Quantifying Uncertainty in Soil Volume Estimates - 9320

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ABSTRACT

Proper planning and design for remediating contaminated environmental media require an adequate understanding of the types of contaminants and the lateral and vertical extent of contamination. In the case of contaminated soils, this generally takes the form of volume estimates that are prepared as part of a Feasibility Study for Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites and/or as part of the remedial design. These estimates are typically single values representing what is believed to be the most likely volume of contaminated soil present at the site. These single-value estimates, however, do not convey the level of confidence associated with the estimates. Unfortunately, the experience has been that pre-remediation soil volume estimates often significantly underestimate the actual volume of contaminated soils that are encountered during the course of remediation. This underestimation has significant implications, both technically (e.g., inappropriate remedial designs) and programmatically (e.g., establishing technically defensible budget and schedule baselines). Argonne National Laboratory (Argonne) has developed a joint Bayesian/geostatistical methodology for estimating contaminated soil volumes based on sampling results, that also provides upper and lower probabilistic bounds on those volumes. This paper evaluates the performance of this method in a retrospective study that compares volume estimates derived using this technique with actual excavated soil volumes for select Formerly Utilized Sites Remedial Action Program (FUSRAP) Maywood properties that have completed remedial action by the U.S. Army Corps of Engineers (USACE) New York District.

INTRODUCTION

Hazardous waste site decision-making is filled with uncertainty. One example of that uncertainty is the process of estimating contaminated soil volumes for remedial design purposes. Historical experience at most sites has been that actual volumes removed and/or remediated during the course of remedial work typically significantly exceed the contaminated soil volumes estimated to be present. Volume overruns are problematic because they produce cost overruns for projects and often raise concerns that remediation work was "sloppy," perhaps involving unnecessary removal of soils. Additionally, they result in schedules slipping and milestones being missed, and they can erode stakeholder confidence in the problem-holder's understanding of site conditions and the environmental problems present.

The U.S. Army Corps of Engineers (USACE) Formerly Utilized Sites Remedial Action Program (FUSRAP) program has experienced these problems. In response, the USACE has implemented a variety of measures to bring contaminated volume overruns under control. These have included investing in pre-design data collection to augment remedial investigations (RI) datasets; "front-loading" final status survey data collection work to flush out unexpected contamination early in the remediation process; implementing Triad-based data collection programs using real-time measurement techniques and dynamic work strategies so that contamination can be pursued until bounded during data collection; and applying more sophisticated volume estimation methodologies developed by Argonne National Laboratory (Argonne) that provide not only best estimates of contaminated soil volumes present, but also upper and lower bounds on those estimates to give some sense of how much uncertainty is present.

This paper presents a retrospective study that applies the volume estimation methodologies developed by Argonne to a FUSRAP project that is now completed, the Cluster 4 vicinity properties associated with the USACE New York District's FUSRAP Maywood Superfund Site (FMSS). The Cluster 4 properties were identified as containing contamination above cleanup standards, volume estimates were prepared based on data that existed at the time, and remediation was completed in 2001. The final remediation volume significantly exceeded the original estimate. To evaluate the efficacy of Argonne's volume estimation methodology, the data used to support the original Cluster 4 vicinity property volume estimate were provided to Argonne. The final excavated volume and associated footprint were not. Argonne used the original data along with its volume estimation methodologies to calculate a volume estimate along with uncertainty bounds for the Maywood Cluster 4 vicinity properties. This volume estimate was compared to the volume of soil ultimately removed by the Cluster 4 remedial effort.

METHODOLOGY

Argonne's volume estimation process uses a combination of Bayesian analysis and indicator geostatistics to calculate likely contaminated volume estimates and associated uncertainty bounds. Bayesian analysis allows the quantitative integration of "soft" information (e.g., historical air photos, site infrastructure locations) with sampling results in the estimation of contaminated soil volumes. Indicator geostatistics allows the extrapolation of sample results from locations with data to areas without. A detailed description of the methodology can be found in Johnson et al. (1). In practice, volume estimation using Argonne's methodology follows these steps:

1. A Conceptual Site Model (CSM) is developed for the site of interest. The CSM describes those features of the site pertinent to the potential presence and extent of contamination above action levels. Information supporting the CSM can come from a variety of sources, including historical records about releases, interviews, aerial photographs (present and historical), nonintrusive geophysics, site walk-downs, depictions of the layout of infrastructure present or other physical features pertinent to contamination location, gamma walkover surveys, and down-hole gamma scans.

