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FIELD MAGNETOMETRY FROM GEOSTATISTICAL PERSPECTIVE

MAGNETOMETRIA TERENOWA Z GEOSTATYSTYCZNEJ PERSPEKTYWY

Abstract: Field magnetometry is a method used for investigations of soil pollution, especially for screening and determination of locations with the highest concentration of pollutants ("hot spots"). The advantages and limitations of this method are still intensively discussed in the literature.

Field magnetometry is an example of measuring method that can be effectively supported by geostatistical methods. Often, during field measurements, even several types of magnetometric measurements are carried out, frequently combined with chemical ones. In a result, obtained data sets differ in a precision and give different information about potential soil contamination with heavy metals. Similarly to other methods, also in field magnetometry the most convenient, rapid and cost-effective measurements performed on soil surface are simultaneously less precise and often perturbed by many environmental and anthropogenic factors. Such data are often characterized by complex spatial distributions and neighboring measurements are not spatially independent. Consequently, classical statistical methods have limited applications.

In the studies of soil quality, it is crucial to investigate spatial correlations of studied phenomena. Accordingly, improper location of the measurement points at the study area may be a source of uncertainty and errors that will be much higher than errors connected with measurement devices. In addition, the cost of the field surveys can increase.

Geostatistics can be very effective tool that makes it possible to plan optimal measuring nets, integrate different types of measurements, minimize the cost of field surveys, and perform complex analyses with the assumed precision. Additionally, applications of geostatistics in field magnetometry may enable to eliminate errors connected with often controversial expert evaluations.

This work outlines possible applications of geostatistical methods in field magnetometry, and gives some recommendations in this subject.

Keywords: field magnetometry, magnetic susceptibility, geostatistics, heavy metals, soils, data integration, ecological risk

One of the inseparable characteristics of environmental data is a spatial nature of phenomena and linked with that spatial correlations. If samples collected in the field will be investigated using classic statistical methods, there will be impossible to take

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into account spatial relations between samples. In contrast, geostatistics provides many tools that makes it possible to analyze spatially correlated data and spatial relationships between them [1, 2]. It is possible to describe and analyze spatial correlations that characterize studied phenomena using different geostatistical measures of spatial variability. Apart from that, using a variety of methods as cokriging or Co_Est [3–5] it is possible to integrate different types of data due to cross-correlations that exists between different types of measurements performed in the field.Data integration finds application especially when some type of measurement is difficult to sample or too expensive.

Above-mentioned advantages of geostatistics are especially beneficial in environmental studies [6, 7], where very often some measurements are difficult to carry out or expensive. At the same time, it is possible to use large data sets of cheap and easy-to-measure data, like information about soil, forest type etc. Moreover, in the studies of soil quality, it is crucial to investigate spatial correlations of studied phenomena. Accordingly, improper location of the measurement points at the study area may be a source of uncertainty and errors that will be much higher than errors connected with measurement devices. In addition, the cost of the field surveys can be increased.

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Geostatisitcs

In the beginning, geostatistics was developed for the needs of the mining and petroleum exploration industry. After some time, geostatistical methods found applications in numerous other branches like hydrology, geology, environmental engineering etc. The theory of geostatistics was started by works of Danie Krige in the 1950's and later the mathematical formalization was given by Georges Matheron. The main goal of geostatistics is to describe and analyze data considering its spatial characteristics and spatial variability.

One of the most important tools of geostatistics is a semivariance function, which is a measure of spatial continuity. [3–5, 8]. The experimental semivariance is calculated as one-half of the average squared difference between values measured at sample points separated by vector **h**. The following formula is used for the semivariance calculations:

$$\gamma(\mathbf{h}) = \frac{1}{2N}\sum_{i=1}^{N}[Z(\mathbf{x}_i) - Z(\mathbf{x}_i + \mathbf{h})]^2 \tag{1}$$

where $\mathbf{x}_i$ is a data location, **h** is a lag vector, $Z(x_i)$ is the data value at location $\mathbf{x}_i$, and N is the number of data pairs spaced a distance and direction **h** units apart.

