Geostatistics for radiological characterization: overview and application cases

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ASTRACT

The objective of radiological characterization is to find a suitable balance between gathering data (constrained by cost, deadlines, accessibility or radiation) and managing the issues (waste volumes, levels of activity or exposure). It is necessary to have enough information to have confidence in the results without multiplying useless data.

Geostatistics processing of data considers all available pieces of information: historical data, non-destructive measurements and laboratory analyses of samples. The spatial structure modelling is then used to produce maps and to estimate the extent of radioactive contamination (surface and depth). Quantifications of local and global uncertainties are powerful decision-making tools for better management of remediation projects at contaminated sites, and for decontamination and dismantling projects at nuclear facilities. They can be used to identify hot spots, estimate contamination of surfaces and volumes, classify radioactive waste according to thresholds, estimate source terms, and so on.

The spatial structure of radioactive contamination makes the optimization of sampling (number and position of data points) particularly important. Geostatistics methodology can help determine the initial mesh size and reduce estimation uncertainties.

Several show cases are presented to illustrate why and how geostatistics can be applied to a range of radiological characterization where investigated units can represent very small areas (a few m2 or a few m3) or very large sites (at a country scale). The focus is then put on experience gained over years in the use of geostatistics and sampling optimization.

Introduction

Dismantling and decommissioning of nuclear facilities or remediation of contaminated sites are industrial projects with huge challenges. Precise knowledge of the contamination state is required. Radiological evaluations have multiple objectives to be considered: determination of average activity levels, to allow the categorization of surfaces or volumes (sorted into different radioactive waste categories); location of hot spots (small areas with significant activity levels); and estimation of the source term (total activity) contained in soils or building structures. In addition there are radiation protection and other logistics considerations.

Estimates are essential for the proper management of these projects. Currently, characterization remains relatively empirical. Accumulated approximations often have serious consequences that threaten the project's successful completion, for example through over-categorization or unexpected contamination.

Radioactive contamination is generally complex and involves numerous parameters: radiological fingerprint, transfer path, type of contaminated materials, presence of different matrices (soils, concrete), and so on. Numerical modelling often turns out to be very difficult.

The characterization phase should be efficient and the sampling strategy has to be rational. However, investigations also represent capital expenditure; the cost of radiation protection constraints and laboratory analysis can be thousands of Euros, depending on the radionuclide. Therefore the entire sampling strategy should be optimized to reduce useless samples and unnecessary measures [1].

The geostatistical approach, which provides consistent estimates and reliable maps, is an appropriate solution for data analysis. Geostatistics aims to describe structured phenomena in space, possibly in time, and to quantify global or local estimation uncertainties. Estimates are calculated from a partial sampling and result in different representations of the contamination, including interpolation mapping (by an algorithm called 'kriging'). But the added value of geostatistics goes beyond this. Its benefit is its ability to quantify estimation uncertainty and provide risk analysis for decision making.

Applied to radioactive contamination, this data analysis and data processing framework is novel. However, it has been used for more than 50 years by the mining industry for resource assessment, the oil and gas sector for reservoir characterization and in recent decades for environmental issues such as hydrogeology, air quality monitoring, conventional pollutants (heavy metals, hydrocarbons), soil science, and so on. It is now increasingly used to characterize radioactive contamination in nuclear facilities, sites and soils.

Spatial structure and variography

Geostatistics assumes spatial continuity for radioactive contamination [2]. Variability behavior over distance between data points is the spatial signature of the phenomenon being studied. This spatial structure is analysed and interpreted through the variogram, which plots the average variation between pairs of points. Typically for a structured phenomenon, this variability increases gradually and stabilizes at a certain sill for a characteristic distance called 'range'.

Figure 1 illustrates three phenomena with the same statistical characteristics (in terms of a histogram). However they have very different spatial organization (variograms):

- On the left, a spatial random phenomenon with a pure nugget model as a variogram, in which the variability equals the experimental variance whatever the distance. Even for two very close points, the variability is very high. It can be the case for contaminated materials from different origins in trenches. In that case, geostatistics will only give the same results as classical statistics.
- In the center, a largely continuous phenomenon with a linear increase in variability at small scale, then a sill at 15m range. This case is quite common with radiological contaminations (soils, concrete…).

- On the right, a continuous phenomenon with a progressive increase in variability at small scale, then a sill at 15m range. This case can be faced with phenomenon that can partly be modelled deterministically (activation, dispersion plume, contaminated groundwater…).

The variogram, which is based on data, allows the interpretation and modelling of the spatial continuity of the phenomenon. This spatial structure is crucial for the overall geostatistical approach. Contrary to datasets presented in Figure 1, values are generally sparsely available (punctual points, regular grid, random locations…) and the experimental variogram is fitted to interpret and model the spatial structure.

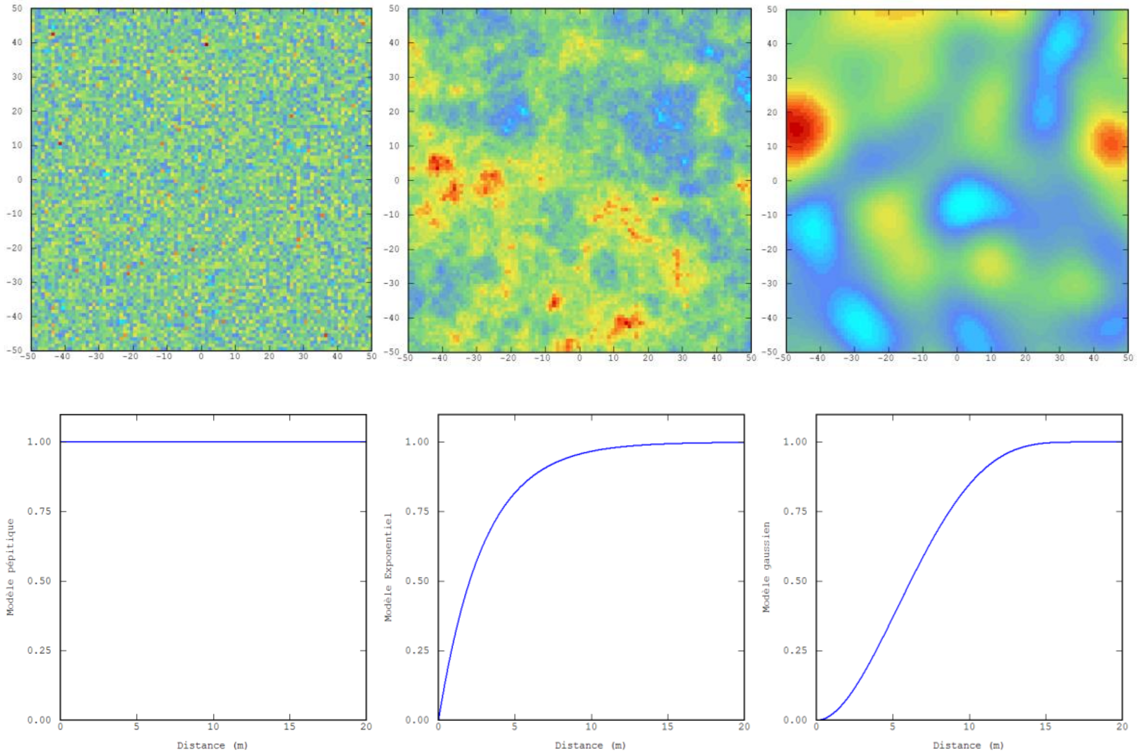

Figure 1: Three phenomena with the same statistical distribution (on the top)
but with significantly different spatial structures (corresponding variograms on the bottom part)

Interpolation and uncertainty quantification

With input data and the spatial structure identified through the variogram, geostatistical techniques estimate the studied variable by a method similar to regression analysis called kriging (best linear unbiased estimator). This always includes a quantification of the associated uncertainty.

More advanced and sophisticated geostatistical methods, such as conditional expectation or geostatistical simulations, can be used to quantify different uncertainties—risk of exceeding the threshold, for instance. These estimates are powerful decision-making aids when classifying surfaces and volumes before decontamination starts (based on different thresholds as well as considering the remediation support impact).

Finally, multivariate geostatistics allows different kinds of information to be combined to improve estimates, using the spatial correlations between variables. Physical and historical data and non-destructive measurement results (for example dose rate or in situ gamma spectrometry) are integrated to improve understanding and prediction of the main variable (results of laboratory analysis, for example) while reducing the estimation uncertainty.

Data consolidation and geostatistics

To use geostatistics, datasets must be consistent for correct data processing: the same sampling protocol must be used, measurement or analysis must be performed in a short period if the decay rate is sensitive; data of the same type must be expressed in the same unit, and so on.

This may seem obvious, but a lot of time can be lost in correcting errors and ensuring that the data are really consistent: coordinates, dates, units, physical and radiological heterogeneities, etc. A strong exploratory data analysis enables identifying and correcting these inconsistencies thank to statistical and geostatistical visual tools: basemap, histogram, correlation, variographic cloud, as presented in Figure 2:

- Left picture is the base map of a GPS record (real-time acquisition while walking). Trace deviation and coordinates inside surrounding building are identified and require preliminary corrections according to sampling number for instance (two consecutive points are expected to be at a distance of a few tens of centimers).

- Middle picture shows correlation between elevations of a unique geological unit according to two interpretations of core logs. Points are expected to be along the first bisector line. Red squares and blue stars (far from this diagonal black line) require explanations and possibly corrections.

- Right picture shows the correlation between two nuclides. For a unique fingerprint, all points should be approximately lined up. In this case one point (red square) seems to be an outlier (real outlier?, or a factor ten mistyping in the input file (decimal separator not correctly located)?) and a dozen of points shows proportionally higher Co-60 activity level than Cs-137 in comparison to the rest of datapoints.

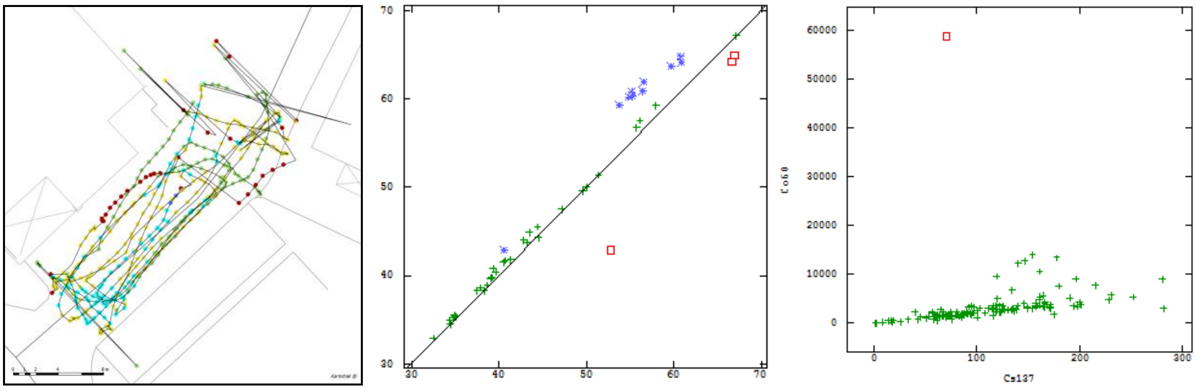

Figure 2: Examples of datasets that require preliminary correction before geostatistics processing (GPS coordinates, elevation deviation between two campaigns, outliers from nuclide correlation).