2. From this CSM, a quantitative probabilistic model of the site is constructed; the model specifies for each location of the site the likelihood that contamination is present at levels of concern. This can be done in two dimensions if the concern is only with surface contamination or with the lateral extent of subsurface contamination, or in three dimensions. Details about how the CSM is converted into a probabilistic contamination model can be found in Johnson et al. (1).

3. Using a combination of Bayesian analysis and indicator geostatistics, the quantitative CSM is updated with existing sampling information. For CSM updating purposes, sample results are treated as binary values: either a sample encountered contamination above the appropriate cleanup criteria or it did not. The updating process requires coding sample results as either "0" or "1" indicator values depending on the concentrations observed relative to cleanup criteria, and determining a spatial autocorrelation range appropriate for the site. The spatial autocorrelation range refers to the distance over which correlation in sample results can be expected. Any contamination event that exhibits spatial patterning (which includes almost all contamination scenarios) has spatial autocorrelation present. If sufficient historical data exist, spatial autocorrelation ranges can be estimated from historical data by using variogram estimation software. Alternatively, gamma walkover survey results can be used to estimate a variogram range. If no historical data are available, the spatial autocorrelation range is based on best technical judgment. The assumed range can be revisited and revised if and as more sample data are collected from the site.

4. The updated quantitative probabilistic model serves as the basis for contaminated volume estimates. The updated probabilities of contamination across a site can be used to both provide a most likely estimate of the volume present, and bound the potential volume that might be present. For example, determining the volume of soil that has a 0.5 chance or greater of being contaminated above action levels would be a reasonable guess of the volume present. Alternatively, one can use expected value statistics to obtain a single volume estimate. Identifying the volume of soil that has greater than a 0.8 probability of being contaminated would provide a minimum estimate of the contamination present. Determining the volume of soil that has a 0.2 chance or greater of being contaminated would provide a more conservative (and probably much larger) volume of potentially contaminated material. In each case, a footprint can be identified associated with the volume. The difference between the minimum volume footprint and the maximum volume footprint identifies areas where existing data are not conclusive about the absence or presence of contamination; these areas, in turn, are likely candidates for additional sampling if the range of estimated soil volumes was unacceptable.

5. If additional sampling were desired to further refine volume estimates, any new results can be used to further update the probability model and produce presumably more refined volume estimates (i.e., volume estimates with a smaller difference between the minimum amount of contaminated material present and the potential maximum amount). If "real-time" measurement technologies are available, this data collection effort can be implemented within a Triad framework using dynamic work strategies (2). In this case, sampling locations can be selected iteratively in response to real-time results and probability model updates, resulting in a data collection effort that efficiently targets areas contributing the most uncertainty to estimated volumes.

A two-dimensional version of Argonne's methodology is available as public-domain software called "BAASS" (Bayesian Approaches for Adaptive Spatial Sampling) (3).

FMSS CLUSTER 4 CSM

The FMSS is located in the Boroughs of Maywood and Lodi, New Jersey. Portions of the FMSS were contaminated with process waste and residue associated with thorium refining and recovery activities by the Maywood Chemical Works (MCW) from 1916 to 1956. The MCW waste was a fine, sand-like material containing thorium and other naturally occurring radioactive elements. Waste and residues were stored west of the main facility in areas that were originally undeveloped, identified as the Sears and Stephan properties in Figure 1. Subsequently, significant property development took place that included the placement of major roads (New Jersey State Highway 17 and Interstate 80) and the construction of residences and businesses. The FMSS consists of 88 designated residential, commercial, municipal, state, and federal properties believed to have been affected by MCW waste material (4). The Cluster 4 properties are part of these 88. The Cluster 4 properties are west of the MCW, and directly south of where waste material was stored (Figure 1).

