Demonstration of SmartSampling™ at the Mound Canal Site

Introduction

In January 1969, plutonium-bearing solutions were released through a rupture in an underground pipeline at the U.S. Department of Energy's Mound Advanced Technologies facility near Miamisburg, Ohio. Some of the soils contaminated by this spill were washed downhill and into a abandoned section of the historical Miami-Erie canal by heavy rainfall before remediation could be completed. Remedial efforts during early 1969 failed to remove all contamination, and sampling programs conducted in 1971, 1975, 1992, and 1993 confirmed that plutonium-238 (^{238}Pu) activities could be found, primarily in the uppermost foot of canal soils. The Mound plant environmental restoration program is implementing the Operable Unit-4 Miami-Erie canal removal action to prevent exposure of the public to potentially hazardous levels of plutonium-contaminated soil.

Current Activity

Current remediation work at the canal site consists of excavating plutonium-contaminated soils and shipping these materials for off-site disposal. The regulatory agreements covering the Mound canal project call for no more than 5 percent of post-remediation verification samples over 75 picocuries per gram (pCi/g) with no samples exceeding 150 pCi/g.

Concurrently with the on-going staged excavation of the canal, three canal segments, N23, N24, and N25, were designated for a demonstration of the SmartSampling™ methodology for cost minimization. Overall remedial activities in these canal segments were to proceed as originally planned. However, additional sampling and geostatistical analyses were performed in accordance with the SmartSampling™ methodology, and the volumes of soil and other cost factors that would have been incurred have been computed for comparison with the actual remedial volumes and costs under standard practice. Because SmartSampling™ involves a probabilistic decision framework, we interpret the two-part remediation standard of 75/150 pCi/g as follows. We decide to remediate (excavate soil) if the modeled probability of a given selective remediation unit exceeding 75 pCi/g is greater than 5 percent *or* if the probability of exceeding 150 pCi/g is greater than 1 percent. Under the SmartSampling™ methodology, the only means to achieve a pre-examination probability of failure equal to precisely zero is to excavate and remediate the entire area of concern.

Methodology

Soil samples measuring approximately 0.33 ft (4 inches) in diameter and 0.5 ft (6 inches) long were collected from canal segments N23–N25 on a nominal 10-ft spacing using a randomized grid pattern in each different canal segment. Samples were analyzed for total ^{238}Pu using laboratory fixed-geometry sodium-iodide scintillometry; values are reported in picocuries per gram (pCi/g). The actual sample pattern used for canal segments N23–N25 is shown in figure 1. Note the existence of eight sets of closely spaced sample locations, which have been used to refine estimates of the small-scale spatial variability used in the modeling process.

A histogram of plutonium activities for the 152 soil samples is presented in figure 2(a). The distribution of values is fairly typical of many contaminated sites, with a relatively few very high activities and a much larger fraction of relatively low values. The raw plutonium activity data were

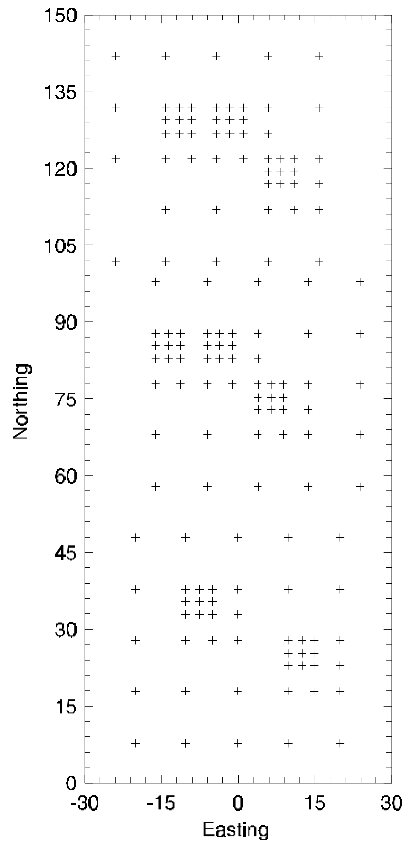


Figure 1. Index map showing the locations of samples used in modeling segments N23–N25 of the Miami-Erie canal.

converted to their equivalent normal-score transformed values [fig. 2(b)] using the Gaussian-transform program, NSCORE (Deutsch and Journel, 1992). The normal-score transform process preserves the quantile relationships of the original values while converting the histogram to a normal distribution for modeling purposes. Because the transform is quantile-preserving, the spatial correlation structure of the measured data is essentially unchanged.

Variograms were computed for the normal-score transformed plutonium values shown in figure 2(b), and the resulting variograms and the fitted spatial continuity models are presented in figure 3. Figure 3(a) illustrates spatial continuity along the long axis of the Miami-Erie canal, which runs approximately north–south in this area, whereas figure 3(b) shows spatial continuity in the perpendicular direction (nominally east–west). As anticipated, the plutonium analyses indicate significantly greater spatial correlation along the axis of the canal, indicating a fairly pronounced anisotropy. The experimental variogram plots have been fitted for modeling purposes with a set of two nested spherical variograms using the parameters given in table 1.

