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A Subsurface Decision Model for Supporting Environmental Compliance

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A Subsurface Decision Model for Supporting Environmental Compliance

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Abstract

This document provides a geospatial modeling and decision framework for conducting a subsurface compliance survey and analysis for sites that have been remediated for radioactive contamination. This framework proposes a method to extend the Multi-Agency Site Survey Investigation Manual (MARSSIM) guidance, which only treats surface surveys, into the subsurface. It combines and organizes survey methods into a highly flexible sampling, modeling, and decision analysis approach that emphasizes the quality of decision making throughout the investigation. Major challenges face this goal, including lack of clear exposure mechanisms, inaccessibility of the subsurface, lack of comprehensive scans, and an increase in media complexity.

The US EPAs Triad model focuses on decision quality and methods that maximize available information, technologies, and expertise to address and mitigate sources of uncertainty. This document uses Triad to extend MARSSIM into the subsurface using a substantial and continually advancing set of tools including spatial analysis, modeling, and the GIS community. Recommendations are made on information that forms, updates, and evolves a spatial variation of the conceptual site model, called the Contamination Concern Map. This map focuses on the likelihood of exceeding a decision criterion at a local scale and directly addresses uncertainty in volume extent and location. The map matures over each major phase of the investigation and provides a decision framework. Results of this approach can inform investigators and regulators alike of a reasonable course of action in the final site assessment.

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Executive Summary

Purpose

This document provides a geospatial modeling, decision framework for conducting a subsurface, vadose zone compliance survey and analysis. This framework proposes a method to extend the Multi-Agency Site Survey Investigation Manual (MARSSIM) guidance into the vadose zone, with possible applications to groundwater as well. At present, MARSSIM is largely a surface application framework that takes advantage of circumstances prevalent at the surface. These circumstances include a clear method for deriving acceptable radiological limits, easy access to the contaminated media, and scanning technologies that can provide a comprehensive coverage of the study area. The subsurface does not afford these luxuries. Rather, the opposite is true; exposure mechanisms are unclear and groundwater may be a more pressing issue. The subsurface is largely inaccessible and exhaustive scanning is impossible. Finally, the vadose zone can present substantial heterogeneities and complex processes that are difficult to assess. These are substantial obstacles that plague any environmental investigation of the subsurface, whether radiological or not. Any framework intended to assess compliance with a decision limit is not immune to these problems.

In lieu of extraordinary costs associated with intense sampling and in lieu of complete subsurface removal, the framework presented in this document acknowledges these prevailing circumstances and responds by placing a focus on the quality of the final compliance decision and the reasonable mitigation of uncertainty. This is accomplished by expanding compliance assessment and brining to bear the full volume of site knowledge, scientific information, multiple forms of data, modeling outcomes, and so forth to the decision process.

Methods

Recently, the US Environmental Protection Agency has invested in a second generation data quality framework referred to as Triad (Crumbling, 2008). The Triad approach emphasizes the contributions of all available information, including expertise, modeling, multiple forms of data, and relevant computer technologies to assist with clarifying and mitigating decision uncertainties in a complex environment. To date, this approach has largely been applied at Brownsfield facilities, but other organizations such as Superfund are beginning to adopt this method as well. At the heart of this approach is a conceptual site model, which may have a simple beginning, but evolves and directs activities as the investigation proceeds. The conceptual site model is therefore the vehicle which describes the current state of knowledge about history, samples, processes, and so forth. Virtually all activities surround the development of this model and include systematic project planning, dynamic work strategies, real time measurement techniques, use of field methods in the decision, and an iterative approach to the analysis.

This document shares this approach in a very specific manner. The heart of this framework is a particular implementation of the conceptual site model called the contamination concern map (CCM). This 3D model continuously maps and documents the state of knowledge regarding the extent, location, and severity of contamination

relative to the decision criteria. The map may begin qualitatively, but through the use of efficient sampling and modeling efforts moves towards a highly detailed map regarding potential compliance violations at very small scale. With the CCM, subsurface estimates and uncertainty measures serve as surrogates to scanning and can move the decision process forward. From this small granularity, aggregation can be conducted to check for compliance at different scales, including local, areal, and site wide.

To accomplish this merging of methods, the full and quickly advancing capabilities of geospatial modeling tools, geographic information science, decision analysis, and the like are brought to bear on the problem. This will necessarily increase the base technical requirements of all stakeholders, including managers and regulators. In the interest of sound science, this is likely unavoidable as we necessarily move away from simple statistical tools and move toward more spatially relevant methods.

Results

The result is a six phase assessment approach that begins with a historical site assessment and ends with compliance recommendations. The centerpiece of each phase is the contamination concern map which is evolved from a qualitative beginning to a quantitative and highly detailed ending. During each operational phase (scoping, characterization, remediation, and compliance) the methods to accomplish these are left to the investigators. However, an emphasis is placed on updating the CCM and a set of specific sampling, modeling, and decision frameworks are presented that are directly relevant to this activity.

Conclusions

A subsurface decision framework was developed that should be flexible enough to handle a variety of circumstances. Choices regarding the formation of multidisciplinary teams, models, sampling technologies and the like are left appropriately to the investigators. The added piece is the emphasis on the contamination concern map, which is used as a numerical tool for spatially expressing site knowledge, directing the investigation, mitigating uncertainty, and supporting decision processes. Methods for using and updating the model for eventual use as a compliance support product are presented but by no means comprise the full set of methods available to an investigation effort. NRC should be advised that this is a field that is continually evolving, and this framework should adapt accordingly.

Acronyms

AOC	Area of concern
CCM	Contamination concern map
CDF	Cumulative distribution function
COC	Contaminants of concern
DCGL	Derived concentration guideline
DQO	Data quality objectives
ESRI	Environmental Systems Research Institute
GIS	Geographic information system
GRASS	Geographic Resources Analysis Support System
HSA	Historical site assessment
SADA	Spatial Analysis and Decision Assistance

1 Introduction

The Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) provides guidance for determining whether a site is in compliance with a radiation dose or risk-based value (USNRC, 2000). Specifically, the guidance is focused on contamination at the surface, either in the top soil layer or on hard surfaces such as buildings. Compliance assessment is driven by two key concerns: 1) determining if the site wide average exceeds an established activity limit and 2) determining if there are any local areas with activity levels above a safe local activity limit. These questions are addressed using simple hypothesis tests and sampling strategies to determine the number and location of samples that in combination with a scanning device cover the entire surface area. More specifically, the scanning device is used to detect local elevations between samples. While the details can be tedious, these are tractable approaches facilitated by the ease of access to contaminated media, standard statistical methods, and by inexpensive scanning technologies that check between sample locations.

The goal of this framework is to extend MARSSIM principles (average and local checks) into the vadose zone. Unfortunately, two major obstacles become immediately evident. First, there is no easy access to contaminated media. That is, there is no direct way to observe the subsurface content from the surface without substantially disturbing the site. As a result, scanning technologies are no longer viable for providing comprehensive coverage of the affected media. Second, the media itself becomes substantially more complex. Changing soil properties, presence of water, and other contributing factors create a heterogeneous environment within which an assessment must be carried out.

These problems are all too well known by environmental scientists. The subsurface presents a number of serious challenges, some of which have already been listed. These include limited access to affected areas, limitation in sampling technology, media complexity, process uncertainty, unclear exposure scenarios, and inadequate sample sizes. These complexities can reduce the relevance of simple statistical tools and must be replaced by more advanced methods that require specialized expertise and the formation of multi-disciplinary teams.

From a MARSSIM perspective, one can estimate average activity in the vadose zone but must be careful about the spatial support given the heterogeneity of the volume. On the other hand, the importance of average activity levels is tightly connected to exposure assessment. In the subsurface, exposure pathways are not as clear as at the surface. Exposure would depend on the land use and how the subsurface may be disturbed. What is likely more important in the immediate future is the total contaminant volume or mass in the subsurface. This may be particularly interesting to groundwater investigators who often see vadose contamination as a non-point source term for input into the groundwater model. There is a fine line drawn here between the assessment of the vadose and the needs of a groundwater investigation; however, the authors do recognize the importance and note that the framework presented here may be equally valuable in estimating the source term content and location. No groundwater compliance questions are addressed here, though.

What cannot be done is thoroughly check for elevated areas using scan technologies. Between sample locations, there is no means of collecting direct data measurements or comprehensive scan measurements, yet the demand for reasonable certainty is still high. Scans down boreholes can be conducted, but due to the physics of radiation, they will only detect a large amount of activity at a very limited distance (few feet). The number of

boreholes would then need to be increased geometrically to meet MARSSIM grade requirements. Still, the need for higher data collection persists, and this increased demand will require additional access costs and intrusive measures (such as core holes). Continued adherence to strictly high quality lab results will likely be cost prohibitive, as well.

The best alternative from a conservative public health perspective is to respond to these limitations by removing the entire subsurface in the impacted region. The boundary of the impact region could be checked by MARSSIM techniques. After removal is complete, the newly revealed subterranean surface could be approached with the surface methods described in MARSSIM. For those sites where total removal is not feasible, a framework is needed that maximizes the available information, technologies, and expertise; addresses and mitigates sources of uncertainty; and is meaningful within a compliance setting. The United States Environmental Protection Agency (EPA) has developed the Triad model with this intent.

Triad is an update in thinking about hazardous waste cleanup that embraces 20-30 years of advances in science, engineering, and regulatory experience. These advances have yielded many new and innovative sampling and analysis technologies and modeling tools that add to a broad foundation of knowledge gained from field experience. At the heart of this approach is an earnest effort in developing and evolving the conceptual site model (CSM). The CSM both stores the collective knowledge about the site and directs the investigation. Three core elements of the model that support the CSM are: 1) systematic planning, 2) dynamic work strategies, and 3) real-time measurement techniques (Crumbling, 2008). The goal of Triad is to control project costs and protect public health, by including many data forms and information sources. These include less accurate field detection methods, geophysical survey results, surrogate measurements, and the like. The Triad model continues to emphasize the goal of "sound science" by placing an emphasis on decision quality and recasting data quality within this new context.

This document brings these ideas together in a very real and tangible way. The product is a framework for the support of regulatory practice that extends MARSSIM principles into the subsurface using Triad-based approaches. This document emphasizes the spatial relevance of the subsurface and brings to bear a substantial and continually advancing set of tools from spatial analysis, modeling, and the GIS community.

Specifically, recommendations are made on the flow and arrangement of components that form, update, and evolve an explicitly constructed, spatial variation of the conceptual site model (CSM). While the role of conceptual site models is very broad, this framework uses a very specific implementation that focuses on the likelihood of exceeding a decision criteria at the local scale, directly addressing uncertainty in those "between sample" values. To evolve the CSM, the framework brings to bear the full complement of geospatial modeling and GIS technologies that have evolved considerably over the past 10 years. The framework crosses all major phases of the investigation and is flexible enough to include data and knowledge from a variety of sources and contributions. The CSM is combined with a set of possible compliance-minded decision frameworks to inform investigators and regulators alike of a reasonable course of action in the final assessment. Decision outcomes include estimates of contaminant volume, mass, and location; local probability of elevated activities; quantification of decision uncertainty; and proposed rules for compliance assessment. The discussion begins with some background information and motivating circumstances.

2 Background

2.1 MARSSIM

MARSSIM is the product of cooperation among key US federal agencies responsible for managing radioactive materials: the Department of Energy, the Department of Defense, the Environmental Protection Agency, and the Nuclear Regulatory Commission. This document provides guidance for determining whether a site is in compliance with a radiation dose or risk-based regulation (USNRC, 2000). The scope is intended for surface applications such as the top layer of soil or a building surface.

In the MARSSIM framework, a site is divided into homogenous geographical areas called *survey units.* A survey unit is a geographical area with a specific size and shape that will serve as the basis of the investigation and over which compliance with a release decision will be made. Three survey unit classifications are possible: Class I, Class II, and Class III. These can be described as “most certainly contaminated”, “possibly contaminated”, and “most likely uncontaminated”, respectively. The selected path of investigation within MARSSIM depends on this classification. In general, MARSSIM is motivated by two criteria. The first criterion is referred to as the Derived Concentration Guideline for site wide activity ($DCGL_w$). The $DCGL_w$ is the release criterion by which estimates of site wide activity are compared. The second criterion is referred to as the Derived Concentration Guideline for elevated measurement comparisons or $DCGL_{emc}$. This value pertains to the upper limit permitted by localized areas of elevated activity. MARSSIM is therefore concerned with the survey wide activity level and localized activities within the unit. If a survey unit fails either criterion, additional steps may be taken prior to release.

A $DCGL_w$ value is derived by adopting a representative exposure model and calculating the corresponding limit protective of public health under that scenario. Obviously, the choice for the exposure model is important and will necessarily assume certain types of human activities on the site. The $DCGL_{emc}$ is trivially calculated from the $DCGL_w$ through the use of area factors (F_A): $DCGL_{EMC} = F_A \times DCGL_W$.

For the survey unit-wide comparison, simple statistical tests are used that assume independence in the observations. Typically, non-parametric tests, such as the Sign test or Wilcoxon Rank Sum (WRS) test, are used to test the hypothesis that the survey unit-wide average is less than the $DCGL_W$. Comparisons for the local activity levels are conducted by comparing scanning results and/or sample measurements directly against the $DCGL_{EMC}$. Any result that exceeds the $DCGL_{EMC}$ requires additional investigation or remedial action before the survey unit can be released.

Knowledge of the forthcoming assessment permits the beforehand estimation of the number of samples required under the assumption of spatial independence. The number of samples will be statistically sufficient to achieve certain Type I and Type II error rates given the $DCGL_w$, certain assumptions about sample variance, and a parameter called the Lower Bound of the Gray region (LBGR). Estimates for the number of samples may be affected by background samples as well if the radionuclide is naturally occurring. Either way, the samples must also have a sufficient density in the survey unit to ensure that any potential elevated areas will be discovered with high probability (Class I and II units). A measurement is elevated if it exceeds the $DCGL_{EMC}$. This comparison may be conducted not only against direct measurements but against radiological scan data as well.

Conversion of scan data into activity levels requires source geometry. Typically, this is the infinite plane or a uniform distribution in the top 6 inches of the scan window. If scan data are required, then limitations of the scan instrument come to bear, and sampling densities may need to be increased to offset any scan limitations.

MARSSIM therefore has the following important properties (succinctly described):

- A historical site assessment is conducted. This determines the likelihood of contamination in a very qualitative way.
- If warranted, a scoping survey is performed to assess the severity and magnitude of the assessment and possible remedial action.
- If warranted, a characterization effort is conducted to better delineate the extent of contamination.
- If warranted, a remediation effort can be conducted to remove or mitigate activity levels below each DCGL.
- A final status survey is conducted.
- Survey units must pass a survey-wide activity limit ($DCGL_W$) and a local activity limit ($DCGL_{EMC}$), both of which are dependent on an exposure scenario.
- Survey units pass the survey wide limit by a formal statistical hypothesis test that assumes independence among observations.
- Survey units pass the $DCGL_{EMC}$ by direct measurement comparison but also with comprehensive scan data with assumed source geometry.
- Because of these well formed decision outcomes, it is possible to estimate the number of samples required prior to the investigation.
- The assessment is conducted and the site passes or fails.

The important facts about surface compliance can be summarized as follows:

- Assume no knowledge is available regarding contaminant location (other than the designation of Class I, II, or III).
- The surface is easy to access.
- Samples are relatively inexpensive and easy to acquire.
- Scanning can provide a comprehensive “reality check”.

Subsurface contamination presents circumstances that do not warrant a direct application of MARSSIM. First, the calculation of a $DCGL_W$ is problematic. One would need to formulate an exposure scenario that would occur in the subsurface. Examples include groundwater contamination scenarios and future scenarios where the subsurface is disturbed by bringing it to the surface (e.g., excavation). The $DCGL_{EMC}$ is therefore also problematic. Both assume that some reasonable future scenario is available and both DCGLs can be computed.

The second problem arises with definition of the statistical population and the $DCGL_w$. Statistical hypothesis testing assumes that the samples come from the same population. That is, there is nothing fundamentally different occurring that would imply sampling has occurred over two populations. In the subsurface, this may not be the case. Different depth layers may be characterized by changes in soil type and density. Water content, soil chemistry, and the like may cause changes in the underlying support. In other words, it is inconceivable that if N samples are required for the presumably homogenous surface, that N

samples would suffice for the subsurface under an assumption of complete homogeneity. The naïve grouping of all samples into a classic hypothesis test will likely fall short of any decisional merit. Therefore, from a cost perspective, the number of samples would need to increase, potentially causing severe pressure on budgetary resources. This problem is precisely the challenge addressed by Triad.

The greatest difficulty comes from the fact that investigators cannot completely scan the subsurface. The lack of comprehensive coverage so easily gained at the surface now presents a real obstacle in determining activity levels at depth. For gamma emitters, such as Cs-137 and Co-60, scanning boreholes is possible; however, it is difficult to specify a geometry for the source term, thereby limiting the interpretation of count data in terms of activity levels and location.

The problems with adapting MARSSIM to the subsurface include:

- Assuming no explicit knowledge is contradictory to the investigation
- The subsurface is difficult to access
- Volume (not area) is being investigated, increasing sampling requirements
- No comprehensive scans are possible

This document addresses how these limitations may be approached using the Triad model with the best technologies and tools that environmental sampling, modeling, decision analysis, and GIS advancements have to offer. The discussion now continues with an overview of Triad.

2.2 Triad

The Triad model is an EPA initiative to foster modernization of technical practices for characterization and remediation of contaminated sites. Triad is a result of the combined efforts and expertise of experienced practitioners from the public and private sector to formulate a framework for managing decision uncertainty and increasing confidence that decisions are made as efficiently and accurately as possible (Crumbling, 2008).

There are often two conflicting goals in an environmental investigation that can deter, distract, and even cripple the decision process. On the one hand, environmental decision making should be based on sound science. On the other hand, projects are usually expected to control costs and be as inexpensive as possible. Sound science implies that a sufficient amount of quality data be collected to fully understand the underlying processes. Given the complex conditions that plague many sites, this usually requires numerous samples. Depending on the measurement requirements and access costs, the price can be staggering.

This is further exasperated by the common interpretation of the phrase “data quality”. Historically, the focus has been on analytic quality, which in practice emphasizes the highest possible accuracy for each measurement. This has been driven to some degree by regulatory pressure on sample accuracy, evidenced in the rejection of screening and field detection methods in many final decisions. Unfortunately, higher analytic accuracy requires higher cost. As a result, project managers may necessarily limit the number of samples collected (Crumbling 2002).

Triad approaches this problem by expanding the concept of data quality from an analytic viewpoint to a decision support viewpoint. Furthermore, emphasis is placed on the use of alternative and real time measurements along with alternative lines of evidence to inform understanding and clarify uncertainty. This brings to the front the idea of sufficient data accuracy and the value of perfect information (Back, et al, 2007, Dakins et al., 1996, Lyon, et al. 1994, Kaplan, 1993). The value of information and its accuracy must be questioned in light of how well it supports the decision process rather than purely how accurate is the value. As a trivial example, suppose a decision limit of 100pCi/g is established. Method A, an expensive analytical technology, is able to detect trace radioactivity as low as 0.1 pCi/g and measure it to several significant digits. Method A, however, does no better in supporting the decision than a less expensive method, B, which can detect activities as low as 20 pCi/g and measure it with +/- 1pCi/g. Both are well below the criteria of 100pCi/g. Therefore, overly accurate sampling wastes valuable resources.

The problem is a two edged sword, as expensive sampling choices ultimately reduce the total number of samples afforded. In light of decision quality, data quality shifts from a question of accuracy to a question of sufficiency. With the gravitational center shifted from a solely data view to a decision quality view, the value of understanding data quality is increased rather than diminished. In fact, data quality is assigned a larger purpose, namely how well it informs the conceptual site model. When more data are available, greater detail is possible in the CSM. Therefore, within the context of this subsurface decision framework, further emphasis is placed on sample location as environmental processes are always a spatial problem.

In a perfect world, “decision quality” would be equivalent to “decision correctness”. However, decision correctness is often unknown (usually even unknowable) at the time a decision must be made. In many cases, correctness may never be known, due to the situational complexity and conditions that evolve over time. The term ‘‘decision quality’’ therefore means that decisions are defensible against reasonable scientific or legal challenges (Crumbling, 2002) given the best available information and knowledge afforded by financial and professional resources at the time.

There are three core elements to the Triad approach (taken from Crumbling, 2008).

Systematic Project Planning

Systematic planning includes:

- Building an atmosphere of trust; transparent, open communication; and cooperation between parties working toward a protective, yet cost-effective resolution of the “problem”
- Gaining consensus on the desired outcome for the project
- Development of a conceptual site model (CSM) from existing information

The conceptual site model plays a central role in the Triad approach. The CSM represents the current state of knowledge, including processes, history, exposure, and sampling results. The idea is to continually mature and evolve the CSM as more information and understanding unfold. The CSM is the foundation of confident project decision making and should be taken seriously. Many site managers do maintain an accurate and operational CSM that can inform the regulatory endgame; but unfortunately, regulatory practice rarely develops this concept to its logical conclusion (Crumbling, 2008). In this

document, an implementation of the CSM, called the contaminant concern map (CCM), does bring this concept to a logical conclusion in the compliance endgame.

Dynamic Work Strategies

This managerial element encourages the use of dynamic, flexible planning processes that permit the use and evolution of the CSM in determining where resources should be spent. This is referred to by Crumbling (2008) as “process” QC and can lead to tremendous project savings and improved decision outcomes.

Real Time Measurement Technologies

This element really embodies several themes. First is the use of cheaper, faster, sufficient accurate data that can be collected in greater abundance and analyzed in a timely fashion to positively impact CSM evolution. A greater abundance of data can lead to a more detailed and defensible CSM. Examples include in situ methods, geophysics, and rapid turn-arounds from traditional labs. Second is the use of computer tools to capture, store, display, manipulate, and model measurements to support evolution of the CSM. This component is an important focus of this document, as the authors bring the full power of GIS and spatial modeling systems to the center of the discussion, explicitly for the purpose of updating the CSM.

2.3 Integrating MARSSIM with Triad under a Subsurface Framework

Simply stated, the subsurface framework replaces the information that scanning and intensive sampling would have provided with all forms of available and useable data, scientific information and modeling outcomes that estimate the local activity level and the probability of exceeding an established decision criteria. Modeled values therefore provide decision makers with a surrogate in lieu of exhaustive and directly measured values. These “surrogate” values are accompanied by a model of uncertainty that can direct the placement of valuable resources as the investigation proceeds. This process is spatial in nature and represented in a specific implementation of the conceptual site model, called the *contamination concern map* (CCM). The CCM is concerned with mapping, in continuous 3D space, estimates of activity levels and uncertainties about those values. The CCM is not a schematic or diagram but a spatially explicit, numerical model that will require the use of geographical mapping tools (e.g., GIS) and other spatial modeling software to implement.

These goals will require the use of a wider set of mathematical, statistical, and decision models that emphasize spatial processes. A rich set of mathematical models is available for assessing and modeling spatially distributed information in various forms as well as quantifying underlying uncertainty. These models exist in a variety of domains. This document discusses geostatistical approaches and how they may be integrated in explicit decision frameworks. These are of particular interest due to their ability to integrate various forms of data with varying accuracy into a single model. Recent advances in this field include models that are even capable of integrating physical laws into the geostatistical model (Christakos, 2001).

This subsurface framework adds specific detail to the process by communicating, showcasing, and in some situations developing specific sample design strategies that can both use and update the CCM. These strategies can efficiently locate samples in areas of concern, areas where the CCM is uncertain, and areas where compliance checks may be

valuable in the end game. Furthermore, the document presents potentially relevant geospatial modeling tools that may support the CCM evolution. Finally, the subsurface framework presents decision frameworks that can direct sample design, remediation regulatory activities. The MARSSIM approach is comprised of 5 major phases: historical site assessment, scoping, characterization, remediation, and final compliance check. This subsurface framework will discuss the evolving CCM, the associated sample designs, spatial models, and decision support methods for each of these major phases.

Depending on the anticipated route of exposure, statements about the mean may still have some importance in the subsurface. If so, then statistical tests can be brought to bear with a cautious eye on the presence of spatial autocorrelation. Alternatively, by estimating activity locally, a more accurate estimate of the site-wide activity may be available as an average of model values. In some cases, by averaging model values together, effects such as clustering and sampling can be mitigated. This document will therefore focus on local estimation and uncertainty.

The major principles of this subsurface design can be summarized as follows:

- Use all available information in a numerical and constantly maturing 3D CSM.
- Open the compliance toolbox wider to include a rich set of sampling, modeling, and decision tools.
- Quantify and mitigate when possible uncertainty about contamination.
- Support sound science to the best extent possible with available resources.

There are two challenges in the practical accomplishment of this framework. First, the framework must be tractable to a technically competent set of investigators. Second, the decision outcomes must be articulated as simply as possible without losing valuable meaning. Such an undertaking will necessarily demand the use of computer technologies in GIS, geospatial modeling, visualization, and data management. These tools have advanced considerably in the last ten years and are well positioned to serve as vital components in the decision process.

In closing, the Triad approach is itself a scientific and technical initiative and not a regulatory approach; however, as Crumbling (2008) writes, it is hoped that regulatory bodies will recognize, through guidance modifications, that scientific and technical knowledge has advanced considerably in the last 20-30 years. This is, in fact, the purpose of this document: to extend MARSSIM principles into the subsurface by combining elements of Triad with the aid of advancing tools in GIS, spatial modeling, and decision analysis. The next chapter begins with an overview of the proposed decision framework.

3 Overview of the Subsurface Decision Framework

"As complexity rises, precise statements lose meaning, and meaningful statements lose precision"– Dr. Lotfi Zadeh, Professor Emeritus, UC Berkeley.

3.1 Introduction

In a surface assessment, exposure scenarios are well defined, measurements are easily accessible, and comprehensive scans provide a safety net regarding whether a survey unit is safe or not. MARSSIM takes advantage of these factors through a well defined set of hypothesis tests and scanning technologies to determine number and placement of samples. In the subsurface, exposure scenarios are less clear, measurements are highly inaccessible, and no comprehensive scans exist. In lieu of some technological breakthrough in subsurface measurements, there are only three broad possibilities.

- Continue to approach the problem in a rigid and classical manner despite the lack of comprehensive scanning data and the cost of sample collection. Accept only the highest quality measurements and use only simple, formal hypothesis tests. The number of samples is likely to be few in number, highly correlated, and poorly represent the total volume of the study area. While a MARSSIM styled hypothesis test, such as Sign Test or Wilcoxon Rank sum, can certainly be applied, its practical worth may be highly questionable without a clear exposure outcome that depends on the site average.
- Dig the entire site up and sample or scan as you go. For example, scrape off a few inches to a foot or so at a time and MARSSIM is repeated on each revealed surface until a level is reached that passes.
- Acknowledge the reality of the situation, including the cost of lab measurements, the severe limitations of scanning, the heterogeneity of the subsurface, and the likely presence of spatial correlation. Use a framework that can bring and use all information and knowledge available, particularly those with an emphasis on the spatial context. Such a framework should integrate and maximize various types of input, resulting in a better informed decision.

The first option simply is not feasible, as a matter of course. The number of lab measurements is likely to be insufficient to make any kind of decision at a fine spatial granularity (i.e., local activity). In addition, the spatial context is almost completely impossible to ignore when dealing with the subsurface. The second option may be preferable from a public view but may not be affordable from a principle party's view, except for well funded or small sites. That is, remove anything that might possibly be contaminated, including a lot of uncontaminated soil, if necessary. In lieu of remediation for the entire site, this discussion will focus on the final option.

The last subsurface option necessarily requires moving away some from simple statistical tools and moving toward more spatially relevant methods. Also, all data that can help control uncertainty and provide finer detail in the CCM will need to be included. This includes not only field detection or field screening results but alternative data products, such as gamma count and geophysical results. As the quote from Zadeh suggests, we must move away from methods that result in simple precise statements (e.g., standard hypothesis

testing) that operate under narrowly defined assumptions (often violated within a spatial context). We must move toward more sophisticated analyses that yield meaningful outcomes and improve the decision quality.

The timing for this kind of work is good. Guidance, such as EPA's Triad model (mentioned in the previous chapter), are already embracing the notion of mitigating uncertainty by using cheaper, sufficiently accurate means and bringing to bear computer technologies to do so (Crumbling, 2008). The field of GIS and geospatial analysis fits well with this approach by providing a rich variety of spatial statistics and spatial modeling exercises that can further extend the information provided by sampling. An arrangement, modification, and perhaps extension of some of these statistics to suit subsurface compliance support are proposed. The framework must, however, be tractable in daily application and supported by current or near-future sampling technologies. Before the subsurface framework is presented, the concept of the CCM must first be introduced.

3.2 The Contamination Concern Map (CCM)

At the center of the Triad approach is the conceptual site model. Under Triad, an emphasis is placed on evolving this model to reflect the latest knowledge about site history, processes, exposure routes, sampling, and so forth. In this subsurface framework, a very particular implementation of the conceptual site model is used, called the contamination concern map (CCM). The CCM is a spatially explicit, numerically defined, implementation of a conceptual site model aimed at estimating activity level and concern for exceeding decision criteria at a very granular level. More specifically, it continuously maps, in 3D space, the likelihood of contamination across the site.

In the beginning, the CCM may necessarily be very qualitative in nature. For example, investigators may begin with categorical statements, such as "Very likely contaminated" or "Unlikely". Figure 3.1 shows perhaps the simplest form of a CCM where these qualitative categories are used. Despite the qualitative nature of the map categories, this provides a valuable insight into where contamination may be and where compliance may fail.

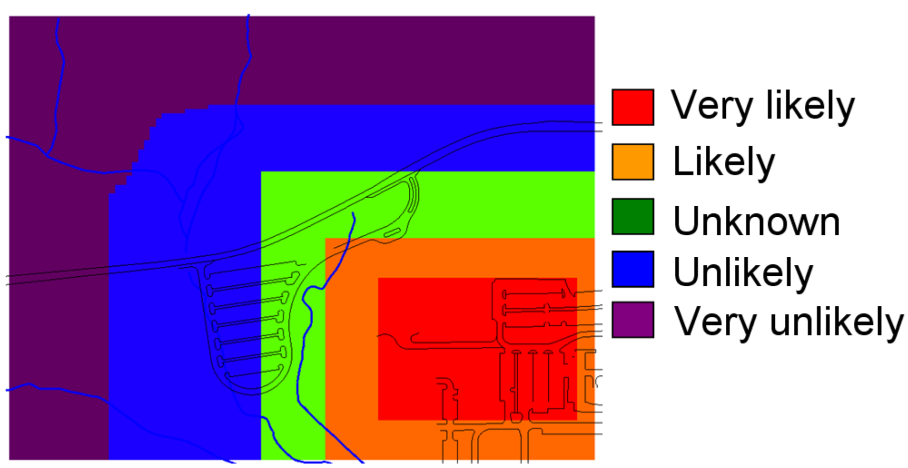

Figure 3.1 A highly qualitative, but useful spatial delineation of where contamination may occur in the subsurface.

