EPRI Report: Review of Geostatistical Approaches to Characterization of Subsurface Contamination - 17442

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ABSTRACT

The key metric in the final release of a nuclear facility from radiological controls following plant decommissioning is the potential long-term radiation exposure to future users of the site. This is estimated from modeling of the exposure that could conceivably result from residual contamination remaining on the site in buildings, soil and groundwater after the completion of decontamination, dismantlement and remediation activities. A key input to such modelling is characterization data obtained from surveys and sampling.

To date, the regulatory guidance for conducting the final status survey required to show compliance with regulator approved site release limits (i.e., radionuclide concentrations or contamination levels) has been limited to surface contamination. EPRI has completed a project that provides guidance for use of geostatistics in the development of a site final status survey that will address the impact of dose to a future user of the site from subsurface contamination.

INTRODUCTION

EPRI has recently published a report (EPRI Report # 3002007554, *Guidance for Using Geostatistics in Developing a Site Final Status Survey Program for Plant Decommissioning*) that provides a background for the capabilities of geostatistics and how it could be cost-effectively used to help design characterization and final status surveys for subsurface areas at nuclear power plants (NPPs). The following summarizes the major subject areas of the EPRI report:

- Provide a theoretical introduction to the key concepts of geostatistics
- Review industrial applications of geostatistics outside of decommissioning at Nuclear Power Plants (NPPs)
- Review experience in the application of geostatistics at decommissioning sites
- Review available products for performing geostatistical analysis

- From the reviews above, derive guidance for using geostatistics to develop a site final status survey program
- Guidance related to application of geostatistics for other stages of decommissioning is also given, although not the central focus.

BACKGROUND

Statistical approaches such as described in MARSSIM (NUREG 1575) have typically been used in the US to design a characterization program and to evaluate the characterization results to show that radiation dose-based site release criteria have been satisfied. However, such approaches have historically explicitly considered characterization only of surface contamination. When performed, subsurface characterization has been addressed using non-standard, site-specific approaches.

This limitation of historical site characterization methodologies has prompted regulators worldwide (e.g., France, Spain and the US) to question handling of suspected or known subsurface contamination in verification of site release requirements. The nuclear power industry has worked to develop a more standardized approach to explicitly include subsurface contamination in the final status survey protocol. An example is the use of a geostatistical approach that uses spatial relationships to develop a three dimensional contamination map based on sampling and measurement results from discrete points. Use of geostatistics is well established in other fields, including mining, hydrogeology and environmental monitoring and would improve the technical basis for the release of a nuclear power plant site.

Challenges to Demonstrating Subsurface Compliance

Surface compliance frameworks often rely on surface scanning technologies to characterize the spatial variation of contamination. There is no analogous option for the subsurface in the current regulatory guidance. The extension from the surface to the subsurface increases the number of dimensions, resulting in generally sparser data sets. A framework is required that may make compliance possible in spite of spatial uncertainty.

The subsurface environment can present heterogeneity and complex processes which:

- Places new emphasis on integrating data-driven analysis with a conceptual or physical understanding of the environment
- Compounds the risk of hot spots in the subsurface environment

The subsurface sample design requires vertical characterization in addition to lateral characterization of contamination. This introduces complexities such as:

- The compliance network may need to accommodate different subsurface measurements, including those from core boring, laboratory samples collected at well locations, or borehole gamma logging
- Differences in the spatial variation in lateral directions versus the vertical direction need to be accounted for
- Sample costs increase, which places a premium on the empirical science used to derive information from samples
- The exposure pathways for subsurface contamination are distinct from the surface, including groundwater migration and excavation scenarios.

What is Geostatistics?

Geostatistics is a class of methods that can be used to:

- Infer patterns from spatially structured data using:
    - Sparse or large data sets
    - Structured or unstructured grids
    - Multidimensional spaces
- Make predictions at an arbitrary point (or manifold) in space, crediting spatial correlation. Many such predictions can be made to attain a virtually continuous representation of the spatial variable.
- Associate uncertainty with each prediction such as:
    - Large uncertainty in areas of considerable spatial variation or at large distances from measured data points
    - Low uncertainty near measured data points

The use of geostatistics is prevalent in a number of fields, including mining, oil and gas, hydrogeology, environmental monitoring, climate science, and epidemiology.

