoring over this period of time is at least $2,333,029. The accuracy of these cost estimates is largely dependent on the TOR and monitoring requirements. As a result of the high TOR estimates and associated life cycle costs as well as the loss of efficiency associated with MNA of the chloroethenes in the source area resulting from air sparging, additional optimization at Site 3 is recommended.

Table 6. Estimated Cost for MNA at NAS Cecil Field, Site 3.

Description	Annual Costs
Performance monitoring, reporting, and project management	$100,000
Total (TCE)[1]	$2,037,079[3]
Total (Naphthalene)[2]	$2,333,029[3]

[1] TND = 43 years
[2] TND = >69 years
[3] Assuming a 4% return on investment

5.2.2 Implementation Cost Analysis

An estimate of the cost to implement a model in conjunction with the scope of work associated with the RI/FS is highly site-specific. Comprehensive models for groundwater flow and contaminant transport are often used to evaluate a range of remedial strategies. Direct cost comparison to a previously implemented site (e.g., NAES Lakehurst) is problematic because work associated with implementation of models is typically buried inside the total cost of conducting a feasibility study at a site.

Table 7 provides a comparison of implementation costs for the two methods, quantifying TOR using NAS (v2) and using a comprehensive model. Although NAS is designed to be used by personnel who may not have adequate education and/or training to implement a comprehensive model, the same hourly rate ($150/hr) is used for this comparison. The development of a modeling plan entails evaluation of site data (hydrogeologic, contaminant, and redox indicator data), description of a conceptual model, and detailed plans for construction of the numerical model and parameter estimation. The latter task is not required for NAS but constitutes a significant labor cost for a comprehensive model. As reflected in the costs shown in Table 7, less documentation is required for NAS. To implement a flow and transport model at the same site, larger time requirements are largely due to the efficiency of NAS and the difficulty in constructing and calibrating a fully 3-D (or even 2-D) numerical model. In addition, the reporting requirements are substantially greater for documenting the comprehensive approach.

The ratio of the estimated cost of using NAS compared to the cost of using a comprehensive model is equal to the ratio of the estimated hours (5.6:1) to complete the analysis ($19,200 and $108,000, respectively). Note that the costs shown in this comparison do not account for establishment of a contract, management of this contract, or contracting rates and fees. It is reasonable to assume that the sum of these costs will be larger for an investigation using a comprehensive model. In addition, it is reasonable to assume that level of oversight by both a senior technical expert and regulating agencies will be greater in this case relative to NAS, resulting in higher costs for the use of a comprehensive model. Thus, the cost comparison (Table 7) may represent only a third or less of the overall cost.

Table 7. Cost Comparison of TOR Analysis Using NAS Versus a Comprehensive Model.

Task Description	NASv2	Comprehensive Model
Modeling plan	$6,000	$31,500
Model construction	$1,200	$12,000
Calibration and sensitivity analysis	$2,400	$24,000
Tor simulation	$3,600	$22,500
Reporting	$6,000	$18,000
Total	$19,200	$108,000

Another cost-saving feature of NAS is the number of monitoring wells required for TOR analysis. In the comprehensive modeling approach, data (concentration and hydraulic head) from monitoring wells throughout the site are used for model calibration. Because NAS only requires data from the approximate plume centerline, costs associated with sample collection and analysis can be substantially reduced using NAS.

For purpose of a comparison of the total cost savings, two hypothetical sites are considered; the “small site” and the “large site,” consisting of 20 and 50 monitoring wells, respectively. The small site consists of a stable attenuated plume <100 m in length. At the large site, the combination of the source mass flux and natural attenuation capacity results in a longer, but stable, plume. Although the number of active monitoring wells varies considerably from site to site, these values are for the purpose of illustration and calculation of cost savings. In the case of the small site, it is assumed that seven monitoring wells will reasonably represent the plume centerline. For the large site, the number of wells required to define the centerline is assumed to be eleven. These assumptions are based in part on the NAS site applications described in this report. Costs for laboratory and field analysis of groundwater constituents used for this comparison are $300 per sample for quantifying contaminant concentrations and $150 per sample for redox indicator data (inorganic constituents and dissolved oxygen). Analytical costs are for a one-time event and do not reflect monitoring over the life cycle of a site. Costs to implement a modeling approach at small sites are given in Table 7. For the large site cost analysis, the increases in modeling costs equal 10% and 20% for the small and large sites, respectively.

