ground water

Issue Paper/

Groundwater Remediation: The Next 30 Years

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Abstract

Groundwater remediation technologies are designed, installed, and operated based on the conceptual models of contaminant hydrogeology that are accepted at that time. However, conceptual models of remediation can change as new research, new technologies, and new performance data become available. Over the past few years, results from multiple-site remediation performance studies have shown that achieving drinking water standards (i.e., Maximum Contaminant Levels, MCLs) at contaminated groundwater sites is very difficult. Recent groundwater research has shown that the process of matrix diffusion is one key constraint. New developments, such as mass discharge, orders of magnitude (OoMs), and SMART objectives are now being discussed more frequently by the groundwater remediation community. In this paper, the authors provide their perspectives on the existing "reach MCLs" approach that has historically guided groundwater remediation projects, and advocate a new approach built around the concepts of OoMs and mass discharge.

Introduction

In 1976, the discovery of chemicals buried beneath houses in Love Canal, New York was the front-page news across the United States. Prior to that time, the primary public concern regarding drinking water focused on its taste. But soon after Love Canal, groundwater contamination problems began popping up everywhere, and public interests and perceptions changed dramatically. Most of the people realized that chemicals disposed in landfills, surface impoundments, or simply dumped on the ground had seeped into the underlying groundwater.

Before long, more accurate and extensive sampling at industrial facilities and water supply systems confirmed the presence of thousands of groundwater "plumes," some of which were impacting drinking water supply wells. Volatile organic compounds (VOCs) seemed to be the most widespread type of contamination actually reaching water supply wells.

Generally, when contamination was discovered, the impacted supply wells were taken out of service or fitted with treatment systems. Enforcement proceedings and lawsuits followed at many sites. Citizen-led organizations were formed to advocate swift and complete cleanup. Regulatory agencies, consulting firms, industry, and law firms all added staff at a breakneck pace. Plume characterization and remediation activities were initiated. The public's interest shifted dramatically from, "What makes my water taste bad?" to, "What bad things are in my water that I can't even taste?"

Virtually all of these developments associated with discovery of contaminated groundwater were guided by a single motivating factor—the numerical criterion known as the maximum contaminant level (MCL) for drinking water (Box 1).

MCLs and Cleanups

In 1974, the Safe Drinking Water Act (SDWA) was passed and required U.S. EPA to regulate contaminants which presented health risks to public water supplies and to set enforceable limits which consider cost, technological feasibility, and health goals (USEPA 1999). Congress later passed the 1986 SDWA Amendments that required

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Box 1

Getting to MCLs

The MCL was originally developed as a criterion for evaluating public drinking water supplies, both from surface water and groundwater sources. However, soon after the Love Canal Superfund Site was discovered, MCLs were being widely applied as cleanup criteria for plumes of contaminated groundwater, regardless of whether or not such plumes would ever enter drinking water supply wells. Since then, the term ‘‘getting to MCLs’’ has become the catch-phrase typifying the life of those working in the remediation community.

U.S. EPA to set MCLs for 83 named contaminants, including several VOCs. Despite the intention that MCLs had been developed to evaluate public water supply systems, the urgency of addressing the ever-increasing scope of groundwater contamination soon led to widespread use of MCLs as cleanup goals for all plumes, even those not threatening water supply systems.

History of Groundwater Remediation Goals and Technologies

The MCL was a satisfactory criterion for evaluating water supply wells, building enforcement cases, conducting site characterization, and explaining sampling results to the public. However, once groundwater remediation systems were installed, several discouraging observations became apparent to the remediation community.

Contaminated aquifers were very difficult to restore to pre-contaminated conditions. Sometimes the levels of contamination in groundwater rebounded after remediation was thought to be complete. Remediation of every liter of contaminated groundwater at tens of thousands of contaminated sites to MCLs seemed daunting, if not impossible. The MCL was almost never associated with a volume of groundwater, which would have created a sense of scale and allowed some type of averaging. Instead, it was typically implemented as a universal goal at every point in a plume.

