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I. DETAILS OF REQUEST FOR RELEASE

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Meeting/Journal: World and Environmental Resources Congress

Location: Anchorage Alaska USA

Meeting Date: 5/15/2005 to 5/19/2005

II. DOE-SR ACTION

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Conf. Dates 5/15/2005 to 5/19/2005

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WSRC-MS-2004-00691

Monitored Natural Attenuation and Enhanced Attenuation for Chlorinated Solvent Plumes - It's All About Balance

by

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MONITORED NATURAL ATTENUATION AND ENHANCED ATTENUATION FOR CHLORINATED SOLVENT PLUMES – IT'S ALL ABOUT BALANCE

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Abstract: Nature's inherent ability to cleanse itself is at the heart of Monitored Natural Attenuation (MNA). The complexity comes when one attempts to measure and calculate this inherent ability, called the Natural Attenuation Capacity (NAC), and determine if it is sufficient to cleanse the system to agreed upon criteria. An approach that is simple in concept for determining whether the NAC is sufficient for MNA to work is the concept of a mass balance.

Mass balance is a robust framework upon which all decisions can be made. The inflows to and outflows from the system are balanced against the NAC of the subsurface system. For MNA to be acceptable, the NAC is balanced against the contaminant loading to the subsurface system with the resulting outflow from the system being in a range that is acceptable to the regulating and decision-making parties. When the system is such that the resulting outflow is not within an

acceptable range, the idea of taking actions that are sustainable and that will bring the system within the acceptable range of outflows is evaluated. These sustainable enhancements are being developed under the Enhanced Attenuation (EA) concept.

Introduction

Transition from active treatment of chlorinated solvent plumes into efficient-effective MNA or EA is a crucial step in responsible environmental management. Chlorinated solvents represent many of the largest and most challenging plumes at Department of Energy (DOE) sites and across the U.S. To facilitate and accelerate implementation of MNA and EA, the DOE is sponsoring a three-year project that is identifying promising science and technology development topics and funding targeted field research, resulting in publishing technical guidance for selecting and implementing the new concepts. Specifically, the project is focused on encouraging the use of MNA and other sustainable enhancement methods in accordance with the principles embodied in the 1998 EPA protocol and 1999 EPA Office of Solid Waste and Emergency Response Directive. Three central concepts have emerged and are being developed. They are the mass balance framework, sustainable enhancements, and characterization and monitoring.

At a site with active attenuation processes, the development of a contaminant plume (Figure 1) can be roughly described in four stages: expanding, stable, shrinking and exhausted. The general requirements for environmental strategies that rely on attenuation are that the plume pose minimal risk (often by meeting a concentration standard at an agreed location) and the plume not expand. Thus, a key element in implementing MNA and EA is documenting that the plume is stable, shrinking or exhausted. Plume stability can be conceptualized as a balance between the delivery to and removal of contaminants from any groundwater system.

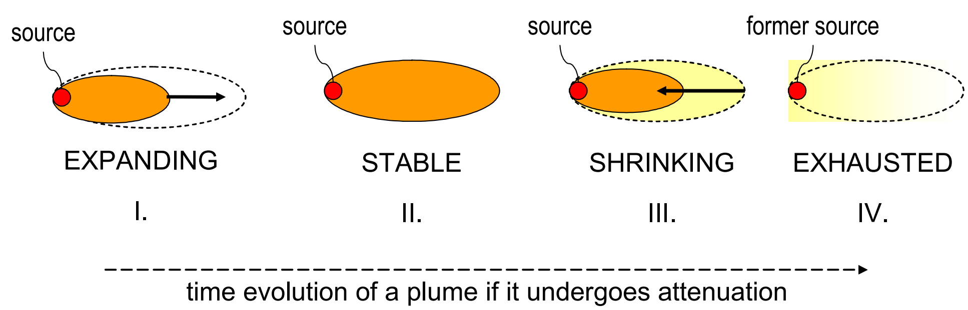

Figure 1. The four stages describing the development of a contaminant plume (adapted from Newell and Conner, 1998)

This information contained in this paper is a summary of the document, *Mass Balance: A Key to Advancing Monitored and Enhanced Attenuation for Chlorinated Solvents (Looney, et al. 2005, in progress)*.