Table 8 summarizes the total cost for each case using the two modeling approaches. Analytical cost components are based on the rates presented above, while modeling cost components are presented in Table 7. The results show an overall per site cost savings between $94,650 and $126,030 can be realized by using NAS as the modeling approach. Although cost savings at any given site may exceed or be less than this range, the results suggest that considerable savings can be achieved to calculate TOR using NAS relative to comprehensive modeling (Figure 7). Since sampling labor was not accounted for, per application cost savings could be considerably higher.

Table 8. Cost Comparison and Savings for Two Hypothetical Sites of Differing Size.

Site	Conventional			NASv2			Cost Savings	
	Samples	Analytical[1]	Total[2, 3]	Samples	Analytical[1]	Total[2, 3]	Analytical	Total
Small	20	$9,000	$117,000	7	$3,150	$22,350	$5,850	$94,650
Large	50	$22,500	$152,100	11	$4,950	$26,070	$17,550	$126,030

[1] Analytical sampling and analysis costs = $300/well for contaminants and $150/well for redox indicators
[2] Total costs = Sum of analytical and modeling (Table 7)
[3] Cost increases for modeling large sites = 20% and 10% using conventional models and NAS, respectively

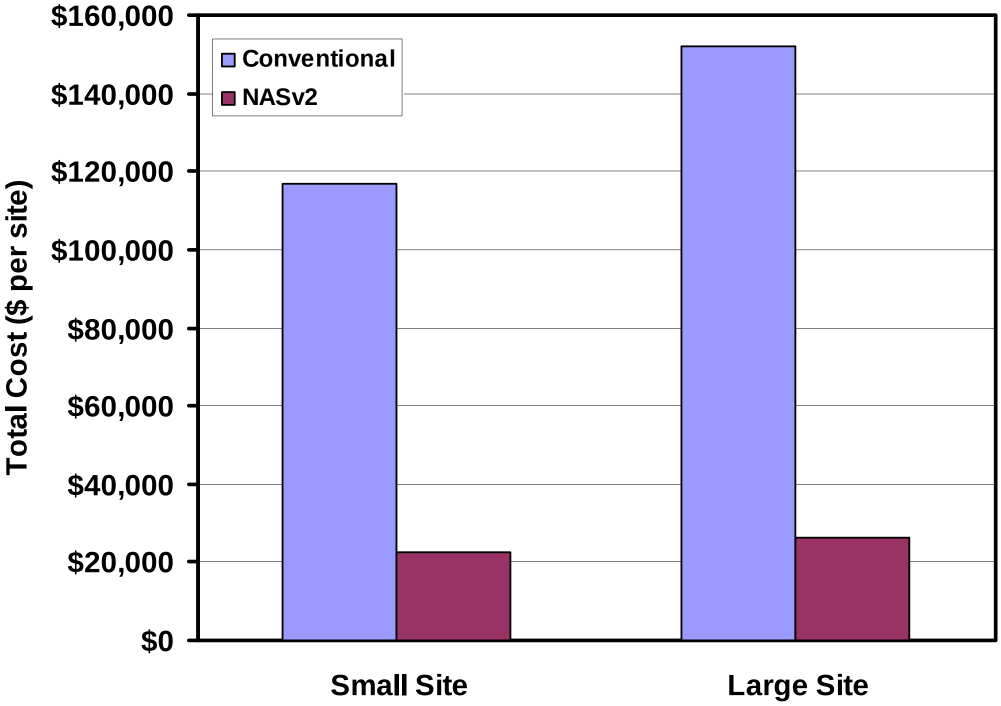


Figure 7. Cost Comparison for TOR Analysis at a Single Site Using a Comprehensive Model and NAS for Two Cases: Small and Large Sites
(20 and 50 monitoring wells, respectively).

A cost comparison illustrating potential cost savings achieved at multiple sites over a 5-year period is shown in Figure 8. The cumulative cost savings potentially realized by implementation of NAS on a national level by DoD RPM was calculated by assuming that NAS is being used to calculate TOR on an incremental basis over time. In this scenario, one site per month is modeled using NAS in year 1. In years 2 and 3, the number of sites increases to two and four per month, respectively, as a result of technology transfer efforts focused on the use and benefits of NAS. In years 4 and 5, the number of sites evaluated using NAS becomes five per month, resulting in the total of 204 sites evaluated using NAS. During the 5-year period, it is assumed that 75% of the NAS applications take place at small sites.