DISCUSSION

As part of the research performed under this project, EPRI reviewed a large set of geostatistical software products. These software products were appraised against factors such as:

- Cost

- User interface
- Flexibility
- Algorithm availability
- Visualization capabilities

The review extended to contemporary standalone software, contemporary libraries deployed by common programming languages, and software with historical precedent. Figure 1 provides a matrix which summarizes the results of the EPRI evaluation.

Software (Developer)	Cost	Dimensionality	Directed Workflow?	Exploratory Data Analysis	Sample Design / Optimization	Structural Analysis	Anisotropic Variograms	Point Kriging	Block Kriging	Universal Kriging	Co-Kriging	Indicator Kriging	Spatial-Temporal Krging	Discontinuities / Complex Geometries	Conditional Simulation	Cross-Validation	Fate and Transport Modeling	Dose Assessment	Geographical Information System	Highlights
ASCEM (U.S. DOE)	Proprietary	3D	n	n	n	n	n	n	n	n	n	n	n	n	n	y	y	n	n	model assimilation with flow and transport predictions
Earth Volumetric Studio (C Tech)	High	3D	n	y	y	y	y	y	n	n	n	y	n	n	n	n	n	n	y	block diagram interface, treatment of geological lithofication, borehole optimization
geoR and RGeostats (R Software)	Free	3D	n	y	n	y	y	y	y	y	y	y	n	y	y	y	n	n	n	exemplary combination of breadth and depth
Geostatistical Analyst (ESRI)	High	2D	y	y	n	y	y	y	n	y	y	y	n	n	y	y	n	n	y	high degree of user control, user-friendliness
GS+ (Gamma Design Software)	Low	2D	n	y	n	y	y	y	y	y	y	y	n	y	y	y	n	n	n	abundance of autocorrelation measures
GsTL (C++)	Free	3D	n	n	n	n	n	y	n	y	y	y	n	n	y	n	n	n	n	generic programming paradigm
HPGL (Python)	Free	3D	n	n	n	y	y	y	n	y	y	y	n	n	y	n	n	n	n	efficient and parallelized algorithms
HydroGeoAnalyst (Schlumberger)	High	3D	n	n	n	n	n	y	y	y	n	n	n	n	n	n	n	n	y	integrated data management utilities
Isatis (Geovariances)	High	3D	y	y	n	y	y	y	y	y	y	y	n	y	y	y	n	n	y	journal file, principal component analysis, abundance of variogram model forms, block kriging in complex subregions, suppored by active R&D
Kartotrak (Geovariances)	High	3D	y	y	y	y	n	y	n	n	y	n	n	n	n	n	n	n	y	real-time data streaming, highly structured workflow, MARSSIM and ISO 8550 sampling protocols
mGstat (MATLAB)	Free	3D	n	n	n	y	y	y	n	y	n	n	y	n	y	n	n	n	n	interfaces for gstat and SGeMS
Native command set (SAS)	Free	2D	n	y	n	y	y	y	n	y	n	n	n	n	y	n	n	n	n	automated exploration of many variograms
SADA (University of Tennessee)	Free	3D	y	y	y	y	y	y	n	n	y	y	n	n	y	y	n	y	y	area of concern maps, map arithmetic, sampling optimization, remediation cost-benefit analysis
SGeMS (Stanford)	Free	3D	n	y	n	y	y	y	y	y	y	y	n	n	y	n	n	n	n	optional command line interface, downscaling predictions, multiple-point geostatistics
Surfer (Golden Software)	Low	2D	n	y	n	y	y	y	y	y	n	n	n	y	n	y	n	n	y	native scripting language
T-Progs (Lawrence Livermore)	Free	3D	n	n	n	y	y	n	n	n	n	y	n	y	y	n	n	n	n	transition probability / Markov chain geostatistics
VSP (Pacific Northwest NL)	Free	2D	y	y	y	y	n	y	y	n	n	y	y	n	n	n	n	n	n	Walsh's outlier test, data quality objective (DQO) based sampling planning, economic analysis