The support effect

Non-destructive assays or destructive samples must be associated with a physical attribute. For example, materials collected with samples may represent a few grams or a few kilograms; they can be collected at a single location or over a large area.

This is referred to as the ‘support effect’ and it has a direct impact on the spatial structure identified in the variogram. Figure 3 illustrates this regularizing influence with a phenomenon that is similar to the intermediate case in Figure 1. Three cases are shown: 1x1 pixel, 3x3 pixels and 5x5 pixels. First, the overall variability (statistical variance, shown as dotted horizontal line) decreases. In addition, with the increasing size of the support effect, the variogram slope at small scale decreases as well. These differences are not related to the phenomenon itself, but stem from the measuring conditions. With the pure random case (left illustration in Figure 1), the support effect is most important, while it is almost negligible in the most continuous case (right illustration in Figure 1).

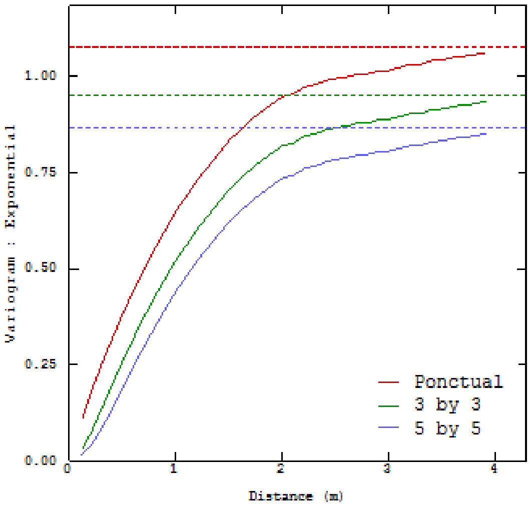

Figure 3: Support effect impact on spatial structure. Dashed line: experimental variance.

The way the data is sampled (whether the measured surface or the sample size) therefore affects collected values. The phenomenon’s spatial structure should influence the measurement or sampling technique selection.

Sampling optimization

With geostatistics, three sequential phases are optimally used to characterize contamination:

- Historical and functional analysis, based on operation records and former operators’ testimonies
- Radiation maps from non-destructive measurements, where possible. These are usually semi-quantitative values, providing contamination spatialization
- Characterization of activity levels and depth profiles by collecting samples by coring, hammering, and so on, for laboratory analysis.

Each step can be repeated, to reach acceptable levels of confidence or precision. With radiation mapping, prior information about spatial structures of radioactive contamination is used to determine the initial sampling mesh. By default for soils, 200 data points per hectare (corresponding to a 7 m mesh size) allows a first analysis of the phenomenon spatial structure for contaminated soils around nuclear facilities. This initial mesh may range from 5 m to 10 m according to the available information (historical and functional analyses, prior measurements…). More generally, with larger size for example, the tenth or the twentieth of the site size is a good candidate for the initial mesh size of the regular grid[1]. For building structures (mainly concrete) a 1 m mesh size may be relevant to conduct a first geostatistical analysis. Similarly, this size has to be adapted to the size of the building, the stakes and the expected spatial structure.

Adding extra data points is a then good way to reduce estimation uncertainty. This is quickly obtained by analyzing early mapping results. For geometric uncertainties, the kriging error variance easily identifies areas with a lower sampling density. For high variability areas, the confidence interval around the estimated value is used to detect, for instance, the boundaries of contaminated areas.

For probability results, the risk of exceeding a given threshold allows surfaces or volumes to be categorized in order to optimize radioactive waste management. Figure 4 illustrates the use of a probability of exceeding a threshold to identify an area misclassification risk [3]. This nuclear facility surface area is 800 m2. Surface contamination measurements were made using a regular grid with a 66 cm mesh. Fifty sampling points were used to collect samples for laboratory analysis. Here, the risk under study is the false negative, in which an area is declared to be below the threshold using estimate results, but in reality exceeds the threshold. Additional sample points can be intelligently allocated. Depending on the threshold, acceptable risks may vary and identified areas will change.

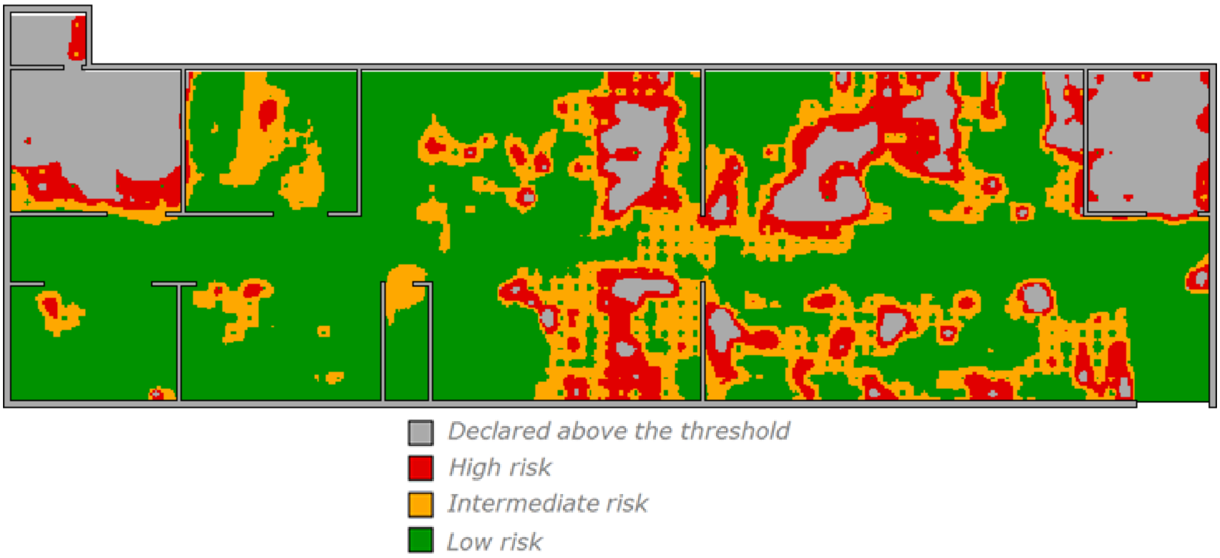

Figure 4: Map of the false negative risk (declaration of a contaminated area as clean).

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[1] To map the Fukushima accident at the NPP scale, a 20 m to 30 m mesh size makes possible the localisation and mapping of irradiating areas (projected debris) to prioritize materials to be removed and radiological protection for workers. At a larger scale, still for Fukushima accident (third example of Figure 5), a 20 km to 30 km mesh size makes it possible to identify contaminated areas (atmospheric fallout) to determine exclusion zones, evacuation zones and monitored zones at Japan scale.

Various application cases

Geostatistics can be applied to a range of radiological characterization. The only limitation is the quality of the input data, since they are fundamental to describing spatial structure of the phenomenon. Geostatistics maps can cover very small areas (a few m2 or a few m3) or very large sites (at a country scale) as presented in Figure 5. Corresponding references are cited for more details.

- Top picture: For an area of about 400 m^2 and to a depth of 10 m, 20 drill holes were made to take samples every 30 cm or 50 cm at a former army fort [4]. Characterizing this in-depth contamination gives a better understanding of its extent, and integrating it with the ancient topography, allows radioactive waste production to be optimized. Samples have been collected in four drilling campaigns (in a 10 year period). This iterative process enables the optimization of the number and localization of each additional borehole. Without this important characterization stage, the initial contamination spot found at 4 meters below ground surface would not have been correctly remediated as it is in fact the upper part of a deeper contamination (remediation works and forecasted waste volumes would have been significantly underestimated).

- Bottom left picture: In a nuclear facility under decommissioning, dose rate measurements were collected according to a regular grid (1.5 m mesh) over a total area of 1,500 m2 on two levels [5]. Assessing the structures and identifying contaminated areas helped determine sample locations to characterize concrete contamination. These 2D radiation maps inversed the initial samples repartition (15 in the basement level and 5 in the first floor level) based on history and expected activity levels. Geostatistics demonstrates than contamination in the basement level was very continuous while some singular spots in the first floor required more destructive sampling at the end.

- Bottom right picture: On the basis of about 2,000 dose rate measurements within a radius of 150 km around the Fukushima Daiichi nuclear power plant, mainly in the closest 80 km, a post-accident mapping exercise identified under-investigated areas in relation to population exposure limits. Integrating the topography also helped interpret the atmospheric dispersion and deposition of radioactive dust on the ground. Using geostatistics during the acquisition campaign (which has not been the case) would have given a different and optimized repartition of measurement points, initially localized according to circular grids.

