THEME C: ASSESSMENT AND MONITORING

THS C2.1 Geohydrology & Geostatistics

EXPERIENCE FEEDBACK ABOUT THE USE OF GEOSTATISTICS FOR CONTAMINATED SITE CHARACTERIZATION (RECORD NETWORK)

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ABSTRACT

Geostatistics is now recognized as one of the relevant solutions for the characterization of contaminated sites. It provides a sound methodological framework that can meet several objectives: sampling optimization, contamination mapping, assessment of land use compatibility regarding future site, integration of several kinds of measurements when available.

However, its added value and the condition necessary to its successful application are still difficult to assess. The main purpose of the project summarized in this paper is therefore to draw up a 15 years report of the use of geostatistics for contaminated sites, both at national and international levels. A particular focus is made on the complementarity of this methodology with other approaches such as geophysical or on-site measurements.

This critical and objective feedback includes several themes: state of the art regarding these methods and the integration of indirect measurements such as geophysics, international literature review, actual training and software offer, position of regulatory authorities, survey amongst actors involved in the characterization of contaminated sites who faced this kind of approach, real case illustrations.

These elements help in assessing the current use of geostatistics for characterizing contaminated sites. Benefits have been identified as well as potential barriers for a more common application. Recommendations are also provided to ensure the success of geostatistical projects and improve their operational integration during site remediation. Finally, research and development themes which could answer the encountered problems are suggested.

INTRODUCTION

Geostatistics has been used for the characterization of contaminated sites for about fifteen years. After a period of doubt, its benefits are now identified by the different actors thanks to many real case studies. Several Ph.D. theses have been dedicated to the subject, both for chemical and radiological pollution

(Jeannée, 2001; Demougeot-Renard, 2002; Desnoyers, 2010). Thanks also to the working groups such as GeoSiPol1 in France, geostatistics is now recognized as one of the appropriate solution for the characterization of contaminated sites. It provides a thorough methodological framework for optimiz ing sampling strategies, mapping the contamination and assessing the compatibility with future land use. In addition, it allows the integration of several types of measures when available: laboratory analyses, on-site measurements, geophysical surveys, etc. However geostatistics is not a universal answer and its application requires expertise and an effective communication between the different actors. When some of these elements are lacking, it can generate disappointment and provide inadequate results.

In this framework and benefiting from funds of the RECORD[2] network, the project described in this paper consists in making a critical and objective feedback of the use of geostatistics. The objective is to draw up a factual report (On how many known cases of polluted sites was geostatistics used? Under which circumstances and for which objectives?), and then to make a detailed analysis of the results (Did results provided by geostatistics give satisfaction? What are the reasons that led to the success or failure of the operation?) to deduce possible ways of improving the current situation.

Several elements of analysis have been developed to achieve this review: analysis of the complementarity between geostatistics and the acquisition of geophysical or in situ measurements, international literature review, survey among actors involved in the characterization of contaminated sites (consulting firms, industrial groups and institutional agencies), analysis of the regulatory context in different countries, illustrative case studies. These elements have been completed by an overview summarizing the main objectives and geostatistical concepts and the answers they provide to issues encountered in the context of contaminated sites. The results of works already funded by ADEME (R&D projects Outrage and Reperage, reports of the working group GeoSiPol) have also been integrated. This project, however, differs from the preceding ones by having a broader and more critical point of view.

The project addresses the issue of chemical and radiological pollution, whether diffuse or localized, potentially affecting the following media: soil (wasteland, dumps...), sediment (rivers, harbors...) and concrete (installations being dismantled). Groundwater pollution is beyond the scope of this study.

First, elements of analysis are briefly described. Then, the main outcomes of the project are described: review of the current use of geostatistics, including its benefits but also remaining issues, lessons learned and recommendations, practical answers to questions commonly asked by practitioners about geostatistics and its implementation, research and development perspectives.

ELEMENTS OF ANALYSIS

Practical geostatistics for contaminated sites

The characterization of contaminated sites is compulsory for their management in multiple contexts: accidental pollution, disposal or acquisition of a site, management of excavated soils for a real estate project, decommissioning of a nuclear facility, forecast before dredging a river or a harbor in order to restore good sailing conditions. This characterization may aim at reaching various objectives.