The plot of experimental semivariance is often referred as to variogram and is usually characterized by a range of correlation that is the distance at values are no more spatially correlated, and a sill that is a plateau of the variogram. Another important parameter of a variogram is a nugget effect that represents the vertical discontinuity at the origin. It is a combination of sampling error and short-scale variation that occurs at a scale smaller than the closest sample spacing.

In geostatistics, it is possible to investigate spatial correlations not only between one variable but also between several variables. Such spatial correlations can be investigated using cross-semivariance:

$$\gamma_{WZ}(\mathbf{h}) = \frac{1}{2N}\sum_{i=1}^{N}[W(\mathbf{x}_i) - W(\mathbf{x}_i + \mathbf{h})][Z(\mathbf{x}_i) - Z(\mathbf{x}_i + \mathbf{h})] \tag{2}$$

where $\mathbf{x}_i$ is a data location, $\mathbf{h}$ is a lag vector, $Z(\mathbf{x}_i)$ and $W(\mathbf{x}_i)$ are the data values at location $\mathbf{x}_i$ of different quantities, and N is the number of different type data pairs separated by length of the vector $\mathbf{h}$. The cross-semivariogram quantifies the joint cross-correlation between two different variables. In some situations, it is necessary to calculate measure of joint spatial variability that is called the pseudo-cross-semivariogram:

$$\gamma_{WZ}(\mathbf{h}) = \frac{1}{2N}\sum_{i=1}^{N}[W(\mathbf{x}_i) - W(\mathbf{x}_i + \mathbf{h})]^2 \tag{3}$$

Such measure is especially useful in case of small data sets, when classic cross-variograms cannot be reliable.

The main geostatistical method of spatial estimation is kriging that is a linear estimator:

$$Z^* = \sum_{i=1}^{n}\lambda_i z_i \tag{4}$$

where: λ_i are the weights, z_i are the known data values.

Kriging weights are calculated by minimizing the variance of estimation and simultaneously the average estimation error is set to zero.

It is possible to perform spatial estimation using more than one variable. The method that makes is possible to use multiple variables, which ought to be strongly correlated with each other, is called cokriging [4, 5]. It finds application when samples of primary variable (often referred as to hard data) are difficult to collect, are too expensive or too rarely sampled. Data integration is done due to cross-correlations between primary and secondary variables (often referred as to soft data). Such integration of multivariate information is especially advantageous in environmental studies, where some measurements eg chemical ones are difficult to obtain or are expensive, whereas another type of information is cheap or relatively easy to obtain (eg magnetic susceptibility). Similarly to kriging, cokriging minimizes variance of estimation error of primary variable, utilizing cross-correlations between primary variable and secondary variables. The value of primary variable, estimated at unknown location, is calculated using linear combination of both variables:

$$Z^{*}(\mathbf{x}_0) = \sum_{k=j}^{N_1} a_j\, z(\mathbf{x}_j) + \sum_{l=1}^{N_2} b_l\, w(\mathbf{x}_l) \tag{5}$$

where: z($\mathbf{x}_j$) is the j-th nearby sample primary value weighted by a_j, and z($\mathbf{x}_l$) is the i-th nearby secondary value weighted by b_i, N_1 and N_2 are, respectively, the numbers of nearby sample primary values and nearby secondary values.

Typically, cokriging gives more precise results than kriging. However, it is necessary that the hard and soft data must be strongly correlated, and the value of classical Pearson correlation coefficient should equal about 0.4 to 0.9. If correlations between hard and soft data are too weak, cokriging can give even worse estimation results than kriging. Conversely, if correlations between hard and soft data are very high and the Pearson correlation coefficient is close to one it is not advantageous to use cokriging because it gives the similar results like multivariate linear regression.

It is the most difficult to apply cokriging when only small number of measurements is available (often referred as to small dataset problem). If the number of soft data is large but the number of primary samples is too low, it can be very difficult, or almost impossible to calculate and model reliable variograms and cross-variograms. According to our experience with data integration in field magnetometry, at least 40 to 50 measurements of primary variable are needed to calculate reliable cross-variograms and use cokriging method. In such situations, it is necessary to use different methods of data integration (eg Co_Est method) or calculate some robust estimators instead of cross-variograms (eg pseudo cross-variograms).

