A PROPOSED STRATEGY FOR RESTORATION OF CONTAMINATED GROUND WATER

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ABSTRACT

The Department of Energy has recently completed a review of the groundwater contamination issues at sites throughout the complex. Data from 20 sites covering 134 plumes indicates substantial effort and cost will be required to meet regulatory requirements over a period of hundreds of years. As a consequence, the Department has developed a strategy for groundwater restoration aimed at minimizing unnecessary costs. The strategy is structured around the current EPA programmatic expectations and the practicability of meeting specific goals in reasonable timeframes. For sites that will require extensive restoration efforts, the approach is divided into threes phases aimed at source control, containment and, ultimately, restoration. This paper describes the strategy and the decision logic that drives it. Ramifications with respect to cost savings and alternant investigation approaches are also addressed.

INTRODUCTION

Restoration of ground water contaminated from activities at sites for which the Department of Energy (DOE) is responsible poses a daunting task. Challenges arise as a result of difficult hydrogeologic settings (e.g., karst, fractured rock, extreme depth), unique contaminants (e.g., tritium, technetium 99, dense non aqueous phase liquids [DNAPL]), and the sheer volume of water and contaminants involved. With remedies selected or proposed for 97 of 134 plumes identified in a recent Departmental survey, the annual cost of operation and maintenance for remedies is estimated to be $78 million per year. When extrapolated across the estimated years of operation, the reported cost exceeds $3.1 billion. These estimates are only a portion of the ultimate cost, since they do not reflect all the plumes and in several cases, time frames likely have been underestimated. Total cost is likely to exceed $4 billion. As a consequence, there are clear incentives to develop a groundwater restoration strategy to help identify the sequence of activities that will provide the greatest level of risk reduction/resource restoration for a given level of expenditure.

Currently, the greatest cost for restoration of ground water at DOE sites is associated with operation and maintenance of pump and treat systems. Pump and treat is often applied as the default remedy for ground water and is specified as the sole remedy or a portion of the remedy in two thirds of the DOE plumes for which remedies have been selected. Most of these systems were selected under the assumption that they will be able to restore the aquifer to a quality that would support potable use of water. However, experience has shown that pump and treat remedies cannot achieve such restoration in reasonable time frames in many settings typical at DOE sites. Indeed, in a 1994 review of pump and treat remedies in the U.S., the National Research Council (1) determined that at 69 of 77 sites studied, restoration had not been achieved to date and could take extended periods of performance for contaminant concentrations to be reduced below Maximum Concentration Limits (MCLs). In general, once initial concentrations have been reduced, the pump and treat operation transitions into a mode where large quantities of relatively dilute water are pumped for decades with little or no real reductions in concentration. Thus, the cost/benefit ratio of operating the systems plummets with larger and larger sums being expended for little, if any reduction in risk. At this point, there may be more efficient ways to restore the aquifer in similar time frames. Transition to these more cost-effective approaches can save substantial amounts of money with no real loss of risk reduction.

DESIGNING OPTIMAL RESPONSE STRATEGIES

Faced with the reality of how pump and treat systems have performed historically, there is need to more fully consider its important, but limited role in aquifer restoration, and to recognize that once higher concentrations have been removed, there may be more efficient ways (e.g., monitored natural restoration, permeable treatment barriers) to restore the aquifer in similar time frames. In this context, aquifer restoration can be viewed as a multi-part activity: 1) **source removal phase** - in which remedial measures eliminate the active source(s) contributing contaminants to the subsurface; 2) **mass removal and/or containment** - in which the higher level concentrations are removed to effectively control contaminant migration and contribute to the "containment" of the plume ; and 3) **aquifer restoration** - in which natural processes attenuate residual, lower level concentrations to below the specified cleanup criterion. In situations where complete restoration is considered technically impracticable, response measures to control a plume or minimize the potential impacts to the environment also may involve multiple activities or phases.

