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4 the International Institute of Aerospace Survey and Earth Sciences (ITC)
5 Geographical Institute, University of Utrecht
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# Land qualities in space and time

Proceedings of a symposium organized by the International Society of Soil Science (ISSS), Wageningen, the Netherlands, 22-26 August 1988

J. Bouma and A.K. Bregt (editors)

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# Introductory papers

# LAND QUALITIES IN SPACE AND TIME

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## Introduction.

This introductory paper attempts to describe the particular focus and character of this symposium and to provide a broad introduction to the invited papers. Several conferences have been held in 1988 with topics that relate to the one of this Symposium. Utah State University sponsored an International Symposium on: "Water Quality Modeling of Agricultural Non Point Sources" in Cooperation with the International Science and Education Council of the United States Department of Agriculture. The Department of Agronomy of New Mexico State University has sponsored a workshop on; "Validation of Flow and Transport Models for the Unsaturated Zone" and the University of Minnesota sponsored a Workshop on: "Soil Resources: Their Inventory, Analysis and Interpretation for use in the 1990's". Results of these three Conferences, which were all held during the first part of the year, should be considered during our Symposium. Several participants to these three Conferences will also attend our Symposium and they will share their experiences.
The original concept of our Symposium, as discussed during the ISSS Meetings in 1986 in Hamburg, was to give some emphasis on soil survey and land evaluation aspects here in Wageningen while a second Symposium to be held in Czechoslovakia in the week after August 26, would emphasize hydrological aspects. Unfortunately, the latter Symposium had to be cancelled. With preparations for our Symposium well advanced, the original concept of our Symposium was maintained. A dialogue will be stimulated among fieldworkers, involved with soil survey and land evaluation, and researchers involved with various modern techniques such as simulation modeling, including agronomic, soil physical and soil chemical aspects, geostatistics, remote sensing, geographical information- and data-management systems.

## Land qualities: A basic concept in Land Evaluation.

Land qualities are defined as: "Attributes of Land which act in a distinct manner in their influence on the function of land for a specific kind of use" (FAO, 1976). They are related to Land Characteristics as defined in the Appendix. Examples of Agricultural Land Qualities are the moisture supply capacity, the trafficability and the aeration status of the rootzone. For environmental applications one could also, tentatively, define land qualities, such as the nitrification or denitrification capacity, the phosphate sorption capacity, and the effective leaching capacity of pollutants. To date, however, emphasis has been placed mainly on agricultural land qualities: there is a clear need now to define environmental land qualities as well (e.g. Nielsen, 1987). Be that as it may, land qualities are considered to be diagnostic criteria for land evaluation. Different land qualities, considered to be relevant for a particular Land Utilization Type, are divided into a number of gradations and are combined to form different

land suitability classes ranging from S1 (highly suitable), S2 (moderately suitable), S3 (marginally suitable) to N1 (conditionally suitable) and N2 (permanently unsuitable) (see scheme in Figure 1).

Crop: sorghum

| Crop Requirement | | | Factor Rating | | | |
|---|---|---|---|---|---|---|
| Land Quality | Diagnostic Factor | Unit | Highly suitable s1 | Moderately suitable s2 | Marginally suitable s3 | Not suitable n |
| Oxygen availability | Soil drainage class | Class | Well drained Excessive | Moderately well drained | Imperfectly drained | Poorly. Very poorly drained |
| Rooting conditions | Effective soil depth | cm | > 120 | 50-120 | 30-50 | < 30 |
| Nutrient availability | Soil reaction | pH | 5.5-7.5 | 4.8-5.5 and 7.5-8.0 | 4.5-4.8 and 8.0-8.5 | < 4.5 and > 8.5 |

Fig. 1 Scheme for determining land suitabilities for a particular land utilization type, considering three different land qualities and land characteristics as diagnostic factors (derived from soil survey data) which are used to estimate the qualities.

Selection of relevant land qualities and of the number of gradations for any particular land quality, as well as the combination of different land qualities into different suitability classes, requires empirical decisions which are essentially based on experience. One problem is formed by sharply divided classes in what are in reality continuous populations. Fuzzy clustering may be a better procedure, offering partial membership in different classes (e.g. Kandel, 1986; Chang and Burrough, 1987).
Returning to the basic concept of the land quality itself, different levels of detail may be distinguished when defining land qualities. These may be required because of different types of questions being asked or because of lack of the type of data allowing detailed analyses (Figure 2). The land quality of moisture supply capacity (MSC) will be used here as an arbitrary example but the principles discussed are relevant for other land qualities as well.

First, we assume that the MSC is being estimated for one particular location only. Aspects of spatial variability are to be considered later in this chapter. The amount of data needed to obtain estimates of the MSC for each level in Fig. 2 increases as estimates become more detailed and so do the associated costs. Farmers experience at level 1 is bound to be highly variable among different farmers and it is often questionable whether the MSC as such is specifically being characterized because so many other interacting factors play a role in agricultural production. Still, tapping farmer's experiences is

| | TECHNICAL APPROACH | REQUIRED DATA | RELATIVE COST |
|---|---|---|---|
| LEVEL 1 | Farmer's experience | | |
| LEVEL 2 | Expert judgement | | |
| LEVEL 3 | Available water (0.3-15 bar) | | |
| LEVEL 4 | Simple water balance | | |
| LEVEL 5 | Dynamic simulation (simple) | | |
| LEVEL 6 | Dynamic simulation (complex) | | |

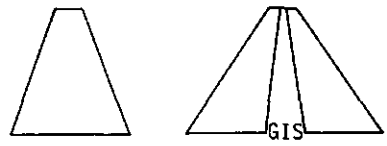


Fig. 2 Six levels of detail for expressing the land quality "moisture supply capacity" and associated required data and costs. Relative cost decreases when data are accessible in a GIS.

important because good farmers see many effects of moisture supply on crop growth which may not be considered in narrow modelling exercises. Use of expert systems may help to systematically express the available experience (e.g. Maes et al., 1987). Level 2 involves the introduction of a systematic scientific approach by experts who can interpret phenomena also from a more theoretical point of view. Moreover, they have visited different regions providing a relatively broad perspective. Level 3 introduces one particular type of measurement which is widely being applied, the "field capacity" (e.g. McKeague et al., 1984). The notion that a static measurement of water held between two water-potentials is a good measure for the MSC has widely been challenged. However, it does provide a means to compare different soils in a reproducible manner. Level 4 includes estimates of fluxes of water at the soil surface and beyond the rootzone. This can be done in a generalized manner, or by simulation modeling. Simple simulation models (e.g. Bouma et al., 1980) had the initial advantage of requiring less computer time. With the rapid advance of computer technology this advantage becomes less important. More complex models (e.g. Belmans et al. 1983; Ritchie, 1986) can now well be run on PC's. **Clearly, the major barrier is not the computing capacity but lack of data.**

The picture shown in Figure 2 is more complicated than it may seem. Once Geographical Information Systems are available with a well-stocked data-base, specific data may be easily available at little or no cost. In turn, an analysis of expected questions and associated data needs is crucial to focus future survey and monitoring programs. Only those different types of data should be gathered that can be used effectively **at the different levels being distinguished in Figure 2.** There is a certain degree of similarity with soil survey procedures where surveys are made at different degrees of detail as reconnaissance surveys (e.g. scales of 1:500.000), as semi-detailed (e.g. 1:50.000) and detailed surveys (e.g. 1:10.000). As mentioned before, focusing of future programs should also be based on an analysis of current and future questions being asked, or - more general - on problem analysis. This is not as simple as it may seem at first glance. Questions that can be answered with knowledge and data of level 1 are not necessarily all simple or broad, nor are questions at level 6 all very complex and specific. In general, though, the degree of detail of questions increases when going from level 1 to 6. **A mixed approach can be followed**

**where a broad screening for a particular question as made at, say, level 2 while more detailed analyses, using simulation, are only made in these areas where such studies are relevant.**

Invited papers of this Symposium cover different types of questions and different degrees of study detail. Small scale studies covering whole continents or countries to be reported by Dumanski, Fournier, Thomasson and Varalyay, are bound to be more general in character in terms of detail of the land qualities being considered and of questions being asked. Necessary data are bound to be less detailed as well. Field scale studies to be presented by Bork and Robert, on the contrary, are and can be more detailed in these three respects. Comerma and Guenni (1987) have presented a case study for Venezuela in which data needs for studies at different scales were analysed and discussed.

Procedures to characterize land qualities are not always associated with the size of the areas being characterized. Driessen and Ritchie describe use of simulation modelling for relatively large areas of land, following a level 5 approach. Thomasson, on the contrary, uses a level 4 procedure for both field and regional level assessments. A critical analysis will be made to determine the necessary degree of detail of data and modelling for problems at different scales (see themes of the discussion groups).

Space.

Soil maps.

Soil survey has traditionally produced maps at different scales, consisting of delineations called mapping units. Each of these is characterized by a so-called: "representative soil profile" on which interpretations are based. Subdivision of a landscape into units that are separated from each other by sharp boundaries (Fig. 3) is unnatural,

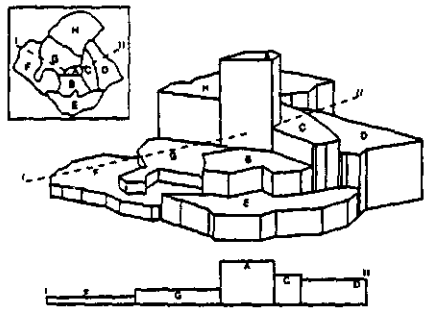

Fig.3 Soil boundaries between mapping units suggest sharp, discrete transitions and identical properties of each of the units as expressed by properties of so-called: "representative soil profiles" (Burrough, 1986).

because natural boundaries tend to be gradual rather than abrupt (see earlier comments on fuzzy clustering). Be that as it may, patterns presented by the soil map can be used as a first approximation to indicate spatial variability patterns at different scales. Kutilek

(1988) has pointed out that the scale problem forms one of the main challenges for soil science in the years ahead. Considering the "representative profile", several soil horizons are usually distinguished which are based on pedological criteria. Differences among pedological soil horizons are not necessarily associated with functional differences as well. **In other words, different horizons from a pedological point of view may behave identically from a functional point of view.** Thus, soil horizons may be combined allowing the distinction of fewer different horizons for simulation purposes. Different combinations can be distinguished for different functions, (see also Bouma, 1988).

Point data.

Selection of a "representative profile" is based on the experienced judgement of a surveyor. His judgement is based on point observation of the soil (borings) and on observation of landscape characteristics and other surface features. An alternative procedure would be to focus on all point observations first and to obtain areal patterns by interpolation (v. Keulen and de Wit, 1987). In other words: "Calculate first, generalize later" instead of "Generalize first and calculate later" (see Fig. 4 from Bouma, 1988).

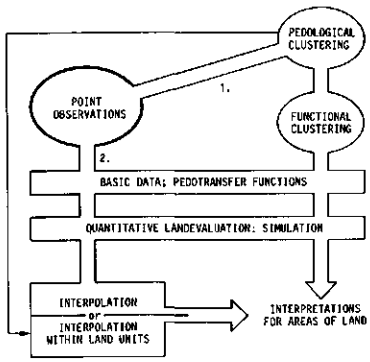


Fig.4 Schematic diagram illustrating the difference between average first-calculate later (procedure 1) and calculate first-average later (procedure 2).

From point to area: interpolation.

Different techniques are available to interpolate point data. An overview of these techniques including a systematic analysis of costs, complexity and specific applicability would be quite useful but appears to be lacking so far. A general reference for prediction methods is Ripley (1981). Broadly, the following techniques may be distinguished:

1. Kriging comprises a group of statistical prediction methods in which the spatial structure of variables is being used, as expressed by e.g. the covariance function (e.g. Matheron, 1973). Predictions of variable-values and the associated error are provided. Methods include: (i) Point kriging, where a point value is predicted; (ii) Block kriging, using average values for a point or an area; (iii) Disjunctive kriging where the predictor is a sum of functions in the

points of measurements, rather than observations with a given weight (e.g. Yates et al., 1986); (iv) Co-kriging which not only uses observations on the parameter to be investigated but also on other and usually more simple and more easily available parameters as well (e.g. Vauclin et al., 1984; Stein et al., 1988a).

2. Trend surface analysis. Assuming independent observations, a polynomical trend surface of a particular degree can be estimated (e.g. Haining, 1987).
3. Time series analysis essentially focuses on changes in time at a given point and has a different character than techniques using different point observations in an area. Methods have a broad impact in statistical prediction techniques (moving averages, smoothing, etc) and are therefore mentioned in this overview. (e.g. Box and Jenkins, 1970).
4. Splines are used as a form of non-parametric regression in which a penalty function is minimized. (e.g. Silverman, 1985; Dubrule, 1984; Watson, 1984).
5. Nearest neighbour. This simple method attaches weights to data points surrounding points at which estimates are to be made proportional to distance to the estimation point (mentioned in Cliff and Ord, 1981).

