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The state of the art in pedometrics

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ABSTRACT

This paper briefly reviews the state of knowledge of the spatial and temporal variation of soil as discussed in the rejoinder session of the Pedometrics Workshop held in Wageningen, 1-3 September 1992. The paper discusses three aspects, namely theory, applications, and tools, in terms of current understanding and the research topics that we should be investigating in the next few years. Future directions for the study of soil variability are discussed in terms of issues for soil survey, issues for modelling, issues for methods and procedures, and finally, issues for effective communication of information about soil variability to users of soil data. An appendix of currently available geostatistical software is also included.

INTRODUCTION

The title of the Wageningen workshop, “Pedometrics”, was coined by Professor Alex McBratney to describe the quantitative study of the variation of field soil. Although the term has another meaning outside soil science, it was immediately clear to soil scientists that the word has two roots: *pedo* refers to field soil and *metric* refers to quantitative approaches both for measurements and area1 characterization. “Pedometrics” is also the eponymous title of a working group of the ISSS, division 5, which was set up to study the quantitative aspects of the spatial and temporal variation of field soil.

Soil scientists have been aware of the problem of the spatial and temporal variation of field soils since the beginning of the 20th century (Beckett and Webster, 1971; Smith, 1938; Webster, 1994). However, it was not until the late 1960’s and 1970’s that field scientists began to study soil variation in a systematic way. The first studies were independent tests o’f soil maps in which soil variation was seen as an unwelcome nuisance that reduced map reliability. Gradually the general nature of soil variation, and its unpredictability, have led us to see variability as a key soil attribute rather than a nuisance,

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though this enlightened view is certainly not shared by everyone, particularly by planners and decision makers who wish to use soil information as a basis for decision making.

The last twenty years have seen many advances in the theory of spatial statistics, in technology for handling data and the availability of quantitative data so that soil variability is now much better understood than it used to be (cf. Webster and Oliver, 1990; Burrougb, 199 1 a). Soil variability has been the subject of a huge research effort in recent years (Burrough, 1993). The aim of this paper is to provide a brief review of the current state of knowledge, as represented by the Wageningen meeting, in terms of

(a) the theory of spatial variation,
(b) applications using information about soil variability,
(c) the tools available.

We review these points, both for the current situation, i.e. the question of "What do we know at present?" and for the foreseeable future, i.e. "What should we know?". In this paper we also identify some issues for future investigation.

THE CURRENT STATE OF KNOWLEDGE ABOUT SOIL VARIABILITY

Theory

The need to take account of spatial variability when modelling soil forming and environmental processes is now abundantly clear. The phenomenon of soil variability has been approached by numerical classification, multivariate statistical methods, continuous (fuzzy) classification, geostatistics, fractal methods, mathematical morphology and chaos theory (Burrough, 1993). The theory of *Geostatistics*, as first elaborated by Matheron (197 1) and then made accessible by Joumel and Huibregts (1978), Isaaks and Srivastava (1989), Webster and Oliver (1990), Cressie (199 1), Deutsch and Journel (1992) and others, has been extremely useful in providing a suitable theoretical framework for studying soil variability, and for providing a sound theoretical basis for interpolation, structural analysis and for the design of optimal sampling networks.

Today it is clear that the estimation of the variance of a soil property has little meaning unless it is expressed in terms of the size and kind of spatial units for which it was estimated. Expressions for variability must be related to georeferenced spatial units. It is also useful to distinguish soil properties with and without direct practical relevance and to note the need to determine the spatial and temporal covariance structures of multivariate land *qualities* from those of *single characteristics (e.g.* FAO, 1976).

Applications

Variability studies are now an integral part of soil science. Studies in the last twenty years have explored the problem of soil variability from many points of view, and have related the phenomenon to problems of efficient soil use (e.g see Bouma, 1989). Soil variability is being linked to the concept of the reliability of soil information: measures of reliability include statements about uncertain factors such as spatial variability, data quality, scaling factors, and simulation models. The reliability/uncertainty issue is becoming increasingly important, especially when variability studies are used by management for decision making.