Regardless of whether aquifer restoration is practicable, the key to designing an optimal strategy is to know what technology to apply for each phase of the response, and when to transition between phases. In addition, decision makers need to determine how best to communicate or "package" the response plan to stakeholders to ensure they fully understand the objectives for each phase, how performance in meeting these objectives will be measured, and how protection will be ensured in the event specific objectives are not fully realized. As a consequence, a groundwater restoration strategy must explicitly consider each of the following: 1) identification of specific remedial action objectives and likely technology(ies) for each phase of the response; 2) development of transition strategies between phases and an exit strategy for when the final phase is complete and remedial objectives have been met; and 3) packaging the response strategy to facilitate stakeholder acceptance. Each of these key considerations is discussed below.

For the following discussion, it is assumed that: 1) any unacceptable risk to human health (e.g., supply wells above threshold concentrations) or the environment (e.g., plume discharge to stream threatening an endangered species) have been addressed such that no unacceptable exposures currently exist; and 2) a conceptual site model for the site has been developed and there is a good understanding of the specific problem(s) being addressed.

IDENTIFICATION OF REMEDIAL ACTION OBJECTIVES AND LIKELY RESPONSE ACTIONS

Traditionally, remedial action objectives (RAOs) have focused on one or more elements of a complete exposure pathway through which unacceptable risk is posed. As such, RAOs historically have ranged from removal of source materials, to termination of release mechanisms or transport routes, or elimination of direct exposure routes to potential receptors. With respect to ground water, however, the U.S. Environmental Protection Agency's (EPA's) goal is to restore ground water to its highest beneficial use regardless of whether the extant contamination poses an actual risk. As a result, this resource-based approach initially narrows the field of candidate RAOs to restoration. At the same time, EPA recognizes that restoration may not always be practicable and therefore has developed a hierarchy of programmatic expectations that provides alternate RAOs as outlined in the following:

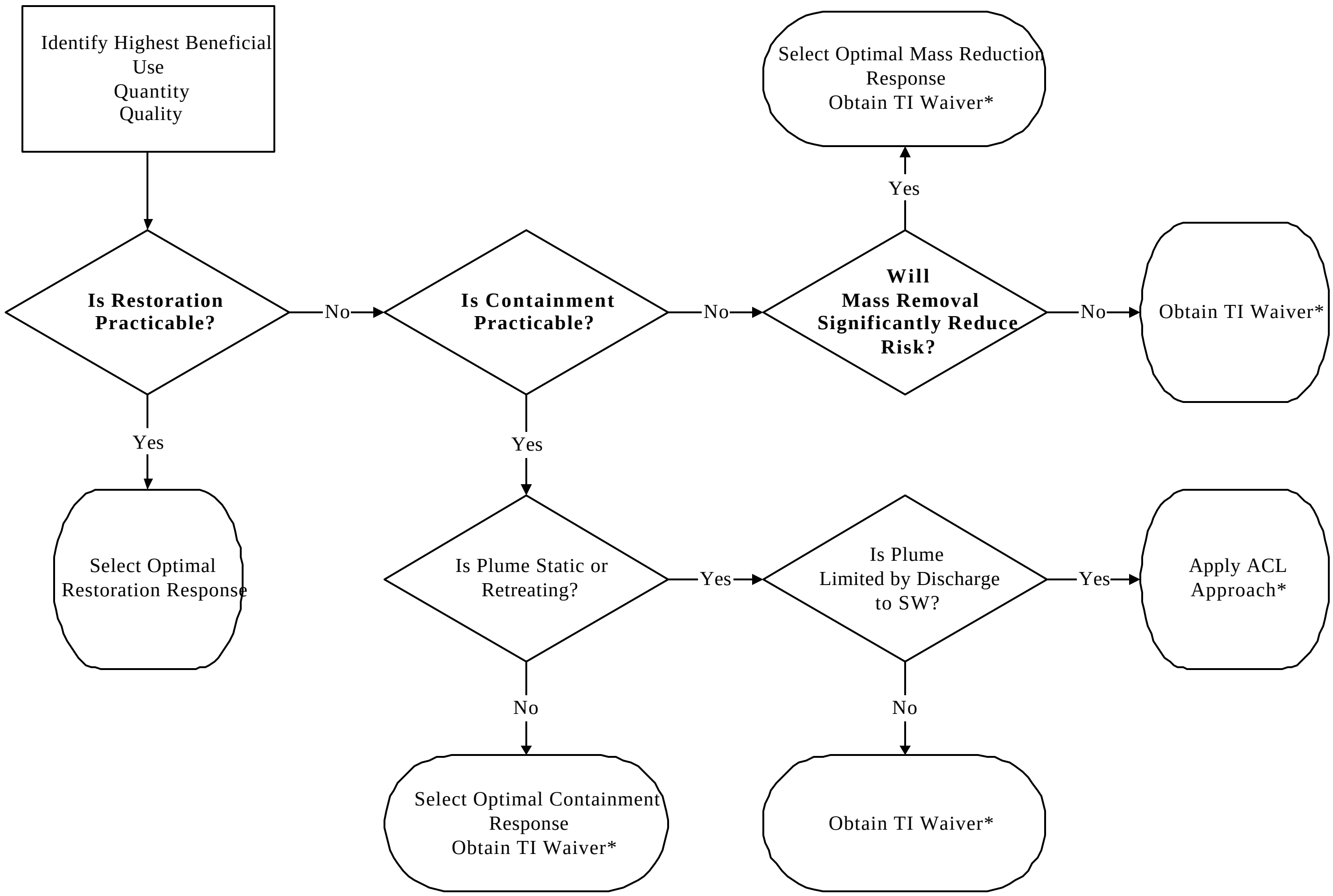
- Restore aquifer to highest beneficial use;
- Stop plume growth and migration of contaminants; and
- Reduce the toxicity, mobility or volume of contaminants.

