Managing Project Uncertainty: Application of the Triad Approach

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1.0 Introduction

Contaminated site investigation activities, driven by the need for cost effective data collection that allow for project decisions to be made with more certainty, are shifting toward adaptive approaches that focus on real-time decision-making logic to guide field activities. Interest in adaptive approaches has fostered development of the Triad Approach. The Triad Approach is a work strategy framework for economically managing decision uncertainties associated with contaminated site projects.

The Triad Approach is a scientific and technical initiative that has come from the US but is not a US specific regulatory approach and therefore can be applied anywhere in the world. The Triad Approach serves as a synthesis of various, yet conceptually similar, work strategies developed by innovative and successful site professionals from the U.S. Department of Energy, Tufts University, the U.S. Army Corp of Engineers, the U.S. Environmental Protection Agency, and practitioners in the private sector (ITRC, 2003).

The individual components of the Triad Approach are not new concepts in the site investigation process. However, the Triad Approach draws on the accumulated technical knowledge and experience gained from the past 20-30 years of contaminated site cleanup and presents a novel package of methods to plan, implement, and improve data collection from contaminated sites. In addition, the Triad Approach proactively exploits new characterisation, treatment and data management tools.

This paper provides an overview of how the Triad Approach can be used to better manage uncertainties associated with contaminated site projects leading to improved decision making. Initially a discussion of uncertainty in contaminated site projects is provided before giving an overview of the Triad Approach. Finally, a discussion of how the Triad Approach can be applied to manage project uncertainty and improve decision making on contaminated sites is provided.

2.0 Background

The site management industry has long relied on workplans to guide investigation and cleanup of contaminated properties. Through these plans, practitioners define parameters such as data needs and objectives, sampling locations, sampling methodology, sample analysis, and the data evaluation methods. These workplans often use standard sample collection techniques and fixed-base laboratories. In addition, they provide little opportunity for changes to the prescribed approach based on the limited amount of information learned during the field activities. This static approach creates a scenario where multiple iterative cycles of sample collection, laboratory analysis and decision making are made based on the sample results. This approach generally occurs in a linear fashion (i.e. Phase I, II, IIA, III etc.).

Since the number of iterations before investigation or cleanup is complete are typically proportional to project costs, a decision-making framework that reduces the number of investigation cycles may offer cost savings. In addition, dynamic work planning allows the project to proceed more rapidly, by allowing modifications to occur in the field.

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3.0 Triad Approach for Managing Uncertainty

The concepts embodied in the Triad Approach are not new. The Triad Approach is a re-articulation and broadening of the original Data Quality Objectives (DQO) concepts for contaminated site cleanups. The Triad Approach adds emphasis, however, on "recognising, identifying, and managing uncertainty" as the mechanism through which good science is practiced and defensible decisions are made within the environmental cleanup context. A very important source of project decision uncertainty is the representativeness of the data sets upon which project decisions are based. Data uncertainty, when unresolved, can lead to decision errors that affect the protectiveness of human health and the environment and the extent and efficiency of cleanup activities.

3.1 Sources of Uncertainty

The basic sources of uncertainty associated with contaminated sites include:

- **Decision Uncertainty.** Decision uncertainty is equivalent to the likelihood of making the wrong decision, such as concluding that an area complies with cleanup criteria when in fact it does not. Decision quality is the degree to which an actual decision coincides with the decision that would have been made if complete and fully accurate information was available at the time. Cost-effectively managing decision uncertainty is the primary focus of the Triad for contaminated site cleanup activities. Decision uncertainty is the aggregated uncertainty contributed by political, economic, and public perception factors, along with model, analytical, sampling, and relational uncertainties (Crumbling, 2002). The last three, taken together, are often referred to as data uncertainty.