The exhaustive spatial distribution of likely plutonium contamination across the three canal segments was modeled using sequential Gaussian simulation, as implemented in the computer program SGSIM (Deutsch and Journel, 1992), conditioned to the 152 measured values. Conditional simulation algorithms attempt to generate a suite of geologically plausible models of a variable of

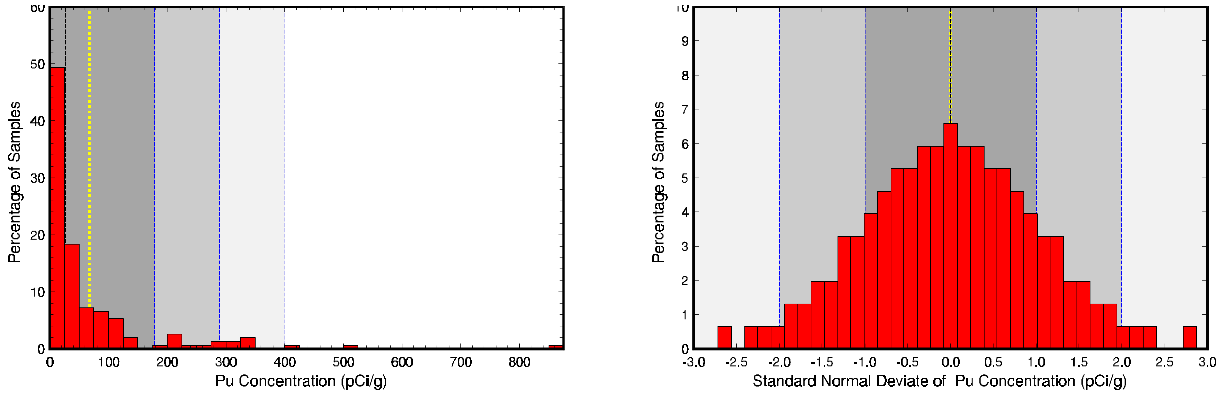


Figure 2. (a) Histogram of measured plutonium activities from Mound canal segments N23–N25. (b) Normal-score transformed plutonium activities.

(a) (b)

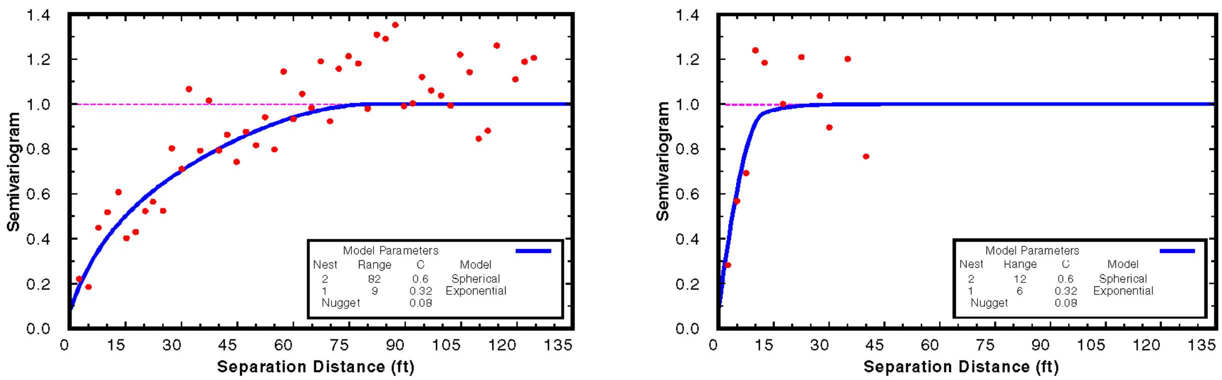


Figure 3. Normal-score variograms of plutonium activity: (a) parallel to canal axis; (b) normal to canal axis. Parameters of fitted variogram model are given in table 1.

Table 1: Variogram Model Parameters

Nest No.	Model Type	Range (ft)		Sill
		Maximum	Minimum	
--	Nugget	--	--	0.08
1	Exponential	9	6	0.60
2	Spherical	82	12	0.32

interest that (1) reproduce the measured values at the locations of the actual samples, (2) reproduce the statistical properties of the measured data ensemble (i.e., the histogram), and (3) reproduce essentially the same spatial correlation patterns as inferred from the data values. The concept is that because there is no objective basis for determining which of a large number of stochastic simulations is the "true" distribution of the variable, the variability among a suite of simulated models is a quantitative representation of uncertainty.

