NEAR REAL-TIME CHARACTERIZATION OF RADIO-CONTAMINATED SOILS IN FRANCE: CHALLENGES AND METHODS

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ABSTRACT

Over the last 10 years, the French Atomic Energy Commission (CEA, Commissariat à l'Energie Atomique) has set up an innovative methodology aiming at characterizing radiological contaminations. The application of the latter relies on various tools such as expertise vehicles with embedded measurement devices and a recently developed software platform called Kartotrak. A Geographic Information System tailored to radiological needs constitutes the heart of the platform; it is surrounded by several modules aiming at (i) sampling preparation, (ii) data analysis and geostatistical modeling and (iii) real-time monitoring and data acquisition.

This paper presents a methodological framework for the follow-up of decontamination projects, from doubt removal to the verification of the decontamination process. The use of the radiological characterization methodology and its related developments leads to a better appreciation of the contamination and, most importantly, to the optimization of the waste volumes and the reduction of the global cost of the remediation process.

1. INTRODUCTION

Environmental characterization and remediation of radio-contaminated sites is of crucial importance due to possible environmental hazards, impacts on human beings and also as regards their potential reuse for new facilities or economical projects. Concerned sites are widely spread in all countries where nuclear research has occurred, sometimes since the 19th century: soils surrounding nuclear facilities, surface waste storage sites, orphan sites, some of the latter being also impacted by chemical pollution, etc. Though sharing some aspects with the chemical case, characterization of radiological contaminations requires specific measurement techniques and the integration of key information such as historical analysis.

In France, there is no unified regulatory framework that covers the different sectors concerned. For instance in the nuclear sphere of activity, there is no regulatory text for contaminated soils included in the perimeter of nuclear facilities. Available relevant texts include the February 2007 circular of the Ministry of Environment related to the remediation of chemically contaminated sites and also the IRSN guide for the management of sites potentially contaminated by radioactive substances.

Within this context, the French Atomic Energy Commission (CEA, Commissariat à l'Energie Atomique) has implemented an innovative methodology to address the issue of contaminated soils and its specificities. This methodology relies on various solutions developed by the CEA of Fontenay-aux-Roses, among which expertise vehicles with comprehensive detection performances (LAMAS and VEGAS) and a software platform (Kartotrak), in partnership with Geovariances. This software provides users with both a Geographic Information System component tailored to radiological needs and several modules for sampling optimization, real-time monitoring, data analysis and geostatistical modeling. Then extensive in situ campaigns provide reliable surface maps due to geo-positioning and relevant non destructive measurement devices. In-depth characterization follows up using samples or drillholes. As a result, radioactive waste categorization and optimization are performed through the geostatistical approach which takes into account uncertainties and risk analyses.

This paper presents the whole methodology for the follow-up of site characterization and remediation projects, from initial survey up to verification of the decontamination process, in order to get to a better assessment of the residual contamination. These solutions have been successfully applied to more than 100 sites over the past few years and constitute key elements to optimize the estimation of contaminated volumes and minimize the cost of the remediation process. Thanks to a better upstream characterization of the contamination with surface and in-depth measures, the decommissioning project benefits of a better management of the remediation operations, respecting the projected cost and deadlines.

2. CLEANUP METHODOLOGY

In parallel to the facilities' dismantling, exterior contaminated parcels are also considered for remediation. In 2000, CEA formalized, for the Nuclear Safety Authority, its decontamination methodology that was already applied for several years to CEA centers. This methodology is partly based on the guide: "Managing places potentially contaminated by radioactive substances" [1].