- **Model Uncertainty.** Model uncertainty refers to the uncertainty associated with the "correctness" of models (e.g., fate and transport, risk pathway analysis, etc.) used in a conceptual site model (CSM) to represent key features or characteristics of a contaminated site. Correctness refers to the ability of a model to accurately portray a key site feature (e.g., risk pathway, fate and transport prediction, etc.). Key site features are those important for decision-making purposes. Model uncertainty is distinct from the uncertainty introduced into a CSM, its associated models, and decision-making by data collection efforts. Models make use of data sets, and can amplify data uncertainty when making decisions if significant model uncertainty also exists.

- **Analytical Uncertainty.** Analytical uncertainty refers to the uncertainty associated with analytical results for media samples. Analytical uncertainty stems from the limitations of analytical and determination methods. Common contributors to analytical uncertainty include poor detection limits, analytical bias, lack of precision, and susceptibility to interferences. Analytical uncertainty and its reduction have been the primary focus of uncertainty management for traditional cleanup programs, but the contribution of analytical uncertainty to overall decision uncertainty is often insignificant compared to other sources of uncertainty (e.g., sampling uncertainty).

- **Sampling Uncertainty.** Sampling uncertainty reflects the degree to which sample results represent actual conditions for the population sampled, neglecting the contributions of analytical or relational uncertainty. Sampling uncertainty is an inclusive, catch-all phrase referring to all factors not associated with the analytical method that contribute to data uncertainty. The primary contributors to sampling uncertainty are the heterogeneity in contamination distributions across the area being sampled and the potential non-representativeness of sampling procedures. Other contributors include problems with sample processing (e.g., improper handling, incomplete sampling equipment decontamination, etc.) and sampling methods (e.g. smearing by membrane interface probe [MIP], using a bailer to sample groundwater for analysis of volatile organic compounds [VOCs]). Sampling uncertainty's contribution to data uncertainty is typically significantly greater than that from analytical uncertainty.

- **Relational Uncertainty.** Relational uncertainty is the uncertainty associated with the relationship between a parameter being measured, and the true parameter of interest from a decision-making perspective (Crumbling, 2001). Relational uncertainty can become a concern for real-time measurement methods that are non-specific in nature (e.g., immunoassay kits, MIPs), or that measure a parameter other than the primary parameter of concern using the measured parameter as a proxy when site decisions are made. Relational uncertainty can be of concern for traditional data collection programs when traditional fixed-laboratory methods produce data used as a surrogate for more difficult to obtain information. For example, total chromium concentrations are sometimes used as a proxy for the toxic chromium(VI) fraction, and total metals concentrations are often used to estimate exposure risk if estimates of the bioavailable fraction are not available.

3.2 Sample Representativeness

Uncertainty is a given with environmental decisions. Contaminated site decisions are primarily based on the results of environmental measurements. These measurements have traditionally taken the form of laboratory analyses of discrete samples from site media. Advances in measurement systems and analytics have increased the number of options for obtaining analytical data. Systems are now available that can measure the presence of contamination in the field (e.g., X-Ray Fluorescence [XRF] for certain metals), or that can provide rapid analysis of media samples on-site (e.g., immunoassay technologies). In addition, off-site laboratories often provide the option for expedited sample turn-around (which may be at the expense of perceived ‘quality’ parameters such as higher practical quantification limits).

Typically we have paid most attention to analytical uncertainty, while the uncertainty associated with sampling uncertainty or sample representativeness typically far exceeds the potential uncertainty introduced by analytical error.

The root cause of sampling uncertainty is contaminant heterogeneity within environmental matrices. When contaminants are released to the environment and migrate, heterogeneity is created on large and small spatial scales. When relatively few samples are used to characterise a heterogeneous matrix, there is little confidence that contaminant populations are understood well enough to support decision-making. Sampling uncertainty manifests itself when the data user does not know whether the results from 1-gram samples analysed in the laboratory can be legitimately extrapolated to represent the contaminant concentration for the area from which the samples came often representing many square metres of a site or cubic metres of soil. Sampling uncertainty is reduced by collecting more samples from the area of interest, and by concentrating samples in those areas of greatest decision uncertainty.

