Improving Decision Quality: Making the Case for Adopting Next-Generation Site Characterization Practices

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Better site characterization is critical for cheaper, faster, and more effective cleanup. This fact is especially true as cleanup decisions increasingly include site redevelopment and reuse considerations. However, established attitudes about what constitutes "data quality" create many barriers to exciting new tools capable of achieving better characterization, slowing their dissemination into the mainstream. Traditional approaches to environmental "data quality" rest on simplifying assumptions that are rarely acknowledged by the environmental community. Data quality assessments focus on the quality of the analysis, while seldom asking what impact matrix heterogeneity has had on analytical results. Assessments of data quality typically assume that chemical contaminants are distributed nearly homogeneously throughout environmental matrices and that contaminant-matrix interactions are well behaved during analysis. Yet, these assumptions seldom hold true for real-world matrices and contaminants at scales relevant to accurate risk assessment and efficient remedial design. For the site cleanup industry to continue technical advancement, over-simplified paradigms must give way to next-generation models that are built on current scientific understanding. If reuse programs such as Brownfields are to thrive, the scientific defensibility of individual projects must be maintained at the same time as characterization and cleanup costs are lowered. The U.S. Environmental Protection Agency (EPA) offers the Triad Approach as an alternative paradigm to foster highly defensible, yet extremely cost-effective reuse decisions.

INTRODUCTION

A number of exciting developments are emerging in the field of environmental cleanup and revitalization. This period of exploration and transition provides tremendous opportunities for evolving the practices and expectations of this dynamic arena. The accumulation of institutional experience is transforming the field as we understand more fully what works and what does not work for real-world site investigation and cleanup. Continued investment of public and private dollars into basic and applied research adds to a growing understanding of the mechanisms governing contaminant release, fate, transport, transformation, and interaction with biotic systems, and how these mechanisms are influenced by human-engineered interventions. Our ability to understand and predict contaminant behavior improves as new sampling and analytical tools are developed that permit better spatial resolution of contaminant distributions. Better resolution, in turn, supports better site characterizations that support more defensible decisions about whether site-specific contamination may pose risks, and if so, what risk reduction strategies can give the most "bang for the buck." Yet, important barriers exist that hinder widespread use of these tools.

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It is U.S. Environmental Protection Agency (EPA) policy to make decisions based on sound science. If sampling for contamination and its effects is poorly done, the accuracy of the resulting conceptual site model *and all subsequent decisions based on it* (especially risk estimation and remedy design) may be faulty. To support the scientific defensibility of decisions involving contaminated sites, EPA has articulated the Triad Approach (Crumbling, 2001a). The Triad is a conceptual and strategic framework that explicitly recognizes the scientific and technical complexities of site characterization, risk estimation, and treatment design. In particular, the Triad Approach acknowledges that environmental media are fundamentally heterogeneous on a variety of scales, a fact that complicates sampling design, analytical method performance, and toxicity estimations.

The challenge of adopting the Triad into routine practice is significant. The normal growing pains experienced by any science-based field of endeavor are magnified for the environmental cleanup industry. Relationships among federal, state, and local regulators and the regulated community are complex. These relationships intersect with an array of other players including consulting engineering firms, property investors, academia, citizen stakeholders, technology vendors, and non-governmental organizations. The diverse interests and motivations of these stakeholders influence the site investigation and cleanup process. Modifying familiar regulatory, procurement, business, and technical practices to accommodate evolving scientific knowledge and technology requires intensive coordination and outreach. For the entire field to embrace improved strategies and technologies, all parties must "move" together: regulators must be open to innovations in order for vendors to risk marketing them; consulting firms must offer innovative services to their clients while the clients, as educated consumers, must encourage consulting firms to "think outside of the box." Everyone must be willing to break out of traditional comfort zones to apply the benefits of scientific progress to regulation and field practices. Second-generation tools and strategies will produce better data quality and decision defensibility than the first-generation procedures inherited from the 1970s and 1980s that continue to be used today.

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HETEROGENEITY AS A FUNDAMENTAL DRIVER FOR CHANGE

For the vast majority of site investigations, contaminant data are generated by taking a relatively few small-volume samples from an environmental or waste matrix. The per-sample costs for trace level analysis are high because satisfactory analytical performance requires sophisticated instrumentation along with experienced and well-educated operators. Therefore, there is strong financial motivation to minimize the number of samples. Compounding the potential for a non-representative data set is the fact that, especially for solid samples, an even smaller volume of the sample (i.e., a subsample) is analyzed to generate the result. Consequently, the volume of matrix actually analyzed is tiny compared with the volume of parent matrix to which the sample results will be extrapolated, increasing the risk of highly variable results and skewed data sets (Gilbert & Doctor, 1985). If contaminants of interest occurred at nearly constant concentrations throughout the parent matrix, then drawing conclusions about the parent matrix from a few small samples would be fairly straightforward. Unfortunately, real environmental matrices are seldom homogeneous.

Good science involves making observations (such as generating data results) and drawing conclusions from those observations to make decisions. Key to good science is not extrapolating beyond the evidence. Field studies show that matrix heterogeneity severely limits the confidence with which analytical results can be justifiably extrapolated beyond the tiny sample analyzed. Environmental heterogeneity is a consequence of the release mechanism(s) and the partitioning behavior of the analyte in conjunction with the transport and transformation mechanisms offered by the environment. For example, Exhibit 1 illustrates data from extensive studies of explosive residues performed by the Cold Regions Research and Engineering Laboratory (CRREL) of the U.S. Army Corps of Engineers (Jenkins et al., 1996). As you can see, there is tremendous contaminant concentration variability over a very small area. The site soils depicted by this particular data set were contaminated due to activities that spilled solid explosive material from decommissioned munitions. To characterize the short-range variability of trinitrotoluene (TNT, in units of ppm) in surface soil, grab samples were collected in a seven-location wheel configuration. The diameter of the wheel was 4 feet; therefore each sample within the wheel is only about 2 feet from its nearest neighbors. Individual grab samples were collected from a 0- to 6-inch depth using a 2-inch diameter stainless steel auger. Each of the seven soil cores was thoroughly homogenized in separate containers. [Homogenization was critical because the particulate nature of matrix constituents create ample opportunities for subsampling procedures to exacerbate data variability (Gerlach et al., 2002; Ramsey & Shuggs, 2001).] Subsamples from each homogenized sample were analyzed by both an on-site analytical method (EnSys Colorimetric Test Kit; EPA SW-846 Method 8515) and by a traditional laboratory method (EPA SW-846 HPLC Method 8330).