Early Models, Early Efforts at Remediation of (D)NAPLs

Initially there was a belief that partitioning between the aquifer matrix and dissolved phase contamination was the dominant attenuation process (McCarty et al. 1981; Mackay et al. 1985). Designers of early pump-and-treat systems therefore assumed that passing several pore volumes of water through the aquifer would remove almost all of the dissolved and sorbed contaminant (see Figure 1). Where many orders of magnitude (OoMs) reduction (say, 6 OoMs or 99.9999% reduction) were necessary to reach the MCL, groundwater scientists believed that continuous flushing of the contaminated aquifer with clean water would eventually accomplish the cleanup goal of reaching MCLs everywhere.

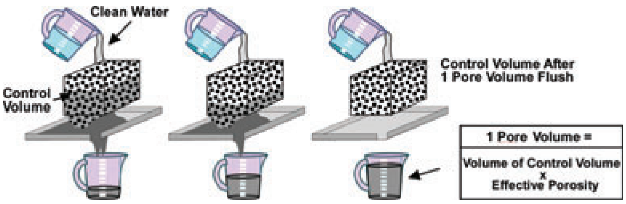


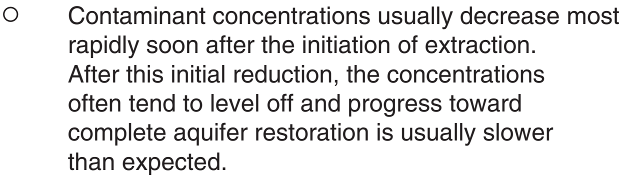
Figure 1. Depiction of pore volumes in porous media. A simple porous media flushing model predicts that after the initial flush, each pore volume results in an order of magnitude reduction in concentration absent of retardation and other sources (Wiedemeier et al. 1999).

Accordingly, most groundwater remediation projects in the late 1970s and 1980s relied on a pump-and-treat philosophy to remove contaminated groundwater. Pump-and-treat systems were intended to “halt” the spread of the contamination and clean up the plume. This approach drove many Superfund projects throughout the 1980s and early 1990s (USEPA 1989; NRC 1994).

Bad News—Slow Progress and the Dawning of DNAPL

By the late 1980s, some of the brightest scientists in the world were engaged in research to develop methods and technologies to better understand groundwater contamination. The research community and U.S. EPA began to focus on why groundwater remediation projects were not meeting cleanup expectations.

In 1989, Mackay and Cherry discussed why progress was slow and identified NAPLs as under-appreciated contaminant sources within aquifers. Later that same year, a U.S. EPA study of 19 pump-and-treat systems found that remediation progress “is usually slower than expected” (Figure 2) after early progress is achieved (USEPA 1989). A follow-up study in 1992 identified the presence of NAPLs as a particular concern (USEPA 1992a). The U.S. EPA responded by publishing several DNAPL-oriented Issue Papers, Fact Sheets, and other documents that characterized DNAPLs as difficult-to-detect, difficult-to-remove, and long-term sources of groundwater contamination (e.g., Huling and Weaver 1991; USEPA 1992b, 1992c). The National Research Council took up the challenge of understanding why groundwater cleanups were not going as originally anticipated (NRC 1994). They investigated constraints in the performance of pump-and-treat systems and concluded



○ Contaminant concentrations usually decrease most rapidly soon after the initiation of extraction. After this initial reduction, the concentrations often tend to level off and progress toward complete aquifer restoration is usually slower than expected.

Figure 2. Excerpt from 1989 U.S. EPA study of 19 pump-and-treat systems.

that geologic heterogeneity and NAPL presence were significant constraints to groundwater cleanup.

With NAPLs, the groundwater community eventually adopted a "candle and flame" conceptual model where the source is the "candle" and the plume is the "flame." Remove or isolate the candle and the flame dies. This metaphor is graphically depicted as cover art in one U.S. EPA document (Figure 3). Thus, for many sites, the initial "dissolved-only" conceptual model was superseded by a new approach that also addressed the presence of NAPL.

2000s: Matrix Diffusion

By the early 2000s, groundwater scientists began to better appreciate matrix diffusion as a potential long-term source contributing contaminants to groundwater. Although research on this topic reached back to the 1970s, by the 2000s, the seeming inability to reach MCLs at most sites resulted in a more detailed re-evaluation of groundwater processes.