   Interpolations can be made within a given area of land or within defined land units which are distinguished on the basis of soil and land characteristics. As such, this would represent input by soil survey in the interpolation proces. Stein et al. (1988a) have demonstrated an increased accuracy of predictions when interpolations for moisture deficit were made within delineated areas for each of three major soil types rather than within the study area as a whole. They also estimated the most efficient sampling density for the particular land quality being considered. The general rule - of-thumb of soil survey requiring at least three observations per $cm^2$ map area, turned out to result in a highly inefficient sampling program. At the 1:10.000 scale, an identical degree of accuracy of predictions was achieved when only a third of the number of traditionally required observations was used. (Stein et al., 1988b). Obviously, spatial variability patterns must be known to establish the most efficient sampling program. Exploratory surveys can be made, for example, by using nested sampling schemes (e.g. Burrough, 1986). Before applying exploratory surveys - which may take considerable time to perform - it is relevant to know the geological and pedological properties of an area. Some areas are very homogeneous. Stein et al. (1988c) used sequential t-testing to avoid making too many exploratory measurements in homogeneous areas.

Time.

The most simple procedure for dealing with variability in time is to make repeated measurements for the land quality being considered. This is time consuming and costly. Returning to the land quality MSC, measurement would involve determination of the water balance during at least a number of growing seasons, requiring e.g. elaborate instrumentation of soil profiles with tensiometers and neutron probes, and measurement of hydraulic conductivity and moisture retention data. In addition, remote sensing data are very useful to provide information related to the moisture status of crops particularly of course, in moisture stress conditions. Series of measurements are needed to allow

estimates of the MSC which relates to the entire growing season. Obviously, only conditions of the monitoring years would be available and these represent a highly restricted database. Use of validated computer simulation techniques is necessary to obtain MSC values for a wide range of conditions. Models and associated data needs will be discussed by Driessen (SOW), Ritchie (IBSNAT) and Wagenet. Wagenet will present data-analysis using the super-computer of Cornell University. This allows a reflection of the effects of variability of each of the soil or land characteristics being considered in the simulation model.

An analysis of the use of models for studies of land qualities at different scales is likely to be part of presentations by other speakers as well.

Basic data.

Different types of data are needed to characterize land qualities. Focusing again on the MSC, the diagram of Figure 5 (from Bouma and v. Lanen, 1987) can be used to illustrate how existing data, which cannot

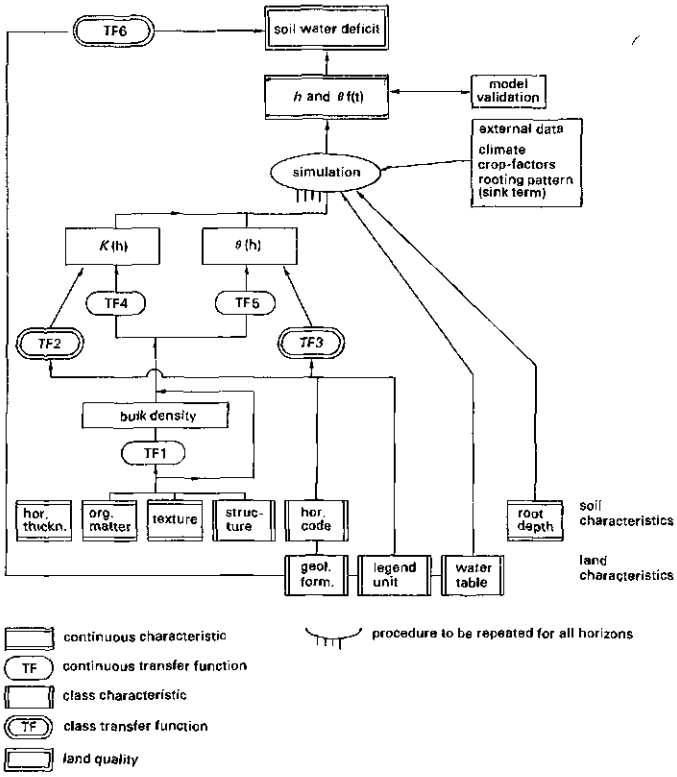


Fig. 5 Flow diagram illustrating different procedures to estimate the land quality soil water deficit. For terminology reference is made to the the Appendix.

be used by themselves, can be transformed into data that can be used. In this context we use the term "pedo-transfer-functions" which are expressions relating different land and soil characteristics and properties with one another and to land qualities. For terminology used, reference is made to Appendix 1.The water regime is expressed here as the water deficit (WD) rather than as the moisture supply capacity. We consider here a level 5 approach (see Figure 2).

Four levels of detail may be distinguished when determining WD in figure 5.

(1) Use of the name of the soil-legend-unit together with watertable fluctuations, if relevant, as a "carrier" of WD data (TF 6). This implies that determinations have been made in this unit elsewhere. The procedure is rapid, cheap and relatively unreliable because the same legend unit may have different WD values in different locations, e.g. because of different subsoil textures.

(2) Use of the legend-unit and a particular soil horizon (TF2 and 3). This procedure is more specific than (1) and still cheap. Use of pedogenic soil horizons as "carriers" of information (here: hydraulic conductivity and moisture retention) may be quite attractive. Horizons have lateral dimensions and they are well defined. If different horizons behave in an identical manner, they can be combined with no problems (see earlier section on "space"). In the Netherlands, a series of 35 horizons has been defined with characteristic hydraulic conductivity and moisture retention data. (Wösten et al., 1987; Wösten and van Genuchten, 1988). These are used for feeding simulation models for the water regime. Other data needed for simulation (Fig. 5) are estimated.

(3) Use of soil characteristics such as texture, organic matter, density and structure to derive hydraulic conductivity and moisture retention data by regression analysis. In principle, this procedure is more specific than (2) (see Van Genuchten et al. and Petach and Wagenet; this issue).

(4) Direct measurement of hydraulic characteristics and other data such as climate, groundwater and rooting depth. This procedure is both time consuming and very expensive.

Choice of methods and procedures is to be determined by: (1) an analysis of the necessary degree of detail of the answers being pursued; (2) the reliability of available data and (3) the prevailing spatial and temporal variability. Discussing this choice is a key purpose of the symposium. Reliability of data is very important. Pleyzier (1986) has shown the existence of a high variability when the same chemical analysis is applied to identical samples at different laboratories. Use of physical methods can also result in high variabilities when methods are used under unsuitable conditions or by untrained personel. Use of small sampling volumes can produce unrepresentative results when measuring soil permeability (e.g. Lauren et al. 1988). Sampling schemes in soils that do not take into account the occurrence of different soil horizons may result in larger variability among replicate measurements than schemes which use soil profile descriptions when sampling. Little attention is generally paid to operational aspects of methods. Rather, emphasis is placed on technical and theoretical aspects (e.g. Burke et al., 1987).

## Geographic information technology

Soil surveys contain geographic information both in terms of soil data and geographic distribution patterns, which is useful to define land qualities in space and time. A recent workshop on Soil Resources in the 1990's (Finney and Anderson, 1988) demonstrated once again the urgent need for rapid communication of research results to users in a user-friendly form. Geographical Information Systems (GIS) allow this type of communication, providing a new dimension to the transfer of soil information (e.g. Burrough, 1986 and Burrough, this issue).

Building up relevant databases for natural resources to be used in a GIS is a high priority. In this context, special attention will be paid to generating a database at the $1:10^6$ scale in the SOTER project. This topic is to be discussed by Baumgardner.

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APPENDIX with a modified proposal from Bouma and Van Lanen (1987) covering the following terms:

Soil and land characteristics are attributes being obtained during soil survey that provide information on soil composition, structure and topography (for example texture, org. matter content, soil structure type, slope-class). A subdivision is made between continuous characteristics which can have a wide range of values (e.g. % clay, % org. matter) and class characteristics which are characterized by either a specified narrow range of values (e.g. texture class) or by a symbol (e.g. horizon designation, mapping unit).

Land qualities are attributes which act in a distinct manner in their influence on the function of land for a specific kind of use. Land qualities can be related to soil and land characteristics.

Pedotransfer functions (TF) relate different characteristics with one another or to land qualities. Two types of pedotransfer functions are distinguished:
Those using continuous characteristics are called: continuous pedotransfer functions. Those using class characteristics are called: class pedotransfer functions.
Simulation-models solve differential equations describing one or more physical and/or chemical processes in the soil-plant-atmosphere system which are related to land qualities or to land suitability by using external information, and land characteristics.
Land suitability is the fitness of a given type of land for a specified kind of land use.

# LAND QUALITIES AND THEIR VARIABILITY - PRACTICAL IMPLICATIONS, AND SOME OF FAO'S RESPONSES

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## Introduction

As indicated in Bouma's introduction, the main object of this symposium is to foster a dialogue between

- producers and interpreters of regionally distributed field information (the soil surveyors-land evaluators);
- natural resource-information manipulators, whether using geographic information systems or other computer-based systems of data base management and interpretation, and
- manipulators and interpreters of remotely sensed information, the results of which can be linked to those from the first two groups;
- modelers of processes either in the time domain or in the spatial domain, necessarily working alternately, since a complete integration of process models in time and space would multiply computing and memory requirements beyond presently practicable bounds. The modelers' results serve as a check on present work by the first three groups; their work also provides insight in temporal aspects of land qualities and land suitability at selected locations (defined in conceptual rather than spatial terms); or in spatial aspects of land properties or derived qualities viewed as scalar variables, generally denuded of their time dimension.

The interaction between these different groups, and especially meetings such as these, help to keep us honest and efficient in a scientific sense. The eventual customers, however, who are absent here, are the only ones who can keep us honest in the commercial sense. Are we delivering value for money to the practicing farmers; to the planning departments; to the researchers needing to tune their products, such as new cultivars, to specific, well defined and if possible delineated physical environments, and well defined groups of farmers?

## FAO's concerns; some early work

FAO is concerned with these questions, both for the near term and for its long-term perspective planning. Its primary role is that of an information broker, stimulating the transfer and adaptation of methods aiding agricultural development to farmers, planners and researchers in developing countries, from both developed and other developing countries. Only where necessary does FAO engage in methodology development, or in standardization of methods. This has been the case in land evaluation: in the early seventies, FAO jointly with the Agricultural University, Wageningen, the International Land Reclamation Institute and the International Agricultural Centre, initiated the undertaking of a Framework for Land Evaluation, which has since become a de facto minimum standard in many countries.

A minimum standard: several aspects were not addressed or touched upon but lightly. About a decade ago, the need for an overview of the extents of potentially cultivable lands of the developing world became evident. In principle, this could be made by putting together the soil map of the world data and the land evaluation framework. No ready-made methods were available to produce such an assessment on the basis of the available worldwide information, namely the soil map of the world with its explanatory memoranda, and long-term climatic means for a large number of stations. Therefore, a methodology was developed while the work progressed.

The agro-ecological zones study was the result, covering most of the developing countries (FAO, 1978-1981). Requirements of eleven mainly tropical crops with respect to climate and soil-based land qualities were translated into simple, classed variables that could be estimated from the available long-term climate means and soils information. Variations in space were recognized at two levels: by agroecological map units, which consisted of soil map units subdivided by length of growing period zones; and by their estimated percentage composition (but not spatial distribution) in terms of individual soil units, slope classes, surface texture classes and phases (if any). Even at that time, the dynamic nature of land qualities was well recognized even though year-to-year variability was necessarily dealt with as an agro-climatic constraint. Length of growing period, for example, was derived from the seasonally fluctuating moisture availability, under a simple assumption for soil moisture storage.

A growing period was considered to start when mean rainfall exceeds half potential evapotranspiration (PET), and to extend into a dry season until the rainfall deficit (the accumulated excess of potential evapotranspiration over mean rainfall) reaches 100 mm. It was considered to be broken into two growing periods by a rainfall deficit of 50 mm or more (the case for strongly bimodal rainfall). The growing period was not considered to be broken, but merely at a standstill, for any period with mean 24-hour temperatures less than 5§o§ C. Moisture limitations because of the small available water capacity and small or inexistent capillary supply of most coarsetextured or shallow soils were taken into account in a later stage of the procedure, together with other limitations resulting from the nature of the soil unit, phase or slope.

A recent example: Land resources appraisal for Bangladesh

The considerable amount of soil survey information, published at a scale of 1:125 000, for virtually all of the country made it possible to produce a computerized land resources appraisal of Bangladesh (Brammer et al., 1986-1988) which can be used in various ways to further agricultural development. This land suitability assessment programme passes each individual basic unit of the land resources inventory (component of land mapping unit) through a series of "suitability sieves" (Fig. 1). This is done separately for each crop or crop group and for each input level (traditional or modern management), on the basis of climatic moisture (Fig. 2) and thermal regimes; soils and landform information (Fig. 3); inundation regime (Fig. 4). This vast amount of repetitive computation was done effectively, in the case of Bangladesh, on a minicomputer.