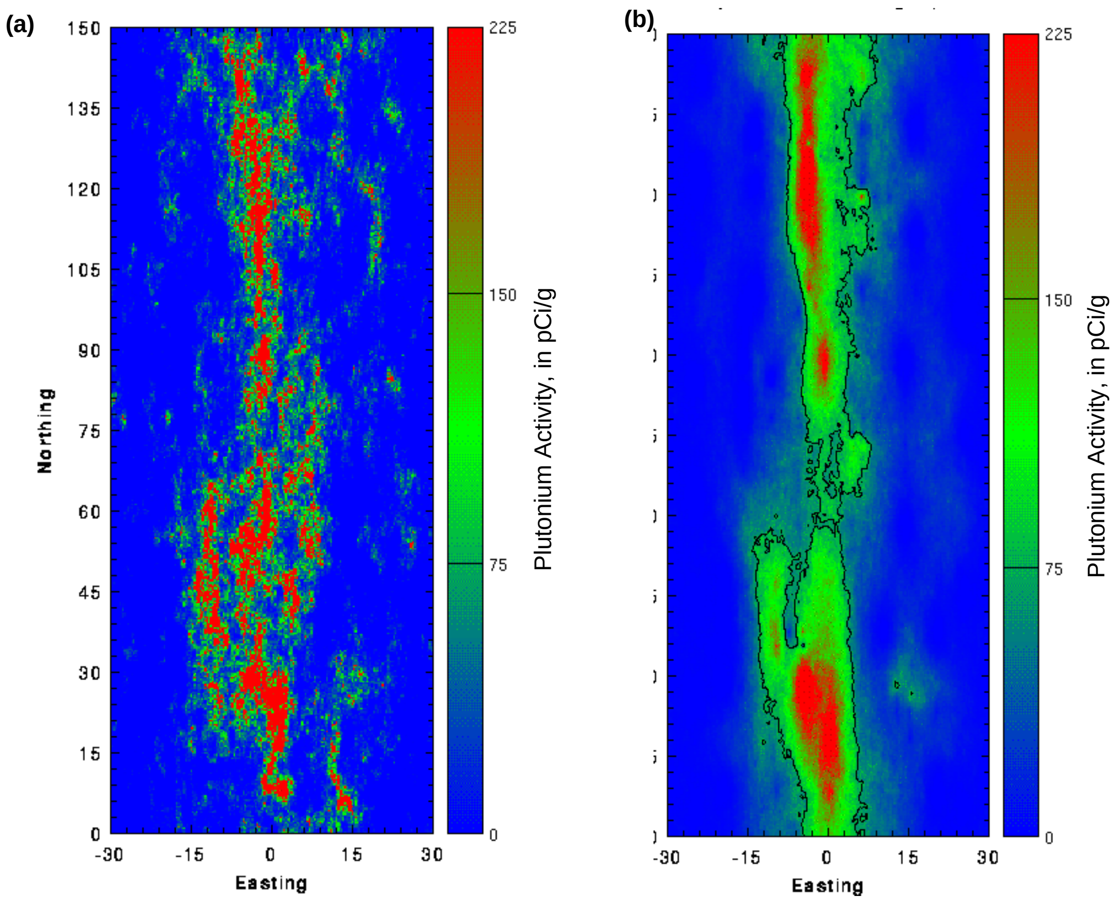
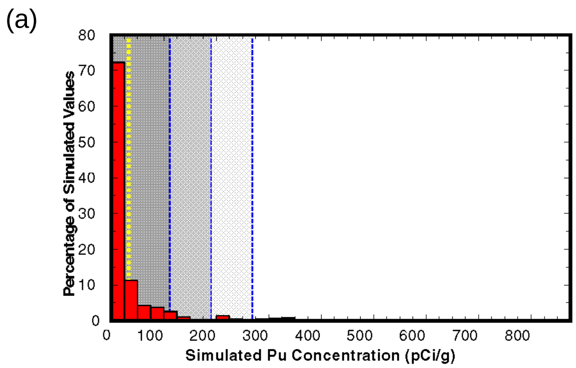


Figure 4. (a) One simulated model of plausible plutonium activity in segments N23–N25 of the Miami-Erie canal. (b) Interpolated (E-type, or expected-value) model of plutonium activity in segments N23–N25 (the contour line encloses those pixels exceeding 150 pCi/g).

Figure 4 shows one such simulated model of plutonium contamination in canal segments N23–N25; the histogram and variograms computed for this simulated model are shown in figure 5. The model consists of individual soil-sample-sized pixels arranged on a 0.33×0.33-ft square grid. Because the measured data in this exercise represent the plutonium activity of 0.33-ft diameter soil core plugs, the modeled pixels essentially abut one another (fig. 6), providing a virtually exhaustive description of plutonium contamination. The figure is in *canal coordinates*, where the *y*-axis is distance along the canal, and the *x*-axis is normal to that direction.

However, remediation decisions in the field cannot be made on the scale of soil samples, and the scale of the remediation map must consider the minimum-size excavation unit that can be re-



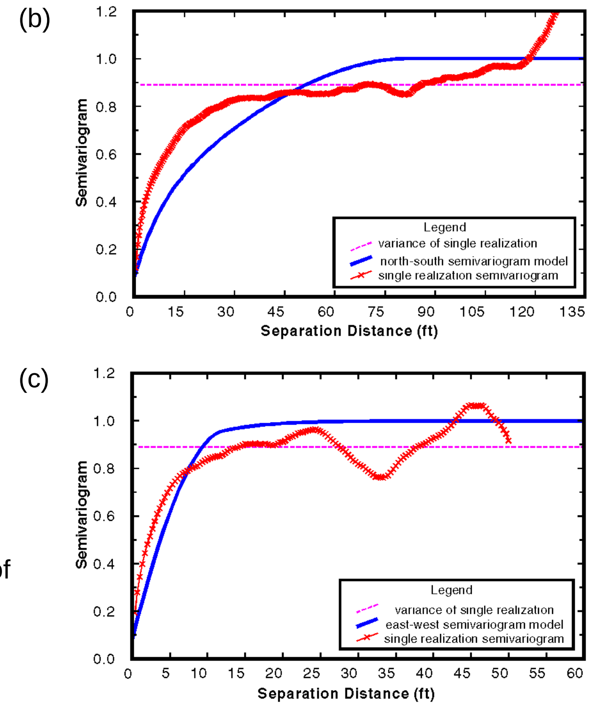


Figure 5. (a) Histogram and (b) north-south and (c) east-west variograms for a single simulated model of plutonium activity.