Large amounts of chlorinated solvents can be stored in low-permeability zones, later to slowly diffuse out and cause MCL exceedences (e.g., Chapman and Parker 2005; Sale et al. 2008) (Figure 4). At some plumes, the stored mass in the low-permeability compartment of the plume downgradient of the source may eventually become greater than the stored mass in the source zone. This can lead to a very different plume response to remediation than predicted by the "candle and flame" conceptual model.

Figure 3. Cover art for EPA MNA guidance depicting NAPL and plume metaphor as candle and flame (USEPA 1998).

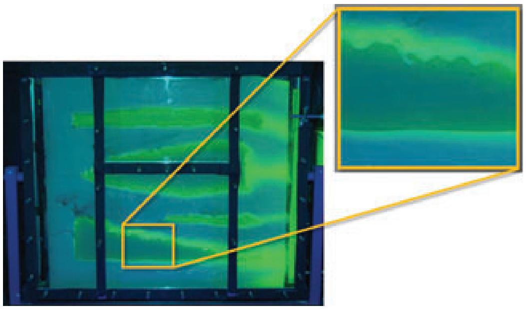


Figure 4. Sand tank experiment showing matrix diffusion of dye into low-permeability zones (Doner and Sale 2008).

Several studies have evaluated the ability of groundwater remediation technologies to reach MCLs. Kavanaugh et al. (2003) concluded that MCLs are not likely to be achieved within a reasonable time frame in the source zones at a majority of DNAPL sites. McGuire et al. (2006) showed pre- and post-remediation data from 59 chlorinated solvent sites; no sites reached MCLs, although a few came close. The U.S. Navy concluded that cleanup standards based on state and federal MCLs are "extremely unlikely to be met" at chlorinated solvent sites (NAVFAC 2007). In 2011, a group of consultants, industrial representatives, academics, and regulators concluded that DNAPL source zones are a "daunting environmental challenge" and restoring these sites is "exceptionally difficult." They recommended a procedure for developing more realistic goals for source zone remediation (ITRC 2011). Several highly cited remediation performance studies have addressed remediation expectations (e.g., McGuire et al. 2006; Kingston et al. 2010; Krembs et al. 2010).

To summarize, previous conceptual models used to guide cleanups were missing key processes, and the slow progress of many cleanups was inexplicable. But today, after more than 30 years of research and experience, we have reached a far better understanding not only of key contaminant processes, but also of what groundwater remediation can realistically achieve.

Current Metrics and Problems

Most remediaton projects assume that the groundwater needs to be restored for safe human consumption. However, the act of pumping the resource is generally not considered when evaluating the potential impacts of the contamination. Pumping from a contaminated aquifer often introduces clean water into a well, preferentially capturing far more water from transmissive zones than from low-permeability zones. The water delivered by a supply well can be of a much different quality than that measured in monitoring wells intended to intercept the highest levels of contamination (Box 2).

Despite all of the attention given to cleaning up contaminated aquifers, the "all or none" aspect of reaching MCLs everywhere is not a practical metric for measuring remediation progress. For example, if a remediation

Box 2

Remediation Metrics and Volume

Groundwater is in constant motion. The most sinister aspect of groundwater contamination is that it can travel long distances before being detected, sometimes being first observed in drinking water supply wells. Should not some measure of the volume of contaminated water in motion be accounted for in a metric of groundwater contamination?

project reduces plume concentrations to one half or less of its strength, how could this project be considered a "success" if the only metric is the comparison to the MCL at every point in the plume? A project that shrinks the size of a plume by half could be labeled "unsuccessful" or "incomplete" using an MCL-everywhere remediation objective. At the same time, key research that leads to useful metrics for cleanups has generally been disregarded when pursuing the "getting to MCLs everywhere" goal.

Proposed New Remediation Metric

Regulatory agencies and others have gravitated to the MCL as the key criterion for groundwater remediation. However, these same entities utilize different types of metrics for other environmental programs. For example, the total maximum daily load (TMDL) is a term used in surface water systems to denote the maximum amount of a pollutant that a body of water can receive while still meeting concentration-based water quality standards. TMDLs were first described in U.S. regulations published in 1992, and have broadened significantly in the last decade to include many watershed-scale management plans. The TMDL approach for surface waters is very much analogous to the mass discharge approach for groundwater (M_{d}, the mass per time crossing a transect or entering a well or stream; sometimes referred to as "mass flux"; Figure 5).