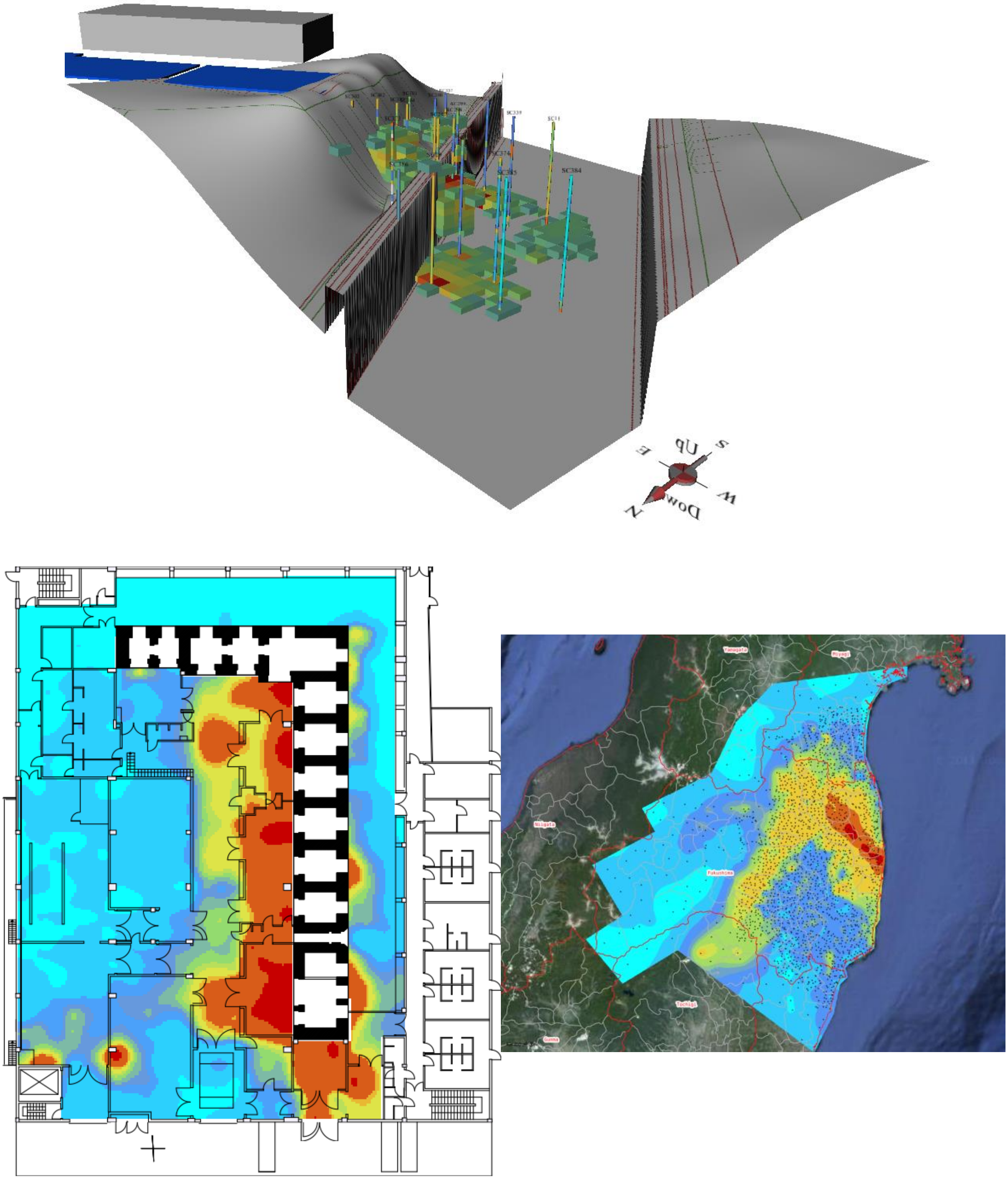

Figure 5: Application cases of geostatistics with in-depth contamination, building structure characterization and post-accident mapping

Conclusion

The objective of radiological characterization is to find a suitable balance between gathering data (constrained by cost, deadlines, accessibility or radiation) and managing the issues (waste volumes, levels of activity or exposure). It is necessary to have enough information to have confidence in the results without multiplying useless data. Geostatistical data processing considers all available pieces of information: historical data, non-destructive measurements and laboratory analyses of samples. The spatial structure modeling is then used to produce maps and to estimate the extent of radioactive contamination (surface and depth). Quantifications of local and global uncertainties are powerful decision-making tools for better management of remediation projects at contaminated sites, and for decontamination and dismantling projects at nuclear facilities. They can be used to identify hot spots, estimate contamination of surfaces and volumes, classify radioactive waste according to thresholds, estimate source terms, and so on.

The spatial structure of radioactive contamination makes the optimization of sampling (number and position of data points) particularly important. Geostatistical data can help determine the initial mesh size and reduce estimation uncertainties.

In addition geostatistics is a very powerful tool to analyze, consolidate and give value to collected pieces of information. The exploratory data analysis, in combination with the spatial structure interpretation (variogram) is probably the most interesting part of the characterization.

References

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[3] Bechler, A., Romary, T., Jeannee, N., Desnoyers, Y., Geostatistical sampling optimization of contaminated facilities, in Stochastic Environmental Research and Risk Assessment (December 2013) Volume 27, Issue 8, pp 1967-1974.C. Name3, D.E. Name4, "Title of the second publication", *Other Rev. Name* **12**, 59-65, 2015.

[4] Desnoyers, Y., De Moura, P., Characterization of a deep radiological contamination: integration of geostatistical processing and historical data, in Proc. of ICEM 2011 congress, in press, Reims, France

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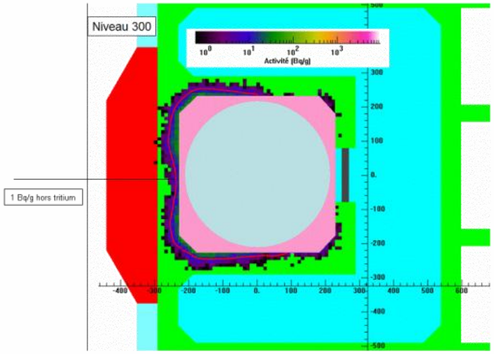
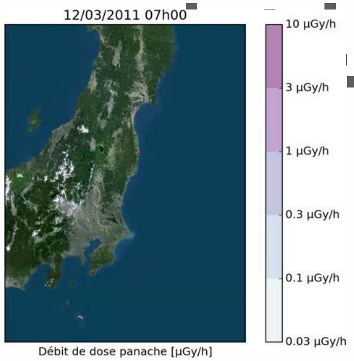
Geovariances

Data processing: where is the model?

- Deterministic models
  - Based on physical behavior / mathematical formulae
  - Calibration on data
  - Examples: migration, activation, flow transport…



SILOE Reactor: Activation model of the concrete pool block
Source: DAPNIA



Atmospheric spreading Fukushima
Source: IRSN

- Added values of geostatistics
  - The model is within the data!
  - Implemented in the methodology for the radiological waste characterization in former nuclear facilities (site, building and equipment) thanks to uncertainty quantification
  - Sampling optimization according to spatial structure inventory

Spatial structure: central point of geostatistics

- Geo + Statistics: integration of the phenomenon spatial continuity
- Main tool of geostatistics: the variogram
  (describes the variability between 2 points)
  - on average, the difference between two CLOSE measures is LOW
  - on average, the difference between two DISTANT measures is HIGH

$$\gamma(h) = \frac{1}{2} E\left[Z(x) - Z(x+h)\right]^2$$

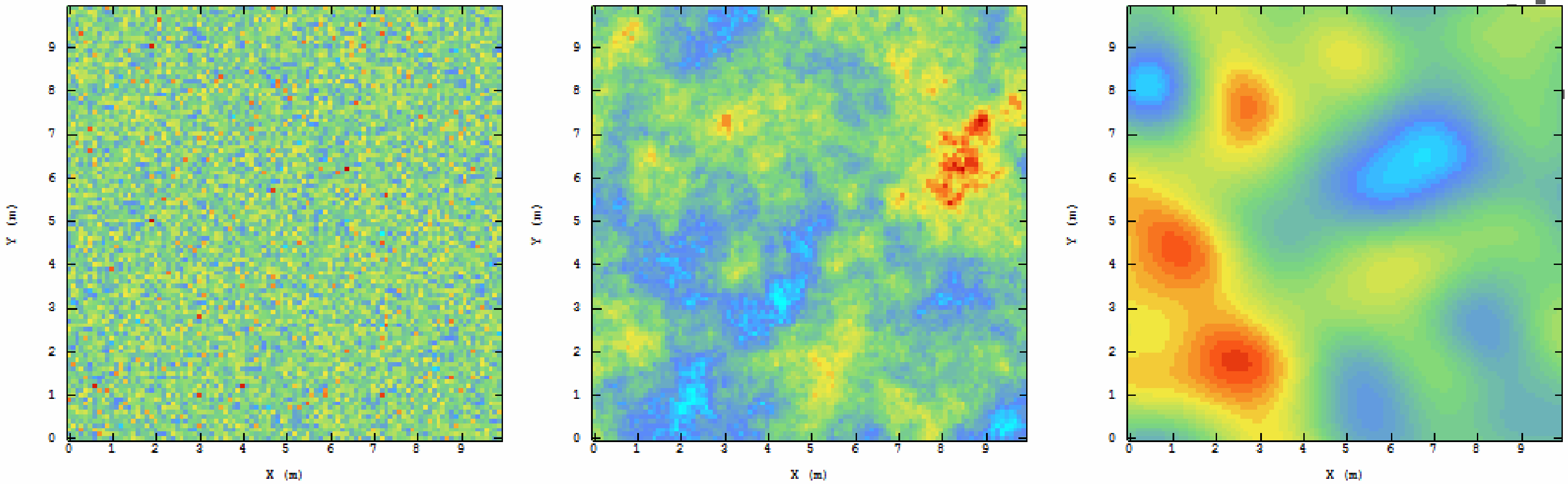
- The way the variogram increases with distance is linked to the phenomenon spatial variability

Model

Experimental

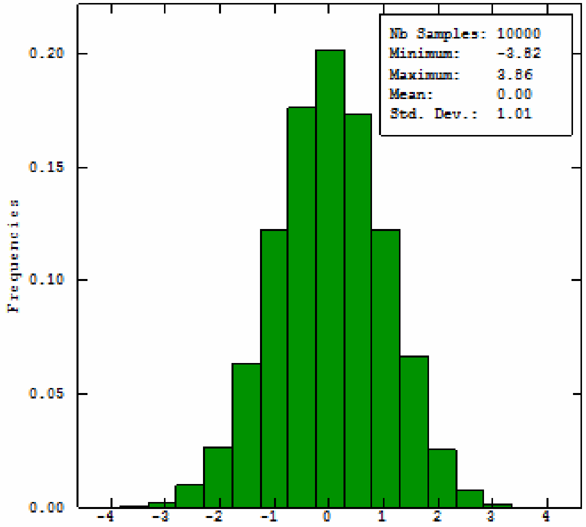
Spatial structure analysis: experimental variogram and its modelling