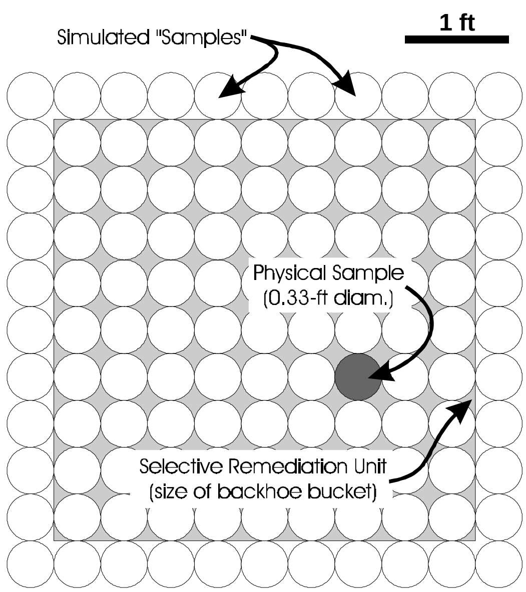


Figure 6. Spatial arrangement of simulated plutonium values, each approximately representing a 0.33-ft diameter cylindrical soil-plug "sample," within a 3-ft×3-ft selective remediation unit.

moved or otherwise dealt with at reasonable cost. For purposes of this analysis, we have assumed that excavation of contaminated soil from the canal is performed with mechanized equipment, and that the minimum size of a selective remediation unit is 3 ft by 3 ft, or approximately the footprint of a backhoe bucket. We therefore require a scaling and decision rule that can be applied to the replicate, statistically indistinguishable exhaustive contaminant models to decide which 3-ft×3-ft remediation panels will be excavated and which will be left in place as “uncontaminated.” In fact, we apply two slightly different decision rules, both of which are “consistent” (though with different interpretations) with the two-part regulatory clean-up criteria in place for the Mound site. These rules are summarized in Table 2. As with all SmartSampling™ applications, we hold that there is no absolute certainty in the activity of a contaminant at an unsampled location, and thus the substitution of the one-percent probability value.

Table 2: Decision Rules Applied to Simulated Exhaustive Models of Plutonium Contamination for Canal Segments N23, N24, and N25

Identifier	Decision Rule
Panel Average	Excavate if the average simulated ^{238}Pu activity within this 3-ft by 3-ft panel exceeds 75 pCi/g with a probability level greater than 5 percent or exceeds 150 pCi/g with a probability of more than 1 percent.
Panel Maximum	Excavate if the ^{238}Pu activity of *any* 0.33-ft diameter soil “sample” within this 3-ft by 3-ft panel exceeds 75 pCi/g with a probability level greater than 5 percent or exceeds 150 pCi/g with a probability of more than 1 percent.

Results

Figure 7 examines the *likelihood*, given the available sample analyses, that the plutonium activity *averaged across any 3-ft by 3-ft selective remediation panel* exceeds the action levels specified for the Mound canal removal action. Because we have simulated adjoining 0.33-ft “sample-sized” volumes (fig. 6) across the entire 3-segment portion of the canal, we can easily compute a close approximation of the volume-upscaled activity using the arithmetic average of the simulated plutonium activity of the 3-ft÷0.33ft/sample=9×9=81 individual simulated values that are contained within a single remediation panel. Part (a) of figure 7 shows the color-coded probability that any given panel exceeds 75 pCi/g. The contour line encloses all those panels for which this probability is greater than 5 percent. Part (b) of the same figure is a similar probability map, only in this case the map represents the probability of exceeding 150 pCi/g, and the contour line encloses those panels that have a greater than 1 percent likelihood of so doing. The non-blue portions of part (c) of figure 7 simply show the union of parts (a) and (b), and may be considered an excavation map designed under the two-part criteria applicable to the canal project. The total volume of soil scheduled for excavation under this remediation plan is 5,872 ft^3.

Note that although the actual remediation criteria in effect at the Mound canal site is “not to exceed 150 pCi/g,” implying that the probability of exceeding 150 pCi/g should be precisely zero, this is a practical impossibility. The only mechanism to ensure that there is no probability whatsoever of exceeding 150 pCi/g is to remediate the entire canal area.

Figure 8 is a presentation identical to that of figure 7, only in this case we investigate the likelihood that any single sample taken within the 3-ft by 3-ft remediation panel exceeds the two-part