When applied as a decision logic flow, these programmatic expectations can be used to guide the identification of the RAO(s) that should be selected and, ultimately, the response(s) that should be taken. In other words, this hierarchy can be used to construct a strategy to investigate and restore ground water, or when the latter is impracticable, to establish alternative approaches to ensuring human health and the environment are protected adequately..

Aquifer Restoration

As illustrated in Figure 1, the decision logic begins with a determination of the highest beneficial use for the aquifer. Although most states and the EPA hold that groundwater should be considered a source of potable water regardless of its current use, physical and chemical limitations may preclude such use. In general, aquifers are not considered as sources of drinking water if they have excessive salinity or if they cannot yield sufficient water. The actual threshold values for quality and yield differ from state to state and must be determined on a site-specific basis. However, the existence of such thresholds establishes two high priority information needs as: 1) ambient water quality with respect to salinity and any natural toxins (e.g., arsenic); and 2) aquifer yield.

If the aquifer qualifies as a potable supply, restoration will be required for any contaminants observed above their respective MCL. If the aquifer does not qualify as a potable supply, it will be necessary to determine what its classification is, what criteria apply to that classification, and whether any contaminants exceed their respective criterion. In general, if no contaminants are present above their criterion, no restoration is required. (This is not universal, since states with promulgated non degradation standards can require restoration even when drinking water criteria have not been exceeded.) If criteria are exceeded, first priority is placed on restoration to a quality that does



*Will require long-term monitoring and access restrictions

Figure 1. Decision Logic Flow for Groundwater Response not exceed criteria.

