Spatial Data Analysis and Modeling of Radioactively-Contaminated Territories: Lessons Learned from Chernobyl

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Abstract. The paper is devoted to the review of spatial data analysis and modeling of radioactively contaminated territories after the Chernobyl accident. The Chernobyl accident resulted in radioactive contamination in different European regions. The main objectives of the work are to present the data and the results of the modeling on surface contamination after the fallout with the help of different models and tools – geostatistics, machine learning algorithms, statistical learning theory, and to discuss some generic problems, concerning environmental spatial data analysis. The spatial patterns of the Chernobyl fallout are very sophisticated and highly spotty. This is a result of complex meteorological, physical and chemical processes involved. High variability of the surface contamination with different radionuclides at different geographical scales (from meters in populated sites to hundreds of kilometers – continental scale) complicates the analysis, processing and presentation of both the raw data and the results. From different points of view the Chernobyl case study is a unique one with many lessons to be learned.

An accident occurred at the Chernobyl nuclear power plant in Ukraine on April 26, 1986. This accident appeared to be one of the most serious catastrophes in the history of nuclear power. A test designed to assess the reactor's safety margins at the fourth unit of the power plant, led under a combination of circumstances to a steam explosion. The explosion destroyed the reactor's integrity and caused a release of radioactive materials into the atmosphere. Vast fires and heating of the fuel due to radioactive decay resulted in continuous releases of burning graphite products, radioactive gases, aerosols, and finely dispersed fuel particles with dimensions ranging from fractions of a micron to hundreds of microns. The release lasted for 10 days during which a significant part of the core content went out. Since the reactor (Unit 4) had been in use for over two years, the core content was rich in a wide range of radioactive fission products. There were two major components of the release: radionuclides that were part of the matrix of the dispersed fuel and released in the form of radioactive dust particles (contamination of the near zone), and volatile radionuclides in the form of gases or aerosols, which evaporated from the fuel (contamination of the middle and far zones).

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As a result of the accident vast territories were contaminated with radionuclides (ATLAS 1997). The total amount of ^{137}Cs (about 3 MCi) was deposited in Europe: Belarus – 33.5%, Russia – 24%, Ukraine – 20%, Sweden – 4.4%, Finland – 4.3%, Bulgaria – 2.8%, Austria – 2.7%, Norway – 2.3%, Germany – 1.1% etc. Comprehensive information on environmental and man made contamination and on the corresponding consequences has been collected after the accident. At present, well-developed specialized data bases, including both qualitative and quantitative information about contaminated populated sites, contain hundreds of records covering different aspects of the problem (see home page of IBRAE, http://www.ibrae.ac.ru). Spatial data analysis, presented in the report, is only one facet of the whole problem of the decision making process.

Spatial data analysis and modeling of the Chernobyl data are particularly challenging for many reasons: uncertainty of the source term and meteorological conditions, high spatial and temporal variability of environmental and pollution patterns, spatial and temporal non-stationarity, multivariate nature of the phenomenon with linearly and nonlinearly correlated variables, clustered monitoring networks, error measurements, etc.

Advanced methodology for the analysis, processing and presentation of the radioactively contaminated territories was developed [Kanevski et al 1997a, Kanevski et al 1997b, Kanevski et al 1999). Basically, it includes:

1. comprehensive statistical analysis of spatio-temporal data,
2. monitoring networks analysis and modeling (description and understanding of spatial and dimensional resolution of the networks, representativity of the data),
3. structural analysis (variography and cross-variography) – description and modeling of spatial correlation patterns,
4. multivariate geostatistical models for spatial estimations/co-estimations (family of kriging/co-kriging models),
5. estimation of local probability density functions and conditional stochastic simulations (both parametric and non-parametric) – quantitative description of spatial variability and uncertainty, risk mapping
6. development and adaptation of robust nonlinear non-parametric models based on machine learning algorithms for the decision oriented mapping:
    - artificial neural networks of different architectures (multilayer perceptron, radial basis functions, general regression neural networks, self-organized maps),
    - Statistical Learning Theory (Support Vector Machines) – Support Vector Classification and Support Vector Regression.
7. application of new ideas in Bayesian maximum entropy approach for the probabilistic mapping of radioactively contaminated territories.

Machine learning algorithms can be widely used for multivariate data integration, even when relationships between variables are nonlinear. It was shown, that combination of machine learning with geostatistics – hybrid models – is an efficient approach for information extraction and modeling from noisy and highly variable spatial data. The application of the methodology improves prediction mapping and the quality of decisions. Important developments were related to the connection between spatial data analysis and presentation of the raw data and the results using Geographical Information Systems.

There are many aspects concerning radioactively contaminated territories where contemporary geostatistical methodology can improve both understanding the phenomenon and quality of the decisions: comprehensive valorization of data, data and knowledge (science based/physical models) integration, decision-oriented mapping of contaminated territories including probabilistic risk mapping, monitoring networks design and redesign, physical models calibration and development. Selection of the "best models" depends on the quality and quantity of the data, the objectives and the final decisions to be taken. Application of different approaches and methods can improve the quality of the decisions to be made. Comprehensive studies of different Chernobyl data sets have stimulated new developments in spatial data analysis methodology (adaptation of machine learning algorithms, hybrid models, etc.) and integration with Geographical Information Systems.

The power and capabilities of the model based geostatistical methodology and the data driven approach of machine learning algorithms can be developed and applied wider to facilitate and improve decision making process on radioactively contaminated territories.

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