A more quantitative, detailed map may be possible, even at the beginning. For example, a geostatistically driven probability map, contour map, or a map informed strongly by a geophysical survey may be possible. On the other hand, a completely uninformed CCM may be the reality (e.g., a CCM with every region marked “unknown”). Regardless of the sophistication and detail of this initial CCM, it does represent the state of knowledge at the start.

The CCM forms a “drawing board” that investigators may return to again and again as the investigation proceeds. It is completely acceptable to form multiple CCMs as separate lines of evidence. In fact, multiple CCMs can bright line differences in the scientific understanding and identify locations where sampling may provide clarification. Under these circumstances, the goal would be to merge the various CCMs as more information becomes available.

As the investigation proceeds and data are collected and modeled, the CCM will be updated to reflect the new findings. There are both heuristic and mathematical frameworks for updating CCMs, and these will be covered later. As each update is performed, the intent is to move away from a qualitative understanding to a quantitative understanding. During each phase, the CCM can be used to inform the next sample survey as well as reflect any past sampling surveys.

The CCM can inform all phases of the investigation, including scoping survey, characterization activities, and remedial efforts. This framework pushes the CCM to its logical conclusion, as a basis for compliance assessment as the study area moves toward closure. The CCM is therefore a cradle to grave concept that can improve the performance of sampling designs, modeling, and decisions alike. The following figure captures this intent. In the upper left hand corner, the investigation may begin in a qualitative way. As the investigation proceeds, the CCM is used to inform and update the site status along the way to compliance.

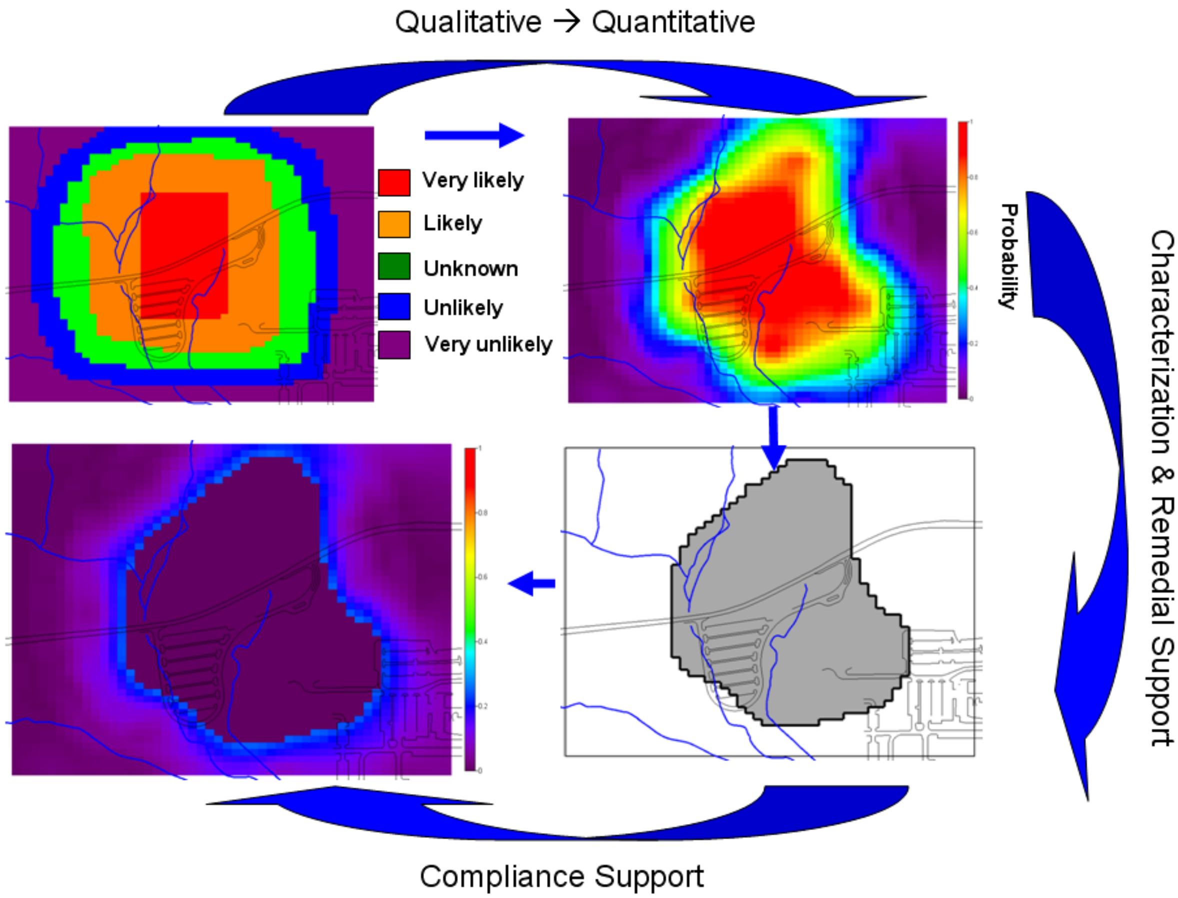

Figure 3.2 CCM moves from qualitative to quantitative and supports various stages of the compliance life cycle.

The phases of the decision framework can be discussed with respect to the CCM.

3.3 Stages of the Subsurface Decision Framework

Figure 3.3 shows the general flow of the subsurface framework. The different phases depict how the subsurface analysis moves from a very qualitative beginning to a more quantitative conclusion through a series of phases that are identified in the MARSSIM guidance. Each circle represents a major phase in the investigation. These phases are broadly defined to permit the flexibility needed to deal with varying situations. Each arrow shows a potential path through the framework and is annotated by the output content from the previous phase. In turn, this output becomes the input content for the next phase. The major theme is to use the Historical Site Assessment (HAS) to create an initial CCM. Then, the output of each major phase (which serves as input into the next phase) includes the latest CCM update as well as other relevant products. The end result is success in the compliance phase or a return to an interim phase under compliance failure. The framework suggests some methods that may be useful in compliance phase activities.

A Performance Based, Compliance Driven Framework for Subsurface

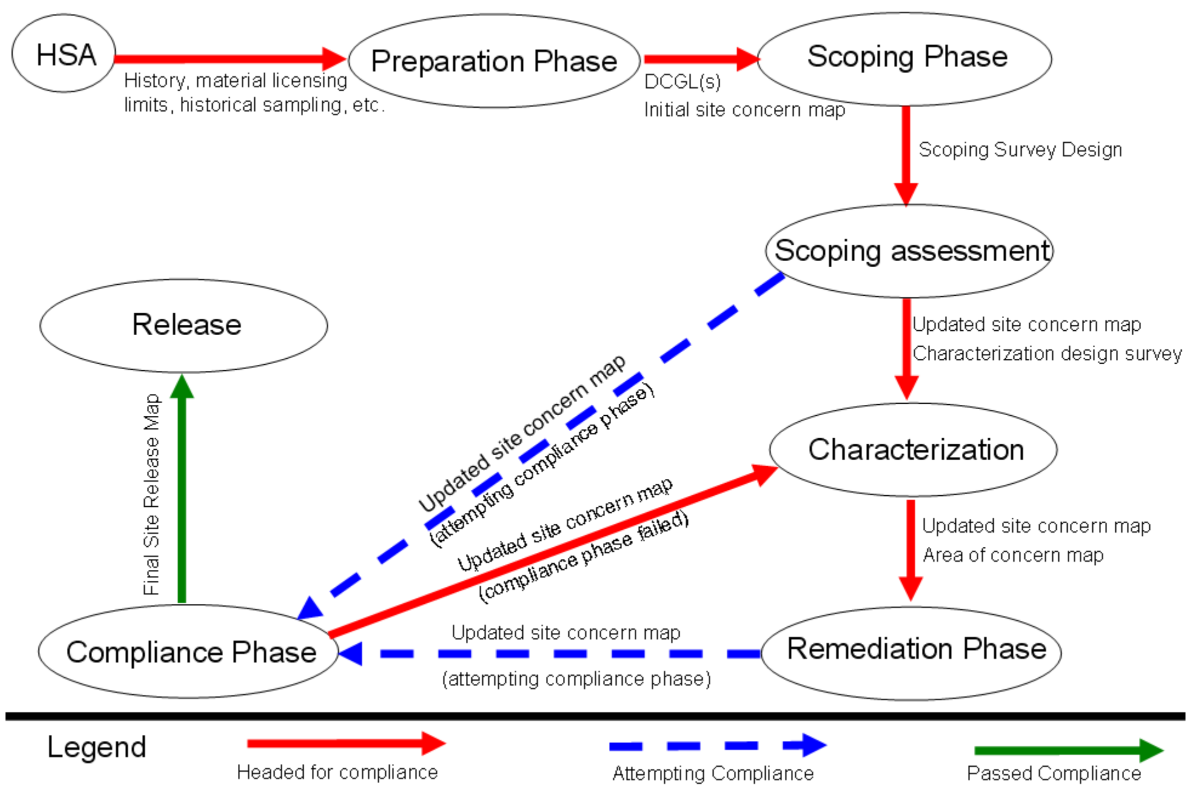

Figure 3.3 Flow diagram for the performance based subsurface compliance framework.

Historical Site Assessment (HSA)

In this first stage, investigators should collect all relevant information regarding the potential study area. As information is sought and retrieved, the investigators should be mindful of constructing the initial CCM and, potentially, the full conceptual site model. Any inquiries that may contribute to the CCM are particularly useful to this framework. Background information on geological properties, groundwater flow, and historical samples and their locations are all useful in creating a CCM that is as informed as possible in the preparation phase. From a spatial analysis view, one can anticipate that a GIS or similar spatial analysis tool will be involved in the creation and maintenance of the CCM. For this reason, the coordinate system (and possibly the projection) of any spatially referenced information should be noted. This includes not only sample locations but other GIS content such as road layers, building layers, topography, property boundaries and so forth. Once a historical query has been exhausted, the investigation moves to the preparation phase.

Preparation Phase

This phase is defined by four objectives. First, the set of decision criteria should be developed. The term “derived concentration guideline limit” or DCGL will be used here, as with MARSSIM. The term should be broad enough to capture any scenario of concern; how these are derived is not the focus of this work. It is assumed a future exposure scenario is

plausible (e.g., excavation) or a value protective of groundwater is derived. When this stage is complete, at least one DCGL is available.

The second objective is to determine the boundaries of the *study area*. Study area here is defined as the geographical region that is just large enough to conservatively capture the area of potential contamination. The study area should be defined based on the results of the HSA and should reflect a reasonable guess at the limits of the investigation. Since the study area also includes the subsurface, the vertical extent should be divided into layers of some reasonable thickness. Motivations for layer selection include geology, anticipated vertical averaging in the samples, or reasonable thicknesses related to the exposure model used in the criteria development. In lieu of any motivating factor, one may consider 2ft intervals as a maximum thickness. The question is how many layers or how deep? In the preparation phase, this will likely be answered by known processes, expert judgment, or the contributions of a geologic survey (to identify impermeable or semi-permeable layers). One outcome of the process may be that the survey needs to extend further down, and this framework can accommodate such a result.

The third objective is to create the CCM within the study area. Using all the information gathered in the HSA, create a continuous map of the likelihood that contamination exists in the study area. More specifically, delineate throughout the entire area the currently known likelihood that the DCGL would be exceeded. The CCM should be used to inform the scoping phase of the project. The CCM can be created in true 3d or in 2d at this point if no useful variation by depth is available. For a 3d creation, each layer in the subsurface would need to be delineated relative to the decision criteria. This is a preferable scenario but may not be feasible at this time. If not, then a 2d map shows where contamination may exist *at some depth* in the subsurface.

Scoping Phase

This phase has one primary objective: estimate a reasonable number and location for a set of scoping samples. There are a number of initial sample design strategies in the literature that may prove useful. The SADA software also provides a number of *informed* initial design strategies, where prior information like the CCM is used to assist in survey design (Stewart et al., 2009). Among these strategies is the *check and cover* strategy. This sample design seeks to check those locations where contamination is more likely to exist while at the same time providing some coverage to low probability areas.

Scoping Assessment

In this phase, the survey data are collected and analyzed relative to the DCGL. If there are no exceedances of the DCGL, then investigators may consider attempting to move into the compliance phase. If there are exceedances, these need to be addressed in the characterization phase and/or remediation phase. Either way, the CCM is updated with the results of the survey and passed to the next phase.

Characterization Phase

In this phase, investigators attempt to model the contamination event to estimate both the extent and volume of the contaminated media. If more samples are needed in this phase, there are a variety of secondary sampling designs that can assist. One of the more relevant designs is the *area of concern boundary design* (Stewart et al., 2009). This

secondary design seeks to take samples in viable locations in order to determine the extent and volume of the area of concern. Advanced geospatial methods are available to delineate the area of concern and associated uncertainties regarding the exact boundary location. This type of characterization approach can improve the efficiency of the characterization process and lead more rapidly to a remedial design phase. The outcome of this phase is 1) an updated CCM map and 2) an Area of Concern map that will inform the remedial phase. For groundwater applications, the area of concern map may be synonymous with the source term delineation.

Remedial Phase

In this phase, some action is taken to correct the DCGL exceedances. If the investigators choose to use the characterization phase, then an area of concern map should be available to inform the remedial design. Alternatively, remediation can take place without characterization, by sampling as remediation is done in order to determine the contaminant boundaries. If remedial sampling is conducted in real time, the CCM can be continually updated to reflect new contaminant boundaries. When remediation is complete, the CCM should be updated to reflect the remedial activity. This CCM should be assessed for moving into the compliance phase.

Compliance Phase

This is the final phase of the process. Here, the CCM is used as the basis for developing a compliance survey. The *check and cover* sample design used in the scoping process may be useful here as well. This design will double check problem areas and provide coverage for areas thought to be unaffected as well. Samples are collected and the CCM is updated a final time. Based on the results of the final survey and the impact on the CCM, regulators can issue a compliance decision. In this way, the CCM provides a repeatable, transparent process on which compliance is based. If compliance fails due to survey samples failing the DCGL comparison or through uncertainties and problems with the CCM, investigators would return either to the characterization or remediation phase to gather more information.

3.4 The Example: Cesium Site

An example site will be used throughout the process to demonstrate how the framework can be applied. The example site is completely synthetic but is constructed to capture some of the common issues in environmental characterization without going into too many complicated site specific details. A synthetic data set is necessary, since an exhaustive spatial coverage of the subsurface is needed to demonstrate sampling designs in each phase. When possible, the SADA software package will be used to demonstrate how the CCM may evolve as information becomes available. This is strictly for explanatory purposes, and it is not required that SADA be used.

The site, referred to as “Cesium Site”, is a processing and storage facility with Cs-137 contamination. Cs-137 is a typical radionuclide of interest to the NRC, with a half-life of about 30 years. In particular, there is a tank area and underground pipe that is of considerable concern to the investigation. Cesium Site will be used in each phase to demonstrate how the framework can be applied. Any similarity of Cesium Site to any real site is completely coincidental. Furthermore the authors do not insist that similar scenarios

must be approached in exactly the same way. Cesium Site is nothing more than a teaching tool.

Figure 3.4 shows a GIS map of Cesium Site. The site is covered with gravel in the upper left hand corner, asphalt surrounds the buildings and grass covers the remainder. A road leads into the facility from the left and forks in the center of the site. In the gravel area are two tanks that are leaking and a subsurface pipe that is leaking near the tanks. Cs-137 is being leaked onto both the surface and subsurface at the base of these tanks.

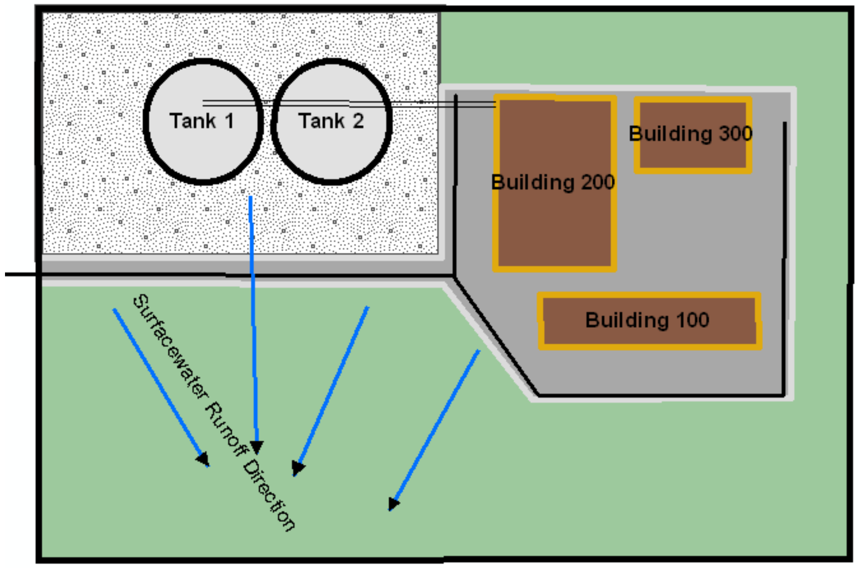

Figure 3.4 Map of Cesium Site.

To demonstrate the framework, a complete synthetic model of Cs-137 concentrations was created that could later be sampled and characterized. Figure 3.5 shows a 3d rendering of the “true” Cs-137 values.

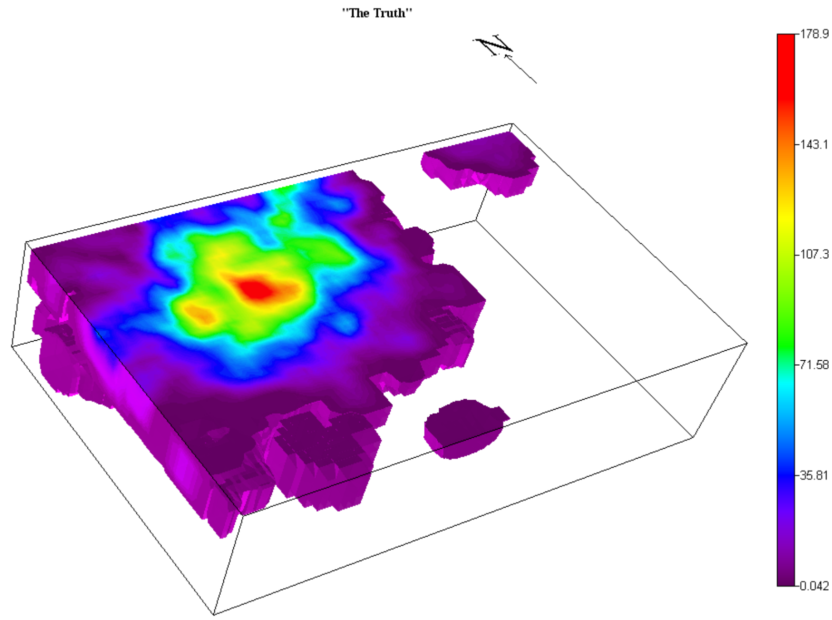

Figure 3.5 A 3d rendering of the “true” Cs-137 values.

The phases of the subsurface framework are now discussed in some detail, beginning with the historical site assessment, where information is gathered to produce the first CCM. Each section attempts to present a flexible protocol where a variety of relevant tools and analyses may contribute to the process.

4 Historical Site Assessment

In MARSSIM, the historical site assessment (HSA) is a well documented process from which this framework will draw considerable content. Many of the same questions, steps, and philosophies presented in Chapter 3 of MARSSIM are quite general and will be reproduced here with an emphasis on the CCM in subsurface. MARSSIM will have greater details regarding the HSA than will be presented here. Therefore, readers are encouraged to concurrently read Chapter 3 of MARSSIM.

In this investigative phase, all the available information regarding the operational history of the site, the geography, geology, licensed materials, and so forth would be collected. For NRC licensees, there should be records maintained throughout their operations (MARSSIM, 2000). This information is an excellent start for the HSA and may lead to a more rapid evaluation. The purpose of the HSA briefly summarized is:

1) to identify potential, likely, or known sources of radioactive material and radioactive contamination based on existing or derived information,
2) to distinguish between areas that need further action and those that pose no threat to human health,
3) to provide information useful in scoping and characterization surveys, and
4) to inform the first CCM.

The content gathered in this phase can be both qualitative and quantitative in nature. The documentation of facility operations, historical contamination events, location of waterways, soil types, nearby affected populations and so forth can comprise an important qualitative investigation. Investigators may also have access to on-going monitoring data, historical surveys, formal geophysical surveys and other geological descriptions. In some cases, information may be incomplete, potentially gathered for non-HSA purposes, or provide unclear descriptions of accuracy. At this point, any information is welcome, whether it is qualitative or quantitative and regardless of questions about accuracy and current relevancy.

4.1 Quantitative Data

Quantitative forms of data may be already available during the HSA. Direct measurements of radioactive contaminants may be available from existing monitoring programs or historical site evaluations conducted for other reasons. For well documented sites, there may be a quantitative understanding of geology or hydrogeology. Quantitative data may include groundwater modeling efforts, geophysical surveys, direct geological characterization, land cover data, and so forth.

For this framework, a particular emphasis is placed on location in space and the use of geographic tools, such as GIS, to represent site circumstances. Recall that the common ground for decision making among many lines of evidence will be the CCM, which is spatially and numerically defined. Therefore, obtaining sample values as well as sample locations is imperative.

A precaution regarding historical measurements cannot be overlooked. Conditions may have changed on the site since those measurements where conducted, radionuclides with short half-lives may have already decayed substantially, additional releases may have

occurred, or decontamination may have already been performed. It is important to document how relevant data are for the current HAS, although no data should be omitted from the report. Guidance on these evaluations is provided by the Data Quality Assessment (DQA) process outlined in USEPA, 2006a.

4.2 Qualitative Data

Qualitative data are highly valuable in this phase and can directly impact the conceptual site model and associated CCM. Examples include the acquisition and review of licenses, site permits, special authorizations, and operating records. These records can shed light on site activities, contamination control procedures, demolition, effluent releases, and various discharges. Records on storage, infrastructure failures, leaks, onsite landfills, decommissioning activities, research activities, test activities, fires, and so forth are highly relevant to this framework. Contacts, interviews, site visits and so forth provide considerable insight as well (USNRC, 2000). Logs and notes from these efforts should be included in the body of knowledge.

For the CCM, particular emphasis is placed on location and extent. If qualitative data can be expressed as location on a map, this is particularly useful. Obvious and direct examples include site plats, blueprints, sketches of structures, photographs, and modern GIS data, including roads, land cover, processing locations and so forth. Investigators should not be reluctant to manually add their knowledge to the map, even though they may not currently be in a digital format. This could include bright lining areas that appear suspicious following a site visit, expressing expert judgment about where contamination might have moved, and so forth. Geospatial projects such as these encourage the use of qualitative data, informal notes, metadata, use of multimedia (video, animation) and so forth. There may be some reluctance to include information that is uncertain in nature or may not seem relevant at the time; however, these data should be included as their benefit and relevancy may appear only later in the process. The discussion now turns to more specific types of information that should be collected.

4.3 Identify Potential Contaminants of Concern

Efforts should be made to identify the radionuclides used at the site. This list of potential *contaminants of concern* (COCs) can be evaluated to assess the potential for residual contamination. For sites with long operational histories, certain short lived radionuclides may have already decayed sufficiently below any threshold for human health effects. Knowing which radionuclides may be present can also influence factors important to the subsurface, such as mobility.

4.4 Identify Potential Locations of Concern

This subsurface framework presents several points where decisions can be made or where case distinctions may lead to a more efficient use of resources. One such example is when investigators make a distinction between impacted and non-impacted. This is an important early distinction, since limited resources should be focused on potentially impacted areas. Table 3.1 in MARSSIM offers some guidance in this process by providing a set of questions and commentary that can motivate or stimulate the investigation in the right direction. A shorter list of questions is produced here, based on Table 3.1, and when possible, questions are combined into more general statements. The purpose of this more generalized list is to set the stage for the kind of processes and evaluations that comprise

this framework. If the answer to any of these questions is yes, it indicates a higher probability that the area is impacted (USNRC, 2000).

- Was the site ever licensed for the manufacture, use, or distribution of radioactive materials?
- Did the site ever have permits to store, dispose or incinerate radioactive materials?
- Was the site used to conduct research or perform tests that included the use of radioactive materials?
- Was the site used for decontamination, maintenance, or storage of radioactively contaminated equipment?
- Was the site involved in using, processing, storing, or disposing of naturally occurring radioactive materials?

If the recommendations found herein are used as a technical basis for a future guidance document, Table 3.1 of MARSSIM should be revisited for the greater level of detail it provides.

Non-impacted areas are identified through knowledge of site history or previous survey information, specifically those areas where there is no reasonable possibility for residual contamination, including some quantitative evidence from historical surveys or knowledge about decay rates.

Impacted areas are those where operational history suggests contamination may exist or where historical survey results indicate a problem exists. Operational histories that suggest a more detailed investigation should be conducted include (USNRC, 2000):

- Locations where radioactive materials were used and stored,
- Records that indicate locations of spills, discharges or other unusual occurrences, or
- Locations where radioactive materials were buried or disposed.

Areas immediately surrounding or adjacent to these locations are included as well, because contamination may have spread. The meaning of adjacent here is an important subject matter, particularly for subsurface. In subsurface, adjacency includes not only horizontal but vertical space. The size of the adjacent region can greatly impact the cost and extent of the sampling design. In the upcoming preparation phase, the framework permits a fuzzy boundary approach rather than a hard boundary (Fisher, 2000). In fuzzy designation or fuzzy modeling, classifications are permitted on a gradient. In some sense, MARSSIM is already doing this by permitting a Class I, II, or III designation. Class I and III are each on the “hard” end of the spectrum and correspond to most likely contaminated and most likely not contaminated. In the middle is Class II, which has been reserved largely for “unknown”.

Suppose the location of a known spill could be identified. In a hard boundary view, a 50ft buffer around the location could be designated as an area of concern. Why 50 feet? Why not 75? Why not 40? The boundary is therefore subjective, to some degree. Instead, a fuzzy gradient could be used to designate the level of concern investigators have as the distance from the spill increases (Figure 4.1).

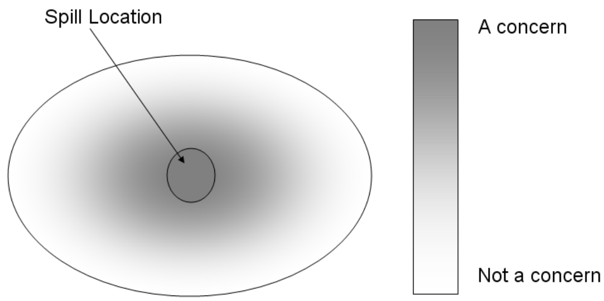

Figure 4.1 A fuzzy delineation of concern level surrounding a spill location.

Gradients or categories could be used to better reflect true site knowledge and more efficiently utilize resources. The SADA software and others permit this type of designation, with graphical tools that allow one to add such content to the map (Stewart et al., 2009).

4.5 Impacted Media

MARSSIM provides a considerable level of guidance on how to assess the media types that have been impacted. This document is largely concerned with subsurface soil but may have a role to play in groundwater evaluations as well. The questions found in this section draw on MARSSIM regarding subsurface evaluation.

- Are there areas of known or suspected surface soil contamination? Given the type of radionuclide involved and the underlying geology, could migration to the subsurface reasonably occur?
- Is there a reasonable chance for enhanced mobility of radionuclides? Certain other analytes can facilitate mobility in the soil.
- Has the surface or subsurface been disturbed? Inexpensive geophysical surveys or simple visual inspection may provide clues.
- Are there buried pipes? Trenches? Subsurface structures (basements)? Buried pits/landfills?

Similar questions exist for groundwater, and the reader is directed to Chapter 3 of MARSSIM for a discussion of those.

4.6 Preparing for a Contamination concern model/Conceptual site model

The HSA is the first opportunity to think ahead in creating the first CCM. From a spatial analysis view, one can anticipate that a GIS or similar spatial analysis tool will be involved in the creation and maintenance of the CCM (and conceptual site model as well). Recently, a premium has been placed on putting together sound geospatial projects, particularly within EPA. In 2003, EPA released a guidance document on geospatial data quality assurance that outlines planning for a geospatial project (USEPA, 2003). This framework is very much a geospatial project and special attention will be placed on these themes.

During the HSA, the coordinate system of any spatially referenced information should be noted. This includes not only sample locations but other GIS content, such as road layers, building layers, topography, land use, property boundaries, and so forth. Sample locations may be reported separately from sample values, may have different coordinate systems, and may have poor levels of accuracy. Older sites may provide sample locations in a relative format rather than in a standard reporting system. For example, Sample A was taken 20m south of Building X and 10m east. Modern sampling reports may include GPS grade location values reported in one or more coordinate systems (e.g., UTM, lat/long, state plane). GIS technologies provide tools for georeferencing and placing data with heterogeneous coordinate systems on the same map (Lo and Yeung, 2006).

4.7 The Historical Site Assessment Report

When the HSA phase is complete, the investigators should have enough operational history to know the types of contaminants and impacted and non-impacted areas and have some qualitative or quantitative information about potential contaminant location. These should be included in a report or other dynamic content modes, such as websites or sharepoints. In the next phase, decision criteria are developed and used as the basis for the CCM, which extends the conceptual site model with respect to a particular decision criterion.

4.8 The Example: HSA for "Cesium Site"

A historical assessment for Cesium Site indicates that the site was a processing/storage facility with possible Cs-137 contamination of the subsurface. In Figure 4.2, the layout of the site is portrayed. Two tanks reside in the northwestern portion of the site. These tanks, along with the piping that connects them to the processing facility (Building 200), are the focus of concern. The facilities themselves are unlikely to contribute to subsurface contamination and will likely be handled by MARSSIM as surface/building applications. A road enters the site from the west and forks and heads to the piping area where trucks are loaded. The other fork leads to an administrative building (Building 100) and to a warehouse in the back (Building 300).

There are three types of land cover on this site. In the northwestern portion of the site, the tanks are surrounded by gravel. The green areas to the south and east are grass areas (lawns). The solid gray region indicates asphalt. An additional concern is the surface water runoff that leads south from the tank area and could potentially move any surface contaminants offsite.

The geology of the site is sandy topsoil underpinned by clay and then bedrock at about 20 feet below the surface. No spatially explicit geological model of the subsurface is available from the HSA. The facility has been in operation for 10 years until processing ceased last year.