Exhibit 1 shows that there is general agreement of the on-site colorimetric results with the off-site HPLC results, in marked contrast to the differences among the seven

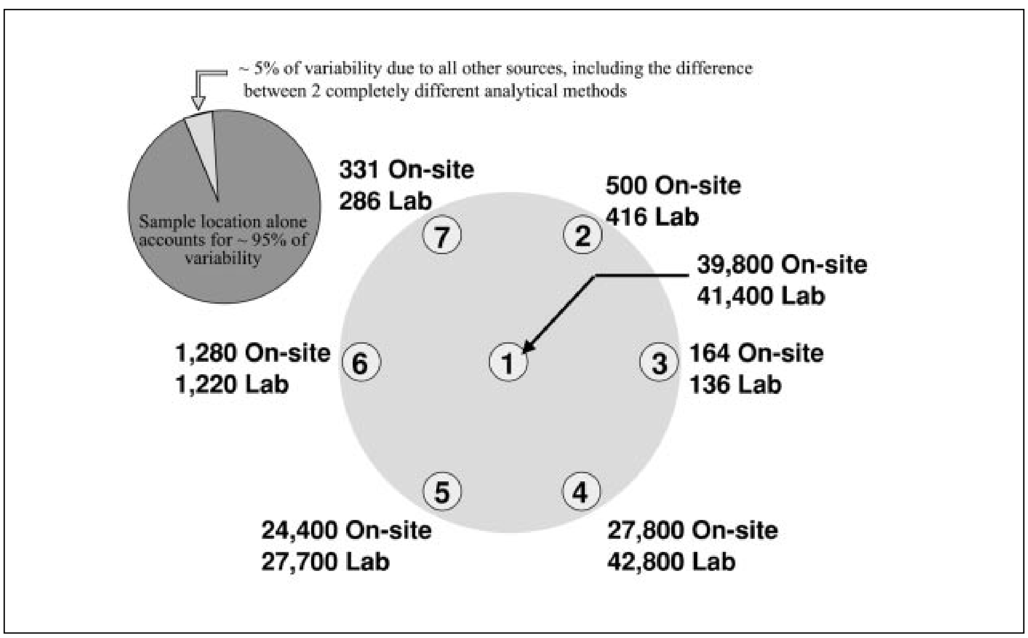

Exhibit 1. Variability of TNT in soil across a 4-foot diameter circle (units = ppm) (from Jenkins et al., 1996).

sampling locations. Using common grab sampling scenarios, any one of these samples could have been collected and assumed to represent the TNT concentration for an area much larger than the 2-inch diameter core. But that standard assumption would be erroneous. A single grab sample from location 1 would lead to very different conclusions about the degree of TNT contamination than a sample from location #3 only 2 feet away. When the variability in this data set of 14 results is partitioned, at least 95 percent of the total variability (as statistical variance) in this data set is due simply to sample position (that is, a consequence of matrix heterogeneity), whereas using two very different analytical methods contributes no more than 5 percent of the variation. Stated another way, matrix heterogeneity over a distance of only 4 feet caused over 19 times more variability (i.e., uncertainty) in data results than did the choice of analytical method. Improving the performance of the analytical methods would not reduce the uncertainty in the data set, since nearly all of the variability is caused by true sample-to-sample variation.

Heterogeneity of soil pollutants is not limited to explosives contamination.

Conclusions from this CRREL study on TNT residues found "enormous short-range heterogeneity and sampling error [that] overwhelmed analytical error." The investigators recommended that the quality of site characterization data from explosives-contaminated sites could be improved by "reducing sampling error…using composite sampling, in-field sample homogenization, and on-site analysis [as] an efficient method of producing data that are accurate and precise, and also representative of the area" (Jenkins et al., 1996). Similar extremes of heterogeneity have been found for other explosive residues. "Spatial heterogeneity of HMX concentrations was large on both short- and mid-range scales and this factor dominated the overall uncertainty associated with site characterization. Relatively minor uncertainties were due to analytical error" (Jenkins et al., 1997).

Heterogeneity of soil pollutants is not limited to explosives contamination. The ratio of sampling to analytical variability was estimated for a data set from a Brownfields redevelopment project (a former scrap-yard site). The data set was composed of 291 analyses for a suite of metal contaminants and 570 analyses for a suite of polycyclic aromatic hydrocarbon compounds (PAHs). Samples were collected in an approximate grid design from an area roughly 800 × 300 feet to a depth of 12 feet (a volume of about 110,000 cubic yards of site materials). Despite the large number of samples, the combined volume of field samples represents something on the order of one-millionth of the site volume. If the volume of the subsamples actually analyzed is compared to the volume of original matrix, the fraction is more on the order of one-billionth. No wonder then that the contribution of sampling variability to overall data uncertainty ranged to 99.9999 percent and more for those analytes that tended to show hotspot patterns attributable to discrete spills (lead and PAH analytes). Arsenic, on the other hand, demonstrated a low natural background that tended to even out its variability, making it one of the "better"-behaved analytes with only 90 percent of the data uncertainty contributed by sampling considerations.

Nor is environmental heterogeneity confined to vadose soils. As technologies such as direct push-deployed detection systems and passive diffusion samplers are applied to subsurface and aquifer characterization, marked vertical heterogeneities in contaminant concentrations are being found (Vroblesky, 2001). This high degree of heterogeneity complicates interpretation of groundwater data since the proportion of mixing between water from more contaminated horizons with water from less contaminated horizons is an uncontrolled and unconsidered variable for the vast majority of monitoring well sampling plans. Yet this variable determines the contaminant concentrations in the samples received by the laboratory. On the other hand, careful delineation of vertical heterogeneity supports vastly improved sampling designs, as well as better targeting of remediation strategies to save time and money (Tillman & Sohl, 2001).

REPRESENTATIVENESS TOO COSTLY UNDER THE TRADITIONAL MODEL

Actually, the impact of heterogeneity on data uncertainty has been known for some time. By the 1980s, investigators were discovering that matrix heterogeneity compromised their ability to draw reliable conclusions from analytical data. Consequently, EPA issued guidance documents with suggestions for focusing efforts on understanding and managing sampling uncertainties for commonly heterogeneous matrices such as soils. These documents introduced the concept of "sample support" (the physical volume, orientation, and particulate makeup of samples) as critical to sampling design and data interpretation (USEPA, 1989, 1990). EPA also published the deliberations of an expert panel convened in 1991 to explore the ramifications of environmental variability. The panel noted that studies were showing that 70 to 90 percent of data variability was caused by "natural," in-place variability, with only 10 to 30 percent of variability being contributed by the rest of the data generation process (such as the sample collection procedures, sample handling, laboratory handling and cleanup, laboratory analyses, data handling, data reporting, and data interpretation). The import was summarized by a panel member: "So when you think about where you might get the best advantage by spending another dollar, in the lab versus spending the same increment of money to get a better handle on that natural population variability, it is obvious that you get a much bigger bang for your buck by determining natural population variability. That is where the real bulk of the error is typically found" (Homsher et al., 1991).

> It was much easier to oversee "data quality" if that concept was defined in terms of analytical methods and laboratory performance.