Because of the importance of managing sampling uncertainty to improve decision making at contaminated sites, it is important that uncertainties associated with the following are understood:

- Selection of sampling methods (e.g. low flow sampling of groundwater versus using a bailer, or geoprobe versus auger for soil samples)
- Selection of sample type (e.g. grab sample versus a composite sample)
- Design of the sampling approach (e.g. systematic sampling versus judgemental selection of sample locations)

- How well a sample represents site conditions (e.g. smearing of soil during MIPs data collection, or groundwater well screen length influencing groundwater concentration data – generally larger screens provide “average” concentration data for aquifer and short screens provide discrete samples)
- Consistency of sampling methods during a site investigation (e.g. groundwater purging, mixing of composite samples, duration of measurement at each depth interval for MIP)
- Geochemical changes after sample collection (e.g. oxidation of samples when exposed to the air, or volatilisation of volatile compounds)
- Initial and continuing calibration of field and lab equipment

There are diminishing returns to investments in reducing sampling uncertainty. In general, sampling uncertainty is reduced as the square root of additional sample numbers (Crumbling, 2002). For example, to reduce sampling uncertainty by a factor of four often requires increasing sample numbers by a factor of sixteen.

4.0 Second Generation Data Quality Model

Triad embraces a second-generation data quality model (Crumbling, 2003), where sampling quality is just as important to data quality as analytical quality is. This evolution in thinking about what “data quality” truly means requires adjustment to the typical view of data produced by screening analytical methods.

4.1 Screening versus Definitive Data

We have historically relied upon an oversimplified data quality model where the data quality is equivalent to the nature of the analytical method. We have assumed:

- Definitive analytical methods automatically produce definitive quality data.
- Screening analytical methods automatically produce screening quality data.

The difference between definitive and screening methods is the perceived amount of uncertainty in analyte detection or in analyte quantification. Screening methods have (or are perceived to have) more uncertainty in one or both tasks than definitive methods (Crumbling, 2002).

The goal of generating data is to support decision making and definitive data are seen as supporting a defensible decision; whereas screening data are seen as not defensible, at least, not with that data by itself. So you could say that the perceived difference between definitive data and screening data is the amount of uncertainty in the data set with respect to the decision to be made (Crumbling, 2002).

However, it does not always hold true that definitive analytical methods always generate defensible decisions. Similarly, it does not hold true that screening analytical methods always generate decisions which are indefensible. A case where a definitive analytical method would produce data that did not support good decisions (i.e., would not be “defensible”) could be a scenario where the sampling procedures or design used were not representative for the decision to be made (e.g. limited soil samples were collected from a specific area and used to decide whether the entire site required remediation or not).

Screening analytical methods can be used to make perfectly defensible and confident decisions. For example: the Dexsil L2000 instrument will detect all organochlorine compounds that can be extracted with the extraction solvent used but does not distinguish which organochlorine compounds are present in its response. If the instrument is used with careful control over extraction efficiencies, detection limit concerns, and other data comparability issues, and found no organochlorine contaminants in any samples from a dense sampling scheme across a site, there is high confidence that a decision based on that data (ie. the concentration of organochlorine contaminants across the site are less than the method detection limit) is correct. This data set (in conjunction with the QC data that demonstrates adequate method performance) may be considered "defensible" as far as that decision is concerned.

So deciding whether data generated is of definitive quality or screening quality depends not on how the data was generated but rather what the data results represent and how they are being interpreted and used.

4.2 Good Data versus Bad Data

If the assessment of data quality is grounded in defensible decisions, then the concept of data quality must extend beyond just the quality of the analysis. If a sample is not representative of the feature under investigation, "bad data" is produced even if the analysis is perfectly accurate. It is "bad data" because data generated on non-representative samples will be misleading (i.e., will lead to erroneous conclusions).