In this way, CEA initiated the radiological characterization of the whole site of the Fontenay-aux-Roses centre many years ago. This approach is based on several steps:

- **Historical investigations** [2]. Understanding the radiological past of the target area is fundamental to calibrate/orientate the subsequent characterization. This includes gathering information from archives, operational characteristics, handled materials, measurement results, accidents, interviews (workers, residents), maps and aerial views, records about former characterizations or remediations.
- **Assumption of a contaminated area**. A radiological control with a simple radiation detector shows high level of radioactivity in some areas. The contamination must be confirmed with more measurements.
- **Confirmation of the contamination**. The dose limits for people may be exceeded implying the determination of a necessary protection level for workers undertaking further characterizations.
- **Surface characterization**. A detailed map of the radiological activity has to be established thanks to surface measurements (in situ gamma spectrometry, soil surface samples). The risks regarding the environment can be identified this way.
- **In-depth characterization**. A campaign of drill holes indicates the contamination depth in the ground. The drilling samples should also be chemically characterized to complete the detailed evaluation. Any potential transfer towards the groundwater has to be considered.

- **Rehabilitation objectives**. The remediation scenario of the contaminated area is being set up implying actions to carry out in order to excavate and leave a satisfactory residual activity. The waste zoning is established thanks to the previous characterization: 2D maps and 3D volumes.
- **Remediation process**. Together with the removal of the contaminations, a survey of the operations is performed to guarantee the safety of the workers.
- **Final characterization**. Samples are collected to validate the achievement of the remediation (end-point dose assessment) and to keep information about the radiological status of the area for any future use.

To fulfill the requirements of the different steps of this remediation methodology, CEA identified the "need" for industrial radiological evaluation, which led to the creation of various tools: vehicles, measuring devices, software applications [3].

3. THE EXPERTISE VEHICLES

The CEA in Fontenay-aux-Roses has developed three vehicles dedicated to expertise and investigation. The second one, LAMAS II, contributes to the achievement of 2D cartography established from measurements by in situ gamma spectrometry. This vehicle is also equipped with a radiochemistry laboratory allowing the measurement of α emitters (U, Pu) with low detection limits (1 $Bq.kg^{-1}.24h^{-1}$ for ^{238}Pu) and β emitters (< 130 $Bq.kg^{-1}.72h^{-1}$ for Beck ground) within short and operational time period.

Additional devices and the software platform were installed in third prototype vehicle called VEGAS. One of the main innovations of this vehicle is the installation of DSP10 detectors (two 0.5 m² plastic scintillation detectors), newly used in the field of radiological characterization (Figure 1).

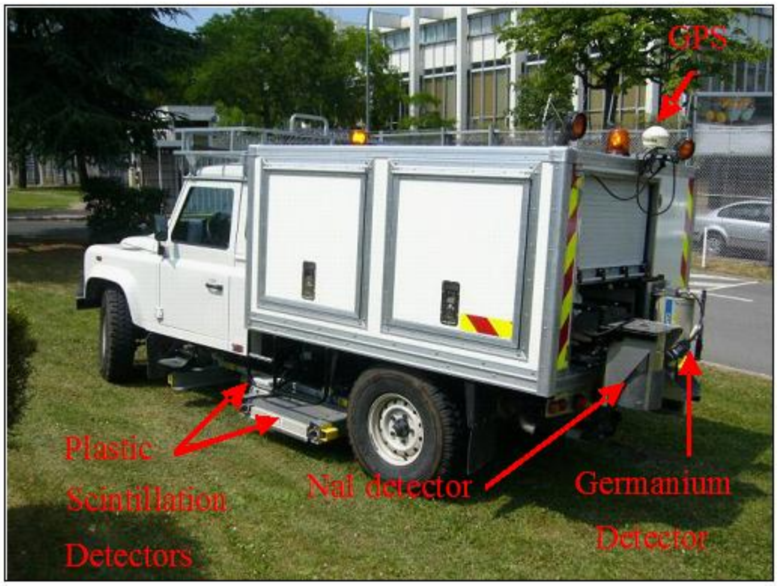


Figure 1: Real-time data acquisition on a CEA site with VEGAS expertise vehicle

These detectors classically count the number of ionizing radiations captured by the scintillation plastic which is prevented from the light and water infiltrations by an aluminum hood. This barrier stops most of charged particles like alpha particles or electrons that can not be counted. Nevertheless, using this measuring device is particularly suited for the detection of radionuclides emitting photons that have an energy level ranged from 120 keV to 10 MeV. Thus, it concerns most radionuclides usually found on sites that are contaminated by nuclear research and industry activities.