- Sampling strategy optimization: how to reach a sufficient level of knowledge in relation to the objective, with the smallest number of data well located?
- Doubt removal (identification of sources, of hot spots...);
- Understanding the spatial behavior of the pollution thanks to mapping;
- Assessment of the soil compatibility with the future land use of the site;
- Computation of contaminated volumes, masses or surfaces beyond a threshold;
- Orientation of the excavation or treatment of contaminated soils and materials (e.g. concrete).

[1] http://www.geosipol.org
[2] http://www.record-net.org

Geostatistics provides a thorough methodological framework to contribute to the achievement of these goals, allowing the modeling of contamination spatial structure and the assessment of spatial uncertainty.

Integration of geophysical data and on-site measurements

Geophysical and on-site data are often used to locate areas suitable for the implantation of surveys or piezometers. Geostatistics is frequently applied successfully to directly interpolate geophysical measurements. Various automatic systems have also been created to collect data in real time, perform a geostatistical processing and display the results while on the site (e.g. Kartotrak from Geovariances, FAST from USEPA Region 5). Geophysical and on-site data can also be integrated into geostatistical models as auxiliary variables, but such integration, however, is still rarely observed in practice.

More generally, the combined use of on-site or geophysical measurements and geostatistics is often perceived by professionals as allowing to: better characterize a site, take good decisions, better assess the risks and finally achieve better remediation. However, several barriers to a more frequent use of these techniques are put forward:

- Institutional: regulations and official guides generally do not consider the concepts of uncertainty, measurement support and other relevant geostatistical concepts; certifications do not yet apply to geostatistical studies: the legal decisions often takes precedence over the success or the technical aspects of remediation...
- Financial: budgets allowed to the study of contaminated sites are often insufficient...
- Individual: fear of not respecting the budget allocated for the study, decision makers not knowing the technical possibilities...

Position of regulatory authorities

Methods and tools for the assessment and remediation of contaminated sites are not mentioned in the legal framework of the different countries, but in the methodological guides, directives and helping guides for professionals. Looking for recommendations on the use of geostatistics in various official guides of some European and North American countries highlights the following positions:

- Since 1989, the environmental protection agency of the United States (U.S. EPA) recommends the use of geostatistics and presents the block kriging technique as a solution for mapping pollution of contaminated sites inside two guides, one for quality assurance of sampling and the other one presenting methods to evaluate the achievement of objectives during remediation of soils.
- Since 2008, the « Centre d'expertise en analyse environnementale du Québec » (depending on the Ministry in charge of environment) mentions geostatistics in its guide for soil sampling as a tool for optimizing the sampling scheme of contaminated sites that have a significant number of samples. In addition, the 2012 Directive on the achievement of toxicological risk assessments published by the National Institute of Public Health recommends the use of geostatistics for sampling data as a support to the evaluation of risks associated to remediation projects.
- Since 2003 in Switzerland, geostatistics is mentioned as a possible tool for data interpretation in the manual of soil sampling published by the Federal Office for the Environment.
- Since 2007 in France, the methodological guide for sites diagnosis from the Ministry in charge of environment mentions geostatistics as a possible tool for data interpretation and considers geostatistics as a method to optimize the mesh pattern for systematic sampling.
- In the state of Baden-Württemberg in Germany, geostatistics is merely mentioned in study or research reports of specific sites conducted during the 1990s and 2000s.
- In Wallonia, the final guide for soil characterization study (GREC) was published in September 2012. Geostatistics is described as a suitable method for the characterization of backfills or the characterization and delineation of pollution spots for complex sites, where data are in large number.

Survey amongst professionals and case studies sheets

A questionnaire was developed during the project to get a feedback on the perception of the application of geostatistics among actors involved in the management of contaminated sites. It was transmitted in both French and English to over a hundred of contacts. A simplified English version has also been distributed within the NICOLE network and Common Forum members. At the end of the survey, 27 replies were received from people who have been faced with geostatistical studies. Among these 27 responses, 3 are from NICOLE and Common Forum networks. Most respondents are based in France and then in Switzerland and Belgium; a particular attention has been paid to the answers from more "distant" countries, such as Ireland, Quebec and Brazil.