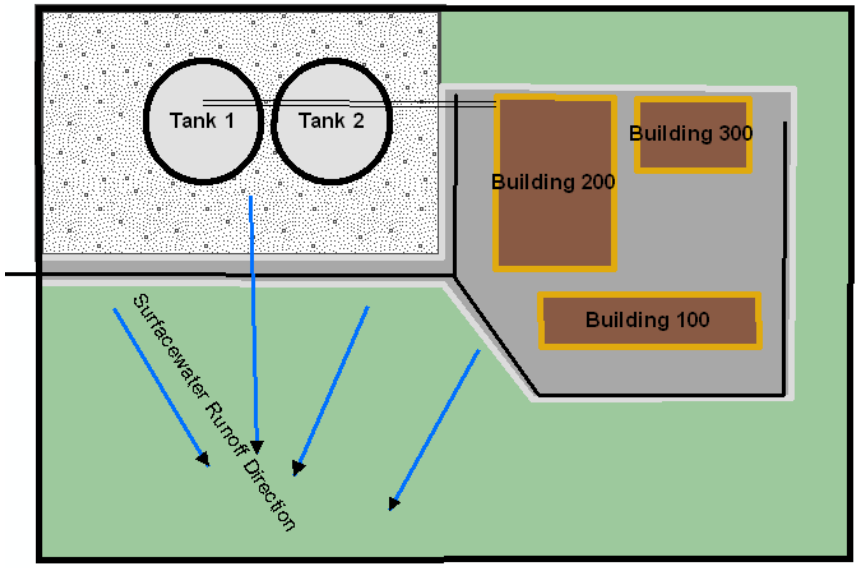

Figure 4.2 Conceptual site model showing facilities, land cover, and surface water runoff direction.

Using operating history, the site has been divided into three regions based on whether the subsurface may have been impacted by Cs-137: likely, unlikely, unknown. Figure 4.3 shows these regions. Note that at this point, no decision criteria regarding the limit for Cs-137 has been formed.

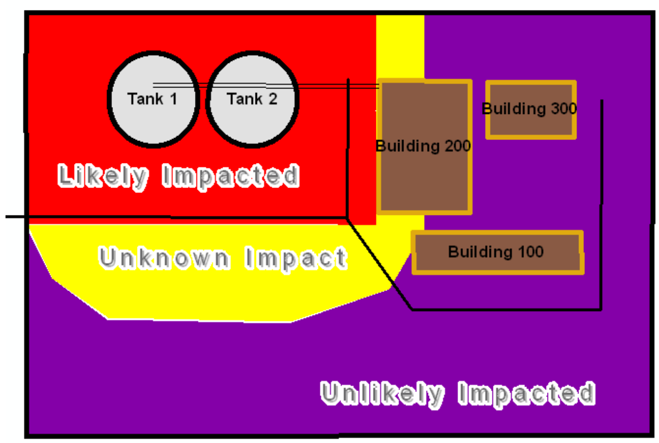

Figure 4.3 Regions of concern for subsurface contamination.

Historical samples (2 scenarios)

Historical examples are available for this site and are presented as two scenarios. In the first scenario, very few measurements were taken recently. In the second scenario, a richer set of data have been collected.

Historical Data (Limited Scenario)

Leaking around the tanks was noted in the past year, and as a result, cores were collected to see if contamination could be detected. One location was directly in front of the tanks, and this 20 ft core revealed significant contamination. The other two cores were taken to the east and south and revealed no contamination at any depth. Figure 4.4 shows the map in SADA indicating the three sample locations color coded for Cs-137 concentrations at the top of the core.

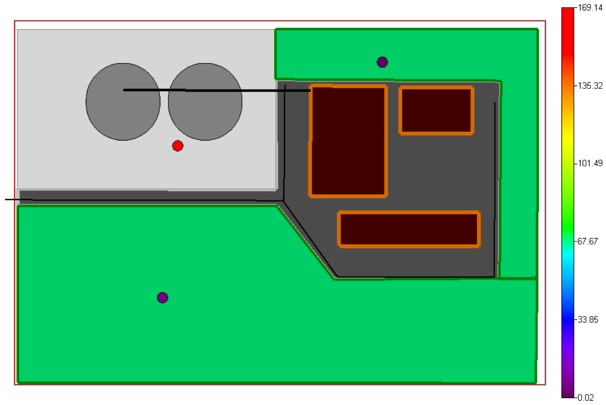

Figure 4.4 Map of Cesium Site showing three sample locations. Units are pCi/g.

Figure 4.5 shows the profiles of the three cores. Contamination appears strongest at the top of the first core. Concentrations are in pCi/g.

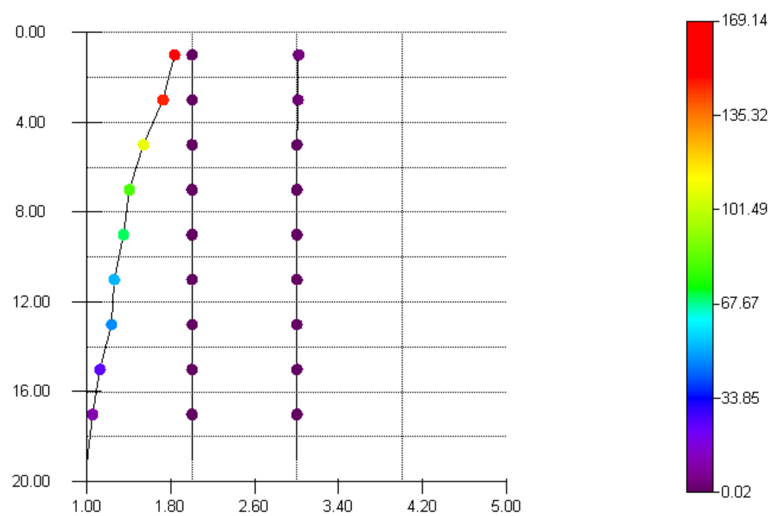

Figure 4.5 Vertical profiles of Cs-137 in the three cores. Depth is in feet, color coding units are pCi/g.

Historical Data (Substantial Data Scenario)

Leaking around the tanks was noted in the past year, and as a result, a substantial set of core samples were taken to see if contamination could be detected. Initial samples were

taken only around the tanks, but after significant contamination was discovered, additional samples were taken around the site. Figure 4.6 shows the core locations along with the core-top sample result.

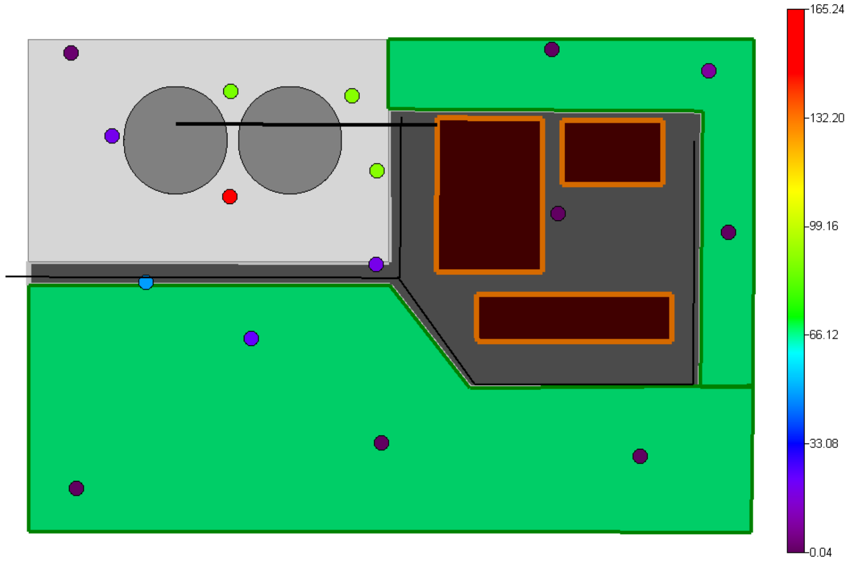

Figure 4.6 Map of Cs-137 core locations for the substantial data scenario.

Figure 4.7 shows the Cs-137 results in a 3d rendering. Contamination appears to have occurred at and under the tanks with a slight migration south.

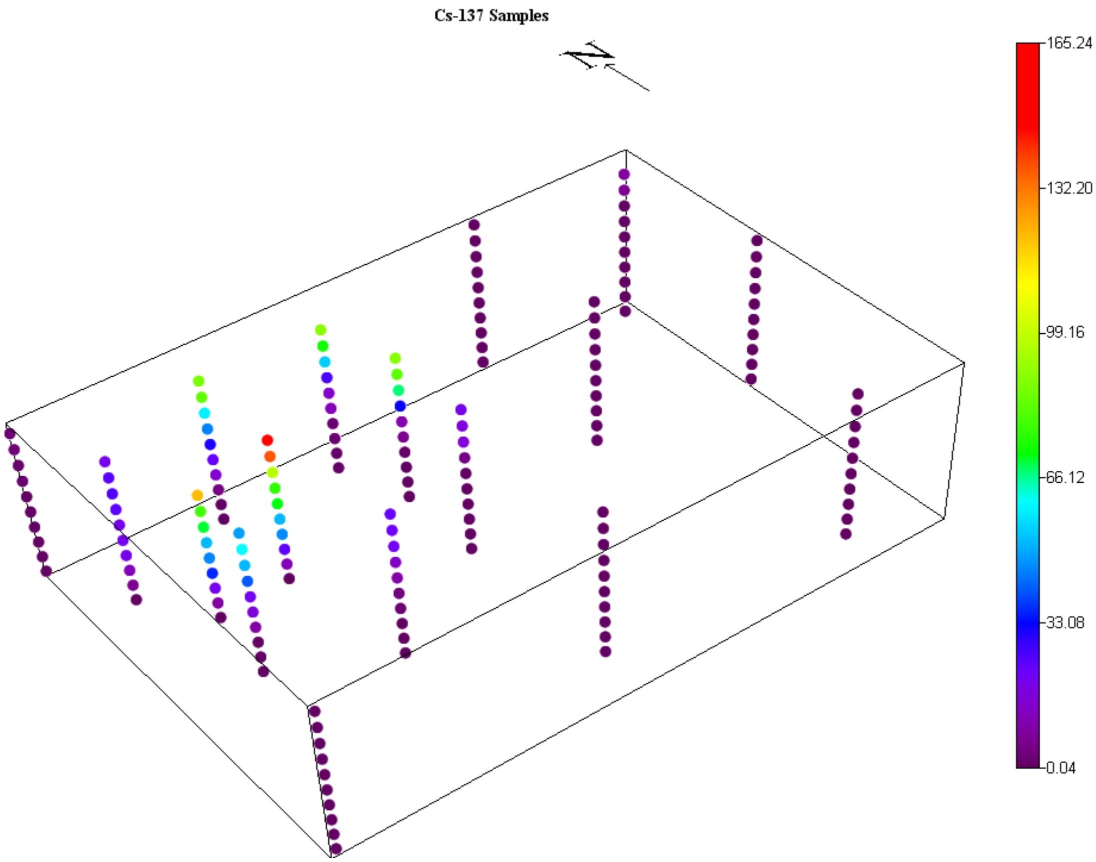

Figure 4.7 Subsurface rendering of the Cs-137 for the substantial data scenario.

The next phase is the preparation phase, where these information inputs are used to create a conceptual site model and a contamination concern model.

5 Preparation Phase

This phase takes the content made available in the HSA and organizes it into a form that can be used to drive the remainder of the framework. The preparation phase could logically be included under the HSA phase and in practice may share an iterative or interconnected relationship with the HSA. It is separated in this document to emphasize its importance. This is the first phase where the CCM is formed alongside the conceptual site model. In coordination with the CCM, this phase will also encourage the derivation of a decision criteria threshold for each COC. It is not imperative at this point to derive the decision criteria, as the following scoping survey can be implemented without it; however, the scoping results phase could use the value and derivation as early as possible and is encouraged.

5.1 The Conceptual Site Model

The DQO process emphasizes the importance of creating a conceptual site model as part of the planning process (USEPA, 2006). The CSM is often a diagram that graphically portrays the different elements of the site and associated processes. Figure 5.1 shows a conceptual site model for an offsite exposure scenario expressed as a simple graphical diagram.

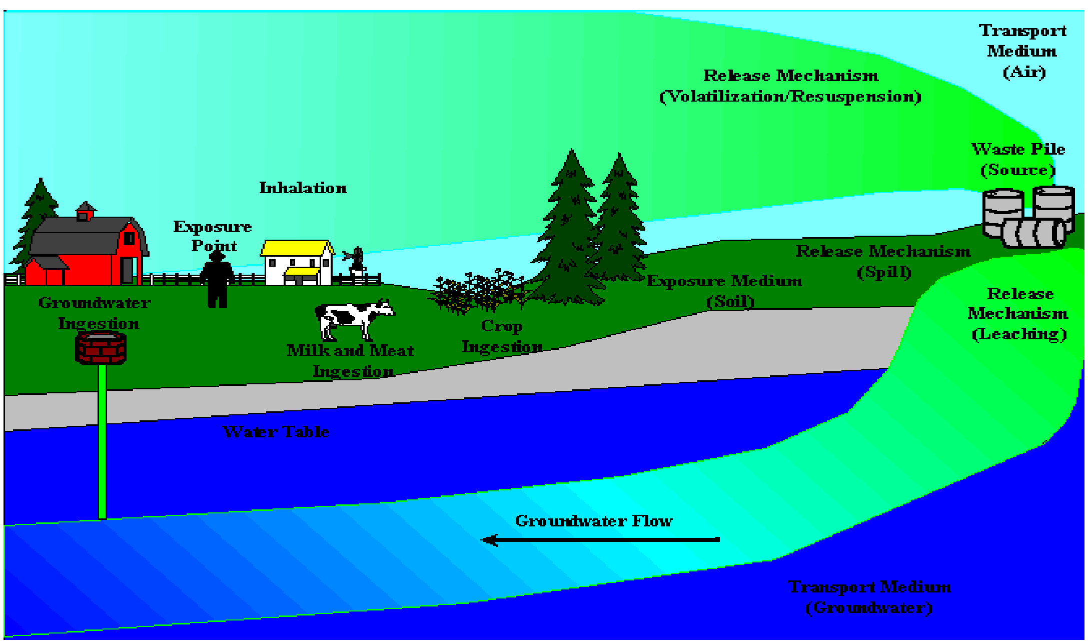

Figure 5.1. Hypothetical conceptual site model for an offsite exposure scenario as a diagram.

The CSM summarizes the relevant processes underway at the site as well as any information relevant to an environmental investigation. Process description can include ongoing or past facility activities. It can also include naturally occurring processes on the site, such as topography, surface water runoff patterns, groundwater flow, geology and so forth. The conceptual site model can also express theoretical relationships that might affect the investigation.

Information such as the known or suspected location of contaminants, environmental releases, deposition, uptake, potential sources, impacted media, and potential exposure scenarios can also be included in the model. Resources for conceptual site models include Last et al. (2004), USEPA (1989), USEPA (1994), and Cygan (2006).

With the emergence of sophisticated GIS technologies, it is possible to produce a CSM as a geographical data model. Modern GIS technologies allow for rich representation of real world entities and their relationships with each other. The output of these rich geographic data models is highly visual and interactive, with maps in two and three dimensions. A discussion of GIS and conceptual site modeling can be found in Albrecht (1997), Kemp (1997), and Crow (2000). Figure 5.2 below shows an example of a conceptual site model encoded into a GIS system. This conceptual site model expresses knowledge regarding aquifer vulnerabilities in Florida (taken from http://www.esri.com/news/arcnews/winter0809articles/florida-aquifer.html).

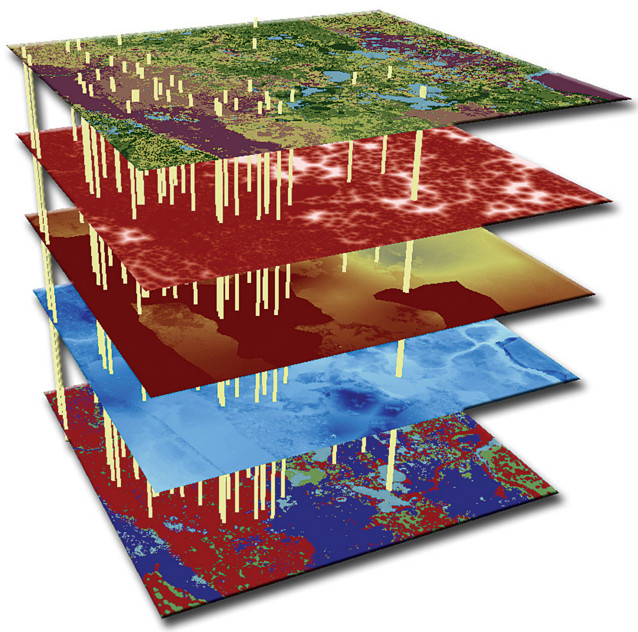

Figure 5.2 A GIS based CSM for aquifer vulnerability. Image is taken from ArcNews on-line winter 2008/2009 edition (link provided above). Full description of the project can be found in Arther, 2007.

Commercial packages capable of supporting a CSM include Environmental Systems Research Institute's (ESRI) ArcInfo suite, found at http://www.esri.com/. Non-commercial packages supported by the US government include the University of Tennessee's Spatial Analysis and Decision Assistance (SADA) freeware package, found at http://www.tiem.utk.edu/~sada/index.shtml. Open source GIS packages are available as well, including Geographic Resources Analysis Support System (GRASS) found at http://grass.itc.it/.

The sophistication of the spatial conceptual model can vary depending on the complexity of the site, the size of the budget, and the ability of the software to implement the model.

The following figures show representative GIS conceptual site models taken from the extreme ends of the spectrum. Figure 5.3 is a very detailed, visually advanced conceptual site model provided courtesy of VisualNavigator.com.

Figure 5.3 An advanced conceptual site model integrated into a GIS/Visualization system (courtesy of VisualNavigator.com).

The following figure shows an exceptionally simple conceptual site model expressed within a GIS environment and created within the SADA freeware package. In this conceptual site model, we see only topography of a burial area and a delineation of where contamination is thought to occur, based on known site processes uncovered in the HSA.

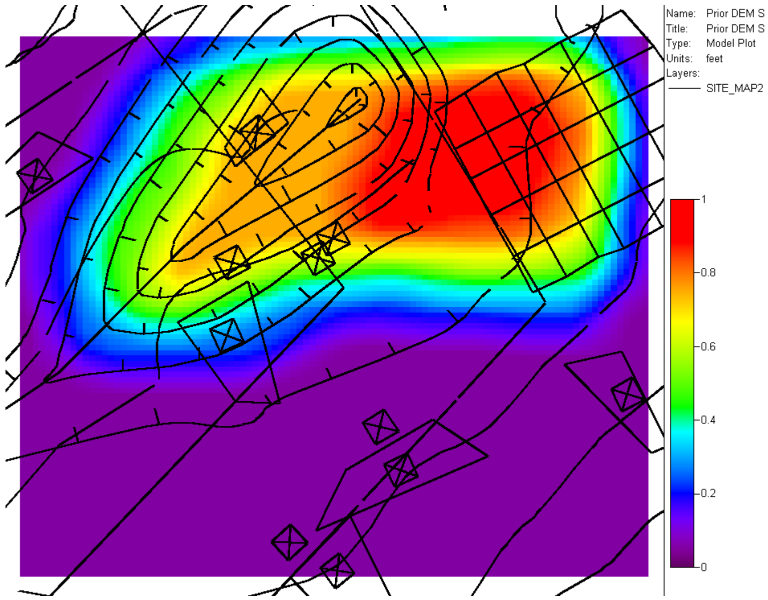

Figure 5.4. A simple conceptual site model encoded in a GIS environment.

Contained within each of these conceptual site models is an important component necessary for this decision framework. The CCM is a spatially explicit description of where contamination is known or suspected to exist. Different CCMs may need to be created for each radionuclide, or a common map capturing the collective contamination process can be created. The term *decision* implies a decision criteria exists at this point in the process. This is not a requirement for scoping phase and is not a requirement for creating a CCM. As the process moves forward toward compliance, a decision criteria (e.g., DCGL) will need to be derived, but at this point a highly qualitative CCM can be constructed.

5.2 Preparing for a geospatial project

This framework requires a spatially explicit, numerical expression of the conceptual site model that focuses on those problem areas of the site. It is necessary, therefore, to prepare for a geospatial project that uses spatial analysis tools, GIS, or a combination of the two. For readers who may not be familiar with spatial tools, a number of software packages, textbooks, and courses are offered on the subject. Recently, such a premium has been placed on putting together sound geospatial projects for environmental investigations, that EPA produced geospatial data quality guidance on preparing for a geospatial project (USEPA, 2003). This document provides guidance directed at geospatial professionals who may not be familiar with formal quality assurance (QA) plans. The effort in forming a sound geospatial infrastructure that is commensurate with the size and complexity of the problem will likely pay much larger dividends in informing the investigation and supporting the credibility of the process. An individual who can provide access to this technology should be added to the planning team during the HSA phase.

The following table provides a non-exhaustive listing of the content one should consider adding to a GIS driven conceptual site model.

Table 5.1 Examples of conceptual site model content in a GIS environment.

Facility boundary	Designated property boundary
Study area boundary	Potentially a larger area than the property boundary, if offsite processes are at play
Buildings	Current and historical structures
Roads	Current and historical roads
Waterways	Natural streams, runoff patterns, ditches, ponds, etc.
Process locations	Approximate boundary of site activities (e.g., location of storage tanks or processing machinery)
Topography	Gives a sense for how the surface varies
Subsurface structures (pipes, buried tanks, etc)	Particularly relevant to subsurface, as leaking pipes often create environmental problems
Subsurface geology	Useful in understanding how deep or how far contaminants may have migrated.
Groundwater/Water table	Location in 3d space
Sampling locations	Historical sampling locations
Monitoring wells	Current and historical monitoring locations
Areas of interest	The area/volume locations where investigators are concerned contamination may be (discussed below)

5.3 Decision Criteria

As mentioned above, it is not necessary to derive formal decision criteria for each radionuclide at this point. Examples of decision criteria include screening limits, exposure based limits, or values that are protective of groundwater. If these are available, then the framework can introduce them at this point. More likely, concern is focused simply on where contamination at any level is known or suspected to be. The first implementation of the CCM can therefore be either qualitative or quantitative. In fact, the framework assumes in most cases that the process will be qualitative at first and move toward a quantitative state. The next step is to develop the first CCM as part of the conceptual site model.

5.4 The First Contamination concern model

The contamination concern model is a particular component of the conceptual site model that will support sample designs, characterization, risk communication, and even compliance under this framework. During its initial state, it may simply map where investigators are concerned that contamination may or does exist. It could be absent of any set decision criteria or any rigorous sampling and modeling efforts. In its mature state, it is based on a rich data set, relevant modeling, and one or more decision criteria. In other words, it moves from a qualitative beginning to a quantitative ending (Figure 5.5).

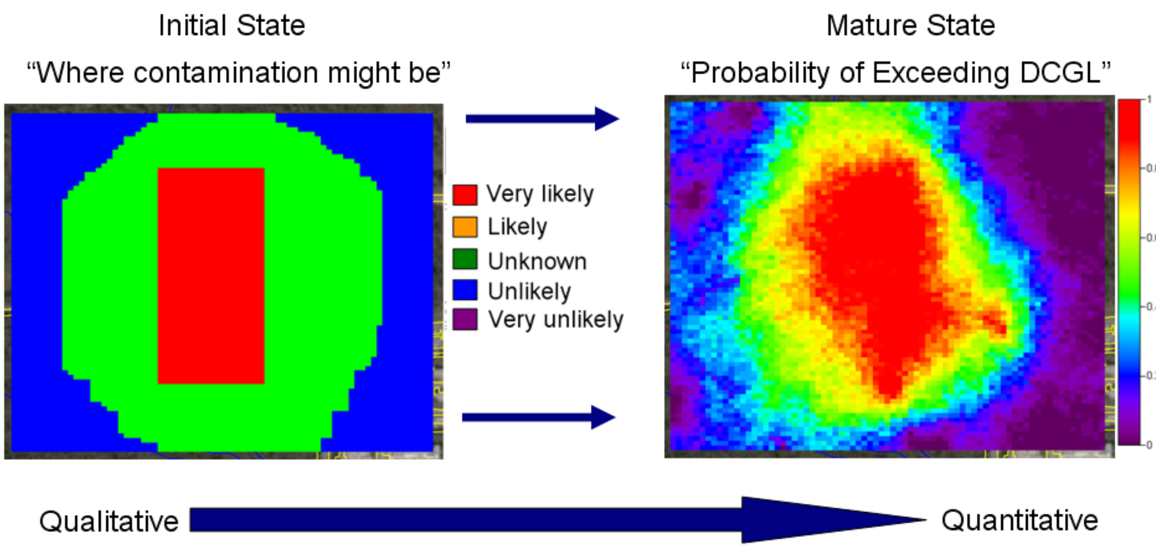

Figure 5.5 A CCM as it matures from a qualitative to a quantitative state.

Depending on the quality of the data found in the HSA, the CCM may begin in a quantitative state. The discussion is continued by bright lining three beginning states for the CCM.

5.5 Qualitative CCM

At a very basic level, one can begin by proposing a qualitative framework for defining a prior CCM. In this very general framework, a DCGL may or may not be available. The idea here is to express a general sort of knowledge about whether contamination exists. This knowledge may be the synthesis of several sources of information, such as expert knowledge, historical surveys, hydrogeologic processes and the like. To express this qualitative type of knowledge, methods are borrowed from fuzzy logic.

Recall from classic set theory that items are divided crisply between established numbers of sets. For example, suppose we are classifying people as either male or female.

A: Person is male
B: Person is female

The results form a crisp or Boolean set, as each point is either in one set or the other. This does not always apply to every situation. Suppose instead we must classify each male as tall or not. The concept of tall is vague.

A: Person is tall.
B: Person is not tall.

Is 5'11 tall? Is 6'4 tall? There are likely to be ranges of height where consensus can be reached about whether someone is tall or not. In the middle of those ranges lies an unclear range (e.g., 5'11 to 6'2 for American men). A person who is exactly 5'11 tall may be tall to some people and not to others. In this sense, a 5'11 tall male belongs to both sets in varying degrees. This is the premise of fuzzy set theory (Openshaw, 2000). This relationship between set membership and height can be graphed as follows. Suppose that a designation

of “not tall” receives a 0 and a designation of “tall” receives a 1. This is in fact a Boolean or crisp classification. If a decision criterion is established, say at 6’0”, then the graph would look something like Figure 5.6.

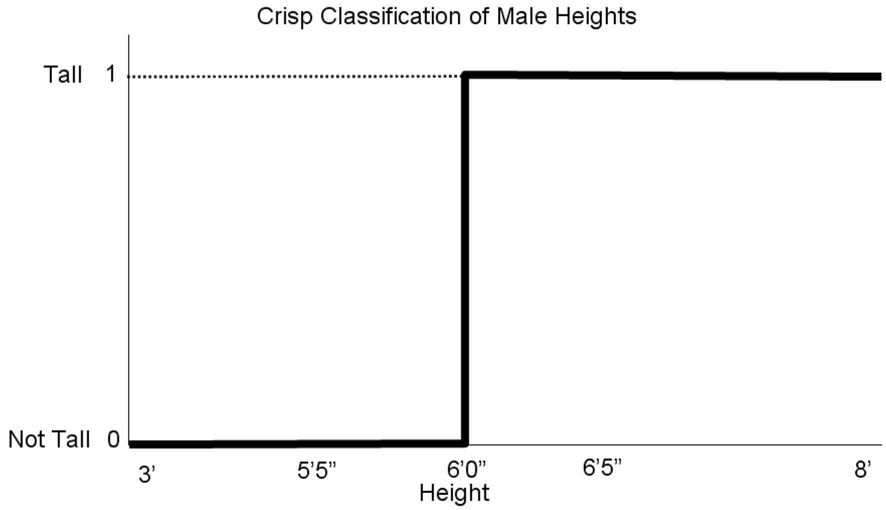

Figure 5.6 A crisp classification of height.

If the decision criterion is relaxed, a gray region is formed that indicates heights that could belong to either Not Tall or Tall and the degree of their membership is stated as a value between 0 and 1. The result is seen in Figure 5.7.

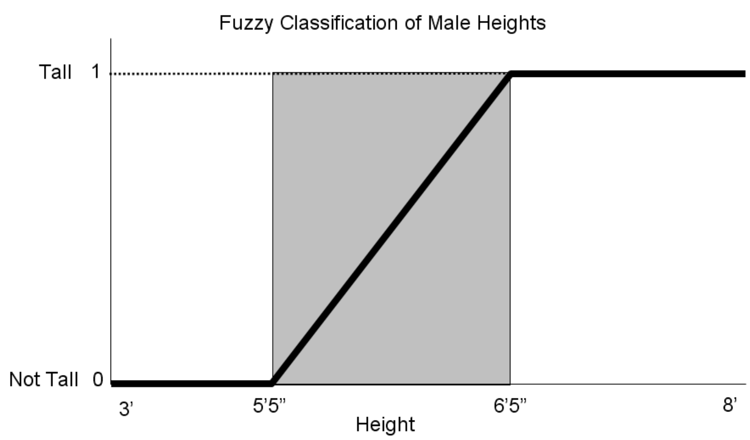

Figure 5.7 A fuzzy classification of height.

Investigators who have used MARSSIM in the past note the similarity between this classification approach and the *lower bound of the gray region* in determining the number of samples. In fact, the idea of relaxing the constraints is common to both the MARSSIM gray region and this scheme; however, the problem domains are different at this point.

This is extremely close to a probabilistic view, but it is different. In a probabilistic view, the object does have a crisp classification, but due to lack of information or some type of heterogeneous process, it is difficult to define. In that case, a probability is assigned to describe the likelihood of the object eventually being assigned to a set.

This trivial example is fairly analogous to environmental contamination, particularly at this stage of the investigation, where focus is on whether the media is contaminated (set A) or not (set B). If a DCGL is available, one could assign probabilities. This may still be an unattractive option at this point. Uncertainty about stating those probabilities may be difficult and may overstate the current level of knowledge about the site. For example, if the investigator assigns a 10% chance that some location exceeds the DCGL based on expert knowledge this may express a level of knowledge that is too precise at this stage of the investigation.

Instead, a fuzzy logic approach could be applied. Consider establishing a scale from 1 to 5 that reflects the evidence the HSA provides regarding the presence of contamination. These values will not represent the site as a whole, but rather will be used to spatially qualify regions that are of greater interest than others (described next). The proposed scale is presented in Figure 5.8. This is truly a low cost of entry approach as both the x and y axes are qualitative in nature.

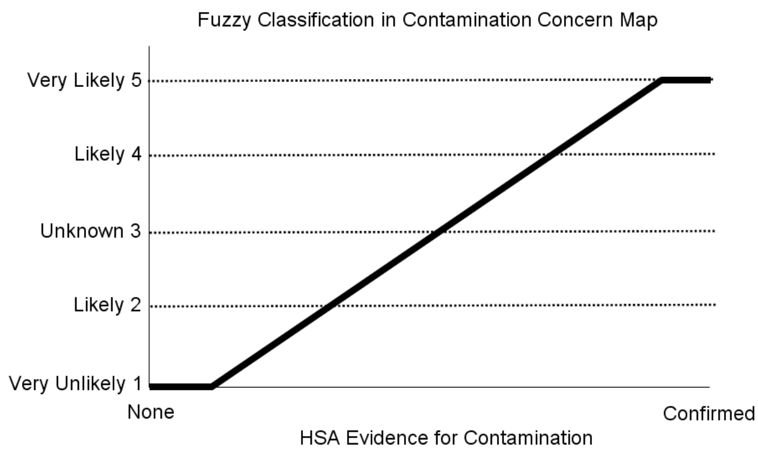

Figure 5.8 A fuzzy scale classification scheme.