The performances of the DSP detector also depend on the contaminated area. Results may vary if the pollution is concentrated on one small spot or if it is spread over a large area. The speed of the vehicle is also very influential on the detection performances. Detection limits are displayed in Table 1 for (i) a sealed source displayed on a road, (ii) a surface contamination over a road and (ii) a homogeneous soil contamination (5 cm thick).

Table 1 : Detection limits of VEGAS detection devices.

Radionuclides	**Punctual source (kBq)**		**Tar roads (kBq/m²)**		**Grounds (kBq/kg)**	
	2.6 km/h	**5 km/h**	**2.6 km/h**	**5 km/h**	**2.6 km/h**	**5 km/h**
^{57}Co	6.0	9.3	5.8	8.1	115	160
^{137}Cs	3.8	5.9	3.7	5.1	68	95
^{60}Co	2.0	3.1	1.9	2.7	36	50
^{152}Eu	2.6	4.0	2.5	3.5	46	64
^{226}Ra	0.2	0.3	0.2	0.3	4.1	5.7

The VEGAS vehicle is mostly efficient for the characterization of extensive pollution. This vehicle can cover about 1 ha per hour for exhaustive measurement on a practicable ground. Thanks to the data georeferencing and the geostatistical process, the geometry and extent of surface contamination can be accurately determined.

4. THE SOFTWARE PLATFORM

Kartotrak has been designed as an all-in-one software solution for the radiological characterization of contaminated sites and facilities. It provides an integrated workflow from in-situ characterization to final control after remediation, in accordance with the presented methodology.

Kartotrak (Figure 2) is a GIS-based software (Geographic Information System) which integrates a real-time data acquisition system (GPS and measuring devices), data analysis and modeling workflows, sampling optimization algorithms and reporting tools [4]. This software embeds geostatistics to give value to data and precisely map the contamination at each step of the characterization sequence with an efficient risk assessment.