The cumulative 5-year cost savings to DoD by implementing NAS relative to a comprehensive model at contaminated sites for the purpose of estimating TOR is $20,900,000. Because this comparison does not factor in a rate of savings over time, the total may underestimate the true savings. This analysis does not factor in the additional potential cost savings to DoD at these sites by implementing an MNA-based strategy with or without source zone reduction. This type of analysis is highly site-specific, as illustrated by the NAS Cecil Field Site 3 example described in Section 5.2.1, Life-Cycle Cost Analysis.

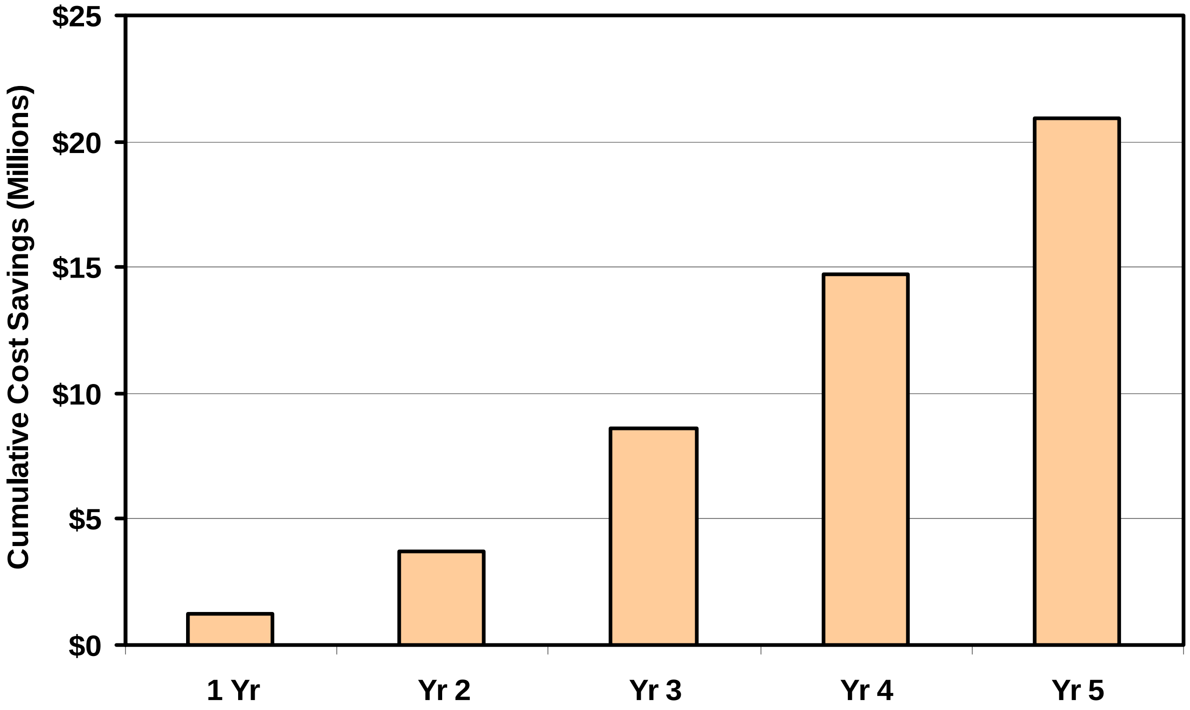


Figure 8. Cost Savings Using NAS Over a 5-Year Period
(beginning with 12 sites in the first year, 24 sites in the second year, and 48 sites in each of the remaining 3 years. The ratio of small sites to large sites is 4:1).