Leu and Hadley (1987) described a method for evaluating hazardous waste sites based on the potential exposure of receptors to toxicants. In the case of groundwater exposures, a plume leaving a site might have a mass discharge so small as to be insignificant to a large public water supply well. The authors also recognized that sufficiently small plumes would not have significant impacts on many receiving streams. Remediation of such small plumes would not measurably improve the quality of water in these cases.

Under their approach, existing or hypothetical water wells could be part of the site evaluation, including a hypothetical private well installed within the plume. By considering a range of potential groundwater uses, from small private wells to large municipal wells, a range of extraction rates are associated with the various uses. Basically, mass discharge is used as a metric for gauging the strength and severity of the contamination. This allows balancing risk reduction necessary to protect public health with the costs and performance of remediation.

In theory, "risk assessment" should also be available as a metric for gauging remediation progress. U.S. EPA typically considers a risk range from 10^{-6} up to 10^{-4} when evaluating the potential need for remediation at waste sites (USEPA 1991). However, as commonly practiced by many federal and state regulators, MCLs are used as a de facto remediation objective throughout a plume regardless of risk. With a mass discharge approach, the compliance point is at the point of exposure (both before and after remediation). This results in a very different approach to plume management compared to the MCLs-everywhere approach (Figure 6).

Researchers have recognized the importance of mass discharge type approaches and their relationship to the risk associated with real-world extraction wells downgradient of plumes (Einarson and Mackay 2001; Farhat et al. 2006; Brooks et al. 2008; ITRC 2010; Newell et al. 2011). Other tools such as the U.S. EPA's REMChlor model also emphasize the usefulness of mass discharge perspectives for managing sites. Recent efforts such as the ITRC's Integrated DNAPL Source Strategy Team (ITRC 2010, 2011) are indicative that these concepts are ripe for a much broader application to site management.

How can these concepts be put into common practice? We feel that distinguishing between near-term achievable *functional goals* and long-term absolute goals (ITRC 2011) such as achieving MCLs is paramount.

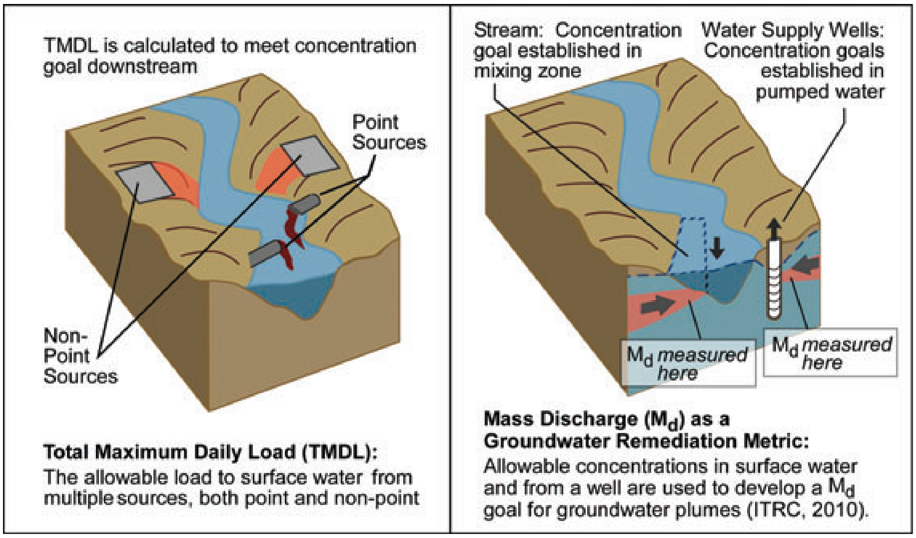


Figure 5. Comparison of total maximum daily load (TMDL) and use of mass discharge as a remediation metric at groundwater sites. Note that mass discharge divided by flowrate yields a concentration estimate in a well (Einarson and Mackay 2001) or in a mixing zone of a stream (Farhat et al. 2006).