In addition to the original placement of waste material, there are several other mechanisms that resulted in the current distribution of contaminated material in the Cluster 4 property vicinity. These mechanisms include land reworking activities associated with road, drainage, and foundation construction; landscaping (local residents were known to use MCW process waste in their lawn and gardens and as fill material); and erosion/stream transport/sedimentation processes via Lodi Brook. The original streambed for Lodi Brook passed through the Cluster 4 properties (Figure 2).
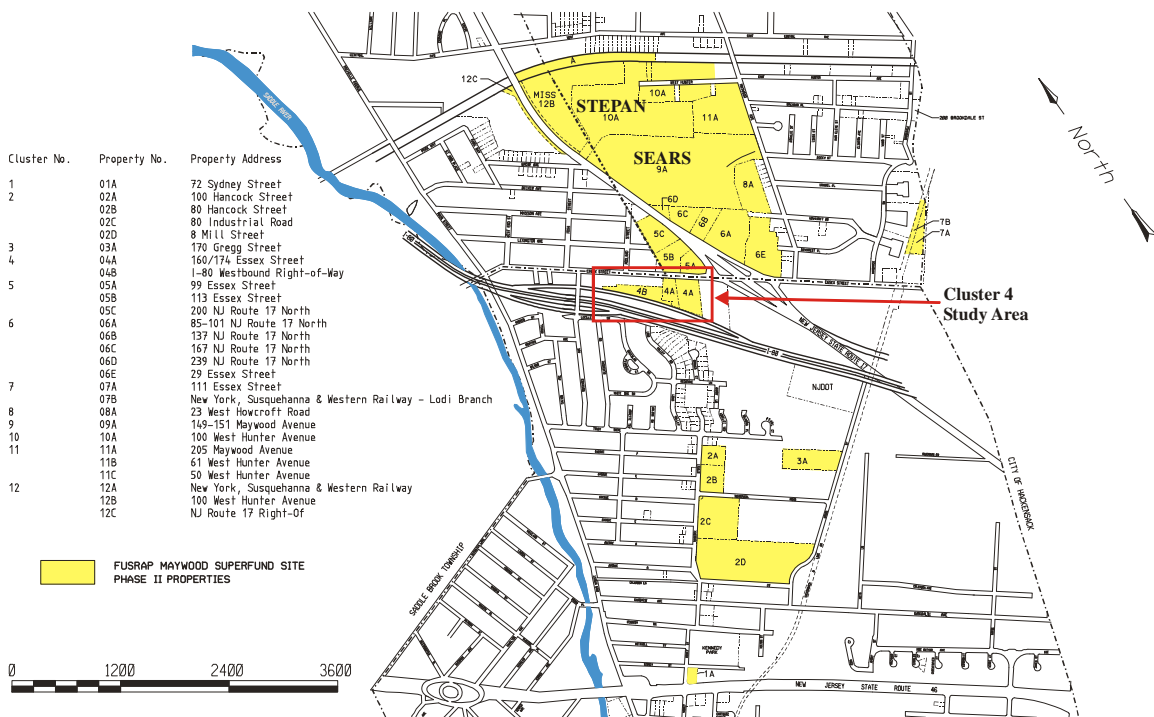

Fig. 1. Location of Cluster 4 study area properties

The Cluster 4 properties consist of three properties, 160 and 174 Essex Street and a portion of the I-80 westbound right-of-way. Figure 2 shows an aerial photo dated 1940 with the properties' footprint and a recent aerial photo (2008) with the same footprint. The first photo was taken after initial impacts but prior to development. The second reflects current land-use status and is post-remediation. The Cluster 4 properties' footprint includes approximately 4.6 acres. Pre-development, the Cluster 4 property area was a combination of wooded areas and farmland. Currently, a majority of the Cluster 4 properties' surfaces are associated with building footprints or are paved.