Natural Attenuation Capacity

The NAC is the sum of all the physical, biological, and chemical processes serving to disperse, biodegrade, chemically transform, immobilize, or permanently sequester contaminants in a groundwater system. The basis for the NAC is the "assimilation capacity", a concept that is well known in soil science and surface water hydrology. NAC refers to the capacity of a ground-water system to transform and/or immobilize pollutants to innocuous byproducts. In surface-water systems, assimilation capacity depends upon abiotic (stream flow, mixing, and hydrodynamic dispersion), and biological (biological oxygen demand) factors and is often assessed using analytical or digital water-quality models. By analogy, a "natural attenuation capacity" for ground-water systems may be thought of as the capacity of an aquifer to lower contaminant concentrations as groundwater flows along the hydrologic gradient. The concept of balancing the loading and attenuation of contaminants in ground-water systems is a powerful framework for conceptualizing MNA.

The challenge in calculating the NAC is in accurately measuring the different processes that contribute to the system's attenuating capacity. Depending on the size of the system, different processes may be active in distinct sectors of the system. Thus, increasing the complexity of defining the NAC.

Mass Balance Concept

Mass balance is a simple accounting process that keeps track of loading (inflows), accumulation, destruction/creation, and releases (outflows). This is easily seen for a system if water is the substance being accounted (Figure 2). As shown, at steady state, the water entering from upgradient plus the water entering as infiltration must equal, or balance, the water flowing out of the system. If infiltration is reduced, then the water flowing out of the system will decrease until a balance is re-established. For systems that include contaminants, the NAC of the system is then included in the mass balance. These NAC processes provide additional outflows to the mass balance.

When a system is balanced with the NAC greater than the loading (inflow) such that the outflow meets agreed upon criteria, the system can be placed in a state of MNA. When a system is unbalanced with the loading greater than the attenuation capacity, the concept of EA is a potential method to bring the system back into balance. The key to EA is to have sustainable enhancements. These are intervention actions that continue to be effective until such a time that the enhancement is no longer required to reduce contaminant concentrations or fluxes. Technologies that fit into the class identified as EA enable the practitioner to segue from active/engineered treatment systems into the natural attenuation, no human intervention remedies.

Quantifying the Mass Balance

For sites where there has been a long, uninterrupted period of monitoring and no currently operating treatment system, use of an empirical approach for describing the

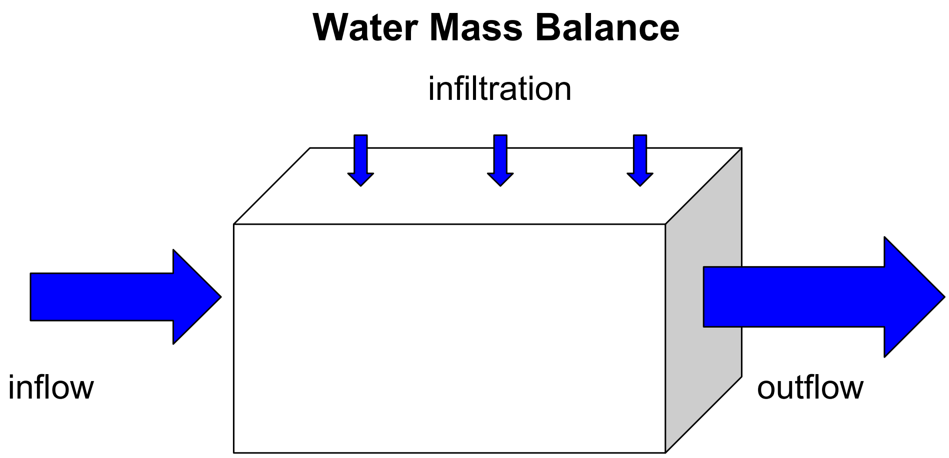

Figure 2. Steady state mass balance example for water in a subsurface system

mass balance is effective. The empirical approach is consistent with the 3 lines of evidence as described in the 1998 EPA protocol. The empirical approach uses site-specific monitoring data and gives the most accurate description of the past and present behavior of the hydrologic system. The empirical approach measures fluxes of contaminants moving through different transects of the hydrologic system directly using properly designed monitoring well networks (Figure 3). In this formulation, the NAC of a given part of the system can be defined as the difference between the flux in upgradient (MF_1) and downgradient (MF_2) transects, and can be expressed in units of contaminant mass attenuated per unit time (Figure 3). The main limitation of using the empirical approach is that one cannot use it to predict future behavior of the system. Because it is based on historical data, this approach does not have the capability to predict changes in NAPL dissolution rates over time, changes in electron donor and acceptor availability and changes in microbial community population and density. This approach cannot be used in situations where active remediation was initiated quickly and is currently operating. It can not be used as a tool to determine how much source removal is needed or when to turn off active remediation and transition to MNA. It can not be used to evaluate potential enhancement options (unless a long period of post enhancement monitoring is planned).