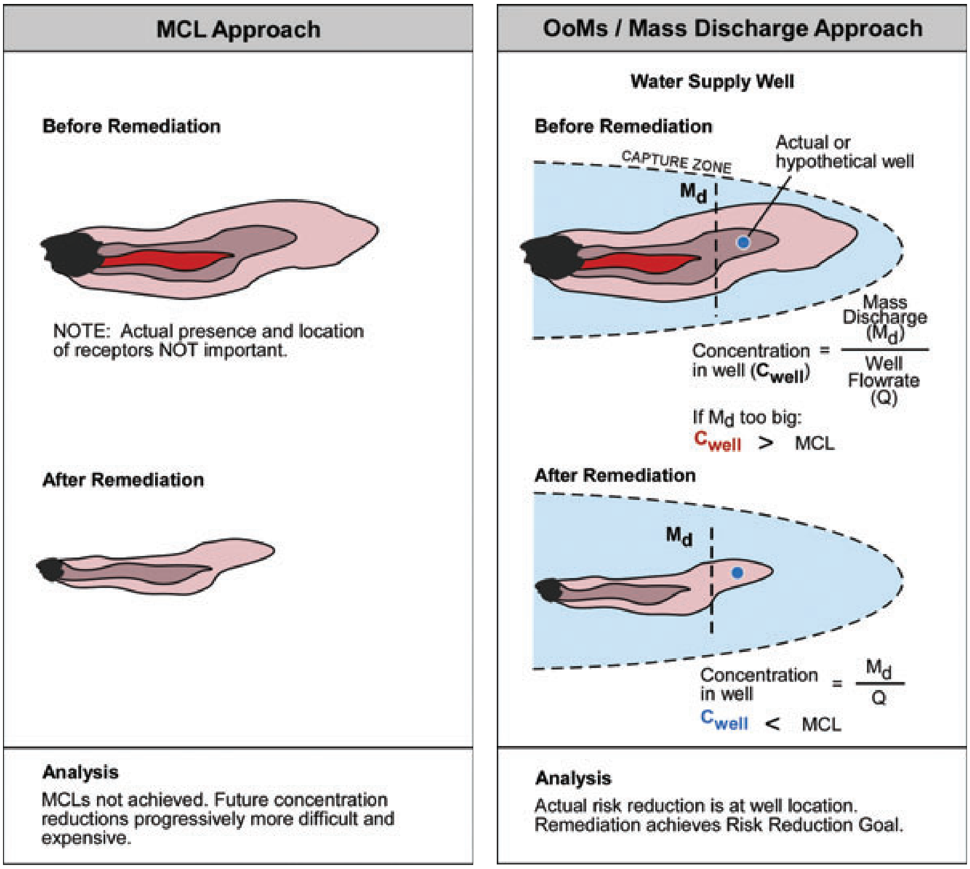


Figure 6. Comparison of MCL approach to plume management vs. OoMs approach.

One Last Feature—OoMs

Newell et al. (2011) determined the necessary mass discharges to impact water supply wells with different flow rates. This method is consistent with the use of TMDLs, the approach of Leu and Hadley, and true risk-based remediation.

Their system is organized in *Orders of Magnitude of mass discharge* from sources and within plumes, referred to in this paper simply as "OoMs." As shown below, plumes are classified into 10 separate categories depending on the mass discharge (in units of g/d). Each category is separated by an order of magnitude; for example, a Mag 5 plume is four OoMs stronger than a Mag 1 plume (Box 3).

The mass discharge categories can also be used to determine risk to certain receptors (Box 4). For example,

- A Mag 3 plume is needed to impact a 150 gallons/d domestic water well >0.005 mg/L
- A Mag 5 plume is needed to impact a 100 gallons/min municipal water well >0.005 mg/L.

Box 3

Order of Magnitude

An **order of magnitude** is the class of scale or magnitude of any amount, where each class contains values of a fixed ratio to the class preceding it. In its most common usage, the amount being scaled is 10 and the scale is the (base 10) exponent being applied to this amount. Such differences in order of magnitude can be measured on the logarithmic scale in "decades" (i.e., factors of 10). This is useful for getting an intuitive sense of the comparative scale of familiar objects (Wikipedia 2011a).