Fig. 1 EPRI Evaluation of Selected Geostatistical Software Programs

As part of the EPRI research, a number of general and software-specific training opportunities provided by software vendors were identified. These included the following:

- C Tech routinely holds training for its Earth Volumetric Studio program

- Advanced Resources and Risk Technology - courses on geostatistics, using SGeMS
- Pacific Northwest National Laboratory - training sessions for the VSP software
- ESRI Inc. - web courses to support their GIS and geostatistical software
- Geovariances offers a number of different training opportunities to support their software products, including Isatis and Kartotrak
- The British Geological Survey offers a three-day course to provide an understanding of regionalized variable theory as the basis for geostatistics

There are also a number of conferences dedicated to geostatistical analysis such as:

- The International Geostatistical Congress
- The International Conference on Geostatistics for Environmental Application
- The European Forum for Geography and Statistics
- The International Association for Mathematical Geosciences

Case Study of the Use of Geostatistics

In the course of the EPRI project, a number of experiences with the use of geostatistics were reviewed. One case study involved the investigation of the Upper Trenton Channel on the Detroit River which had shown contamination of sediments with Polychlorinated Biphenyl's (PCPs), mercury and Polyaromatic Hydrocarbons (PAHs). To inform remedial options, the U.S. Environmental Protection Agency Great Lakes National Program Office has collected samples and applied geostatistical analysis. The EPA work developed 3D geostatistical maps of contaminant concentration and used these to visualize the spatial distribution, identify hot spots, determine secondary sample locations, and inform remediation. Figure 2 shows some of the results of that mapping.

