Editor's Perspective—When One Well Is Enough

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INTRODUCTION

Monitoring groundwater during and after remediation can be costly. Monitoring programs often rely on the network of wells left over from delineation sampling and, thus, result in oversampling for remediation effectiveness purposes. Once contaminant plume boundaries have been defined from delineation sampling and groundwater dynamics are understood from several rounds of sampling key wells, one or a few carefully selected wells usually will suffice for remediation purposes and for public health protection. This guest editor's perspective examines how to consider remediation and postremediation monitoring needs.

CURRENT MONITORING APPROACHES

A distinction should be made between sampling and monitoring. For subsurface hazardous waste sites involving groundwater contamination, successive iterations of sampling at different locations often are needed to define hot spots, sources, confining layers, aquifer interactions, plume boundaries, exposure potential, and intermedia impacts, such as surface water discharges. Such efforts, performed under the rubric of "site investigation" might involve dozens or even hundreds of groundwater sampling wells. Traditionally, these wells often are dubbed "monitoring" wells, which perhaps established the mind-set that problem definition must evolve to solution monitoring. However, good problem definition should define cause-and-effect relationships among sources, remedies, and impacts, which should allow for more cost-effective long-term monitoring. In fact, one goal of site investigation should be a definition of the long-term monitoring requirements.

Examples of current monitoring approaches for hazardous site remediation projects in the public domain include:

- The Johnson County Landfill in Johnson County, Kansas, which has 45 monitoring wells that are sampled for typical landfill parameters on a quarterly basis. The estimated cost to conduct this monitoring is approximately $132,000 (based on 180 samples per year at $400 per sample [all parameters] and $60,000 for sampling and reporting).
- At a munitions disposal site in Harwell in the United Kingdom, there is a substantial pump-and-treat (P&T) system. The monitoring program consists of samples collected

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from 85 locations twice per year, with an additional 27 locations on a quarterly basis. The estimated cost to conduct this monitoring is approximately $73,000 (based on 85 samples annually and 27 samples quarterly [166 samples per year] at $200 per sample [all parameters] and $40,000 for sampling and reporting).

- A chlorinated solvent plume at the Naval Weapons Station in Seal Beach, California, has an enhanced *in situ* bioremediation system with 86 monitoring wells. The wells are sampled at least annually for volatile organic compounds and bioattenuation parameters. The estimated cost to conduct this monitoring is approximately $47,000 (based on 86 samples per year at $200 per sample [all parameters] and $30,000 for sampling and reporting).

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A perpetual (e.g., 100-year) semiannual monitoring program consisting of 50 wells might cost about $10 million in constant dollars[1] with a net present value of about $1.5 million at a real discount rate of 7 percent. Such a program would involve a field crew to collect the samples, analysis and quality control (volatile organic compounds, semivolatile organic compounds, and trace metals), and a short report. If the report is good, it might have effective trend analyses evaluating the possibility of a reduction in monitoring needs. Such analyses might show that some wells are redundant or that concentrations have reached asymptotes.

Or a less elaborate monitoring program could have been established in the first place. The next section discusses when a less elaborate program might *not* be appropriate.

ELABORATE MONITORING NEEDS

As opposed to sampling, the purpose of a monitoring program is to gauge the effectiveness of a remedy (or no action) and to ensure that impacts are permissible. In some cases, conditions are so complex or impacts are so critical that more elaborate monitoring is appropriate. Such cases include:

- *Many or complex sources.* Multiple sources may create multiple impact areas, each of which would likely need monitoring. Similarly, complex sources, such as those having dynamic release characteristics or possible future changes (e.g., future tank ruptures), may require more monitoring locations and higher frequencies.
- *Many impact areas.* Multiple aquifers may be affected, or there may be intermedia transfers, such as discharges to groundwater or vapor intrusion. In such cases, numerous locations and possibly more frequent monitoring might be appropriate.
- *Sensitive receptors.* Contaminated groundwater might pose continuing exposures to humans or ecological receptors such that more frequent monitoring at several locations would be appropriate. Examples include threats to drinking water supplies or via vapor intrusion to homes.
- *Experimental remedies.* More locations and/or frequency might be required to develop a database for evaluating innovative remedies—*in situ* bioremediation, for example. Similarly, more elaborate monitoring might be required to track or to predict aggressive remediation timetables or possible rebound effects.