This type of scale regarding expert opinion is fairly routine and, in this case, appealing due to its flexibility. Notice that at present no 1-1 probability assignment needs to be made to these categories. In other words, it does not need to be defined that “very likely” means 0.9 or similar. This type of classification does not require the strict adherence to probability domains, an area where many decision makers are usually unwilling to tread early in the process. Furthermore, it is likely that any adequate expression of spatial probabilities will be possible at this stage under typical conditions. In those cases where it is possible to specify probabilistic values, the methods that follow can still be used with potentially stronger assertions in the final assessment. In the case of probability assignments, the scales prescribed above can be replaced by either probability categories or probability continuums. Regardless, the next step is to spatially map these values.

5.6 The Example: Cesium Site Qualitative CCM

GIS tools will be used to spatially express these categories for the Cesium Site. This document uses the SADA freeware package, although investigators are free to use the tools they prefer. The SADA User’s guide (Stewart et al. 2009) details how to establish a *user-defined model* to spatially create and edit maps as required.

Figure 5.9 shows the qualitative CCM using the classifications of Figure 5.8 based on the limited historical data scenario. Recall in that scenario that only 3 samples were taken (Figure 4.4): one near the tanks and two others at remote locations. The tank sample found substantially high levels of contamination.

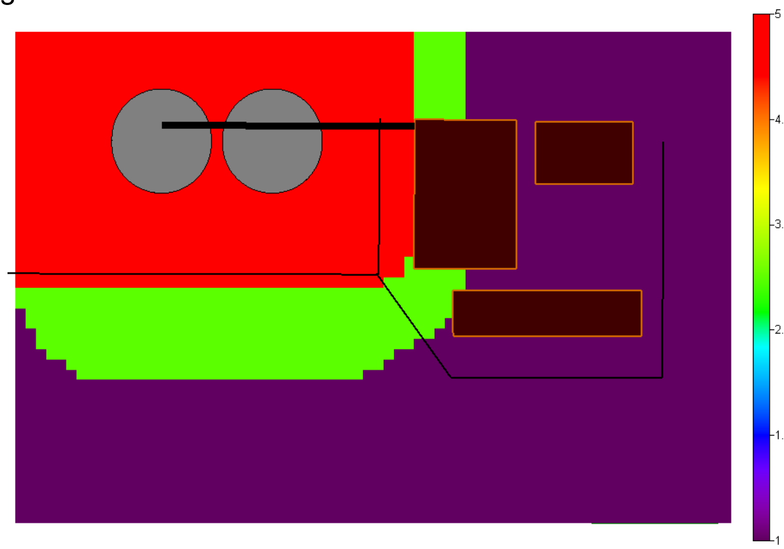

Figure 5.9 A qualitative map broadly showing where contamination is known or suspected to exist.

In the following figure, a kernel smoothing function was applied to the values to create a smooth transition between scale values. This is not necessary but further emphasizes the fuzzy or relaxed view of the current state of knowledge.

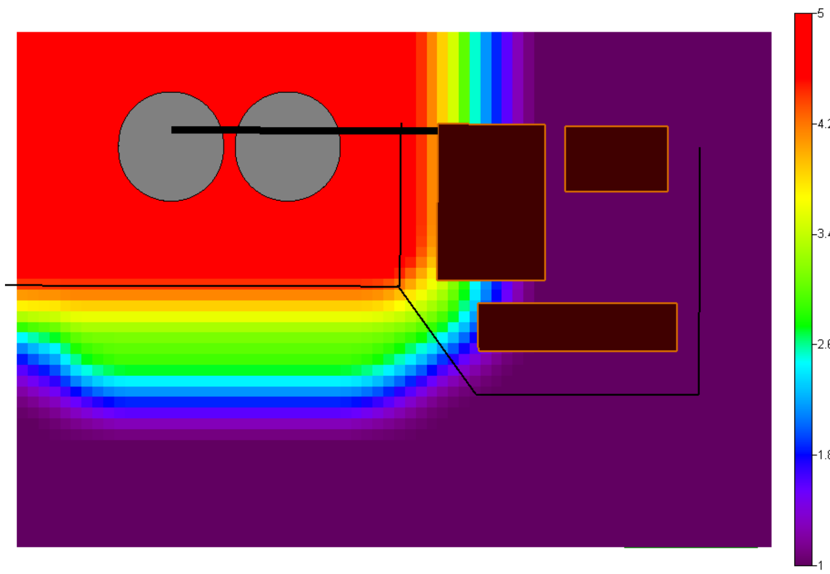

Figure 5.10 Qualitative designations are smoothed to further emphasize fuzzy state of knowledge about contamination, particularly transitions between scale areas.

The model is actually a 3d contamination concern model, although it is not necessary to create a 3d model at this point if nothing substantial can be mapped. The model was created by defining 2 foot layers to a depth of 20 feet. The HSA indicates that bedrock may

be reached at about 20 feet. There is also reason to believe that Cs-137 would not have migrated the entire way to bedrock, although the possibility has been left open. Figure 5.11 shows the 3d model in the SADA 3d viewer.

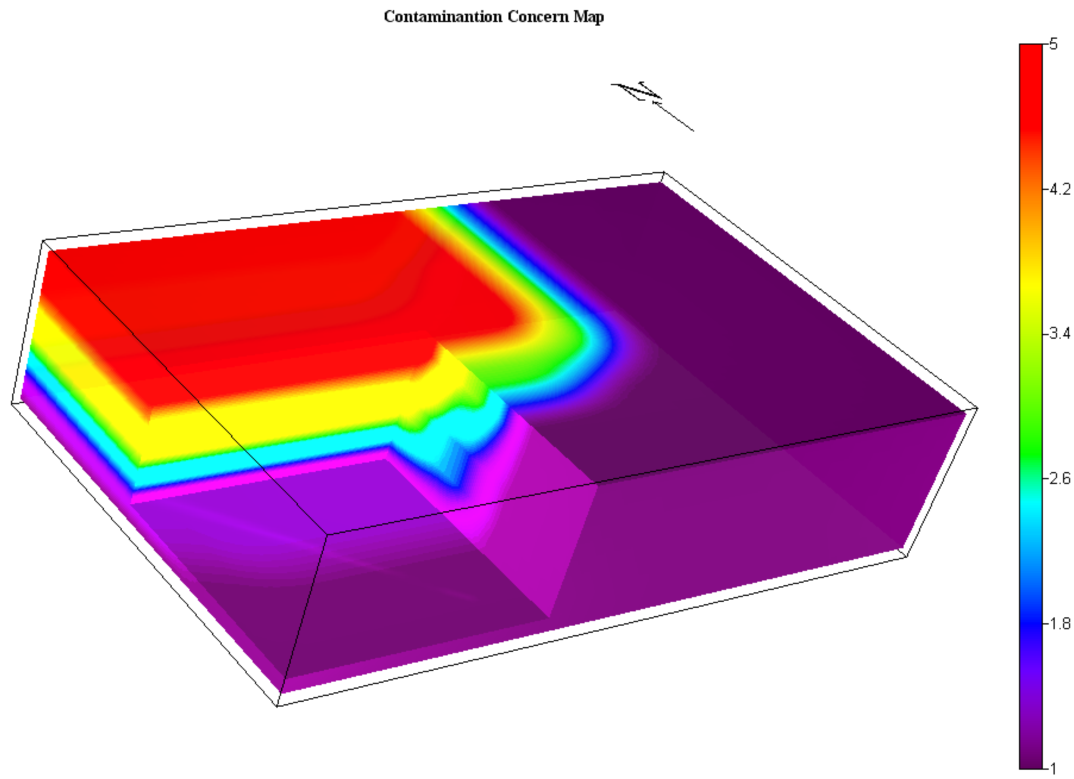

Figure 5.11 Contamination concern model for example site.

It is not necessary to adhere to values shown in Figure 5.8. Establishing a scale is a decision that investigators should discuss as part of the process.

5.7 Semi-Quantitative CCM

In a semi-quantitative CCM, a DCGL or similar decision criteria threshold is available. In addition, there is quantitative information available sufficient for site investigators to spatially map the probability values of exceeding this DCGL. As with the qualitative type, there are several sources of information that must by synthesized by the investigator. If all sources of information are quantitative, then the quantitative approach may be appropriate (see below).

In a semi-quantitative CCM, probability values are manually assigned rather than fuzzy scale values. The process is exactly the same as with the qualitative approach. Any appropriate GIS software can be used. SADA provides a way to manually establish probability maps for surface and subsurface. The procedure is exactly the same and will not be repeated. It is anticipated that this will be an unpopular approach for creating the first CCM because investigators must assign probabilities as the expression of their expert judgment.

5.8 Quantitative CCM

In this scenario, a substantial amount of historical data is available and maintains some relevancy at the time of this investigation. These data were able to inform a spatial model (e.g., geostatistical model) sufficient to produce a map of either concentration values or probability of exceeding a decision criterion.

If the historical data present this opportunity, there are many methods available for producing this quantitative CCM. If historical data warrant a geostatistical estimation or uncertainty assessment about the data directly, then advanced geospatial methods can be used to advance this cause. Many of these are discussed as well in this framework in the sections regarding characterization and remediation. In addition, there are a number of excellent texts on geostatistics as well as a number of geostatistical or contouring software packages available (e.g., Isaaks, 1989, Deutsch, 1992, and Goovaerts, 1997).

5.9 The Example: Cesium Site Quantitative CCM

In the following example, the substantial data set from Historical Data Scenario 2 was used in a geostatistical analysis. In Figure 5.12, Gaussian simulations of Cs-137 values were used to produce a local estimation map.

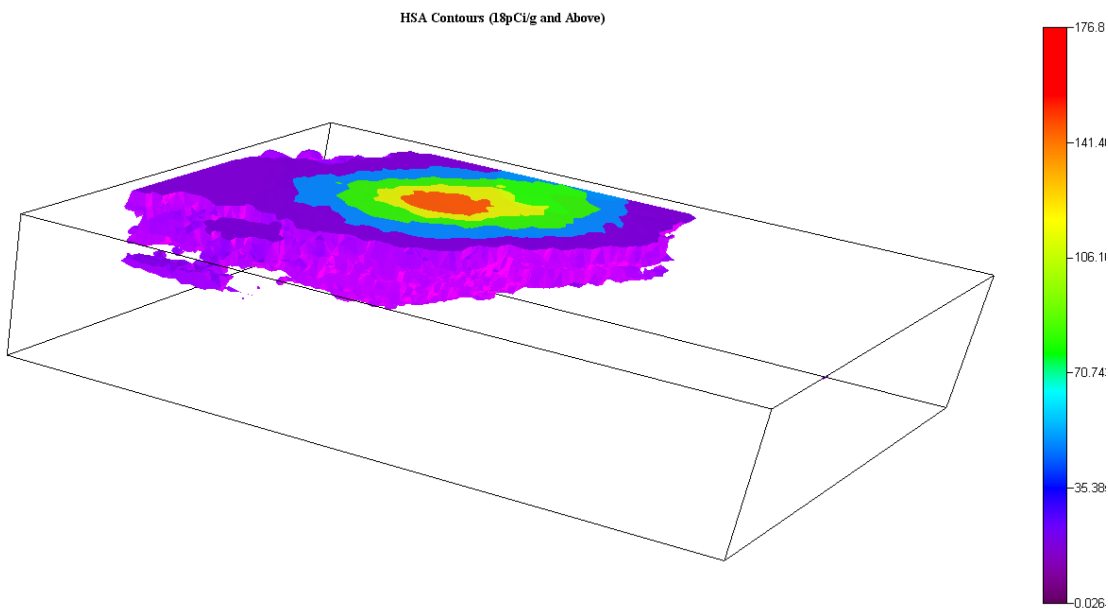

Figure 5.12 Contours of historical Cs-137 data for 18 pCi/g and above.

If a DCGL value is used, then a probability of exceedance map can be created from these simulations as well. Figure 5.13 shows the probability of exceeding 18 pCi/g based on a conservative residential ingestion scenario.

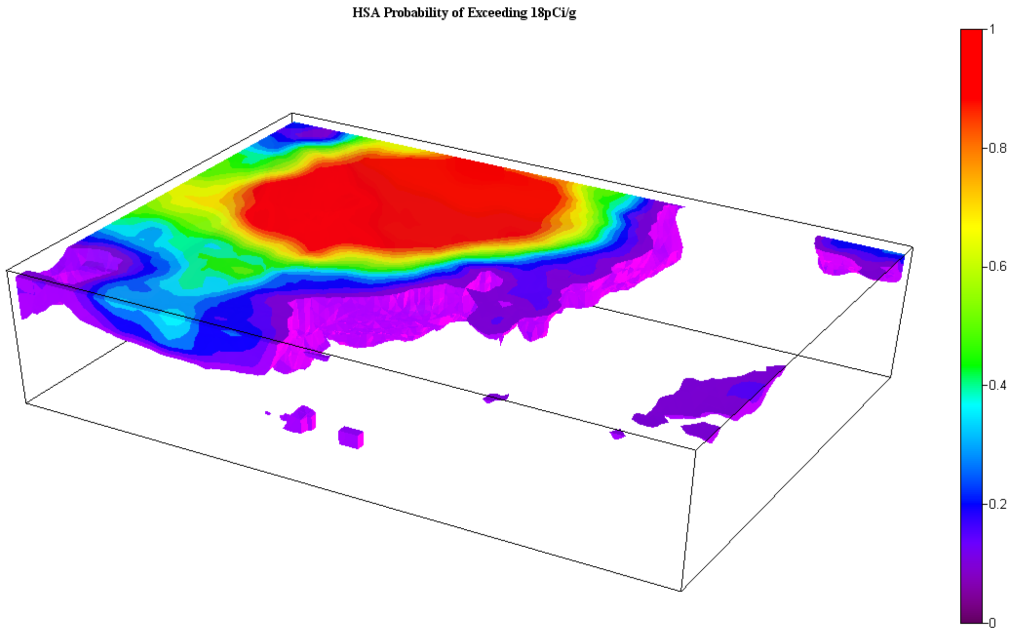

Figure 5.13 Probability of Cs-137 measurements exceeding 18 pCi/g based on HSA data.

5.10 Summary

At the end of the preparation phase, investigators should have created an initial CCM as part of the CSM. This section presented three ways to create an initial contamination concern map: qualitative, semi-quantitative, and quantitative. If a DCGL(s) can be derived at this point, the framework can be quickly focused, even at this stage, on the final decision. The next step is to use this contamination concern model to determine the need for a scoping phase. As with MARSSIM, if there is any evidence through knowledge of site processes or historical sampling, then a scoping phase should be entered. The next section discusses this phase and how the contamination concern model can be used to inform the sample design.

6 Scoping Phase

For those sites where the HSA indicates impacted areas, a scoping survey should be conducted to provide further clarification. From a decision perspective, the scoping phase should reinforce the CCM with quantitative evidence that the site has been impacted or not. This includes sample location information, which can add detail about where contamination might be.

There are numerous initial sampling strategies in the literature and in practice. Examples include judgmental designs, grids, and random designs (e.g., Gilbert, 1987, USEPA 2002, Johnson et al., 2005, Stewart et al., 2009). It is not uncommon for many of these traditional designs to make little or no use of any prior information. In recent years, this has begun to change, as sample designs have been developed that make use of spatially explicit information. In this chapter, one such design is presented: the “check and cover” design (Stewart, 201_). When the samples have been collected, they should be used to update the CCM. Methods for accomplishing this are suggested.

6.1 Determining Location of Samples

If site investigators know something about contamination processes in the CCM, this knowledge can be valuable in maximizing the information gained in a sampling effort. Traditional initial sample designs are either geometric (grid), motivated by classical statistics (random), or judgmental. In practice, few of them use prior information. During the scoping phase, the investigator should choose the sample design best suited to their situation.

This section introduces a new sample design that arose out of this research effort and was developed in Stewart (2011). The design, called *Check and Cover*, seeks to provide an exploratory balance between sampling areas that are of the greatest concern while providing some coverage in those areas thought unaffected.

6.2 Check and Cover Sample Design

Suppose that an investigator wishes to place samples where contamination is known or suspected to exist. This appears to be a reasonable course of action, but validity depends on how close expert opinion or available lines of evidence coincide with reality. For this reason, investigators may wish to also place some samples in those locations believed to be uncontaminated. Sampling at both locations does two things. First, it mitigates the risk that current lines of evidence are wrong. Secondly, if contamination is encountered in anticipated locations, samples in uncontaminated regions can provide some geographic limit to how widespread the contamination may be. This approach to sampling is biased by design, since the intent is to locate and characterize the extent of contamination. Any attempt to impart some statistical test or moment on these data may first require de-clustering. In summary, two simultaneous objectives are at play.

- Check: Sample where contamination is known or suspected to exist.
- Cover: Provide some sample coverage across the rest of the site.

This problem is extraordinarily close to a defining problem found in an entirely different application domain. Location theorists have long studied the *facility location* problem. The facility location problem is spatial by nature and concerns finding the optimal or near-optimal locations for certain activities to occur (Miller and Shaw, 2001). In its most general sense, one has a spatial domain in which importance, interest, or value varies across space. One can then respond to this spatially varying importance by locating an event or activity that maximizes the return on investment. Most often, this problem is formulated within an economic context where the spatially varying interest is *demand* (e.g., consumers) and the activity is *supply* (e.g., retail) placement. There, the objective is to optimally locate supply facilities within the demand field to minimize some accessibility constraint, whether economic, distance, or a combination.

Within an environmental context, the spatially varying interest is the likely location of contamination, and the activity is sampling. In particular, the CCM provides both the spatial domain (i.e., the site) and the spatially varying interest pattern (i.e., likelihood of contamination). Sampling is then the activity that responds to this spatially varying demand for information.

Facility location theory provides a number of mathematical approaches to this problem. One of the more viable approaches is the *Median Problem* formulation. Median problem algorithms seek to minimize the demand-weighted distance between locations of importance and the activity they are associated with. In this approach, a balance is struck across the varying levels of importance (i.e., likelihood of contamination) and the activity that serves them (i.e., sampling). Normally, discussions of facility location algorithms are described using the economic language of supply and demand for retailers and consumers. Those have been used here as well to introduce the concepts. For the remainder of this discussion, the language of environmental sampling will be used instead.

One of the most commonly applied approaches is the *p-median* problem. Drawing on the formulation presented in Neema et al. (2008), the continuous case p-median (within an environmental sampling context) is formally written as:

$$\text{Minimize} \quad \sum_{\text{i-1}}^{\text{p}} \sum_{j=1}^{n} a_{ij} d_{ij} w_{ij}$$

$$\text{subject to} \sum_{\text{i=1}}^{\text{p}} a_{ij} = 1,\ j = 1, \ldots, n, \qquad \text{(Eq 6.1)}$$

where:
p = number of samples,
n = number of grid nodes in contamination concern model,
i = sample location point,
j = grid node point,
w_j = likelihood of exceedance at node j,

$$a_{ij} = \begin{cases} 1 \text{ if node j is associated with sample i} \\ 0 \text{ otherwise} \end{cases},$$

$$d_{ij} = \left[(x_i - x_j)^2 + (y_i - y_j)^2\right]^{1/2}$$

where:
(x_i, y_i) is location of sample point i
(x_j, y_j) is location of grid node j

The solution to the p-median is classified as *nondeterministic polynomial complete* (*NP-complete).* This means that an exact or optimal solution technique is not feasible for the solution due to the potentially enormous computing time. As an alternative, heuristic approaches have been developed that can produce near-optimal solutions in a feasible amount of time. One common requirement in these heuristic approaches is that an initial guess be made. For example, if one wishes to place P samples, one must begin by making a guess at where those P locations might be. The guess can be rough, perhaps even naïve, in some cases. The algorithms will then move the locations toward an optimal solution.

The following shows a p-median placement of 12 samples for Cesium Site using the qualitative CCM and an initial grid guess. As Figure 6.1 demonstrates, p-median assumes that the underlying demand map is accurate and pursues those areas of interest.

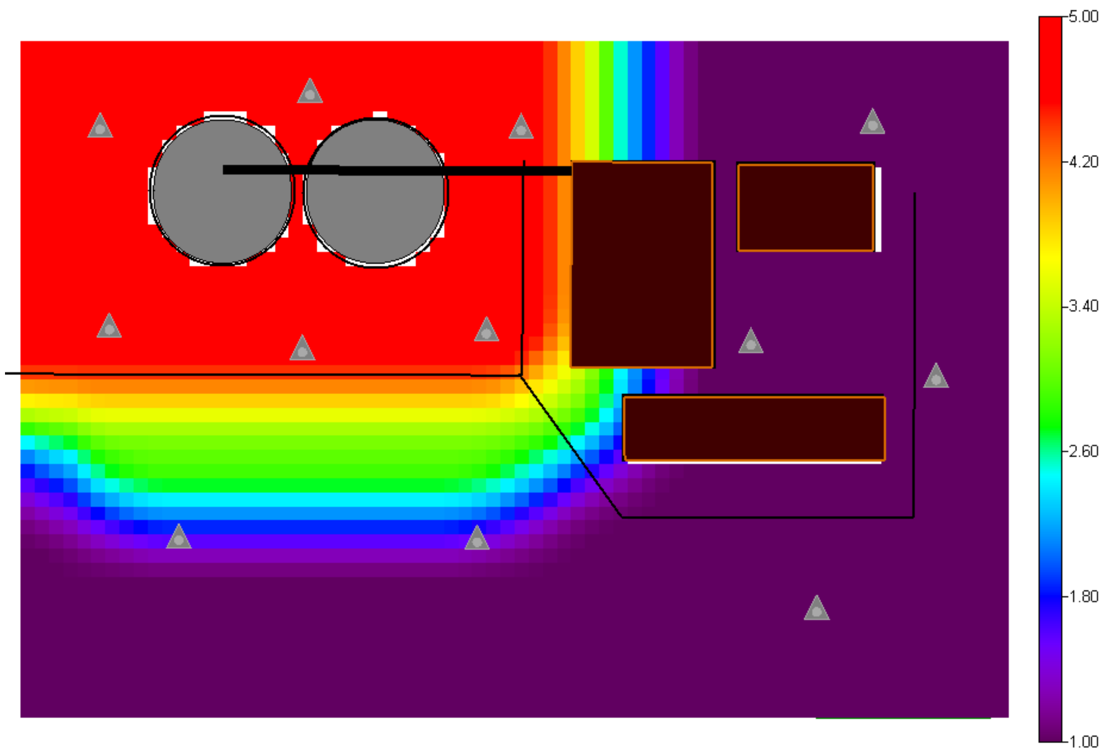

Figure 6.1 P-median placements of 12 samples on the Cesium Site using a qualitative CCM.

Applications of p-median to environmental contamination are already available in the literature. For example, Meyer and Brill (1988) apply a variation of p-median called the maximum covering location problem to the optimal placement of groundwater wells. More recently, p-median is applied to ecological diversity sampling (Hortal et al., 2009). In both of these scenarios, there is a spatial model with some continually varying attribute of importance (e.g., modeled groundwater concentrations or ecological diversity). P-median is then applied to optimally locate a set number of samples.

There may be some doubt about the validity of the underlying model (CCM), however, particularly in the scoping phase. What is needed is a way to allow the CCM to influence the decision without completely relying on it. Check and cover extends the p-median algorithm by accounting for the investigator's desired reliance on the contamination concern map. In practice, the lines of evidence that inform the CCM may have varying levels of credibility. For CCMs with low levels of credibility, one may wish to rely on the map less and migrate away from a CCM informed p-median approach towards an uninformed grid design. On the other hand, strong lines of evidence may justify a strong reliance on the CCM and p-median prevails. Both of these are possible under check and cover. Credibility is a qualitative component to the process that regulators and investigators may apply using expert judgment. While it is difficult to measure or quantify such a fuzzy parameter as credibility within a practical application, it can provide great flexibility in the investigation.

If the focus is on whether or not selected points may exceed a decision criteria, then from a probabilistic viewpoint, the case of "no known information" corresponds to 0.5. Therefore, if one wishes to disregard all information about the location of contamination, a 0.5 value would be placed at every node. In the case of the Cesium Site, a scale value of 3 would be selected (corresponds to unknown category in Figure 5.8). Figure 6.2 shows the "no knowledge state" for Cesium Site.

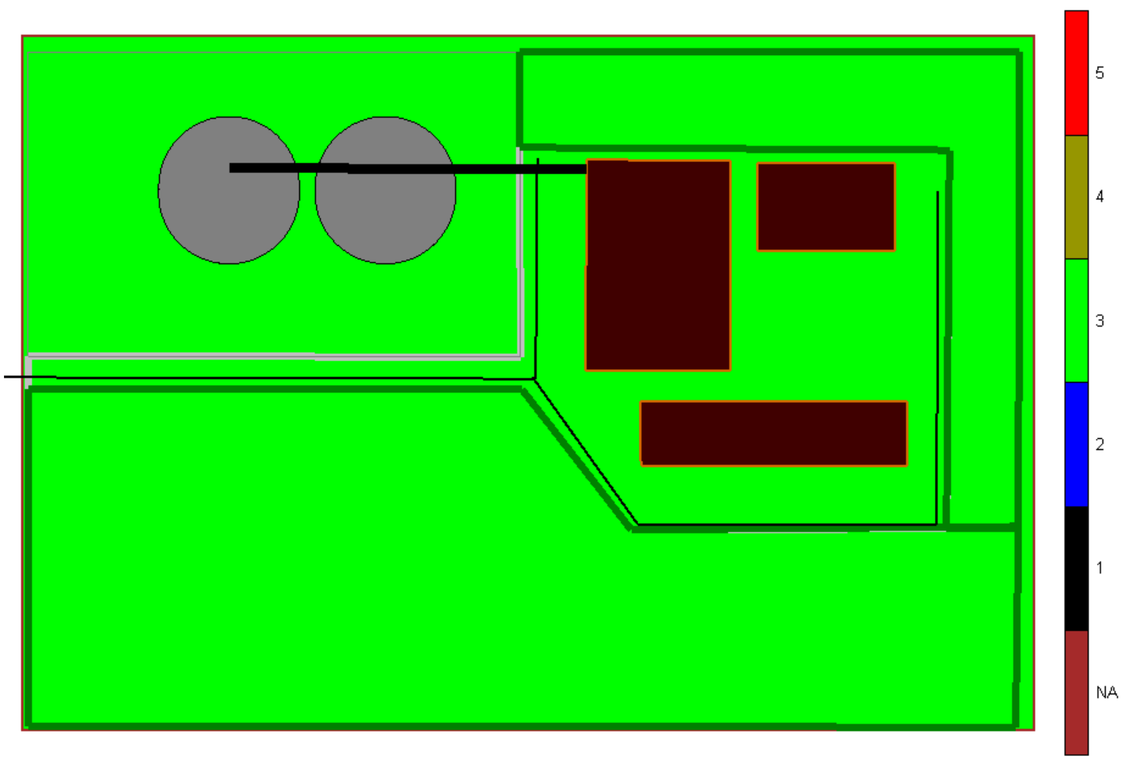

Figure 6.2 No knowledge state for Cesium Site.

Check and cover uses this principle to balance the location of p-median samples. Given a CCM map, a reliance factor (0-1), and a know-nothing value (e.g., 0.5), check and cover will adjust the CCM map values toward a "know nothing state", as the reliance factor decreases from one to zero. More specifically, equation 6.2 is used to transform the CCM map according to the reliance factor.

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$$CCM_{adjusted}(i) = CCM_i + (S_{nothing} - CCM(i))(1 - R_{factor}) \; for \; i = 1, \ldots, N_{n}$$
$$R_{factor} \in [0,1] \qquad \text{(Eq 6.2)}$$

In Equation 6.2, CCM(i) is the contamination concern model value at node i, and $CCM_{adjusted}(i)$ is the contamination concern model adjusted for the reliance factor, R_{factor}. $S_{nothing}$ is the state value for "no information", and N_{nodes} is the number of nodes in the CCM. Notice that, when the reliance factor is 1, the $CCM_{adjusted}$ and the CCM are the same. When the reliance factor is 0, the $CCM_{adjusted}$ becomes the $S_{nothing}$ state ($CCM_{nothing}$) everywhere. For intermediary values between 0 and 1, adjusted values between CCM and $CCM_{nothing}$ are used. The discussion switches momentarily to another site, where the effects of map reliance on the CCM become more pronounced. Figure 6.3 shows how Eq 6.2 adjusts the CCM for select values of R_{factor} and a "know nothing" value of 0.5.

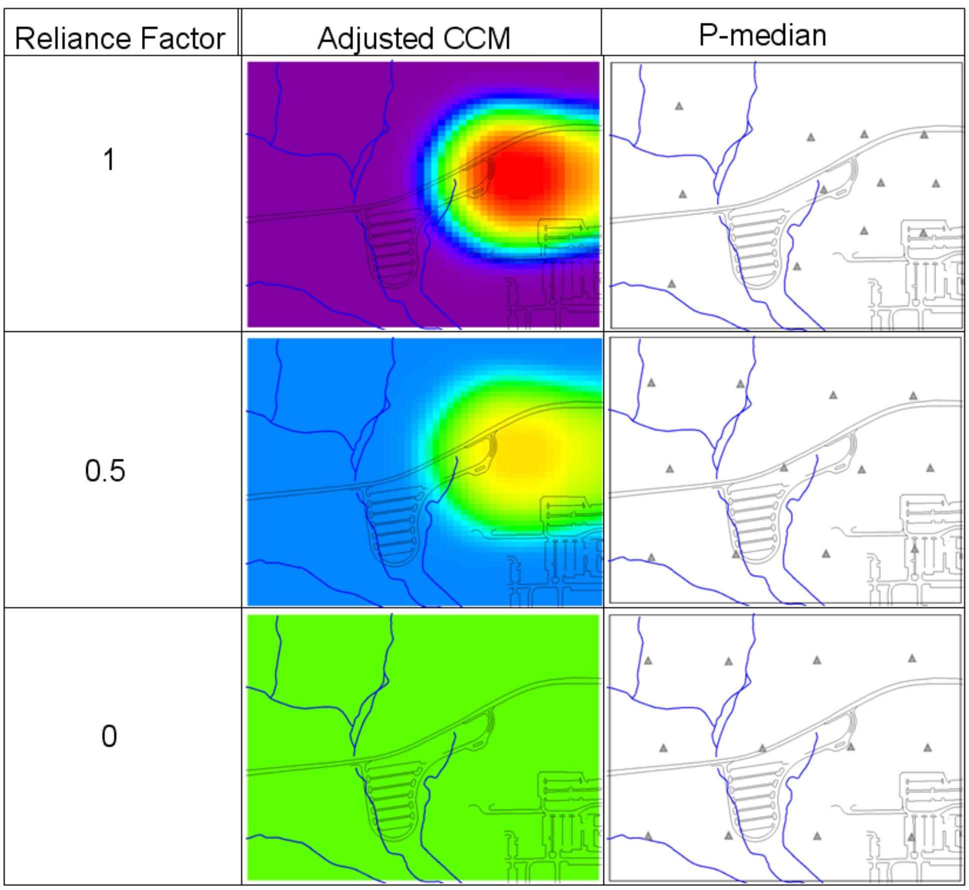


Figure 6.3 Check and Cover Values for different map reliability factors.