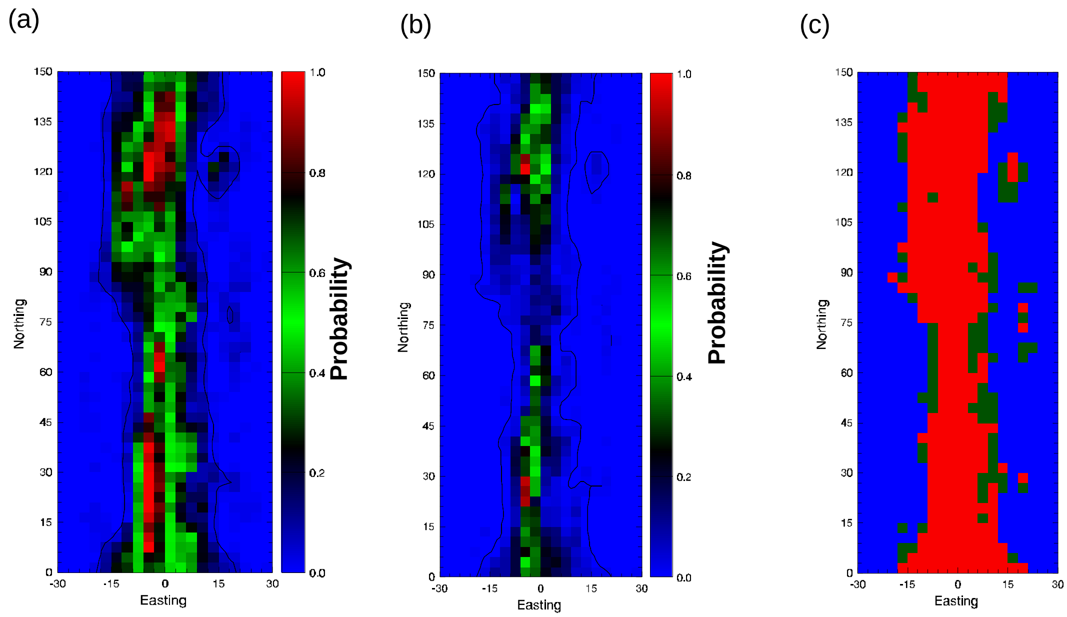


Figure 7. Probability maps constructed using true volume-averaged plutonium activity of 3-ft by 3-ft remediation panels showing likelihood of exceeding (a) 75 pCi/g (the contour line encloses those panels that have a greater than 5-percent risk of exceeding 75 pCi/g), and (b) 150 pCi/g (the contour line encloses those panels that have a greater than 1-percent risk of exceeding this activity). (c) Composite excavation map incorporating joint criteria.

remediation criterion. This decision rule may be characterized as a worst-case “hot-spot” method, as in a real-world implementation of the decision rule one would generally only take a single sample within the remediation panel, yet we assume that this single sample always identifies the highest plutonium activity. Part (a) of figure 8 is the probability of exceeding 75 pCi/g at a risk level of 5 percent, part (b) is the probability of exceeding 150 pCi/g with a risk level of 1 percent, and the non-blue portions of part (c) are the union of (a) and (b). The total volume of soil material to be excavated using this interpretation of the two-part remediation criterion is 12,163 ft^3.

Cost Minimization through Further Application of SmartSampling™

For the Mound canal removal action, threshold values for action levels and residual contamination had already been negotiated and agreed to by the various stakeholder parties. In fact, SmartSampling™ was designed with the intent of identifying, in collaboration with concerned and knowledgeable parties, the overall true minimum-cost remediation plan. This cost-minimization is achieved by balancing and trading-off against one another the various costs involved in characterization, remediation, and potential failure of the remediation effort to perform as desired. The cost equation is as follows:

$$\text{Minimize: } C_{total} = C_{char} + C_{remed} + C_{fail} \times P_{fail}\,, \qquad (1)$$

where C_{total} is the total cost of a given remediation alternative; C_{char} is the cost of site characterization and similar activities; C_{remed} is the cost of remediation including excavation, treatment, off-site disposal, and similar items; and C_{fail} is the cost of failure actually incurred if the remediation

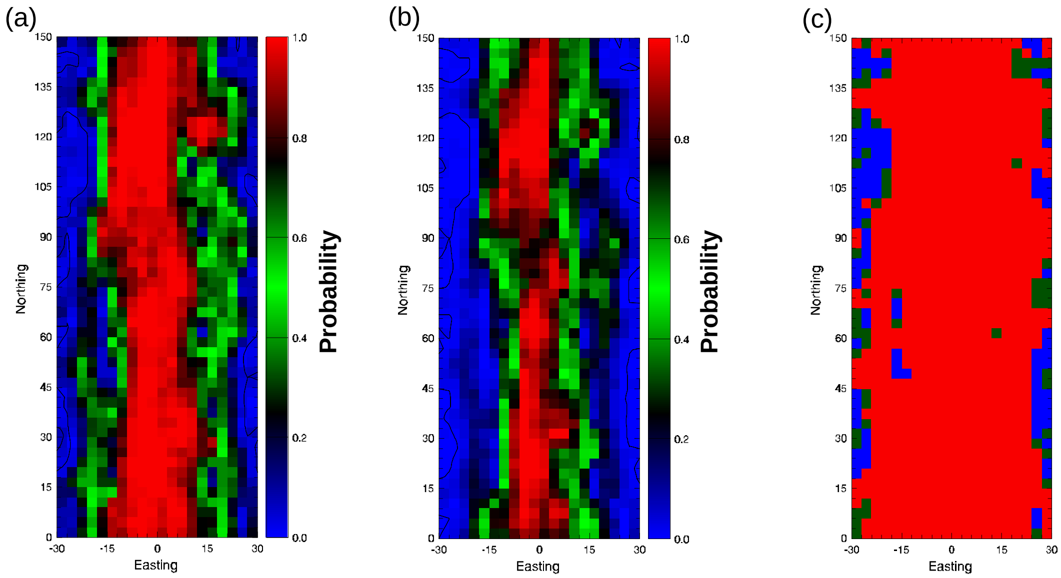


Figure 8. Probability maps constructed using maximum plutonium activity of 3-ft by 3-ft remediation panels showing likelihood of exceeding (a) 75 pCi/g at 5-percent risk and (b) 150 pCi/g at 1-percent risk. (c) Composite excavation map incorporating joint criteria.

effort is not successful. P_{fail} is the probability of such failure, and this term can be estimated empirically, yet quantitatively, through geostatistical methods. Note that the cost terms require estimates that reflect accurately and fairly *all* costs, both fixed and variable, associated with the various remediation alternatives being considered. In particular, the cost terms must include the costs to society, particularly with respect to the cost of failure. Costs and other assumptions used in this section are presented in table 3.