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Analytical limitations or real variability around sensitive thresholds also might justify more elaborate monitoring. For example, if contamination hovers around the analytical detection limit, which is also a level of potential health concern in drinking water, more elaborate monitoring should be performed, unless a more sensitive analytical method can be used and appropriate precision demonstrated.

Even though these example conditions would argue for more elaborate monitoring, it is still possible that current programs addressing such conditions are excessive. A framework for considering long-term monitoring requirements is needed. It is possible to have too much data. Besides wasting money that might otherwise be better spent, too much data can hide important details.

MONITORING CRITERIA

The first criterion for designing an effective monitoring program is to define the purpose in specific enough terms to be meaningful. Too often, the objective is so general as to be meaningless, for example:

The purpose of the monitoring program is to monitor the effectiveness of the remedy.

More specificity would not only ensure better cost effectiveness but also would help guide technical effectiveness. An example with more specificity might be:

> The purpose of the monitoring program is to evaluate the effectiveness of the P&T system to contain the contaminant plume and to ensure that the neighborhood across the street is protected from vapor intrusion.

With the second definition, two specific monitoring objectives become evident: (1) plume expansion and (2) vapor intrusion. Plume expansion might be monitored with a single sentinel well at or near the downgradient boundary. This same well may be sufficient to satisfy the second objective (vapor intrusion) if the plume has not yet crossed into the neighborhood. From the stated objective, it is unclear why multiple wells in the interior of the plume must be monitored. If there are indeed such reasons, perhaps because there are already vapor intrusion issues within the plume area, they should be stated in the design objectives. Is it possible that those plume-interior wells will be monitored simply because they are there?

A framework for considering long-term monitoring requirements is needed. It is possible to have too much data. Besides wasting money that might otherwise be better spent, too much data can hide important details.

Four considerations for the design of monitoring programs are:

1. Plume nature/extent defined.
    - Most likely there will be some gaps in information, but are they important?
2. Relatively stable aquifer.
    - No aquifer will be completely stable, but are the fluctuations important?
3. No new sources.
    - If so, the first criterion is unlikely to have been met.
4. No need for more complex downgradient user monitoring.

- Downgradient uses of the aquifer (e.g., drinking supply) might require more locations/frequency, but consideration should be given to whether the aquifer or the use should be monitored in a more complex manner.

Hazardous waste site sampling and monitoring has been performed for over 30 years. It is safe to say that the science has reached a level of sophistication that should allow for well-rationalized monitoring, not just data for data's sake. A framework for such rationalization is provided next.

The objective statement for the monitoring program must specifically address the issues for which the data are needed.

Monitoring Framework

Objective Statement

As noted, the objective statement for the monitoring program must specifically address the issues for which the data are needed. If an issue is not stated, it should be assumed not necessary. The process of creating such a specific statement will help flush out remedial expectations as well as impact concerns.

Special Conditions

This section should list the conditions that will affect or create a need for the monitoring. Possibilities include:

- Aquifer characteristics, such as more than one zone, complex flows (e.g., karst geology), and variable rates or directions
- Seasonal variability
- Actual versus potential (realistic) impacts/impact areas
- Sensitive receptor issues
- Remedy characteristics (e.g., P&T capture zone or remedy unknowns)

Design Locations for Objectives

Design a monitoring element that specifically addresses each element of the objective statement, including the minimum requirement and any need for redundancy. For example, if the objective is plume expansion and there is only one contaminated aquifer, one well at the boundary may suffice. If the objective is protection of a water supply aquifer or capture zone, one sentinel well between the plume and the supply aquifer may suffice. If the objective is to prevent or to mitigate vapor intrusion, one sentinel well upgradient of a neighborhood may suffice for the former but multiple wells in the neighborhood might be required for the latter. From this exercise, spurious locations often can be eliminated.

Design Frequency for Objectives

Each objective in the objective statement should offer insight for data frequency needs. For example, if vapor intrusion issues are seasonal because of water table fluctuations and

Remediation DOI: 10.1002/rem

if the contaminant plume has already reached the neighborhood, more rounds than one per year may be needed—one during high water and one to confirm that the water table has dropped below the elevation of concern, although the second round may be limited to elevation measurement. A water supply sentinel well can be monitored at a frequency defined by the travel time to the supply wells along with further remediation installation timing, should a violation occur. Once appropriate frequencies have been defined, their future reduction should be considered. This can be done in light of the final criterion, discussed next.