Variograms of three examples

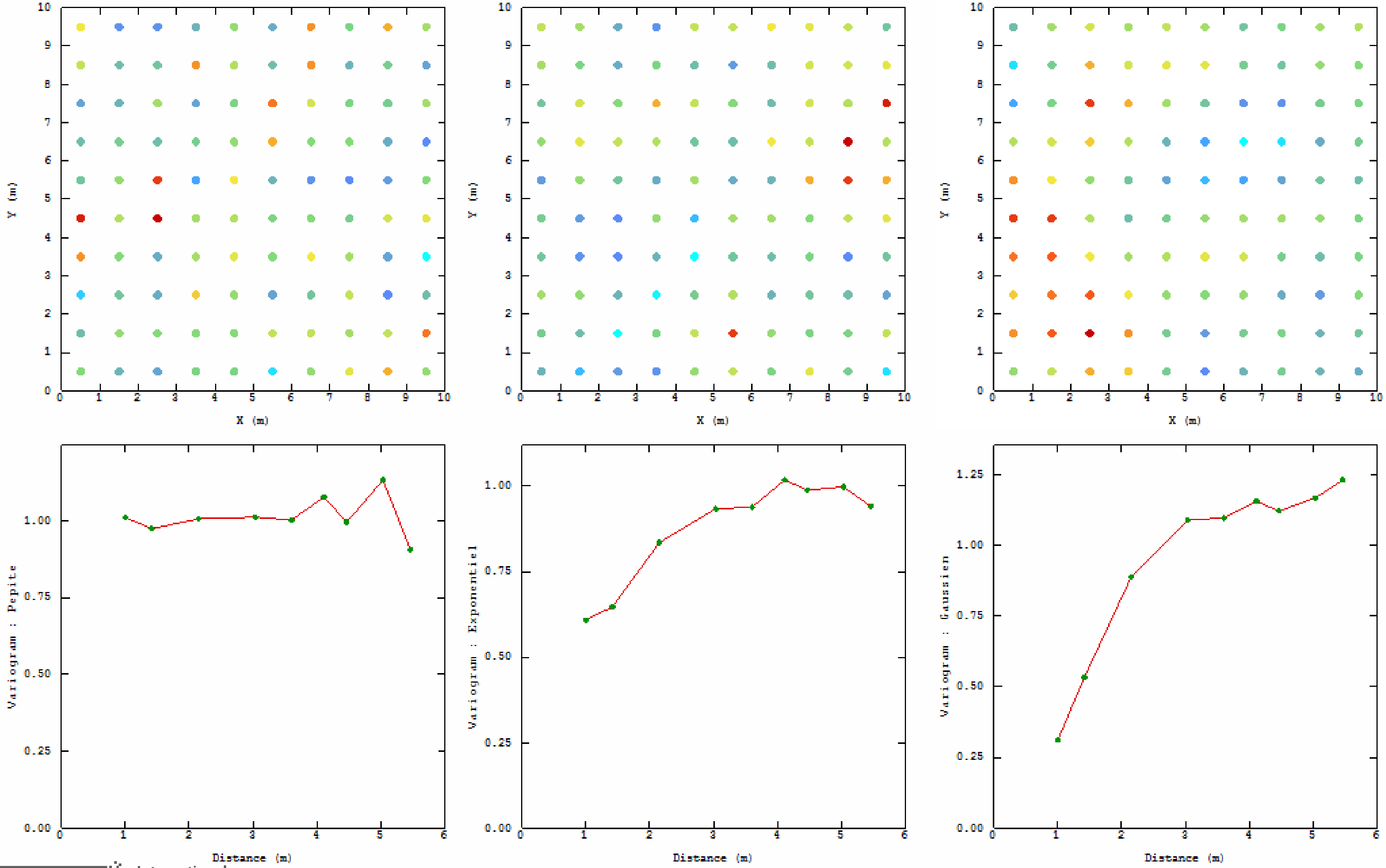


- Three spatial phenomena with the same statistical distribution

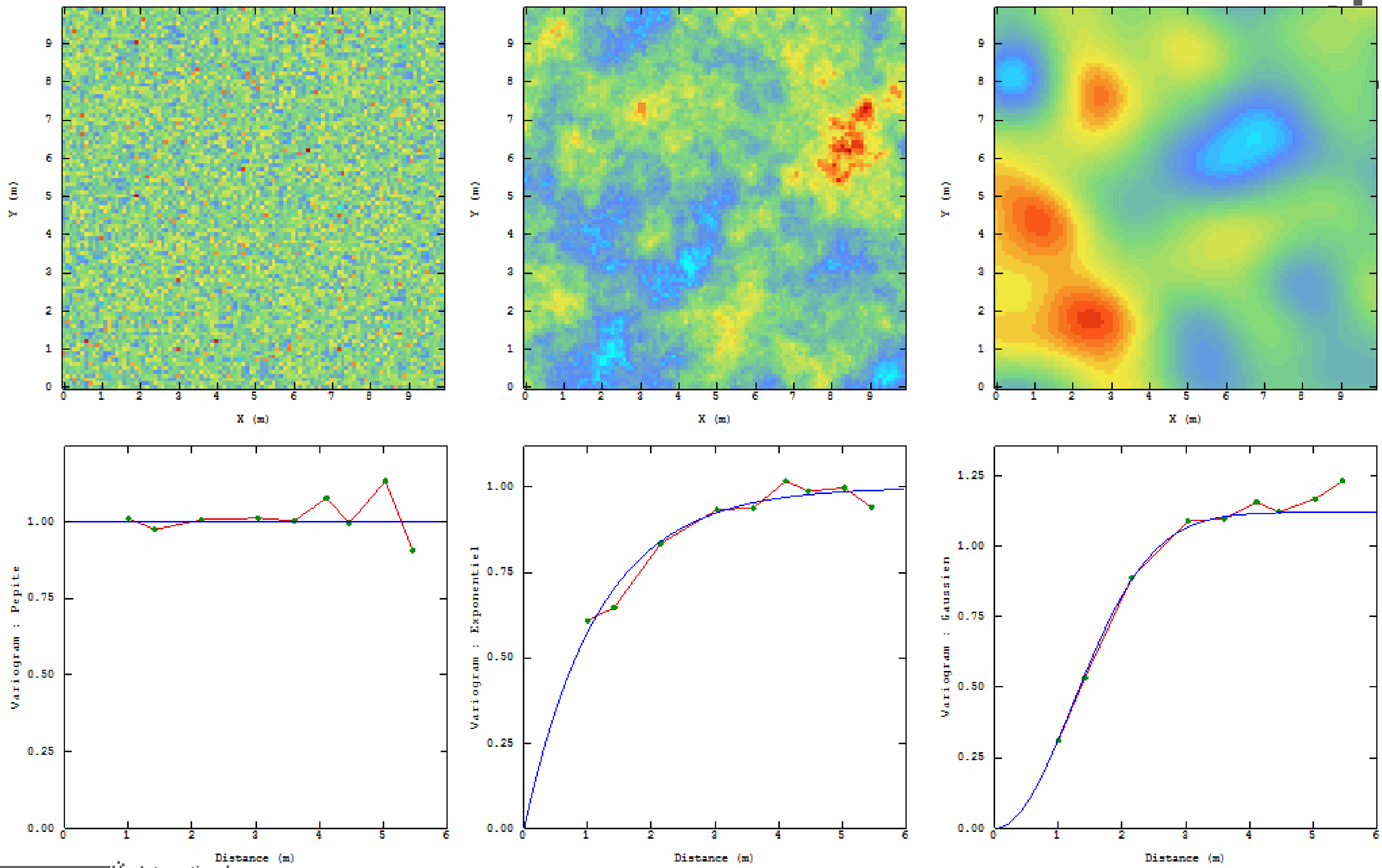
- Characterisation of the spatial structure thanks to a regular sampling grid