The issue of sampling representativeness and its relationship to the ability of data to support decision-making (and the challenges posed when sampling heterogeneous environmental media) have been discussed for years in many different forums. But because of the complexities of sampling and analysing environmental materials, these issues and their ramifications are not well understood by many environmental decision-makers.

Unfortunately, there is a widespread misconception that highly accurate analyses automatically produce accurate data. This has caused a great deal of energy to be focused on trying to create one-size-fits-all lists that prescribe exactly what analytical methods should be used for evaluating contaminated sites. This thinking fails to consider the many variables that impact the adequacy of environmental data for decision-making purposes, so it ultimately fails to achieve its purpose.

4.3 Collaborative Data Sets

The cost of traditional laboratory analysis discourages project managers from collecting sufficient samples with consideration to the contaminant heterogeneity. Therefore the sampling representativeness of the laboratory results is frequently unknown, and as a consequence, the data would be considered screening quality at best. In addition, depending on the decisions for which the data might be used, the laboratory results may be insufficient to support defensible decisions.

Screening analytical methods may permit greater sampling densities needed to establish a good picture of contaminant distributions despite greater analytical uncertainty. Depending on the nature of the decision for which the data might be used, a particular screening analytical method may be sufficient to support decision-making on its own. However, the analytical uncertainty in screening methods is generally too high to support risk assessment decisions and other decisions that require analyte-specific, quantitative data.

Good data quality at an affordable cost can be generated by using both screening and more definitive methods together. Because of their lower cost, screening analytical methods are best for generating higher data densities that can manage uncertainty due to environmental heterogeneity (sampling uncertainty). Representative samples can then be selected for more rigorous analysis as needed to manage remaining analytical uncertainty.

Collaborative data sets complement each other in that uncertainty in one data set is managed by the information in the other. The data sets must be used together to manage all major sources of potential error in the data sets. This is similar to a weight-of-evidence approach which recognises that there may be several sources of information contributing to a decision, and those sources cannot always be combined in a quantitative way.

4.4 Data Quality for Heterogeneous Matrices

Data quality for heterogeneous matrices is achieved by collaborating results between less expensive, more rapid methods (to provide cost-effective high density sampling and build the CSM) and more rigorous (but also more expensive) analyses able to manage any important analytical uncertainty “left over” from the less expensive method. Under this second-generation data quality model, samples for more expensive analyses are chosen once their sample representativeness (i.e., the contaminant population they represent) has been established through the CSM. The ability to mature the CSM to establish data representativeness in the context of specific project decisions is not available if expensive fixed laboratory analyses are viewed as the only reliable method.

5.0 Elements of the Triad Approach

The goal of the Triad Approach is to manage decision uncertainty, that is, to increase confidence that project decisions (about contaminant presence, location, fate, exposure, and risk reduction choices and design) are made correctly and cost-effectively.

Triad is not an acronym, but the word Triad is intended to convey that there are three key elements of the technical initiative. The three interconnected elements are:

- Systematic planning;
- Dynamic work plans; and
- Real-time measurement technologies.

Of these concepts, systematic planning forms the backbone of the process since it serves as the framework upon which uncertainties are defined and defensible decisions can be made. The intent of the Triad Approach is to only perform activities for clear and specific reasons and to only investigate what is needed to achieve closure or the desired project objective.

The Triad Approach is adaptable and flexible and can be implemented at any contaminated site. The ITRC (2003) state that the “*Universal concepts underlying the Triad Approach apply to any site, no matter what stage of investigation or remediation, and no matter what size or complexity of the site*”.