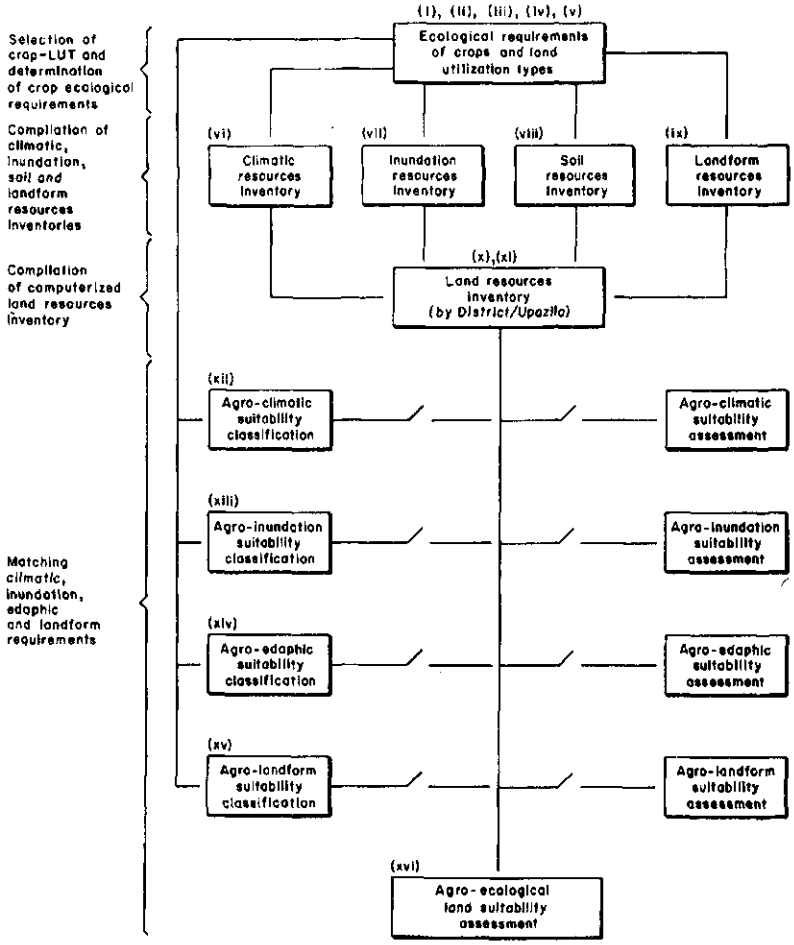



Fig. 1. Schematic outline of the Bangladesh AEZ methodology (activity numbers in parenthesis).

Bangladesh has more than one main period in which crops are grown, even though there is one monsoon-type wet season, locally called kharif, which is the main wetland crop season. Because this is a single country study, it was necessary to analyze the growing period in much more detail than was done in the broad, worldscale agro-ecological zones study. The moisture conditions were characterized for 207 locations using historical daily and monthly rainfall data. The considerable year-to-year variability was taken into account by calculating for every station for each year the lengths of the pre-kharif transition period, the (main) kharif growing period, and the rabi (dryseason) growing period from the end of the wet season onwards (Fig. 2). These lengths of growing periods, with their standard deviations, were reported in table and map form. Mean starting and ending dates for the different periods, with their standard deviations, are available in tabular form for 75 stations in Bangladesh.

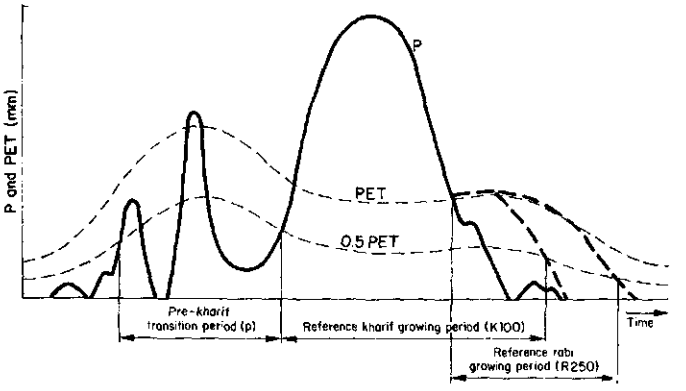



Fig. 2. Schematic model for characterization of the moisture regime, using decad values for individual years.

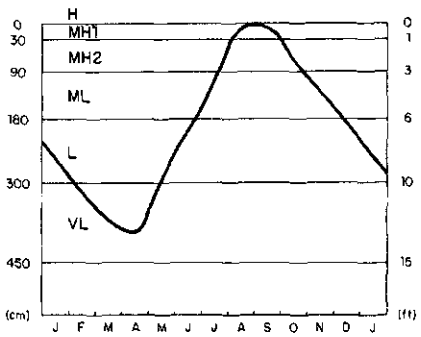
The kharif growing period is the season in which rainfed wetland rice and (wetland) jute can be grown on level land with suitably low hydraulic conductivity and appropriate inundation levels. It starts in the first decad (10-day period) for which rainfall exceeds 0.5 PET and for which the preceding decad had at least 50 mm rainfall. Bunded fields begin to be inundated about that time. This main growing period ends in the first decad after the wet season when the accumulated moisture deficit (PET minus rainfall) exceeds 100 mm (the assumed supply from ponded water) plus 0.5 PET for that decad. This climate-determined growing period is not considered in isolation, but is modified according to the inundation regime, discussed below.

The rabi growing period, used for dryland crops after the wet season, starts in the first decad when rainfall is again less than PET, and ends in the decad when the accumulated moisture deficit exceeds 250 mm plus 0.5 PET. These 250 mm may seem a very large reference value for soil moisture storage, but this is based on the range of 200 to more than 300 mm total available soil moisture per metre soil depth found in the loam to silty clay loam texture range of all Holocene sediments in Bangladesh, the main soils on which rainfed rabi crops are grown. For soils in older materials, and for Holocene sandy loams and clayey soils, the values are about 150 mm; for sandy materials 50-100 mm per m. These differences are taken into account for the calculation of moisture supply of dryland crops.

The inundation regime, relevant in areas with seasonal flooding such as most of Bangladesh, has been summarized in terms of normal maximum inundation depth (Fig. 3, 4) and three aspects of disastrous flooding hazard: rapid rise or flow of floodwater; storm surges, with or without cyclones; and river erosion or burial by fresh alluvium. The probability of each of these is estimated for each land level in a mapping unit: <2%, 2-6, 6-20, 20-50 and >50% of years. These probabilities are used in downgrading suitability ratings for all crops. The normal inundation depth is matched against the requirements of individual crops, also taking into account the growing period of the crop and its position in the year, compared with the timing of the highest floodwater levels and with begin and end dates of inundation for each land type (Fig. 4).

| General Soil Type | | Noncalcareous Dark Grey Floodplain Soils | | | | | | |
|---|---|---|---|---|---|---|---|---|
| FAO soil unit | | Eutric Gleysols | | | | | | |
| Land type | Soil series | | | | | | | |
| Highland | Homesteads | | | | | | | |
| Medium Highland | | Tippera | Jalkundi | Dhamti | | | | |
| Medium Lowland | | | | | Barura | Debidwar | | |
| Lowland | | | | | | | Burichang | Water |
| % of association | 10 | 5 | 5 | 10 | 30 | 10 | 25 | 5 |
| **Soil descriptions** | | | | | | | | |
| Drainage class | | p | p | p | poor(p) | p | p | |
| Topsoil colour | | og | dg | dg | dg-dog | g | dg-vdg | |
| Topsoil texture | | sil-sicl | sil-sicl | sil-sicl | sil | sicl-sic | sicl-sic | |
| Subsoil colour | | o-og | log-oy | og-dg | vdgb/o-og | g+yb | vdg-vdgb/lob | |
| Subsoil texture | | sil | sil-sicl | sil | sil | sicl | sicl-sic | |
| A1 thickness (cm) | | 0 | 15 | 15-50 | 15-50 | 0 | 25-50+ | |
| **Selected laboratory data** | | | | | | | | |
| Topsoil OM % | | 1.7 | 3.1 | 1.5 | 1.4 | 2.0 | 2.9 | |
| Topsoil pH | | 5.0 | 5.3 | 5.4 | 5.7 | 5.9 | 5.4 | |
| Subsoil pH | | 7.5 | 7.3 | 7.3 | 7.7 | 7.1 | 6.4 | |
| Subsoil clay % | | 24 | 18 | 18 | 16 | 45 | 37 | |

Fig. 3. Relationship of soils to land types in one soil association (Inundation depths and periods in Fig. 4)




| LT | IL | BI | EI | IP | SRI |
|---|---|---|---|---|---|
| H | 0 | 23/8 | 23/8 | 0 | - |
| MH1 | 15 | 7/8 | 25/9 | 48 | 0.9 |
| MH1/2 | 30 | 4/8 | 30/9 | 56 | 5.0 |
| MH2 | 60 | 27/7 | 10/10 | 73 | 4.3 |
| MH2/ML | 90 | 20/7 | 26/10 | 96 | 4.3 |
| ML | 135 | 5/7 | 21/11 | 136 | 3.0 |
| ML/L | 180 | 23/6 | 8/12 | 165 | 3.8 |
| L | 240 | 29/5 | 10/1 | 221 | 2.5 |
| L/VL | 300 | 12/5 | 8/2 | 266 | 3.5 |
| VL | 375 | 24/4 | 25/3 | 331 | 4.2 |
| VL | 450 | - | - | - | - |

Fig. 4. Average annual profile of water level in relation to land types (names in Fig. 3). Inundation Level (cm); Begin and End dates of Inundation Period (days). Specific Rate of Increase (cm/day) during period of most rapid rise.

## Some other studies

Studies similar to the one in Bangladesh have been completed in Mozambique (Kassam et al., 1981, 1982); work is underway or planned in various countries. Tables of crop requirements and other aspects of the methodology are being adapted to local conditions and data sets, and agro-ecological zones studies undertaken, in countries such as Thailand (Murata, 1988), Indonesia and the Philippines with very modest - mainly moral and advisory - support from FAO. Several other countries have requested UNDP-funded-assistance by FAO for agro-ecological zones studies or related work.

Kenya has extensive natural resource data as well as several national planning models, but does not yet have an effective link between the two. It provided a focus for efforts by FAO to produce information on potential population supporting capacity at a subnational level, involving food balances at different input levels for present and projected populations, including both crops and livestock, as well as fuel supply and demand. Also, the main non-food crops are to be included (fibre crops, stimulants such as coffee, tea, etc.). This is a prerequisite for results that can form an operational link with the planners, who presently tend to rely on statistical - e.g. census - data for large internally undifferentiated sections of a country.

As a basis for the work in Kenya and other countries, a set of computer programs to run detailed country studies is being developed, which work adequately for seven foodgrains, six food legumes, three root crops, three perennial food crops (banana, oil palm, sugarcane), and grass. The livestock model in the program set is being improved; a fuelwood model still needs to be added. The program set can be expanded to include fruits and vegetables, fodder crops, stimulants (coffee, cacao, tea, tobacco), fibre-crops, etc.

A module containing semi-quantitative land suitability assessments for the fodder crop Stylosanthes hamata cv verano and a number of other crops was recently completed for West Africa by Kassam et al. (1988a, b). Work on other fodders is in preparation.

Interannual variability in land qualities: importance to planners, small farmers and land evaluators

A planning model does not merely require long term average yields and inputs, as normally provided by land evaluation activities; an estimate of interannual variability is required as well. This is provided by straightforward climatic analysis as done in Mozambique or Bangladesh, or by more sophisticated methods such as those developed by ICARDA, which help farmers in semiarid Syria decide on N topdressing on wheat or barley on the basis of conditional rainfall probabilities. An example of year-toyear rainfall variability as reflected in the length of growing period is given in Fig. 5 for a station in Mozambique. The Mozambique study (Kassam et al., 1981, 1982) used the proportions of different length of growing period classes over the years of record as the temporal equivalent of a soil association: the proportions of different soils or kinds of land in a mapping unit. This made it possible to estimate productivities averaged over each mapping unit as well as over time, taking into account the interannual variability.