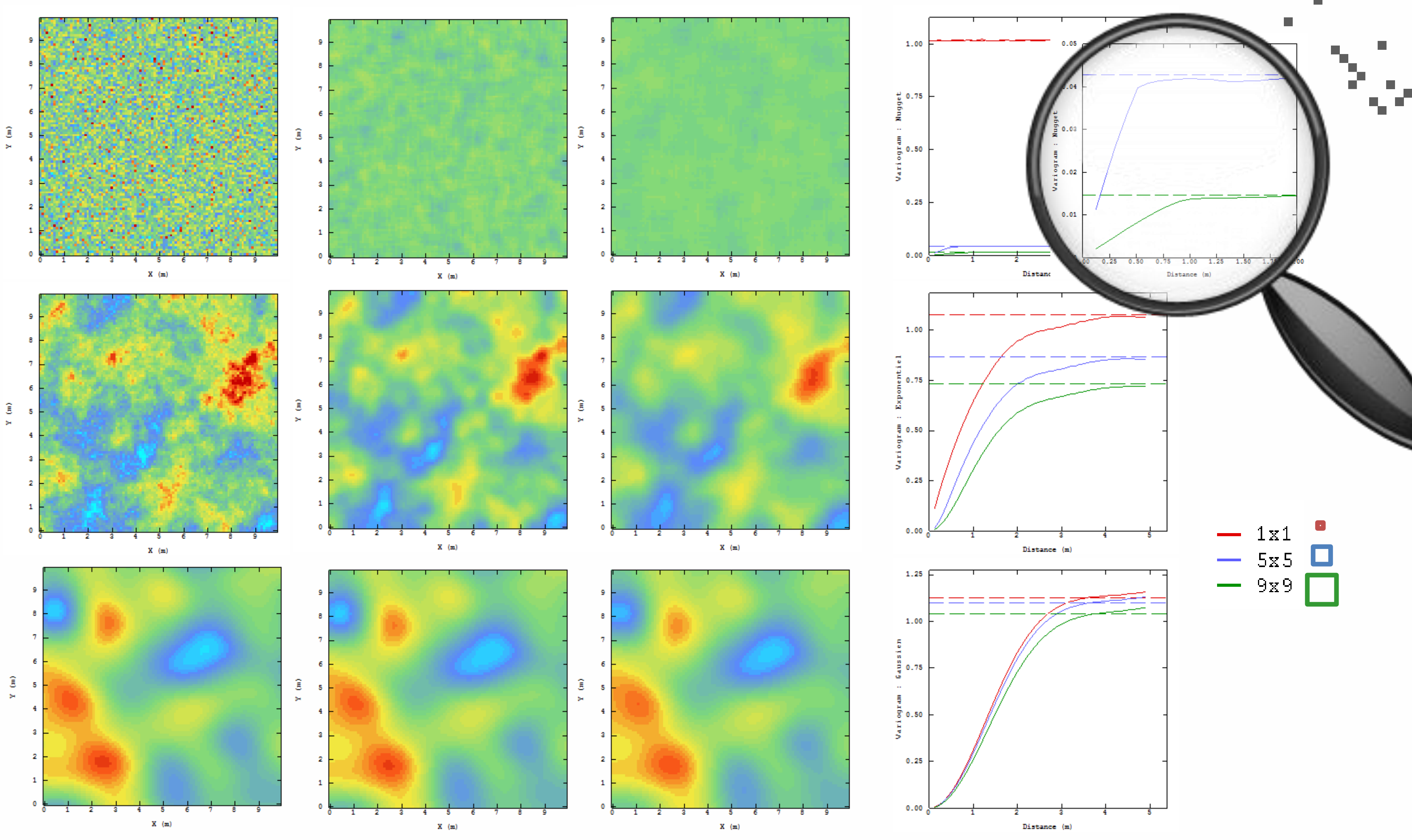
Variograms of three examples



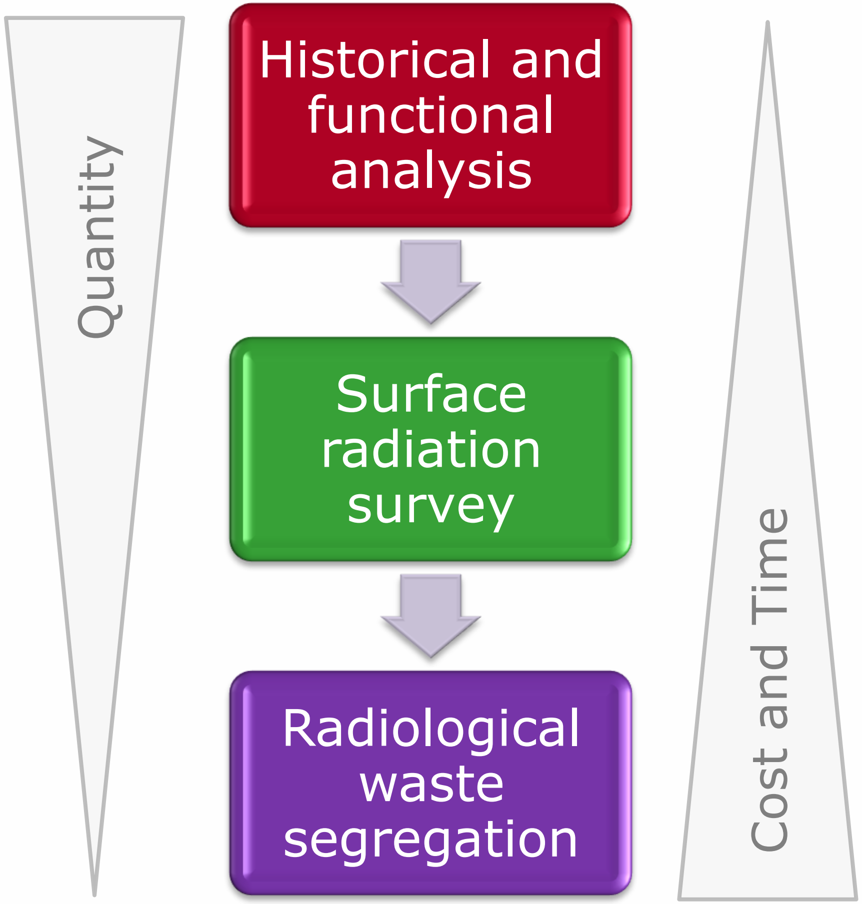
Variograms of three examples



Support effect and spatial structure



Multivariate approach for characterization methodology



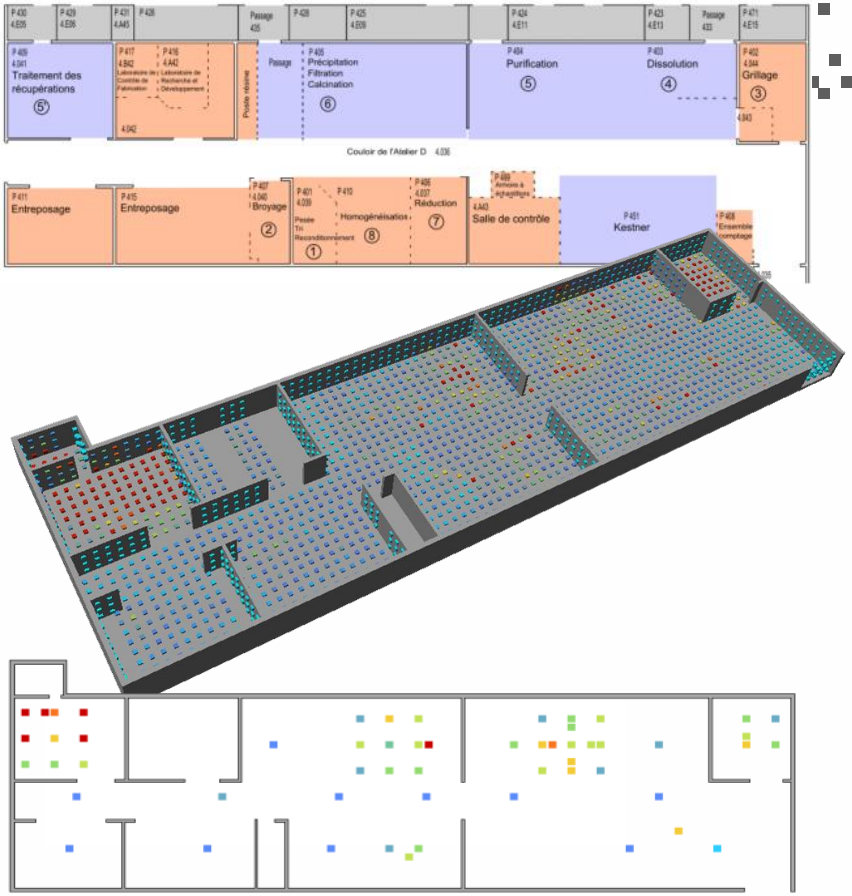
Quantity

Historical and functional analysis

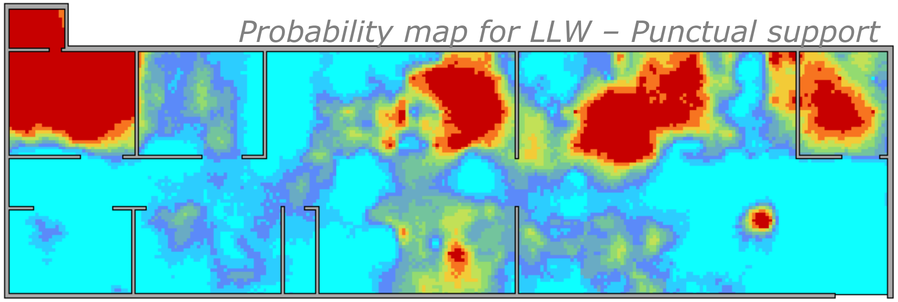
Surface radiation survey

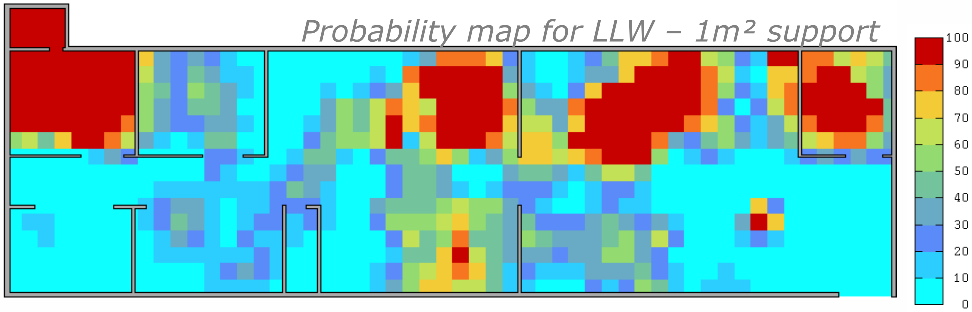
Radiological waste segregation

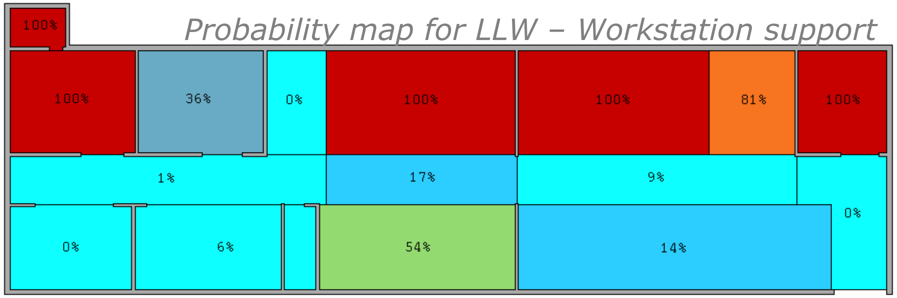
Cost and Time



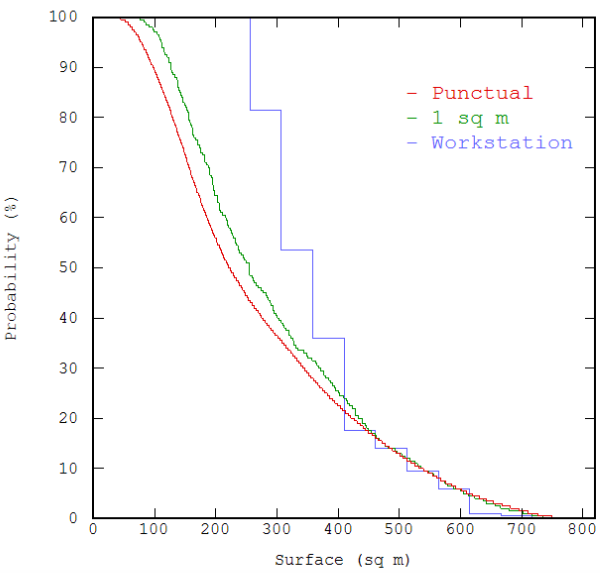
Risk analysis & estimation support


Probability map for LLW – Punctual support


Probability map for LLW – 1m² support

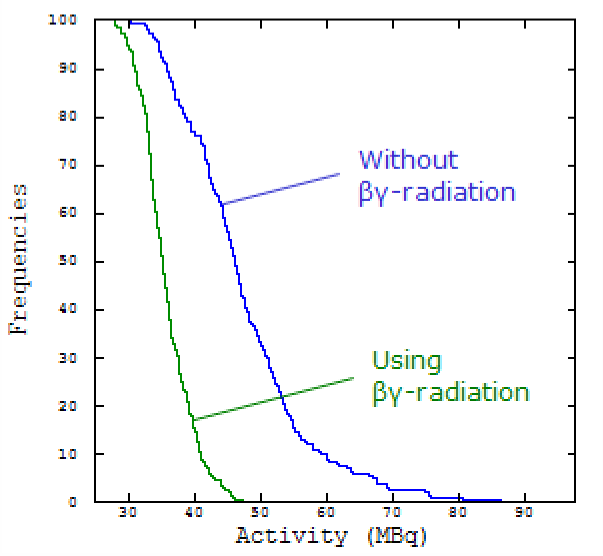

Probability map for LLW – Workstation support

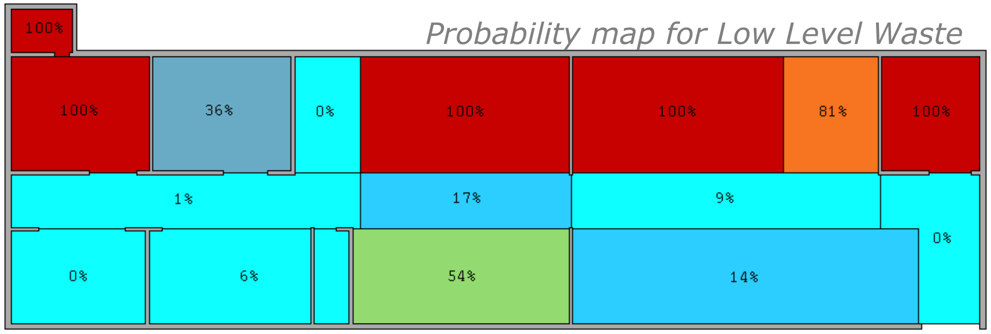
- Taking the decision support into account:
  - Punctual → Hot spots
  - Block → Waste category
- Impact on categorisation surfaces (averaging)

