Uncertainty assessment for soil remediation projects

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Abstract—Uncertainty evaluation provides crucial information for soil contamination assessment. However, for remediation planning, uncertainty has to be combined with risk evaluation and subsequent costs. This paper proposes a new model to integrate uncertainty and average remediation costs to define risk target areas for decision making.

Keywords: soil contamination, geostatistics, cost functions

I. INTRODUCTION

The environmental impacts due to soil pollution are a priority in the Environmental Program established by the European Union. New legal obligations will soon be delivered and Portugal will have to develop rules for soil contamination regulation following the same procedure applied a few years ago for preventing and assessing water and air pollution. Therefore, the application of evaluation methods suited for soil contamination assessment will be required to supply essential information for remediation actions planning. In this context, uncertainty assessment is one of the issues to consider in the decision-making process of determining soil contamination risk and further remediation. Geostatistics provides valuable tools for space-time uncertainty evaluation and for decision making (see, for example, Barabas, Goovaerts and Adriens, 2001; Demougeot-Renard, de Fouquet and Renard, 2004; Goovaerts et al., 2008).

Usually uncertainty is measured by the local dispersion variance computed for a set of equiprobable images representing the spatial distribution of soil contaminants. But, for decision-making, the spatial knowledge of contaminated areas and the attached uncertainty it is not enough to build a realistic and successful remediation project. Decision about remediation needs to consider the risk evaluation and the subsequent costs. If these costs are non-linear functions of pollutant concentrations then the uncertainty must be quantified in the space of remediation costs. Based on these requirements, we developed a methodology to build soil contamination risk maps with the following main steps:

- simulation of the pollutant spatial distribution;
- application of a cost function to the previous maps considering different remediation techniques suitable for the type, extent and degree of soil/sediment contamination;
- integration of cost average and cost uncertainty to produce a classification of risk areas needing remediation.

II. MATERIALS, METHODS AND RESULTS

A. Study Area

The study area is a coastal lagoon named Barrinha de Esmoniz, located in the Portuguese North Region and included in the list of natural sites of Natura Network 2000 (Fig.1). The lagoon is about 1500 m length and 700 m width, and is surrounded by dense vegetation (reeds and scrub) and bordered by the dune. The sea is about 400 m distance and it connects with the lagoon through a 50 m width channel. Two water ditches flow into the lagoon, coming from the North and from the South, using the lagoon as a discharge point from the water basin. A sedimentation process has been taking place in the last decades, reducing the lagoon's area and water depth. Also, there have been reports of serious pollution discharges from the North ditch, mainly industrial water discharges coming from the industrial sites located in the North part of the water basin. Evidences of this pollution have already been reported in a previous soil contamination assessment.

![Study area and soil sampling locations](image)

Figure 1. Study area and soil sampling locations

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B. Soil Contamination Data

A soil sampling campaign was performed in December 2008. The first 20 cm of topsoil were collected in 74 locations positioned in the lagoon water channels and surrounding areas (Fig.1). For the water channels, a sample was collected in the channel section and in each margin. The purpose was to verify if there was a preferential contamination pattern according to the water flow and contaminated sediment accumulation in the channel's margins. Several organic and inorganic compounds were analyzed. For this paper, we selected soil contamination data regarding copper (Cu) and polychlorinated biphenyls (PCBs) (Fig.2 and Fig.4, respectively). For the 74 topsoil samples collected, the main statistical parameters are presented in Fig.3 (Cu) and Fig.5 (PCBs).