5.1 Systematic Planning

The most important element of the Triad Approach, systematic project planning (called “strategic planning” by some), supports the ultimate Triad goal of confident decision-making. Systematic planning includes three primary elements:

- **Framing the Problem:** The systematic planning foundation is formed by identifying stakeholders, articulating objectives, addressing constraints, recognising the regulatory framework, and specifying decision statements. The key to laying the foundation is achieving cooperation between all stakeholders working toward a protective, cost-effective resolution of the contamination issue through an atmosphere of trust and transparent, open communication. This would normally involve one or more meetings at the start of the project with all stakeholders to achieve consensus on the desired outcome (i.e. end goal) for the site/project. The initial meeting or a second meeting (which may involve a subset of the full list of stakeholders) will be used to develop a complete list of the various scientific and engineering decisions that must be made in order to achieve the desired outcome. Additionally, the constraints to achieving the desired outcome and answering the specific regulatory, scientific or engineering questions need to be addressed. After project objectives have been defined and pertinent constraints identified and understood, the planning team needs to capture project objectives in the form of decision statements. The nature of decision statements will depend on where a site is in the cleanup process. Statements may be qualitative or quantitative, but should lay the foundation for the planning team to focus resources and define the boundaries of activities that will be necessary to reach a defensible decision. Primary decision statements will likely lead to more detailed, secondary decisions that are used collectively to make the primary decision.

- **Developing a CSM:** The foundation for site-related decisions is the CSM. A CSM uses all available historical and current information to estimate where contamination is (or might be) located, how much is (or might be) there, how variable concentrations may be and how much spatial patterning may be present, what is happening to contaminants as far as fate and migration, who might be exposed to contaminants or harmful degradation products, and what might be done to manage risk by mitigating exposure. As a primary Triad product, an accurate CSM will distinguish and delineate different contaminant populations for which decisions about risk and remediation will differ. Distinguishing between different contaminant populations improves the quality and interpretation of data, as well as the confidence and resource effectiveness of project decisions. The CSM developed during the strategic planning phase of Triad synthesises and crystallises what is already known about a site that is pertinent to decision-making requirements. After constructing the preliminary CSM it is continuously updated as new information and data is collected or becomes available.

- **Evaluating and Managing Uncertainty:** This element involves evaluating and managing the uncertainty associated with decision-making in the context of the CSM so that decisions can be made with acceptable levels of confidence. Given that the CSM is the foundation for site related decisions, this element of Systematic Planning primarily involves:
    - Identifying a list of unknowns that stand in the way of constructing or maturing the CSM to a point that the uncertainty in making decisions is acceptable.
    - Identifying specific strategies to eliminate, reduce, or “manage around” the unknowns (uncertainties).
    - Identifying proactive controls and methods to manage the greatest sources of uncertainty.

The most effective uncertainty management strategy often relies on a weight-of-evidence approach to decision support.

5.2 Dynamic Work Strategies

Dynamic work strategies refer to strategies that incorporate the ability to adapt project activities to site conditions as new information becomes available while work is underway. This adaptation may be in response to data collection activities designed to address CSM unknowns, or it may be in response to completely unexpected site conditions encountered during the course of work.

As part of a Triad Approach, dynamic work strategies can be integrated into almost every activity associated with contaminated site characterisation and remediation. This includes overall project strategies, sampling and analysis programs for characterisation purposes, remedial action design and plans, implementation, and performance monitoring, long-term monitoring for sites that require it, closure plans, and quality assurance/quality control activities.

Information generated as part of field activities associated with a dynamic work strategy contributes to the refinement and maturation of the CSM. The refined CSM, in turn, forms the basis for future decisions and additional data collection as necessary. Contingency planning is a critical step in formulating dynamic work strategies. Contingency planning addresses situations where different possible field activity outcomes require different responses. These are usually captured as "if-then" statements, and often formalised as a decision tree.

Dynamic work strategies are captured in planning documents and it is under the dynamic work plan that operational decision points in a project may be answered by the field team, based on the data that is being collected. Major decisions however, are more likely addressed by the stakeholder team using logic defined during systematic planning element. There are several important considerations that must be addressed when developing a dynamic work strategy for a site under the Triad. These include logistics of real time data collection, lines of authority for decision making, documentation requirements for data collection and decision making, and the potential need for service provider and/or vendor involvement in dynamic work strategies development.