The panel's recommendation that environmental workers focus more on understanding sampling variability had little impact on regulatory paradigms and field practices at the time. Although representativeness was considered important to data quality [it is the "R" in the "PARCC parameters" of Precision, Accuracy/Bias, Representativeness, Comparability, and Completeness (USEPA, 1998)], careful management of sampling representativeness was inconceivable from a cost standpoint when standard laboratory analyses were the only game in town. It was much easier to oversee "data quality" if that concept was defined in terms of analytical methods and laboratory performance. The problem with defining data quality in that way is that analytical data are generated from *environmental samples*, and even perfect analytical quality is no guarantee that sample collection will produce data that are representative of the decisions the data ultimately are used to make. The more heterogeneous the matrix, the more likely it is that a small data set will be skewed by the "luck of the draw."

THE CONSEQUENCES OF IGNORING HETEROGENEITY AND REPRESENTATIVENESS

Decisions about risk are usually based on an estimate of average concentrations across an exposure unit. In contrast, decisions about risk reduction strategies are usually based on discriminating between zones with higher concentrations requiring treatment or removal and lower concentrations that may not require remedial attention. If data are not representative of the decision being made (averages in one case, extremes in the other case), the data will lead to flawed decisions. The first-generation data quality model that considers data quality only in terms of analytical method performance ignores sampling uncertainties and the impacts of matrix heterogeneity. Given what we know now, this cannot be considered "sound science." It is imperative that environmental programs update their data quality model to reflect current scientific understanding. Fortunately, technological tools now exist to cost-effectively implement a sounder data quality model (USEPA, 2002). Another encouraging trend is greater emphasis on geostatistical analysis. Whereas classical statistical models may be more appropriate for evaluating risk, geostatistics is better suited for modeling spatial patterning that may drive more cost-effective remedial designs.

An even more compelling reason to update the first-generation data quality model is to reduce the financial and liability risks created when non-representative data lead to erroneous decisions. Attempts to save resources in the short run by skimping on the data collection program subsequently waste far more resources (including client and stakeholder good will) when erroneous decisions are discovered. For example, a quality assurance manager for a major consulting firm observed that "[r]eductions in the comprehensiveness of the field investigation, based on budgetary considerations, schedule-driven approval of incomplete plans, superficial or protocol-oriented reviews by technically unqualified agency personnel, all come back to haunt the stakeholders at remediation time…remedial action case histories have, in fact, proved [that] the perception of site conditions based upon site investigation does not reflect reality. Use of site investigation data invariably leads to underestimating or overestimating the extent of contamination, sometimes on an alarming scale. In either case, ramifications may be substantial with respect to remediation budgets and public perception of the environmental industry" (Popek, 1997).

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THE TRIAD APPROACH: A FRAMEWORK TO MOVE BEYOND FIRST-GENERATION DATA PARADIGMS

So how can the environmental community move toward next-generation paradigms that are scientifically sound and protective, yet lower project costs so that more sites can be investigated and returned to productive reuse? What vision should guide the environmental cleanup field as it matures its fundamental assumptions, its regulatory expectations, its scientific and technology sophistication, and its implementation strategies? EPA has articulated the Triad Approach to fill this role. As illustrated in Exhibit 2, the Triad refers to three primary elements: (1) detailed and specific **systematic project planning** that begins by *clearly* defining desired project outcomes (e.g., potential goals for site reuse), and exploring the uncertainties (i.e., unknowns) that stand in the way of achieving those outcomes; (2) **dynamic work planning strategies** that can drastically save time and money over the project lifetime; and (3) **real-time data** generation and interpretation to support the real-time decision making of the dynamic work plan, while cost-effectively managing sampling uncertainty and data representativeness. The Triad Approach allows the investigator to adjust field activities to address specific conditions, increasing site-specific information in an efficient and inexpensive manner and improving decision-making confidence.

The Triad Approach is a continuation and synthesis of efforts begun in the 1980s by Jacqueline Burton and colleagues to make site investigation and cleanup more effective and less costly (US DOE, 1998). Over the years, like-minded innovators

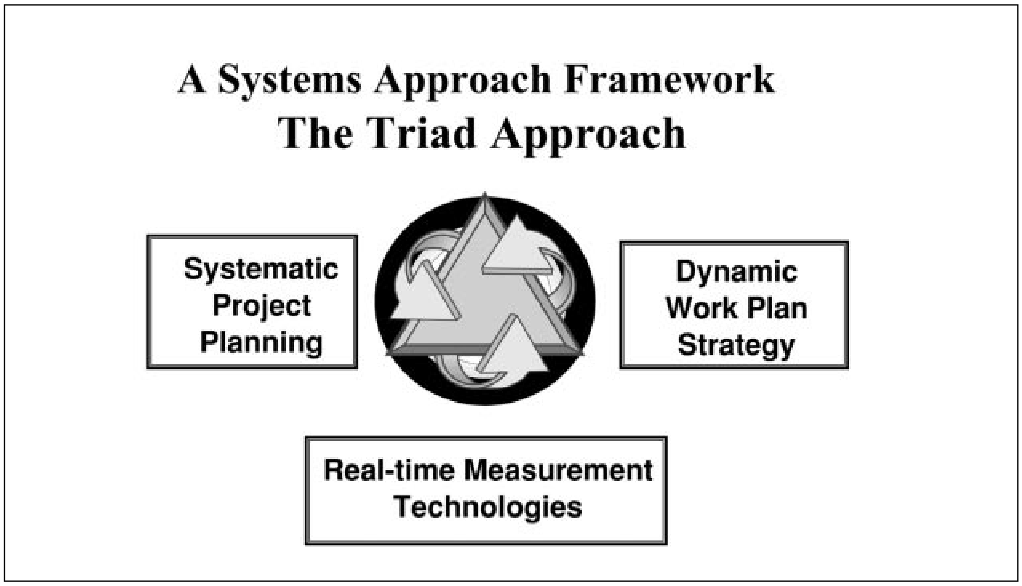

Exhibit 2. All three elements of the Triad Approach are necessary to decrease investigation and cleanup costs, but systematic planning is the critical foundation for successful projects.

from the governmental, academic, and private sectors have contributed to the theoretical and practical considerations that the Triad Approach embraces (Tetra Tech EM Inc., 1997).

The Triad Approach revolves around identifying, understanding, and managing the uncertainty in site decisions. When scientific data are used to provide input to the decision-making process, the uncertainty in that data needs to be managed to a degree commensurate with the desired decision confidence. Because most data uncertainty stems from sampling variability, the Triad Approach maximizes the use of new technologies to cost-effectively increase sampling density so that contaminant distributions and spatial heterogeneity can be explicitly characterized at the scale of project decisions. Dynamic work plans are used to simultaneously cut project costs while improving decision quality: data gaps are identified and resolved in the field so that the number of remobilizations back to the site can be minimized (Robbat, 1997). Better site characterization (decreased uncertainty in the conceptual site model) is possible because plumes can be chased and spatial patterns delineated in real time by daily adapting the sampling design according to newly acquired information (US DOE, 2002).