Box 4

Plume Magnitude Classification System (Newell et al. 2011)

Mag 1 Plume: <0.001 g/d
Mag 2 Plume: 0.001 to <0.01 g/d
Mag 3 Plume: 0.01 to <0.1 g/d
Mag 4 Plume: 0.1 to <1 g/d
Mag 5 Plume: 1 to <10 g/d
Mag 6 Plume: 10 to <100 g/d
Mag 7 Plume: 100 to <1000 g/d
Mag 8 Plume: 1000 to <10,000 g/d
Mag 9 Plume: 10,000 to <100,000 g/d
Mag 10 Plume: ≥100,000 g/d

We propose that site stakeholders use *OoMs of mass discharge* as the key metric of remediation performance and progress toward near-term functional goals.

How Can OoMs Be Applied?

The key point behind the OoMs approach is to have specific, attainable *functional* remediation goals. For example, a site could apply the following remediation strategy where the upper level ("absolute") goals are protection of public health and the environment and the restoration of groundwater, but in conjunction with four specific, achievable functional goals:

- Functional Goal 1: Ensure that there are no unsafe exposures to the contaminants in groundwater. Replace contaminated water supplies or provide treatment to users of the contaminated groundwater. Institute appropriate measures to prevent unmanaged new usage of groundwater within a suitable proximity of the plume. Confirm that no unsafe vapor intrusion problems are present; if present, eliminate this exposure.
- Functional Goal 2: Confirm that natural processes are controlling further unacceptable plume migration. If not, apply plume control/containment strategies to ensure no further plume migration.
- Functional Goal 3: Use existing technologies (including Monitored Natural Attenuation, MNA) to meet a remediation goal of 1 OoM reduction in mass discharge over a 10-year period. (The 10-year time frame was selected based on recommendations made by the ITRC Integrated DNAPL Site Strategy team that *functional goals* should have time frames of 20 years or less; ITRC 2011).
- Functional Goal 4: Apply MNA until the absolute goal of groundwater restoration is achieved (which may take many decades).

This simple example shows how functional objectives are used to protect receptors, prevent further resource deterioration, improve the site to an attainable goal, and eventually restore the groundwater. A key difference compared with the historical approach is that all goals for active remediation systems are achievable in a relatively short time frame (with the exception if long-term active containment measures are needed as part of Functional Goal 2) (Box 5).

A second example is to use a simple mass balance calculation to protect a groundwater supply well (Einarson and Mackay 2001; Newell et al. 2011). The well's pumping rate is used to calculate an acceptable mass discharge rate (M_d in units of g/d, including an appropriate safety factor) that will not cause an exceedence of the MCL in the pumped groundwater. While most regulatory programs assume that any concentration above an MCL is an exceedence, this approach assumes that target concentrations would be averaged over a 30-year period for the carcinogenic compounds that drive many risk assessments.

Box 5

Groundwater Is an Orders of Magnitude (OoMs) Endeavor

The OoMs approach is useful because much of the environmental data associated with groundwater remediation is expressed in factors of 10, such as:

- Hydraulic conductivity (for example, a sand might be "10^{-3} cm/s," while a clay might be "10^{-6} cm/s"). Some groundwater professionals describe the hydraulic conductivity of a water-bearing unit as a "10 to the minus 3 unit" or "10 to the minus 6 unit." This is an example of an OoMs approach (powers of 10) being used to describe a key variable, hydraulic conductivity.
- Concentration of VOCs is often expressed in powers of 10. For example, many concentration isocontour maps show power of 10 isocontours, such as 1 µg/L, 10 µg/L, 100 µg/L, 1000 µg/L, and 10,000 µg/L.
- Mass discharge of contaminant plumes: One study showed a range of mass discharge measurements from contaminant plumes ranging from 0.00078 g/d to 56,000 g/d, or a range of 71 million (almost 8 OoMs). This is not surprising as mass discharge is the product of hydraulic conductivity and concentration data, both of which span many powers of 10.
- Carcinogenic risk is commonly presented in OoMs: U.S. EPA's allowable risk ranges from 10^{-6} to 10^{-4}—another important factor expressed in orders of magnitude.
- Remediation projects and decision tools are beginning to apply OoMs concepts to management of groundwater plumes. For example, a Frequently Asked Questions document for DNAPLs proposed a "rule of thumb" (Sale et al. 2008) that indicated the typical reduction in concentration in groundwater achieved by chlorinated solvent remediation projects was "one to possibly two" OoMs. A landmark study of thermal remediation performance data used OoMs to report remediation performance at 14 well-studied thermal projects (Kingston et al. 2010).
- OoMs are a key aspect when using the 14-Compartment Model for developing site conceptual models and developing remediation strategies (Sale and Newell 2011). OoMs are used to visualize what remediation can do at different media (vapor, DNAPL, aqueous, sorbed) and different locations at a site (source vs. plume).