Alternatively, a deterministic approach can be used to assess mass balance and plume stability. In this approach, the physical, chemical, and biological attenuation processes are used to assess contaminant loading and attenuation (Figure 4). The deterministic approach has the advantage that, when sufficient hydrologic, geochemical, and microbiological data are available, it is possible to project how a system will respond to contaminant removal actions or enhancements of natural attenuation processes. The main disadvantage of the deterministic approach is that it is difficult to measure all or most of the relevant hydrologic, geochemical, and biological parameters with any certainty. Nevertheless, because of the time-dependent formulation of the mass-balance equation, it becomes possible to estimate the future

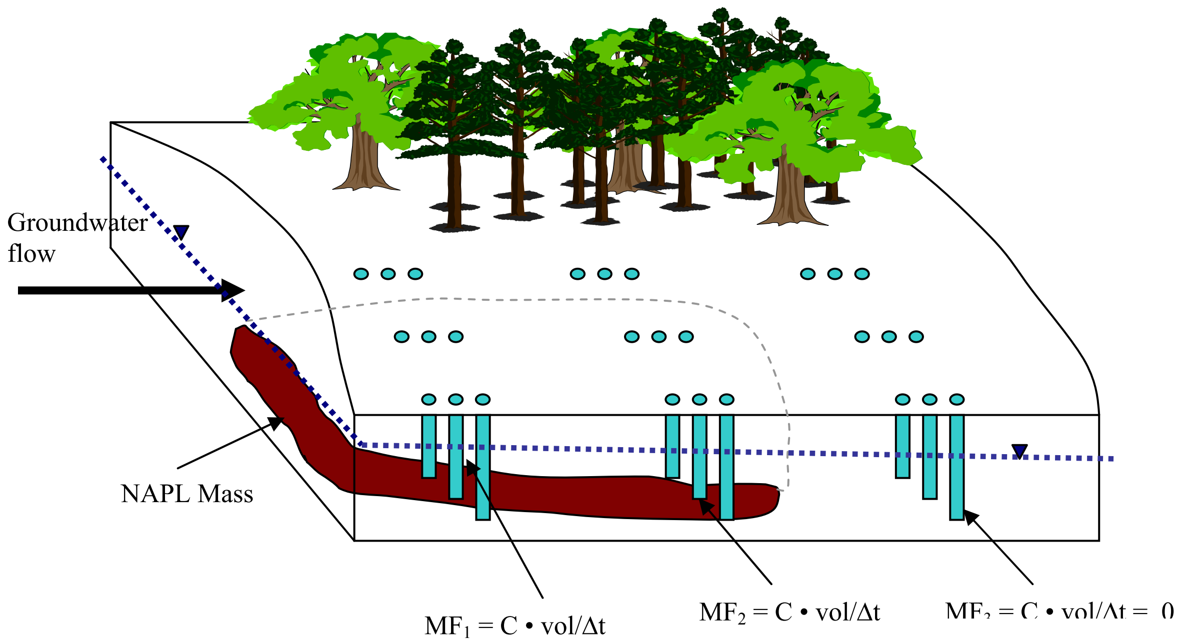

Figure 3. The Empirical Approach to describing the mass balance of a system depends on site-specific monitoring data.