Table 3: Costs and Assumptions Used in Cost-Minimization

Assumption	Cost ($)
Panel size (selective remediation unit): 3 ft × 3 ft × 1.5 ft avg. depth = 13.5 ft^3	--
Remediation cost, initial, per ft^3 of soil: = $2.91 transp. + $0.24 car liner + $6.60 disposal + $1.48 O&M	11.23

Table 3: Costs and Assumptions Used in Cost-Minimization (Continued)

Assumption	Cost ($)
Re-remediation cost (upon failure), per ft^3 of soil (Pu activity ≤ 150 pCi/g): Cost factor × 2	22.46
Re-remediation cost (upon failure), per ft^3 of soil (Pu activity > 150 pCi/g): Cost factor × 5	56.15
Base-case excavation volume: based on cross-section profile of canal segment N-24, 64 ft^2 × 150 ft = 9600ft^3× $11.23.$ft^3$	$107,808
Plutonium contamination cannot be found outside the physical limits of the canal; therefore a set of "dummy" samples with zero activity have been placed at 10-ft intervals along the margins of the canal.	

Probability and the Expected Cost of Failure

Under the SmartSampling™ methodology, we hold that there is a finite probability that soil exceeding the stated regulatory levels has been left in-place after completion of the initial excavation plan. In the current instance, the probability that any one selective remediation unit is above 75 pCi/g is 5 percent, and above 150 pCi/g, 1 percent. Any such soil that does exist constitutes a "regulatory" failure. However, absent additional sampling, there is no means to determine which, if any, of the remaining selective remediation units in fact do exceed the action levels. It is possible, however, to examine probabilistically the likely, or expected, cost of regulatory failure at these (or any other) probability thresholds.

SmartSampling™ is based on the generation of a large number of physically plausible contaminant distribution fields, all of which are essentially identical statistically and indistinguishable objectively from our actual-but-limited knowledge of the true contaminant distribution. Collectively, these replicate simulations represent uncertainty. If we assume that excavation is completely effective (i.e., that after excavation, there can be no contaminant in that area), it is possible for each unexcavated remediation panel to count the fraction of the simulated contaminant fields that exceed the relevant threshold value(s), and to assign an "expected" dollar value to each such panel. If the likely cost of failure exceeds the likely cost of additional sampling (more generally, additional characterization), it may be worthwhile to obtain additional samples and determine whether or not the real-world remediation panel in fact passes or fails to meet regulatory criteria.

Because computers are good for performing repetitive calculations quickly, it is possible to "relax" the action level thresholds hypothetically, and to examine whether or not the current Mound canal remediation requirements actually reflect a minimum-cost clean-up alternative for society as a whole. For this exercise, we consider only variations in the risk-tolerance level, and we assume that we maintain the two-part action-level criterion such that the ratio between the risk accepted that the 150 pCi/g level is one-fifth (0.2) the risk associated with the lower 75 pCi/g threshold.

We have assumed (table 3) very modest dollar costs associated with regulatory failures. Specifically, we have assumed a cost factor of twice the basic remediation cost in the event that verification sampling identifies material indicates that soil exceeding 75 pCi/g (but not exceeding 150 pCi/g) has been left after initial excavation. This cost factor is somewhat arbitrary, but it is intended to capture the fact that some verification sampling (as many as 5 percent of the total number of such samples) is allowed to exceed this activity level without triggering "punitive" type damages. For verification sampling that exceeds 150 pCi/g, we have assumed a cost factor of times five. Again, the specific value is arbitrary, in that it is not based on accounting data. However, under a regulatory agreement of "…not to exceed…," the value is intended to capture the cost of re-excavating the offending area following surface restoration (it is presumed that the results of verification sampling are received following initial "closure" of the remediated canal), additional sampling to define more precisely the extent of the misclassified soil, and removing and disposing of this material.

Discussion

Comparison of Excavation Plans Under Current Standards

If we retain current action thresholds and risk levels, we find that there is a pronounced difference between the two decision rules defined in table 2. Note that under the first alternative interpretation, it is the average plutonium activity across the entire 3-ft×3-ft remediation panel that is critical in determining "success" or "failure." This alternative explicitly recognizes that smaller regions within the selective remediation unit may exhibit higher activities, but that such elevated activities are inconsequential below the 3-ft×3-ft physical scale. In contrast, the second alternative from table 2 emphasizes the "hot-spot" nature of individual 0.33-ft diameter soil volumes. Once such a hot-spot has been identified (we assume that somehow we are always able to find the "hottest" of each set of 81 possible soil samples), however, there is no alternative but to excavate the full selective remediation unit panel. Given the anticipated effects of scale-averaging and scale-maximization, the difference in the volumes of soil identified for excavation by the two approaches is not surprising.