It is this element that allows projects to be completed more cost effectively than under traditional site characterisation strategies. Work planning documents written in a dynamic or flexible mode guide the course of the project to adapt in real-time.

5.3 Real Time Data Analysis

Real-time measurement systems represent the third element of the Triad Approach. They are essential for implementing the dynamic work strategies because they feed timely data to the decision-making process. Real-time measurement technologies makes dynamic work strategies possible by gathering, interpreting, and sharing data fast enough to support real-time decisions.

The Triad Approach is only possible because of the tremendous technological changes that have occurred in the area of sample acquisition and real-time measurement systems in the last decade of which New Zealand is still to reap the full benefits. The innovation rate in this area has been rapid and the pace will likely continue in the years ahead. The Triad Approach provides a technically defensible context in which to select and deploy real-time measurement technologies. For Triad purposes, the term "real-time measurement systems" includes any analytical or measurement technology capable of producing data quickly enough to direct the progress of field activities (characterisation or remediation) while they are underway.

The range of technologies supporting real-time measurements includes hand-held field analytical instrumentation and mobile laboratories (e.g. field-portable GC-MS), *in situ* sensing systems (e.g. MIP, laser induced fluorescence [LIF] probe, soil conductivity probe), geophysics, petroleum indicator dye tests (e.g. Cheiron OilScreen Shake Tests), vertical groundwater profiling (e.g. Waterloo Profiler), rapid turn-around from traditional laboratories, and computer applications that assist project planning and collect, store, display, map, manipulate and share data.

One of the critical steps in designing a cost-effective and technically-defensible Triad-based data collection program is selecting the appropriate combination of measurement technologies that will be deployed. This is one outcome of the systematic planning process.

Real-time decision support, appropriate standard operating procedures, method applicability studies, and strategies for collaborative data analysis are all important dimensions for successful measurement technology implementation. The Triad definition of real-time measurement systems includes sample acquisition technologies and data management/analysis activities once data have been generated. For example, this may involve the daily uploading of MIP field data to a website and updating the 3D visualisation of the contaminant plume (i.e. updated CSM) so that decisions can be made on sample locations for the next field day.

A fundamental project question that must be answered is how data within a Triad collaborative data set will be used to support decision-making. Approaches can be as simple as treating data from different sources separately for decision-making purposes (a weight-of-evidence approach), or as complicated as using sophisticated geo-statistical routines to quantitatively blend data from different sources with different levels of spatial density, analytical quality, and inter-method correlation.

5.4 Triad Characteristics

Beyond the primary Triad components (systematic planning, dynamic work strategies, and real-time measurement systems), a successful Triad implementation for contaminated site decision-making has several additional characteristics. These include:

- **Appropriate Quality Assurance/Quality Control Strategies.** A Triad Approach emphasises collaborative data sets, with data coming from potentially a variety of analytical sources. For some of these sources (e.g., certified laboratories), quality assurance and quality control (QA/QC) programs may already be in place and pre-defined. For many real-time measurement sources, however, appropriate quality assurance and control strategies will need to be specified. The Triad Approach offers the opportunity for quality control to also adapt or change to reflect the status of quality control indicators.

- **Multi-Disciplinary Technical Teams.** The Triad places heavy emphasis on systematic planning for sites, including the development of CSMs and the selection of appropriate real-time measurement systems along with their associated QA/QC requirements. For this to be successful requires a multi-disciplinary team approach to work plan development and decision-making. While the specific nature of the team will vary depending on site peculiarities, there will invariably be a need for analytical chemistry, geochemistry, hydrogeology, sampling program design, contaminant fate and transport, risk assessment, and remediation technology screening and design. Perhaps the most important member(s) of the multi-disciplinary team for the successful implementation of the Triad Approach are the experienced field staff who are capable of following the dynamic work plan, making the right decisions in the field and knowing for which decisions they have to consult other stakeholders.