Current soil surveys provide some information on the internal variability of mapping units but we do not know whether *permanent soil* characteristics (e.g. texture) have *characteristic spatial structures* within different occurrences or delineations of the same soil series. Many soil properties are not constant (e.g. level of nutrients, moisture, bulk density) and their spatial structures are also a function of time and process. Also, if a mapped unit is treated as homogeneous in the decision-making process (i.e., for ground water vulnerability assessment), the ramifications may be considerable and the assessment may be seriously flawed.

There is now a broad consensus that interpretative statements derived from soil maps need to include an expression of reliability. Conventional soil maps are increasingly being supported with information about the variability of mapped units and quality control in soil survey is becoming routine as mapping methods become more automated (e.g. Bregt, 1989).

Quantitative data on soil variability are stored in geographical information systems: they are used for mapping and for optimising soil survey (Bregt, 1989; Burrough, 1991a). Digital databases and improved methods for data collection and geostatistical analysis mean that detailed studies of soil variability and the consequences thereof can easily be made. The contribution of soil variability to (a) errors in maps, (b) uncertainty in the results of quantitative models of landscape processes, and (c) the reliability of land evaluation studies can be estimated and surveys can be optimized accordingly. The need to take account of spatial variability when modelling soil formation and environmental processes, such as runoff and soil erosion (De Roo et al., 1992) is now abundantly clear.

Tools

The publication of single computer programs for analysing spatial variability (e.g. in *Computers and Geosciences)* has been complemented and improved upon by the provision of theoretical texts (Journel and Huijbregts, 1978; Webster and Oliver, 1990; Cressie, 1991; Olea, 1991) and by the development of software packages for statistics and geostatistics (see Appendix). Cheap, powerful personal computers have made geostatistics available to many people and have stimulated the teaching of the methods in universities to soil scientists, physical geographers, geologists and hydrologists. The availability of geographical information systems (GIS) and soil information systems (SIS) for storing soil data in digital form, for mapping and for integrating soil data with information on other aspects of the environment (Burrough, 199 1 b) has stimulated work on the problems and the practical applications of soil variability (e.g. Okx and Kuipers, 199 I).

While tools in data analysis have improved, and laboratory methods of chemical analysis have become more automated, there have been relatively few advances in the rapid collection of data in the field. Collecting soil samples is still expensive and time consuming, though advances in instrumentation permit rapid, reproducible measurement of many physical properties of the soil (e.g. Schellentrager and Doolittle, 199 1).

ACTION FOR IMPROVING KNOWLEDGE ABOUT SOIL VARIABILITY

Theory

Although geostatistics remains a popular research area, we probably have sufficient theory for many practical purposes in soil science. However, the role of soil forming processes in generating soil variability in space and time is still generally only understood in qualitative terms. There is little understanding of how soil forming processes can result in the various kinds of spatial variation shown in Fig. 1. Most studies of soil variability have been *post hoc*, i.e. unknown patterns of distribution are sampled in an attempt to map the true variation by interpolation rather than by predicting the spatial or temporal distribution from a physical understanding of soil forming and soil changing processes. There are few equivalents to the hydrological runoff or groundwater model in soil science, and research in this area is needed,

Although superficially quantitative, many of the more advanced approaches to modelling soil variability (such as fractals and chaos theory — *e.g.* Burrough, 1993) are more truly descriptive than prescriptive: it may never be possible to say exactly how a given pattern of soil variability in any specific area results from a particular set of non-linear processes.