Notice that as the adjusted CCM moves from a "knowledge" state to a "no knowledge state", the samples move from a clustered design to a triangular grid just as one should expect.

Accounting for Existing Samples

Check and cover can account for existing samples in SADA 5.1. The algorithm has been equipped to recognize the location of previous samples in the optimization routine. In Figure 6.4, check and cover is applied to the Cs-137 site under two scenarios: 1) 3 cores have already been taken and 2) no previous cores are available.

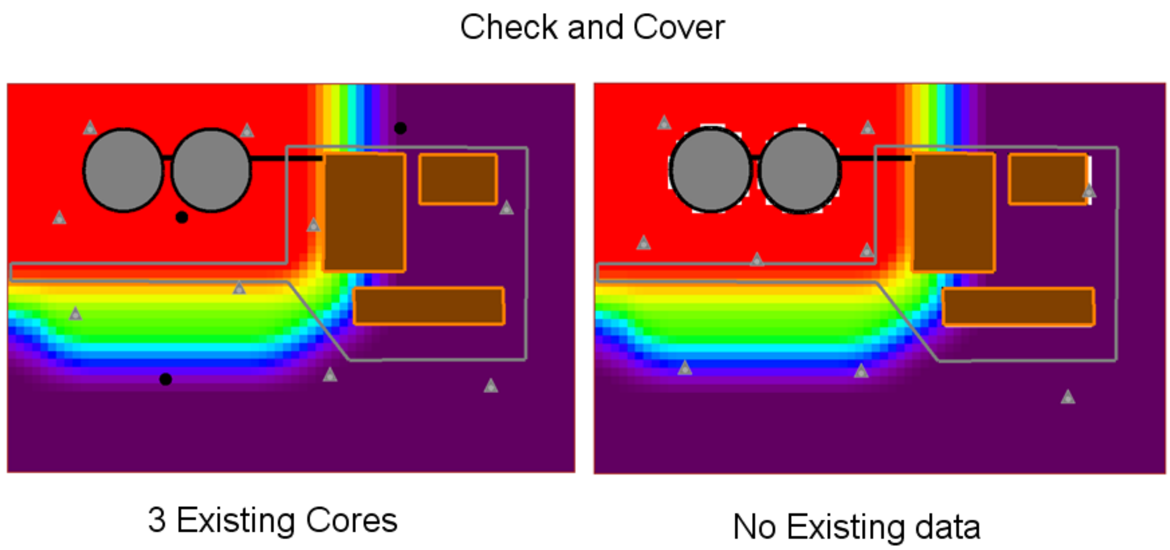


Figure 6.4 Check and cover adapts to previous sampling locations.

Recall that it is not required to use Check and Cover in the scoping phase. The sample design should be selected to match the needs of the investigation. The important emphasis should be on improving the representativeness of the CCM, and the scoping phase is the first opportunity to move in that direction.

6.3 Determining Number of Samples

With a continuous framework such as the CCM, where emphasis is placed on understanding processes at a very granular level, determining the number of samples can be problematic. One way is to estimate the number of samples based on their “worth” or based on some metric of interest (e.g., Back, et al., 2007). There are several ways in which the number of samples might be determined in this phase.

Metric Based

The size of samples during a scoping phase may be a qualitative decision influenced primarily by cost considerations. Some sample designs, such as check and cover, can provide a *metric based* determination of the number of samples. Designs that place new samples based on minimizing or maximizing some value can report the progress as each new sample is produced. For example, check and cover seeks to minimize the maximum sum of value-weighted distances. In Figure 6.5, the addition of each new sample produces a smaller sum. Eventually, the curve will flatten out, indicating a smaller return on investment for each additional sample.

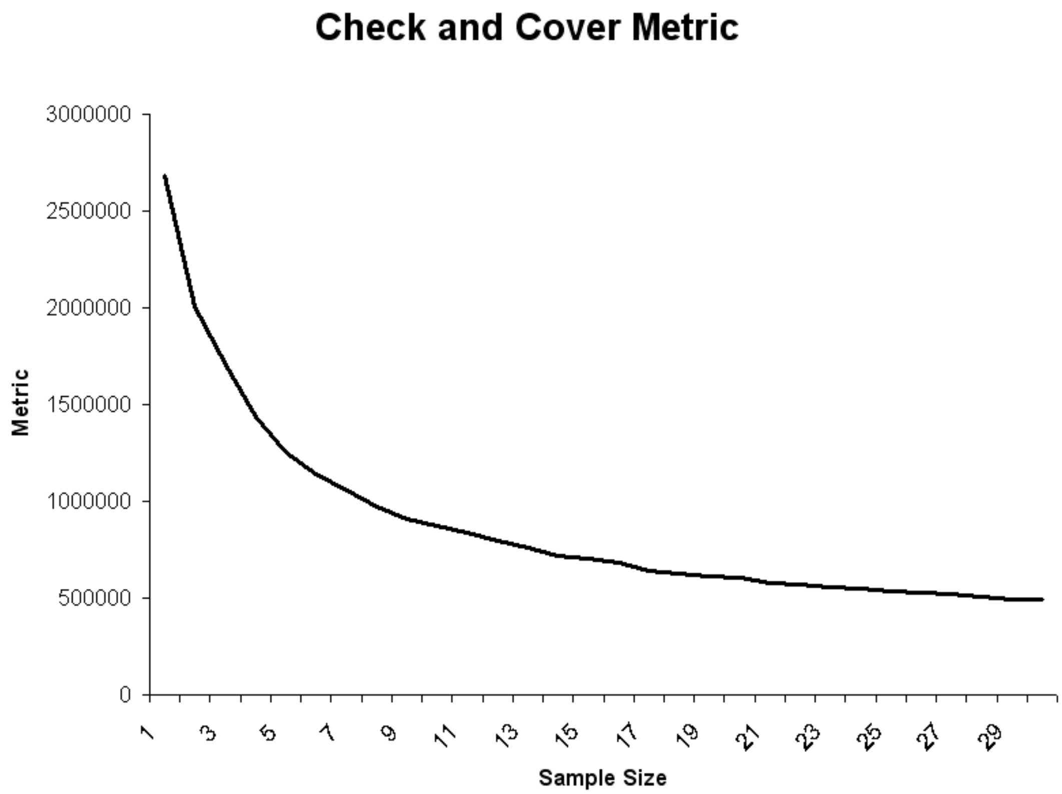


Figure 6.5 Sample design metrics can indicate when each additional sample is providing little additional information.

Coverage Based

A variation of p-median is the maximum coverage location problem. In this variation, a *maximum distance of service* is specified (Miller and Shaw, 2001). Samples are added until the distance between each node and its assigned sample is less than this constraint. This is an example of a stop rule. When stop rules are applied, the sample size is increased until some criteria is met.

Mitigating Costs

The x-axis in Figure 6.5 can be replaced by the cost associated with taking this number of samples. Costs can be mitigated by using cheaper sampling methods that can serve the needs of the survey. Recent publications by EPA discuss the TRIAD approach, which encourages the use of such sampling technologies that are sufficient to meet the objectives of the study (Crumbling, 2001).

The sample design selected simply may not have a clear metric or statistical basis for determining the number of samples at this point. More than likely, the decision will be made based on available financial resources. Hence, heuristic-based approaches are important for determining the number of samples.

6.4 Updating the CCM

At issue is now how to update the CCM with the scoping survey results. If the CCM is purely qualitative, one approach is to completely replace the CCM content with a geospatial model of scoping phase values to create the first purely quantitative CCM. This could even be an approach used for an initial quantitative CCM. In this case, a wide selection of spatial modeling and process modeling tools are available to create a new quantitative CCM. This approach, while cleaner to implement, may discard valuable knowledge in lieu of a smaller data set.

It is also possible to update both qualitative and quantitative CCMs using covariate geospatial models (e.g., Markov-Bayes, cokriging, and others). In this scenario, the prior knowledge is used to condition the model, along with the hard sample values. These kinds of models are found in a variety of geostatistical packages (e.g., SADA, GSLIB, and so forth). One problem occurs if the prior CCM is out of agreement with the scoping results. In this case, investigators might revisit those prior assumptions about site processes and develop a new CCM that reconciles the differences. If there is disagreement, the updated CCM may appear unusual, as the model attempts to reconcile the two. Investigators may need to rethink the prior CCM in this case.

In some cases, it may be possible to first add the scoping data to the data set that originally formed the prior CCM and then create a new CCM based on the combined data sets. If data sources vary in terms of what they are measuring, some method of merging them to a common unit of measurement is needed. In some cases, there may be a physical relationship between them that permits conversion of one data set into another prior to modeling. For example, gamma counts might be converted to activity levels under some assumption of geometry. If, for whatever reason, this is not possible, then multivariate geostatistical methods such as cokriging and Markov-Bayes (Goovaerts, 1997) can be used to statistically combine these methods together. In this case, the units will be the values of direct target measurements (e.g., pCi/g).

On the other hand, one might retain the qualitative nature of the CCM and manually modify boundaries of the scale values to reflect sample results. This may defer the move to a quantitative CCM or to the characterization or compliance assessment.

6.5 Deciding between Compliance and Characterization

The decision to move forward to compliance following the scoping survey or to first conduct some characterization is obviously up to the investigator and regulator involved. This section presents some guidelines for consideration by both parties in moving toward compliance or toward characterization/remediation.

Could consider compliance phase

The investigation may consider a compliance assessment at this point if the number of samples is sufficient (e.g., by a metric, data worth, or expert opinion) and:

- The prior CCM indicated low-no chance of exceeding the DCGL anywhere and the scoping survey was in agreement.
- The prior CCM conservatively used the “no knowledge” state everywhere and the scoping survey found no contamination.

In both of these suggestions, all stakeholders would of course need to agree on the CCM.

Could consider characterization

The investigation may consider a characterization or remediation activity if:

- Any data value exceeds the DCGL either historically or in the scoping phase
- The prior CCM was highly reliable and indicated a strong concern for exceeding the DCGL, regardless of what the scoping survey indicated.

6.6 The Example: Cesium Site Scoping Phase

For the Cesium Site, two example CCMs were presented: a qualitative and quantitative model. This section will proceed with the qualitative model. The check and cover sample design was applied to the Cesium Site using 8 samples (indicated by the grey triangles) and moderate reliance on the map. The results are in Figure 6.6

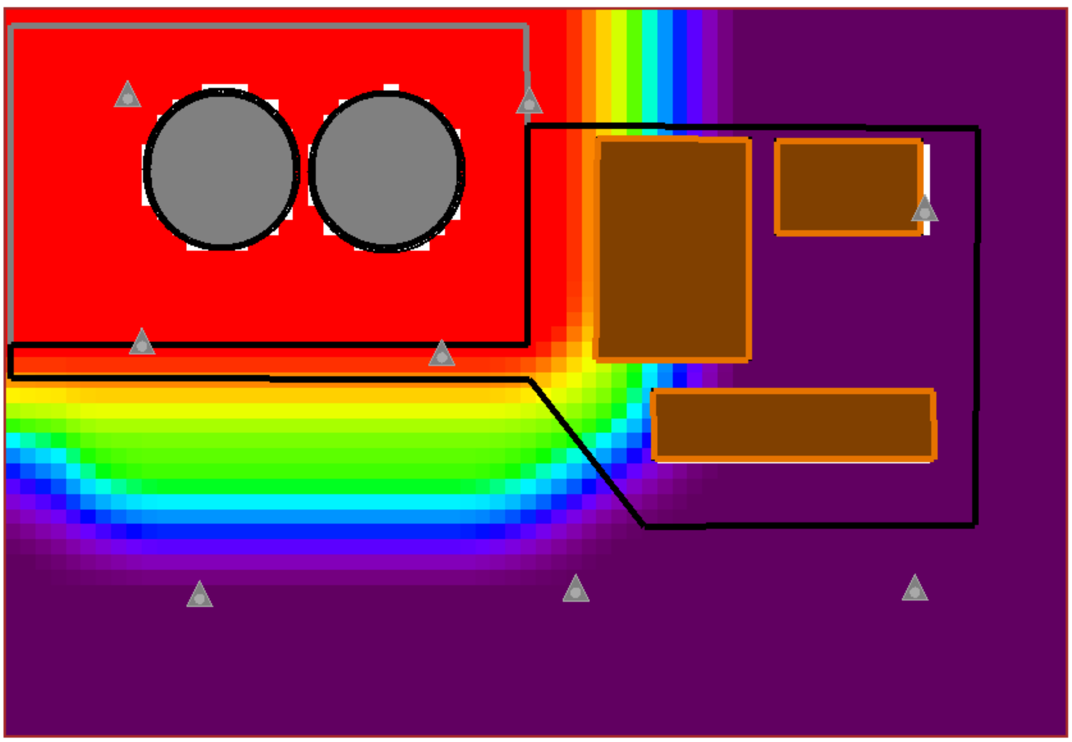


Figure 6.6 Check and Cover applied to Cesium Site with moderate map reliance.

Results for the collected samples can be seen in Figure 6.7 where two maps are provided. In the first map, values that exceed the DCGL are shown as red spheres. Purple spheres are in compliance. The map to the right shows concentration values.

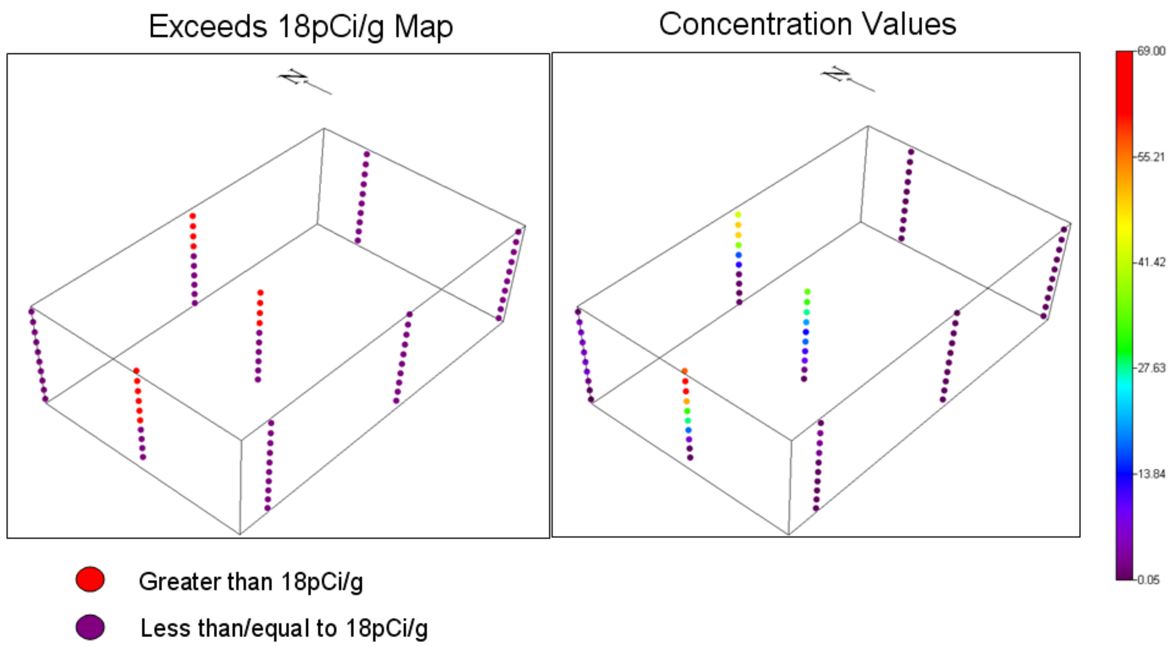
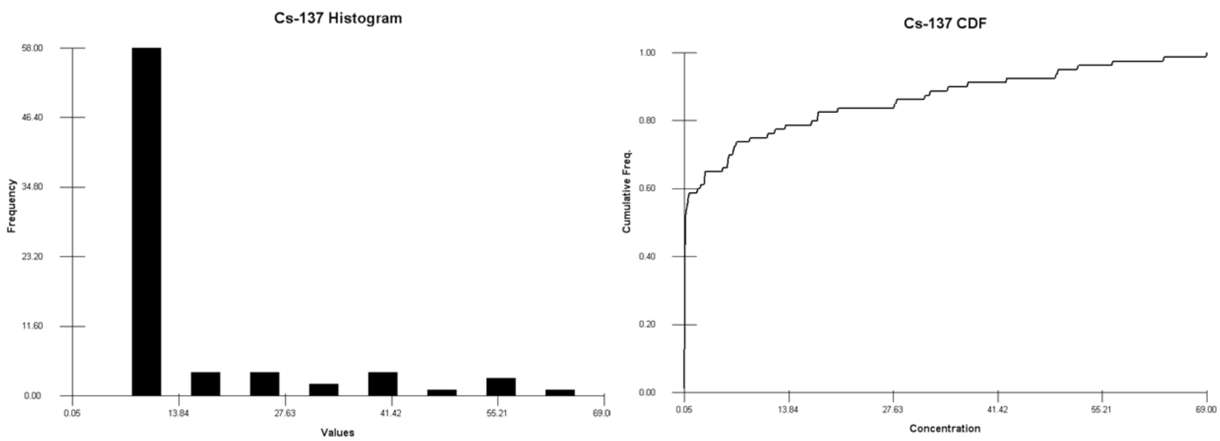


Figure 6.7. Scoping phase sample results. Left map is exceedances of the DCGL. Right map is the concentration values.

The scoping phase has demonstrated that at least some points are out of compliance with respect to a DCGL of 18pCi/g. At this point, no DCGL may be available. This is fine, since the framework does not necessarily require it during the scoping phase. This is a good time to start considering what the DCGL might be. The scoping phase evaluation can move on without the DCGL, and the following discussion shows how to proceed with and without this value.

Exploratory Tools

Once the data have been collected, it is important to assess the results. Some analysis has already been done by plotting the results and highlighting those points that are out of compliance in Figure 6.8. Other useful steps include analyzing the histogram, the cumulative distribution function (CDF), and sample statistics. Figure 6.8 shows the histogram and the cumulative distribution function.



(a) (b)

Figure 6.8 (a) Cesium-137 histogram and (b) Cesium-137 CDF.

As with most environmental data, Cesium presents a highly skewed histogram. The severe gradient in the CDF indicates that many samples are likely non-detects. Table 6.1 shows a statistical summary of the samples.

Table 6.1 Scoping Phase Summary Statistics

Statistics	Value
Number of Samples	80
Number of Detects	38
Mean	9.37
Median	0.03
Variance	286.54
Standard Deviation	16.93
Minimum Overall	0.02
Maximum Overall	69.00
Range	68.98
Interquartile Range	10.99
Skewness	2.01
Kurtosis	3.16
Minimum Detect	0.30
Maximum Detect	69.00
Minimum Nondetect	0.02
Maximum Nondetect	0.25

Updating the CCM

For the Cesium Site, in the interest of brevity, the scoping results were used to simply create a new CCM rather than integrate the qualitative prior map. In Figure 6.9, geostatistical simulations of the Cesium results are processed to produce a contour map.

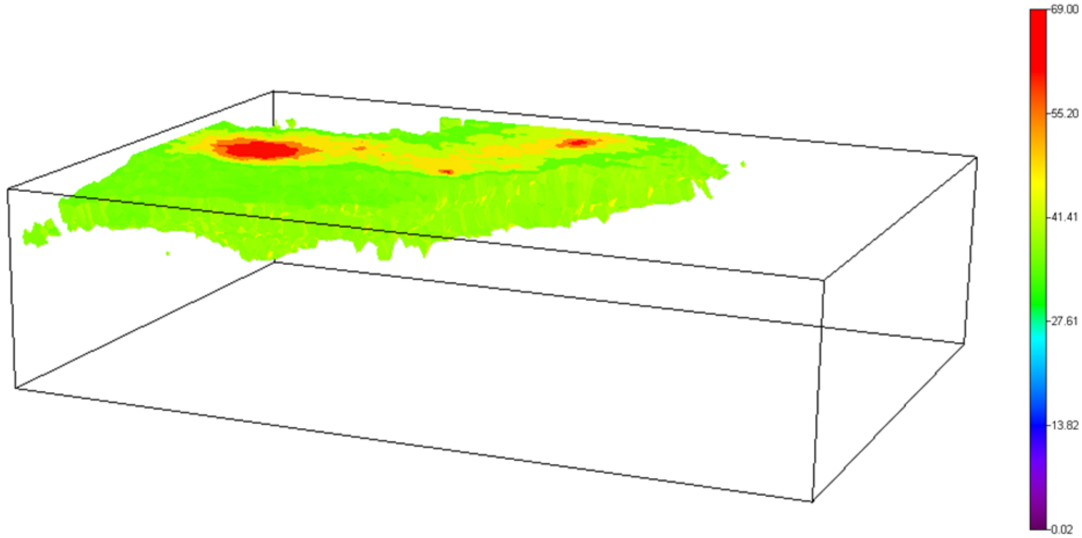


Figure 6.9 Cesium-137 concentrations modeled via post-processed geostatistical simulations. Only values above 30pCi/g are shown to reveal the elevated area.

Figure 6.10 introduces the DCGL of 18pCi/g into the assessment. Here, the probability of exceeding the DCGL at each given point is presented.

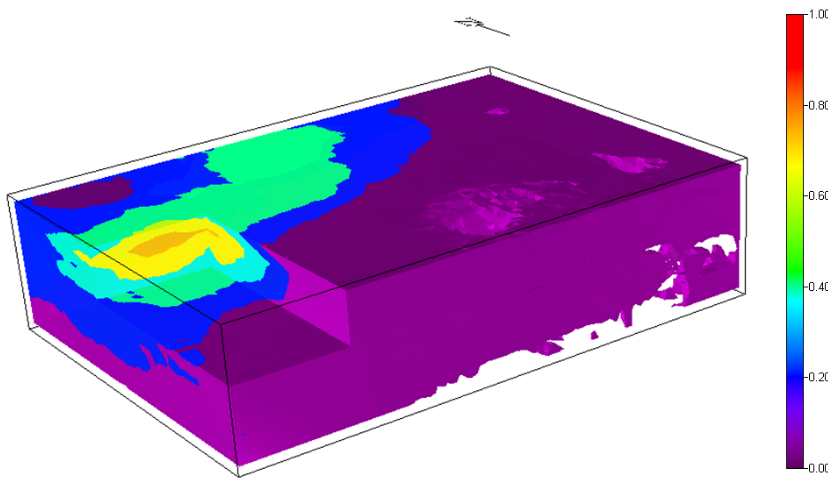


Figure 6.10 Probability of Cs-137 values exceeding 18pCi/g based on geostatistical simulation.

Both of these analyses are *point* or local analyses. Using geostatistical simulations, one can also estimate the probability of locally elevated areas of a given size or volume. Given a concentration decision criteria and a volume of interest, SADA Version 5 will post-process a set of geostatistical simulations to estimate the probability that an elevated area with specified volume will exist. *Note: At this point in the study, derivation of the correlation model(s), an important step in a geostatistical estimation, may be difficult for small data sets. Some expert judgment and rule of thumb approaches may be needed until a richer data set becomes available.*

Compliance or Characterization

Clearly, with the exceedance of the DCGL in so many locations, a characterization phase is warranted. If no DCGL is established, the presence of Cs-137 in the subsurface in such quantities should lead to the same conclusion.

7 Characterization Phase

7.1 Overview

Characterization is an extremely site-specific task, and methods from several problem domains (e.g., geophysics, hydrogeology) may be required in the process. As a result, this document does not intend to offer particular guidance in this phase but rather emphasize the contribution of the characterization phase to the CCM. To that end, two particular geospatial decision tools and a related sampling design are showcased, because of their strong connection with the CCM. The decision tools are the *Area of Concern Map* and AOC Boundary Sampling Design (Stewart et al., 2009). If these methods are deemed to be unimportant to a particular site, the reader should focus on the later section, updating the contamination concern map.

7.2 The Area of Concern Map

An Area of Concern (AOC) map is based on the CCM and indicates those regions that may require some remedial action. Based on the decision threshold, one can estimate where the boundaries of the area of concern should be, given the data at hand and the latest CCM. From these boundaries, one can also calculate volume and mass and include overburden (the clean soil on top of contaminated soil). Furthermore, one can also view uncertainty bands around the area of concern. Stewart et al. 2009 provides a discussion of the AOC map within SADA 5 that is tightly connected with this framework and will serve as the focus of this discussion. The investigator is not required to use SADA or adhere to this particular AOC derivation. This section is merely intended to stimulate thinking about AOCs and CCMs.

Scale

Areas within the AOC can contribute to a decision criteria failure at two different scales: *block scale* and *site scale*. At the block scale level, if an individual cell value exceeds the decision criteria, it is included in the AOC. At the site scale level, all blocks (grid cells) are sorted from highest to lowest modeled values. Beginning with the most contaminated block, the algorithm simulates the remediation of individual blocks from most to least contaminated until the average of all blocks no longer exceeds the decision criteria. There are many interesting details involved in developing the AOC, such as overburden calculations, benching angles, and density/mass considerations. The interested reader is encouraged to read *An Introduction to SADA* (Stewart et al., 2009) for more information. The important issue emphasized here is how AOCs are built through a grid-cell level classification that can retain the uncertainty in the CCM within the AOC map.

There are four major grid cell classifications that comprise an AOC. These classifications quantitatively report model knowledge and uncertainty related to point-wise exceedance of the DCGL.

1. Cell is not part of the AOC and at low risk of being misclassified.
2. Cell is not part of the AOC and at risk of being misclassified
3. Cell is part of the AOC and at risk of being misclassified.
4. Cell is part of the AOC and at low risk of being misclassified

Concentration Based AOC

Geostatistical methods can support this type of classification and uncertainty in a couple of ways. Recall that geostatistical methods are based on a stochastic view and permit the derivation of probability distribution functions or cumulative distribution functions (cdf) at each cell center. So unlike deterministic spatial models (e.g., inverse distance, spline, etc.) that produce a single estimate, geostatistical models recognize a range of likely concentration values. To draw a geostatistical map, a representative value is selected from each cdf. Typically, this is the mean of the distribution or the E-type estimate (Deutsch and Journel, 1995). One can also choose to map one or more percentiles of the distribution. Consider the 25th, 50th, and 75th percentile maps. Applying the AOC method to each of these would produce a result similar to Figure 7.1

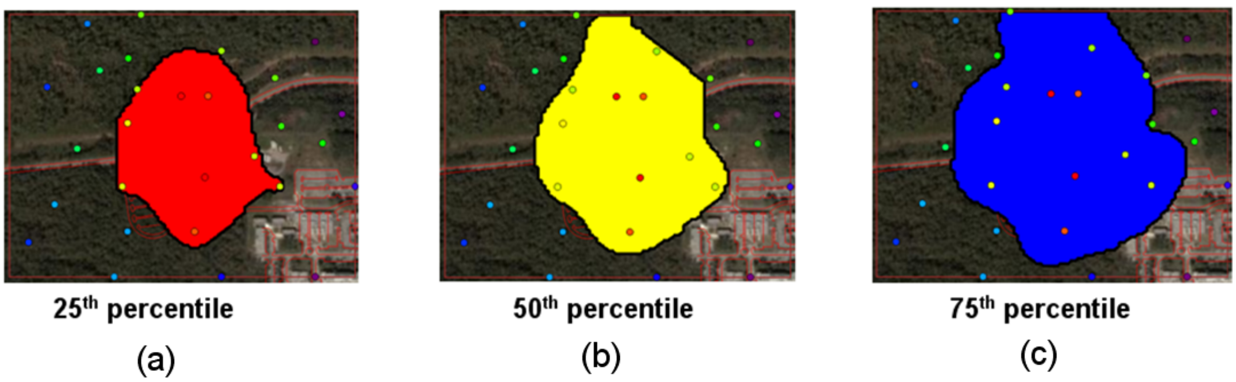


Figure 7.1 AOC design with a decision criteria of 3.0 pCi/g applied to a supplemental site (not Cesium Site) (a) 25th percentile AOC, (b) 50th percentile AOC, (c) 75th percentile AOC.

If these maps overlaid each other, the result would be a map of the cell classifications in Figure 7.2.

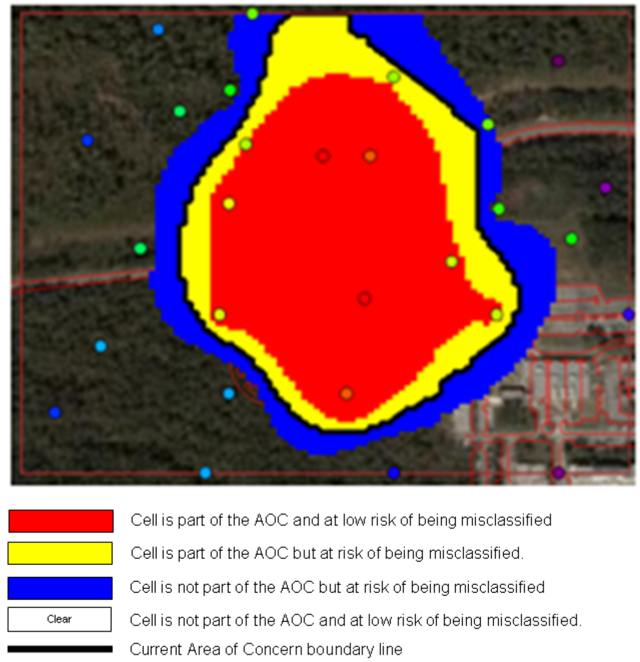


Figure 7.2 Overlay of AOC Regions.

For non-geostatistical methods, a heuristic approach can be used by selecting a lower and upper bound on the decision criteria itself rather than on the block percentile. For example, if the DCGL of 18 is used, one could express uncertainty in the boundary line as uncertainty in the DCGL. In Figure 7.3, the AOC map is created with 18+/-5 pCi/g. The idea here is to remediate to a lower criteria in order to create some insurance against leaving behind contamination.