Why This Is Important for Cost vs. Benefit

The costs of groundwater remediation are not insignificant. One market research firm estimated the cost for remediation at $5 billion per year over the past 5 years (Farkas and Frangione 2010). With many groundwater remediation technologies costing millions of dollars per acre (Sale et al. 2008), the inability to achieve MCL-based goals is an expensive and troublesome phenomenon.

Clearly, society has to balance cost and benefits associated with the remediation industry. For example, the "Decision Chart: Benefits from Full-Scale Applications of Source Depletion" presented in Kavanaugh et al. (2003) lists nine separate metrics for evaluating the need (i.e., if the benefits exceed the costs) for source depletion (source zone remediation) at DNAPL source zones. In this particular tool, resource value, risk, and even issues of stewardship for future generations are evaluated. Overall, by using tools such as this Decision Chart and the OoMs approach, we feel that the cost and benefits of groundwater cleanup can be balanced successfully.

In addition to cost, there has been a recent focus on the environmental footprints of cleanup, particularly those associated with energy-intensive engineered systems (SURF 2009). Remediation professionals now have access to literature, computer tools, and a growing body of case studies that consider the environmental footprints (another type of cost). This has also led to consideration of how to make better decisions about remediation projects, including developing better remediation objectives.

SMART attributes (Box 6) were originally developed for setting objectives in the business world, but are suitable for improving virtually any project requiring even a modest amount of management. SMART attributes have previously been mentioned with regard to management of environmental contamination (USEPA 2005). Establishing SMART objectives for remediation projects is now advocated by the ITRC's Integrated DNAPL Site Strategy Team (ITRC 2011). One key quality of the SMART approach to establishing objectives is that it creates accountability for the persons managing and implementing the project.

Historically, the remedy selection process has sought "cost" or "cost-effectiveness" as a criterion. Since achieving MCLs everywhere is unlikely and often unrealistic, it is difficult to determine the true cost or cost-effectiveness of MCL-driven remediation projects. However, with the OoMs approach and SMART objectives, comparing cost and cost effectiveness becomes more relevant.

Box 6

SMARTness

In business management, an acronym has been created to aid in the development of better, more focused objectives for projects (Doran 1981; Wikipedia 2011b). That acronym is:
S = Specific
M = Measurable
A = Attainable
R = Relevant
T = Time bound

OoMs, MCLs, or Both?

Table 1 provides a sharp contrast between the OoMs and MCL approaches in planning, designing, and evaluating groundwater remediation. One clear advantage of the OoMs approach is that it includes the scale of the potential problem that contamination poses on public health and the environment.

It is a challenge to integrate OoMs at sites where the MCLs-everywhere approach has been used. OoMs can accommodate MCLs by assessing the volume of water that can be safely delivered by an extraction well tapping into the contaminated zone. Whether this actually occurs at sites depends on the inclinations of the parties involved and their willingness to address the question of scale.

Concluding Remarks

The sense of urgency surrounding groundwater contamination brought to light in the late 1970s is entirely understandable. Since then, extensive testing of water supply wells has been conducted. Follow-on activities have reduced or eliminated exposure, and remediation efforts have been conducted at thousands of sites. We should not overlook the fact that the MCLs-everywhere approach has been the driving force for much of this progress.