The questionnaires were built so as to understand, depending on the type of actor answering, his use of geostatistics (expertise, subcontracting, confrontation as an authority…), his/her perceived usefulness of the approach as well as recommendations and perspectives that would optimize its efficiency.

The main results of the survey are summarized in the following “RESULTS” section.

In addition, "case study sheets" were sent to observe real cases of use of geostatistics and get some valuable examples in the study. These "case study sheets " are presented in the report and four of them have been detailed in a specific chapter illustrating the context (site, pollution, author of the study), the expected objectives and the chosen approach, the results and a critical analysis. Among others, it is interesting to mention that:

- There has been an opportunity to successfully validate with actual remediation data the prediction of contaminated volumes on a former oil deposit (Faucheux & Jeannée, 2012);
- A case study on a CEA site illustrated the added value of geostatistics to improve the understanding of a deep radiological contamination; this allowed to start the remediation with confidence, the delineation of the contaminated area being otherwise poorly understood (Faucheux et al., 2013).

Existing software and training offer

A non-exhaustive list of currently available software and trainings has been drawn. The 13 identified software fall into five broad categories: 1) software dedicated to geostatistics, 2) geographic information systems (GIS, 2D) which integrate geostatistical tools, 3) 3D software for the subsurface visualization (geotechnical engineering, mining, environment) incorporating geostatistical tools, 4) 3D modeling software for underground reservoirs (oil, mining) incorporating geostatistical tools, 5) programming languages enabling the development of computational tools needed for geostatistical modeling.

Geostatistical training offers for professionals are of two types: 1) trainings to take in hand a geostatistical software or to develop his own tools, and 2) training to learn the concepts of geostatistics and the conditions of its application to a given domain.

On-going research themes

Analysis of the latest research related to the application of geostatistics to contaminated sites highlighted the following trends.

- Geostatistical approaches tailored to the issues raised by the contaminated sites are now well established. The current research efforts are led to refine existing methods and find solutions to some remaining problems.
- Some comparisons of geostatistical methods to emerging spatio-temporal modeling have been conducted in recent years, but without convincing demonstration of the superiority of one method over the other.
- The coupling of geostatistics with other models useful to assess the contamination has been tested. It emphasizes its interest to include the uncertainty due to the spatial variability of pollution, whether in health risk assessment, modeling of flow and transport of pollutants or multi criteria analysis that assist in the selection of the remediation projects.

- Many studies have been devoted to the search for optimized sampling strategies, based on a geostatistical model allowing the quantification of local (mapping) or global uncertainties in order to choose the "best" locations for additional sampling points. Joint use of rapid on-site measurements and geostatistical techniques allow considering for rapid investigation campaigns where the number of collected data is multiplied and with an optimized positioning, while converging to a better accuracy of maps and estimates of pollution quantities of contaminated materials.
- Validity tests to confront geostatistical models with reality are rare in the literature, probably partly because of the difficulty of the question and the scarcity of available data sets. The few available examples show a good consistency between the model and reality, provided that the model reproduces finely the data intended to represent the reality.
- The application of geostatistics for modeling pollutant mass flux through a transect appears as an emerging field over the last five years. It comes with the current trend to characterize small-scale flux of pollutants whose spatial variability can be very large decimeter or centimeter, such as chlorinated hydrocarbons.

RESULTS

Assessment of the present use of geostatistics

The survey shows that geostatistics has been applied during the last 15 years on a significant number of sites corresponding to varied activities and issues. Geostatistical studies appear to be frequently accomplished by people having a good level in geostatistics and led for most of them to a total or partial success. The most common objectives are pollution mapping and quantification of contaminated volumes.

Actors who have been faced to it evoke the interest of the geostatistical approach to visualize the pollution in 2 or 3 dimensions, to assess the volumes of soil to be remediated, to quantify the uncertainties and financial risks and to optimize new sampling campaigns given the already collected information. The cost / benefit ratio of a geostatistical modeling is also considered as positive by a majority of the survey participants.