The indicator methods that include both kriging and cokriging are especially usefully applied in field magnetometry. In this procedure, the measured values are transformed into indicator values: ie measured value is assigned with 0 if it is less than pre-defined cutoff level, or otherwise it is assigned with 1. Indicator techniques are very resistant to outliers and are appropriate for non-Gaussian distributions. Furthermore, using these methods it is possible to include in analyses also the additional qualitative information like soil type, land use, forest type, etc.

Field magnetometry

Field magnetometry is a method used for investigations of soil pollution, especially for screening and determination of locations with the highest concentration of pollutants ("hot spots"). The advantages and limitations of this method are still intensively discussed in the literature [2, 9–13].

Field magnetometry is an example of measuring method that can be effectively supported by geostatistical methods. Often, during field measurements, even several types of magnetometric measurements are carried out, frequently combined with chemical ones. In a result, obtained data sets differ in a precision and give different information about potential soil contamination with heavy metals. Similarly to other methods, also in field magnetometry the most convenient, rapid and cost-effective measurements performed on soil surface are simultaneously the less precise and often perturbed by many environmental and anthropogenic factors. Such data are often characterized by complex spatial distributions and neighboring measurements are not spatially independent. Consequently, classical statistical methods have limited applications.

Geostatistical issues in field magnetometry

Selection and split of the study area

Frequently, a study area can be composed of sub-areas, with different types of forest (deciduous or coniferous) or of forest with different age. In case of high heterogeneity of a development of particular soil horizons, especially the top ones (Ol – organic litter, Of – organic fermentation, Oh – organic humic), magnetic particles of anthropogenic origin may be accumulated at different depths. Furthermore, magnetic particles may be also dispersed in soil layers of different thickness. In a result, it may happen that despite of the same industrial dust deposition the values of magnetic susceptibility measured at the soil surface will be different.

In such cases, it is advantageous to investigate these sub-areas individually. It is needed because of the possible significant differences in spatial variability of magnetic susceptibility measured at those sub-areas. However, in order to distinguish better these sub-areas it highly useful to calculate and model global semivariance, which shows the ranges of spatial correlations. Similarly, the vertical semivariances of magnetic susceptibility should be calculated and modeled separately for each heterogeneous sub-area.

Planning measuring net

Geostatistical methods allow for significant decrease of the cost of expensive environmental studies. However, magnetometric measurements should be carefully planned in order to maximize the effectiveness of geostatistical methods. Many geostatistical methods, especially those used for data integration (like cokriging), are very sensitive to sampling grid configuration, number of samples etc., but in the same time, there is no need for a use of strictly regular measuring networks. The negative effect of an irregularity in sampling grids may be decreased by use of geostatistical methods. Moreover, it is often even advantageous to avoid regular sampling schemes. Regular sampling may cause the appearance of the periodical effects, and in a result, difficulties in modeling of spatial variability of magnetic susceptibility.

Measurements of magnetic susceptibility should be carried out with such sampling density that assures that an average distance between samples is about 30 % to 50 % of characteristic scale of spatial variability (Fig. 1). An use of such sampling density enables to investigate spatial variability of magnetic susceptibility only in that scale that

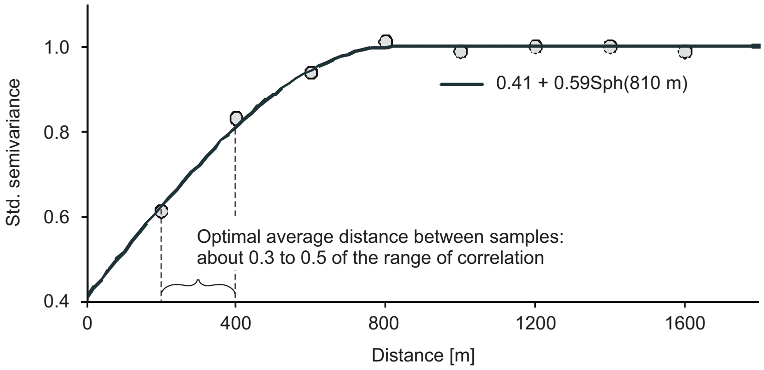

Fig. 1. Assessing of an optimal average distance between measuring points

will be used for modeling of spatial distributions. This way, spatial variability characteristic for smaller scale will not have negative influence on the modeled spatial distributions.