Until now, pedometricians have paid most attention to the problem of spatial variation. The time component is rarely included in geostatistical analyses. Typically, the scientist is confronted either with spatially rich/temporally poor or temporally rich/spatially poor data. As a consequence, only limited use can be made of the data. There is a lack of suitable theory for describing the variability in time of critical soil properties such as moisture supply and organic matter content. For the typical geostatistical data set, cer-

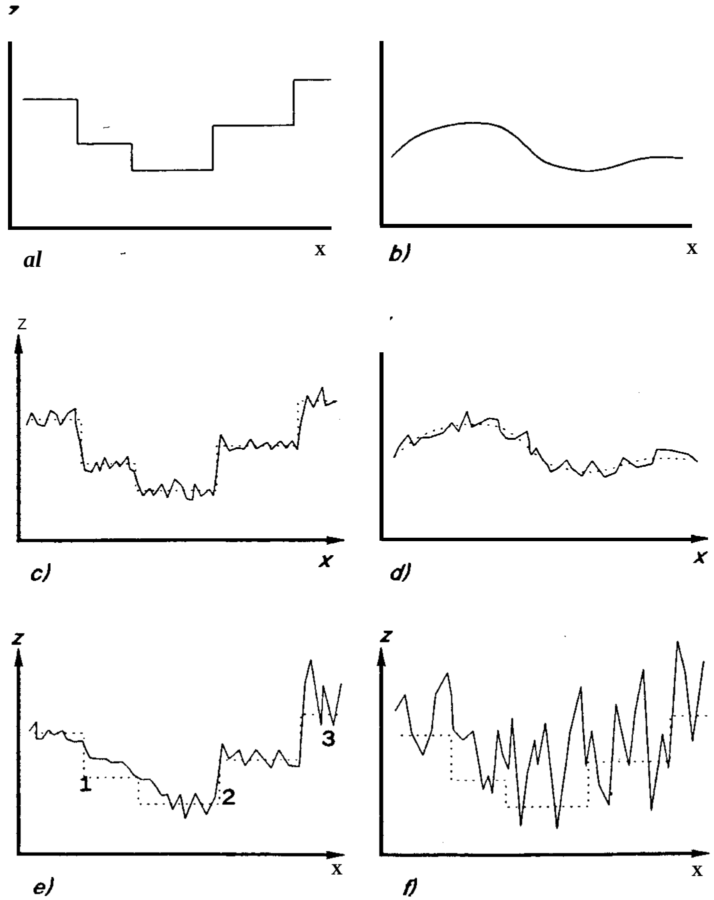

Fig. 1. Hypothetical models of various forms of spatial variation that can occur in soil. (a) Idealized homogenous variation within map units having sharp boundaries that are often used to approximate some of the following real kinds ofvariation. (b) Continuous smooth variation, typical of some landforms. (c) Within-unit variation smaller than between unit variation as can occur when soil variation is dominated by differences in homogeneous geological units. (d) Continuous smooth variation with local noise that is common for many hydrological properties such as groundwater levels. (e) Non-stationary variation including a trend (1), abrupt change (2) and larger than average within-unit variation (3) that occurs with many soil attributes. (f) Variation where short range effects such as periglacial features or local levels of soil pollutants can swamp all other signals.

tain questions can be answered but, if the attribute changes over time, a full scale sampling effort is required to update the information. Work on temporal variation of soil will probably require collaboration with scientists in other disciplines such as meteorology and hydrology.

In spite of a huge research literature, knowledge about soil variability is still dispersed and not organized in such a way that there is a general theory or rule base for predicting soil variability. There is a need to organize and systematize our knowledge on soil variability in such a way that users of soil information unskilled in geostatistics and modelling can make the best possible decisions under conditions of uncertainty. Once the knowledge has been gathered and organized, then it may be sensible to use expert systems to help the user choose how best to deal with uncertainty.

For regional, continental and global studies we face the problem that the spatial resolution of the application is often quite different from the spatial resolution (or the support) of the observations (representative profiles, point samples, pedons). Because it is known that soil variability is often large within spatial units, such as soil associations used for regional studies, we need to ask if it is sensible to use point data and detailed models to make regional estimates of attributes such as expected crop yields (Bregt and Beemster, 1989). For areas which also have soil maps at larger scales it may be more sensible to make weighted average estimates for sub-units of the terrain. Where no large scale maps exist it will be necessary to use all available knowledge (possibly encapsulated in an expert system) and avoid pseudo accuracy.