Restoration is achieved in one of two ways: 1) sufficient contaminant mass is removed from or immobilized in the affected area; or 2) sufficient contaminant mass is destroyed to reduce soluble concentrations below target criteria levels. Heterogeneity, isotropy, permeability, extraction potential and solubility determine our ability to remove contaminants from or to deliver reagents in the matrix. The lower the required criterion, the more difficult it is to remove or destroy a sufficient mass of contaminant. In general, restoration is more easily accomplished in aquifers that are homogeneous, isotropic and highly conductive. Similarly, restoration is easiest with contaminants that are highly soluble, readily extracted from water, and assigned higher concentrations for MCLs. Restoration becomes more difficult with heterogeneity, anisotropy, reduced permeability, reduced solubility, low MCL levels, and increased difficulty of extraction or destruction. Examples of circumstances that pose a severe challenge to restoration are dense non-aqueous phase liquids (DNAPL) and chemicals with a target concentration of less than 5 ppb in complex alluvium, fractured rock or karst systems.

Although EPA has not explicitly established a limit on what constitutes a "reasonable time" for restoring ground water, several EPA Records of Decision (RODs) have made findings of technical impracticability when restoration would require more than 100 years. The Department believes a threshold of 100 years is an appropriate yardstick on which to base determination of practicability. As indicated above, the practicability of restoration within that time frame will be a function of both the contaminant(s) and the matrix. Therefore, the focus of investigations turns to an evaluation of the nature and extent of the contamination and the aquifer matrix *to the degree required to determine if restoration is practicable, i.e., to predict the time required for candidate responses to achieve criteria concentration* *levels in the aquifer*. Essential data include estimates of contaminant inventory, pore water flushing times, partitioning, and connectivity. Important considerations are:

- Pump and treat will flush the permeable conduits while contaminant migration from less permeable zones will be diffusion limited and may sustain ppb range concentrations indefinitely
- Pump and treat systems will not extract DNAPL effectively
- The difficulty in locating DNAPL and the high degree of effectiveness required for removal or destruction of DNAPL hinder the ability of current technologies to reduce restoration times to less than 100 years
- If reagents are not significantly more mobile than contaminants, in situ approaches based on the introduction of chemicals will suffer the same limitations as pump and treat
- Passive remedies such as permeable treatment walls require the contaminants to come to them and therefore are constrained to natural flushing times

Given these considerations and the low criteria levels associated with many contaminants, practicability may be less frequent than originally anticipated. However, a conclusion that restoration is impracticable (i.e., will take longer than 100 years) is simply a recognition that remedial measures using currently available technologies are unable to achieve the desired goal in a reasonable time frame. Implicit in this conclusion is that the cost-to-risk reduction efficiencies in pursuing active restoration are minimal and that a different focus will be needed to provide the necessary assurances that human health and the environment are adequately protected in the near term. As discussed in the following, this shift in focus to alternate RAOs may result in the consideration of similar technologies initially evaluated for the restoration RAO, but whose use (and system design) are now evaluated within the context of achieving a different objective. Furthermore, the implementation of remedial measures to meet these alternate RAOs may very well contribute to the ultimate restoration of an aquifer, but not in a time frame that would be considered reasonable to an affected stakeholder. If restoration is not practicable, a waiver of Applicable or Relevant and Appropriate Requirements (ARARs) on the basis of technical impracticability (aka TI waiver) may be necessary.

Limit Plume Growth & Contaminant Migration

If impaired ground water can not be restored in a reasonable time frame, the focus of remediation turns to minimizing the volume of environment subsequently contaminated as a result of plume expansion or contaminant migration. This expectation is aligned with a RAO of plume containment. Containment is often achieved hydraulicly through implementation of pump and treat systems at the leading edge of a plume with pumping rates set to match or exceed the flux of contaminated water. (Treated water may be reinjected to create mounding at the perimeter as a way to enhance capture.) Containment may also be accomplished with physical barriers (e.g., permeable treatment walls) designed with sufficient width to provide the contact time needed to capture or degrade contaminants to the target concentration level. Less frequently, impermeable barriers are installed, but only in concert with extraction systems to prevent the build up of excess water. Aggressive mass reduction in the higher concentration areas of a plume also can serve to contain plume growth (while possibly having the additional benefit of promoting the eventual restoration of the affected aquifer as discussed later).