Monitoring Duration

Monitoring shutdown criteria should be established as part of the design. This involves two steps: (1) definition of triggers for shutdown and (2) consideration of rebounding. Shutdown of each monitoring component should be considered separately. A common shutdown trigger is shutdown of the remedy (e.g., the P&T system), and a common rebound evaluation includes monitoring for a certain number of rounds after the trigger. Frequency increases might be appropriate when considering shutdown. For example, quarterly monitoring for 2 years might be considered after P&T shutdown while considering rebounding in order to ensure a timely resumption if rebounding occurs, whereas annual monitoring was sufficient during the remedy. Once durations are established, it is appropriate to consider frequency step changes for each monitoring component. Such step changes might also have criteria. For example, semiannual monitoring for plume expansion might be changed to annual if certain data requirements are met, such as a concentration asymptote or a trend derivative.

Exhibit 1 shows a flowchart for design of a groundwater monitoring program. For a well-defined source with a well-defined contaminant plume in a single aquifer with minimal *actual* threats to receptors, there is no reason why one well cannot suffice.

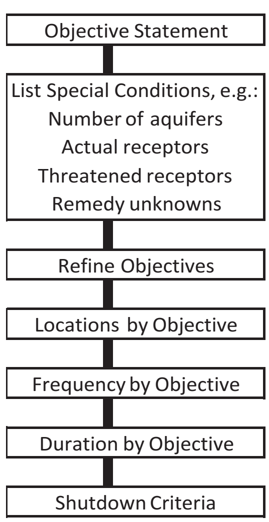

Exhibit 1. Monitoring program design

Checklist*

		Y	N	Issue, Further Action
1	Plume(s) delineated	x		1 plume in 1 aquifer
2	Plume dynamics defined	x		Minor seasonal variations
3	Sources defined	x		Former spill
4	Sources stable	x		Nothing beyond the spill
5	No sensitive impacts	x		No supply wells, vapor intrusion, etc.
6	Remedial action	x		Conventional P&T

Design Objectives	Design Element
Program Objective:	Monitor the P&T system to ensure plume decreases and to ensure no expansion into downgradient, sensitve aquifers.
Objective 1: Remedy Operation	Influent/Effluent flow and concentration monitoring.
Objective 2: Plume Improvement	1 well along plume centerline about 2/3 from source, sampled 4/yr until seasonal fluctuations are understood, after which 2/yr or 1/yr depending on dynamics. Monitor until 2 years after remedy termination.
Objective 3: Plume Expansion	Add 1 sentinal well beyond plume boundary if increasing or steady trend observed in centerline well. 1/yr as long as ND; 4/yr if/when >ND. Monitor 2 years after return to ND or go to Objective 4.
Objective 4: Further Response	Reevaluate monitoring and remedial action if sentinel well shows increasing trend.

Shutdown Criteria

Conventional P&T	Below all xyz gw criteria in plume. Once centerline well reaches X% of criteria where X = centerline well/dirtiest well concentration during delineation sampling, sample other wells in plume 4 times to ensure criteria met everywhere, terminate system and monitor centerline well for 8 quarters to ensure no rebound.

* If any item is checked "no", develop specific objectives to address.

Exhibit 2. Monitoring program checklist

Exhibit 2 provides an example of a monitoring program design checklist leading to design objectives and program elements that address those objectives. Every monitoring program should address the four basic objectives shown in the table. Additional objectives will become evident from the checklist. Although somewhat idealized (one contaminated aquifer, presumably a source that has been removed, and a conventional P&T system with no sensitive *actual* receptors), it is actually a quite common condition. As shown, a

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sufficient groundwater monitoring program can consist of one well with planned responses if that well does not meet expectations.

NOTE

1. Twice per year: $8,000 for field crew, preparation, mobilization, and sampling disposal, $800/sample for analysis, shipping, quality control, and database update, and $5,000 for reporting.

Neil S. Shifrin, PhD, is a director at Gnarus LLC. He has practiced as a consulting environmental engineer for 40 years, with work on essentially every kind of environmental project—water, soils, groundwater, and air. Specializing in hazardous waste sites for the past 30 years, Dr. Shifrin has worked on Love Canal and other major projects involving polychlorinated biphenyls, chlorinated solvents, pesticides, sediments, manufactured gas plants, trace metals, perchlorates, and landfills, among others. He has a BS in chemical engineering from the University of Pennsylvania and a PhD from MIT in environmental engineering.