Applications

Future applications of knowledge of soil variability will be in monitoring (determining derived variables using pedo-transfer functions, remote sensing, etc.), for predicting values of attributes that are too expensive to measure directly or cannot be measured directly, and for environmental modelling. The last is particularly important as the uncertainty in model results may often be due largely to the uncertainties caused by spatial and temporal variability in both the data and the model parameters (Bouma, 1989; Heuvelink et al., 1989).

Many variability studies are made in a pedological context, where soil descriptions are based on genetic horizons. Applications such as land evaluation studies should also consider the kinds of variation that are induced within a given type of soil by soil management. Different types of management can often have a major impact on soil behaviour, because they affect soil structure or the content of organic matter. In studying soil variability, scientists should be more aware of this phenomenon and Stratification of soil data by land management rather than by soil type may occasionally be profitable (Brus, 1994). This example emphasises the need for a critical analysis of the parameters and data that are most relevant for any particular type of applied study (e.g. Bouma, 1992).

Simulation modelling is increasingly being used for quantitative land evaluation. Water and solute flow is usually described in deterministic models by the Darcy/Richard equation which implicitly assumes soils to be homogeneous and isotropic. Most field soils are neither homogeneous nor isotropic and contain either contrasting soil horizons or macropores, such as cracks in swelling soils and biopores in biologically active soils. Because many land qualities, such as moisture availability or trafficability, are assessed by using simulation studies that implicitly assume the soil to be homogeneous, results may be misleading. There is also a risk that large spatial or temporal variability in the basic soil characteristics of texture, organic matter and bulk density, which are used as model inputs, may give incorrect assessments (Bouma, 199 1). If simulation models are so sensitive to variations in input data as to yield unreliable results then their relevance and usefulness should be questioned. The interplay between soil variability and the sensitivity of mathematical models to spatial and temporal variations in data and parameter values should lead to the development of robuster models and to an improved understanding of the limitations of current linear modeiling (De Roo et al., 1992).

Future applications in agriculture and environmental management will require detailed knowledge of soil variability in both space and time. For example, fertilizers can be applied more efficiently, with reduced consequences to the environment if the application to a crop can take account of levels of fertilizer that are already in the soil (e.g. Finke, 1993). Irrigation water can also be applied in a site-specific way, thereby avoiding over-saturation or insufficient water. Prototype systems have been developed which apply fertilizers to fields using computer controlled applicators which are guided by digital maps of the field variability. However, it is still unclear how well these systems protect ground water from contamination. Data on soil variability will be used to generate confidence levels on model predictions that are used by planners and decision makers. The use of models and geographical information systems that include data on soil variability will allow different land use scenarios to be compared effectively.

Tools

Geostatistics has proved to be a very useful tool for quantifying soil variability, though its use has raised many questions about numbers of samples, how to model a variogram, how to stratify data, and when and where particular techniques are most appropriate. These issues need to be addressed and tools need to be made available that permit users to explore these questions easily. Methods of exploratory data analysis (EDA) linked to multiwindowing statistical programs on microcomputers (e.g. *REGARD* — Haslett et al., 1990) allow the user to explore complex multivariate data sets easily and to remove outliers or strange clusters. The ways in which EDA can assist geostatistical analyses need to be further investigated.

The development of geostatistical software for allowing users to work with qualitative data (e.g. Bierkens and Burrough, 1993) or quantitative data in a probabilistic way (e.g. Yates and Yates, 1988; Deutsch and Journel, 1992) needs to be encouraged. Tools like ADAM (Wesseling and Heuvelink, 199 1) for analysing how errors in data affect the results of environmental models need to be made widely available. In the United States, a recent National Academy of Science Committee concerned with methods for assessing ground water vulnerability stressed the need for methods which yield results in probabilistic terms. In the committee's opinion only this type of information will enable land-use managers to make informed decisions, especially in the presence of uncertainty. Methods which do not provide probabilities may mislead the user into believing the model output is certain.

The main stumbling block to better studies of soil variability is lack of data. Methods need to be developed for gathering good data quickly, and in large amounts. There is a need to integrate modem remote sensing systems with geographical information systems to provide data with a better resolution in space and time than is now usually possible. Geoelectrical and geophysical systems such as ground penetrating radar (Schellentrager and Doolittle, 199 1) or electro-magnetic measurements (e.g. Brus et al., 1992) may be useful in some circumstances.