SYSTEMATIC PLANNING FOCUSES ON MANAGING UNCERTAINTY TO REACH PROJECT GOALS

Detailed project-specific systematic planning is the most critical element of the Triad. Without it, applications of the other two elements can become mired in confusion and quickly lose focus and direction. A dynamic work plan strategy might save as much as 50 percent of overall project costs, but only if there has been sufficient investment in up-front planning. In a cost-consciousness world, a significant barrier to the Triad is that most budget and staffing structures are not designed to support this level of intense planning. Revisions to these structures would permit a greater investment of resources before the fieldwork phase begins in order to save time and resources later.

Successful projects tend to actively engage all stakeholders in transparent, consensus-driven project planning, implementation, and decision making. A conceptual site model (CSM) that goes beyond the typical exposure modeling for risk assessment is an essential planning and communication tool. The CSM is any graphical or descriptive device used to organize what already is known about the site and what needs to be known in order to reach the project's ultimate goals. Articulation of the CSM helps the project team identify areas of decision uncertainty and determine what additional information must be obtained in order to support decision making. Once the data gaps contributing to decision uncertainty are identified, site characterization activities are planned to provide the required information. By working from the top-down, a clear articulation of decision uncertainty allows identification of data gaps. This saves money during data generation because only data that is valuable and necessary to decision making is collected. Development of the CSM should involve multidisciplinary expertise to clarify project goals, predict technical and legal issues likely to arise, identify risk assessment data needs, and anticipate cleanup alternatives. All these considerations should drive data gathering (sampling and analysis) strategies. The various factors to be considered during systematic planning for remediation projects are covered by the U.S. Army Corps of Engineers in their *Engineering Manual for Technical Project Planning* (USACE, 1998).

Successful projects show that the selection of analytical methods is best mixed and matched according to the site-specific data needs.

Systematic planning for the dynamic work plan often involves developing a series of "if-then" statements or a decision tree that can be implemented in real time as data fills knowledge gaps. If certain unknowns cannot be cost-effectively filled, then the decision-making process can be constructed to accommodate that limitation. Sometimes it is more cost-effective to manage decision uncertainty by erring on the side of caution and taking the most protective action rather than paying to generate the data needed to prove whether the action is absolutely necessary. In this way, decisions can be made despite some unresolved uncertainties, yet the decisions still remain protective of human health and the environment.

The real-time decision making of dynamic work plans requires that the data used to implement the decision tree be turned around in an equivalent "real-time" time frame. Successful projects show that the selection of analytical methods is best mixed and matched according to the site-specific data needs. Depending on the nature of the project, real-time measurements have been provided by field-portable methods (such as hand-held instruments and kits of varying technical complexity), by mobile laboratories (which may run kits, standard laboratory instrumentation, or both), by rapid turnaround analysis at a traditional fixed laboratory, or a combination of all three. Contracting to operate screening analytical methods in traditional laboratories can be more cost-effective than trying to operate kits under certain circumstances, such as difficult field conditions. Variables that may compromise kit performance in the field, such as ambient temperature, dust, humidity, reagent storage, water and power supplies can be much better controlled in a mobile or fixed laboratory setting. If a fixed laboratory happens to be located nearby, rapid turnaround to support a dynamic work plan may be just as feasible as doing the analyses in the field.

ANCHORING DATA QUALITY IN DECISION MAKING

Systematic planning is critical for managing the analytical uncertainty inherent to all environmental data. This is particularly important for measurements produced in the field. Yet current practices present many opportunities for errors. As noted previously, field methods provide important advantages: real-time results can support a dynamic work plan, and increased numbers of samples can support management of sampling uncertainty. However, many practitioners associate common field methods with "field screening," and the first-generation data quality model assumes that "screening quality data" is of little value. Updating our current data quality model means updating this thinking. If "data quality" is assessed according to the ability to support confident decisions, then "screening quality data" should be defined as those data that provide some useful information, but not enough information to alone support decision making at the desired level of certainty (Crumbling, 2001b). Since the term "data quality" must include the concept of "sampling quality," as well as the more familiar analytical quality, uncertainty either about the sample representativeness OR about the analytical quality (or both) *with respect to the intended decision* could render data as screening quality. Therefore, perfectly accurate analytical methods will produce screening quality data if the representativeness of the sample is not known. On the other hand, screening analytical methods may produce data effective for making decisions if both the sampling representativeness and the analytical quality are known to be sufficient to meet decision-making needs.

When discussing data quality concepts, the Triad Approach makes careful distinctions that explicitly link data quality assessment to the data's ability to help manage decision uncertainty.

Even if the analytical quality produced by a field method is not sufficient to support final decisions about risk assessment or regulatory compliance, the field method may serve a critical role in managing the sampling uncertainty of fixed laboratory data. This is, in fact, what many practitioners intend to convey when they talk about "field screening." However, because of pervasive confusion about the relationships between analytical method performance, data quality, and the decision-making process, many regulators have reacted with distrust to the term "field screening" and its associated technologies. To move the environmental field past this hurdle, it would be wise to change several common practices.

Recommended Change: Stop using the term "field screening." As currently used, this term is ambiguous and misleading. It echoes and perpetuates the myths of the first-generation data quality model (Crumbling, 2002). The truth is that not all field methods are screening analytical methods (although it is true that many are). Additionally, the location where data are generated (i.e., in a fixed laboratory or in the field) should not be assumed to dictate the quality of the data. As should be clear by now, data generated in a traditional laboratory setting should be considered screening quality if the sampling representativeness, a key aspect of data quality, is unknown. Instead of "field screening," more neutral and accurate terms, such as "field analytical," "on-site measurement," "real-time analysis," and similar terms, should be used to avoid implying that data quality is tarnished simply by virtue of being produced in the field.

Recommended Change: Use internally consistent and clearly defined terms. When discussing data quality concepts, the Triad Approach makes careful distinctions that explicitly link data quality assessment to the data's ability to help manage decision uncertainty.

1. Data of known quality: These are data for which each step of the sampling, subsampling, and analytical procedures and performance is documented. This allows a data user to establish estimates for the sampling representativeness, for the analytical bias, precision, and reporting limits, and for the possible impact of interferences on the measurement process. This allows the data user to decide whether or not the uncertainty in the data is excessive with respect to the desired data use.

2. Data of unknown quality: Data are of unknown quality when critical steps in the data generation process are improperly performed or have not been documented, creating irresolvable uncertainty about whether the data results are credible. Here are some examples of data of unknown quality: (A) Improper soil collection procedures or lack of documentation about what procedures were used that creates significant uncertainty about whether or not there has been significant loss of volatile compounds from the sample prior to analysis, possibly invalidating the results for decision-making purposes. (B) Inadequate analytical quality control or lack of documentation that creates uncertainty about whether the analytical instrument was calibrated correctly, so it is unknown whether results are reliable. (C) Failure to consider the performance limitations of an analytical method in the context of the project that creates uncertainty whether interferences that were likely present in the samples caused the data to be biased. Improperly interpreting this data without acknowledging the possible impact of interferences could lead to decision errors beyond what can be tolerated.