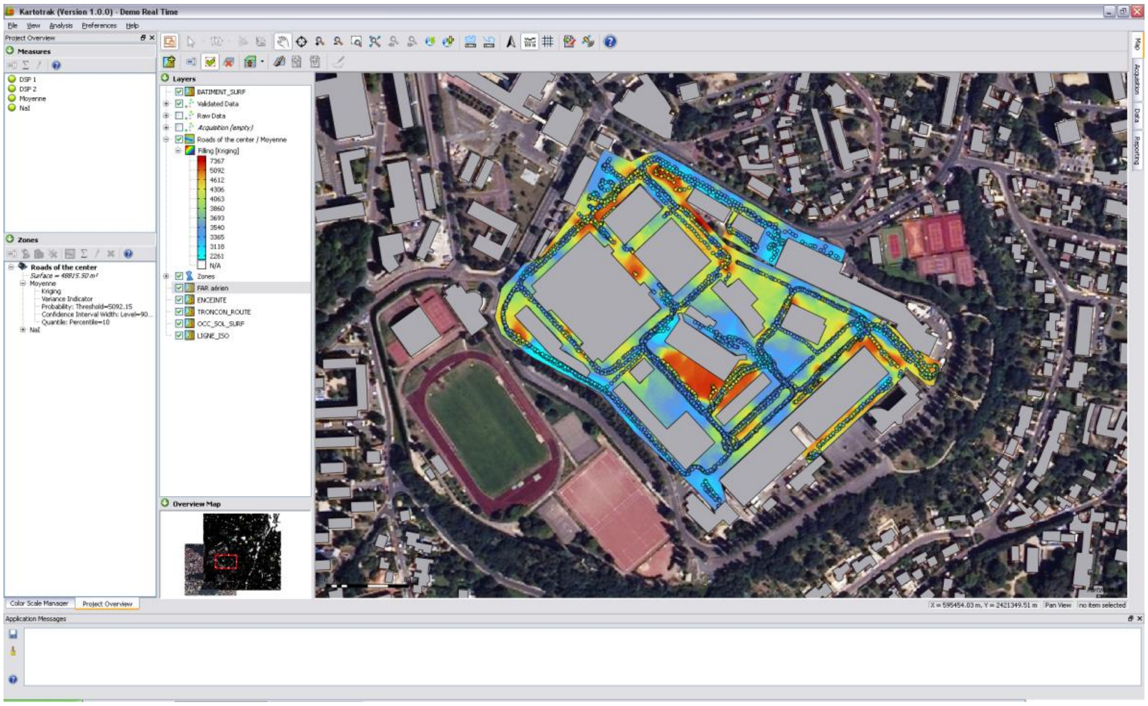


Figure 2: Overview of Kartotrak's main window, illustrating the GIS component.

4.1 Integrated workflow

Kartotrak is designed to facilitate the acquisition of data and the mapping of the contamination. A basic workflow is presented in Figure 3, with the main steps of the project being made using the software.

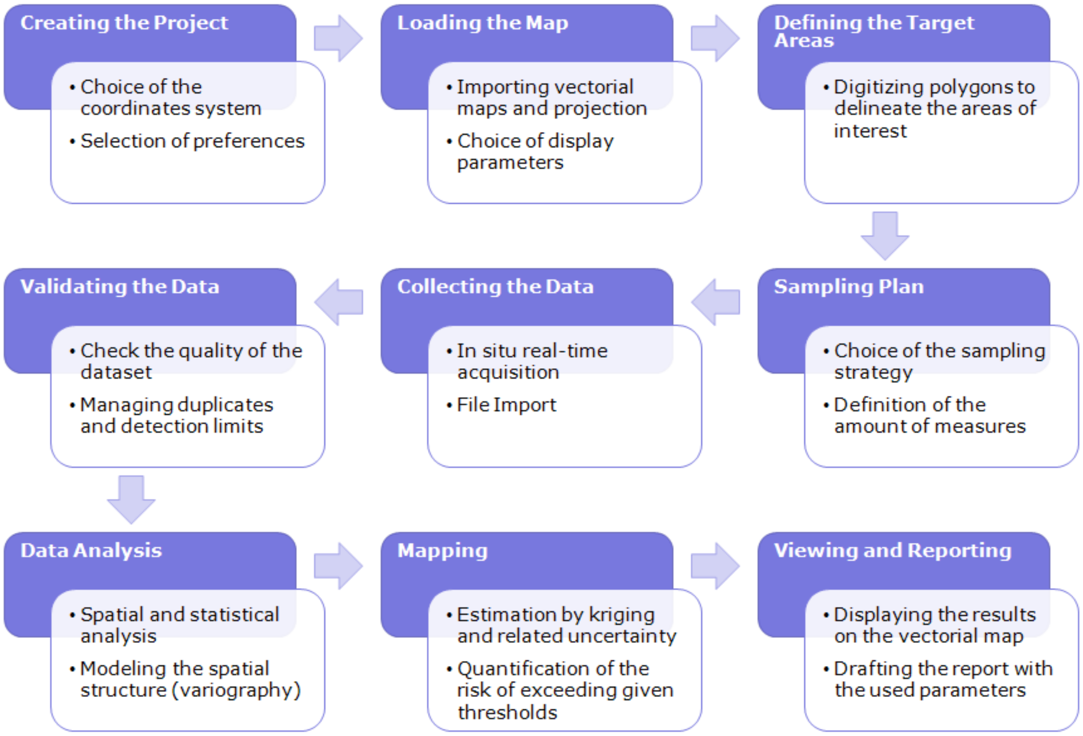


Figure 3: Classical workflow in Kartotrak for the mapping of a contamination.