6.0 IMPLEMENTATION ISSUES

6.1 COST OBSERVATIONS

NAS is designed for use by site managers and consultants who have an educational background in groundwater hydrology and contaminant transport but who do not necessarily have advanced degrees in the area of numerical modeling. The cost to contract a consultant to implement NAS is consistent with a consultant's hourly rate to conduct an investigation using a comprehensive numerical model (with an identical TOR-based modeling objective). The primary difference in cost is attributed to the greater number of hours required for the latter to develop and set up the site model (both groundwater flow and solute transport) to perform calibration and sensitivity analyses and to document the work. Given a common starting point where data needs are sufficient for both approaches, it is estimated that the time required to complete the analysis with NAS is no more than 20% of the total number of hours expected to complete an investigation with a comprehensive flow and transport model. It is important to note that one conclusion of an application of NAS is the need to apply a comprehensive numerical modeling to a site to more adequately address site remediation options and TOR questions. However, the initial work with NAS, including data assembly and model results, will likely benefit the additional work and lead to cost savings through efficiency of effort.

6.2 PERFORMANCE OBSERVATIONS

NAS met all performance objectives and criteria. In cases where significant model assumptions were not violated, NAS was able to provide accurate estimates in the range of TOR. For the particular case of TOS calculations, NAS was applied in a predictive mode without calibration. Thus, the performance assessment of NAS to match observed data was not based on the results of a data fitting exercise. In addition to accuracy, the versatility of NAS was demonstrated in a variety of hydrogeological settings. Four sites were located in coastal plain regions, and the other four sites reflect more diverse and complex hydrogeologic settings. For the latter set of sites, a reasonable match between observed data and NAS simulation results of TOS and TND was obtained. NAS was employed at sites where several different source remediation technologies were applied. NAS proved to be reliable and applicable to each of the eight sites. Even for the case of a containment wall (Hill AFB) where the assumption of uniform flow was violated, the NAS application resulted in an adequate match with observed data at monitoring wells located a sufficient distance away from the wall where the groundwater flow returned to a natural condition.

6.3 SCALE-UP

Not applicable.

6.4 OTHER SIGNIFICANT OBSERVATIONS

Performance of NAS to predict the equilibrium concentration at a downgradient monitoring well following source remediation (TOS) is dependent on data quality (in this case, concentration of VOC in groundwater) and the proximity of the monitoring to the plume centerline. Experience has shown that data assembly and the development of a site conceptual model are not trivial efforts. It is beneficial to complete this step before proceeding with an application of NAS to a site. The data requirements for NAS are not excessive but should be considered in data collection strategies.

6.5 LESSONS LEARNED

NAS can be applied to sites either (1) as a stand-alone screening tool using preremediation data to determine what contaminant concentration leaving the source zone is needed to meet a site-specific remedial action objective (RAO) or (2) following source remediation using observed source zone data. For this demonstration, NAS was employed for the latter case where the observed, postremediation concentration at monitoring wells immediately downgradient of the source zone served as input to NAS.

In testing the DOS/TOS option, the point of the application at five sites was to show what NAS predicts at downgradient wells without fitting the results to the data (i.e., it was not a curve-fitting exercise). The NAS applications honored the source concentration following remediation observed at the field sites, and these inputs to NAS were not tweaked or modified to improve the fit to the data. In either case, NAS self-calibrates a steady-state solution to the preremediation plume concentration data and then calculates concentration versus time at downgradient monitoring wells using the field-measured source concentration following remediation. The best matches between the observed and simulated concentrations, including inflection points, were achieved at the monitoring wells closest to the source (travel distances ranging from 18 to 407 ft with an average of 185 ft from source). In general, less accurate results were observed at monitoring wells located further downgradient from the source. At one site where excavation was employed for source remediation (Seneca), a decrease in the apparent source width was observed following remediation that repositioned the plume centerline. NAS accounts only for a reduction in the contaminant concentration leaving the source zone and does not account for changes in the source width following remediation. The issue is amplified at sites where time fluctuations in the direction and magnitude of the groundwater velocity impact plume concentrations. Time fluctuations in concentration can be expected in situations where the contaminant mass flux “misses” the well if the direction of groundwater flow changes seasonally. The most accurate results were observed at NSB Kings Bay where the groundwater velocity was calculated based on tracer test data. These findings suggest that accurate determinations of the groundwater velocity and sorption parameters are required for improved accuracy of TOS following source zone remediation at all sites.