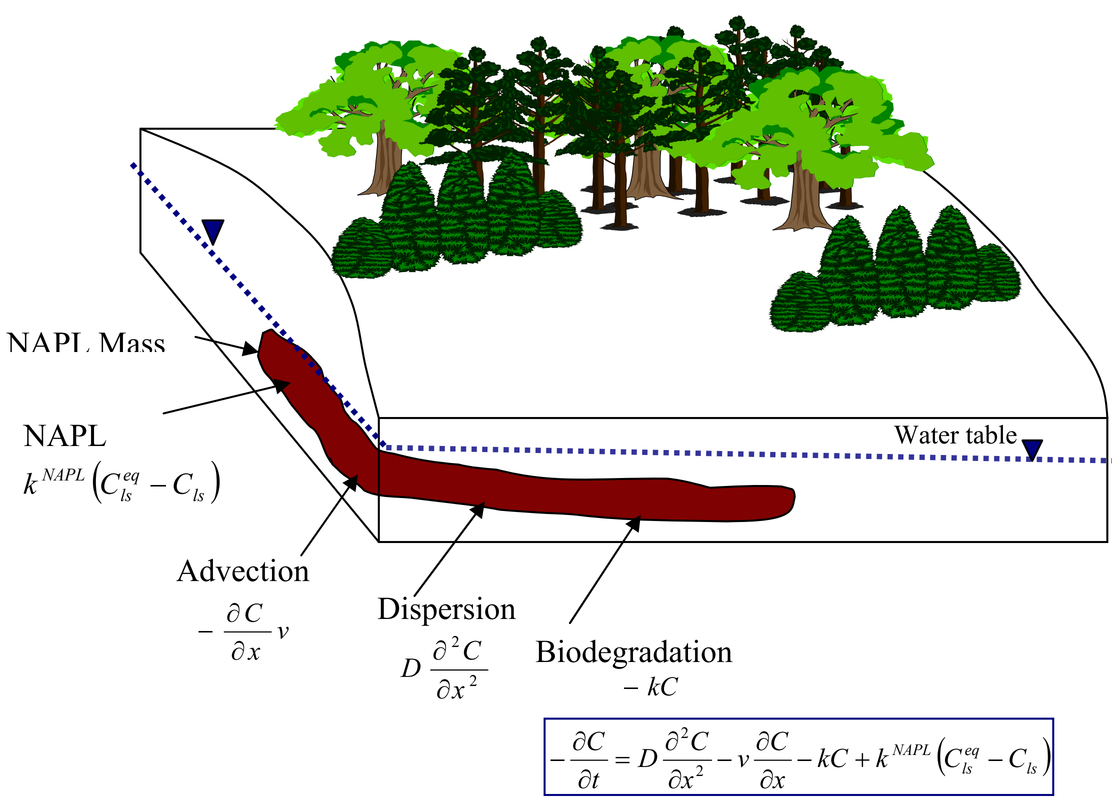

Figure 4. The Deterministic Approach to describing the mass balance of a system depends on site-independent principles of physics and chemistry.

behavior of the contaminant plume. That, in turn, raises the possibility that times to complete remediation associated with different remedial strategies may also be estimated.

An important way that the deterministic mass balance approach can be used has to do with what has been termed the time of remediation (TOR) associated with monitored natural attenuation. According to EPA guidance, MNA is appropriate to use as a remedial strategy when *"...it will meet site remediation objectives within a timeframe that is reasonable compared to that offered by other methods*" (EPA, 1999). Thus, estimating the amount of time required for natural or enhanced attenuation processes to attain regulatory objectives is a necessary step when evaluating MNA as a remedial technology. In concept, estimating the length of time required for natural processes to remove a particular contaminant from a ground-water system ($t_{remediation}$) is also a simple mass balance problem.

$$t_{remediation} = {\left[M_0 - M_{threshold}\right]} \Big/ {R_{NA}} = TOR \qquad (1)$$

where, M_0 is the initial mass of the contaminant, $M_{threshold}$ is the acceptable contaminant mass and R_{NA} is the rate of the natural attenuation processes.

In addition to providing a working definition of TOR, equation 1 indicates the kinds of information necessary to make remediation time estimates. This information includes 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 variables. In practice, however, the problem is much more complex then indicated by equation 1. The rate of natural attenuation processes, particularly rates of biodegradation, may vary with time, so the rate that contaminants are destroyed may not be constant but rather vary as a function of time (and/or space). One way to address these complexities is to combine the empirical and deterministic approaches.

Integrating the Empirical and Deterministic Approaches to MNA

While fundamentally different, the empirical and deterministic approaches to describing and evaluating mass balance associated with MNA are not mutually exclusive. If applied systematically, these approaches can be highly synergistic. The empirical approach, for example, is entirely based on site-specific monitoring data and provides a mass balance that describes a site at only that point in time. As such, it is capable of giving the most accurate description of past and present conditions *providing sufficient data have been collected.* On the other hand, the deterministic approach is based on universal, quantifiable physical and chemical processes that apply to all sites. Furthermore, the mass balance equations developed are time-dependent (Equation 1). This, in turn, raises the possibility that the deterministic approach can provide estimates of the future behavior of sites. The accuracy of these predictions depends on how well the time-dependent mass balance equations are constrained by actual site data. As such, the deterministic approach is capable of providing the most accurate description of future conditions *providing sufficient data have been collected.* Thus, the empirical and deterministic approaches can be blended to most accurately describe the past and present behavior of a given site, as well as predict its future behavior.