In older, mature plumes, plume growth may be constrained already as a result of:

- Attenuation mechanisms exceeding the contaminant flux at the perimeter such that the individual isopleths are static or recede with time; or
- Discharge into surface waters with sufficient flow volume to dilute contaminants below detection or background levels.

In the first case, the plume is at equilibrium and thus may qualify for monitored natural attenuation as the remedy of choice (2). In the second case, if access to affected ground water can be controlled, the site may be managed through an alternate concentration limit (ACL) approach under CERCLA (OSWER Directive 9283.1-2).

Containment is often more readily accomplished than restoration, however, it is not assured. In aquifer matrices with poor connectivity such as fractured bedrock and karst, or in sites with poorly mapped preferential conduits, it may not be practicable to capture all contaminated flow. In other settings, flow in conduits such as solution channels may be so large as to render containment infeasible. Hence, if the plume is not static, it is important to determine if capture/containment can be achieved. If it cannot, the focus then shifts to reducing the toxicity, mobility or volume of contaminants.

Mobility, Toxicity or Volume (MTV) Reduction

MTV reduction can be achieved by removing the contaminant (e.g., pump and treat or air sparging), destroying the contaminant in place (e.g., in-situ chemical oxidation), or changing the chemical to a less toxic or less mobile form (e.g., in-situ reduction of chromium VI to chromium III). Taken literally, this expectation can always be met since removal of any contaminant constitutes a reduction of mass (i.e., even the act of sampling alone removes mass if the sample is contaminated). However, the intent of MTV reduction ultimately is to affect meaningful reduction in risk. Otherwise, the costs incurred without a commensurate reduction of risk does not satisfy the cost-effectiveness requirement under the National Contingency Plan.

In this context, proposals aimed at an MTV reduction RAO should be characterized in a manner that can demonstrate quantifiable risk reduction. For example, reduction of contaminants on a significant fraction of a plume could restore that fraction to a point where institutional controls or access restrictions could be lifted in a time frame much sooner than for the remainder of the plume. Reduction of risk may be realized in spatial (reduced plume size) and/or temporal (reduced time until restoration is achieved). In some situations, however, demonstrating a quantifiable reduction of risk can be more difficult than it sounds. For example, at sites where DNAPL is present as a source of contamination, removal of anything less than 99 percent of the DNAPL may not result in reduction in the dissolved concentration of the contaminant in the ground water for an extended time, and removal of DNAPL at such a high level is questionable under most circumstances. Similarly, in diffusion limited sites, rebound from contaminants trapped in the matrix may return ground water to pre-remediation levels after implementation. Even if long-term concentration reductions can be achieved, if the resulting concentration is not below the MCL, the water cannot be used for drinking. Hence, use restrictions will remain in place and the net risk reduction is still dependent on those measures rather than the active remedy.

Given the challenges DNAPL and diffusion-limited sites pose, the focus of MTV reduction analysis is whether the response being considered will significantly change the time frames or the areas over which water use restrictions must be kept in place. If a mass removal action will reduce the time to restoration from the distant future to the near term, incurring implementation costs may be appropriate. Reductions of years or even tens of years from estimated time frames that are hundreds or thousands of years long probably do not. When restoration is not expected to occur in less than ~100 years, it may be better to conserve current resources and revisit the remedy decision as a part of the required 5-year review process, thus being able to take advantage of new, more efficient technologies that may be developed in the interim. Ultimately, the deferral to such an approach will require consensus among the Department and the cognizant regulators.

It should be noted that one meaningful result of mass reduction can be to serve as the intermediate step between the source control phase and the restoration phase when restoration is considered practicable. In these cases, the goal is to remove sufficient mass to bring a plume to equilibrium such that remediation can eventually transition over to monitored natural attenuation. With this approach, mass removal is targeted to reduce the inventory of contaminant to a level where the flux outward is less than the flux attenuated at the plume boundary. This strategy is tantamount to applying mass removal to achieve containment.