The term "effective data" is a short way to say "data that are effective for decision making."

3. Decision quality data (or "effective data"): This term is defined as "data of known quality that are demonstrated to be effective for making the specified decision because both the sampling and analytical uncertainties have been managed to the degree necessary to meet clearly defined and specified decision confidence goals." The term "effective data" is a short way to say "data that are effective for decision making." Note the strong intuitive linkage of data quality to decisions. Any claims of "decision quality data" or "effective data" in a project-specific context are meaningless unless it is very clear what decisions the data will be (or, are being) used to support.

4. Screening quality data: Under the Triad paradigm, this term describes data of known quality that may contribute some useful information to the decision-making process, but by itself, the data set is inadequate (i.e., too uncertain or incomplete) to support confident decision making. It is possible that a screening quality data set can be used carefully and collaboratively in conjunction with other data or information that manages the residual uncertainties (see below).

5. Collaborative data: These are separate data sets that are used together to manage different aspects of data uncertainty. For example, because of the high cost of traditional laboratory analyses, it is generally cost-prohibitive to take enough samples for traditional analysis to develop a good understanding of contaminant distributions and patterning. Because of this problem, when used on their own, traditional "definitive" environmental methods may produce results that have excellent analytical quality on tiny samples, but huge uncertainty remains about whether those results can be extrapolated to larger portions of the matrix (i.e., the sampling representativeness). On the other hand, less expensive methods frequently used in the field are often based on screening analytical methodology, but they can provide the higher sampling densities needed to manage sampling uncertainty. Yet the analytical quality may be insufficient for purposes of risk assessment or for demonstrating regulatory clean closure. The solution to this dilemma is to use both method types collaboratively according to their individual strengths. This concept is illustrated in Exhibits 3 and 4.

Be aware that mathematically merging different data sets created by different methods may not always be possible or advisable. Very often, collaborative data sets may not be statistically comparable to each other for a number of reasons. For example, they may be based on different analytical principles and so respond to target analytes differently, or a different sample preparation method in the analytical chain may cause different analytical bias and precision. However, this does not detract from their usefulness. One data set can

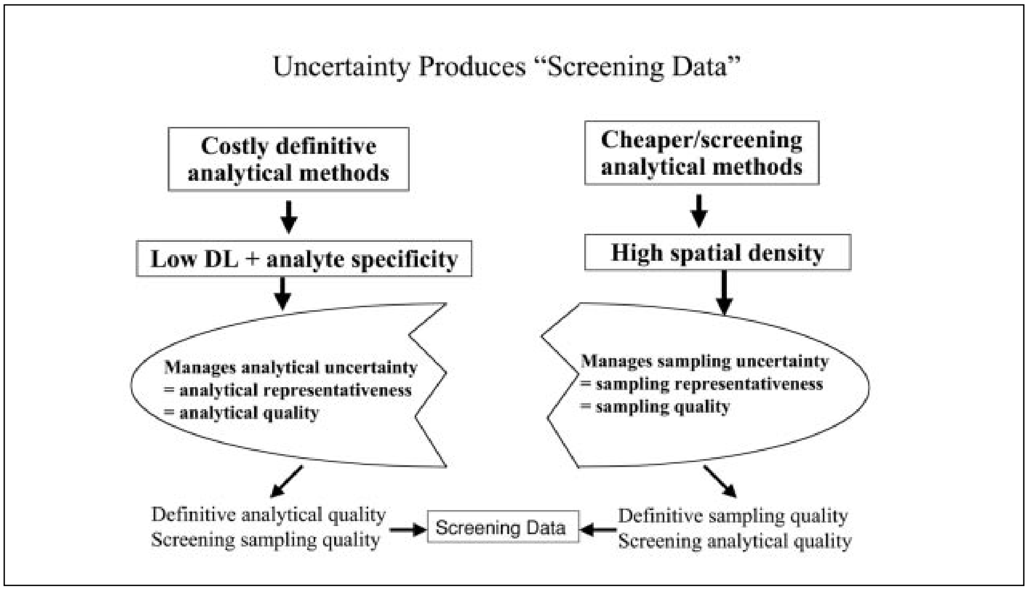

Exhibit 3. It is extremely difficult to cost-effectively manage all relevant sampling and analytical aspects of data uncertainties using just one analytical method. (DL = detection/quantitation limits.)

be used to make decisions about one aspect of uncertainty (such as contaminant distributions), whereas another data set is used to manage other contributions to overall data uncertainty. For example, the data produced by a screening method might be used to delineate different contaminant populations (this is termed "stratification" in statistical terminology) that are then considered separately for purposes of subsequent data gathering or remedial decision making. After sampling representativeness has been established using the cheaper method, a follow-up sampling scheme can be designed for sending proportionally fewer samples for more expensive analysis to the extent needed to manage the analytical uncertainty remaining in the data set produced by the screening method. An example of how this can be done is presented in the "Tree Fruit Site" case study (USEPA, 2000).

Recommended Change: Data must be of known quality. When any analytical method is used with inadequate quality control (QC), the data produced is of unknown quality, and may be justifiably rejected by regulatory agencies. There are enough anecdotal reports to suggest that data generated in the field *under current practice* is often of unknown quality. No doubt this has contributed to regulator distrust of field data. No data user should have to accept data values on faith. There is no excuse for neglecting to do QC on field methods, even if field data are "only" used to manage sampling uncertainty. No matter what the data use, the data *must* be of known and documented quality to permit correct interpretation with respect to the decision. Relying on simple checklists or blanket rules to assemble a QC program usually fails to serve the goal of scientific defensibility. The solution is reliance on a multidisciplinary technical team that includes appropriate analytical chemistry expertise to support project planning and implementation.