The most accurate results for concentration reductions following source remediation (TOS) were observed at the NSB Kings Bay, Georgia, site where the groundwater velocity was calculated based on tracer test data. These results suggest that because of uncertainty regarding hydrogeology, that NAS-derived TOR results (and not unlike any other model results) should not be viewed as a precise answer but as an initial estimate that will need further refining over time. These findings suggest that site resources directed toward quantifying groundwater velocity and sorption parameters will reduce uncertainly of TOS estimate following source zone remediation.

Results of the TND simulations show that NAS was capable of simulating the dissolution and dissipation of individual NAPL components at the remaining three sites listed in Table 6. In these applications, a match between observed and simulated concentrations at source area monitoring wells was achieved based on reasonable estimates of the mass and dimensions of the source zone along with composition of the NAPL. 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, the dependency of concentration versus time results on source zone mass and length, along with NAPL composition, suggests that source characterization methods have the potential to reduce the uncertainty associated with source dissipation calculations using NAS. The NAS simulation results also demonstrate the value and efficiency of refining TND predictions using postremediation data.

One finding of this demonstration was that NAS proved to be applicable to all eight sites, independent of hydrogeology, contaminants, characteristics of the source zone, or ERA. Therefore, the simplifying assumptions associated with the analytical solutions and the numerical source zone model do not appear to render NAS ineffective but, in fact, demonstrate the applicability and utility of NAS to a wide range of contaminated sites. In contrast, comprehensive three-dimensional numerical models that are constructed to simulate the complexities of a groundwater system and features of a plume often are subject to limited data and may include unrealistic boundary conditions that do not honor the actual field conditions. For example, the source term in many models (e.g., RT3D) is not based on the concept of mass balance. In contrast, the source model in NAS implements the NAPL dissolution package of SEAM3D in which mass is conserved for all components in the aqueous, solid, and NAPL phases. The results of this demonstration clearly suggest that because NAS is based on sound science, it can serve as an effective tool for decision making, data analysis, and cost optimization at a wide range of contaminated sites and is not limited to a small subset of “simple sites” because of its simplicity. However, there are many sites where complex hydrogeology, highly non-uniform groundwater flow, and the desire to simulate complicated remediation strategies will dictate the use of a comprehensive numerical model. At other sites, it may prove to be efficient to employ NAS as a precursor to a comprehensive (numerical) solute transport modeling investigation or as a follow-up to a previously completed modeling study.

6.6 END-USER ISSUES

Stakeholder buy-in is evident by the support provided by Navy Engineering Field Divisions. This is exemplified by the recently funded NAS upgrade to allow for incorporating of a source removal term. Earlier versions of NAS have been the subject of Navy-supported conference presentations (e.g., the annual RPM Conference in Port Hueneme) and a Remediation Innovative Technology Seminar (RITS) course module. End-user concerns, reservations, and buy-in factors all point to the RPM willingness to utilize the NAS approach versus a more comprehensive modeling effort. Concerns with implementation have been addressed through the NAS site applications using feedback from users during this demonstration.

NAS is designed for application to sites where the plume is reasonably well-characterized, stable, and not expanding with time. NAS is ideal for application to sites where data collection has followed DoD/EPA protocols for MNA. NAS provides value-added to sites where long-term performance monitoring and redox indicator data has been collected. NAS has helped to address at least one major criticism of MNA protocols. Specifically, technical guidance focused on what data to collect but did not adequately explain how to quantitatively utilize the data to address TOR and other MNA-related remediation questions. NAS provided the framework, technical guidance, and computational tool to achieve this end.

6.7 APPROACH TO REGULATORY COMPLIANCE AND ACCEPTANCE

NAS already is widely visible to regulatory agencies. NAS training has been delivered at many venues throughout the United States over the last 4 years. This includes 21 short courses to various professional organizations. Many have involved regulators, and in some cases, the project principal investigators have delivered courses and training directly to state and federal agencies. The principal investigators participated in seven invited presentations through the U.S. Navy RITS in which EPA and state regulators were present. In general, NAS appears to be widely accepted by regulatory agencies and in compliance with state and federal guidelines for site remediation investigations.

By documenting the effectiveness of NAS as a tool to predict time of remediation, regulatory acceptance will be facilitated. Furthermore, management decisions regarding source zone treatment can be enhanced through appropriate data collection activities driven by model input requirements followed by NAS simulations and cost benefit analyses.

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APPENDIX A

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