- In the case of the Cluster 4 properties, the assumed contamination scenario is as follows. An unknown but significant quantity of contaminated process waste material from the operation of the MCW was placed on the Sears Site and/or the Stephan Chemical Site. The Sears Site is immediately adjacent to and north of the Cluster 4 properties (Figure 1). The Stephan Chemical Site is a bit further north of the Cluster 4 properties (Figure 1). Both properties fall within the drainage of Lodi Brook. Contaminated materials were carried onto the Cluster 4 properties by erosional processes via Lodi Brook, contaminating the streambed and low-lying vicinity areas. Contaminated soils may have also been brought to the properties as fill material during subsequent property development. Contaminated sediments associated with Lodi Brook may have been removed and placed along the brook by stream maintenance activities and would have been redistributed by the various land development activities that took place. Lodi Brook currently is predominantly carried by subsurface culverts, with only a short stretch of surficial expression as an open-flowing drainage feature.
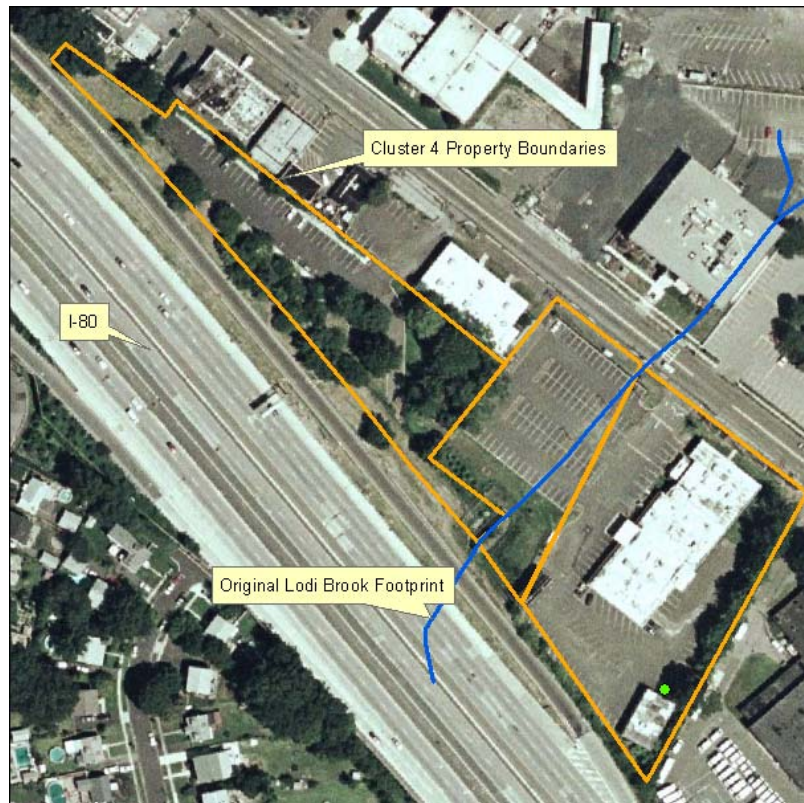
Fig. 2. 1940 and 2008 air photos of Cluster 4 properties
The current culvert footprints do not conform to the original streambed.

Based on this, one would expect to potentially find contamination associated with:

- The current Lodi Brook footprint;
- Subsurface soils aligned with the original streambed and what were originally adjacent low-lying areas;
- Surface and subsurface soils at property locations where fill activities took place; and
- Surface and subsurface backfill adjacent to buried infrastructure (e.g., drain lines, utilities) installed during property development.

Contamination would not be expected where surface development resulted in the removal of surface soils with no subsequent fill, or where surface soils were not significantly disturbed, fill was not required, and soils were not adjacent to the original Lodi Brook streambed or its replacement drain-line footprint.

Because of surface landscaping/paving activities, one would expect the majority of soil contamination present at the Cluster 4 properties to be beneath at least pavement, and possibly beneath clean fill material as well. Consequently, this contamination would not be identifiable by standard gamma walkover surveys.

The primary contaminants of concern from a radiological perspective are thorium-232 (Th-232), radium-226 (Ra-226), and uranium-238 (U-238) and their daughter products. Of these three, Th-232 is the primary driver for decision-making purposes. The cleanup requirements for the three radionuclides were 5 picocuries per gram (pCi/g), 5 pCi/g, and 50 pCi/g, respectively. Cleanup requirements were incremental to background. Background for the three radionculides was reported as 1

pCi/g, 0.7 pCi/g, and 1 pCi/g, respectively. Because there were multiple radionuclides, a sum of ratios (SOR) calculation was used to evaluate sample results against the cleanup requirements.