Even seemingly simple field kits are based on not-so-simple analytical principles, with ample potential for instrument failure and analytical interferences. Although technician-level staff may be appropriate to *operate* simpler field kits, this should be done under the supervision of a chemist knowledgeable about field analysis and the limitations of the particular kit being used. Selection of the proper kit, modification of extraction or analysis procedures, interpretation of the results, selection of appropriate QC mea-

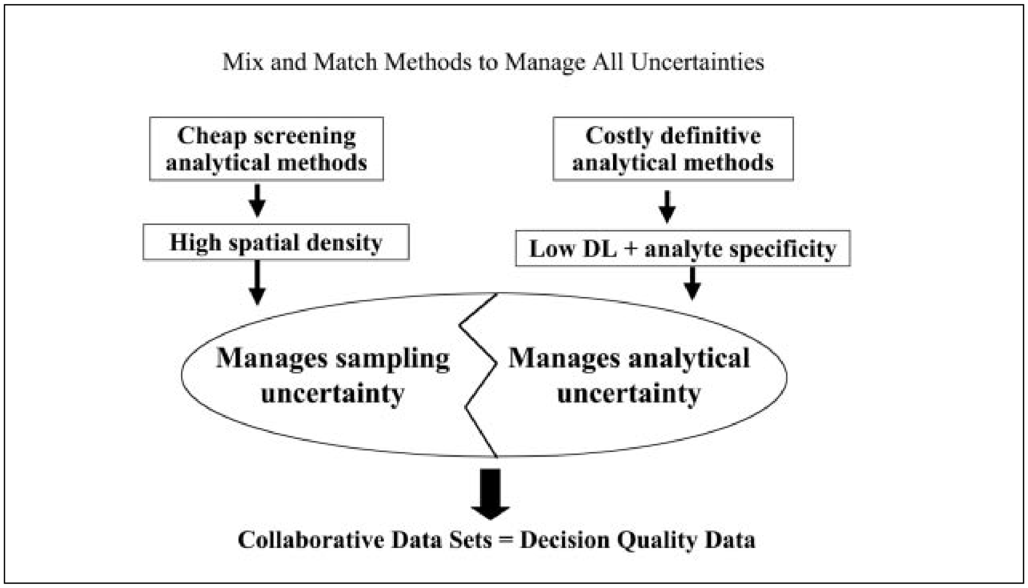

Exhibit 4. Collaborative data sets are designed to complement each other so that all sources of data uncertainty important to decision defensibility are managed. (DL = detection/quantitation limits.)

sures, maintenance of equipment, and trouble-shooting of the problems that inevitably arise: all require instrumental analytical chemistry knowledge and experience. All too often, those implementing cleanup activities avoid collaborating with in-house or contracted chemists during project planning or data collection. This is a mistake, and it hurts the quality and cost-effectiveness of *all* environmental chemistry data, not just data produced in the field. The first-generation data quality paradigm expects the lab to magically produce "definitive data" in spite of having no information about potential project-specific interferences and how the data will be used. As attractive as it might be, this expectation is simply unreasonable (Crumbling, 2002).

For the Triad Approach to become mainstream, patterns derived from the first-generation data quality model must be broken. Under the Triad Approach, summarizing project-specific analytical performance based on an evaluation of QC data is a critical aspect of assessing analytical uncertainty. The plan for how data of known quality will be produced at the project level needs to be documented (often in a project-specific quality assurance plan usually called a "QAPP"). Evaluation of QC data is an integral part of data interpretation and it should be documented in projects reports (Lesnik & Crumbling, 2001).

A dangerous, yet very common, assumption is that the reliability of field data can be established *solely* through splitting a certain percentage of randomly selected samples (a frequently heard ratio is 1 in 10) and sending them to a traditional laboratory. It is true that careful homogenization and splitting of specially selected samples can help establish the comparability of the field data with the more rigorous analytical techniques. Split samples are often a very important component of QC for field data. However, splits are too often done without considering either the impact of sample heterogeneity on split results, or without attention to the specific uncertainty(ies) that the splits should manage. To produce scientifically defensible data, the number of samples to be split and the rationale for their selection should be guided by the need to manage uncertainty, not by rules of thumb. For example, if field data are to be used to make decisions about whether or not soils exceed a regulatory threshold, then if at all possible, most of the split samples should be taken around that decision point to build a data set that demonstrates that field decisions around that action level are correct.

Another factor to recognize is that when the laboratory confirmation results do not exactly match the field analysis results, it does not automatically mean that the field analysis is worthless. Because of method bias or imprecision, it may be necessary to derive project- and kit-specific thresholds to make field decisions on the basis of kit results. In other words, a result of 10 ppm from the kit may actually correspond to a result of 5 ppm by more traditional methods. This is a common consideration for using certain methods, such as immunoassays, that are deliberately calibrated in the factory to be biased high. In addition, kits that respond to a suite of related compounds cannot be expected to numerically match results provided by more selective laboratory methods. Users of these methods must accommodate these considerations. For example, before the proposed analytical design is finalized, "pilot studies," also called "demonstrations of method applicability," are used by successful practitioners to predict the performance of field methods, the need for method modifications, the appropriate analytical QC procedures to use in the field, and the comparability of the data to regulatory actions (USEPA, 2000).

MOVING TOWARD "ALLIED ENVIRONMENTAL PROFESSIONALS"

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With the advent of more specialized technologies and skills, there are striking parallels between the evolution of medical practice and the evolution of environmental cleanup practice. In the old days country doctors did everything themselves. They examined the patient, ran the few tests available at the time, made the diagnosis, selected the treatment, and administered it. This was reasonable when the options for all these activities (i.e., the list of known diagnoses, the number of testing procedures, and the potential treatments) were quite limited. Obviously, that situation changed dramatically as medicine was transformed by science and technology. Every organ system now merits its own medical specialty. Powerful, complex diagnostic imaging and laboratory testing techniques have proliferated, as have options for pharmaceutical or surgical treatment.

We no longer expect one physician to know or do everything. Nor would we have much confidence in a technician or doctor who reads a "cookbook" to operate testing equipment or perform surgery. Since the body of knowledge and skills is too great for any single person to master, good patient care requires that various disciplines share responsibilities through specialization. Allied health professionals in nursing, the laboratory, "X-ray," the pharmacy, physical therapy, etc., all function as a multidisciplinary team that collectively possesses up-to-date knowledge for each discipline and applies it for modern patient care, diagnostics, and treatment. Likewise, for environmental health and economics to benefit from a rapidly growing body of knowledge, open partnerships between multidisciplinary experts representing the "allied environmental professions" of engineering, geology, hydrology, soil science, analytical chemistry, statistics, law, contracting, community relations, etc., will be necessary to interface technical knowledge and skills with routine business and field practices.

A CLASSIC CASE STUDY ILLUSTRATING THE TRIAD APPROACH

Within this article we have referred to the "Tree Fruit Site" case study. This project was run by the U.S. Army Corps of Engineers (USACE) to clean up pesticide contamination at the Wenatchee Tree Fruit Test Plot Site using a dynamic work plan strategy (US EPA, 2000). The project provides concrete examples for several of the concepts discussed in the paper. The full case study, along with actual work plans used by the USACE, are downloadable from the Clean-Up Information Web site (http://cluin.org) of EPA's Technology Innovation Office. Briefly, two immunoassay kits (one for each of two major pesticide groups, the cyclodiene and the DDT families) were used to locate and delineate soil contamination for precision removal and segregation into three categories: clean soil (i.e., meeting regulatory requirements) that was ultimately reused as backfill; lesser contaminated soil that was destined for final disposal in a landfill; and highly contaminated soil that required incineration for final disposal. In total, site characterization and cleanup involved analyzing 230 site samples by immunoassay, with 29 samples selected for splitting for fixed laboratory analysis. In addition to the thorough quality control performed in the field on the immunoassay kits (3-point calibration curves with continuing calibration verification, reagent blanks, matrix duplicates, and commercial performance evaluation (PE) samples used as laboratory control samples), data from the 29 splits were used to aid interpretation of the immunoassay results and to derive and adjust the action levels used to make decisions in the field on the basis of kit results.