One scenario of how the empirical and deterministic approaches can be integrated to assess the ability of MNA to attain site-specific remediation goals is shown in Figure 5. It begins with an entirely empirical description of the system, with the natural attenuation capacity being estimated from monitoring data. Based on this data, a determination of whether MNA is by itself sufficient to attain site-specific remediation goals can be made. In practice, this usually consists of demonstrating that the plume is stable or shrinking, and that it is not impacting sensitive receptors. In cases where MNA is not by itself sufficient, at least two approaches can then be taken (Figure 5). On one hand, removal or treatment of highly-contaminated source-areas can be undertaken in order to lower the delivery of contaminant mass to the system. Alternatively, the attenuation capacity of the aquifer can be enhanced using engineered methods such as biostimulation, bioaugmentation, or phytoremediation. In either case, now that the system has been perturbed, the empirical approach is no longer sufficient to assess site behavior. To assess how the newly engineered system will behave over time, in particular estimating when remediation goals may be reached, requires the deterministic approach.

One of the useful features of an empirical description of a system is that data are available for "harvesting" model variables such as D, v, K_d, k_{bio} from site data. Once these variables have been estimated, it is possible to construct a site-specific deterministic model (Figure 5). These models, in turn, can be used to estimate the future behavior of the site. In particular, it is possible to project into the future to estimate when site-specific remedial goals may be reached. While such projections are estimates, constrained entirely by the accuracy of the assumed model variables, they can be useful in comparing times of remediation associated with different engineering approaches. If the deterministic models indicate remedial goals may *not* be reached, it is possible to cycle back to the source removal/enhance NAC step and make appropriate adjustments. Several difficult problems remain, however. For example, if the NAC is not sufficient (Figure 5, dashed line) – How much source removal, enhancement and/or active remediation will be needed? How can NAC be estimated to allow turn-off of active remediation, when several years of empirical data without the system operating and with multiple lines of evidence are typically "required?" Here too, the mass balance concept may be helpful to develop a defensible and appropriate final flowchart with additional deterministic steps inserted to facilitate decisions.