It is becoming increasingly important to know the exact geographical location of soil observations in order to relate them accurately to landscape features such as geology, landform, local relief and hydrology. Hand-held global positioning systems (GPS) that receive information from a network of space satellites are coming into use for this.

Tools, such as expert systems, need to be developed to provide users with up-to-date information on how to tackle soil variability and how it affects issues such as crop yield estimation, environmental management etc. A recent example of a useful expert system is *ALES* (Rossiter, 1989).

DISCUSSION AND CONCLUSIONS: THE IMPORTANT ISSUES

Issues for soil survey

Current soil surveys provide some information on the internal variability of mapping units but we do not know whether *permanent* soil characteristics (e.g. texture) have *characteristic spatial structures* within different occurrences or delineations of the same soil series. Note that many soil properties are not permanent (nutrients, moisture, bulk density) and their spatial structures are also a function of time and process. There is a need for a systematic spatial variability analysis of permanent properties in multiple delineations Of soil series.

At farm level, soil variability is now being interpreted in terms of alternative forms of management for different sub-areas of a field. Variability is being seen as a key attribute rather than just a nuisance. So far, attention has been focused on soil fertility but moisture supply, tillage practices, planting and seeding, and biocide applications will follow. We need to be able to define objective procedures for defining sub-areas within fields that act as relatively homogeneous management units. There is a need for procedures to assist stratification by area1 survey or by remote sensing. Simulation models could be used to define variability over time when the underlying physics of the system is known. Other methods are needed for defining the time-rate of change in soil variability for properties where the physics is largely unknown or misunderstood. Inclusions of different soil types in a mapped unit may cause severe uncertainty when determining appropriate uses for land. For example, an unreported, included soil type, even if it represents a small portion of the total, can be devastating to ground water quality if the properties of the included soil enhance transport. These impurities are similar to fractures or other structural features. Methods for delineating, characterizing and reporting this information are needed.

For regional, continental and global studies we face the problem that the spatial resolution of the application is quite different from the spatial resolution of the observations (representative profiles, point samples, pedons). When soil variability is known to be large within the spatial units used for regional studies it is necessary to know how to generalise point data for modelling potential crop yields and other difficult to measure properties. For areas with soil maps at larger scales, sound methods for making proportional or weighted average estimates of soil property values for sub-units are needed. Where no larger scale maps exist we must use all available knowledge (possibly encapsulated in an expert system) and avoid pseudo accuracy. Also since processes, problems and decisions, occur at various scales, methods are needed which operate at these scales, that translate information from one scale to another and provide the uncertainty of doing so.

Issues for modelling

Because of the effect of weather on soil behaviour, temporal variation is also very important. We can model processes retrospectively and can calibrate and “validate” (or quasi-validate) the models. For land management and planning we need to predict future conditions for alternative land use scenarios. It will be essential to know if real time modelling checked by real time monitoring and medium term weather forecasts is useful and affordable. It is necessary to know how the probable, large inaccuracies of long-term weather forecasts can affect model predictions and therefore to know how accurately soil characteristics must be measured or defined given the likely large temporal and spatial variability of weather and climate. The interaction of various related processes needs to be understood if accurate modelling will ever be achieved. This becomes more important as studies encompass larger areas (e.g. the global scale).

It is important to determine the uncertainty in the data as well as in the predictive methods. Resource managers are quite dismayed at the current levels of uncertainty present in modelling efforts. If confidence bands are too large, then the methods are not helpful for practical decisions, regardless of detail. As the size of the area to be managed increases, simpler approaches may become more useful and it is necessary to be able to determine the appropriate level of detail of models and supporting information for any given use. It seems likely that geostatistical methods could be used to determine the level of complexity a model should encompass given the level of detail of the available information.