Seven historical air photos spanning the 1940 to 2008 time period were combined with existing surface gross gamma readings, anecdotal information, and a civil survey of the site to construct an initial quantitative CSM that is displayed in Figure 3. The maps in Figure 3 are color-coded based on the probability that contamination above cleanup requirements was present. The initial quantitative CSM reflects all that is known about the Cluster 4 properties, without the benefit of sample results.

Fig. 3. Initial and updated Cluster 4 property CSM

VOLUME ESTIMATION

The initial quantitative CSM can be used to obtain initial volume estimates, even without the benefit of sample results. Table I contains volume estimates based on the initial quantitative CSM for different contamination probability levels. The volume estimates were obtained by using an estimated depth of contamination along with the lateral footprint associated with different contamination probability levels. The low and high contamination probability

Table I. Contaminated Soil Volume Estimates as a Function of Contamination Probability

Probability	Initial Volume	Updated Volume	Updated Volume plus Layback
>0.14	6,679 m^3 (8,735 yd^3)	12,499 m^3 (16,347 yd^3)	14,159 m^3 (18,518 yd^3)
>0.25	5,001 m^3 (6,541 yd^3)	9,178 m^3 (12,004 yd^3)	11,668 m^3 (15,260 yd^3)
>0.40	2,565 m^3 (3,355 yd^3)	7,225 m^3 (9,450 yd^3)	9,987 m^3 (13,062 yd^3)
>0.60	1,254 m^3 (1,640 yd^3)	1,978 m^3 (2,587 yd^3)	2,675 m^3 (3,498 yd^3)
>0.75	150 m^3 (196 yd^3)	1,044 m^3 (1,365 yd^3)	1,460 m^3 (1,909 yd^3)
>0.86	150 m^3 (196 yd^3)	583 m^3 (762 yd^3)	898 m^3 (1,175 yd^3)

provides bounds on the possible contaminated soil volume based on the information contained in the initial quantitative CSM.

There are several ways to estimate a single likely contaminated volume. The first uses the contaminated volume associated with the 0.5 probability level, acting in some sense as a median estimate. With this approach, a single likely contaminated volume estimate based solely on this initial quantitative CSM would be 1,900 m^3 (2,500 yd^3). Another method would be to multiply the contamination probability by its associated volume in an expected value calculation. This yields an estimate of 2,700 m^3 (3,500 yd^3).

In the case of the Cluster 4 properties, there were four characterization data collection efforts that yielded results that could be used to refine these initial volume estimates. The first two occurred in the 1980s and involved data collection by Oak Ridge National Laboratory (ORNL) and Bechtel National, Inc. (BNI). The latter two were in the late 1990s and involved Stone & Webster, Inc, (S&W) and the New Jersey Department of Transportation (NJDOT). The purpose of the ORNL investigation was to determine whether soil contamination existed above likely cleanup requirements. The purpose of the BNI investigation was to further explore contamination encountered by ORNL. The goal of the S&W and NJDOT efforts was to provide the data necessary to design the excavation to remove contamination that was at levels of concern.

All four sampling programs involved soil cores to depth, combined with sample acquisition and analysis from selected core intervals. Three of the four (ORNL, BNI, and S&W) also include extensive down-hole gamma surveys of soil core holes to better characterize the vertical profile. Soil sample analytical results provided data support an SOR calculation that can be compared to the cleanup criteria. In

contrast, down-hole gamma scan results provide a gross indication of the general levels of possible contamination present.

In all, there were 145 soil cores with at least some data available for the Cluster 4 properties. In some cases, cores had only down-hole gamma results. In other cases, cores had a mixture of sample analytical data and down-hole gamma results. In still other cases, only one or two soil samples might have been available.

The BAASS software was used to update the initial quantitative CSM with soil core datasets. Because accurate elevation information was not available for the cores, the volume estimation problem was treated in two dimensions. The maximum sample or down-hole gamma result was used at each core location to determine the likely presence of contamination above action levels for that core. These data, in turn, were used by BAASS to estimate likely lateral contamination footprints. The depth of contamination was estimated based on individual core results for given areas. The average depth of contamination was combined with the lateral extents to obtain volume estimates for different probability levels.