At least two aspects of a longer time dimension are important for the planner: the annual yield vector over the economic lifetime of a perennial such as oil palm or a fuelwood or timber crop as a function of environmental parameters; and the yield changes to be expected in each kind of produce, especially under rainfed conditions, as a function of climate changes. Risk of consecutive years of drought in an agricultural area or of drought upstream are other major concerns to planners of dryland and irrigated agriculture. Yield functions with age for forest crops have been made operational, for example in the context of an FAO study on forest management, afforestation and utilization (FAO, 1986a, b; Lindgren, 1986). With respect to climatic changes, a small study is underway in FAO to estimate changes in population

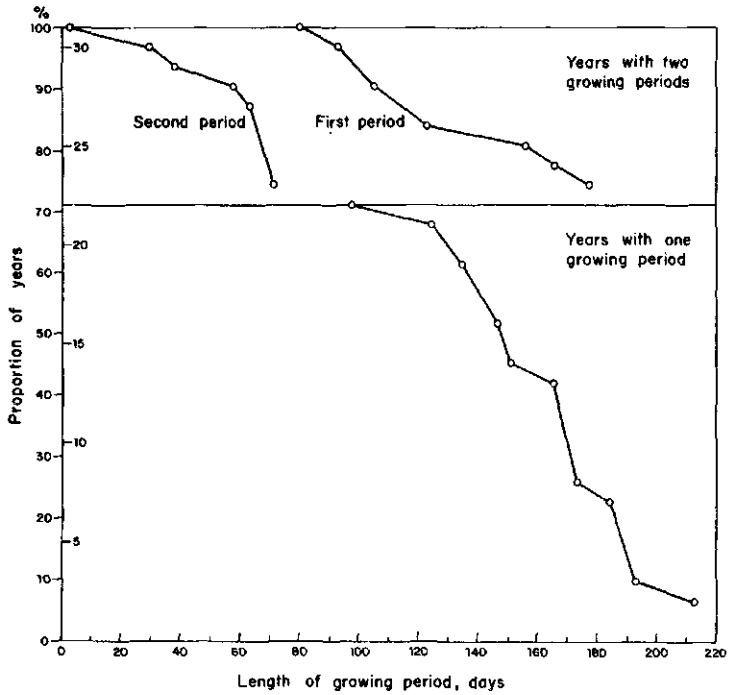



Fig. 5. Distribution of lengths of growing periods for Porto AmeliaPemba, Mozambique (mean annual rainfall 890 mm). Of the 31 years of record (ordinate), 9 had two growing periods separated by a dry period.

supporting capacity in West Africa by re-running the algorithms of the original study (which used climatic normals) with the rainfall data available for the last 15 years. Long-term climate trends or fluctuations are being studied by others; as results become available, FAO intends to interpret them for their food and nutrition implications in so far as is feasible and resources allow.

Temporal variability in land qualities may require modification in part of the procedure of the two-stage approach in land evaluation. The year-to-year variability of land qualities such as moisture availability is normally reflected in similar variability in production of farm households. However, there is a generally nonlinear relation between production level and benefits particularly in the case of the small farmer. This makes the two-stage approach in land evaluation less appropriate than the parallel approach and may require that productivity estimates produced in a first stage be reported for sequences of individual years on as probability distributions, rather than as means. A qualitative example is summarized below.

The small farmer's marginal benefits from production are smaller at high production levels (in years with good rainfall, for example) than in a medium year because of generally low produce prices during a glut. They are higher, generally much higher, in years with low production: not only because of scarcity driving up prices, but also because in

such years the small farmer generally has to borrow to buy grain, at effective interest rates that may exceed 100% per year. Thus, the value of a unit of produce may easily be 2 to 4 times higher in a year of scarcity than in a year of abundance.

The curvature of the function relating the farmer's benefits to the varying production levels at constant inputs, is a measure of the cost of year-to-year variability to the farmer. This transfer function should be measured, estimated or inferred, and included in the year-to-year calculation of benefits and inputs on the basis of a historic or modelled sequence of years, before averaging or otherwise summarizing the results, if a quantitative land suitability estimate is to be meaningful to small farmers-in a variable environment.

In contrast, the function of benefits against year-to-year production variations is essentially linear for a farmer with access to commercial banking facilities and facing small produce price variations. Only in such cases can physical land suitability estimates be completed before considering the socio-economic aspects of the land utilization type.

Structure of a GIS-based land evaluation program

A good, practically useful GIS-based land evaluation program should be like a glass onion: every successive shell is clear, but the outer one attracts the eye. As the customer works with this first shell, new results are produced from the data using previously established (default) relationships and algorithms, in response to the customer's specifications of the conditions which he wishes to explore. This should work by "easy" interaction with informative, readily understood screens with questions and guidance for the user. The specifications of conditions should include transfer functions from yields to benefits in cases such as discussed earlier.

The second shell should be equally clear. As new information becomes available, for example about the environmental requirements of a crop or use not yet included in the system, this again should be elicited from the user of the system by a listing of the variables for which values are needed, with examples for other crops or uses, and an indication or summary of how these values are used to transform natural resources data into suitability ratings.

The third shell concerns the structural details of these transformation algorithms, which are subject to change and improvement as more processtype information becomes available, such as validated yield or production models for another crop.

The inner two parts are the structure and composition of the resource data as recorded in the data base (often in a different form, and summarized, from the data as recorded in the field); and the internal relational structure of the data base itself.

The Bangladesh study used proven techniques, with some newly developed modifications to take account, among other things, of seasonal and interannual variability in rainfall and of the peculiar seasonal flooding conditions in much of the country; it used a modern data management system that can be joined to a GIS; it is based on large amounts of information that can be collected relatively simply.

This study has provided a developing country with a development and planning tool that works in practice, both at national and provincial or district levels - and that is hoped to be relevant to the practical farmers' conditions.

I shared some of the results from the work of Bangladeshi and international colleagues with you, not with the illusion that these would contribute decisively to the state of the art or to the level of the science. They are examples of a balance between on the one hand, models and data sets tending to grow unmanageable by size and complexity, and on the other, simplifications tending to shrink too far from reality.

Land evaluation methods need to be further developed so that the results are more closely tuned not only yo the needs of planners, but also to those of farmers and agronomists. Methods should be developed that:

- capture and express the interannual variability of land qualities; and
- link this variability to early-season observations that will enable conditional probabilities to be reported, not only a priori probability distributions for the season's qualities.

The results should enable farmers to respond to, and make good use of these conditional probabilities by appropriately deferred decisions on variations in management and inputs.

Methods are also needed to:

- systematically identify the land requirements of innovations, which are improvements or modifications of a use, rahter than of the use as a whole;
- define the land qualities corresponding to these requirements in operational terms, with proference for readily observable or mapped land data; and
- define the recommendation domain of such an innovation by identifying and delineating land areas ecologically and economically suitable.

The methods should be readily usable for a range of persons, rather than for land evaluation specialists only, and should be transparant with respect to assumptions, parameters and procedures used. The results, too, should be in a form that is clear to a non-specialist and readily usable for land use planning or for land management. Such developments would considerably widen the range of practical uses of land evaluation in developing countries.

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# THE EFFECT OF HUMAN ACTIVITY ON SOIL QUALITY

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## Summary

The transformation of soils by human activity causes a variation in their quality in the course of time. By undertaking comparison with the natural environment, this paper analyses the variation in soils in the course of time as they are influenced by agriculture, urbanisation, recreation, and by industrial and mining activities.

## Introduction

The variation in soil quality throughout time and space is currently the subject of attention by scientists and decision-makers because the earth, from which man derives his sustenance, is a limited, degradable resource. This variation is mainly the result of soil transformation by man. Transformation is beneficial when it is translated into terms of increased production from the resources used. It is harmful when it entails degradation of the soils and their qualities. Unfortunately, the second phenomenon occurs too often as a result of human activity.

## The natural environment

The surface of the world is of necessity subject to a number of processes which depend in the first place on climatic conditions in the surrounding atmosphere, the associated hydraulic conditions and the biogeochemical cycles which characterise the biosphere. Under the influence of these processes, plants and animals become established in various parts of the world. These creatures are often typified by some diversity, but also by relative temporal constancy. Even though it is relative, this constancy is maintained by the condition of the environment and the plants and animals it nourishes. The surface of the earth may be regarded as being concerned with a 'natural' environment, that is, one that has not been 'disturbed.' Such an environment may be the subject of human attention but it remains undisturbed as long as these activities do not modify the intensity of the spontaneous processes which typify the original system. On the other hand, the environment is gradually transformed when human activities affect the intensity of the processes mentioned and modify both plants and animals. One of the final results is a variation in soil quality in the course of time.

## Agriculture and soil quality

### Soil fertility

The importance of soil fertility in determining agricultural production has long been recognised. The fertilization of alluvial plains by deposits of clay during semi-annual floods made the valleys

of the Nile and the Tigris the granaries of ancient times. In the course of time, traditional systems for maintaining fertility were used and are still being used. Animal and human faeces have maintained soil fertility for thousands of years in China and during the period of Greek and Roman civilisation. In our time, the farm midden and slurry continue the practice. Vergil knew the value of legumes in restoring soil fertility through the symbiotic fixation of nitrogen.

In our times, the growth of the world's population and the resultant need for food have caused an intensification of agriculture by ploughing hitherto unused land, by increasing the yield from land already under cultivation by the introduction of new varieties and the application of artificial fertilizers.

But it should be remembered that the 50 hundredweight of wheat that may be harvested from an acre require at least 130 kg of nitrogen, 65 kg of $P_2O_5$, 80 kg of $K_2O$ and 16 kg of CaO a year. A plantation of first-class pine producing 15 $m^3$/ha requires only 15 kg of nitrogen, 3 kg of $P_2O_5$, 8 kg of $K_2O$ and 16 kg of CaO. This serves to emphasise on the one hand the changes in biogeochemical cycles which may take place when deforestation is undertaken and the trees are replaced by crops, but on the other hand it also emphasises the part played by the use of artificial fertilizers, not only to compensate for the chemical elements extracted by the crops but also to increase the yield. The FAO has stated (cf. FAO Fertilizers Yearbooks) that world consumption of artificial fertilizers increased between 1938/39 to 1980/81 from:

- 2.6 million tonnes of nitrogenous fertilizers to 60.7 million;
- 3.6 million tonnes of phosphates to 32.8 million;
- 3.8 million tonnes of potash to 25.2 million.

Work on the soil, the impact of mechanisation

By definition, agriculture implies the use of different instruments and the use of energy to handle them. These instruments need to be adapted to the soil treatments required and to the crops and animals being used. Manual labour and then tending the crops dominated the past, but from the end of the 19th Century considerable progress was made in powering agricultural machinery. Cultivation by machine put in its appearance and developed rapidly. In France, for instance, the birth of mechanisation did not take place until about 1850; but 130 years later, in 1980, 99% of agricultural operations are mechanised. This implies the use of 1,400,000 tractors and 150,000 self-propelled machines. Mechanisation has more than doubled agricultural production during the last thirty years while bringing about a reduction of a quarter in the area under cultivation.

From the soil's viewpoint, the transformations brought about in this way have created good physical condition, synonymous with a good structural state and drainage to a satisfactory depth. Such conditions bring about distribution suitable to the porosity, optimise the conditions for aeration and water dispersion and create temperatures favourable for root development. But on the other hand, work not properly adapted to the soil, for example carried out by machinery that is too heavy or by too frequent movements, etc..., may bring about negative transformations in the soil, such as the oxidation of organic material, the destruction of fills, reduced porosity in deeper layers, the formation of subsidence: all these phenomena adversely affect conditions of aeration, drainage and vegetable growth. Although it may be generally admitted that mechanisation is indispensable for rural development, it is obvious that strategies have to be defined for using

it and finding the right balance between increased production and danger to the environment from unsuitable methods. An example from the Tropics, perhaps an extreme one but nevertheless revealing, illustrates this problem.

Before mechanised cultivation of the ground nut was introduced in Sefa, in Casamance (Sénégal), the structural stability and permeability of the ferruginous tropical soils were satisfactory (Henin Instability Index between 0.43 and 0.57; permeability up to 47 mm/hour). Deforestation raised the Henin Index to 1.21 within two years and reduced the permeability to between 20 and 30 mm/hour. Then, the mechanised cultivation succeeding deforestation caused the dispersion of the entire fine soil fraction within six years. The degree of mechanisation has had to be rethought (reduction in the runs associated with new rotation of crops) so as to produce without destroying.

## The role of organic material

Pedologists and agriculturists recognise the importance of the organic materials present in the soil. They are known to provide micro-organisms with energy and carbon. In decomposing these materials, the micro-organisms contribute to the formation of humus and by-products of decomposition, essential factors for the existence of a good structure composed of stable masses. As a result, organic materials tend to enhance the porosity and aeration of the soil. They also contribute to raise the infiltration rate and the capacity to absorb water. Like a 'canopy,' they protect the soil against the effects of raindrops and wind. As they mineralise, they release nutrients; in so doing they increase the fertility of the soil.

One may imagine how catastrophic may be their disappearance because of the destruction of vegetation without its being replaced, because of excessive or ill-adapted working of the soil, because of the non-return of the residues of cultivation, because of erosion. Equally deleterious is poor evolution under the influence of particular pedological conditions, whether natural or artificial.

## Crop protection

In traditional methods of agriculture, the practicalities of production were supposed to make the crops resistant to insects and weeds. There were some losses, but they were considered to be inevitable and were disregarded. But gradually the use of pesticides and herbicides was developed to help maintain agricultural production at the high levels which it had attained in response to accumulating demand. The intensification of agriculture, on the other hand, made crops more susceptible to attacks from animal or vegetable pests. Dusting the plants and the soil with pesticides and herbicides has been carried out with increasing frequency over the past fifty years. In 1982 the world market for crop-protective chemicals was approaching USD 13.3 billion, herbicides accounting for 39.5%, insecticides for 32.7%, fungicides for 21.9% and miscellaneous chemicals 5.9%.