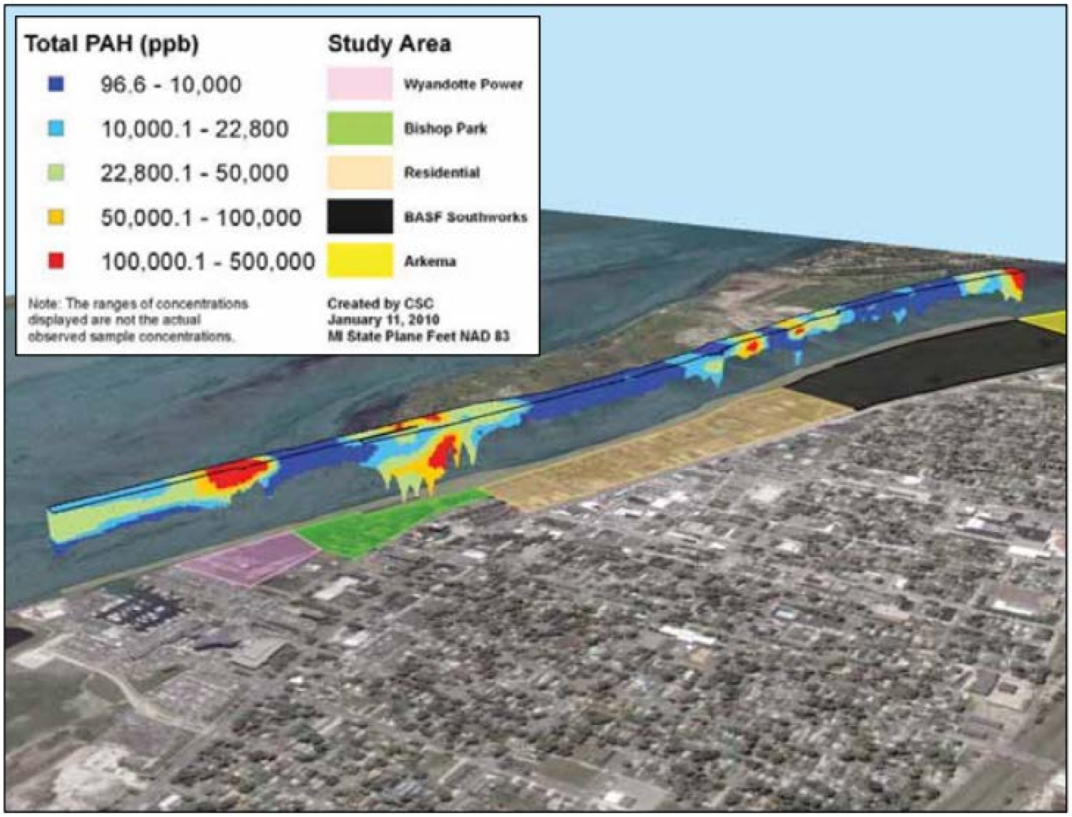

Fig. 2 Sample Results for PAHs in the Upper Trenton Channel

The geostatistical analysis also predicted the probability of exceeding at least one threshold of concern, across the three studied contaminants, as a function of location. Figure 3 shows the results of that probability analysis. Based on the probability of exceedance map, remediation costs were estimated.

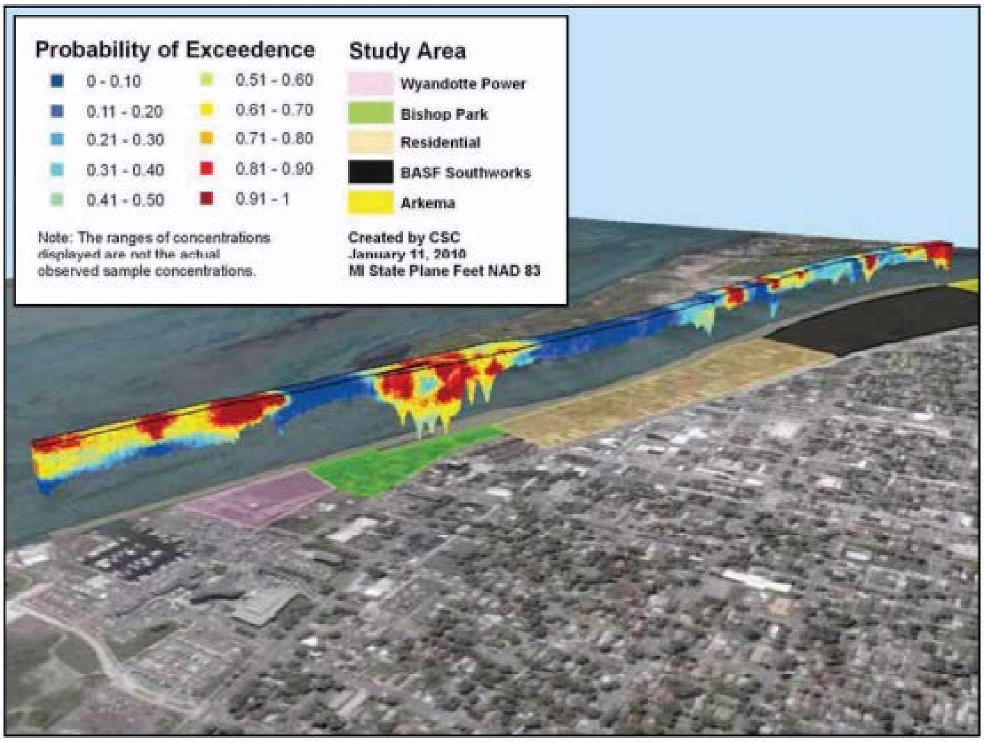

Fig. 3 Probability of exceeding a threshold of concern for the Upper Trenton Channel

Summary of EPRI Guidance

In the previously mentioned EPRI report on geostatistics, there is a roadmap identifying:

- The major phases of geostatistical analysis
- Steps within each phase
- Key questions associated with each step
- Figure 4 shows the actions in each of the roadmap steps

The EPRI report also includes recommendations for a subsurface compliance framework.