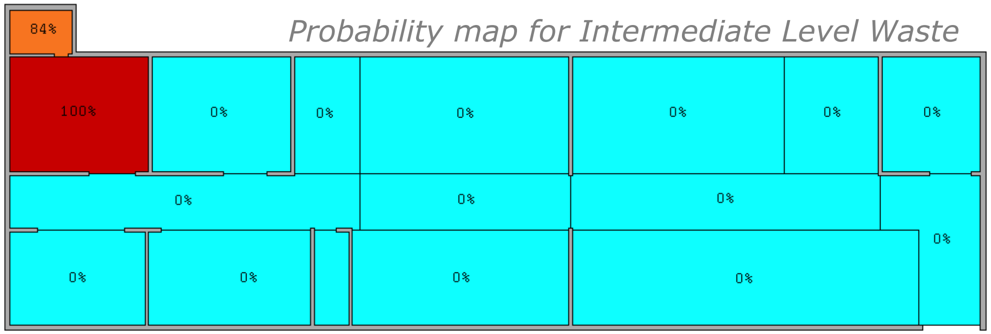


Radiological categorization

- Decision-making tools for decontamination process:
  - Waste segregation according to activity levels and risk levels
  - Average activity per “decontamination unit”
  - Accumulation (total amount of activity)



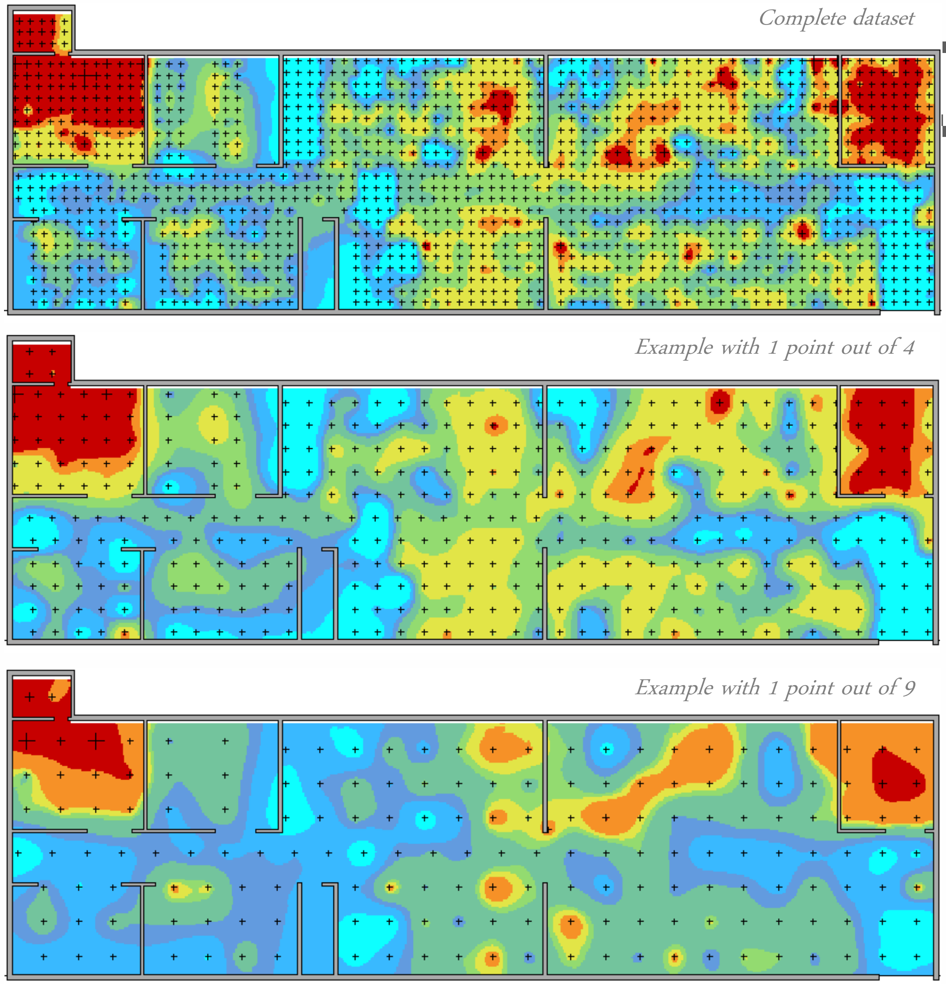

Probability map for Low Level Waste


Probability map for Intermediate Level Waste

Sampling optimization

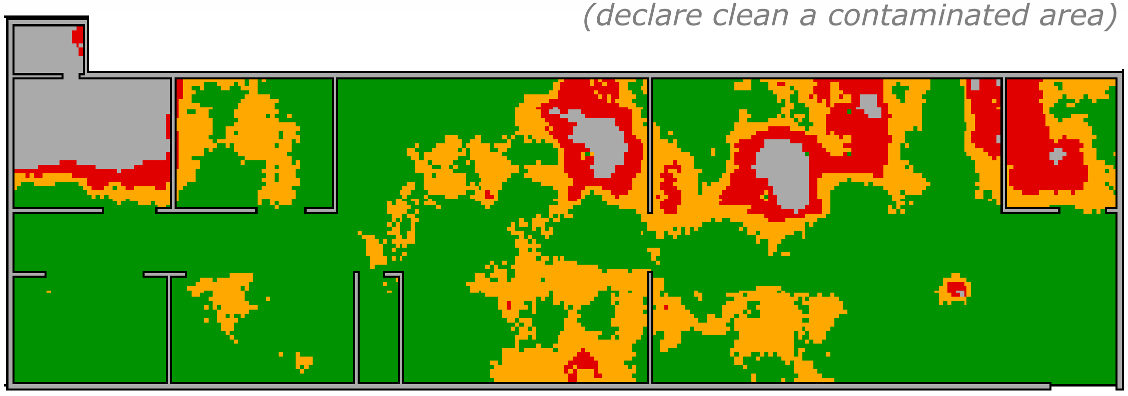
- Impact of the initial mesh on the estimation maps:
  - 0.66m, 1.3m, 2.0m

- What is your objective?
  - Hot spots
  - Average dose rate
  - Waste zoning
  - …



Sampling optimization

- Integration of the geostatistical analysis of values to optimize the number and location of data points
  - Initial mesh determination (feedback on spatial structures)
  - Defining additional points (on risk maps)



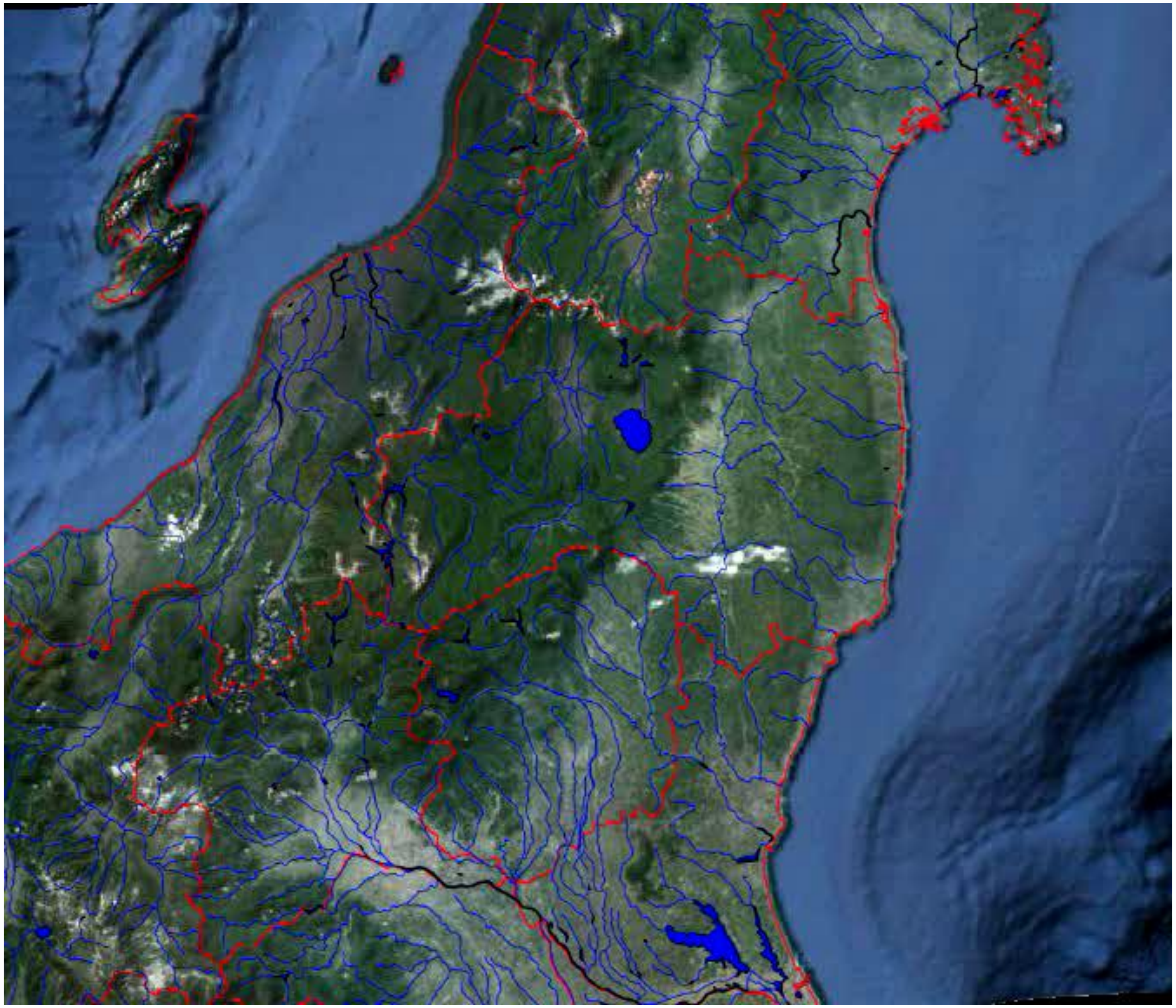
Map of the false negative risk

(declare clean a contaminated area)

▨ *Declared above the threshold*
🟥 *High risk*
🟧 *Intermediate risk*
🟩 *Low risk*