Of course this workflow is not unique and the previous figure is only one working possibility offered by Kartotrak. In particular, on-site mapping results may impact the initial sampling plan by requiring additional investigations in areas highlighted through the geostatistical analysis. This way, the dataset can be advantageously completed by extra samples or measurements to quickly improve the contamination characterization.

4.2 Sampling plan and data acquisition

The preparation of the sampling plan is a crucial stage within the global workflow and characterization process. It needs to be in accordance with the evaluation objective. Kartotrak thus proposes three different sampling strategies as presented in Figure 4:

- Circular grid, to evaluate the contamination diffusion from one emission point (radiological gradient in the environment from the source).
- Regular mesh, to estimate and map the contamination through the geostatistical processing (presented in section 4.3). The pattern size is determined using the CEA experience feedback on previous radiological evaluations and on various graphic indicators like the probability of reaching a target.
- Random design, to perform classical statistical tests to determine the activity of residual contamination, at the end of the decontamination process (demonstrating compliance during the final status survey). The optimum amount of measurements is evaluated by different statistical relations like Wilks formula [5] or those recommended in the MARSSIM approach [6].

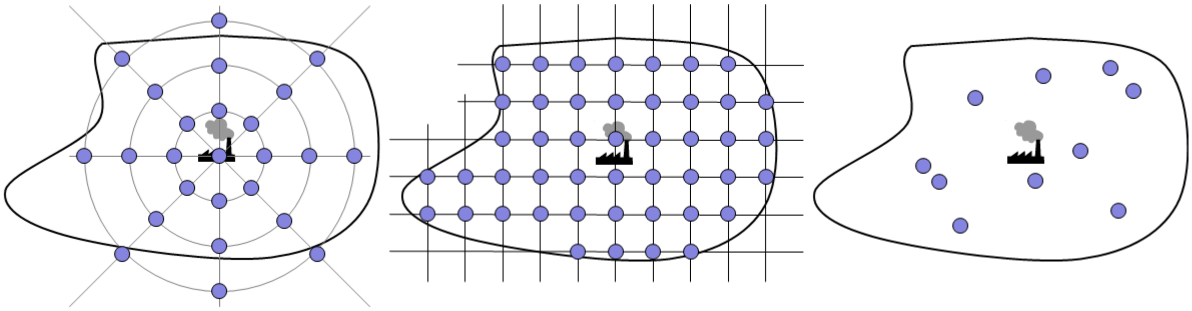


Figure 4: Sampling designs in Kartotrak: circular grid, regular mesh and random design.

Thus, the location of the measurement points is rationally prepared to answer a precise evaluation objective. Judgemental approaches are obviously possible using the interactive digitalization in the map window of the software or more directly in the project database.