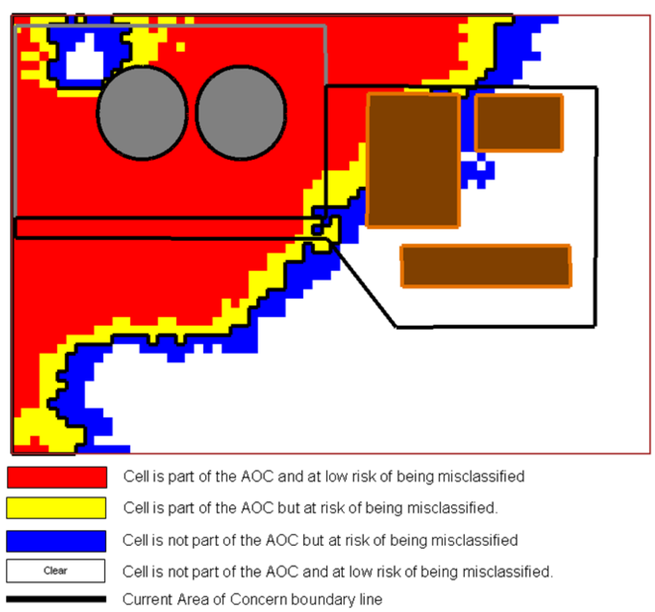


Figure 7.3 AOC map for DCGL of 18+/-5 pCi/g at 2-4 ft.

While this does produce a model of uncertainty that may serve a practical purpose, it is not as rigorous as a geostatistically based map.

Probability Based AOC

In the same manner, these classifications can be used in a probability map. In Figure 5.13, the probability of exceeding 18 pCi/g is mapped in 3d space. A highly conservative AOC design was applied to this probability map. Any cell with a greater than 10% chance of exceeding the criteria is included in the AOC. The uncertainty range for the lower side is 0.05 and the upper side is 0.4. This is an unbalanced uncertainty range selected to demonstrate the role of probability in making Type I and Type II errors. In Figure 7.4, those areas in red have a 50% or greater chance of exceeding 18 pCi/g and are definitely included in the AOC. Those areas in yellow are currently in the AOC but may be unnecessarily included due to the conservative nature of the decision. Any cell in the yellow region has between a 10% and 50% chance of exceeding the criteria. Those cells with a value of 40% will be remediated even though there is a 60% chance they are below the concentration limit. The blue areas represent locations that might be included in the AOC since their probability of exceeding is between 0.05 and 0.1. So, this region is considerably smaller, as it should be, since the 0.1 decision criteria represents a risk aversion to leaving behind any contamination in a remedial activity.

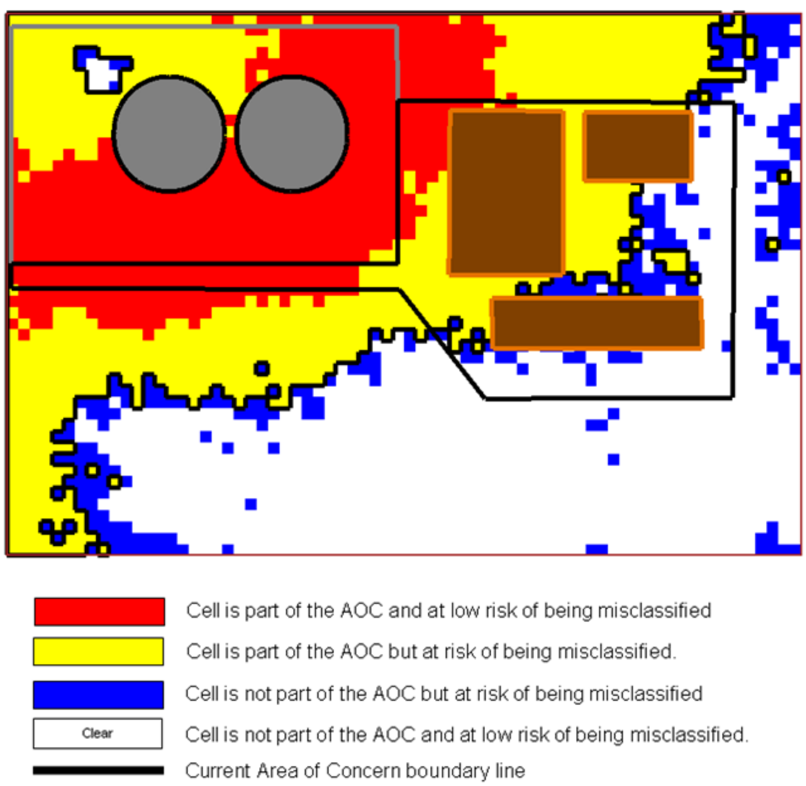


Figure 7.4 AOC map based on probability of exceeding 18 pCi/g at 0-2ft.

SADA 5 records the summary statistics for this remedial design for both cell count (Table 7.1) and volume (Table 7.2).

Table 7.1 Remedial cell counts for scoping phase results

Description	Subtotal	Total
Total Number Of Blocks Outside AOC		18296
Low Misclassification Risk	15081	
Moderate Misclassification Risk	3215	
Total Blocks Inside AOC		15304
Low Misclassification Risk	4024	
Moderate Misclassification Risk	11280	

Table 7.2 Remedial volumes for scoping phase results

Description	Subtotal	Total
Total Volume Outside AOC		14636800.00
Low Misclassification Risk	12064800.00	
Moderate Misclassification Risk	2572000.00	
Total Volume Within AOC		12243200.00
Low Misclassification Risk	3219200.00	
Moderate Misclassification Risk	9024000.00	

Large areas of uncertainty are expected at this point in the study. After only a scoping phase, the amount of data is likely insufficient to create substantial geospatial models with any certainty. The characterization phase may have several objectives, depending on the particular circumstances. Certainly, one objective could be to reduce the uncertainty associated with the location and volume of contamination. The following design places samples with this objective in mind.

7.3 Potentially Relevant Sample Designs

There are two approaches to reducing uncertainty about volume and area showcased here: the AOC boundary design and threshold radial.

AOC Boundary Design

There are two methods available for AOC boundary design. In the first method, samples are placed along the boundary line in the AOC map. In particular, those nodes that have a value closest to the decision criteria are the targets of the design. They are selected in order to more readily distinguish between contaminated and uncontaminated zones. This version is currently available in SADA 5, and the reader is encouraged to review the user's guide and the code for more information (Stewart et al. 2009).

The second method is to place samples such that the number of blocks at risk for misclassification is minimized. In this later approach, a value metric is available for determining the number of samples to take.

In Figure 7.5, eight AOC boundary design locations are identified. Keep in mind that in 3d space, boundaries exist vertically as well as horizontally. In some cases, AOC designs will place a new core where the boundary does not seem to be in dispute for a given 2d slice; however, visualization at greater depth reveals the need for additional data to refine the underside of the AOC.

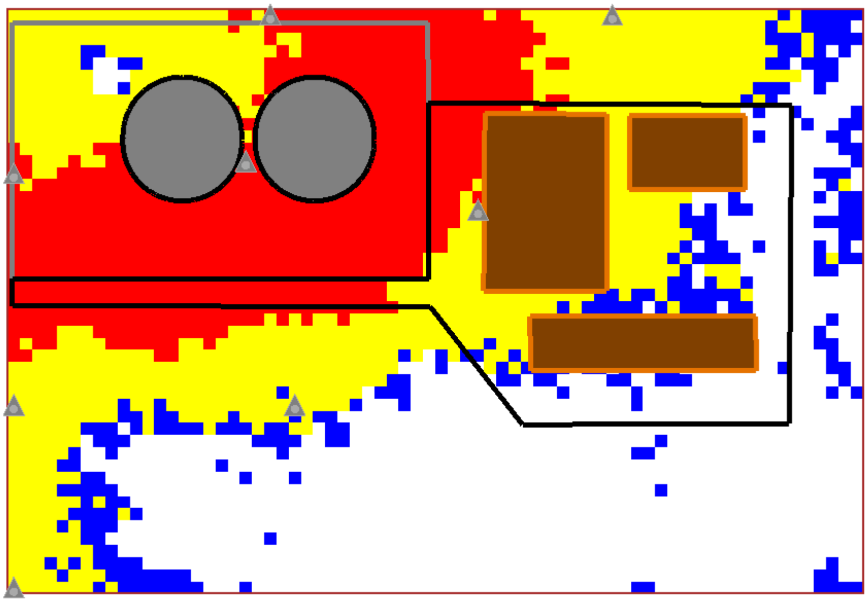


Figure 7.5 Eight AOC boundary design locations.

In this case, the first AOC boundary design was used, since the second method was not yet implemented in SADA at the time this document was written. Otherwise, a metric (such as value in reducing the misclassification volume) would be available to determine the number of samples. In this case, eight values were selected.

Threshold Radial

In some cases, there may be only a single measured value exceeding the DCGL. In this case, engaging in a full AOC boundary design may not be a prudent first step. Threshold radial is a simple tool that does not require a geospatial model. In this design, samples in excess of the DCGL are geometrically locally bounded by a set of samples. A discussion of threshold radial can be found in Stewart et al. 2009. Figure 7.6 shows a threshold radial design for the Cesium site if the DCGL was 60 pCi/g, with only one sample location exceeding this value.

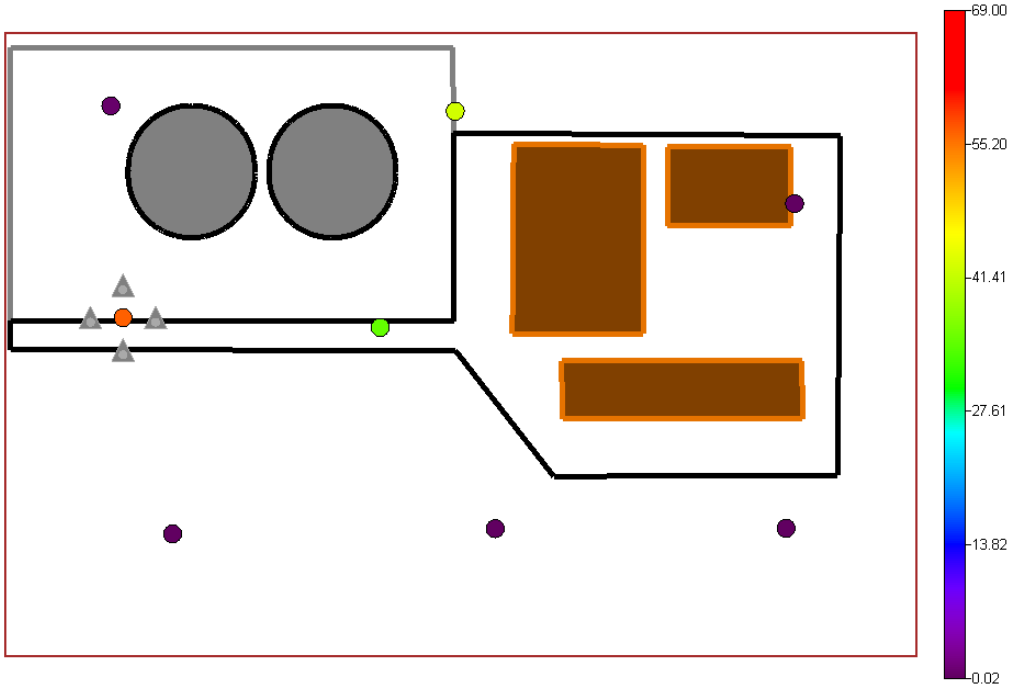


Figure 7.6 Threshold radial design for Cesium Site.

In this example, the value of 18 pCi/g will be the decision criteria, and given the large volumes required for remediation using only the scoping phase (Table 7.2), an area of concern design will be applied.

7.4 Collecting Data and Updating CCM and AOC Maps

The Area of Concern sample design was exported and the samples were acquired. The sample values are added to the existing 8 core samples and are presented in Figure 7.7.

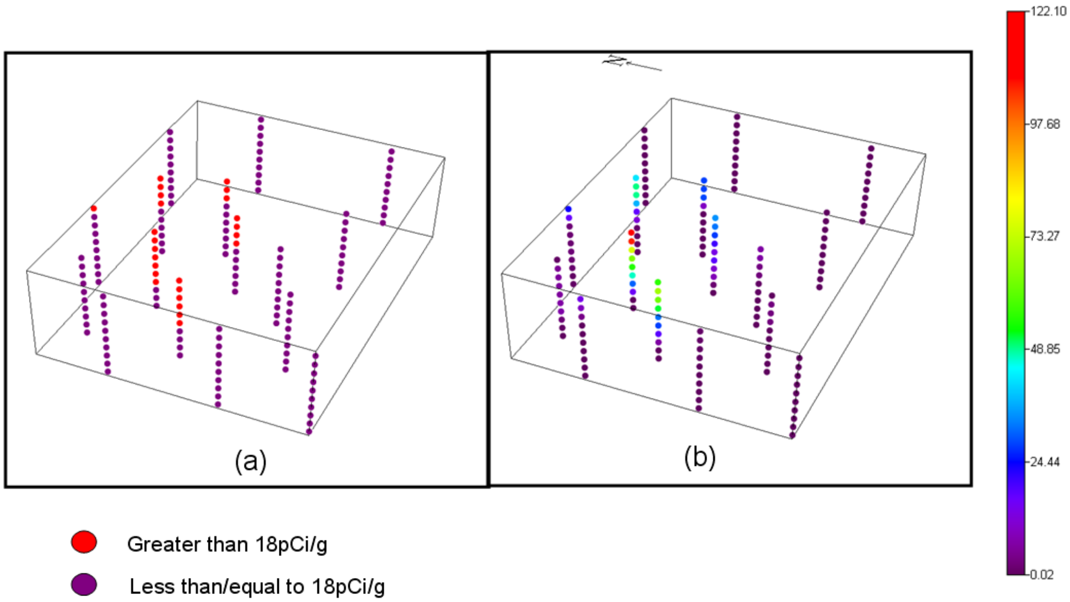


Figure 7.7 (a) Cs-137 concentrations exceeding 18pCi/g (b) Cs-137 concentrations.

It is apparent that higher concentrations of Cs-137 were encountered. After exploratory analysis (statistics, histogram, etc.), the simulations were adjusted for the new data and re-executed to update both the CCM and the AOC. In Figure 7.8 (a), the CCM probability of exceedance model at the end of the scoping phase is shown, along with the volume location associated with 18pCi/g and a 0.1 probability.

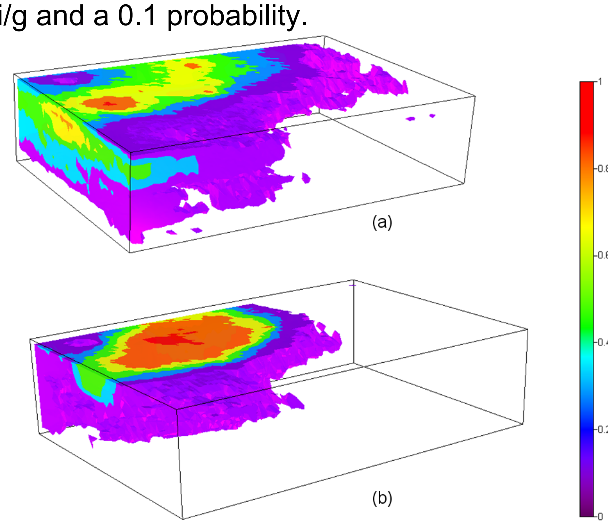


Figure 7.8 (a) Scoping phase remedial volume at 0.1 probability (b) characterization phase volume at 0.1 probability.

The reduction in AOC uncertainty is apparent but is emphasized by Tables 7.3 and 7.4.

Table 7.3 Volume outside Area of Concern

Classification Risk	Scoping	Characterization	Difference
Low	12064800	17877600	5812800
Moderate	2572000	1469600	-1102400
Total	**14636800**	**19347200**	**4710400**

Table 7.4 Volume inside Area of Concern

Classification	Scoping	Characterization	Difference
Low	3219200	3130400	-88800
Moderate	9024000	4402400	-4621600
Total	**12243200**	**7532800**	**-4710400**

The value of these 8 samples is apparent from the reduction in the volume of concern. In particular, 4.7 million cubic feet of soil was reclassified from inside the area of concern to outside the area of concern. Secondly, for both inside and outside the area of concern, the moderate risk values were significantly reduced. The reduction in area with moderate misclassification risk for both inside and outside the AOC is 5,742,000 cubic feet, or about 715,500 cubic feet per sample. One can compare the cost of removing this volume of soil to the cost of 8 additional cores.

At this rate of reduction, it may be worth considering a second characterization sampling effort at Cesium Site. This is in fact a line of reasoning encouraged in the TRIAD approach (Crumbling, 2001). Iterative sampling is not as formidable as it once was. With software that can be brought into the field by laptop and the increasing number of in-field measurement techniques, it may be possible to significantly improve characterization in near real time. For measurements expressed in units other than the DCGL (e.g., pCi/g), conversion models or multivariate geostatistical methods could be used to bring them into the CCM.

7.5 Summary

The characterization approach is extremely site-specific. This section emphasized the role of characterization with respect to the CCM and introduced a potentially relevant form of the CCM, referred to as the AOC map. Two sample design strategies were showcased to support defining the area of concern investigation. An example of how the CCM is updated using new characterization results was also provided. The characterization phase should produce a CCM (or AOC) map with a remedial volume and location estimation. This new CCM/AOC map is then updated for the remedial phase.

8 Remediation Phase

8.1 Overview

As with the characterization phase, remedial activities can vary widely and are highly site-specific. This section will again emphasize the role of data collected during the remedial phase with respect to the CCM. In some cases, as soil removal and processing occurs, in-situ measurement devices are used to test soil as it is exposed and then removed. These are valuable measurements that can be used in updating the CCM, particularly the probabilistic CCM. This section concentrates on how to update the CCM and to account for any soil remediation, removal, or replacement that may occur.

8.2 Remedial sampling

In the course of soil remediation, additional samples may be collected as soil is removed or processed. These can be laboratory samples, field samples, or secondary detection methods, such as gamma scans. This information can guide the removal process as it proceeds, but it can also update the CCM and AOC map. By updating the CCM/AOC map with new information, new light may be shed on where and how far the contaminant may extend. Extent and severity estimates may adjust significantly as the process moves forward. Using this new information in the CCM can allow investigators to preemptively adjust budgetary planning if conditions are drastically different. In extreme cases, remedial activities may need to cease and characterization resume. From this document's perspective, the new samples mean more input in the CCM. The discussion continues by showing the effect of adding rapid remedial data to the CCM during the remedial process.

8.3 Updating the Contamination concern model

One issue that may arise with the use of remedial sampling is severe clustering, particularly if an inexpensive field detection device is used. Spatial clustering can occur as well as clustering among high values. Clustering should be dealt with, particularly for geostatistical methods that attempt to reproduce both the histogram and global mean (e.g., simulation). De-clustering methods (Deutsch and Journel, 1992) weight sample values to more realistically reflect their contribution to the process. For example, samples that are very close to each other will receive less weight. Samples that are further apart receive more weight. These weighted values then are used to better construct histograms and means.

Based on the characterization phase's area of concern model, a remedial boundary was decided upon and soil removal was conducted for Cesium Site. During the soil removal process, a gamma count detector was used to estimate the cesium-137 concentrations. As soil was removed, measurements were taken at various locations. The results are seen in Figure 8.1.

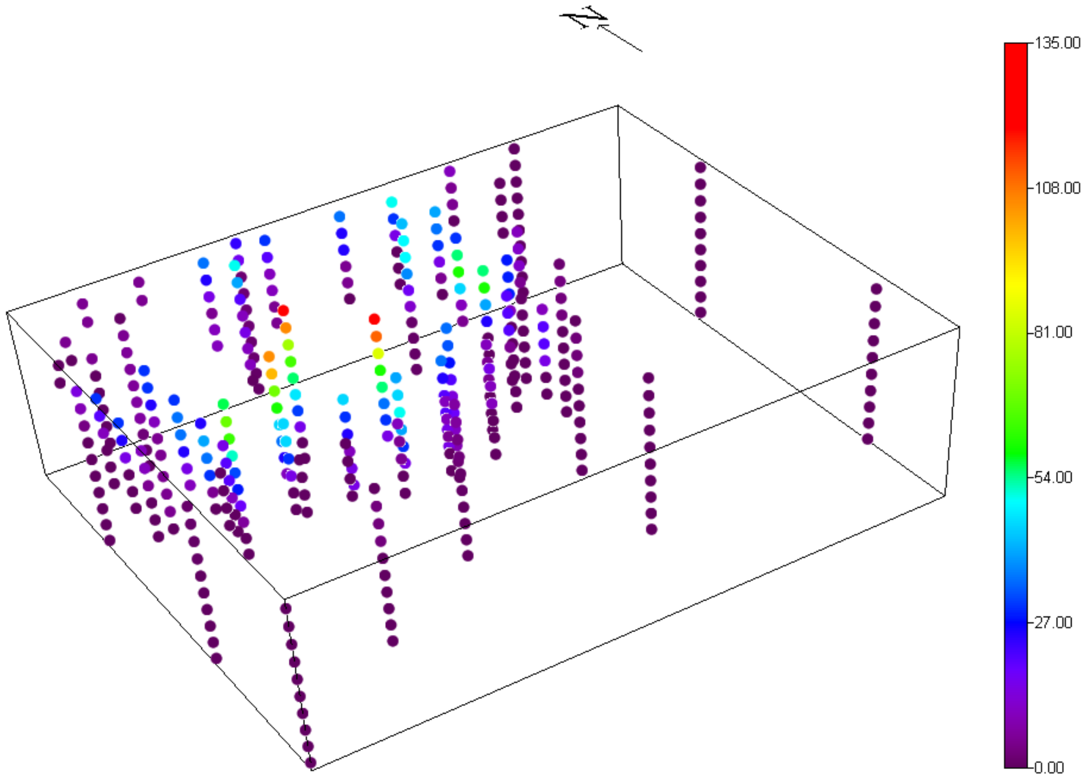


Figure 8.1 Remedial Samples for Cesium Site.

There are a number of ways one can update the CCM, and the method selected will vary with individual site circumstances. For the Cesium Site, one could estimate the concentration contours, as was done in the characterization phase. In order to demonstrate a variety of approaches, a different approach is now showcased. In this case, the DCGL of 18 pCi/g is used to convert all measurements to either 0, if at or below 18 pCi/g, or 1, if above 18 pCi/g. For the Cesium Site data, the results are seen in Figure 8.2.

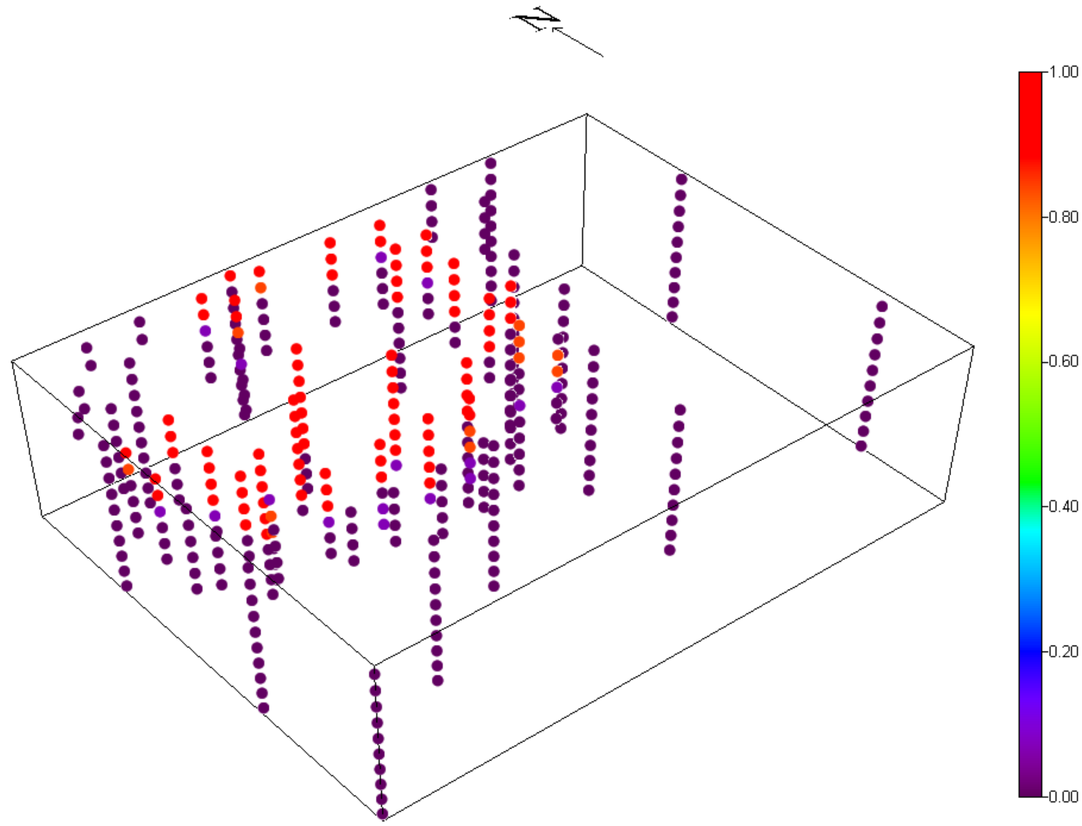


Figure 8.2 Indicator transform of Cs-137 measurements based on a DCGL of 18 pci/g.

One advantage of this approach is that it is easy to simply contour the probability values between sample locations. From a regulatory guidance approach, this may be appealing, as it can be easily supported by a variety of stochastic and deterministic models while still retaining the uncertainty in the assessment. A disadvantage of this approach is that severity is lost. For example, if sample A is 18.1 pCi/g and sample B is 180 pC/g both receive a value of 1. Likewise, if sample A is 17.9 pCi/g and sample B is 1 pCi/g, both receive a value of 0. For this reason, the potential severity of the infraction is lost in the analysis. This is a form of information loss, but at the same time it can create a more tractable formulation by suppressing the influence of outliers on the spatial model.

In Figure 8.3, the indicator values are modeled using a simple Inverse Distance Weighting (IDW) method. More sophisticated models could have been used either on the concentration values or on the transformed values. IDW was used to emphasize a potentially tractable approach that could be accessible by a wide range of users.

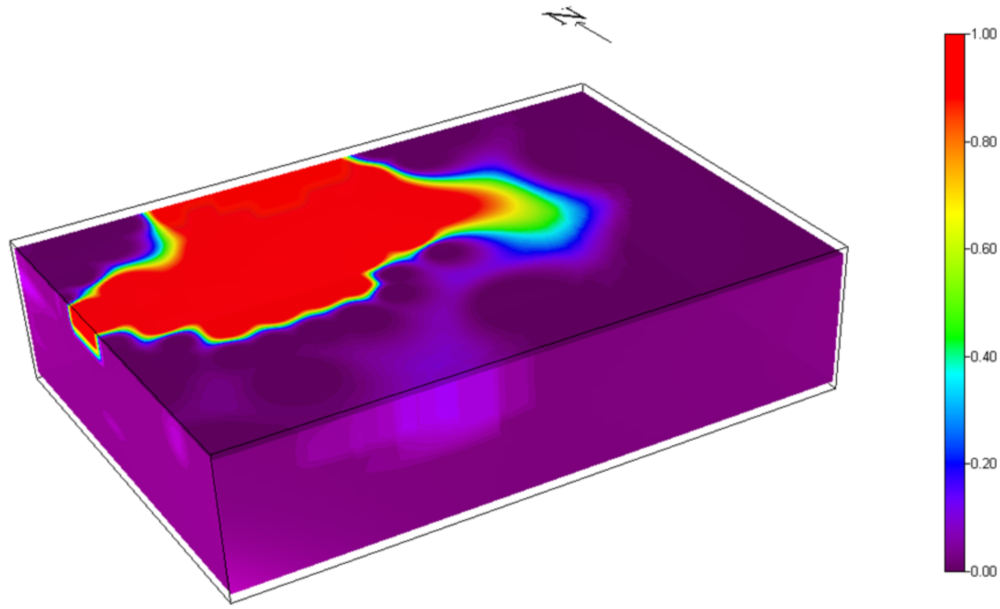


Figure 8.3 Spatial model of indicator transformed data produces a probability of exceeding 18 pCi/g map.

Most of the red area was removed during remediation. If the originally contaminated area is replaced by a non-contaminated backfill, the area potentially remaining above 18 pCi/g is seen in Figure 8.4.

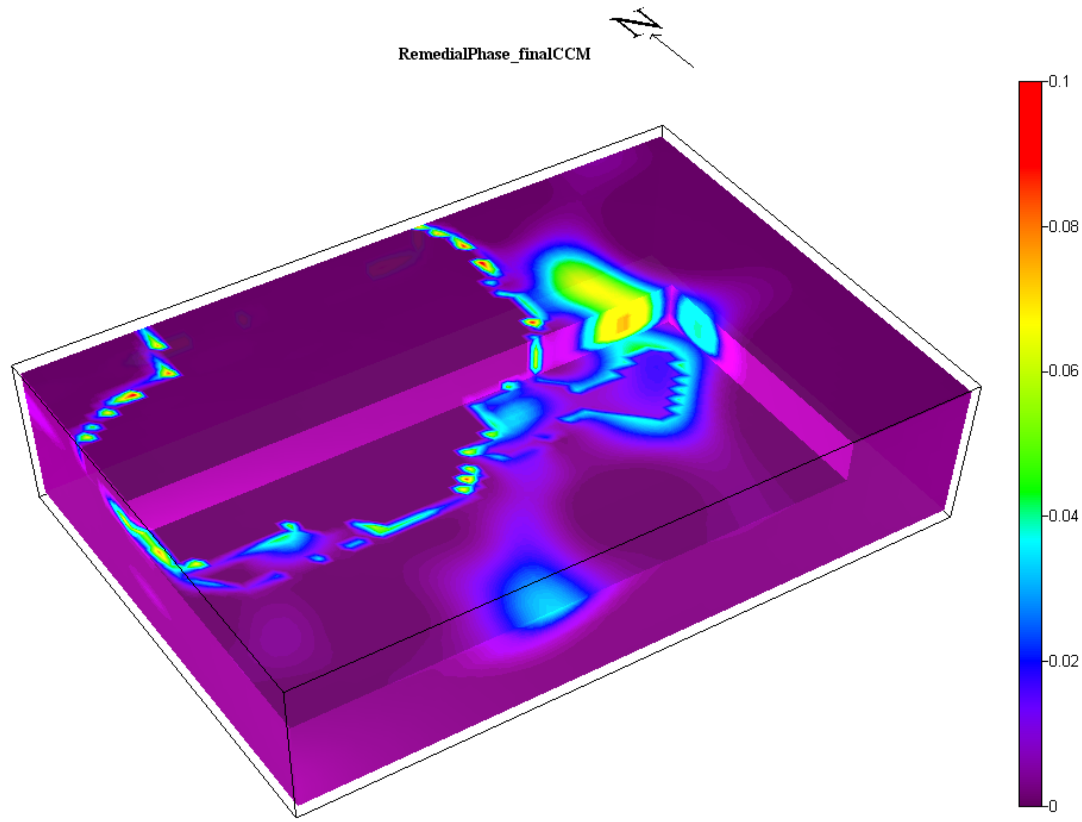


Figure 8.4 Post remedial probability of exceeding 18 pCi/g. No values above 10% remain.

Obviously, the project may require further characterization, but when the stakeholders agree that the contamination has been resolved, this will be the point where the compliance phase is entered. During the compliance phase, more samples will be collected that may or may not demonstrate compliance for the Cesium Site. The compliance phase is entered with all the available information collected for Cesium site as evidence of compliance. Additional independent samples will be collected to substantiate this evidence.