- **Flexible Contracting Mechanisms.** Dynamic work strategies, by definition, result in field activities whose ultimate scope and direction are not completely definable before work begins. Consequently, for a Triad Approach to be implemented effectively requires flexible contracting mechanisms that facilitate modifications to work strategy as work progresses, while at the same time producing cost-effective and defensible contracts.

- **Decision Support for In-Field Decision-Making.** Triad-based data collection programs can produce significant amounts of data rapidly. Effective decision-making based on these data presumes a means for efficiently organising, managing, and presenting these data in a timely fashion to decision-makers. These decision-makers may be on-site, or they may be physically distant from site activities. The need to provide in-field decision support is a unique characteristic of Triad-based work plans. It results in data management requirements that are not typically associated with more traditional sampling programs, where analytical data management only becomes an issue after field work is complete and seldom is time critical.
- **Stakeholder Participation.** While stakeholder participation is necessary for all contaminated site investigation, remediation and closure efforts, it plays a particularly important role in the Triad Approach. This is because of the Triad's reliance on what may be non-standard analyses to support real-time decision-making, and its use of dynamic work strategies that often defer significant sampling program decisions to the field. Successful deployment of a Triad Approach requires stakeholder participation not just in concurring with work plans, but also potentially with decisions that are made in the field in response to conditions/real-time results as they are encountered. This level of participation can have a positive impact on the ultimate outcome of a characterisation or remediation program, since stakeholder issues with data can be addressed while field work is underway.

These requirements are not absolute in all cases for a site to experience at least some of the benefits of a Triad Approach. For example, collaborative data sets combined with systematic planning may produce better quality decisions at reduced costs even if real-time measurements systems and dynamic work strategies are not included.

6.0 Summary

Triad embraces a second-generation data quality model, where sampling quality is just as important to data quality as analytical quality is. This evolution in thinking about what “data quality” truly means requires adjustment to the typical view of data produced by screening analytical methods.

Since the CSM is the foundation of confident project decisions, building and refining a CSM using less expensive methods to delineate populations and help manage sampling uncertainties powerfully improves data quality and reduces data uncertainty. The concept of data representativeness is meaningful only in the context of a reasonably mature CSM in the context of the intended project decisions.

Data quality for heterogeneous matrices is achieved by collaborating results between less expensive, more rapid methods (to provide cost-effective high density sampling and build the CSM) and more rigorous (but also more expensive) analyses able to manage any important analytical uncertainty “left over” from the less expensive method. Under this second-generation data quality model, samples for more expensive analyses are chosen once their sample representativeness (i.e., the contaminant population they represent) has been established through the CSM. The ability to mature the CSM to establish data representativeness in the context of specific project decisions is not available if expensive fixed laboratory analyses are viewed as the only reliable method.

An ideal Triad project would strongly rely on each of the three elements: systematic planning, dynamic work plans, and real-time measurement technologies. But we do not live in an ideal world, and “the perfect should not be the enemy of the good,” as the saying goes. Especially when project teams are first learning Triad concepts and attempting to blend technology and strategy tools into a Triad project, it should not be expected that all Triad projects will be equally strong in every element. However, there are a few fundamental features that define a Triad project:

- Consensus on clearly worded project goals and intended decisions (with expressions of what decision errors are tolerable and which are not) before fieldwork begins;
- A CSM that anticipates site-specific heterogeneities and contaminant distributions;
- Strategies to refine the CSM over the course of the project in relation to the intended decisions; and
- Discussions about the mechanisms to manage sampling and analytical uncertainties in data collection.

The advantages offered by dynamic work strategies, high sampling densities and real-time refinement of the CSM to lower costs and increase decision confidence make them highly desirable, and Triad projects will naturally include them to the extent feasible. But the degree to which they are employed will vary depending on many technical and logistical factors, not the least of which include regulatory, budgetary, contracting and legal constraints and the expertise of the project team.

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