Figure 2. Cu concentrations ("hard" data) and spatial distribution

Figure 4. PCBs concentrations ("hard" data) and spatial distribution

Figure 5. PCBs histogram and main statistical parameters

C. Soil Contamination Assessment

As mentioned before, the first step of the proposed methodology consisted in obtaining the spatial distribution of the pollutant. For Cu and PCB, this spatial distribution was computed using a geostatistical simulation algorithm (Direct Sequential Simulation with Local Anisotropies; Horta, Caeiro, Nunes and Soares, 2008). This algorithm uses the "hard" data available (Fig.2 and Fig.4) and the spatial continuity given by the experimental variograms. Also, it accounts for local spatial trends representing local anisotropy variations given by the meander structure where the variable is to be simulated. For our case study, the meander structures are defined by the existing channels that flow into and inside the coastal lagoon (Fig.1). Local anisotropy directions were visually recognized using a satellite image (Quickbird, 2006) and used to define flow direction vectors. Anisotropy ratios
were calculated using the channel section width and the main range of continuity given by the experimental variogram. Fig.6 and Fig.7 show the resulting mean of 30 equiprobable images for contamination dispersion of Cu and PCBs in the lagoon, where it is possible to identify “hot spots” (red areas).

**D. Remediation Costs Evaluation**

For the second step of the proposed methodology, we calculated the remediation costs to be considered given the type, extent and degree of sediment contamination. According to literature, Cu and PCBs contamination in sediments could be handled using two different techniques:

- in situ remediation by natural attenuation (using, for example, phytoremediation);
- off site remediation using a physical-chemical treatment (such as soil washing).

The first option is cheap and has less environmental impacts but it is time consuming and only reliable for “low” pollution concentrations. As for the second option, since it is performed off site (by sediment dredging), provides remediation in the short time. It also performs better for higher pollutant concentrations. However, it is by far more expensive than natural attenuation. Considering these two remediation techniques, we built a cost function to be applied to soil contamination maps. This function (\(C(x)\)) determines the cost value to be attributed according to the concentration measured at that location \(x\):

\[
C_l(x) = \begin{cases} 
0 & \text{if } z_l(x) \geq z_1 \\
\varphi_1(x) & \text{if } z_1 < z_l(x) \leq z_2 \\
\varphi_2(x) & \text{if } z_l(x) \geq z_2 
\end{cases} 
\]  

(1)

where \(z_l(x)\) is the pollutant concentration at location \(x\), \(\varphi_1(x)\) and \(\varphi_2(x)\) are the proposed remediation techniques (\(\varphi_1(x)\) – in situ; \(\varphi_2(x)\) – off site) and \(z_1\) and \(z_2\) are the thresholds chosen to determine the contamination degree. For Cu, \(z_1\) is 35 mg/kg and \(z_2\) is 135 mg/kg. For PCBs, \(z_1\) is 0.005 mg/kg and \(z_2\) is 0.025 mg/kg. In the cost function defined for this case study, \(\varphi_1(x)\) was set to be an exponential function whereas \(\varphi_2(x)\) is a constant.

Fig.8 and Fig.9 show the average cost maps computed for Cu and PCBs whereas Fig.10 and Fig.11 present the corresponding uncertainty as the variance calculated for the set of 30 simulated images.

**III. Final Remarks**

By analyzing the previous results, we can conclude that the average costs maps obtained are coherent with the spatial distribution of both pollutants. The north part of the study area seems to be, for Cu and PCBs, one of the areas of concern in what regards contamination costs. Concerning the cost uncertainty maps, it is possible to establish an inverse relation between uncertainty and average costs for Cu, being apparently easy to combine information for decision making.

For PCBs it is more difficult to directly analyze both inputs due to the uncertainty scatter pattern. In this case, building an integration tool becomes more important.

To integrate uncertainty and average costs to define the target areas needing urgent remediation, we assumed that the average cost is equal to the average risk. By definition, risk calculation is a product between a probability and a cost. Thus, our assumption can be verified using the definition of the average cost \(mC(x)\) (2) where \(f_{x(i)}\) represents the probability associated with \(C(x_i)\) (cost at a location \(x_i\)). The integration model to be presented further will show how to jointly quantify the average risk and the uncertainty to obtain the final risk map.
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References