Although most of the pesticides deposited in the soil lose their toxicity or remain external to the elements passing through the food chain of men and animals, some may nevertheless persist, such as chlorinated hydrocarbons or phenoxy-chlorinated compounds. The clay and humus fractions of the soil trap them so that they are not attacked by micro-organisms. Others apparently resist biological destruction by

virtue of their structure. Of the insecticides, DDT and dieldrin are relatively resistant. This means that long-term, ill-considered, uncontrolled use of pesticides and herbicides may cause soil pollution with a risk of bringing about serious problems.

Here again, a middle way has to be found between protecting the harvest and combatting the vectors causing harm on the one hand and maintaining the biological equilibrium of the environment on the other. In this context, the most important criterion for final retention is the maintenance of economically viable agricultural production. For example, if the use of fertilizers and irrigation increases the susceptibility of the crops in use to attack by harmful elements, one cannot simply modify these factors in the name of protecting the plants, because they are essential for production. Another path will need to be taken and the cost, the advantages and the inconveniences calculated. This serves to explain why research into varieties resistant to attack by pests has become so vitally important in recent years.

## Irrigation

In recent years, irrigation has perhaps been the most important form of soil transformation affecting their quality. The area of the world under irrigation grew from 149 million hectares in 1965 to 223 million hectares in 1975 and is expected to reach 273 million in 1990. It is estimated that irrigated lands, which cover 15% of the area of the world under cultivation, account for 30% of world agricultural production.

The practice of irrigation goes back to remote periods of history and gave birth to a number of civilisations (Mesopotamia, Egypt, China, etc...). It may give rise to environmental deterioration when the consequences are poorly controlled. Prior to irrigation, a relatively stable balance existed between precipitation, surface water, soil water and vegetation. Irrigation might treble or quadruple the amount of surface water in comparison with normal times. If the consequences are not controlled, this major alteration in water balance may bring about harmful results such as saturation or salination of the soil or subsidence.

However, in most soils changes in water and salt balance are reversible given effective water control, a better distribution of irrigation in the course of time associated with proper drainage and control of underground water supplies. Of the world's 223 million hectares under irrigation in 1975, 45 deserved rehabilitation and 78 had to be drained. These works require major investments which the Governments should be prepared to meet.

## Soil conservation

Conserving soil on the surface of the globe and maintaining their potential for production are the only means possessed by mankind to preserve the earthen capital from which he derives the elements necessary for his survival. It has been estimated that at the present time the cultivated soils of the world are losing a weight in excess of 23 billion tonnes in comparison with soils newly formed by pedogenesis. This is an extremely serious effect and is noticeable in many countries, both industrialised and developing. The United States, for example, estimate that a third of the upper surface of their arable land will have been degraded within 20 years. Half of the area of India is also

suffering from some form of degradation; accelerated erosion is affecting a million and a half square kilometres. Erosion is the key problem on Madagascar, where 65% of the area has been seriously denuded by destructive agricultural practices, deforestation and overgrazing. These few examples, selected from many, are significant. The situation has resulted from the need to increase food production in response to the needs of a constantly increasing world population. It has led to the intensification of agriculture, by opening up new areas for agriculture or by intensifying agriculture in areas already under cultivation. In both these cases, the risks of soil degradation are increased, particularly the risks of erosion. In fact, to increase the area under cultivation entails reclaiming soils whose nature is increasingly fragile and unstable. The intensification of agriculture by its very nature results in multiplying mechanical intervention, reducing the periods during which the soil is protected by covering plants, reducing the replacement of organic materials, etc... If care is not taken, it may lead to degradation of the chemical and physical properties of the soil, particularly the latter, and play a major part in reducing percolation, increasing seepage and finally in soil erosion.

To gloss over the apparent dangers, specialists have used the classic methods of combatting erosion employed in the United States in particular in the late 1930s and in the 1940s. It rapidly became apparent that the methods employed in the past required considerable modification if they were to answer to the socio-economic constraints of the present time. They were in fact employed and developed during a period when world population pressure did not present a problem and when soil conservation work did not put too great a burden on the operating budget. The combination of factors and the particular conditions could be studied in a place where erosion was taking place, and control measures appropriate to the circumstances presenting themselves could be used. In other words, the problems were approached in a series of timely steps. This is no longer conceivable at a time when problems emerge at regional level and when regional development necessitates combined, simultaneous intervention with many methods and techniques for using the soil, as a function of political and economic choice. Solutions for soil conservation can only be found by integrated management employing a combination of methods. This is the reason for the current interest in integrated management of river basins.

It also has to be said that there are more social and economic constraints on the use of soil conservation methods than ever before. They range, for example, from the constraints imposed by a land tenure system to problems of the acceptability of a conservation system by the operators by virtue of their technological level, of their economy in use or quite simply by virtue of their social customs. Further, it is noticeable that a soil conservation strategy has a chance of success only on condition that is is approved by the people, by the people concerned in particular, and that it is understood by the decision-makers. On this last point, it should be emphasised that governments often understand poorly what a soil conservation programme should be, or at least poorly distinguish between the short-term objectives of self-sufficiency in food production and the long-term objectives of maintaining the country's resources.

## Urbanisation, recreation and soil quality

### Urbanisation

When one looks at an urban area, one first notes that it is completely artificial in comparison with the non-urban former situation. The surface of the soil has been made impermeable and the subsoil has been disturbed by the foundation of buildings and a large number of channels of various types. Further, urban centres are places where social and economic activities are concentrated. This implies a concentration of human beings and their means of existence as well as that of basic materials. The consumption and use of these entail the production of all kinds of refuse which are removed from the towns, often at low cost. This last statement is particularly true when one calls for rubbish to be taken to tips, the cost of which is high. This leads to rubbish being dumped at short distances from urban centres. The result is contamination of both soil and water, particularly by nitrates released during the decomposition of organic materials. This is why in France the highest nitrate levels are found in waterways passing through agglomerations or going round them.

An urban agglomeration does not simply affect its immediate boundary but may equally influence the soils and plants in rural areas long distances away.

Among the more obvious facts is acid rain due to the presence of oxides of sulphur and of nitrogen in the air, but of fluorine and other undesirable substances given off by urban ecosystems.

Finally, the complex, diffuse nature of those urban contaminants affecting the quality of the soil should be noted. This is why sludges from urban water purification plants contain much more dangerous mineral elements, such as cadmium, mercury and lead, than do those from agglomerations in rural areas. Hence, spreading them on agricultural land presents problems much more difficult to solve.

### Recreation

The impact of urbanisation cannot be considered in isolation from its corollary: the creation of recreational areas, which may bring about disastrous changes in the environment and cause exceptionally destructive effects on the soils. The effects of the large-scale development of Alpine ski-ing in Savoy, in the French Alps, may be cited as an example. In the river basin at Arcs, in an area of 146 ha, 9 ha (6% of the surface area) have been rendered impermeable through the construction of roads and houses and 28 ha (20% of the surface area) have had their plant coverage removed and have been terraced by heavy earth-moving machinery. As a result, since 1973, the harmless stream draining the basin becomes a torrent and raging water cut through bridges and metallised roadways practically each year. In 1980 an entire hillside became unstable. Hydrological studies showed that the ill-considered creation of the resort increased concentration of the flow in the surface network and hence an increase in the discharge, simultaneously increased volume and permeation by suppressing of the buffer effect of plant cover, increased subsurface flow in the affected areas downstream and finally increased erosion because of the multiplication of mass movements at the level of raised roadways.

## Industrial and mining activities and soil quality

### Industry

In certain respects the impact of these activities on soil quality displays analogies with those noted in urban areas: a concentration of resources, tentacular infrastructure and problems of waste disposal. When a factory occupies a relatively isolated site in a rural environment, it is in fact possible to confine the damage it may cause to nearby soils. Since the responsibilities are relatively easy to define, the industrialists are compelled to cooperate with the local authorities in taking the necessary steps to restrict or reduce the damage they cause. But this is far less simple when large industries linked with a town are concerned.

### Mines

The damage done to the environment by mining activities is difficult to restrict in itself because such activities can hardly be reduced. Certainly rehabilitation of a site when it has been exhausted is often required. But the special characteristic of mining is the extraction of materials underground. The proportion regarded as usable is then separated from that regarded as useless, and the unproductive part is left on site. It accumulates on the soil more or less immediately adjacent to the place from which it was removed. Now in addition to extractible substances, mineral deposits contain a certain number of others, composed of more or less dangerous or harmful ones. When these are left undisturbed, they are released to a greater or lesser extent by oxidation or leaching. But when they are placed in the open air they change under the effect of physical and chemical factors; they then become sources of contamination for soil and water.

This type of contamination has more chance of increasing when the rising cost of raw materials leads to the use of ever poorer lodes. This causes a rapid increase in accumulations of sterile material. In France, which does not have a particularly rich subsoil, such accumulations are estimated to amount to 100 million tonnes a year. The result is degradation of soil and water that cannot be ignored over wide areas. It is much more useful to incorporate this problem in research into the maintenance of soil quality since mining areas often demonstrate high population density and since therefore it becomes important to protect their resources.

## Conclusion

Soil transformation in modern times is characterised by the speed and radical nature of the changes. This necessitates rational planning and the proper use of know-how in managing the undesirable effects of actions which might moreover be positive and in reducing the negative effects of transformations answering to the options available to humanity. This is the price to be paid in maintaining soil quality.

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# Data collection and information systems

# SPACE AND TIME DIMENSIONS OF A WORLD SOILS AND TERRAIN DIGITAL DATABASE

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## New tools for land resource scientists

Several dramatic developments within the past two decades now make it possible for us to conceptualize land resources spatially and temporally as no previous generation has been able to do. Let me illustrate this point in three ways. First, we are the first generation to see the Earth as a whole. In all previous human generations, the consideration of land and land quality was done in a limited spatial context. Human observations were made on very limited areas. The observer would look at a small area and characterize it. Observations of many small areas were placed in a spatial mosaic in an attempt to show how the Earth might appear if it could be seen as a whole. The enterprise of Earth observation has been turned around. The human observer can now see the broad, synoptic view of the land, choose an area of specific interest, and extract detailed information for a selected area from the big picture.

Second, our view of temporal observations has changed dramatically. We have the capability to acquire data sequentially over the same scene on the Earth surface. Not only can we use this capability as a tool to inventory and characterize land features at a given point in time, we can use this capability to quantify changes which are occurring at the Earth surface at a broad range of temporal resolutions-hourly, daily, weekly, monthly, yearly, multi-yearly.

The third point addresses the data storage and analysis issues. We are the first generation of land scientists to have at our disposal the data storage and computational capabilities to extract useful information from the millions of bytes per second of spatially and temporally related Earth observation data which are being transmitted continuously to receiving stations.

## The soil map as a tool for land quality assessment

Perhaps land quality has been a concern related to human survival since pre-history. No doubt land quality and sound management of the soil have been factors in the rise and fall of empires through history. However, the use of scientific data for the assessment of land quality has best been documented in various ways since the development and codification of soil mapping and inventory techniques during the past one hundred years.

It is difficult if not impossible to place a beginning date on the concept of a soil map of the world. However, it has been documented that, at an International Symposium on Tropical Soils held in Madison, Wisconsin, USA in 1960, recommendations were made that led to the establishment in the Food and Agriculture Organization (FAO) Rome of the World Soil Resources Office and, eventually to the Soil Map of the World. At the Madison Symposium, which was sponsored by the

International Society of Soil Science (ISSS), a resolution was adopted which asked for the compilation of all existing soil survey material. FAO, through the World Soil Resources Office, assumed the responsibility not only of compiling the information, but also, of preparing an integrated World Soil Map.

The Soil Map of the World project was an enormous undertaking by FAO from a technical point of view alone. There were problems related to different schools of thought, quality of data to be used, scale to be adopted, nomenclature to be used, and the classification system to apply. A landmark of 1968 was the international agreement on the legend for the Soil Map of the World, obtained at the 9th Congress of the ISSS in Adelaide, Australia.

The World Soil Map by the 1970s proved to be a tool for general assessment of land quality for development, to combat desertification, to establish complementarity between areas with different production potentials, to assess potential population supporting capacities, and to develop a framework for land evaluation.

The FAO/Unesco Soil Map of the World, published at a scale of 1:5M, was the first internationally accepted inventory of world soil resources. It was completed in 1980 and published in ten volumes with nineteen map sheets and in four languages. Recently, a working group of FAO, Unesco and the International Soil Reference and Information Centre (ISRIC) completed and published a revision of the legend for this 1:5M soil map. With the cooperation of the United Nations Environment Programme (UNEP), this map has been digitized using the ARC/INFO system. It is a component of UNEP's GRID (Global Resources Information Database) in Geneva and of FAO's Geographic Information System (GIS), linking forty internal databases.