The total volume of soil marked for excavation under the current regulatory thresholds assuming that volume-upscaling is acceptable is 5,872 ft^3, or 217 yd^3. If the total cost for excavation and removal of soil to off-site disposal is \$11.23/ft^3, the total remediation cost (*not* including any cost of failure) can be calculated as approximately \$65,900. The total volume of soil marked for excavation under the current regulatory thresholds, but assuming that decisions regarding remediation panel selection are made based on the hot-spot plutonium activity of a single (worst-case) 0.33-ft soil sample, is 12,163 ft^3, or 450 yd^3. For the same dollar cost for excavation and disposal, the cost of this remediation option is approximately \$136,600. Note that the difference of \$70,600 or 107 percent (slightly more than a factor of 2) is dependent solely on the basis upon which one decides whether or not to excavate a given panel.

Determination of Optimal Action Levels through SmartSampling™

The results of relaxing the regulatory action threshold values described above are shown in figure 9 for the case involving volume upscaling of activity levels. The cost information [fig. 9(a)] presents three cost curves corresponding to the latter two terms of equation (1) plus their total. The cost of characterization is omitted, as this component of total cost is not a function of risk-tolerance level. Also shown for comparison is the estimated total cost of remediation (\$107,800) for the three canal segments under the standard remediation plan for the entire canal. This standard cost also does not depend upon the risk-tolerance level accepted (risk and its associated expected cost of failure are not considered in the baseline plan).

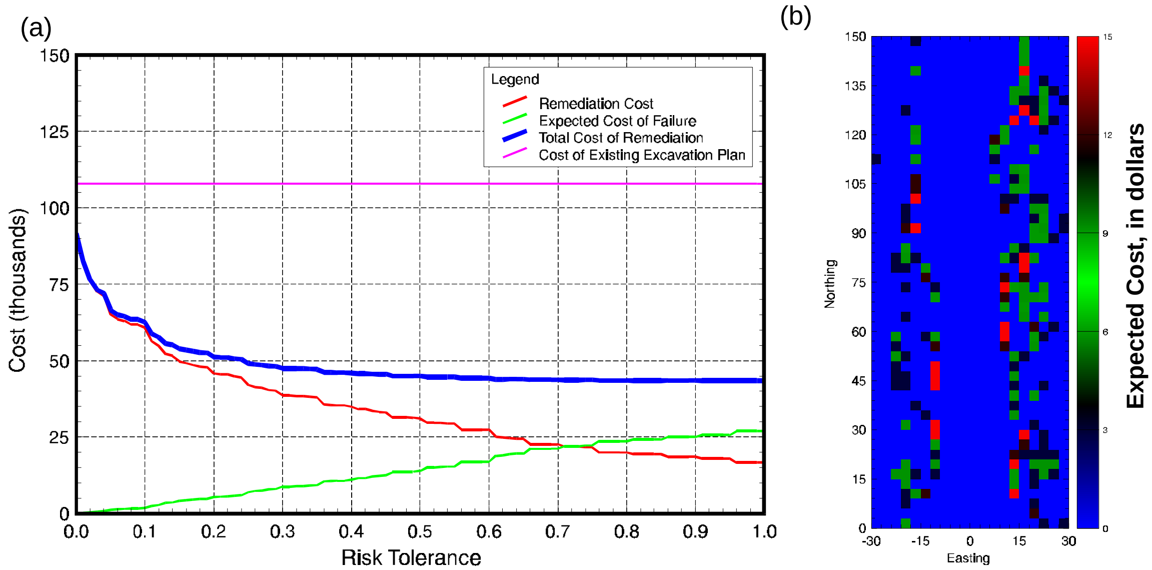


Figure 9. (a) Cost curves as a function of risk tolerance level and (b) map showing the expected cost of failure for upscaled remediation panels at the Mound canal site.

Part (b) of figure 9 is a map showing the spatially distributed expected cost of failure, computed empirically using the replicate simulated and upscaled plutonium-activity models and risk-tolerance-specific excavation plans.

Note that for very low risk-tolerance levels, the total cost of remediation under a SmartSampling™ approach appears to approach that of the baseline case. Note that although the difference it cost between a "clean-everything" risk level for the SmartSampling™ case and the baseline plan is related to relatively small differences in total volumes based on different post-excavation canal profiles, the more selective remediation approach of SmartSampling™ would appear to have allowed substantial reductions in cost. Note that under the costs assumed for this study (table 3), total costs decrease asymptotically to a constant value of approximately $44,000. We attribute this behavior of the cost curves to unrealistically low costs associated with potential failures.

Figure 10 presents the corresponding results for the case in which a panel is designated for excavation and remediation without considering volume-scaling effects. Part (a) of the figure presents the cost curves, whereas part (b) presents a map showing the spatially variable expected dollar-cost of failure term from the objective function. The larger area shaded blue in figure 10(b) compared with that in figure 9 is a function of the more severe original remediation criterion leading to a more extensive initial clean up.