Predicting soil attributes using a digital elevation model and terrain analyses may have many important ramifications for predictive modelling (Jenny, 1941,1961). This approach might be said to be "predicting variability" since the aim is to predict the spatial distribution of soil attributes from easy to obtain, nondestructive, non-soil, high resolution data. If this type of an approach can produce accurate estimates of the mean and variance of the attribute, then truly predictive modelling of near surface processes may be attainable in the (relatively) near future, though Phillips (1989) has warned of the problems that non-linearity may bring.

Issues for methods and procedures

New methods which reduce estimation variance, require fewer samples and can use "soft" information should be encouraged. Methods should be developed which allow estimation in both the spatial and temporal domain simultaneously. Methods should be developed that provide probability information useful for problem solving. New methods for coupling spatial variability to models should be developed.

One serious problem is the need for more and better data. A systematic, detailed spatial analysis of permanent soil characteristics would be ideal, but may not be practical. To do so would require an extensive retraining (or new hiring) of soil survey personnel and the cost of reinvestigating mapped soils may not be politically acceptable. However, at least the basic statistics (i.e., mean and variance) of the characteristics could be supplied instead of a range of "likely" values or a "typical" value. Also, it is important to determine the uncertainty in the data as well as in the predictive methods. Resource managers may not be able to use methods that have too high a level of uncertainty. If the confidence band is too large, then the methods are not useful for making practical decisions, regardless of their level of sophistication. Methods are needed to determine the appropriate level of detail for models and supporting information to achieve particular goals.

Because many soil data are still qualitative, we need to develop procedures for integrating information from soft and hard data for optimizing sampling, interpolation, modelling and prediction. One opportunity to broaden our knowledge base with "hard data" is to expand soil information systems to include data on the quality and quantity of groundwater and surface water. This brings a central issue which is the problem of database integrity and updating. Likewise, we need to pay more attention to the time component of soil variation, particularly with respect to the movements of water, nutrients and pollutants.

Given that GIS are increasingly being used to supply resource managers with data, model results and impressively coloured output, we need to develop sound rules for combining data from different sources that have been collected using different supports, levels of spatial resolution (sample spacing) and methods so that the errors associated with the model outputs are both quantified and minimized.

Issues for effective communication to the users of soil data

A major organisational and social problem is the need to convince colleagues, managers and decision makers in natural resource studies that pedometrics is both necessary and useful. One approach to this will be to gather and organize knowledge on geostatistics for the benefit of statisticians, soil scientists, agricultural advisory staff and managers and decision makers and to demonstrate with suitable case studies that pedometric knowledge provides good answers more cheaply than by conventional means. Information must be easily available on how to work with the problem of soil variability when designing sampling schemes, setting up classification systems and processing soil data. Some of this information could be formalized and made available through easy-to-use expert systems (cf. Burrough, 1992).

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APPENDIX. GEOSTATISTICAL SOFTWARE CURRENTLY AVAILABLE

GEOEAS (Geostatistical Environmental Assessment Software)
US Environmental Protection Agency
Environmental Monitoring Systems Laboratory
P.O. Box 93478
Las Vegas, NV 89 193-3478, USA

Shareware programs for general point and block kriging on PC's (80286/20386/MS-DOS plus coprocessor). User friendly, but limited in size of data sets. Includes basic statistics, variography and graphic display. Data file format is being accepted as standard. Interfaces to GEOPACK. Is being extended to include cokriging and correspondence analysis, etc. See 4 and 11.

2. GEOPACK (Geostatistics for Waste Management)
S.R. Yates
USDA/ARS
U.S. Salinity Laboratory
Riverside, CA 92501, USA

Shareware programs for disjunctive kriging and cokriging, ordinary kriging and cokriging, basic statistics and variography. GEOEAS can be run from a shell.

3. SPATANAL
I.G. Staritsky
Manual for the geostatistical programs SPATANAL, CROSS and MAPIT
Department of Soil Science and Geology
P.O. Box 37
6700 AA Wageningen, The Netherlands
Tel: (31) 8370 8414.5
Fax: (31) 837082419

Shareware PC-Programs for variography (simple and cross variograms), kriging and co-kriging including stratification.