During the 1970s two new Working Groups under ISSS Commission V were established to explore the applications of new technologies to the management of soils resources. The Working Group on Soil Information Systems was charged with the responsibility of examining new data acquistition and analysis systems, including computer technology, and of reporting on how this technology can be used effectively as a tool for the soil scientist in the storage, retrievel and analysis of soils data and in their dissemination.

The Working Group on Pedology and Remote Sensing was charged with the responsibility of examining the specifications and images of new aerospace sensors and to report on and advise how this new technology can be applied in the inventory and monitoring of soil resources.

## ISSS Working Group on world soils and terrain digital database

As a logical evolution of activities in the ISSS along with that of data acquisition, handling, and analysis technologies, an ISSS provisional Working Group was established in 1985 to consider the feasibility and desirability of developing a world soils and terrain digital database at a map scale of 1:1M. A background paper in support of this concept was written by W.G. Sombroek (1985) and distributed in 1985 to more than 60 soils and terrain scientists around the world for their consideration and comments. This background paper served to focus the discussions of the 40 participants in an International Workshop on the Structure of a Digital International Soil Resources Map Annex Database (Baumgardner and Oldeman, 1986). As an outcome of this Workshop held in Wageningen, the Netherlands, in January 1986, a proposal to develop a World Soils and Terrain Digital Database (SOTER) at a scale of 1:1M was written (ISSS, 1986).

THE SOTER PROJECT

At the 13th International Soils Congress in Hamburg, West Germany in August 1986, the SOTER proposal was endorsed and the provisional Working Group was given formal status and charged with implementing the SOTER Project. During the months which followed the Congress, contacts were made with many potential national and international funding agencies to solicit support for the Project.

Because of their intense interest in global databases for environmental sciences, officials of UNEP expressed an interest in SOTER, especially if the Project could make a significant contribution to the assessment of degradation of global soils and terrain resources.

Fifteen soil scientists representing the SOTER Working Group were invited by UNEP to an Expert Group Meeting on the Feasibility and Methodology of Global Soil Degradation Assessment. This meeting was held at UNEP Headquarters in Nairobi in May 1987. As a result of this meeting a UNEP Project Document entitled "Global Assessment of Soil Degradation" was prepared, and in September 1987 a contract was awarded by UNEP for Phase 1 of the SOTER Project. There are two primary tasks under this contract. The first is to produce a general soil degradation map of the world at a scale of 1:15M. The second is to develop a soils and terrain digital database at a scale of 1:1M for an area of 250,000 sq km which includes portions of Argentina, Brazil, and Uruguay. The remainder of this paper will discuss the objectives and approach to the development of a global soils and terrain digital database at a scale of 1:1M.

Objectives

The long range objective of the SOTER Project is to utilize emerging information technology to produce a world soils and terrain digital database containing digitized map unit boundaries and their attribute database, and supported by a file of chosen point data. In the implementation of the Project an attempt will be made to include in the database some minimum density of ground observation data. The database will have the following characteristics:

a) general average scale, or accuracy, of 1:1M;
b) compatible with global databases of other environmental resources and features;
c) amenable to updating and purging of obsolete and/or irrelevant data;
d) accessible to a broad array of international, regional, and national decision-makers and policy-makers;
e) transferable to and useable by developing countries for national database development at larger scales (greater detail).

This is an exceedingly ambitious project, one which will require sustained, innovative effort over a period of many years.

Specific short range objectives are required in the initial phases of the Project to provide a logical and orderly sequence of activities to produce an operational world soils and terrain digital database. Emphasis will be on research, development and testing of methodologies in the field and in the laboratory and demonstration of the uses of the database. Specific short term objectives are as follows:

a) development of implementation plan;
b) adoption of a universal legend for a World Soils and Terrain Digital Database at 1:1M;
c) development of guidelines for the correlation of soils and terrain

mapping units;

d) definition of soils and terrain parameters and specifications to be included in the database;
e) development of a detailed set of specifications and logic which define the minimum set of capabilities/functions required for the database;
f) selection of three specific areas of 250,000 sq km each in developing countries for initial database construction;
g) acquisition and correlation of all relevant maps and data about the selected areas essential for the database;
h) input of data, including digitized maps, into the database;
i) test and demonstration of the reliability, accuracy and utility of the database;
j) conduct of an assessment of current geographic information systems and development of recommendations on the optimal system for the SOTER Project; and
k) documentation of results, conclusions and recommendations from the initial phase of the SOTER Project.

Approach

1. Implementation Plan. Upon receiving financial support for SOTER Phase 1, an implementation plan was developed which defined specific tasks and assigned responsibilities and a schedule to bring Phase 1 to completion on 31 December 1989. A Project manager for this phase was assigned and the Project officially began in September 1987.
2. Universal Legend. An international committee of soil scientists was appointed in January 1986 to develop a universal legend for soils and terrain data to be entered into the SOTER database. A draft version was distributed in March 1988 entitled "SOTER Procedures Manual for Small Scale Map and Database Compilation" (Shields and Coote, 1988).

This Manual describes and contains procedures for compiling and coding the following kinds of data for entry into the SOTER database (Figure 1):

| | |
|---|---|
| Polygon file | (15 attributes) |
| Terrain component file | (28 attributes) |
| Soil layer file | (73 attributes) |
| Soil degradation file | |

The Manual also presents coding forms on which to enter all the attribute file data which have been translated into the universal legend from whatever soil classification system that is being used.

3. Correlation Guidelines. The Procedures Manual in a sense serves as the primary guideline for the correlation of soils which have been mapped under different classification systems. Further refinement of correlation procedures must be developed during the actual testing of the procedures and legend during field and compilation operations.
4. Definition of Soils and Terrain Parameters for Entry into the Database. Careful attention has been given to the amount and kinds of data to be included in the SOTER database. The tendency is to include more data than can be used or is necessary for a map scale of 1:1M. The legend committee has given tentative definitions in the Procedures Manual. The adequacy of these definitions is being tested during Phase 1.
5. Definition of Detailed Set of Specifications and Logic to Define Minimum Capabilities/Functions of Database. In general, the SOTER

Proposal specifies that the SOTER database should be accessible to a broad base of users for a wide array of uses. During Phase 1

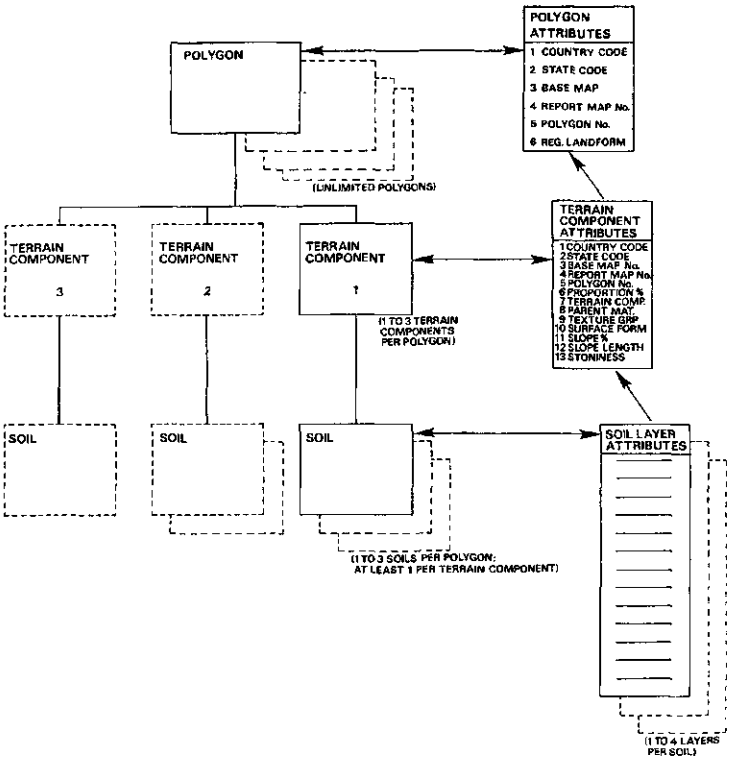


Fig. 1. Relation between Soter attribute files.

the potential users and uses of the Database must be more clearly defined so that the minimum capabilities and functions of the Database can be specified.

6. Selection of Pilot Areas of 250,000 sq km each in developing countries. During the International Workshop in Wageningen in January 1986, approximately twenty areas of 250,000 sq km were suggested as potential pilot or demonstration areas for SOTER. These were prioritized in terms of availability of data and interest of potential funding agencies. These priority areas included regions in South America, East Africa, West Africa, and Southeast Asia.

In consultation with UNEP, the area selected for Phase 1 is an area in excess of 250,000 sq km which includes a portion of Argentina, Uruguay, and Brazil (Figure 2). In March 1988 a SOTER Workshop was held in Montevideo, Uruguay, for soil scientists of the three participating countries and selected members of the SOTER Working Group. The purpose of the Workshop was to present and discuss the concepts of SOTER, to report on the availability of data for the SOTER Database, and to present and discuss thoroughly the Procedures Manual and universal legend for coding data (Peters, 1988).

During April and May 1988 soil scientists of Argentina, Brazil, and

Uruguay tested the Procedures Manual in a relatively small area within their portion of the Pilot Area. The Procedures Manual was used as a

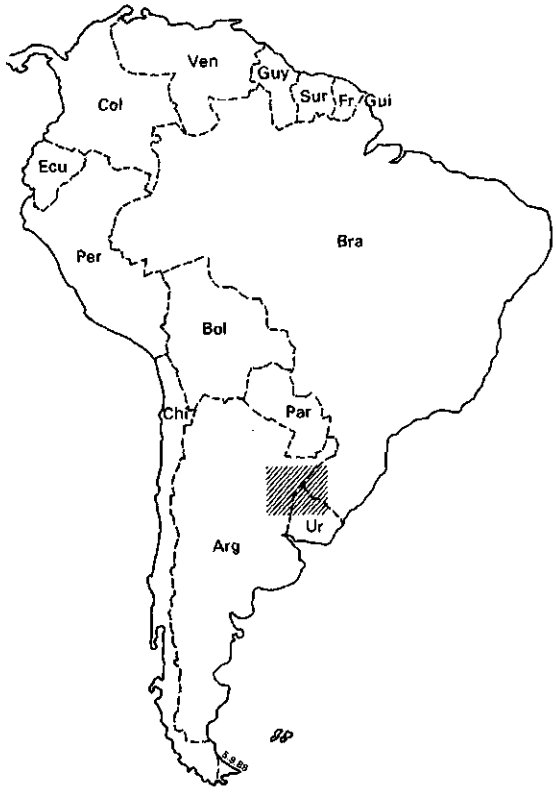


Fig. 2. Pilot area 1: South America.

guide for translating soils and terrain data from their systems to the SOTER legend and for coding the data for input into the SOTER Database.

In June 1988 three external SOTER soils correlators joined participating soil scientists of the three countries for correlation studies. They traveled together to each of the small study areas in each country and discussed the problems which they had encountered with the use of the Procedures Manual. The purpose of this exercise was to refine and improve the Manual and correlation procedures. Each country has appointed a country correlator to work closely and as necessary with the external correlators in order to arbitrate correlation differences.

7. Acquisition and Correlation of Relevant Maps and Data. The Soil Survey organizations of Argentina, Brazil, and Uruguay will be responsible for acquiring relevant map and attribute data and translating the data to the SOTER legend.
8. Entry of Data into the SOTER Database. At this stage of the Project a final decision has not yet been made about this task.

Several possibilities are being considered. It has been agreed that once the Database has been established, one of the places it will reside is UNEP/GRID.

9. Test and Demonstration of Reliability, Accuracy and Utility of the SOTER Database. During 1989 after entry of data into the Database, attention will be given to the testing of the Database.
10. Assessment of Current Geographic Information Systems. As yet no decision has been made on the system to be used for the SOTER Database. The major concern is that whatever system is finally selected, it be compatible with GRID and other global environmental databases. Many different commercial hardware/software systems are available today, and no doubt others will emerge in the future. It is essential that the system selected for SOTER be flexible and economically feasible.
11. Documentation of Results, Conclusions and Recommendations. Phase 1 of SOTER is scheduled for completion on 31 December 1989. The results, conclusions, and recommendations of this phase of the Project will be documented and provide valuable guidelines and experience for the next phases of SOTER.

Expected Results

In general, the overriding objective of the SOTER Project is to improve the capability to deliver accurate, timely, useful information about soils and terrain resources to decision-makers and policy-makers. It is expected that a World Soils and Terrain Digital Database will provide this improved capability of information delivery. There are other, perhaps more specific, results which are expected from the Project.