Roadmap Phase	**Steps Associated with Phase**
Preliminary Steps	■ Perform conventional site characterization steps ■ Educate site characterization team on geospatial data characteristics ■ Select software to support geostatistical analysis ■ Develop expertise with selected software
Exploratory Data Analysis	■ Define and format data for geostatistical analysis ■ Visualize and consolidate data ■ Perform statistical analysis ■ Assess data for violations of the constraints of geostatistical methods ■ Assess inter-variable correlation ■ Perform data manipulation
Structural Analysis	■ Study spatial structure empirically ■ Fit the analytical variogram ■ Assess anisotropy ■ Perform structural analysis for multiple regionalized variables
Geostatistical Interpolation	■ Design the prediction grid ■ Select a geostatistical interpolation method ■ Design the search neighborhood ■ Execute geostatistical interpolation
Post-Processing Steps	■ Perform inverse transformation ■ Perform cross-validation ■ Perform sensitivity testing ■ Apply geostatistical interpolation results ■ Apply results to demonstrate compliance of subsurface contamination ■ Report the geostatistical analysis

Fig. 4 EPRI Guidance – Roadmap for Using Geostatistics for Subsurface FSS Design

CONCLUSSIONS

The use of geostatistics addresses numerous challenges associated with subsurface compliance demonstration and provides additional insight to augment existing procedures for surface characterization. Various nuclear regulators have acknowledged the use of geostatistics as a valid response to challenges associated with subsurface characterization:

- In 2012, the U.S. NRC published NUREG-7021, which endorses the use of geostatistics for decommissioning applications

- In 2016, the CEA published an ISO standard articulating a set of principles, including geostatistical analysis, for sampling strategy and characterization of soils, buildings, and infrastructures

Geostatistics has been deployed for decommissioning nuclear plants, laboratories and research facilities in France, Spain, and Belgium, among other countries, leading to tangible cost savings. At the Brennilis and Chooz A decommissioning sites, for instance, geostatistics has been used to optimize remediation and excavation activities.

Geostatistical analysis has the potential to become a tool deployed for characterization of radionuclides in various media (e.g., concrete, vadose zone, groundwater, surface water) and at various stages of the plant life cycle (e.g., operational monitoring, decontamination/remediation planning, final status survey).

The EPRI report (# 3002007554 published in 2016) mentioned above:

- Captures the concepts of geostatistics
- Illustrated experiences with the use of geostatistics
- Provides a roadmap for the use of geostatistics for subsurface characterization and compliance surveys

REFERENCES

1. EPRI Report # 3002007554, *Guidance for Using Geostatistics in Developing a Site Final Status Survey Program for Plant Decommissioning*, Palo Alto, CA: 2016.
2. NRC Regulations Title 10 CFR 20, Standards for Protection Against Radiation. Subpart E, Radiological Criteria for License Termination. [NRC ADAMS Accession No. ML003676463]
3. “Release of Sites from Regulatory Control on Termination of Practices,” International Atomic Energy Agency No. WS-G-5.1, 2006.
4. EPRI Report # 1025315, *Technical Bases for the Development and Application of Derived Concentration Guidance Levels for Decommissioning and License Termination of Nuclear Power Plants*, Palo Alto, CA: 2012.
5. U.S. Nuclear Regulatory Commission. Office of Nuclear Regulatory Research. *A Subsurface Decision Model for Supporting Environmental Compliance* NUREG/CR-7021, 2012. [NRC ADAMS Accession No. ML12026A022]

6. U.S. Nuclear Regulatory Commission. NUREG-1575/EPA 402-R-97-016, *Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM)*, *Revision 1*, 2000. [NRC ADAMS Accession No. ML003761445]

7. U.S. Environmental Protection Agency. Office of Emergency and Remedial Response. "Guidance on Surface Soil Cleanup at Hazardous Waste Sites. Implementing Clean Up Levels," EPA 9335.0-01, April 2005.

8. U.S. Nuclear Regulatory Commission. Office of Nuclear Material Safety and Safeguards. *Consolidated Decommissioning Guidance. Characterization, Survey, and Determination of Radiological Criteria, Volume 2, Revision 1*, NUREG-1757, Washington, D.C., 2006. [NRC ADAMS Accession No. ML14093A221]

9. EPRI Report # 1015500, *Final Status Survey and Site Release Experience Report*, Palo Alto, CA: March 2008.