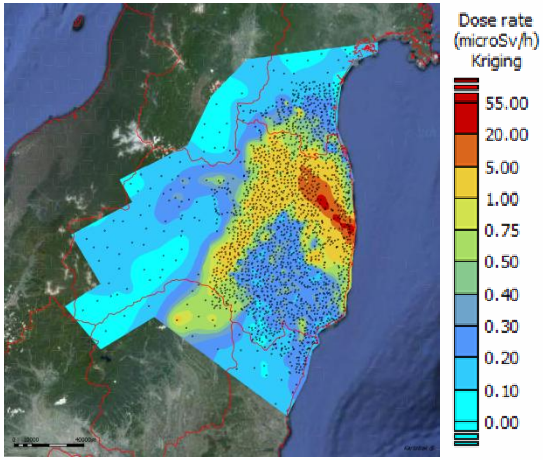
  - Positioning samples on radiation maps (use of the correlation between values)

Post-accidental mapping: Fukushima

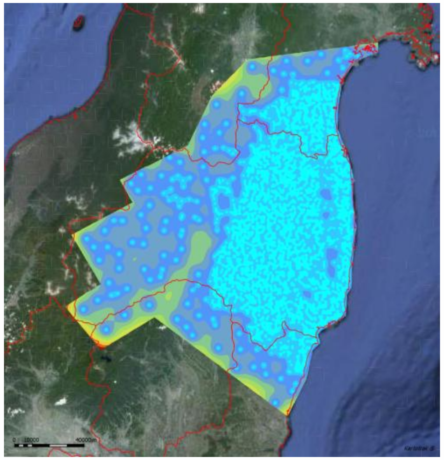


Post-accidental mapping: Fukushima

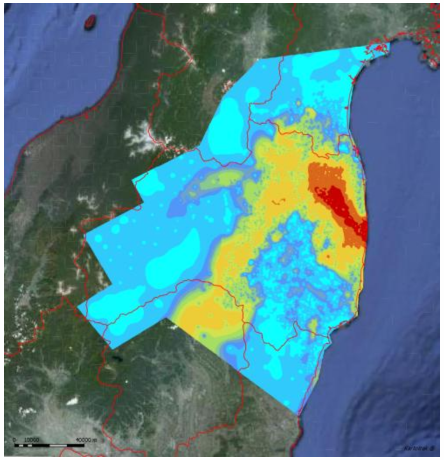
Kriging



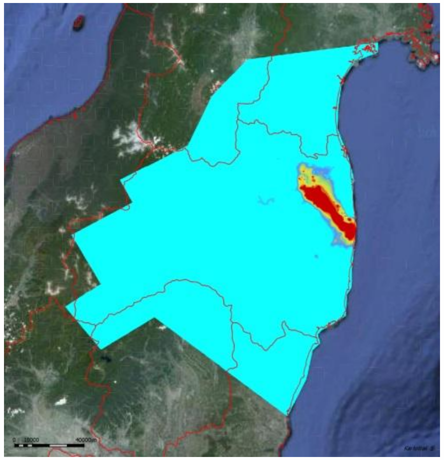
Error variance



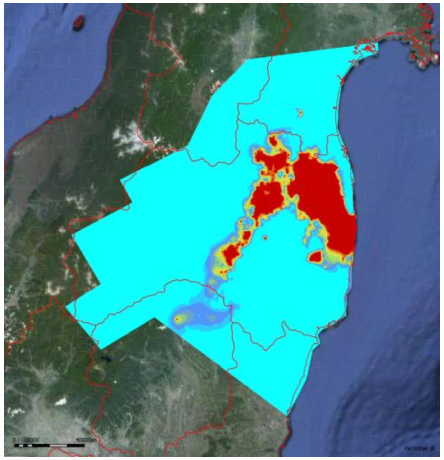
Confidence interval



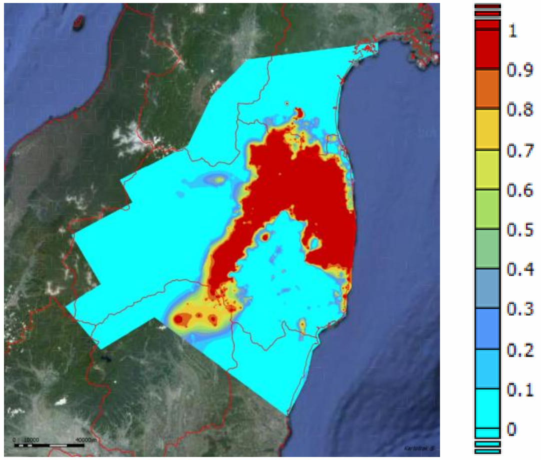
Probability > 5 µSv/h



> 1 µSv/h

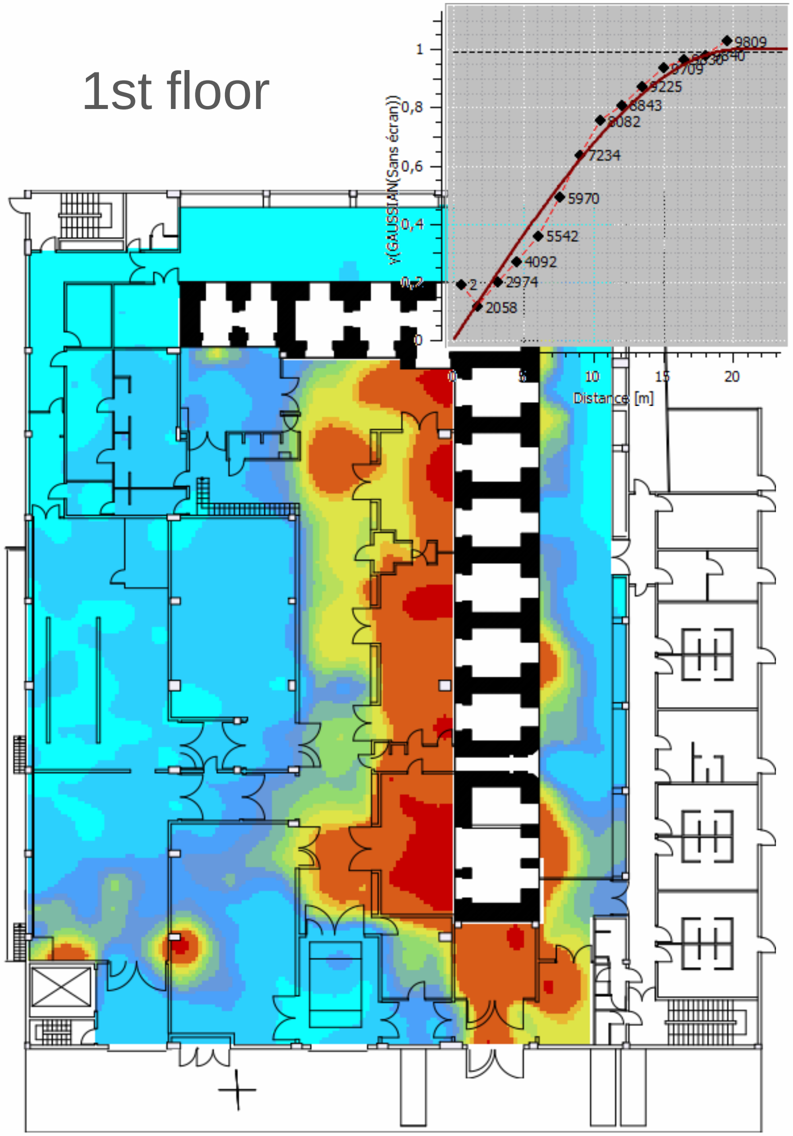


> 0.5 µSv/h

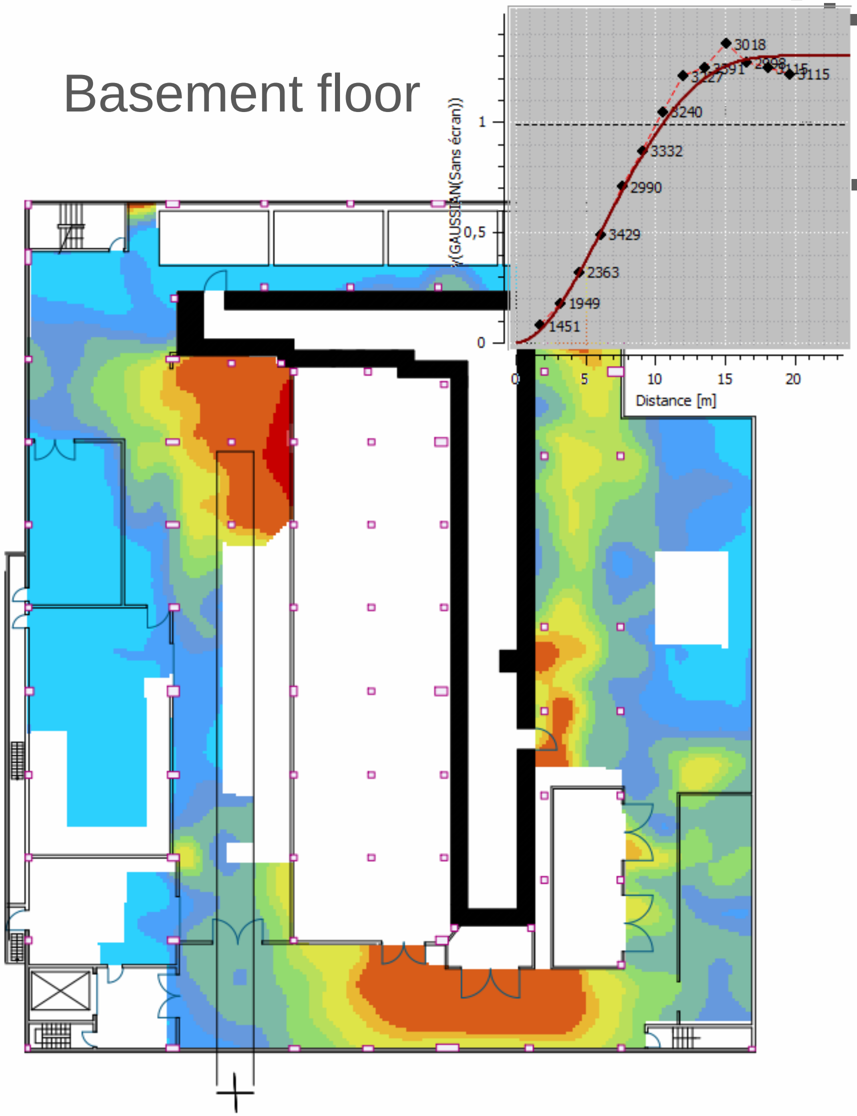


Concrete slab characterisation: RM2 building

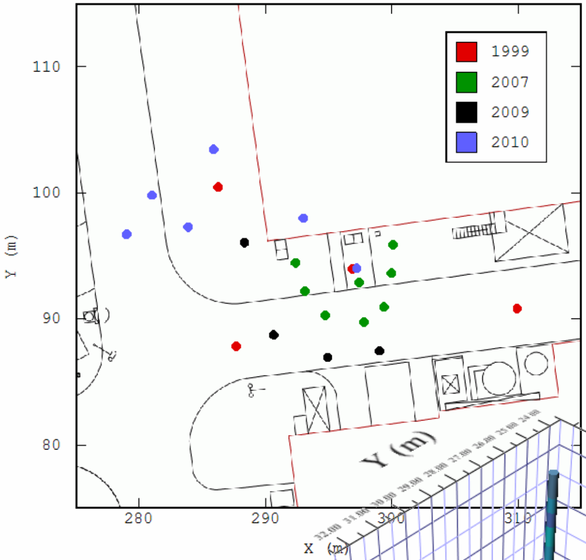
1st floor



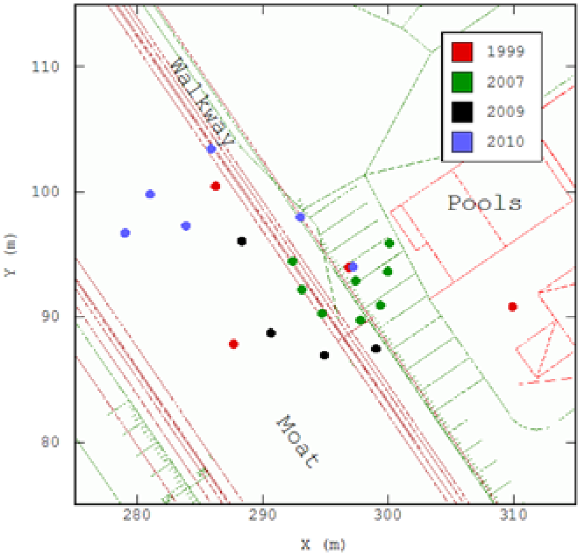
Basement floor



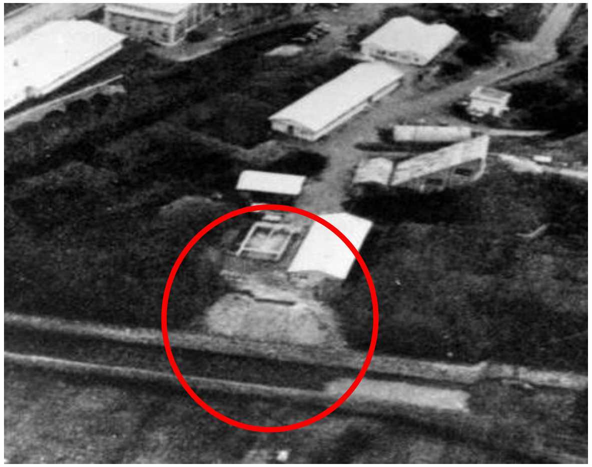
Contaminated soils: a 50 years old case

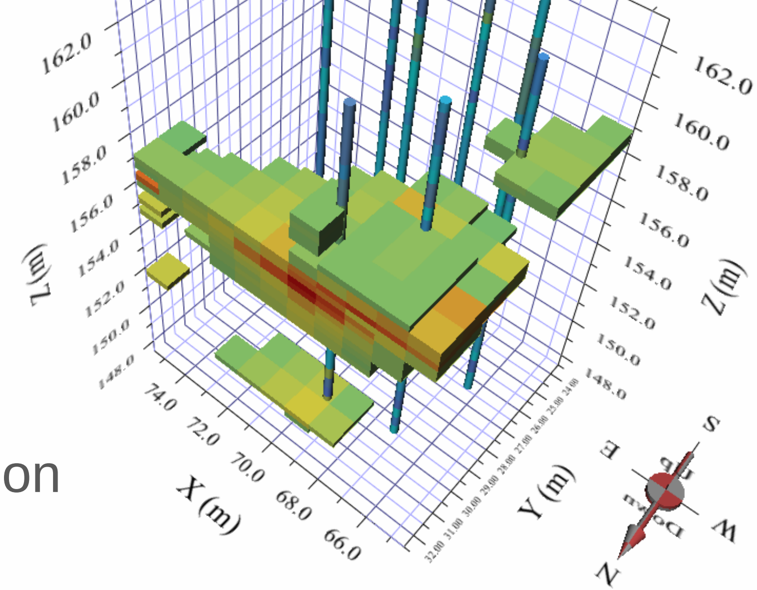


Base map of borehole tops



Historical context

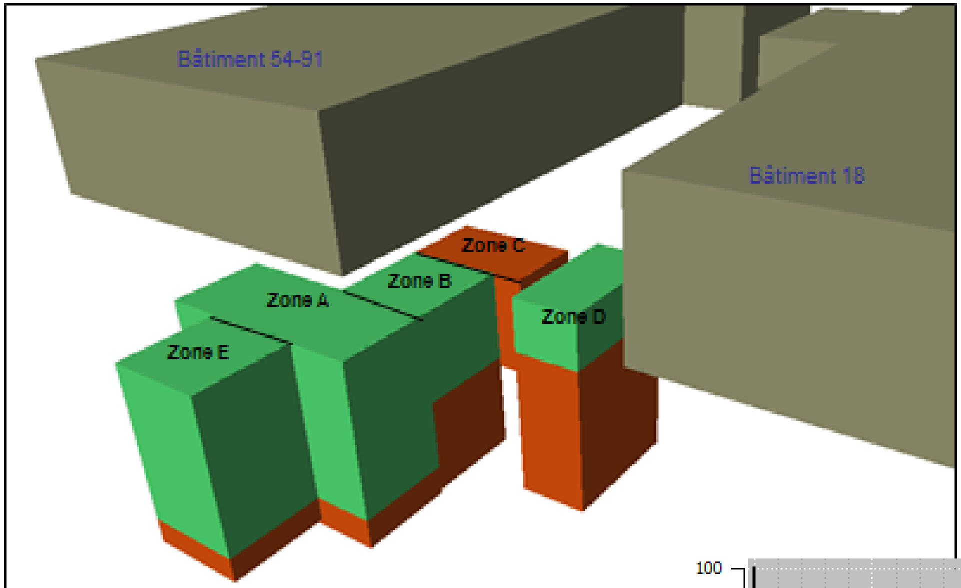




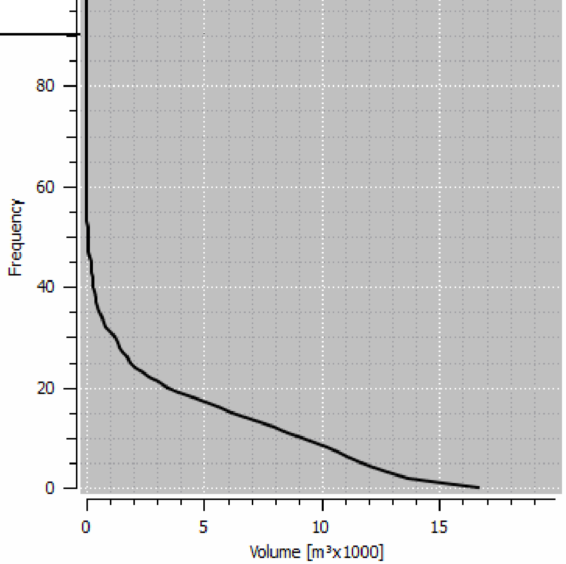
2007
volume
estimation

Contaminated soils: a 50 years old case

Contaminated soils: a 50 years old case



- 2000 m^3 of conventional waste
- 2000 m^3 of VLL waste



To sum up geostatistics

Exploratory data analysis

Understand

- Preliminary stage of geostatistics processing