4. PC-RASTER
Department of Physical Geography
Rijksuniversiteit Utrecht
P.O. Box 80.115
3508 TC Utrecht, The Netherlands
Tel: (31) 30 53 2768
Fax: (31) 30 540604

Shareware programs for variography and ordinary kriging using GEOEAS data format. Raster GIS with 2D and 3D display; programs for 2D spatial simulation. Special package (ADAM) for computing error propagation through spatial modelling with GIS. Software for MS-DOS and Apple. Global trend fitting and removal. Nested analysis of variance. Interfaces to ARC-INFO, ERDAS, SURFER, POSTSCRIPT, GEOEAS, etc. Runs under MS-DOS or UNIX.

5. Geostokos Toolkit
Geostokos Ltd.
36 Baker Street
London WI M l DG, UK
Tel: (44) I 828 9636
Fax: (44) 1 895 0059

GEOSTOKOS — expensive, commercial programs for variography, kriging, cokriging, univcrsal kriging, indicator kriging, global and local trend fitting and removal. Inverse distance and spline interpolation for quick looks.

6. GEOSTAT
Systemes Geostat International Inc.
4385, rue St-Hubert, suite 1
Montreal, Que., Canada H2J 2X1
Tel: (1) 514 521 7544
Fax: (1) 514 525 8484

Commercial programs for data management, data display, grid and contour estimation, statistics, geological modelling, reserve estimation, geostatistics (2D/3D variography block kriging/ disjunctive kriging), reserve reporting, mine design and planning, utilities, specials. PC's and mini's. Each module priced individually.

7. GEOVARIANCES International
1, rue Charles Meunier
772 10 Avon-Fontainbleu, France
Tel: (33) 16422 36 15
Fax: (33) 1 64 22 87 28

GEOVARIANCES is the commercial arm of Centre de Geostatistique. Major software packages including renowned BLUEPACK software for 2D and 3D mining estimation, kriging, etc. Runs on mini's under UNIX.

See also:

GEOSMINE and BLUEPACK-3D
Ecole des Mines de Paris
Centre de Geostatistique
35, rue Saint-Honore
77305 Fontainbleu, France

8. UNIRAS A/S
376 Gladsaxevej
DK-2860 Seborg, Denmark
Tel: (45) 31 67 22 88
Fax: (45) 31 67 60 45

UNIRAS — set of software tools for 2D/3D interpolation and display. Kriging is one module from many. Kriging methods are not particularly explicit. First class graphics in 2D and 3D.

9. United States Department of the Interior
Geological Survey
Statpac and related programs for PC's
W.D. Grundy and A.T. Miesch
Open tile report 87-411-A
List of program names — not particularly informative.

10. Dr. Don Myers
Department of Mathematics
Tucson, AZ 85721, USA
Tel: (1) 602 621 6859
Fax: (1) 602 621 8322

Developer of GEOEAS-format programs for cokriging and correspondence analysis. User friendly — shareware.

11. GENSTAT
NAG Ltd
Wilkinson House
Jordan Hill Road
Oxford OX2 8DR, UK
Tel: (44) 865 511 245
Fax: (44) 865 310 139

GENSTAT — the well-known general statistical package has been extended with variography, point, block and universal kriging (programs supplied by R. Webster et al.).

12. SURFER
Golden Software Inc.
P.O. Box 28 1
Golden, CO 80402, USA
Tel: (1) 303 279 1021
Fax: (1) 303 279 0909

Nice, moderately priced PC package for interpolation (quick) with inverse distance, spline and a simple (i.e. not sophisticated) invisible kriging option. Good contouring display and 3D display in colour.

13. GSLIB

Geostatistical Software Library and User's Guide. Clayton V. Deutsch and Andre Journel. Oxford University Press, October 1992. ISBN 019 50 73924,340 pp. Theory and practice of geostatistics with worked examples. Includes disks with 37 Fortran programs (source code) for variogram estimation (2D, 3D), cross validation, kriging (simple, ordinary, universal, co-kriging, indicator kriging) and conditional simulation.

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