We have learned a few lessons the hard way about what to expect from groundwater remediation projects. Unfortunately, applying expensive and ineffective remedies to try and meet unachievable objectives is a continuing source of concern among remediation professionals

Table 1
OoMs vs. MCLs Everywhere

OoMs	MCLs Everywhere
SMART (specific, measurable, attainable, relevant, time-bound)	Generally not utilized with SMART attributes
Scalable	Not scalable
Fits description of a "model"	Not a "model"
Mass discharge is a vector	MCL is a point measurement
Allows inclusion of other factors	Does not consider other factors
Offers hope for a different future	Identified with shortcomings of the status quo
Dynamic	Static
(Relatively) new	Old
Developed specifically for groundwater remediation	Developed for water systems
Mass transport	Regulatory/enforcement based
Risk-based	Regulatory/enforcement based

today (SURF 2009). The expense and disappointment are not unique to private sector remediation projects. Government-funded remediation projects are subject to the same constraints imposed by the laws of chemistry and physics as are those conducted by the private sector, and are subject to the same shortcomings.

It is now an opportune time for remediation professionals to apply the lessons of the past. Therefore, we propose a groundwater remediation paradigm based on OoMs of mass discharge described above to replace the current approach where MCLs are rigidly applied everywhere.

There is a growing acceptance that restricting access to groundwater because of intractable contamination is an appropriate solution for some groundwater problems. Institutional controls to prevent extraction of contaminated groundwater are now being implemented as an important component of many remediation projects.

An increasing number of regulators (and others) are shifting away from the historical preference for engineered systems as the only way to manage DNAPL source zones. Clearly, the typical cleanups today increasingly involve risk management components to supplement active remedial measures.

Many of these changes have come about through the pragmatic recognition that financial resources are not limitless and that remediation systems cannot deliver the complete restoration once hoped for. But amidst this pragmatism, one thing is still missing: namely a consistent, coherent, and intellectually satisfying approach for managing contaminated aquifers. OoMs would seem to provide much of what is missing from the current framework.

Paradigms, Models, Data, and Progress

Barbour (1997) discussed how the qualities of a "paradigm" (Box 7) in a scientific field form the basis for viewing the world, for constructing a hypothesis, for collecting data, and even for the sources of inspiration that scientists must have to move their research forward. The prevailing scientific paradigm in a particular field is intimately linked to the data that support it, and gives rise to theoretical models that attempt to explain not only the data that conform to prevailing theory, but also to examine the data that challenge it. A healthy and robust paradigm gives rise to high-quality theoretical models and the data derived from testing of such models allow affirmation, rejection, or refinement of the models. All three elements—paradigm, model, and data—are connected together and directly influence one another.

Box 7

Paradigm

The word "paradigm" refers to the methodologies and philosophical or theoretical framework of a scientific field or discipline. A paradigm represents the milieu of laws, theories, and generalizations which support and guide scientific studies, as well as determine the acceptability and significance of experimental results (Merriam-Webster Inc. 2012; Oxford University Press 2012).

For groundwater remediation professionals, the prevailing paradigm for the last 30 years has been typified by the goal of "getting to MCLs." Collectively, the results have consistently fallen short of expectations.

Freeze and Cherry (1989) suggested that the shortcomings of the remediation industry could be solved, although some of their solutions lie with legislative bodies and are beyond the purview of the remediation industry. The authors of this current paper do not disregard the suggestions for broad change made by Freeze and Cherry. However, they offer this current work on OoMs and mass discharge as one change that can be made almost immediately. This same approach has been advocated by a diverse group of remediation professionals such as the ITRC (2010, 2011). It is a change that has started to bear fruit; one Superfund Site Record of Decision now includes a mass discharge remediation goal (USEPA 2009).

The OoMs concept can reshape our ideas about what we can accomplish in our lifetimes and our children's lifetimes. It constitutes a new paradigm that would also allow remediation professionals to accurately assess just how much or how little should be expected from active groundwater remediation efforts. This information would be invaluable for other stakeholders—the public, policymakers, elected officials, and even the media.

Assessing the progress of groundwater remediation is the cornerstone of cost estimating, planning, budgeting, and public policy. Few people would suggest that such assessments do not need to be as accurate as the state of the science will allow. And, if groundwater remediation professionals do not say what to expect and plan for, who will?

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