Proper densities of sampling grids should be determined also according to the local geological conditions. For example, during previous studies, significant differences in spatial variability of magnetic susceptibility measured at loam and sandy soil were also observed. Magnetic susceptibility measured at sandy soils was characterized by almost two-times shorter range of correlation. For that reason, it is recommended to use denser sampling grids at areas occupied by sandy soils. Particular attention should be drawn to the planning of sampling grids when measurements will be integrated using chosen geostatistical methods. Usually the number of hard measurements (eg chemical ones or magnetometric ones in soil profiles) should be greater than 40 to 50, although the number of these samples strongly depends on the scale of the study area as well as on the observed spatial variability. If the number of chemical samples exceeds several dozens, it should be sufficient to calculate reliable cross-variograms, and consequently to use multivariate geostatistical methods like cokriging. The number of magnetometric measurements at soil surface (soft measurements) should be at least a few times greater than the number of hard measurements.

If the number of hard measurements will be very low, it may happen that there will be a need for modeling pseudo cross-variograms or to use different methods of data integrations like Co_Est. In such cases, it is recommended not to perform chemical and magnetometric measurements at the same sample points because it will be impossible to use Co_Est method and to calculate pseudo cross-variograms. It is also useful to spread the locations of hard and soft measurements uniformly at the study area. Local clustering of data usually causes that modeling of spatial variability is more difficult.

It is also advisable to perform measurements in several stages. In the first one, it is recommended to perform the measurements of magnetic susceptibility with a MS2D sensor. This stage can be used as a fast screening method for preliminary recognition of the study area.

Typically, at the selected study area measurements can be performed beginning from the most imprecise, but the cheapest ones and finishing at the the most precise, but expensive ones. Firstly, the measurements of magnetic susceptibility at soil surface can be carried out, after that measurements of magnetic susceptibility in soil profile, and finally chemical analyses. Such measurements usually will not be performed at the same locations. For that reason, it might be difficult to investigate correlations using classic statistics and the Pearson correlation coefficient. It is recommended to use geostatistical measures of spatial correlations and cross correlations, like correlograms and cross-correlograms.

Planning the measurement at sample point

Apart from planning the measurement net, it is also important to use properly the information collected at single sample point. It is especially important in case of measurements that are cheap and easy-to-measure, but give imprecise information about studied phenomena. In field magnetometry, it concerns measurements of magnetic susceptibility performed at soil surface. Usually, at selected sampling point, magnetometric sensor was used to perform a series of 10 to 15 measurements of magnetic susceptibility in a circle of about 2 m diameter. Such methodology was recommended heretofore. However, it would be more advantageous not to average these values before applying further geostatistical analyses. It allows model the spatial variability of magnetic susceptibility more precisely, and no additional information from measurements is lost. It concerns especially the spatial variability in a micro-scale that contributes to the nugget effect. The nugget effect is also connected with measuring errors and it is important to assess the uncertainty of spatial distributions of magnetic susceptibility.

Assessing the extent of polluted area

The degree of development of uppermost soil horizons and its thickness can significantly affect the values measured with MS2D sensor due to its limited to 10 cm penetration range. To avoid these problems, it is recommended to geostatistically integrate these measurements with the thickness of Of, Ol and Ah horizons. Such methodology allows for taking into account the individual characteristic of the study area.

The assessment of the potentially polluted area should be performed rather using robust geostatistical methods like indicator or disjunctive kriging than ordinary one. This is caused due to usually observed complicated distributions of magnetometric data. In order to obtain better precision, geostatistical analyses can be performed separately for sub-areas with different thickness of Of, Ol and Ah horizons.

The extent of polluted area can be quantitatively assessed using measurements of magnetic susceptibility in a soil profile, especially the area under the curve of magnetic susceptibility against the depth. This area should be calculated beginning from the soil surface to the depth where the curve stabilizes. Spatial distributions should be then modeled using some robust geostatistical methods like indicator kriging. However, as often as it is possible, measurements in a soil profile should be integrated with measurements of magnetic susceptibility performed at soil surface with a MS2D sensor. An area under the curve of magnetic susceptibility against the depth is more effective measure of potential pollution than other measures that can be calculated from the measurements in a soil profile, like maximum magnetic susceptibility, or magnetic susceptibility at specified depth. Such measures should be used rather as additional information, which may support the analyses.