Irrespective of the decision as to which programmatic expectation can be achieved at a reasonable cost and within a reasonable time frame, any selected response must protect human health and the environment. As a consequence, it is most likely that alternate water supplies, access restrictions and other institutional controls will be required for many plumes over extensive time periods.

TRANSITION AND EXIT STRATEGIES

Regardless of the specific RAO targeted, the key to development of an optimal groundwater response strategy is knowing when and how to transition from one phase of response to another. The when and the how are typically articulated in a transition or exit strategy that may be viewed simply as the set of information that will be used to demonstrate the desired performance has been achieved and a phase-specific objective has been met, such that it is appropriate to move to the next phase of the response, or terminate all activities if restoration has been attained.

In general, program managers need to address the following questions in order to establish appropriate response objectives and develop effective transition/exit strategies.

- Is source control warranted and how much is enough?
- Is containment feasible and how best is it accomplished?
- Will MTV reduction provide a significant reduction in risk?

Is Source Control Warranted and How Much is Enough?

In general, source materials represent the highest concentration of contaminant in the environment and remedies aimed at these materials offer the greatest value in terms of contaminant addressed per unit expenditure. As a consequence, source control measures are a cost-effective step in most groundwater restoration programs. However, discretion is required in source control actions. Sources to groundwater contamination come in many different forms from pure chemical (either contained e.g., drums or un-contained e.g., DNAPL) to films adsorbed onto soil particles. The concentration, form and location of sources will be important determinants of the cost-effectiveness of control measures. Because the aquifer media is a source for any contaminant that partitions between solids and water, complete source control would be tantamount to aquifer restoration for those chemicals. In recognition of that, source control is directed to "active" sources defined for the Department's purposes as any concentration of contaminants that is adding more mobile contaminants into the plume over a given period of time than is removed by natural attenuation processes.

As indicated earlier, source control is generally one of the first actions to be taken. Transition is a matter of determining when to stop. Depending on the type of source control selected, termination may be based on design or performance criteria. If capping or other means of containment are used for source control, design criteria are applied. The source control phase is complete when the design has been installed and determined to be operational and functional. If removal or destruction of source materials is the selected approach, performance criteria are applied (e.g., excavation or extraction to a given concentration threshold or action limit). When criteria are met, source control is ceased.

Is Containment Feasible and How Best Is It Accomplished?

Once source control has been accomplished or determined to be unnecessary, the primary focus is directed to determining the need for (and approach to) containment of the plume. If the plume is already static or retreating, additional measures to secure containment are not required. If the plume is still expanding or moving, project managers need to determine if engineered barriers are needed or whether mass extraction/contaminant destruction in the higher concentration areas of the plume are most appropriate. If calculations show that stasis can be attained relatively quickly using a mass removal approach, and no significant risk concerns exist in the interim, mass removal may be implemented in lieu of engineered barriers. The decision between these options will require a consideration of costs, risk concerns, and stakeholder input.

Will MTV Reduction Provide a Significant Reduction in Risk?

After containment has been achieved or determined not to be practicable, there may still be merit in further mass removal if it will net significant risk reduction. In order to make that evaluation, it is necessary to evaluate risk over time with and without implementation of the proposed response. Because ground water cannot be used for drinking water purposes if it exceeds MCLs, simply demonstrating concentration reductions (without a decrease in the time it will take for a significant portion of the aquifer to be restored or a reduction of other costs required to maintain protectiveness) is insufficient to justify proceeding with the action. Similarly, any scheduled mass removal should be terminated at the point where further removal does not translate to a significant reduction in future risk.