9 Compliance Support Phase

9.1 Overview

In this chapter, we demonstrate how the CCM may be used to support decision making regarding site release. Using models in this manner relies on assumptions that the model is adequately capturing the process or spatial state of the contaminant event. Unfortunately, there are limited formal methods for proving or disproving this statement. Methods, such as cross validation or other model fit methods, could be used to provide some measure of model relevance. In the absence of complete data coverage though, there cannot be complete certainty as to the success of the evaluation.

The model should be evaluated in terms of its input, its relevance to the current site, and the quality of the model output. This will vary from site to site, and special circumstances are likely to prevail. This is where the expertise of the multi-disciplinary team and the regulator must come to bear. It is the intent of this framework that the CCM arise from efforts described in previous phases; however, if no data has been collected, that data could be collected here as well.

This chapter shows how the CCM can be used to support a regulatory evaluation of the site. The chapter begins by discussing sample size, location, and the role of heuristic approaches for determining each in a spatial context. Some discussion is given to the use of cheaper but adequate sampling strategies. Finally, the proposed frameworks are provided. These frameworks serve as a broad foundation upon which to continue the discussion and permit flexibility to include a wide array of site circumstances, model choices, and contaminant types.

9.2 Elements of the Decision

There are three elements of the compliance decision under this framework. The first element is the agreement that the CCM is a reasonable representation of site contamination given the information, data, modeling, and expertise available. This type of evaluation is part of any environmental assessment, and there is no divergence from that fact here. The second element is the data values themselves. The third element is the data informed CCM (modeled values). In this framework, all three elements are evaluated.

9.3 Decision Scale

The first consideration for the compliance phase regards the geographical scale of compliance. In particular, one could impose a compliance evaluation at a local scale, area scale, or global scale. Decision scale is also a theme in MARSSIM, which provides a check of site wide average (global), composite activity scans between samples (area), and a data screening (local). In this decision framework, the focus is on the CCM, a data and expertise informed 3d model, rather than strictly on data results. The approaches are therefore potentially different at each scale.

A local scale means specifically that each cell or cube of the 3d CCM model will be compared to the decision criteria, and it either passes or fails. The area scale applies a compliance standard to a contiguous cellular region of the volume. Specifically, a group of cell or data values must collectively pass a compliance check. A simple example would state

that the average of a group of cell values must be less than the DCGL. The global scale imposes restrictions on the sum behavior of data and/or cell values across the site. For example, the global average activity level cannot exceed the DCGL, or the total volume of activity levels exceeding the DCGL cannot exceed a volume limit. Table 9.1 shows some examples of scale applied to data.

Table 9.1 Example Scale Compliance Requirements for Data

Scale	**Decision limit applied to**	**Comment**
Local	Data value	Simple Screen
Area	Area Data Average (de-clustered)	Average or Confidence Limit
Global	Global data average (de-clustered)	Average or Confidence Limit

Table 9.2 shows some example decision scales and the type of model required. In this table, deterministic means any method that yields a single estimate for a single set of parameters (e.g., spline). A stochastic method means any method that yields a distribution of possible values for a single set of parameters (e.g., geostatistics).

Table 9.2 Example Scale Compliance Requirements for CCM

Scale	**Decision limit applied to**	**Minimum Model Required**
Local	Cell value	Deterministic
	Cell percentile	Stochastic
	Cell probability	Stochastic
Area	Model average	Deterministic
	Percentage of volume exceedances	Deterministic
	Probability of volume exceedances	Stochastic
Global	Global model average	Deterministic
	Total contaminated volume/mass	Deterministic
	Total exceedance volume/mass	Deterministic
	Joint probability volumes	Stochastic

A comprehensive evaluation might include each of these scales. While parameter choices can affect the analysis, generally speaking, the strictness of the test decreases as the scale moves from local to area to global scales. For example, suppose that a single decision criterion is selected (20 pCi/g). It is possible that the global average will pass the criteria while local values may exceed it.

9.4 Proposed Decision Frameworks

The following frameworks are suggested for consideration. These proposals apply decision criteria at different scales and, when plausible, adhere to a MARSSIM approach regarding scale. In addition, some comment is suggested on the type of modeling that would be required to support the work. When possible, demonstrations for Cesium Site using SADA are provided.

Local Proposals (L)

These assessment proposals are likely the most conservative. In these proposals, both data values and representative local cell values are evaluated against a decision criterion.

These may be too conservative but are presented as a foundation for the multi-scale proposals that follow.

Proposal L1

There are only two steps in determining compliance. If either step fails, the site fails.

- Step 1: Each data point falls below DCGL.
- Step 2: Each cell value, $cell_{model}$ is less than $DCGL_{model}$.

DCGL refers to (for example) criteria developed to be protective of potential receptors directly exposed through subsurface disturbance or by interaction with groundwater. In the case of groundwater, the DCGL would be selected as the vadose zone limit that is protective of the anticipated groundwater scenario. Compliance is conservative, since exposure and contributions to groundwater depend on area or volume contributions rather than point (cell) values.

Here, $cell_{model}$ simply refers to the estimated activity level for the cell and the $DCGL_{model}$ represents a criterion for $cell_{model}$ values. This may be exactly equal to the DCGL or one may use a lower value to conservatively account for uncertainty in site processes. For example, if the DCGL were 18pCi/g, the $DCGL_{model}$ might be selected as half that (9pCi/g) in order to install an added degree of conservatism.

Strictly using geospatial modeling, such as inverse distance or geostatistical models, it is difficult at first to envision a scenario where Step 1 would be met yet Step 2 would fail. It may be possible that the responsible party has a CCM map where prior to remedial action data values exceeded the DCGL; however, due to remediation activities those data locations modeled above the DCGL were removed but volumes were left behind where the modeled values exceed the $DCGL_{model}$. In this proposal, the site should fail compliance under this guideline.

Only deterministic models are required for this approach. Examples from the geospatial model toolbox include: natural neighbor, inverse distance, spline, and minimum tension gridding. Stochastic models, such as kriging and simulation, can also be used, but stochastic properties are not utilized. Depending on the site circumstances, other models outside of simple estimation approaches may be required.

Cesium Site L1 Example

A demonstration of how this model might be applied follows using the Cesium Site as it stood at the end of the characterization phase (before remediation). The DCGL is computed as 30pCi/g.

- Step 1: Each data point falls below DCGL.

A simple GIS/3D plot of the data reveals that this criterion has failed at numerous locations in Figure 9.1.

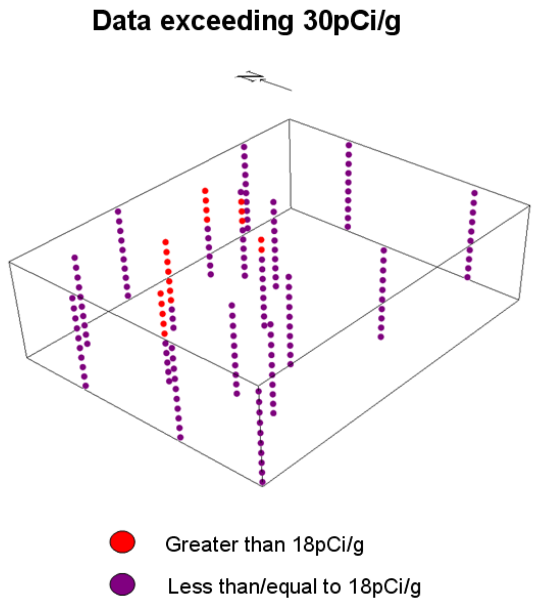


Figure 9.1 Data exceeding 30 pCi/g.

- Step 2: Each cell value, $cell_{model}$ is less than $DCGL_{model}$.

For this example, we assign $DCGL_{model}$ = 30 pCi/g as well. The CCM at the end of the characterization phase was modeled with ordinary kriging and indicated a large number of exceedances of the $DCGL_{model}$ value. Figure 9.2 shows the CCM values that exceed 30 pCi/g. Therefore, this site fails under Proposal L1.

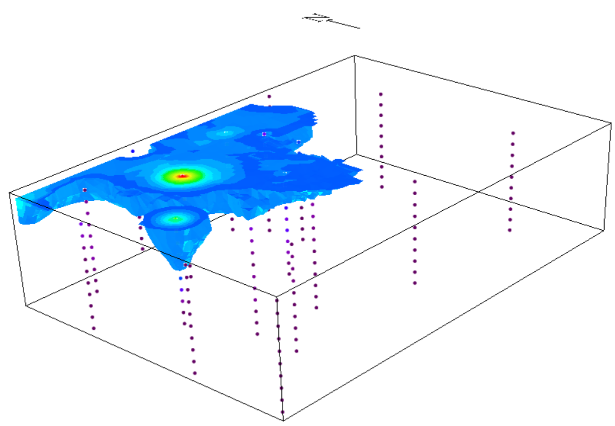


Figure 9.2 CCM values exceeding 30 pCi/g.

Proposal L2

This is potentially even stricter than Proposal L1. Uncertainty is conservatively accounted for through the use of a probability model in the CCM evaluation. There are only two steps in determining this compliance. If either step fails, the site fails.

- Step 1: Each data point falls below DCGL.
- Step 2: Each cell value, $cell_{\varphi}$, is less than DCGL.

Here, DCGL is the same as in Proposal L1. Instead of a single estimate at each cell, this proposal requires a distribution of possible values at each cell. Stochastic geospatial models, such as geostatistics, can provide these distributions. Other methods may be possible as well. In this proposal, $cell_{\varphi}$ refers to the φ percentile (0-1) of the cell distribution. For large values of φ, this produces a measure of how high the cell value could reasonably be for each cell value. Hence, by choosing a large percentile, a degree of conservatism is added by requiring this potentially higher cell value to also pass the DCGL comparison. Unfortunately, if the value for φ is too high (e.g. φ =0.9), then the site will likely fail the test. The use of proposal L2 with high values for φ may be too high a bar for most sites to pass.

Since the proposal is based on cell distributions, it is quite possible for Step 1 to pass and Step 2 to fail for large φ. It may also be possible that the responsible party has a CCM map where prior to remedial action data values exceeded the DCGL; however, due to remediation activities those data locations modeled above the DCGL were removed but volumes were left behind where the modeled values exceed the $DCGL_{model}$. In this proposal, the site should fail compliance under this guideline.

Stochastic modeling is required for this proposal. There are a variety of models that can lead to a local distribution through Monte Carlo simulations. From the geospatial toolbox, a number of methods are available that provide direct estimation of local distributions. These include kriging and simulation.

Cesium Site L2 Example

A demonstration of how this model might be applied follows using the Cesium Site as it stood at the end of the characterization phase (before remediation). The DCGL is computed as 30pCi/g.

- Step 1: Each data point falls below DCGL.

A simple GIS/3d plot of the data reveals that this criterion failed at numerous locations in Figure 9.3.

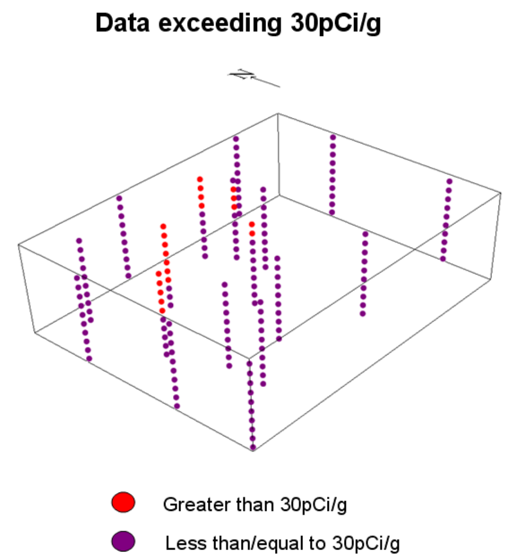


Figure 9.3 Data exceeding 30 pCi/g.

- Step 2: Each cell value, $cell_{\varphi}$, is less than DCGL.

For this example, we assign $DCGL_{model}$ = 30 pCi/g and set φ= 0.75 (75^{th} percentile). The CCM at the end of the characterization phase was created using ordinary kriging and the 75^{th} percentiles were used as the final map result (Figure 9.4). With this more conservative estimate of cell values, $cell_{\varphi}$, a larger region is found out of compliance than in L1. This site fails under Proposal L2.

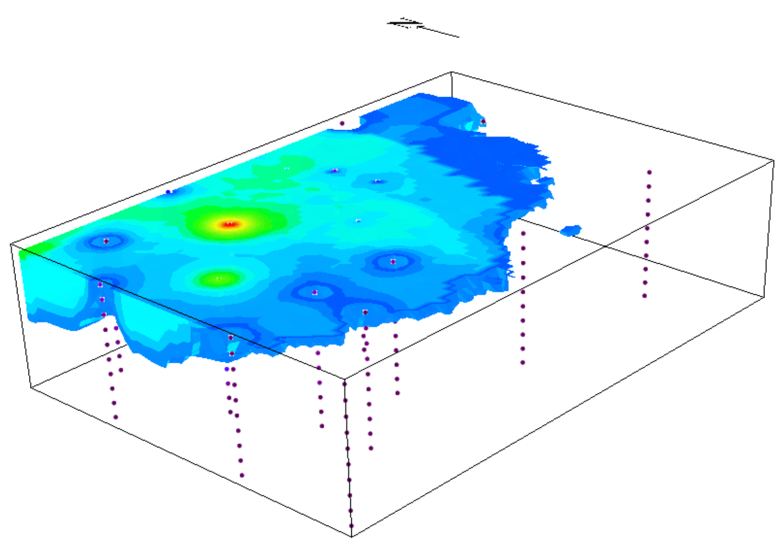


Figure 9.4 CCM values exceeding 30pCi/g.

Proposal L3

This is a variation on Proposal L2 and also requires stochastic capabilities. Evaluations are done again at the local scale, and uncertainty is conservatively accounted for through the use of a probability model. Rather than the distribution percentile, the local probability of

exceeding the DCGL, $cell_\rho$, is used. If $cell_\rho$ is greater than the decision criteria for local probability, ρ, then the cell fails. There are only two steps in determining this compliance. If either step fails, the site fails.

- Step 1: Each data point falls below DCGL.
- Step 2: Each cell value, $cell_\rho$, is less than ρ.

$Cell_\rho$, is the probability of exceeding the DCGL and ρ is the probability limit.

Cesium Site L3 Example

This example returns to the CCM at the end of the remedial phase and applies a DCGL of 18pCi/g. Furthermore, the probability of each cell exceeding this limit should be less than 10%.

- Step 1: Each data point falls below DCGL (18 pCi/g).

Figure 9.5 demonstrates that many of the samples (mostly remedial samples) were in excess of the DCGL. These are highlighted with square screening boxes. Note, however, that all of these data fall within the AOC boundary line (thick irregular black line) and were removed during the process. Therefore, the remaining samples are all below the DCGL and the site passes this step.

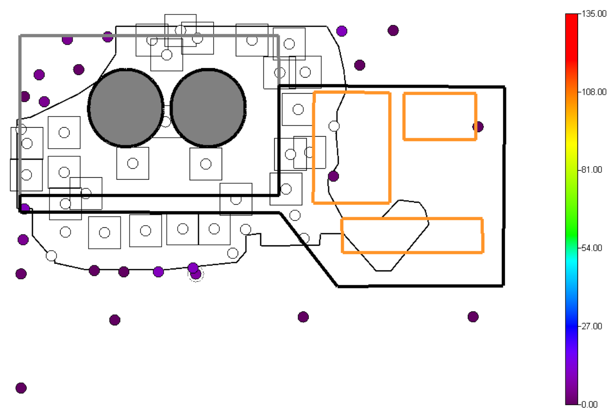


Figure 9.5 Sample values exceeding 18 pCi/g

- Step 2: Each cell value, $cell_\rho$, is less than ρ(0.1).

The CCM was created by first converting the raw data values to a probability of exceeding the DCGL. Normally, this is simply an indicator transform to 0s and 1s, but when cheaper secondary forms of data are used, this may not be the case. Instead, some data may be converted to some probability value between 0 and 1, depending on the technology sensitivity with respect to the DCGL.

Recall that at the end of the remedial phase, soil was removed or remediated, including a number of data locations that were formally exceeding the DCGL. At that time, the decision was made to remove any cell with a 10% or higher chance of exceeding the DCGL. This paid off well, since the probability limit here is set to 10%. Figure 9.6 demonstrates that after remediation no cell has a greater than 10% chance of exceeding 18 pCi/g according to the model. In this case, Cesium Site passes the decision rules.

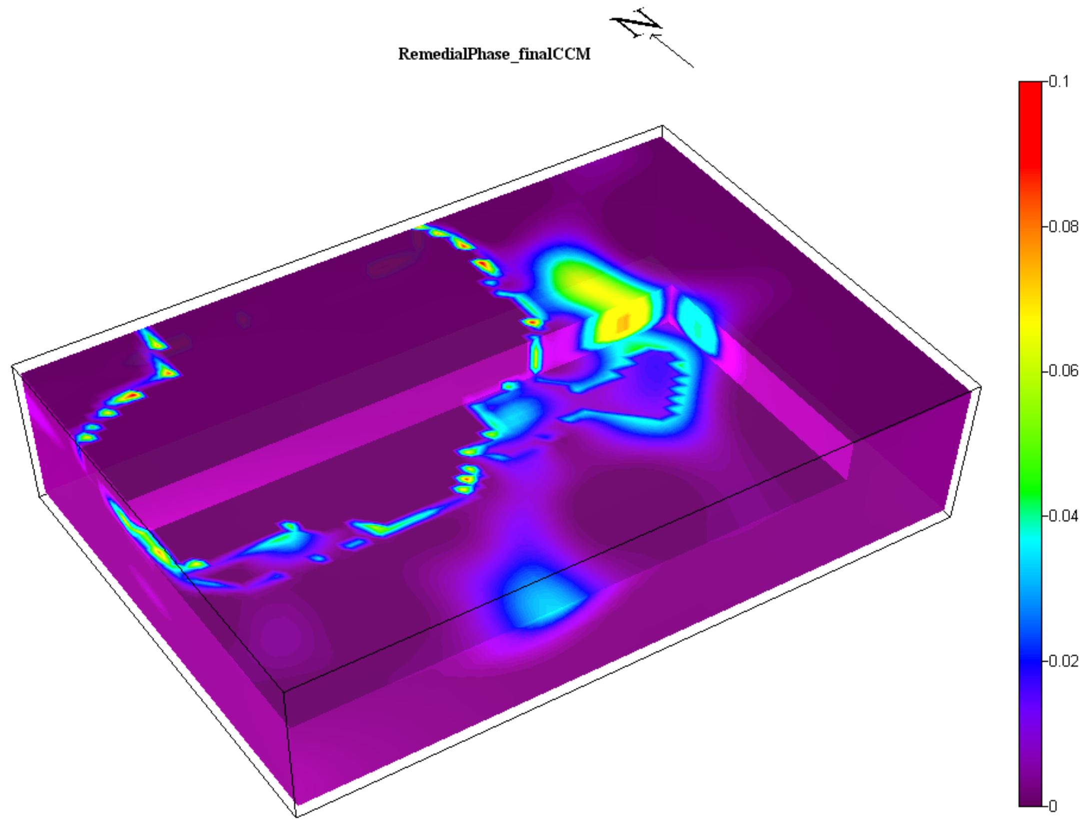


Figure 9.6 No volume with probability of exceeding 18pCi/g is greater than 10%.

Local-Area Proposals (LA)

In these proposals, the compliance check is relaxed by introducing area scale decision criteria for the CCM as continuances of Step 1 and Step 2 in the previous proposals. A few suggestions based on exposure and potential groundwater applications are presented here. These Local-Area proposals may fit well with frameworks where exposure to the subsurface through disturbance (excavation) is of concern.

Proposal LA1

- Step 1: Each data point falls below DCGL.
- Step 2: Each cell value (choose from $cell_{model}$, $cell_{\varphi}$, or $cell_{\rho}$) passes
- Step 3: If Step 1 and Step 2 pass, the site passes. Otherwise continue to Step 4.
- Step 4: No portion of the site with volume V_{limit} has an average greater than $DCGL_{ave}$

Here, V_{limit} is the largest volume permitted that can demonstrate an activity limit of $DCGL_{ave}$.

From a radiological/exposure perspective, $DCGL_{ave}$ may be a function of V_{limit} and therefore, some negotiations regarding choices for each may be required. This is outside the scope of this work. If Steps 1 and 2 pass, step 4 is unnecessary. If Step 4 passes, the site

passes. The cell choice for step 2 will dictate whether a deterministic or stochastic model will be required. Step 4 can be supported by either.

Cesium Site LA1 Example

Again, this example uses the status of the site at the end of characterization phase with a DCGL of 50pCi/g.

- Step 1 and Step 2 were handled exactly as in L3 and will not be repeated here. Refer to Figure 9.5 and 9.6 for the results of Steps 1 and 2 under this framework.
- Step 3: Cesium site fails step 1 and step 2. Move to step 4.
- Step 4: No portion of the site with volume V_{limit} has an average greater than $DCGL_{ave}$.

For this analysis, the DCGL is set equal to 50 pCi/g. There are a number of ways a CCM could support this step. The simplest way is to provide a moving 3d window average of cell values where the volume of the window is set to V_{limit}. Figure 9.7 shows the centroids of those volumes where the average volume exceeds 50 pCi/g. At the center of each volume, the average value is mapped. Again, Cesium Site fails this compliance framework.

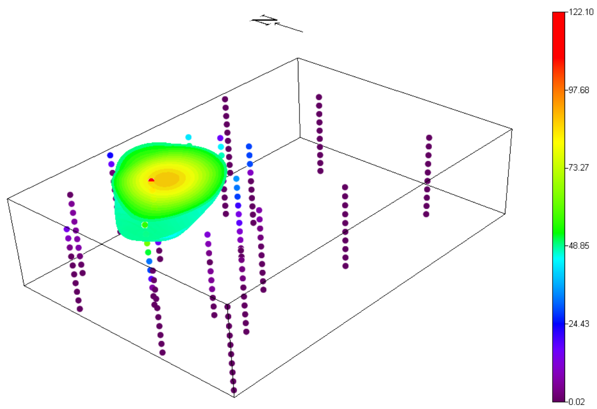


Figure 9.7 Center of volumes where the volume activity exceeds 50Ci/g.

Proposal LA2

- Step 1: Each data point falls below DCGL.
- Step 2: Each cell value (choose from $cell_{model}$, $cell_{\varphi}$, or $cell_{\rho}$) passes.
- Step 3: If Step 1 and Step 2 pass, the site passes. Otherwise continue to Step 4.
- Step 4: The probability that a volume greater than V_{limit} has an average greater than $DCGL_{ave}$ is less than ρ.

Here V_{limit} and $DCGL_{ave}$.have the same meaning as in LA1. The difference is that instead of using only the estimated cell values ($cell_{model}$) to determine volume averages, the joint distribution of volume averages in each region of the site is used. So, for each volume center, the probability that the volume exists with average concentration greater than $DCGL_{ave}$ can be computed.

Stochastic modeling is required for this proposal. In particular, geostatistical methods such as sequential Gaussian, indicator, and Markov-Bayes simulation (Goovaerts, 1997) directly support the analysis in step 4.

Local-Global Proposals (LG)

This set of proposals is suggested with groundwater applications in mind. In this case, the DCGL is some vadose zone limit that is protective of groundwater. Additionally, mass and volume can play an important role in the process.

Proposal LG1

- Step 1: Each data point falls below DCGL.
- Step 2: Each cell value (choose from $cell_{model}$, $cell_{\varphi}$, or $cell_{\rho}$) passes.
- Step 3: If Step 1 and Step 2 pass, the site passes. Otherwise continue to Step 4.
- Step 4: The global average is less than $DCGL_{ave}$.

This is a straightforward decision framework, particularly for step 4. There are two methods for determining a global average. The first method is to use a weighted average of the data values. If clustering has occurred, then a de-clustering algorithm (e.g., Deutsch and Journel, 1992) may be required to properly balance the calculation. Another method is to create a CCM of concentration values and compute model average. This can account for clustering in many cases and provides a spatial relevance to the average statistic. Some caution is exercised in computing global averages for CCM model values though. Be aware that some geostatistical models assume such an average and estimate it based on the data. The modeling environment (deterministic, stochastic) will depend on the choice for step 2.

Proposal LG2

- Step 1: Each data point fall below DCGL.
- Step 2: Each cell value (choose from $cell_{model}$, $cell_{\varphi}$, or $cell_{\rho}$) passes.
- Step 3: If Step 1 and Step 2 pass, the site passes. Otherwise continue to Step 4.
- Step 4: The total contaminated volume (or total contaminant mass) is less than some limit V_{cont} (or M_{cont}).

This framework may be more relevant to groundwater, because of its emphasis on volume and mass. Here, V_{cont} is the maximum permitted contaminated volume and M_{cont} is the maximum contaminant mass. The modeling environment (deterministic, stochastic) will depend on the choice for step 2.

Cesium Site LG2 Example

The Compliance Phase version of the CCM is used to demonstrate this proposal. Steps 1-3 are conducted exactly as in previous proposals and will not be repeated here. Step 4 is trivially calculated from the concentration-based CCM in that phase. Figure 9.8 shows the relationship between the DCGL (X axis) and the volume or mass (density = 0.25 in this case). For any given DCGL, one can directly read the corresponding volume or mass from this type of result. SADA version 5 provides a cost benefit analysis feature that can generate these types of curves automatically.

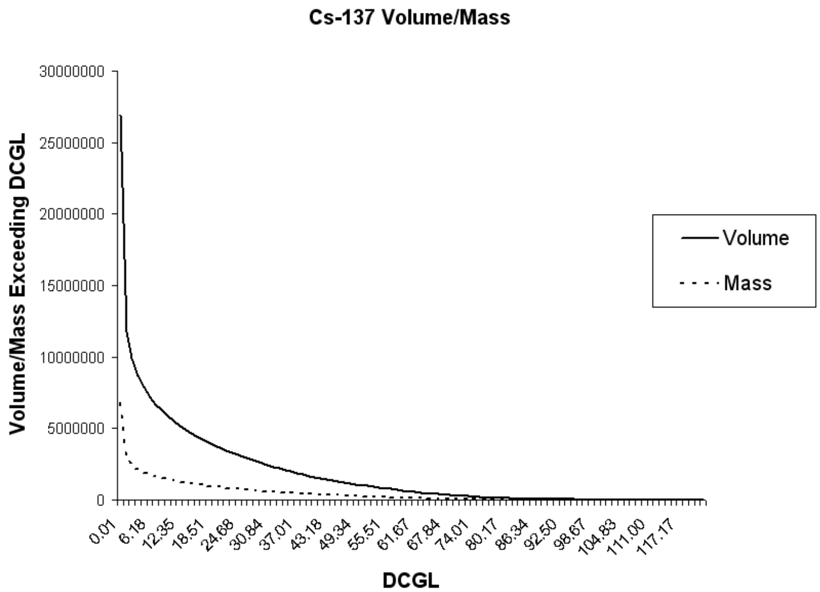


Figure 9.8 Volume/Mass vs. DCGL

Given the options in Table 9.1 and Table 9.2, it becomes apparent that a number of possible combinations can be derived. This section focused on those that bear some relevance to exposure and groundwater scenarios. These are intended to stimulate debate and further development in similar decision frameworks.

9.5 Data Sufficiency

For each of these proposals, the issue is the sufficiency of the data collection. As discussed in each of the previous chapters, determining the number of samples is problematic due to the complexity of the subsurface and the presence of autocorrelation among many measured values. Simply computing the number of samples based on some simple statistical test no longer makes sense. The general approach throughout this framework is to select the number of samples based on a metric. A metric is simply a “return on value” measure that changes (usually becomes less) as the sample size increases *a priori*. From a compliance viewpoint under this framework, evaluation of the site necessarily comes with an evaluation of the CCM (and CSM). Evaluation of the CCM may require a multi-faceted regulatory team to fully understand the full complexity of the site and to professionally evaluate the principle party’s claims regarding absence or presence of contamination. There are two ways to think about collecting samples in this phase.

Trust

In this situation, the responsible party has kept very good records regarding the decision made on collecting the number of samples. Preferably, within this framework’s context, a demonstration of the metric behavior and decision point would be provided for each sampling effort. Given an acceptable number of samples in this context and well formed, highly qualified CCM, the compliance evaluation could accept the CCM and apply the decision rules without further sampling. This is the most liberal approach and may not garner much public support.

Trust but Verify

This famous line from the cold war era may apply here very well. If independent, professional evaluations from all relevant lines of expertise have concluded that the CCM is representative of site conditions, then the site regulator should consider taking additional independent samples to confirm. The level of "trust" here may be on a gradual scale regarding the number and location of samples. For a low trust level, little regard may be given the CCM. For a high trust level, high reliance may be given to the CCM in locating and valuing the samples.

Sampling Approach

If the "trust" approach is used, then no more samples are taken. If the "Trust but Verify" approach is used, then some samples will obviously be collected. The check and cover method presented first in the scoping phase is nicely aligned with the spirit of trust but verify and permits a measure of map reliance that is well correlated with the idea of professional trust. The details of check and cover will not be reproduced again here (see section 6.2 for details); however, the main ideas will be presented again.

Check and Cover can certainly be used during any phase of this process to preferentially located samples. Certainly, the first time it was presented in this framework was during the scoping phase. During the scoping phase, an initial CCM was developed that was likely highly qualitative with very little detail. As the framework moved forward, the CCM became more quantitative with higher spatial detail. From a compliance viewpoint, one could return to that initial use of check and cover, which is captured in the sample design's name. In this phase, though, check and cover could be applied to a highly detailed CCM as a final check for those that might still be of some concern.

There are two ways to apply check and cover to the CCM. In the first approach, the CCM model is used along with data locations previously collected by the responsible party. With these data locations marked in the CCM, check and cover will acknowledge them and adjust accordingly. In the second approach, only the CCM model is used. This provides check and cover with full access to any part of the CCM. This latter choice might be a more generalized use for the compliance phase. First, the data points themselves should have already added their content to the CCM. Hence, they are already represented in the CCM and influencing check and cover in this phase. Second, the use of historical data can be tedious, since some areas may be have been remediated already and the previous sample locations no longer exist (i.e., removed by the remedial process). Finally, if the data are not used, check and cover can theoretically place samples anywhere it chooses. This type of control is appealing in a final check scenario.

Regardless of the choice for using or not using historical data, the map reliance factor can be used to determine the role of the CCM. Certainly, if the regulator wishes to not rely on the CCM at all for lack of trust, it is likely the evaluation suffers from greater problems than just locating new samples in a final check. If there is little or no trust in the CCM, then parties should revisit the problem from the start again. The idea here is that the CCM is the best representation of site processes. The only reason to apply some reduced reliance on it would be to introduce an additional level of conservativeness.