1. Orderly arrangement of resource information. All endeavors involved in the development, management, and conservation of environmental resources require information about those resources which is normally available from a variety of sources, at different levels of detail, including format and scale. An important outcome of the operational Database is to bring into being an orderly arrangement of descriptive and quantitative data about soils and terrain, easily accessible to the user community and compatible with other environmental databases.
2. Improvement in standardization and compatibility of reporting soils and terrain data/information. Inherent in the conceptualization of the Database is the requirement for a "universal" legend and a standard system for both input and output. Another requirement of SOTER is that the Soils and Terrain Database be compatible and have overlay (registration) capabilities with world databases of other environmental resources.
3. Improvement in accessibility of soils and terrain and related resource information. An important component of the Project is that of technology transfer, especially in the provision of training in the access to and utilization of the Database for easy extraction of a broad array of interpretive maps and information essential to resource managers and policymakers. Different methods will be explored for improving communications between the Database and the user community.
4. Dynamic resource information system with updating and purging capabilities. One of the significant benefits of the Database, not possible with previous soils and terrain information systems, will be the instantaneous capability to add new data whenever such data

become available and to delete incorrect, obsolete and irrelevant data.

5. Information service for national resource planning in developing countries. Another of the expected results from an operational database is the valuable resource information service which can be made available to a variety of agencies and organizations involved in national and regional resource planning in developing countries.
6. System model for technology transfer. As the world is being caught up in the "information revolution," there is an increasing need to find innovative and useful methods for transferring this technology. The SOTER Database Project can provide an excellent vehicle for training a cadre of specialists, especially in developing countries, for using the Database, providing new data, and developing new uses of the Database. The operational World Database can also serve as a model for the design and construction of incountry databases with sufficient detail and scale (accuracy) for local and provincial use.

A Supporting Research Agenda

The ultimate test and assessment of any soils and terrain database, at any scale, is the degree to which useful interpretive information can be extracted from the database. Two broad areas of interdisciplinary research must be pursued to bring accurate, useful, and timely soils and terrain databases into operation. The first is the development of the database itself. The second but closely related research area is the development of analysis and interpretive techniques.

1. Development of the database. In this discussion it is assumed that state-of-the-art hardware/software systems will be available commercially. The research to be addressed does not include those aspects of basic geographic information system technology. The following items related to database development should be included in the research agenda:
   a. minimum data quality standards for all map and attribute data for entry into the database;
   b. development and refinement of techniques for using remotely sensed data as a tool for delineating meaningful soil boundaries at different map scales and characterizing soils and terrain where current data are inadequate or non-existent;
   c. development of better methods for generalizing soils and terrain maps from scales 1:10K to 1:50K; from 1:50K to 1:250K; from 1:250K to 1:1M;
   d. improvement of methods for translating, correlating, and coding soils and terrain data (map and attribute) from different classification systems to a uniform legend and standard database.

2. Development of analysis and interpretive techniques. Some current GIS systems have excellent query and information extraction capabilities. However, there are areas of research and development which could contribute significantly to the benefits to be derived from soils and terrain databases.
   a. development of modeling algorithms which would be used to derive maps from the database related to erosion hazard, trafficability, potential biomass production, optimal application rates of herbicides;
   b. using temporal data in the database, development of algorithms to estimate amounts and rates of change in the soil as a source and

sink of materials related to carbon dioxide increase, acidification, nutrient decline, erosion, alkalization, salinization, desertification and other processes.

We live and operate in a multidimensional environment. The effects of human activity in this environment play an increasingly important role in global change. Today, we have a remarkable set of tools with which to observe, monitor and model in space and time the Earth system and global processes. May we have the wisdom to use these tools for the benefit of all humankind for all time to come!

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# MODELLING LAND QUALITIES IN SPACE AND TIME: THE ROLE OF GEOGRAPHICAL INFORMATION SYSTEMS

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## Summary

Good land management needs reliable information about Land Qualities. These complex attributes of land are derived from simpler, directly measurable properties obtained from natural resource surveys. The survey data are stored in geographical information systems where they can be used to estimate the values of appropriate land qualities. Land qualities are derived from the original attributes by using empirical threshold or regression models, or process-based deterministic or stochastic simulation models. In order to make improved estimates of the distribution of land qualities in space and time, the models require data with a much better spatial resolution than is usually available. The problems and dangers associated with the ad hoc linkage of simulation models and GIS are discussed. Particular attention needs to be paid to the problems of error propagation and of costs and benefits when using models.
**Keywords:** Geographical information systems, land evaluation, simulation models, transfer models, land qualities, natural resource survey, error propagation.

## Introduction

Land qualities are complex attributes of land based on simpler, directly measurable properties (characteristics) of the landscape concerning landform, soil, water, biological and human activity (FAO 1976, Bouma 1989). The state of a given land quality is often taken to be diagnostic for evaluating land with respect to a given land utilization type. Knowing the state of the land qualities and the demands of land utilization types allows one to manage the land effectively according to the defined aims of maximizing production or of conservation (Beek 1978).

Because land occupies space, and because the properties of the land, and hence the land qualities, may change with time, any sensible system of land evaluation or land management needs to have information about a) the land quality values and the spatial distribution of those values and b) information about how changes in land quality values may occur. Temporal changes in land quality values will usually be accompanied by changes in the spatial patterns of those values. In order to achieve a working system, we need to consider three basic elements:

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GIS in LU.

i) Inventory to establish actual values of land attributes
ii) Methods for storing and manipulating the data so acquired
iii) Models for linking land qualities to the basic attributes of land, water and climate, and which can simulate how these land qualities may change with time.

The aim of this chapter is to review the ways in which geographical information systems (GIS) and models of spatial and temporal processes can be linked for the purposes of land evaluation. The inherent advantages, weaknesses and pitfalls of this marriage will also be considered.

Data collection

Basic data concerning the properties of land, climate and water may be collected as part of standardized (national) survey programs or during ad hoc special purpose investigations. At reconnaissance level, spatial generalization and classification are used to filter out short-range local variation in order to present general overviews. As survey effort increases more attention is paid to local variation often at the expense of understanding variations over whole landscapes. The kind of data collected also changes, often varying from the broadly descriptive at the reconnaissance level to detailed quantitative at local, site levels. A basic tenet of land evaluation that is not always adhered to is that data should only be used to support decisions at the levels for which they were collected. At all levels there is an increasing tendency in modern surveys to make quantitative observations instead of collecting qualitative data.

The variation in the kind of data collected with the level of survey is a compromise that is not only forced by constraints of time and money, but also by the aim for which the survey was carried out. Sometimes surrogate data need to be used instead of direct observations of the land characteristics desired, and here survey techniques such as aerial photo interpretation and image analysis of remote sensing data can be of use.

Data about the land characteristics are related to locations on the earth's surface either in terms of the single XYZ coordinate of an observation point, a set of XYZ coordinates of a line or traverse, an areal unit such as a soil association delineation, catchment area or land use class occurrence. The square pixel used in remote sensing can be related to a point or an area depending on the scale of resolution and the context of the survey.

Sets of data about the semi-permanent properties of the land such as soil type and land use are usually collected infrequently: the survey is a 'snap shot' of the spatial patterns seen at the time of survey. In contrast, sets of data about more dynamic properties of climate and hydrology are usually collected at discrete sites but at regular time intervals. As with spatial data, time series data can have different levels of resolution.

## Data storage - Geographical Information Systems

Until recently, all spatial data were stored and presented to the user in classified form on paper maps; time series data were presented as lists and graphs. Now, modern geographical information systems allow spatial data to be stored either in raw or classified form. Basic data can now be transformed, combined and displayed as required according to the needs of the user.

Basically, a modern GIS stores spatial data about soil, land use, climate and so on in terms of basic geographic entities such as points, lines and areas. Sets of attributes describing the values of properties that apply to the whole entity are held in an associated relational database (Burrough 1986). The spatial distribution of the points, lines or areas may be represented in either the raster (grid cell) or the vector (symbols and connected lines) form. The basic entities can be recombined to make new maps by reclassifying them in terms of the sets of attributes present. For example, a database of soil series map units will contain data about the properties of the soils. A map showing the variation of the land quality "trafficability" can be made by reclassifying each soil polygon in terms of a model that relates trafficability to the properties of the soil. Entities can also be reclassified in terms of their proximity to other entities having certain sets of attribute. For example, all land parcels having a stream as one of their boundaries could be reclassified and displayed separately.

Data at individual point locations (soil profile pits, groundwater sample tubes) can be given a spatial context in several ways. These are:

a) by reclassifying the area entity in which the point falls
b) by numerical interpolation and threading of contours
c) by using a function such as exponential decay to model variations over space.

When sets of point data are associated with a regular array, such as that used in remote sensing or for an altitude matrix digital elevation model, new data can be computed as a function of spatial differences. For example, a map of slope gradient is one of the many derived products that can be easily calculated from a digital elevation model (Burrough 1986, Evans 1980).

A general formulation of a GIS envisages space as being covered by a cartesian coordinate system. Each separate attribute of the space is described by a separate overlay. so for each point on the surface, the column vector of overlay values defines the values of all the properties or land characteristics at that point (Figure 1). In fact, this is the way many raster GIS work. Each location on each overlay is represented by a single pixel; the value contained in the memory location for that pixel is the value of the property contained in that overlay.

### Deriving new data in a GIS

The act of deriving new data from existing data in a GIS can be generalized as follows. For any given location x, the value of a given land quality $LQ_i$ can be given by one of the three following functions:

a) when no spatial contiguity is taken into account

$$LQ_i = f\ (A,\ B,\ C,\ \ldots\ldots\ldots\ldots) \qquad 1.$$

where A, B, C, ... are the values of the land characteristics used to estimate $LQ_i$.

b) when spatial contiguity is taken into account (i.e. the value of the land quality at the point x is dependent on spatial assocations with the area surrounding x

$$LQ_i(x) = f\ (A_x,\ B_x,\ C_x,\ \ldots\ldots) \qquad 2.$$

c) when the land characteristics vary over time, then the land quality varies with time as

$$LQ_i(x,t) = f\ (A_x,\ B_x,\ C_x,\ \ldots\ldots),\ t \qquad 3.$$

Each of the equations 1, 2, and 3 can be considered as the most general statement of a model of how land qualities at point x at time t depend on the land characteristics. Many different kinds of models are used to estimate land qualities and the main types are discussed next.

## Models

A model is a simplified description of an observed relation or process. Here we are concerned with mathematical or quasi-mathematical models that are used to decribe the relations between the basic properties of land, water and climate and the desired land qualities.

The stages of creating models that relate land qualities to land characteristics are as follows:

a) observation of a relation between land quality and attributes of the landscape
b) empirical description of that relationship
c) testing the generality of the empirical description
d) unraveling the physical processes underlying the relation - followed by a description of the processes in terms of physical or stochastical laws.

## The kinds of models used in land evaluation

Model building in the environmental and agricultural sciences is beginning to come of age. Today, there are many kinds of models available ranging from the extremely simple to the highly complex (e.g. Beven 1985, Bork & Rohdenburg 1986, Comerma & de Guenni 1987, Dumanski & Onofrei 1989, Hornberger et al 1985, Jousma & van der Heyde 1985, Penning de Vries & van Laar 1982, van Diepen et al 1989).

There is no single, accepted classification for models but the following grouping will serve. We can distinguish between empirical models, deterministic process models and stochastic process models. Empirical models are those in which a relation has been observed between a land quality value and the original attribute values, but the exact mechanism is not understood.

Deterministic process models are those where the model attempts to describe a particular process in terms of known physical laws.
Stochastic process models are those where the model attempts to describe a particular process in terms of stochastic theory.
In practice, a given model may consist of sub-models; each sub-model may be of a different kind.

Empirical models.

Empirical models may be of various kinds. We will distinguish between **threshold models** and **regression models**.

**Threshold models** use boundary values of diagnostic properties to establish output values. The input data are often, but not necessarily, already classified data such as soil texture. The output values are usually expressed as a simple binary code (e.g. 0 - unsuitable, 1-suitable) or on a simple nominal scale.
Simple Boolean algebra is often used and a model may be no more complex than:

$$\text{IF} \quad X \geq P_1 \quad \text{AND} \quad Y < P_2 \quad \text{THEN} \quad \text{RESULT} = Z$$

where X and Y are the input data, $P_1$ and $P_2$ are the control parameters and Z is the output. In practice, the values of control parameters are determined by experience. A real danger of threshold models is that when several are used in sequence, or when several discriminating criteria are used together in one model, more land may be excluded than is deemed reasonable (Marsman and de Gruijter 1984). Softening the boundaries by using the methods of fuzzy reasoning may give more useful results in some cases (Chang & Burrough 1987).

**Regression models** use experimentally observed simple or multiple regressions to determine the values of the control parameters. For example:

$$LQ_i = aX + bY + \ldots\ldots$$

where **a, b,** ..... are the control parameters and X, Y, .. are the inputs, assumed to be independent of each other.

Bouma and van Lanen (1987) use the terms **continuous transfer functions** for regression models and **class transfer functions** for threshold models. For other examples see Cosby et al (1984) and Dumanski and Onofrei (1989).