In many respects, the final phase of groundwater restoration always will be monitored natural attenuation (MNA). Even if MNA is not selected as the primary response, the final confirmation monitoring for all other remedies generally in fact is a brief period of monitoring while natural attenuation processes drive concentrations below their respective MCLs or to background. When viewed in that light, the phases of the groundwater restoration strategy can be likened to the MNA approach with transitions occurring as each precondition for application of MNA is met (Figure 2). The first phase, source control, is completed when no active source remains (Condition 1 for determining applicability of MNA). The second phase, containment, is completed when the plume is brought to equilibrium (Condition 2 for determining applicability of MNA). Finally, MNA is implemented when sufficient mass removal has occurred to be able to demonstrate that natural attenuation mechanisms will be able to restore ground water within a time frame that is reasonable as compared to more active measures (the final condition for determining the applicability of MNA). If no active source is present, the first phase is not necessary. If the second phase is capable of going all the way to restoration in a reasonable time frame, then the third phase may be limited to a brief period of post-remedy monitoring. If the second phase is unable to attain restoration directly, (e.g., site conditions or the type of contaminants limit the effectiveness of mass reduction approaches), a longer period of MNA may be required. Transitions between phases are dictated by arrival at a point where the MNA condition is met and implementation of the next phase is deemed more cost-effective than continued application of the last phase.

EFFECTIVE COMMUNICATION

In general, for any groundwater restoration strategy to be successful, it must first be accepted by the effected stakeholders. Given that many sites ultimately will rely on MNA at some point in their groundwater response strategies, project managers need to be cognizant of the current state of public apprehension with respect to MNA as a remedy. As outlined in DOE's MNA framework guide (3), the rationale for the strategy must be well documented and effectively communicated. Key elements of effective communication include:

- Realistic comparison of alternatives with respect to cost and risk reduction benefits
- Explicit identification of uncertainties and the means by which they will be managed

Comparison of Alternatives

While the EPA has developed a hierarchy of programmatic expectations in recognition that aquifer restoration may not be practicable, many stakeholders do not share that recognition. Years of miscommunication and misunderstandings have left many skeptical that emerging alternatives such as MNA are anything but a way to avoid spending the resources necessary to right a wrong.