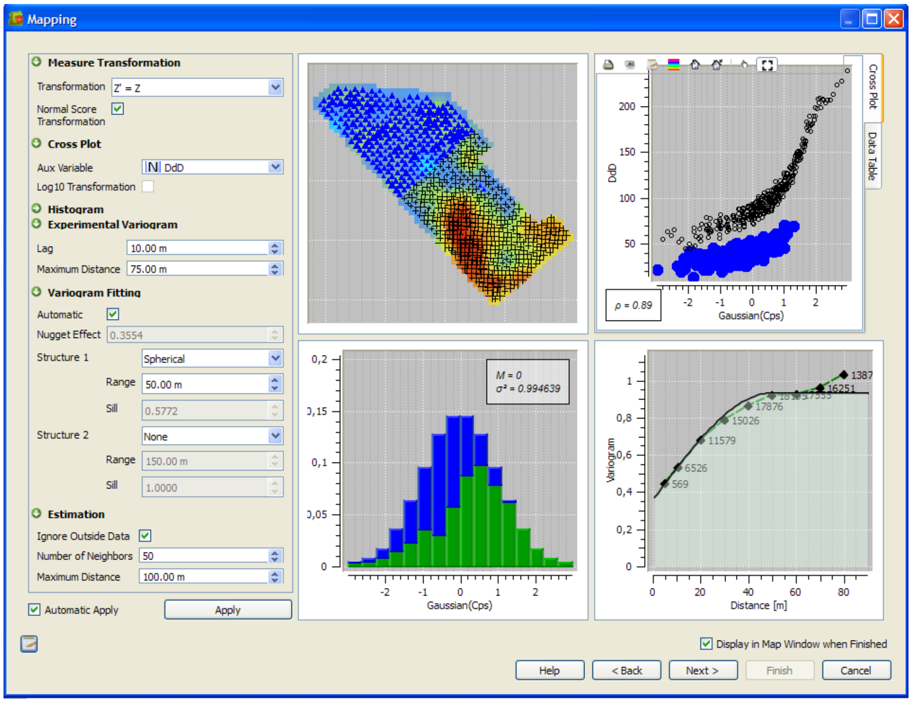
In addition, samples can be loaded from external files or using the real-time acquisition part of Kartotrak, which, when embedded in a vehicle, allows to collect many data with a positioning through GPS connection. This latter acquisition mode is particularly useful to quickly realize a removal of doubt on an area, in order to highlight "areas of interest" which go through further radiological evaluation (more precise non destructive measurements or samples). Therefore, this method can reduce the surface to be thoroughly characterized. An illustration of the real-time acquisition mode of Kartotrak embedded in VEGAS expertise vehicle can be found at Figure 2, representing the road mapping of the Fontenay-aux-Roses CEA center. Using 1-second acquisitions while driving à 2.6 km/h, it only took half an hour to collect the complete dataset.

4.3 Mapping

Geostatistics is an appropriate solution when it comes to modeling spatial data in an intelligent way. It guarantees precision and reliability in results and provides an efficient way out for sampling network optimization, data quality control and analysis, mapping, volume estimation, risk assessment.

The strength of geostatistics lies in the fact that it takes into account the spatial behavior of the data [7]. This spatial behavior is fully described by the variogram which provides information on the spatial correlation between two samples separated by a given distance. A systematic presence of a spatial continuity for radiological contaminations has been shown by multiple case studies carried out by CEA, which proves the relevance of geostatistics for such applications.

Geostatistical data analysis and modeling can be performed using Kartotrak's Mapping tool (Figure 5). Basic statistics are first provided: data basemap, histogram analysis, on-the-fly data transformation (logarithmic and Gaussian transformation). Classical experimental variograms can then be computed and fitted interactively using common basic structures (spherical, exponential, and linear).



Transformation: Z' = Z

Normal Score Transformation ☑

Aux Variable: N DdD

Log10 Transformation ☐

Lag: 10.00 m

Maximum Distance: 75.00 m

Automatic ☑

Nugget Effect: 0.3554

Structure 1: Spherical

Range: 50.00 m

Sill: 0.5772

Structure 2: None

Range: 150.00 m

Sill: 1.0000

Ignore Outside Data ☑

Number of Neighbors: 50

Maximum Distance: 100.00 m

☑ Automatic Apply

☑ Display in Map Window when Finished

Figure 5: Interactive geostatistical analysis using Kartotrak's Mapping tool.

As a result of the kriging procedure, the map of the estimated contamination of the area is displayed (Figure 6). Uncertainty maps and confidence intervals are also provided in order to highlight imprecise areas that require additional measurements. For instance, the right map of the next figure (width of the confidence interval) draws attention to under-sampled areas (in the middle of the data points due to two missing values or on the border of south part of the investigated zone due to extrapolation in possibly contaminated areas). In addition, almost one third of the map is associated to an intermediate confidence level (in yellow and orange). This kind of results may lead to the decision to carry out additional investigations to be more confident in the estimation maps and advantageously reinforce the definition of the contamination extension.