The Triad Approach reflects the recognition, based on experience, of the need for a second-generation model for sampling and analysis.

After all contamination was identified and removed with "surgical" precision, 33 soil samples were collected for fixed laboratory analysis for the 33 constituents of concern. This clean closure data set demonstrated that the cleanup, guided by the field methods and performed using a dynamic work plan, achieved *full* compliance with *all* state regulatory requirements for *all* 33 target analytes to *better than 95 percent statistical confidence*. The entire project cost ($589,000, including disposal of wastes, backfilling and seeding of the site, and all contractor and oversight costs) was less than half the cost projected ($1.2 million) using more traditional investigation and cleanup strategies. Although this was a very small site [85 ft × 33 ft × 6 ft (depth)], the extreme heterogeneity caused by highly toxic pesticide spills required a high sampling density to control sampling errors while making cleanup as cost-effective as possible.

THE TRIAD APPROACH SUPPORTS THE LAND REVITALIZATION ORIENTATION OF CLEANUP PROGRAMS

The Triad Approach reflects the recognition, based on experience, of the need for a second-generation model for sampling and analysis. Cleanup programs as a whole are also experiencing an evolving orientation. These programs are increasingly widening their focus to include not just cleanup, but also the ultimate revitalization or reuse of sites. Building on the popularity of redevelopment-based initiatives such as land recycling and voluntary cleanup efforts at the state level, and the Brownfields effort at the national level, Superfund cleanups, corrective actions under the Resource Conservation and Recovery Act (RCRA) and Underground Storage Tanks (UST) programs are striving towards land revitalization. For some time, remediation decisions at closing military bases and other federal facilities have considered the ultimate disposition and reuse of contaminated property. Land Revitalization, Superfund Site Recycling, RCRA Brownfields, and UST Fields are all recent additions to the EPA waste program lexicon that reflect this trend. These programs promote cleanups that not only meet stringent health and eco-based cleanup requirements, but also benefit communities by including reasonable future use considerations as part of the remedy decision-making process.

This broader view of cleanup presents an excellent opportunity to advance the changing data quality paradigm advocated under the Triad. The Triad provides a technical framework to help realize land revitalization objectives. A cleanup strategy tailored to the end-use of a property should discourage the use of one-size-fits-all approaches to site investigation and instead look at the specific contamination issues in relation to site plans. A robust planning process not only ensures successful redevelopment, it can also ensure that the technical work at the site is done as efficiently as possible. Thus, the Triad can create a technical bridge between regulatory and cleanup requirements and community needs, reuse plans, and resources for a property.

The redevelopment perspective for contaminated sites also creates a market discipline for site cleanup. As the real estate and financial communities evaluate the viability of private site development, the comparison of costs of acquisition and site preparation vs. ultimate worth and revenues of the property creates an incentive to minimize both the financial costs of cleanup as well as the time frames for cleanup. The maxim, "time is money" is especially poignant in the redevelopment setting as is the idea of "striking while the iron is hot." A narrow emphasis on cutting costs and time could encourage less than adequate site characterization. Fortunately, this is counterbalanced by the sensitivity of the development and financial communities to future liability. The ideas of unforeseen, costly, and time-consuming problems during the cleanup and construction process and of future regulatory or tort action after development can have a chilling effect on the market for Brownfields. With its underpinnings of cost-effectively addressing sampling uncertainty and sample representativeness, the Triad can help alleviate the concerns of "missing something" or inadequately remediating a site so that goals of cost-minimization and protectiveness can both be achieved.

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The Triad offers the potential time and cost savings essential to increasing the number of properties that are viable candidates for redevelopment. Even at sites with minimal private development appeal, reducing cleanup costs will allow public entities to address more sites with their finite resources. A long-range view on advancing and demonstrating successful reuse should increase the market of sites to be cleaned up. Environmental practitioners should not view Phase I and Phase II investigations as end products of the Brownfields market or as off-the-shelf commodities. Instead, these tasks should be viewed as stepping-stones to more efficient and seamless site-specific cleanup strategies. The systematic planning process helps ensure that the characterization strategy effectively addresses all aspects of uncertainty in site decisions, thereby increasing the level of comfort with the chosen cleanup strategy. Increasing decision comfort, cutting costs, and reducing time frames are all advantages of the Triad Approach that support land revitalization.

EFFORTS TO PROMOTE THE TRIAD APPROACH IN THE NORTHEAST

The waste site cleanup program directors in the seven Northeast states (Connecticut, Maine, Massachusetts, New Hampshire, New York, Rhode Island, and Vermont) collectively determined that improving the quality of the site characterizations performed was their number one priority for work together as a region.[1] The main state concerns center around two areas: inadequate data collection to support conclusions about the nature and extent of contamination; and submitted characterization reports that do not clearly explain what was done ***and why***, and lack maps and other visual aids to present site data.

The Northeast states support the use of the Triad Approach as a way to address these concerns and would like to see increased use of field-based analytics where appropriate. Therefore, to raise awareness of state and federal concerns about the quality of the site characterizations performed, to promote the Triad Approach, and to begin the process of change, the Northeast Waste Management Officials' Association (NEWMOA)[2], EPA Region 1, and EPA's Technology Innovation Office (TIO) sponsored two one-day conferences in the Northeast, on June 4, 2002, in Manchester, New Hampshire, and again on June 6, 2002, in Farmington, Connecticut. Together, over 300 people, including local, state, and federal regulatory staff, consultants, and facility representatives from the eight Northeast states, attended the conferences. Each conference also included a vendor showcase where attendees could learn more about innovative sampling and analytical equipment, as well as data management software and companies that perform field-based analytical work on a subcontracting basis.

Several issues arose during the interactive portions of the conferences and in a survey that was distributed to participants. One area of concern was the lack of accepted guidelines on how to construct and then implement a dynamic work plan. The consulting community also cited the lack of regulatory agency acceptance of dynamic work plans and field sampling methods as a major barrier to their greater use. Regulatory agencies are mainly concerned that consulting firms might not have the capability to place well-trained staff in the field to operate the field-based analytical equipment properly, and to make on-site decisions. Participants also cited uncertain characterization costs, increased data interpretation, and data defensibility as barriers. In the next phase of the project, NEWMOA plans to undertake efforts to address the issues, both real and perceived.