Figure 11 presents an inventory curve, based on the upscaled remediation-panel activities, showing the number of contaminated panels and their corresponding remediation costs within the three canal segments as a function of the cumulative inventory of ^{238}Pu at selected action-limit

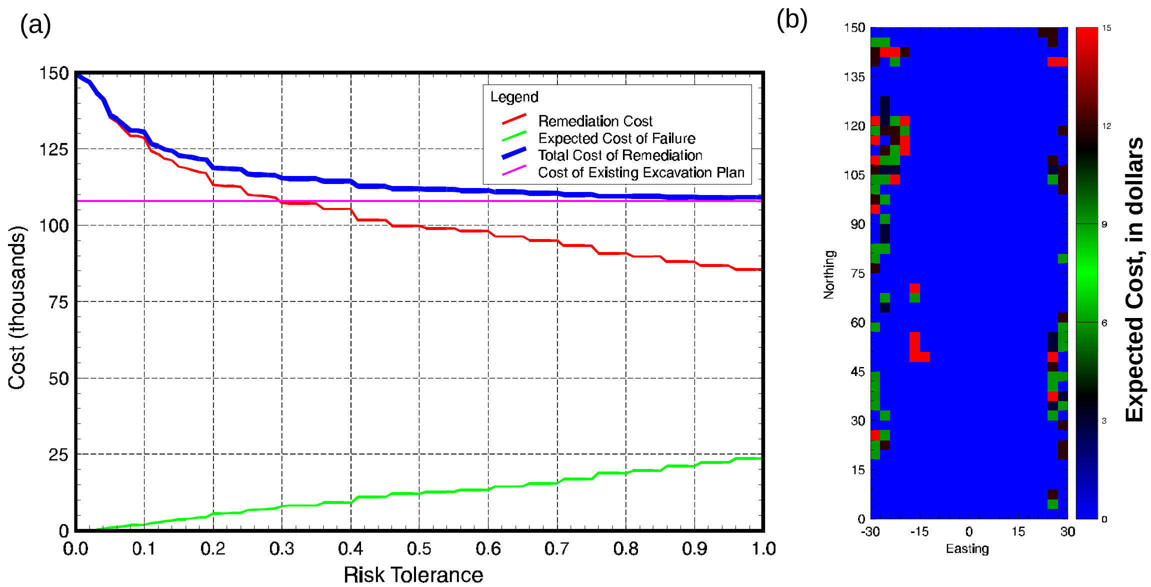


Figure 10. (a) Cost curves as a function of risk tolerance level and (b) map showing the expected cost of failure for remediation panels selected without consideration of sample upscaling at the Mound canal site.

threshold activities in increments of 20 pCi/g. This graph is a convenient means of visualizing the interaction of threshold plutonium activity and its effects both on the cumulative inventory of contaminant and the cost of the remediation effort. For example, the inventory curve of figure 11 indicates that if the action level for ^{238}Pu is 100 pCi/g, somewhat more than one-half (~55 percent) of the total inventory of ^{238}Pu can be removed at a cost of approximately $20,000. A more intensive clean-up effort involving decreasing the action level to 60 pCi/g ^{238}Pu will result in an increase in the fraction of plutonium inventory recovered of approximately 36 percent (to about three-quarters of the total, but the cost would increase roughly 65 percent to approximately $33,000.

Conclusions

The demonstration of SmartSampling™ during the Mound canal removal action has demonstrated that the baseline excavation plan contained in the Mound OU-4 100-percent design report may be excessively conservative and result in the unnecessary removal of significant volumes of soil for off-site disposal that do not exceed the regulatory action levels. Note, however, that this interpretation is wholly dependent upon the use of laboratory-scintillometry screening as the measurement technique and assumes that these measurements of ^{238}Pu activity are substantiated by the results of EPA-standard laboratory analyses.

More or less independently of the use of laboratory screening analytical methods, this demonstration indicates that significant differences in estimates of the volume of contaminated soil may result simply from different definitions of what constitutes a “sample” for purposes of decision-making. Soil volumes in this demonstration varied by a factor of two depending upon whether the determination was based on a single sample or represented a volume-averaged activity across the smallest possible remediation volume. Although ultimately such decisions must be tied closely to

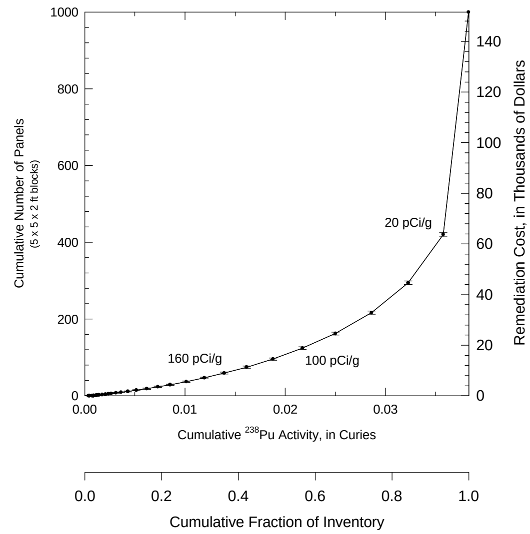


Figure 11. Inventory curve showing cumulative plutonium inventory for 3-ft × 3-ft remediation panels vs number of contaminated panels and approximate dollar cost at selected action-level thresholds.

the related health risks, the determination of action levels cannot be separated from the question of the support scale over which those action levels are to be measured.

Finally, under the cost assumptions employed in this analysis, it would appear that costs could be reduced substantially by accepting a lower level of risk tolerance than the "5 percent over 75 pCi/g–not-to-exceed 150 pCi/g" regulatory limits. If the costs of regulatory failure truly are as inconsequential as assumed, it would be far more cost effective for society to accept the more lax initial clean-up standard and to address remnant contamination on an as-needed basis. These cost functions, however, do illustrate the importance of quantifying actual costs rigorously, particularly the potential costs of failure.

References

Deutsch, C.V., and Journel, A.G., 1992, GSLIB geostatistical software library and user's guide, New York: Oxford University Press, 340 p.