BAASS requires that data be converted to indicator values. In the case of sample results, this conversion was straightforward and based on the SOR value of individual samples. For down-hole gamma results, the analysis was more complex. A non-parametric approach was used to assign lower and upper investigation levels to individual down-hole gamma scan datasets based on soil sample results that also had corresponding gamma scan values. The lower investigation level was selected such that when gamma scan results were below the lower investigation level one could be confident that it was unlikely that a soil sample from the same interval would have yielded an SOR greater than 1. The upper investigation level was selected such that when gamma scan results were above the upper investigation level, it was very likely that a soil sample would yield an SOR greater than 1. Using the lower and upper investigation levels, soil core intervals with down-hole gamma data were either assigned a 0 (scan result less than the lower investigation level), a 1 (scan result greater than the upper investigation level), or a 0.5 (the scan result was between the lower and upper investigation level and so was inconclusive regarding the presence/absence of contamination at levels of concern). The indicator value assigned to each core location was the maximum indicator value observed for the sample and down-hole gamma scan results for that core.

Figure 3 presents a map that shows the soil core locations color-coded by their maximum indicator value and overlain on an updated quantitative CSM, color-coded by the probability of contamination being present above the requirements. Table I provides the updated volume estimates. The updated contaminated volume associated with the 0.5 probability level was 4,600 m^3 (6,000 yd^3). The updated expected contaminated volume was 5,400 m^3 (7,100 yd^3). As a point of comparison, the original design excavation volume as calculated by S&W was 3,734 m^3 (4,884 yd^3), which included layback required for safe slope excavation. Factoring in layback as described by S&W's excavation plan, the updated BAASS-derived volume corresponding to the 0.5 contamination probability level was 6,300 m^3 (8,300 yd^3)and 6,800 m^3 (8,900 yd^3)for the expected contaminated volume calculation. As indicated in Table I, including layback and based on the available datasets, the excavation could plausibly have ranged between 920 and 14,000 m^3 (1,200 and 18,500 yd^3).

The actual excavated in situ volume was 6,278 m^3 (8,211 yd^3). This was greater than what S&W had originally predicted, and reflected the need to expand lateral excavation boundaries in response to buried contamination that was encountered. The actual excavated volume, however, fell within the BAASS-predicted range and compared very well with the likely in situ soil volumes calculated by BAASS.

Figure 4 plots both the initial and updated contaminated volume estimates as a function of contamination probability. One striking feature of the BAASS-volume estimates is that the uncertainty associated with