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Participant suggestions for efforts to reduce barriers to the Triad Approach mainly center on the development of guidance documents:

- develop guidance documents on generating dynamic work plans, including examples of actual work plans
- develop guidance on statistically based sampling for regulatory decision making
- develop guidance/protocols on the use of various field-based analytical methods
- provide more training, especially for regulators
- provide certification courses for users of field-based analytical equipment

Both consultants and state regulatory agencies look towards EPA for leadership on these issues. As can be seen in the following sections, EPA has or is addressing many of these suggestions; however, many seem unaware of these efforts. For more information about the conferences, including copies of the presentations and the results of the participant survey, and to learn about other NEWMOA waste site cleanup-related activities, please visit www.newmoa.org/cleanup.

OTHER STATE REGULATORY EFFORTS

In addition to NEWMOA's activities, the Interstate Technology and Regulatory Council (ITRC) is promoting the Triad Approach. The ITRC is a state-led coalition of personnel from the regulatory and technology programs working together with industry and stakeholders to achieve regulatory acceptance of environmental technologies. ITRC currently consists of more than 40 states, the District of Columbia, multiple federal partners, industry participants, and other stakeholders, all together to break down barriers and reduce compliance costs, making it easier to use new technologies, and maximize resources. An ITRC workgroup is developing a guidance document to help educate state regulators about the importance of the regulator role for supporting the systematic planning needed to implement the Triad Approach. In time, the ITRC plans to provide training courses to aid both regulators and environmental consultants to adopt the Triad Approach (ITRC, 2002).

AN ONLINE RESOURCE TO SUPPORT TRIAD ADOPTION

Through the collaborative efforts of the Innovative Technology Advocate Program of the U.S. Army Corps of Engineers, the Environmental Assessment Division of Argonne National Laboratory, and EPA's Technology Innovation Office, an online resource titled "Handbook of Technical Best Practices for Implementing the Triad Approach" is being developed. The "Triad Handbook" will provide a structure for synthesizing and disseminating technical knowledge and information resources that support contaminated site investigation and cleanup. The Handbook is not itself an EPA guidance, although EPA guidances will be linked into the Handbook as references.

The virtual platform of the Handbook should permit it to fill a number of roles. First and foremost, the Handbook will be a forum to share technical information across geographic barriers to encourage rapid dissemination of successful field practices and strategies for site characterization. The Handbook will serve as an information clearinghouse to direct users to useful technical resources organized according to the typical technical project lifecycle, and if possible, link them electronically for instant access. In a sense, the Handbook will serve as an annotated "library" for technical staff seeking quick access to existing guidance documents and publicly available information relevant to site cleanup policies, procedures, and technical/scientific developments. As it fills these roles, the Handbook will emphasize the role of systematic planning to consider sources of analytical and sampling uncertainties in site cleanup decisions.

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This is an ambitious undertaking, and the completeness of the Handbook's references will depend on participation of site cleanup community to include as many relevant documents and useful Web site links as possible. An important feature of the Handbook will be hyperlinked case studies that more specifically illustrate general principles in project-specific applications. Over time, the Handbook will evolve and change, just as the science and technology underpinning site characterization continues to evolve and change. Public access to the Handbook is expected in the later half of 2003, and will be announced through TechDirect (http://www.cluin.org/newsletters/). Once released, a link to the Handbook will be available through http://clu-in.org.

SOURCES OF ADDITIONAL INFORMATION

Case study reports, published papers and articles (Crumbling et al., 2001) concerning the Triad Approach, dynamic work plans, sample handling and statistics, and a host of related topics are available through the Clu-In Web site (http://clu-in.org) under the "Site Characterization" and "About the Technology Innovation Office/TIO Perspectives" menus. Live and prerecorded Internet-based seminars, including seminars dedicated to the Triad Approach, are available through the Clu-In "Studio." The Clu-In Web site is continually updated as additional support services become available.

The Field Analytical Technologies Encyclopedia (FATE) can be accessed through the Clu-In Web site or directly at its URL (http://fate.clu-in.org/). Offered freely to the public through a partnership between EPA's Technology Innovation Office and the Innovative Technology Advocate Program of the U.S. Army Corps of Engineers, FATE is an on-going effort to provide overview information about analytical chemistry, geophysics, and other technologies used in the field to characterize contaminated soil and ground water, monitor the progress of remedial efforts, and in some cases, for confirmation sampling and analysis for site close out.

Finally, to build an understanding of the requirements, benefits, and limitations of the practical application of the Triad in a reuse setting, EPA, the U.S. Army Corps of Engineers, and Argonne National Laboratories are assisting several communities in implementing the Triad in a Brownfields reuse setting. By providing direct, in-kind technical support through the Brownfields Technology Support Center or BTSC (http://brownfields tsc.org), EPA and its partners hope to improve acceptance of streamlined approaches by all decision makers involved in Brownfields cleanup. An early lesson learned from this work is the importance of building the required flexibility and capacity into the procurement process to allow the proper application of the Triad Approach. The emphasis on the Triad should start with the request for proposals from potential service providers and carry through to the planning and direction required to implement the Triad process. EPA will make these lessons available through case study write-ups on the BTSC Internet site and through Triad training targeting Brownfields localities, contractors, and regulators.

The environmental cleanup community will be challenged to evolve their assumptions and paradigms, as well as their mechanisms for regulatory oversight and procuring services.

SUMMARY

The hazardous waste cleanup arena is changing as a result of 20 to 30 years of practitioner and regulatory program experience, greater scientific sophistication, better options for treatment, and the electronic technology revolution. EPA articulated the Triad Approach to create a conceptual framework that could organize innovative technologies and "smarter" work strategies around the theme of basing environmental regulatory decisions on good science to the extent possible, including acknowledging the impact of uncertainties on decision making.

Although there has been progress toward greater regulatory and practitioner acceptance of these tools and the strategies, significant institutional barriers remain. The environmental cleanup community will be challenged to evolve their assumptions and paradigms, as well as their mechanisms for regulatory oversight and procuring services. Altering staffing and procurement structures to recognize the value of an "allied environmental professionals" approach to project planning and implementation will be a gradual process. But in time, assembling multidisciplinary teams should become easier for both regulatory agencies and contracting firms. Communicating concepts fundamental to managing data uncertainties will continue to be difficult as long as the data quality paradigm begins and ends with the fallacies that environmental data quality is solely a function of the analytical method and that fixed laboratory analyses always produce the best data quality. However, much of the science needed to improve both sampling and analytical quality is falling into place (although there is still much to be learned). A wealth of "lessons learned" and remarkable new technologies are helping to transform how the cleanup community does its job.

NOTES

1. At a Northeast Waste Management Officials' Association (NEWMOA) meeting held on October 21, 1999. Note that New Jersey subsequently joined NEWMOA and participated in more recent activities.

2. NEWMOA is a nonprofit, nonpartisan, interstate association whose membership is composed of the hazardous waste, solid waste, waste site cleanup, and pollution prevention program directors for the environmental agencies in the eight Northeast states (CT, ME, MA, NH, NJ, NY, RI, and VT). NEWMOA's mission is to help states articulate, promote, and implement economically sound regional programs for the enhancement of the environment. NEWMOA is funded by state membership dues and by contracts and EPA grants.

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