- Data consolidation (cleaning errors and dealing with heterogeneities) and first spatial and statistical analyses (base map, histogram, correlation…)

Spatial structure analysis (variography)

Model

- Analysis and modelling of the phenomenon spatial continuity
- Integration of auxiliary variables to improve further estimates (multivariate, external drift…)

Interpolation (kriging estimates)

- Based on the variogram model, mapping of the phenomenon
- Kriging smoothing of the reality

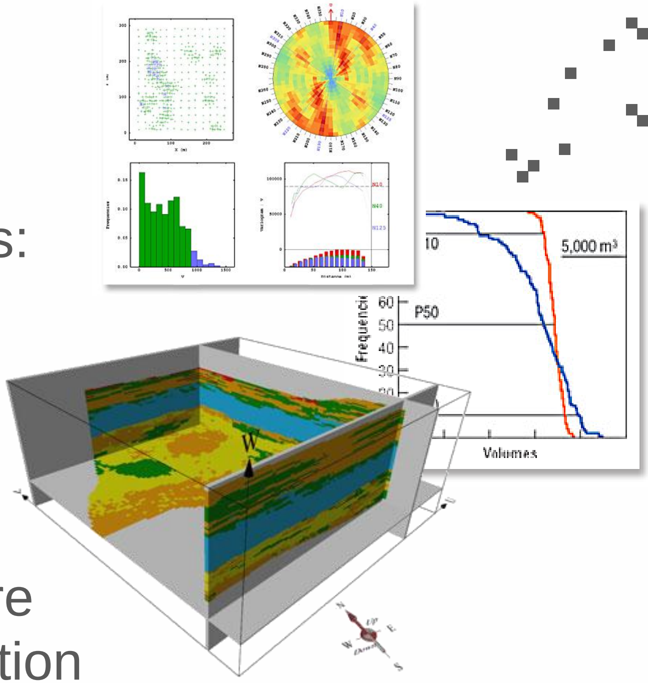
Visualise

Risk analysis (uncertainty)

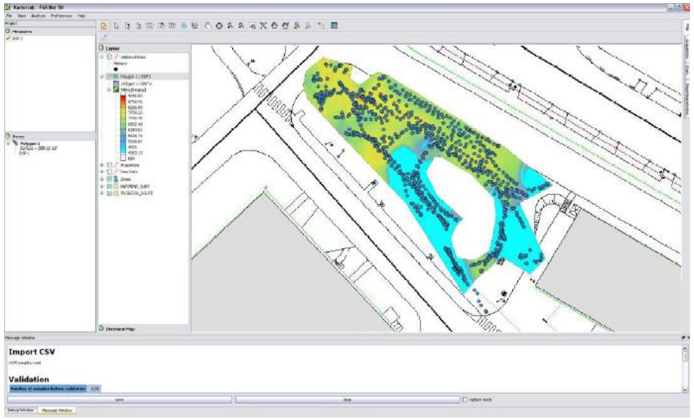
- Local mapping of the uncertainty
  - Geometric uncertainty
  - High variability areas
  - Probability of exceeding a threshold: waste classification
- Global estimates of total surfaces, volumes and accumulation (total activity)

Decide

- World leader in advanced geostatistics
- The most complete solution in geostatistics:
  Innovative Methodologies,
  Experts & Software packages



- kartotrak all-in-one software solution for contaminated site characterization
  - GIS-based with sampling optimization
  - Real-time contamination mapping
  - Risk assessment for decision-making process (2D and 3D modeling)



Developed in partnership with cea