However, people are regularly facing problems which may contribute to disappointment in particular cases; mismatch between the context (site, data) and the expected results of geostatistical modeling, e.g. due to a lack of data, poorly distributed, of poor quality… or to a very heterogeneous pollution. Also, communication problems may occur between the numerous stakeholders (site owner, consulting firm responsible of the diagnosis, geostatistician, site remediation company, authority): the person in charge of the geostatistical study is usually not considered as being a key partner in the project. Communication regarding uncertainties is especially a difficult subject: for example, the lack of uncertainty quantification by empirical or deterministic methods should not be interpreted as an absence of uncertainty. Conversely, uncertainty quantification by geostatistical methods should not be seen as an imperfection of the method...

Several obstacles to a more recurrent use of geostatistics have also been identified:

- Additional cost generated by the geostatistical study: how to convince the client to invest in a methodology that is not discussed in the official methodological guides?
- Authorities' position: how to convince the client of the merits of an approach that is not discussed in the official methodological guides, which are also relatively vague about the choice of the remediation mesh, the type of control samples after cleanup, etc.?
- Software: a certain lack of software tools tailored to the domain of polluted sites is pointed out.
- Training and information: professionals are not enough trained to geostatistical methods and application software, a lack of information of actors involved in the management of contaminated sites is also identified.
- Demonstration: despite significant efforts in recent years, the number of case studies made available to prove the validity of a geostatistical approach is still considered too low; confidentiality issues and

the lack of feedback about the remediation are the main reasons for this low number of demonstration cases.

Lessons and recommendations

Several improvement avenues have been identified to solve the issues and obstacles discussed above:

- Adapt expected outcomes of the geostatistical modeling to the practical case (site, data): before the investigations, it is essential to consider carefully the consistency between the objectives, the nature of the investigations AND the relevance of a geostatistical modeling.
- Improve communication between different actors: by improving the knowledge of the different actors about the geostatistical methodology (concepts, methods, working hypotheses) and involving more closely the geostatistician in the project to ensure he is familiarized with the project practical constraints and expectations.
- Analyze the cost-benefit of a geostatistical study: the cost of a geostatistical study must be weighed against the benefit obtained, either during cleanup or resulting in a better understanding of pollution and thus better decisions. It is important to raise awareness of the clients about the added value of geostatistics and the risks related to a lack of quantification of the uncertainty associated to any volume estimate. It also seems important to avoid a policy of "lowest bidder" during the phase of investigation, and instead to base the decision on the global cost of the project, including both investigation and remediation costs. It is now recognized that a detailed and accurate investigation, even if it results in a higher cost, leads to significant savings during the remediation phase.
- Present the geostatistical methodology in official documents including a discussion of its advantages and limitations.
- Have appropriate software, which offer is increasing, considering various selection criteria: complexity of the studies and their objectives, level of knowledge of geostatistical and programming methods and users' time available, software support and updates provided by the software vendor.
- Develop training and awareness programs.The development of short seminars seems to meet the needs of actors who need to be aware of the geostatistical approach without an effective need to apply it personally.
- Present case studies with contaminated volumes validation: a major effort still needs to be made by the entire profession to make available studies which include comparisons between predicted volumes (using a geostatistical approach) and volumes actually remediated. This type of confrontation is indeed considered as one of the most convincing demonstrations for the added value of geostatistics for contaminated sites.

Assess the relevance of a geostatistical study

Practical answers are given for frequently asked questions about the use of geostatistics to characterize contaminated sites. They aim at helping to evaluate the benefits of a geostatistical study during the investigations stage for a given objective.

- "When should I ask whether geostatistics is relevant in my case?" Ideally at the end of the historical and informative studies and preliminary investigations (diagnosis) which are highlighting a pollution (removal of doubt) that will likely require measures to reduce the risk.
- "Do I have or can I acquire enough data?" The need to collect data comes from both a suspicion of pollution and a lack of understanding about its spatial distribution (insufficient historical information, site heterogeneity, etc.). The study objectives that can be achieved will be more ambitious depending on the amount of data, as seen in Table 1 below.

Table 1: Relationship between study objective, required number of data, geostatistical approach and associated cost/time.