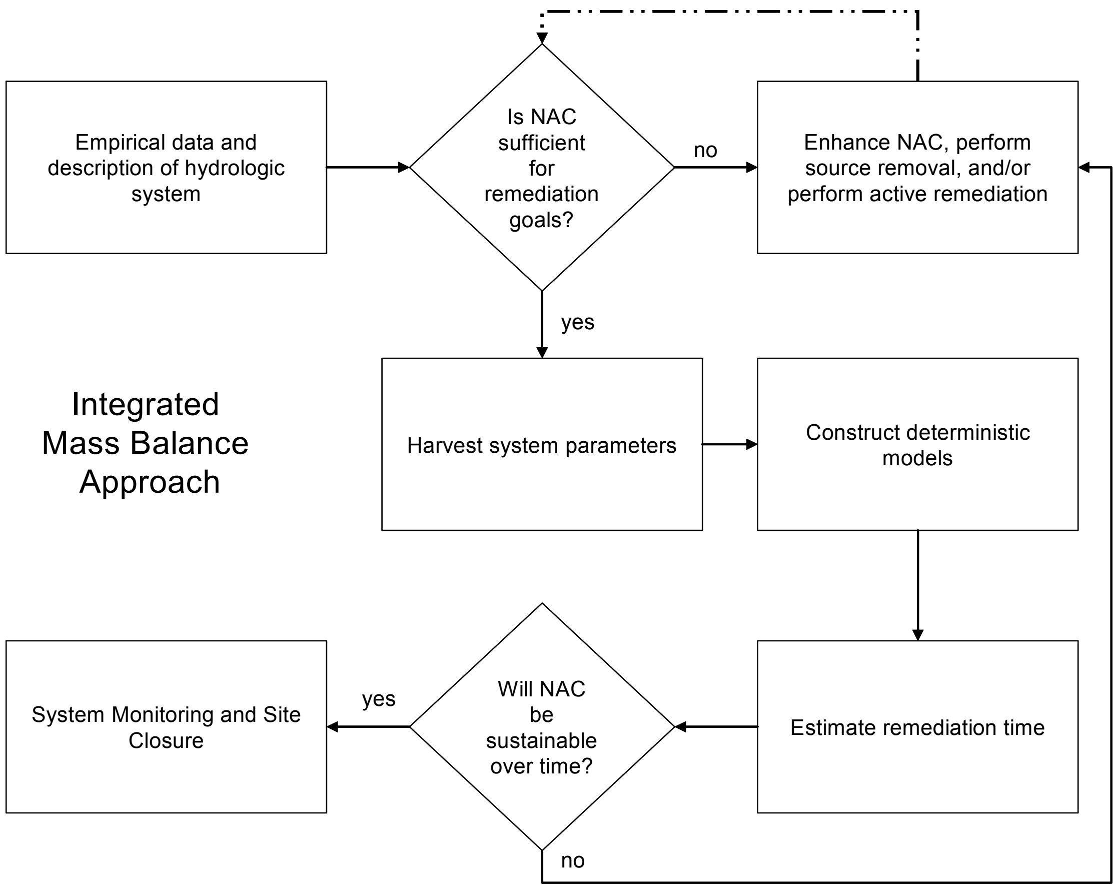

Figure 5. An example of integrating the Empirical and Deterministic Approaches to determining the Mass Balance for a system where MNA is a potential remedy.

Thus, while the empirical and deterministic approaches are very different in scope and application, they can be effectively combined in order to address issues of natural and enhanced attenuation, and issues of time of remediation.

Processes Contributing to the Natural Attenuation Capacity of a System

One of the complexities in calculating the mass balance of a system is that the natural attenuation capacity of the system comprises multiple processes. The relative contribution of each process contributes to the complexity of the mass balance. If one process greatly dominates the other processes, it may be reasonable to focus the evaluation and the resulting monitoring on that process. However, in many instances, there most likely will be several processes that contribute to the NAC such that none greatly dominates the others requiring all to be incorporated into the mass balance.

Thus, knowing this relationship among the attenuating processes is paramount to determining the complexity of the system.

A parametric analysis of various processes was performed. This analysis provides a qualitative understanding the relative importance of various attenuating processes that may be active within a system. The parametric evaluation was based on a sequence of analytical models in which processes and complexity were added one at a time to determine the relative impact on plume stability and maximum plume size.

To support the parametric evaluation, an approximate range of the various key model coefficients was tabulated based on values reported in the literature (Table 1). For each coefficient, a "low," "moderate" and "high" value is provided that generally spans/represents the values typically observed. A few additional bounding values are documented in Table 2 to support the extended analysis. In general, the parametric analysis provides a generic description of the behavior of a plume as a function of the various parameters. The process also generates a specific range of plume sizes for the bounding combinations of parameters from Table 1 (see EPA, 2000 ; Aziz, et al. 2002). As a result, this process will help assess the relative significance of and interactions among the various attenuation mechanisms and provides insight into the actual physical size of plumes controlled by attenuation.

Table 1. Key Site Parameters That Influence MNA/EA

	groundwater seepage velocity, v_s (m/yr)	contaminant retardation factor, $R = v_s / v_c = 1 + (K_d \rho_b / n)$ (dimensionless)	1st order contaminant degradation rate constant in plume, λ (1 / yr)
Low	10	1	10^{-1}
Moderate	25	1.5	1
High	100	5	5

Table 2. Bounding values for remediation goals and the derived parameter (L_λ)

	Required concentration reduction factor to meet goal C / C_0 (--)	Characteristic transport length for bounding calculations, $L_\lambda = (v_s / R\lambda)$ or $= (v_s / \lambda)$, see text (m)
"best case"	10^{-1}	0.4
"intermediate case"	10^{-2}	17
"worst case"	10^{-3}	1000

The processes evaluated were for three cases: a) no dispersion, steady state source, plug flow with degradation, b) longitudinal dispersion, steady state source and c) longitudinal dispersion, decaying source (Figure 6). The analysis does not account for the dilution effects caused by the dispersion of contaminant away from the plume centerline – these factors are left constant in a "worst-case" configuration to allow reasonable assessment of the importance of the included primary factors. Depletion of the source over time is not accounted for in two cases where there is a steady state