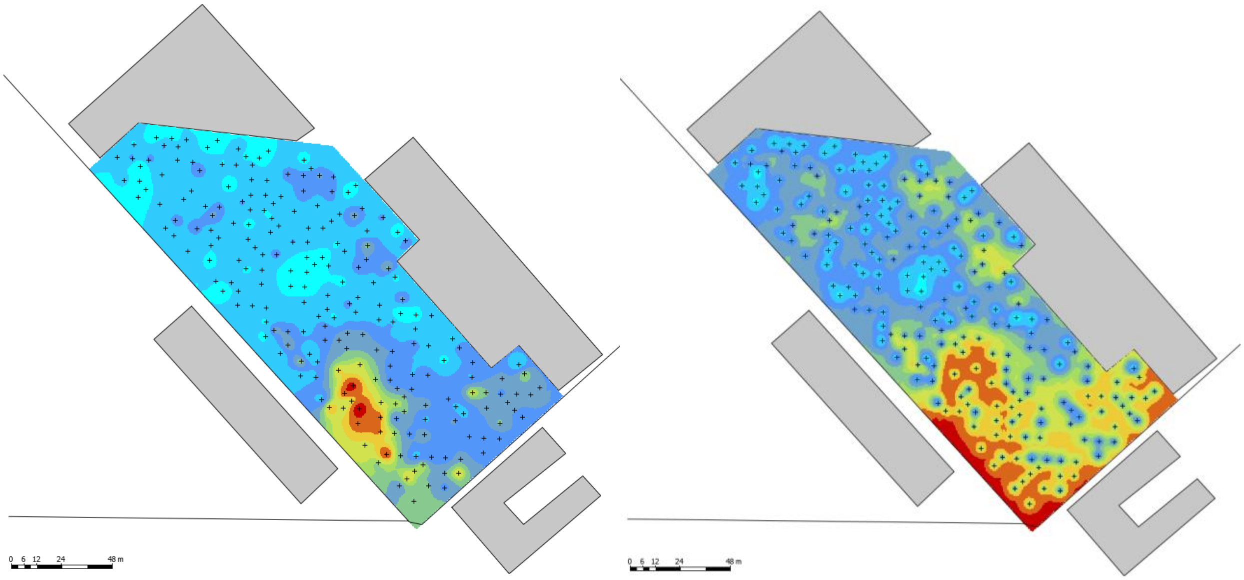


Figure 6: Maps of the kriging estimation and of the width of the confidence interval.

Risk analysis is then performed through the estimation of probabilities of exceeding a given threshold. These results help deciding how many drill holes should be realized for 3D analysis and where to locate them.

5. CONCLUSIONS

In order to address the decontamination of the Fontenay-aux-Roses center, one of the missions of the CEA has consisted in developing radiological characterization methodology. It has implied the setting up of measuring devices embedded in an investigation vehicle VEGAS and an innovative software platform, Kartotrak, improving the process of characterizing the radiological wastes before their removal.

The detection performances of the new detectors allow to measure while driving, in order to quickly highlight contaminated areas in addition to those identified during the analysis of the historical activities. The contaminated areas identified during this removal of doubt then go through further radiological evaluation.

The Kartotrak platform, together with its related modules dedicated to sampling preparation, data analysis and geostatistical modeling, real-time monitoring and data acquisition is now suited to globally manage and achieve a decontamination project. It turns out to be an important tool for project managers to early take the good decisions as regards the contamination remediation and then respect costs and deadlines.

All these developments, already experimented on various sites in France, contribute to the acknowledged know-how of the CEA centre of Fontenay-aux-Roses for radiological characterization and remediation of radioactively contaminated soils.

The transfer of the methodology and related software platform to nuclear facilities is under process, aiming at providing a suitable framework to address a tremendously increasing demand about the characterization of contaminated concrete structures and facilities. The first developments have now grown from prototypes to industrial products, ready to be used for many sites and in many cases.

6. REFERENCES

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