Conclusions

Geostatistical methods are particularly suited for analyzing magnetometric measurements. Combining the field magnetometry and chemical analyses with geostatistical methods enables to better plan the measuring survey. By analyzing of the spatial variability of studied phenomenon (eg soil magnetic susceptibility or the content of heavy metals in soil), it is possible to use proper sampling density, and to place samples in the way that minimizes possible sampling errors and simultaneously maximizes the amount of information collected in the field.

Using geostatistical methods it is also possible to integrate different types of magnetometric measurements eg measurements of magnetic susceptibility in soil profile and those performed at the soil surface as well as combine the magnetometric measurements with geochemical ones, or geological information. Furthermore, it is possible to integrate magnetometric measurements with chemical analyses using geostatistical methods that allow for overcoming the problems connected with small data sets or irregular sampling designs.

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MAGNETOMETRIA TERENOWA Z GEOSTATYSTYCZNEJ PERSPEKTYWY

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Abstrakt: Magnetometria terenowa jest metodą stosowaną do badań zanieczyszczenia gleby, w szczególności wykorzystywaną do wstępnego monitoringu jakości gleby na danym obszarze, wyznaczenia miejsc których występują największe stężenia zanieczyszczeń ("hot spots"). Zalety tej metody i jej ograniczenia są intensywnie dyskutowane w literaturze. Metoda ta jest rozwijana od wielu lat np. w ramach już zakończonego programu międzynarodowego MAGPROX.

Magnetometria terenowa jest wręcz klasycznym przykładem metody pomiarowej, w której można efektywnie wykorzystać metody geostatystyczne. W ramach badań magnetometrycznych zanieczyszczenia gleb wykonywanych jest często jednocześnie nawet kilka różnych typów pomiarów, którym towarzyszą nierzadko pomiary chemiczne. W rezultacie otrzymywane są zbiory danych charakteryzujące się różną precyzją oraz różnym rodzajem informacji na temat potencjalnego zanieczyszczenia gleb metalami ciężkimi. Podobnie jak w innych dziedzinach również w magnetometrii terenowej najbardziej wygodne, szybkie i tanie pomiary powierzchniowe gleby są jednocześnie najmniej dokładne oraz zaburzone poprzez różnorodne czynniki środowiskowe lub antropogenne. Dane te najczęściej mają skomplikowane rozkłady, sąsiednie pomiary nie są niezależne pomiędzy sobą. Tradycyjne obliczenia statystyczne mają więc bardzo ograniczoną przydatność.

Niezwykle ważną rolę w badaniach zanieczyszczenia gleb odgrywa znajomość korelacji przestrzennych badanych zjawisk. W związku z tym niewłaściwe rozplanowanie sieci pomiarowej na badanym obszarze może być przyczyną błędów oceny stężenia i rozkładu zanieczyszczenia gleby znacznie większych niż błędy pomiarowe związane z dokładnością aparatury pomiarowej. Może też radykalnie zwiększać koszty pomiarowe.

Geostatystyka może być również bardzo efektywnym narzędziem pozwalającym na właściwe rozplanowanie sieci pomiarowej, integrację różnorodnych pomiarów, minimalizację kosztów kampanii pomiarowych, wykonanie złożonych analiz i osiągnięcie założonej dokładności badań. Wykorzystanie geostatystyki w badaniach magnetometrycznych gleby pozwolić może w znacznym stopniu na eliminację dyskusyjnych ocen eksperckich. Jednym słowem, stosowanie geostatystyki może znacznie zwiększyć skuteczność stosowania metody magnetometrycznej.

Niniejsza praca prezentuje najważniejsze możliwości wykorzystania metod geostatystycznych w badaniach magnetometrycznej gleb, jak również prezentuje praktyczne zalecenia w tym zakresie.

Słowa kluczowe: magnetometria polowa, podatność magnetyczna, geostatyka, metale ciężkie, gleby, integracja danych, ryzyko ekologiczne