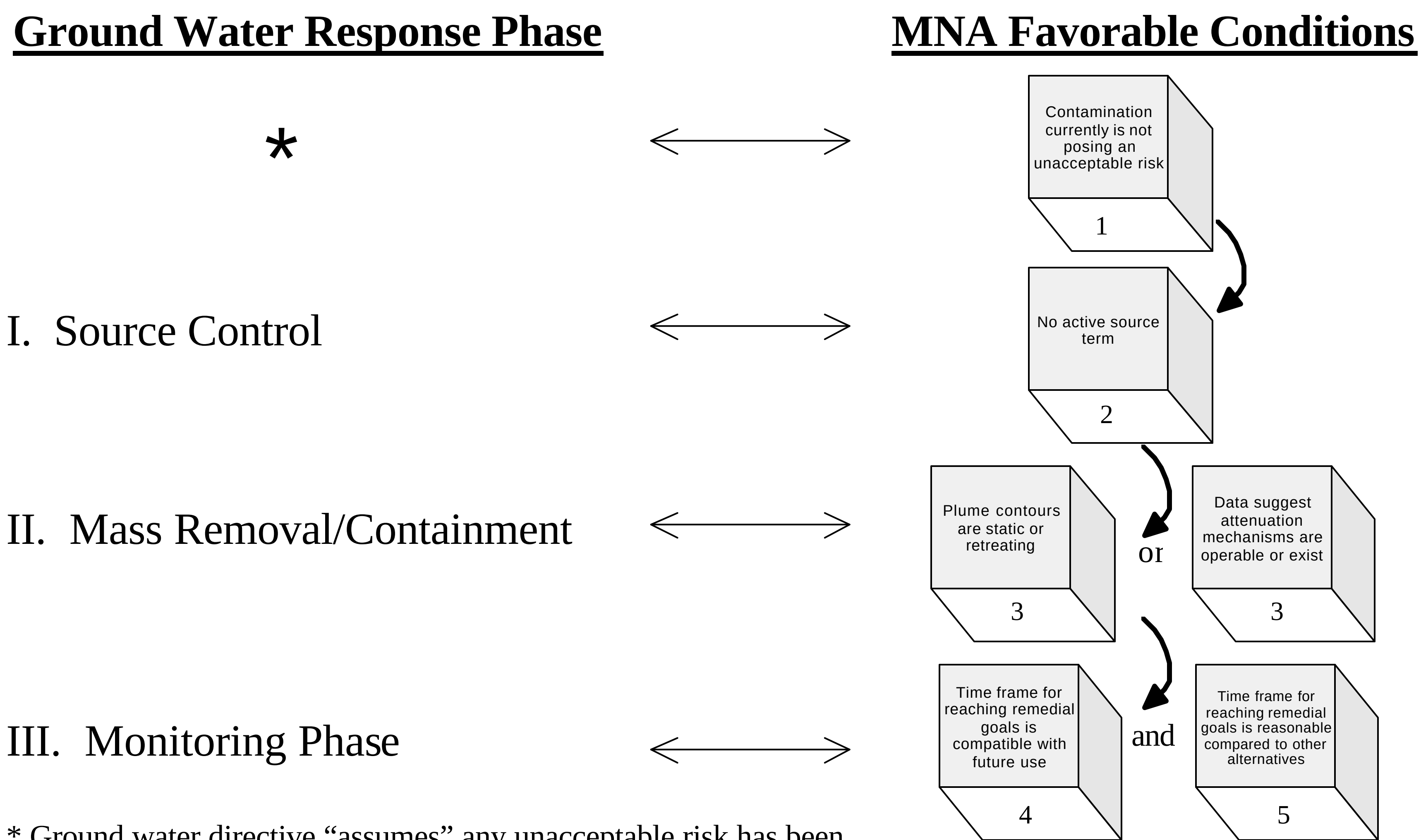
In order to counter such cynicism, it is essential to accurately characterize alternatives and lay the cost benefit balance squarely in front of the risk manager. Each remedy must be assigned an expected performance profile that reflects the likely risk over time so that differences in cost can be compared with differences in risk. Moreover, the ramifications of reduced concentrations must be spelled out. If concentrations cannot be reduced below MCLs, it must be clearly stated that the aquifer will still be restricted from use and that protection arises from the use restrictions, not the mass removal.

Furthermore, it is important that proposed remedies be assigned risk reduction levels objectively. Many times there is a default assumption that a proposed remedy will be effective without drawing on past experience and without considering how performance may be impacted by residual uncertainties. Without objective estimates, remedies of little or no value can be implemented because of a naive assumption that action of some kind must be beneficial. Unfortunately, the opposite may often be the case. In many circumstances, active remedies can trigger unintended movement of contaminants themselves or work to negate the effects of natural attenuation mechanisms (e.g., pump and treat systems lower the water table and promote aeration, thus reversing the anaerobic mechanisms that otherwise degrade chlorinated solvents).

When the true cost and likely benefits are fairly compared, the limited value of many common groundwater remedies become clearer and alternative approaches, including MNA, are more acceptable to stakeholders.

Uncertainty Management

It is virtually impossible to eliminate all the uncertainty associated with environmental restoration prior to selection of a remedy. As a consequence, there will always be a need to manage uncertainties by blending uncertainty reduction (data collection) with uncertainty impact mitigation (use of contingencies) [4]. For the most part, the significant uncertainties associated with restoration of ground water are those related to whether the remedy will be



* Ground water directive "assumes" any unacceptable risk has been addressed and a conceptual site model has been developed.

Fig. 2. Ground Water Response Phases and MNA Favorable Conditions

effective. In order to provide assurance that protectiveness will be maintained, it is necessary to implement a monitoring structure that will provide ample warning of conditions that are no longer protective and have a contingency plan that will mitigate any adverse impacts before there are significant consequences (2).

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