contaminated soil volumes actually grew after the initial quantitative CSM was updated with all of the soil core information. This was primarily due to soil cores that revealed deep contamination unexpectedly along the eastern boundary of the properties, combined with other laterally unbounded "hits" scattered across the site that were not consistent with the original CSM. Presumably, had additional data collection been invested in bounding contamination, the range of plausible contaminated volumes could have been tightened, and the quality of the likely contaminated volume estimate improved.
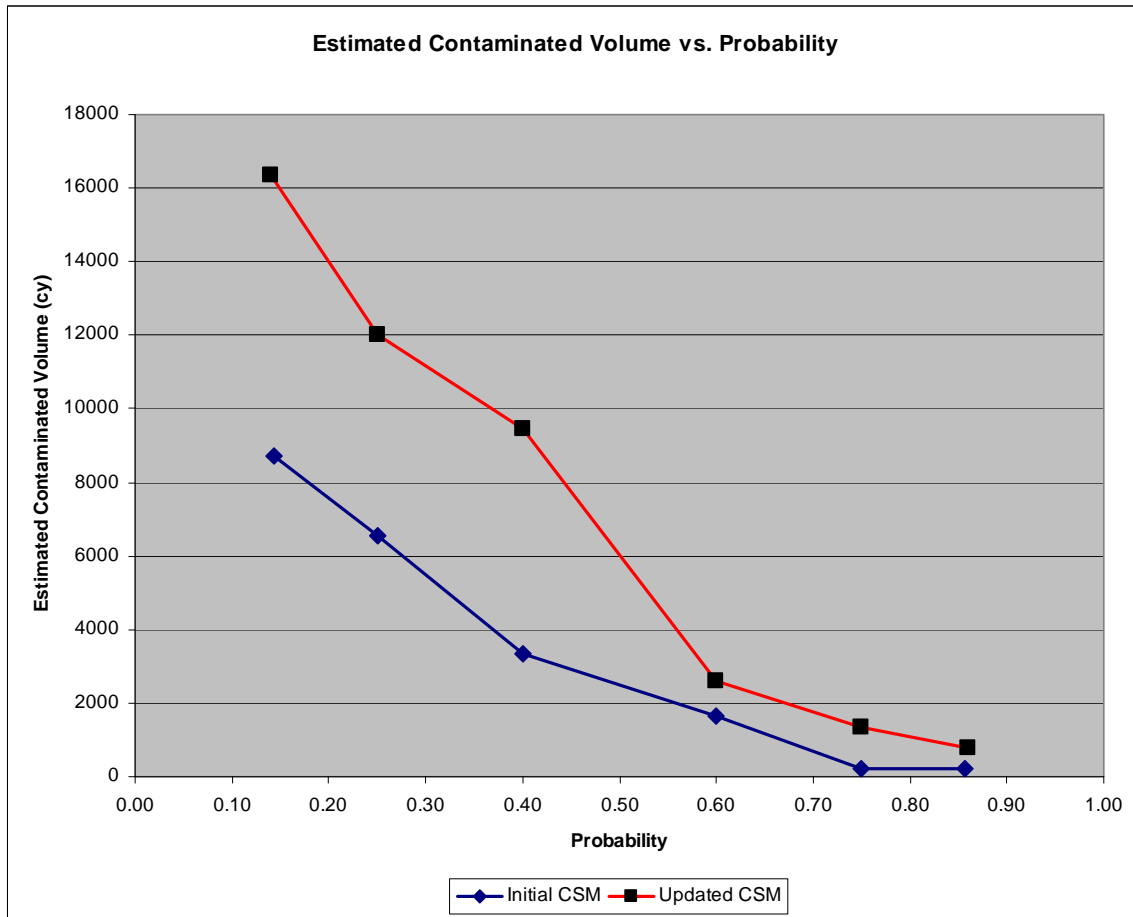

Fig. 4. Estimated contaminated soil volume as a function of contamination probability
The degree of residual volume uncertainty that remained even after 145 soil cores had been placed in these properties underscores the difficulty in obtaining accurate and confident volume estimates when buried contamination is present. It also illustrates the value in having available real-time measurement technologies during data collection so that unexpected contamination can be further explored until adequately bounded, such as is promoted by the U.S. Environmental Protection Agency (EPA) as part of the Triad approach.

Undoubtedly, additional data collection at the Cluster 4 properties would have resulted in a better volume estimate. The challenge with traditional single-volume estimates is that they provide no sense of their quality (level of confidence) or the potential for volume overruns. Using the volume estimation approaches described here provides program managers with a rational basis for determining whether the quality of volume estimation possible with existing data is acceptable and, if not, where additional investments in data collection would most likely yield the greatest return in uncertainty reduction.

If contaminated soil volume uncertainty is clearly understood before remediation, revisions to the overall remediation strategy may result. One example would be to implement a fixed-price excavation that addresses the high-probability contamination areas, along with unitized-cost contract and design contingencies that allow the excavation to expand to pursue contamination as necessary. The prerequisite for this remediation strategy is the availability of suitable real-time measurement technologies that can be used for dig-face characterization while work is underway. In the case of Th-232 contamination, as was present for the Cluster 4 properties, suitable real-time scanning options exist. This can be more of a challenge for radionuclides such as Th-230 if they are not collocated with other, more easily measured contaminants.

CONCLUSIONS

Obtaining accurate pre-remediation volume estimates has been a constant challenge for contaminated soil remediation projects. The volume estimation process developed by Argonne and described in this paper provides one approach for understanding the uncertainty associated with contaminated soil volume estimates. Understanding volume uncertainty is a necessary prerequisite to developing programmatic strategies for either accounting for the uncertainty, or taking steps to reduce it. As illustrated by the FMSS Cluster 4 properties, Argonne's techniques can be used to provide more accurate contaminated soil volume estimates and to quantify the uncertainty associated with those estimates.

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