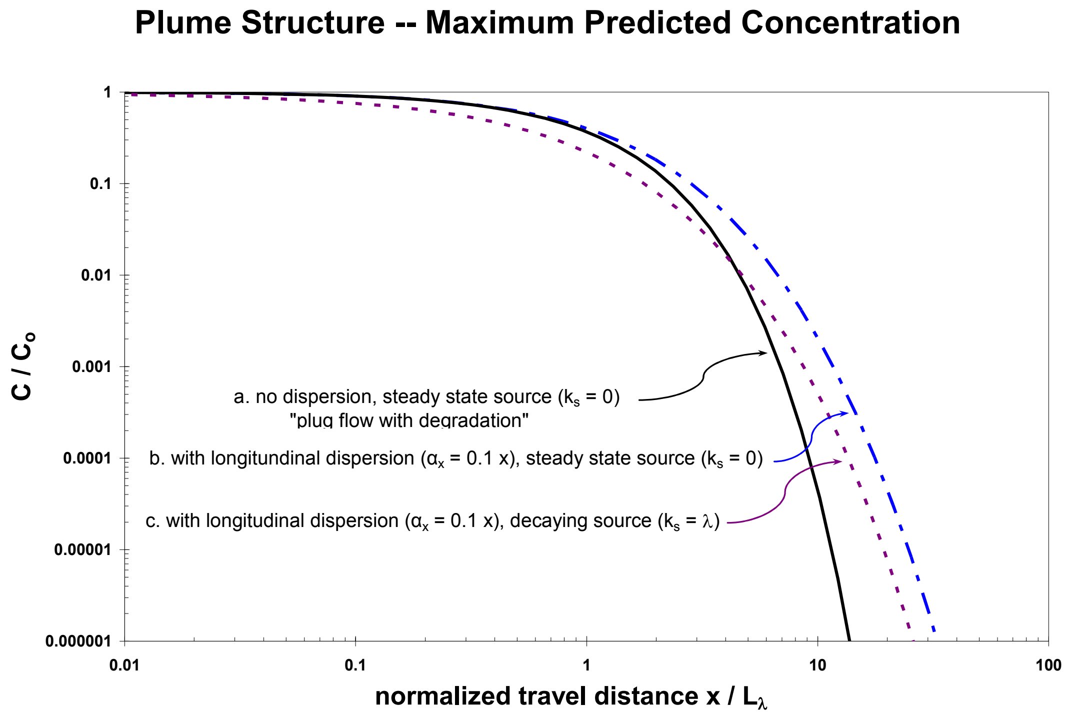

Figure 6. Normalized graph showing plume size and structure for a 1D plume under different assumptions about the source and longitudinal dispersion.

source. The analysis does not follow the formation and fate of daughter products and does not take credit for the lowering of concentrations that result from the size, shape, or mass depletion within the source zone.

The 1D models are all well behaved. In each case, the plume behavior is predictable based on a characteristic transport length -- the reduced variable, L_λ. Figure 6 is a graph of all three 1D cases in which the travel distance has been normalized to L_λ. Each of the cases is now represented by it's type curve. The x-axis is represented by the dimensionless x/L_λ. It is clear from this analysis that the most significant factors controlling the plume are those that are embodied in L_λ. As expected, the most significant factor in spreading the plume is groundwater flow. The factor that has the most potential for contributing to plume stabilization is degradation. If degradation occurs in both the aqueous and sorbed phases, then retardation is also included in L_λ and is significant. As shown in Figure 6, source decay can also play a measurable role in plume stabilization. Longitudinal dispersion tends to increase, rather than decrease, plume size.

The last evaluation conducted was that of transverse dispersion (Figure7). The graph shows the scaled attenuation factor that estimates the impact of transverse dispersion ($f_y/2$) versus the flow distance. This figure clearly documents that concentration reductions and stable plumes (even for continuous and inexhaustible sources) are predicted even in the absence of degradation mechanisms. Importantly, however, the attenuation impacts are much weaker than those that are embodied in L_λ. This is clear in the scale of the graph. The y axis, representing degree of attenuation, spans only three orders of magnitude (versus six orders of magnitude on Figure 6). Also, the x axis, representing the scale over which the attenuation is occurring, has been extended by three orders of magnitude. Nonetheless, the graph suggests that for small sites where concentration reductions of 0.1 to 0.01 are needed, that a stable/shrinking plume less than 1000 m is possible.