Objective	Min. nb. of data	Geostatistical approach	Cost/time
Data QC and summary	~10-15	Basic tools: elementary statistics, histograms, scatter plots, data location maps.	A few hours
2D/3D mapping of contamination	> 20	Kriging interpolation. Recommendation: when data are in a limited number, be careful about the interpretation of the maps and communicate about the uncertainties.	A few hours, usually integrated in the consulting firms services
Estimation of contaminated volumes (3D)	>25-30 (>3-4/ boreholes)	Estimation of contaminated masses and associated uncertainties, soil classification, sampling optimization to reduce uncertainties	A few days to a few weeks, individual service

Remark: on small sites and when pollution understanding is good, the number of measurements is often limited. In those cases, it is not appropriate to try to interpolate the measurements, associated uncertainties being generally very high. Be especially careful with fast deterministic interpolations and prefer a simple representation of the measurements (data location).

- "Do I have data of adequate quality?" Geostatistics is sometimes perceived as needing particular requirements concerning data quality. It is important to keep in mind that it just consists in a formalization of much more general recommendations. Indeed, knowing the complexity of the phenomena to characterize, it is essential to be able to rely on data quality (homogeneity of sampling and analyzing protocols, consistency between campaigns, precise location of measurements…). Therefore, it is important to involve the person in charge of modeling in the discussions about the sampling strategy.

- "Is it possible that my site is completely heterogeneous or too complex?" Some sites may be completely heterogeneous. A lack of spatial continuity for the contamination can then be observed, preventing the sorting of soils between compatible or not given a threshold (except if a very high risk of misclassification of soils is accepted). A sophisticated geostatistical modeling is irrelevant in this case. However, geostatistics can highlight the uncertainty and clarify the sufficient conditions of investigations that could confirm this heterogeneity without increasing much the number of collected data.

- "How much will cost a geostatistical study and for which benefit? Is it worth the effort?" In the favorable case where spatial continuity has been identified, it is possible to make a thorough estimate of the contaminated areas, to quantify uncertainties, etc. The application of geostatistics is then classic, required cost and time then depending on objectives. If it appears that the contamination has no sufficient spatial continuity, the geostatistical approach helps in proving this assumption, for an investment during exploratory analysis usually light.

- "As a client, what are the requirements to ask for a geostatistical study and how to evaluate the quality of the replies?" When writing the specifications, it is important to ask for the following information: experience / competence of the team, references in this area (projects), level of detail of the proposed work, used software, requirements for communication and deliverables …

CONCLUSIONS & PERSPECTIVES

The project presented here, which has been funded by the French RECORD network, aims at making a critical and objective feedback of the use of geostatistics for contaminated site characterization. Several analysis angles have been investigated: (i) state of the art regarding the main geostatistical concepts and methods, together with their relevance for common practical objectives encountered in Site Characterization projects, (ii) complementarity of geostatistics with geophysical investigations and on-site measurements, (iii) review of scientific work published in various countries, (iv) survey amongst practitioners, (v) regulatory contexts, (vi) real case studies.

Based on this work, geostatistics appears as a relevant decision-making tool for the characterization of contaminated sites. It allows improving the understanding of in place pollution, mapping contamination, estimating incompatible volumes, quantifying related uncertainties and optimizing investigation schemes.

Applying geostatistics requires dedicated knowledge and practice. As a consequence, there is a need of dedicated training for engineers in charge of such projects but also a need of awareness for people facing these projects. Communication between the geostatistician, the people in charge of the site characterization, the site owner and the regulatory authority is a key element to ensure the success of geostatistical projects. Several practitioners mentioned a deceiving gap which might occur between the results expected from the geostatistical projects and the actual ones. Knowing that geostatistics should not be systematically applied, an important work has been done to clarify the conditions to be met for its useful application. Also, being recognized within official methodological guides and documents would ease its relevant recommendation by site owners. Finally, the need of demonstration cases illustrating in practice the geostatistical added value is still mentioned by practitioners.

Several R&D themes that would answer some encountered issues have been identified, noticeably:

- Experimental integration of indirect information (PID, geophysics). The objective would be to show how to enhance the use of indirect measurements, such as PID logs or geophysical measurements in a geostatistical framework, on a real case study that would be available for the purpose of experimentation,
- Study of the combination of geostatistical models and health risk assessment models. The objective would be to clarify the conditions required to integrate the spatial distribution of a contamination in the assessment of health risks, and to explain how these results can be used operationally and recognized by the authorities,
- Integration of remediation works constraints in the geostatistical model to ensure as far as possible consistency between the prediction and the remediation works' conditions.

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