The lower the map reliance, the more check and cover resembles a grid. The higher the map reliance, the greater is the use of the CCM content and the potential for greater

preferential sampling. That is, samples are used to “check” known problem areas and to provide some “cover” to the remaining site. This behavior is seen in Figure 9.9, where the adjusted CCM represents numerically the reduced reliance on the map.

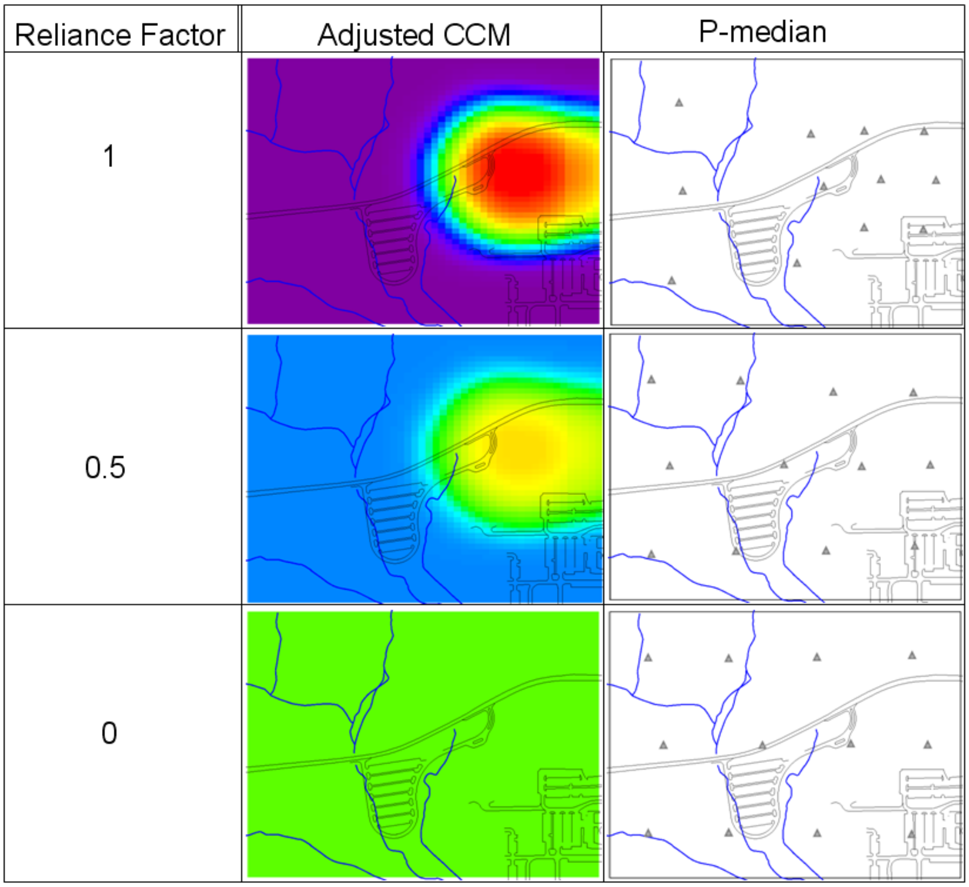


Figure 9.9 Map reliance permits compliance teams to introduce additional degree of independence in the final survey.

Sample Size (Number of Samples)

As discussed in the scoping phase, some sample designs, such as check and cover, can provide a *metric based* determination of the number of samples. Designs that place new samples based on minimizing or maximizing some value can report the progress as each new sample is produced. In the case of check and cover, the goal is to minimize the maximum sum of value-weighted distances. In Figure 9.10, the addition of each new sample produces a smaller minimization. Eventually, the curve will flatten out, indicating a smaller return on investment for each additional sample.

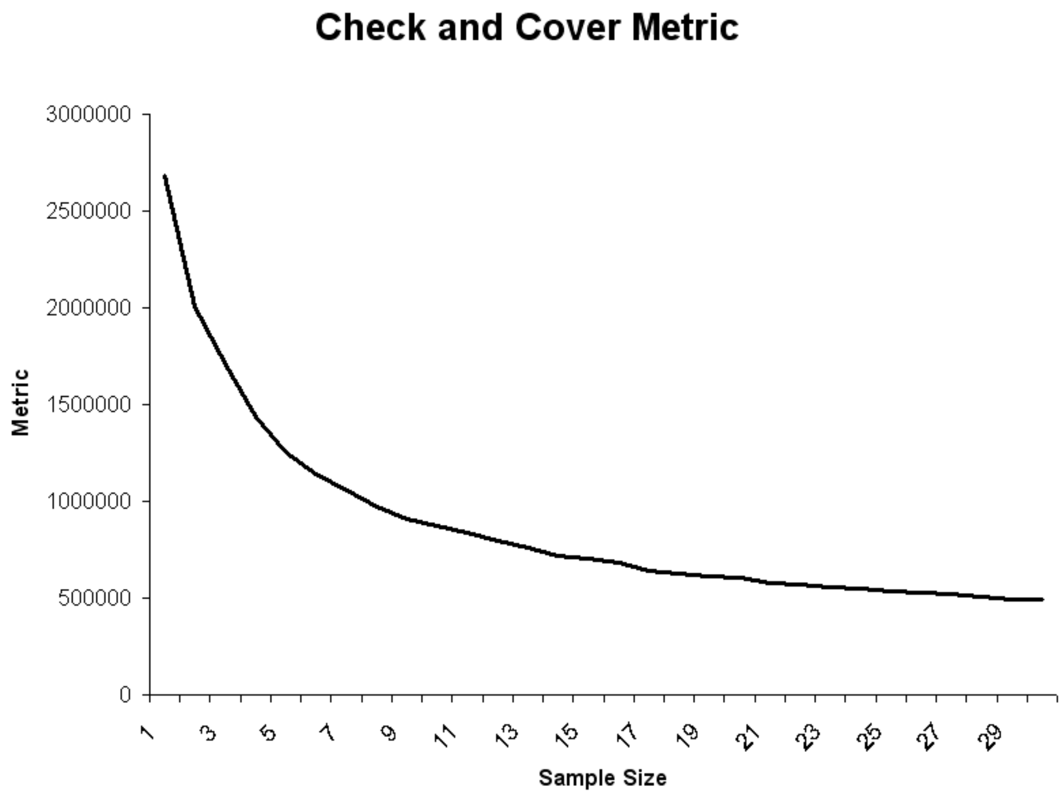


Figure 9.10 Sample design metrics can indicate when each additional sample is providing little additional information.

As the curve flattens out, the value of each sample in discovering an elevated zone is diminishing. From a compliance support view, the number of samples could be selected based on this shape while considering the cost of each new sample. The cost of each sample can be offset through the use of field detection and secondary measurement values. This approach provides a connection between the goal of sound science and the reality of financial limitations.

Cesium Site Example

As an example, the Cesium site CCM from the end of the remedial phase will be used (Figure 9.11). In this example, the site has been remediated, and the local probability of exceeding 18 pCi/g is less than 10% everywhere. Because of this, there is relatively little change in the distribution of sample demand across the site. This is actually ideal, because it means that investigators believe that contamination or the likelihood of contamination has been mitigated. As a result, one should expect to see a grid like result in the final outcome (not necessarily true in all cases).

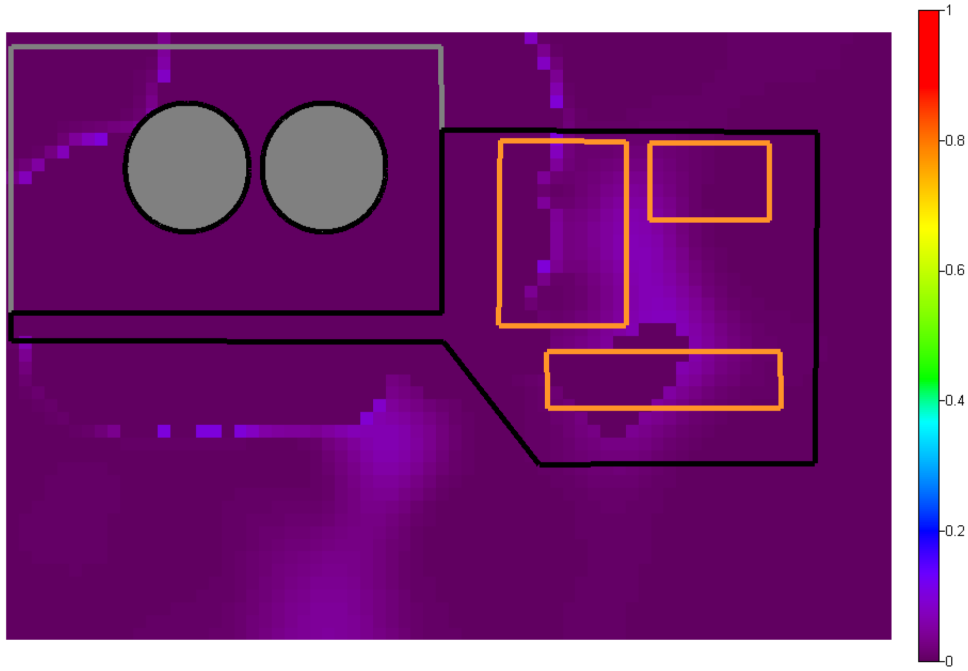


Figure 9.11 CCM for Cesium Site following remediation.

Using the sample size/metric feature in SADA to demonstrate, the metric (minimum sum of demand weighted distances) was evaluated for up to 20 core holes in Figure 9.12.

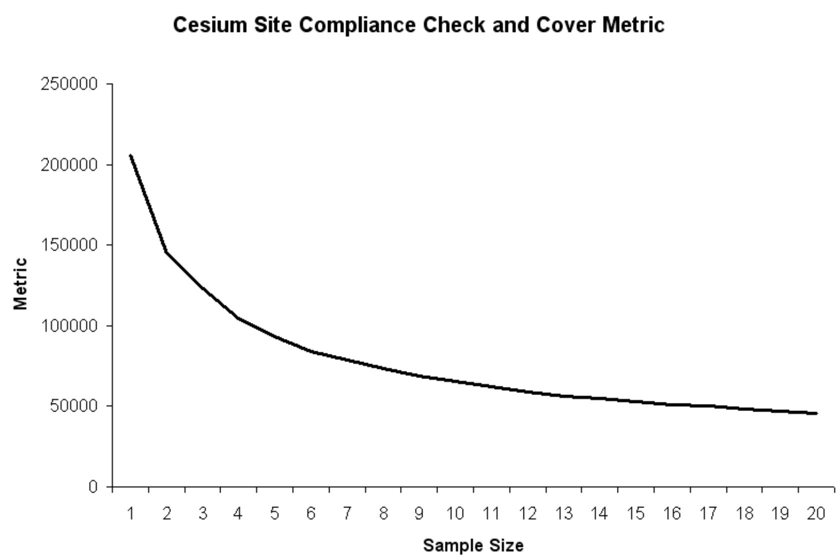


Figure 9.12 Sampling metric versus sample size (number of samples) for Cesium Site.

As the metric decreases, this means that with each additional sample, the information-per-sample is decreasing. This is definitely desirable, as one does not wish for any sample to bear too much importance in the decision outcome. For example, in Figure 9.12, the first sample is essentially representing the entire site. At the other extreme, if every single location on the site was sampled, then each sample would be responsible only for itself (an extremely small portion of the site). This would represent an exhaustive data set, of course.

What is needed is a balance between these extremes. This balance is likely a function of resource limitation. As each sample is added, responsibility in term of representing the site is more evenly distributed among samples. At some point, the distribution begins to asymptotically diminish, and the cost/sample becomes important. In Figure 9.13, this is presented as a percent change in the metric as a function of sample size. There are fluctuations in the percent change due to numerical fluctuations in the solution and due to the relationship between metric value and metric percent.

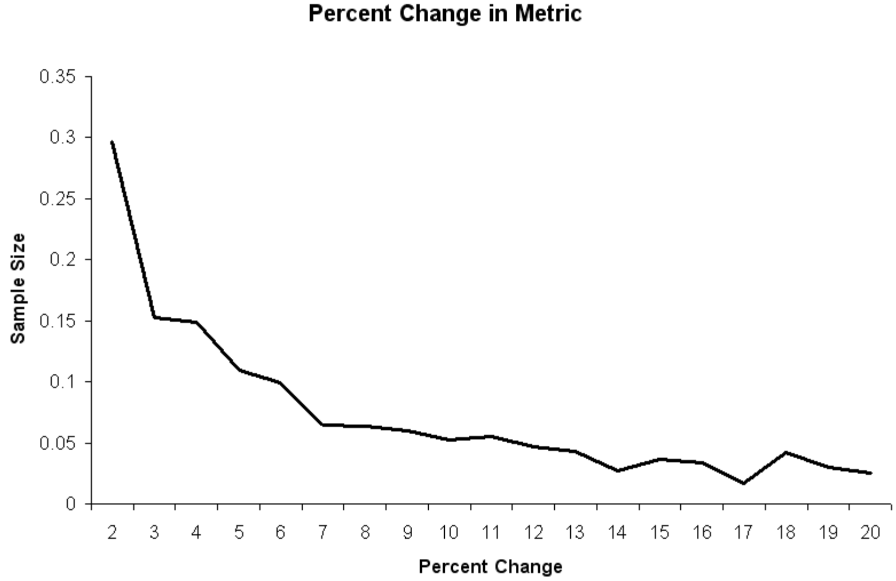


Figure 9.13 Percent reduction in metric as number of samples increase.

For the Cesium Site, after about 11 samples, the percent change is less than 5%. Applying 11 samples to the site with high (not complete) map reliance yields the following, roughly, grid-like sample design (Figure 9.14).

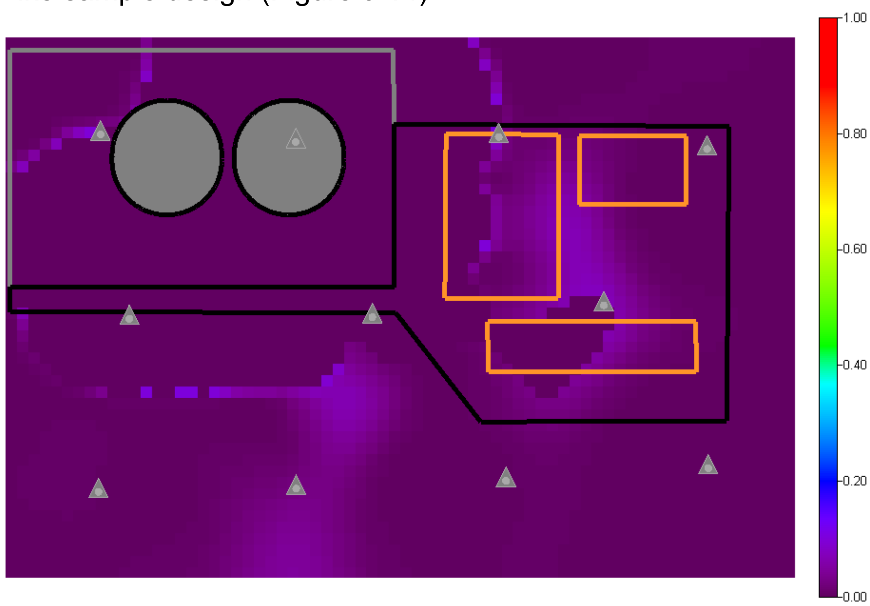


Figure 9.14. Check and cover design for Cesium Site (11 Samples).

These samples could then be used to update the CCM before applying the decision rules suggested above.

Alternate Sampling Strategies

There are other sampling strategies that might be relevant to a compliance check. These include AOC boundary design, threshold radial, high value designs, and Bayesian ellipgrid (Stewart, et al. 2009). AOC boundary design and threshold radial are generally more suited for characterization and remedial design, as they attempt to narrowly define the boundaries between contaminated and uncontaminated soils. High value designs are aimed at confirming that extreme values exist where the model suggests they exist. High value design gives no regard to covering areas that are potentially low in radioactivity and therefore does not truly have a compliance agenda.

Ellipgrid is a fundamental piece of the MARSSIM approach for determining the number and location of samples. The problem with Ellipgrid in the subsurface is that it assumes that contamination does exist and allocates samples such that the contamination is found with a certain percentage (in combination with scanning technologies). For the subsurface, this will likely require too many samples and does not account for spatially varying probabilities that the contamination occurs in the first place. Bayesian ellipgrid is a quick fix for this method by allowing the user to create regions where the probability of contamination is set to some value between 0 and 1. The ellipgrid code input is then preprocessed to account for this reduced likelihood (Stewart, et al, 2009). The fundamental problem with this approach is that it only works with large regions with a uniform probability assignment. As evidenced by the previous chapters, this does not fit well with most modeling output where a premium is placed on spatial detail. Furthermore, conforming to such an output to meet the needs of the Bayesian Ellipgrid input is likely to average out important details in the CCM. While the method can compute the number of samples and place them, the spatial information lost is likely not worth the convenience.

9.6 Limitations, Possible Solutions, and Further Research Needs

The subsurface framework presented here can be quite involved, requiring input and expertise from many areas, including geostatistics, vadose zone modeling, decision analysis, sampling, soil chemistry, and potentially groundwater. For this reason, implementation of the framework as a regulatory exercise is expected to be challenging but beneficial due to the use of the best available data, modeling, and expertise. In most sites, these activities are already ongoing and comprise no serious burden in the implementation of this approach. The challenge will be in bringing these various elements onto common ground, the CCM. This is not an unusual request, as environmental guidance already stresses the use of larger classes of conceptual site models.

As with any approach, there are limitations and weaknesses. Some of these have already been discussed in previous chapters but are consolidated here. These points provide a basis for discussion on where this work would benefit from additional input and research. The authors claim by no means that these are the only limitations; as certainly, technical difficulties will emerge on a site-to-site basis. These are broad areas where further investigation should be considered.

CCM and Data Incongruency

A major obstacle occurs when the *priori* CCM and the data collection process yield results that are not congruent with each other. Two examples are presented: 1) a CCM that is simply wrong and 2) a CCM that is selected in order to remain conservative.

In some cases, at various points in the process, investigators may find the CCM is simply wrong. This is actually a benefit of using the CCM to bright line the discrepancies between understanding of the site and physical results. For example, high activity levels are measured where they are not expected. One cannot reasonably expect an automatic "correction" of the CCM under these circumstances. In particular, if the data are used to update the CCM using mathematical models, such as cokriging, then the updated CCM can produce unexpected results. The idea behind many of these multivariate models is that a measurable and useable amount of congruency or correlation exists between the two elements (CCM and Data) involved in the update. If not, the model will attempt to reverse the CCM content but usually to an unsatisfactory degree. Furthermore, the reversal is not likely to capture the new process knowledge found in the data. In these cases, the CCM will have to be reconstructed in light of the data.

One particular example that might arise early is in implementation. Suppose that one uses a probabilistic CCM and assigns a prior CCM of 0.5 to every location on the map. This corresponds to the "know nothing" scenario. Suppose then that during the scoping phase, a sampling method is used that can only determine yes or no regarding the exceedance of a DCGL. After sampling, every single sample reports a "No". That is, no elevated measurements are found anywhere on the site. This is a form of CCM and data incongruency that may cause some difficulty. If the CCM is representative of the site, then the chance that all "No's" would be collected is very unlikely. Obviously, the owner intended to remain conservative by stating 0.5 everywhere, when the real probability was probably closer to zero. If the owner is willing to assign a uniform probability everywhere or at least to divide the site into large homogenous probability regions, then Bayesian Ellipgrid may be a better choice. Under Bayesian ellipgrid, the number of samples to collect could be computed (assuming a hot spot size) and placed accordingly. This is not a completely satisfactory answer, since the hot spot size is largely unknown in the subsurface (without an exposure scenario).

Difficulties in updating the CCM

There are circumstances where the CCM update may be carried out in one or more ways that can yield results sufficiently different to affect the compliance check. Modelers are well aware of this situation, where different modeling parameters yield different results. From a compliance standpoint, it is important to understand why these differences occur and where additional samples may be useful to resolve the issue. This is the intent of the Triad model, where adaptive sampling and dynamic work strategies are used to mitigate these types of uncertainty. One solution may be to procure an independent CCM formulation to see if substantially different outcomes are produced from a compliance view. If there are differences, the owner may be confronted and required to resolve these issues, or additional samples may be taken as part of the compliance check.

Check and Cover (size)

The check and cover algorithm is convenient for this kind of exercise, because it gives a representative coverage of the area with respect to the compliance needs, and it permits a relaxed reliance on the CCM, if needed. Furthermore, a metric is provided to assist in determining the number of samples to collect. In particular, the location on the metric/sample size curve where the minimization of the metric becomes asymptotic is suggested as one option for sample size. This really depends on the shape of the metric curve and not its magnitude. There is an unusual consequence associated with this: the shape is scale independent. This means that the shape (and therefore the sample size selected) may appear independent of the size of the site. Consider the following.

Suppose that a 1000 x 1000 site were under evaluation and at every location on the site, a probabilistic prior CCM value of 0.5 is assigned. The metric curve for CCM is presented in Figure 9.15.

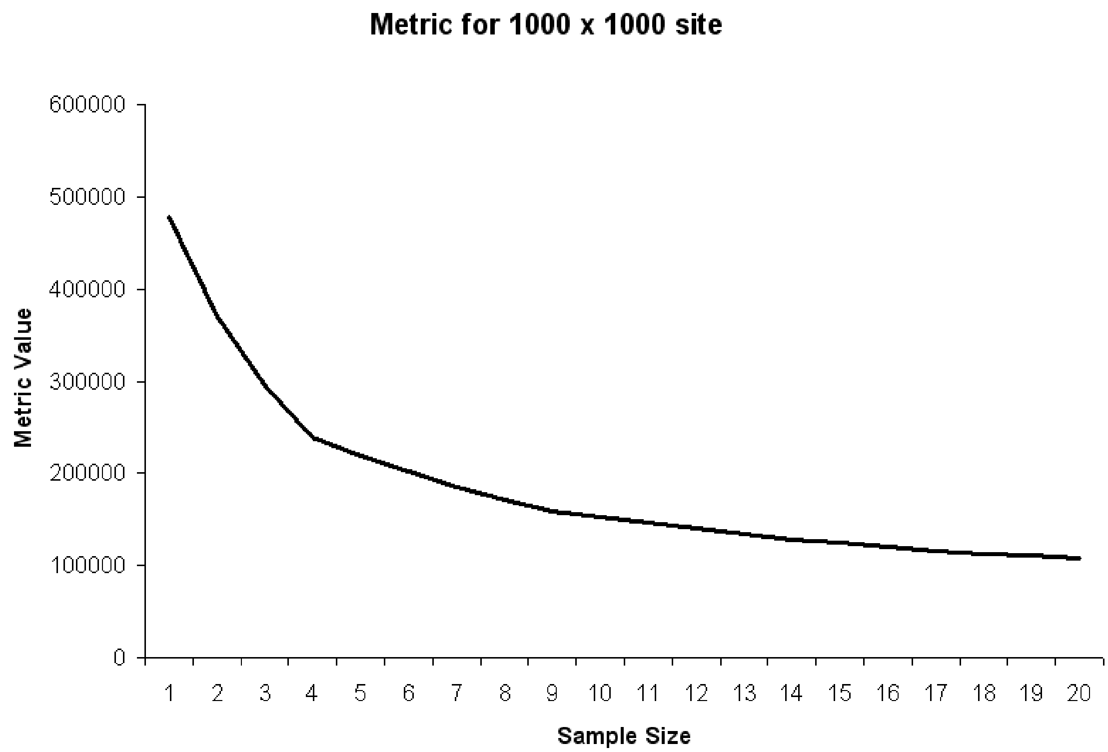


Figure 9.15 Check and Cover Metric for 1000 x 1000 ft site.

Suppose now that a 500 x 500 ft site is created (1/4th the size) with the same uniform distribution of probability everywhere. The metric curve is presented in Figure 9.16.

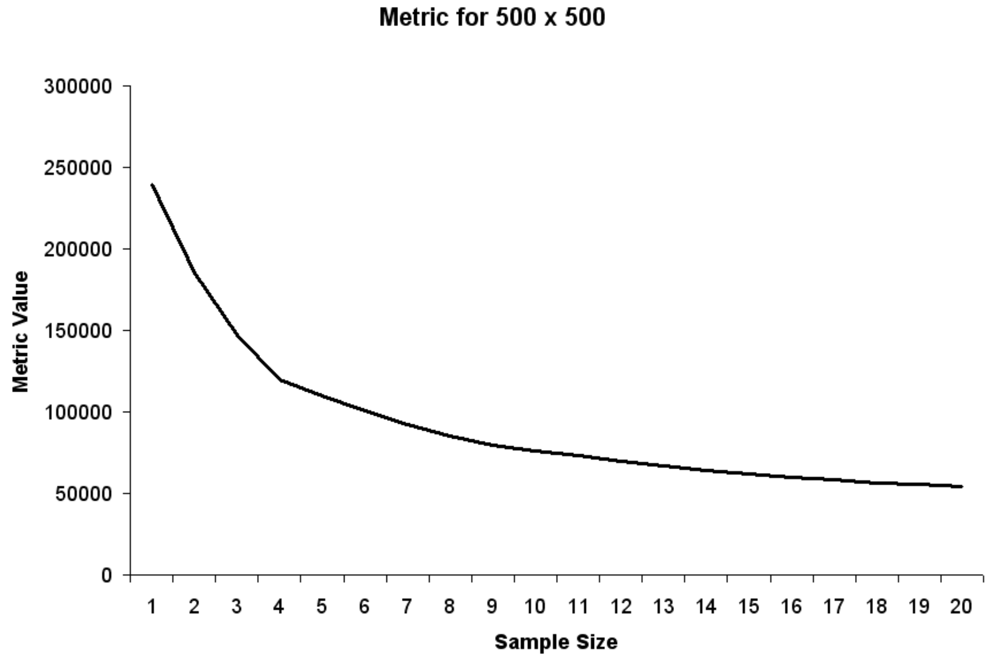


Figure 9.16 Check and Cover Metric for 500 x 500 ft site.

Notice that the metric values are very different, but the shapes are exactly the same. This is because check and cover is driven by spatial differences over the entire site. In some ways, this is troubling but perhaps in the end may be exactly the right thing to do. Consider Cesium Site at the end of the remedial phase (Figure 9.11) and the corresponding metric curve (9.12). Based on this curve, 11 samples were collected. Suppose that Cesium Site had exactly the same spatial patterns but was $1/4^{th}$ its current size. Using only the shape of the curve, 11 samples may still be selected. At first glance, this may seem irrational; however, upon closer inspection, it may be appropriate. If Cesium site had exactly the same spatial pattern in $1/4^{th}$ the space, then this would imply that the site had a much higher spatial variability and would require the same number of samples, even in a small space.

A variation of the p-median algorithm, called the maximum covering problem, could provide the answer. In this formulation, samples are added according to the p-median algorithm until no unsampled location is greater than a specified distance. This would account for the scale issue but requires the use of an additional and unclear parameter (maximum distance).

This is an issue that needs further research, but it should not preclude NRC from considering the sample design in long-term compliance planning. The issue is being taken up by the author in an upcoming paper on the matter.

9.7 Summary

This chapter presented a series of decision frameworks for consideration that may prove operable for soil exposure compliance and groundwater protection efforts alike. Examples using Cesium Site were used to demonstrate the compliance check proposals. A discussion of sample sufficiency with a particular focus on check and cover was presented

as well as a brief mention of some alternative, spatially minded strategies. The section was wrapped up with a brief look at limitations, potential solutions, and areas for further research.

10 Conclusion

This document proposes a framework that may organize the best available methods in a highly flexible sampling, modeling, and decision framework to emphasize the quality of decision making throughout the investigation. There is room in this framework for contributions from all necessary viewpoints: soil scientists, health physicists, modelers, geologists, geophysicists, hydrogeologists, statisticians, mathematicians, GIS scientists, and managers who oversee the operations. In short, this framework seeks to directly use the products and expertise that are already being used in many site investigations. The framework ultimately combines the principles of MARSSIM with EPA's Triad model, which provides direction and insight into the type of circumstances encountered in complex situations such as the subsurface. The combination is made possible by bringing to bear a substantial and continually advancing set of tools from spatial analysis, modeling, and the GIS community. This increase in compliance complexity should be met with commensurate increase in the knowledge, methodology, and technical requirements of all stakeholders involved.

The basis of this framework is a variation of the conceptual site model, called the contamination concern map (CCM). This map, which is constructed with the Triad methodology in mind, is intended to capture all the currently available knowledge about the location and severity of contamination. The CCM begins in a qualitative state and evolves across the investigation phases of MARSSIM (HSA, scoping, characterization, remedial, and compliance). Triad encourages the use of all forms of operational data, including lab samples as well as field detection methods and secondary forms of measurement (e.g., geophysics). That intent is echoed in this framework as well: to bring the CCM to the compliance phase with as much detail and mitigation of uncertainty as possible. The compliance phase then bases its decision on the CCM and possibly some additional samples.

The particular needs of any given site are impossible to predict *a priori*; however, this document tackles the evolution of the CCM across each phase by showcasing particular methods and sample designs that may be useful to investigators in lieu of site-specific requirements. Many of these methods are demonstrated using the freeware package Spatial Analysis and Decision Assistance (SADA), which was modified and expanded to provide readers with some of the particular tools mentioned in this document. A common hypothetical site called "Cesium Site" was used to show the progress from start to finish.

The document concludes with a chapter on potentially relevant compliance frameworks that use the CCM. Particular examples are discussed that may be useful to soil exposure scenarios or to support groundwater modeling efforts. Finally, a discussion on limitations and opportunities for further research are discussed. This document is intended to serve as a starting point for future discussions on how compliance-related activities can be modified to ensure sound science and protection of public health with regards to the radiological contamination in the subsurface.

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10. SUPPLEMENTARY NOTES
George E. Powers, NRC Project Manager

11. ABSTRACT (200 words or less)
This document provides a geospatial modeling and decision framework for conducting a subsurface compliance survey and analysis for sites that have been remediated for radioactive contamination. This framework proposes a method to extend the Multi-Agency Site Survey Investigation Manual (MARSSIM) guidance, which only treats surface surveys, into the subsurface. It combines and organizes survey methods into a highly flexible sampling, modeling, and decision analysis approach that emphasizes the quality of decision making throughout the investigation. Major challenges face this goal, including lack of clear exposure mechanisms, inaccessibility of the subsurface, lack of comprehensive scans, and an increase in media complexity.

The US EPAs Triad model focuses on decision quality and methods that maximize available information, technologies, and expertise to address and mitigate sources of uncertainty. This document uses Triad to extend MARSSIM into the subsurface using a substantial and continually advancing set of tools including spatial analysis, modeling, and the GIS community. Recommendations are made on information that forms, updates, and evolves a spatial variation of the conceptual site model, called the Contamination Concern Map. This map focuses on the likelihood of exceeding a decision criterion at a local scale and directly addresses uncertainty in volume extent and location. The map matures over each major phase of the investigation and provides a decision framework. Results of this approach can inform investigators and regulators alike of a reasonable course of action in the final site assessment.

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