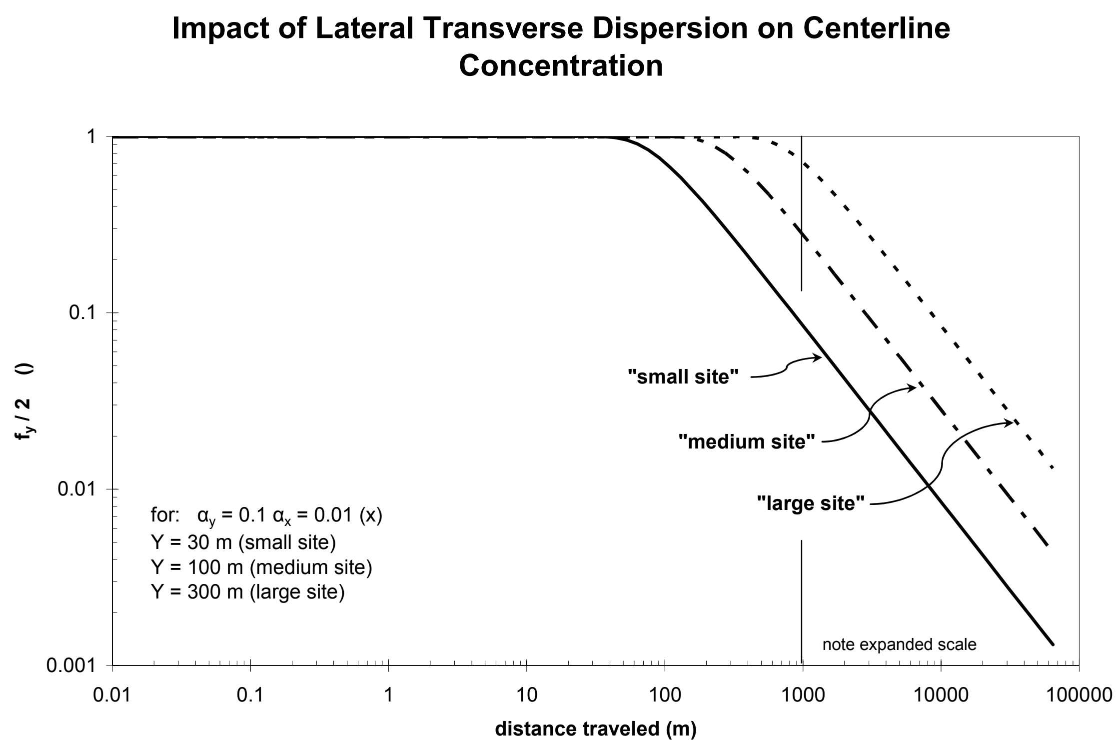

Figure 7. General impact of transverse dispersion on centerline plume concentration – scaled attenuation contribution versus flow distance.

Summary

The conceptual developments and parametric evaluation are the first steps in developing technical guidance related to implementing the mass balance concept. At sites where the empirical approach to evaluating MNA, which is consistent with the EPA lines of evidence approach, produces a robust case supporting or negating the implementation of MNA, the empirical method should be used. However, there will be sites where the complexity of the geologic/hydrogeologic setting and/or the availability of monitoring data will preclude the use of the empirical approach and will lead towards the deterministic approach. By integrating the empirical and deterministic approaches, one uses all the data available for decision-making resulting in a robust case supporting future actions and validated on historical data.

Work is progressing in several directions to further our knowledge. Several research teams are integrating attenuation processes into several models including BIOCHLOR and RT3D. Decision-making tools are being developed to aid practitioners decide on the types of data they should put their resources towards gathering. The project's core technical team will be evaluating the distinct processes that make up the Natural Attenuation Capacity of a system to develop guidance on the viability of these processes in impacting the NAC and thus the mass balance of a system.

References

Aziz, Carol E., C. J. Newell and J.R. Gonzales, 2002. Biochlor Natural Attenuation Decision Support System, Version 2.2, User's Manual Addendum, Groundwater Services Inc., Houston, TX. March 2002.

EPA, 1998. *Technical protocol for evaluating natural attenuation of chlorinated solvents in ground water,* EPA/600/R-98/128: Office of Research and Development, U.S. Environmental Protection Agency, Washington, D.C., p. 232.

EPA, 1999. *Use of Monitored Natural Attenuation at Superfund, RCRA Corrective Action, and Underground Storage Tank Sites, Final*, Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C., April 21. Directive Number 9200.4-17P.

EPA, 2000. *BIOCHLOR Natural Attenuation Decision Support System Users Manual Version 1.0*, EPA/600/R-00/008, U. S. Environmental Protection Agency, Office of Research and Development, Washington DC. January 2000.

Newell, C.J. and J.A. Connor, 1998. *Characteristics of Dissolved Petroleum Hydrocarbon Plumes*, Version 1.1, American Petroleum Institute. December 1998.

Looney, B.B., F. Chapelle, D. Major, M. Ankeny, T. H. Wiedmeier, 2005. *Mass Balance: A Key to Advancing Monitored and Enhanced Attenuation for Chlorinated Solvents,* Westinghouse Savannah River Company, Aiken, SC. In progress.