Deterministic process models

**Deterministic process models** model observed relationships in terms of one or more physical and/or chemical processes in the water/soil/plant/-atmosphere system. The land quality values are obtained by solving differential equations describing the processes. For example, Darcy's law is a differential equation relating the specific discharge of water $q_s$ to the soil permeability k, the piezometric level ø and the distance in the s-direction:

$$q_s = - k \, \delta ø / \delta s$$

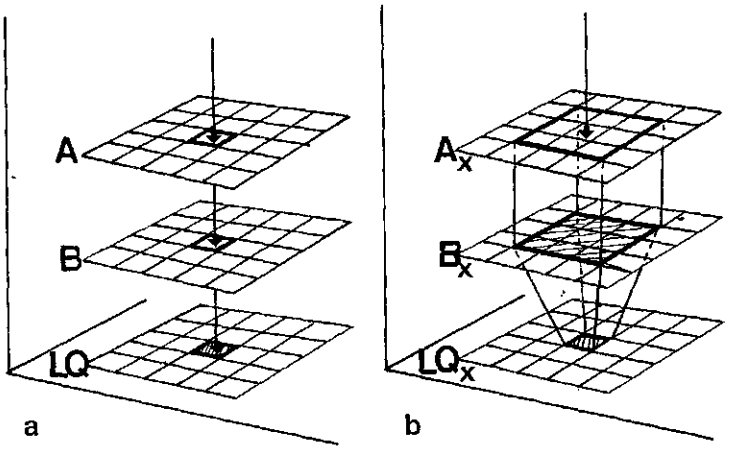


Fig. 1a) The value of a land quality at a given location is a function of the land characteristics of the same location.
b) The value of the land quality at the location is a function of the land characteristics and their spatial distribution around that location.

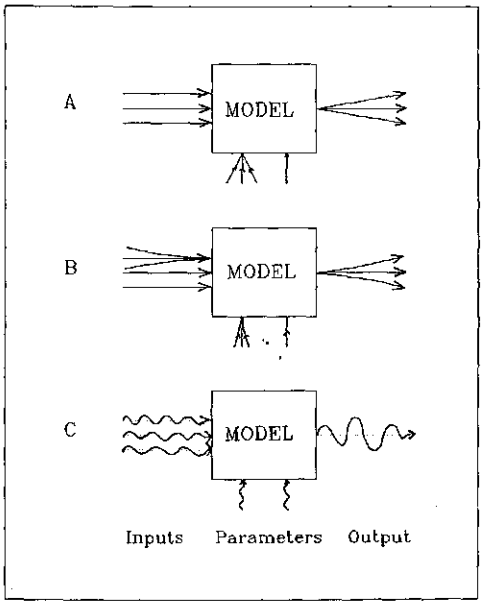


Fig. 2. The results from a model depend on A) the tuning of the control parameters, B) the sensitivity of the model to certain control parameters and input data, and C) the way in which errors in the control parameters and the input data are propagated.

Here $q_s$ is the output, k is the control parameter and ø and s are inputs.

Deterministic process models attempt to model the most important aspects of the processes in terms of well understood physical and chemical laws. The models are applied to large complex areas of land by splitting it up into discrete segments. The process being modelled is followed analytically in each segment whereby the output from one segment forms the input for the next. Such a model is often termed a **distributed model** (e.g. Beven 1985, Moore & Clarke 1981). A possible shortcoming of current distributed models is that existing computer languages (e.g. FORTRAN) constrain the model builder to work sequentially.
This means that each part of the process, and each iteration of the process at different locations, must proceed separately. In reality, many components of an overall process operate simulataneously, or in parallel. Developments in parallel processors and transputers may provide ways in which more realistic modelling can be achieved (e.g. Wayner 1988).

Stochastic process models.

In some situations it is not practicable to model the outcome of a single event but rather the average behaviour of a large number of events. If this average behaviour can be modelled by a well-defined **stochastic process**, such as a Gaussian random field, a Markov chain or a fractal (Mandelbrot 1982) then the model output does not describe an exact result but rather one possible realization within a whole range of results. Because it is not always possible to achieve adequate results when using a fully deterministic model, some researchers are exploring ways to combine deterministic and stochastic approaches in a single model (e.g. Serrano et al 1985a,b,c, Yeh et al 1985a,b,c).

General properties of models

Under control of **state parameters** and within given **boundary conditions**, a model transforms **input data** to produce **results**. In order for the results to carry any actual meaning, the following aspects need careful attention:

a) **calibration of models** - what are the correct values of the control parameters in order to get the correct results at known data points? Closely associated with calibration is the **validation of models** - do the models produce correct results at independent, unsampled locations?

b) **sensitivity analysis** - how do the results of the models depend on variations in the value of control parameters and input data?

c) **error propagation** - how are errors and uncertainties in the values of control parameters and input data transmitted to the results and what are the magnitudes of these errors? Do the errors exceed levels that are acceptable or essential for the proper use of the results?

These three important aspects of models are illustrated schematically in Figure 2. (see also Burrough 1986, chapter 6, Rogers et al 1985).

## Models in space and time

For many models used in land evaluation, the geographical location of the site is not considered to be of overriding importance (i.e. geographical coordinates are not used as inputs nor as control parameters). The variation in model results over space can be obtained by obtaining the inputs from different spatial entities (points or areas) and relating the model outputs to the area in question by either recoding the areal units or by interpolating from the points (c.f. van Diepen et al 1989, Schultink 1987) - see Figures 3 and 4.

For processes such as runoff, erosion, groundwater movement, the leaching of salts or the spread of diseases, there is an interaction between the spatial process and a **substrate**. This substrate provides a one dimensional, two dimensional or three dimensional framework within which the process model can operate.
The substrate may be unaffected by the process (e.g. by simple runoff) or may itself be modified by the process (e.g. erosion or transport and adsorption of pollutants).

The basic unit of the substrate is called a **finite element**. The space in which the process must be modelled is split up into a set of basic units that can be considered to be internally homogeneous at the level studied. Finite elements can be morphologically defined land units such as catchments or slope facets, but more commonly these days they are square cells or cubes. These regular units are often used because of their ease of manipulation inside a computer (Fig. 5a). With two-dimensional models it is now becoming possible to use square cells (pixels) that are small enough to be reasonably uniform and even within a personal computer a two-dimensional array of 150 x 150 cells is not excessive. Three dimensional models used in groundwater modelling (e.g. Fig. 5c) cause greater problems:
a 60 x 60 x 60 cell array (which is trivially coarse) requires 216000 memory elements alone!

## Linking models and GIS

In principle, geographical information systems contain much information needed for running the models mentioned above. GIS can hold many data on static distributions of land attributes in the form of discrete observations or as thematic maps, and they can also store and manipulate two dimensional surface data, and less commonly, three-dimensional volume data. So, for any given study area we might expect that a suitable GIS should contain area-specific values for the control parameters and the boundary conditions, the necessary input data for the models and the information needed to create the two and three-dimensional substrates used in the finite element flow models. Such a GIS could relate model results to existing spatial entities or interpolate them over areas (Figures 3 and 4). By stopping the model at regular time intervals and displaying intermediate results, the change of the patterns of distribution of the land quality over time can be seen (Figure 6). If certain kinds of input data are not available, it may be possible to use surrogate data derived from other data present in the system, provided suitable conversion models are available.

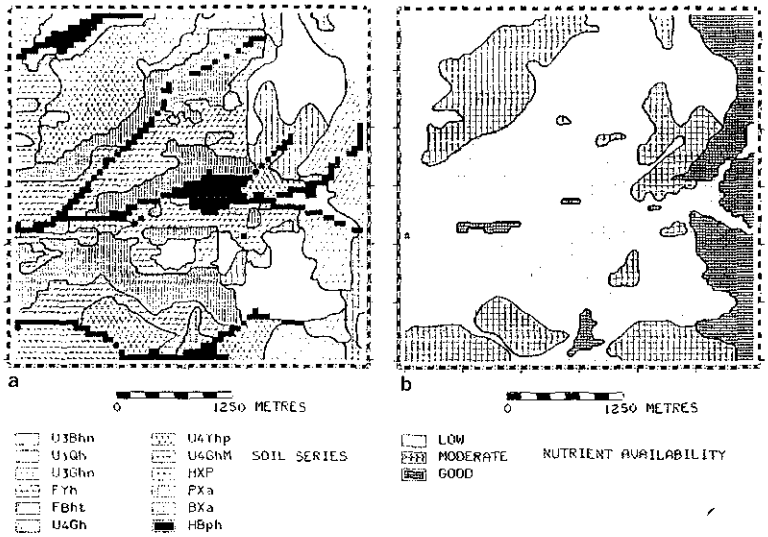


Fig. 3. Simple threshold models can be used to transform a soil map (a) into a map of the land quality "nutrient availability"

Spatial variation of standardized, simulated yields

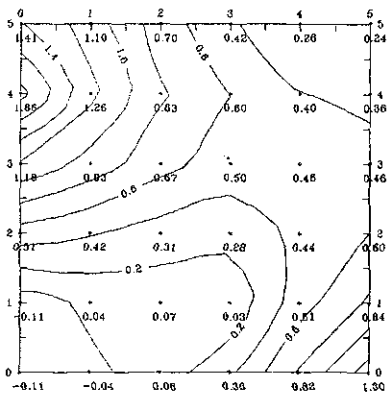

Fig. 4. Interpolation methods such as kriging can be used to relate the results of crop yield simulations based on soil profile data to areas. The yields here are displayed in terms of zero mean and unit standard deviation for the field as a whole

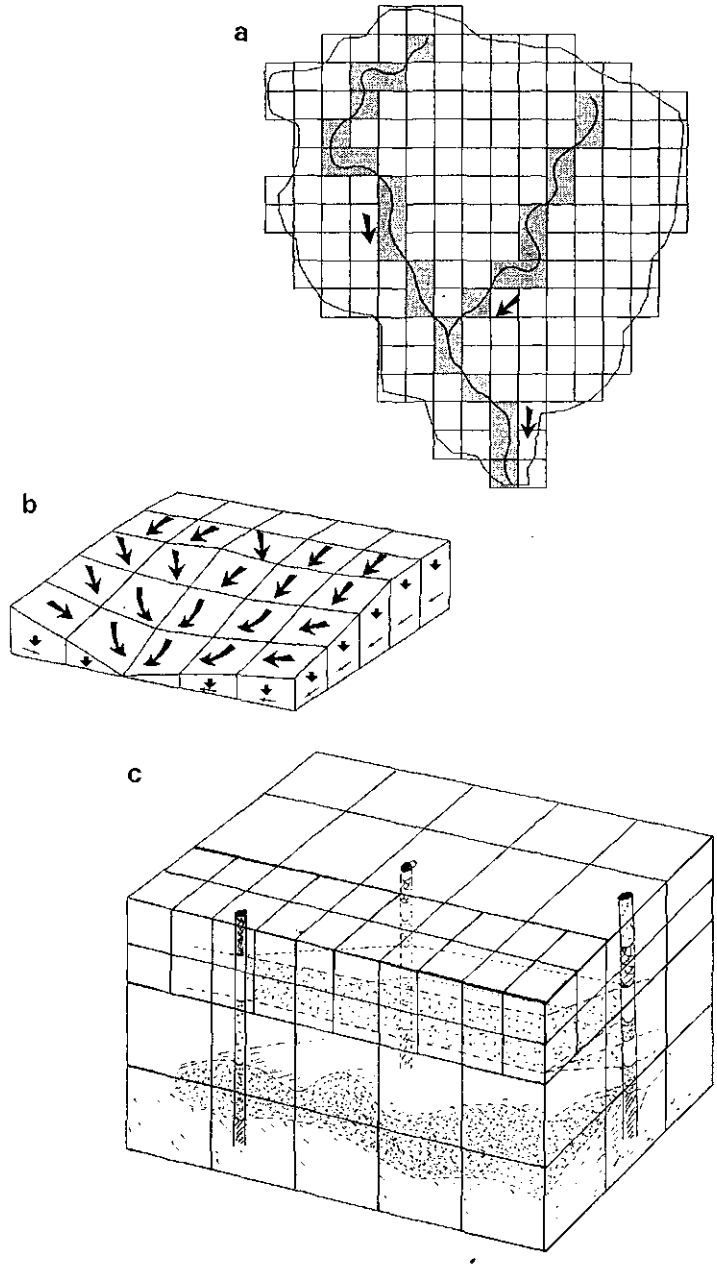


Fig. 5. With dynamic process modelling, a 2-D or 3-D substrate must be created. Commonly, the area or catchment is divided into a regular array of grid cells (a). Each cell needs to carry its own values for inputs and outputs such as runoff, infiltration and subsurface flow (b). The finer the raster, the closer the approximation to reality but the more difficult it is to obtain unique values for each cell. This problem is especially great with sub-surface groundwater modelling where observations are few and costly and the number of cells required is a factor larger than for surface modelling.

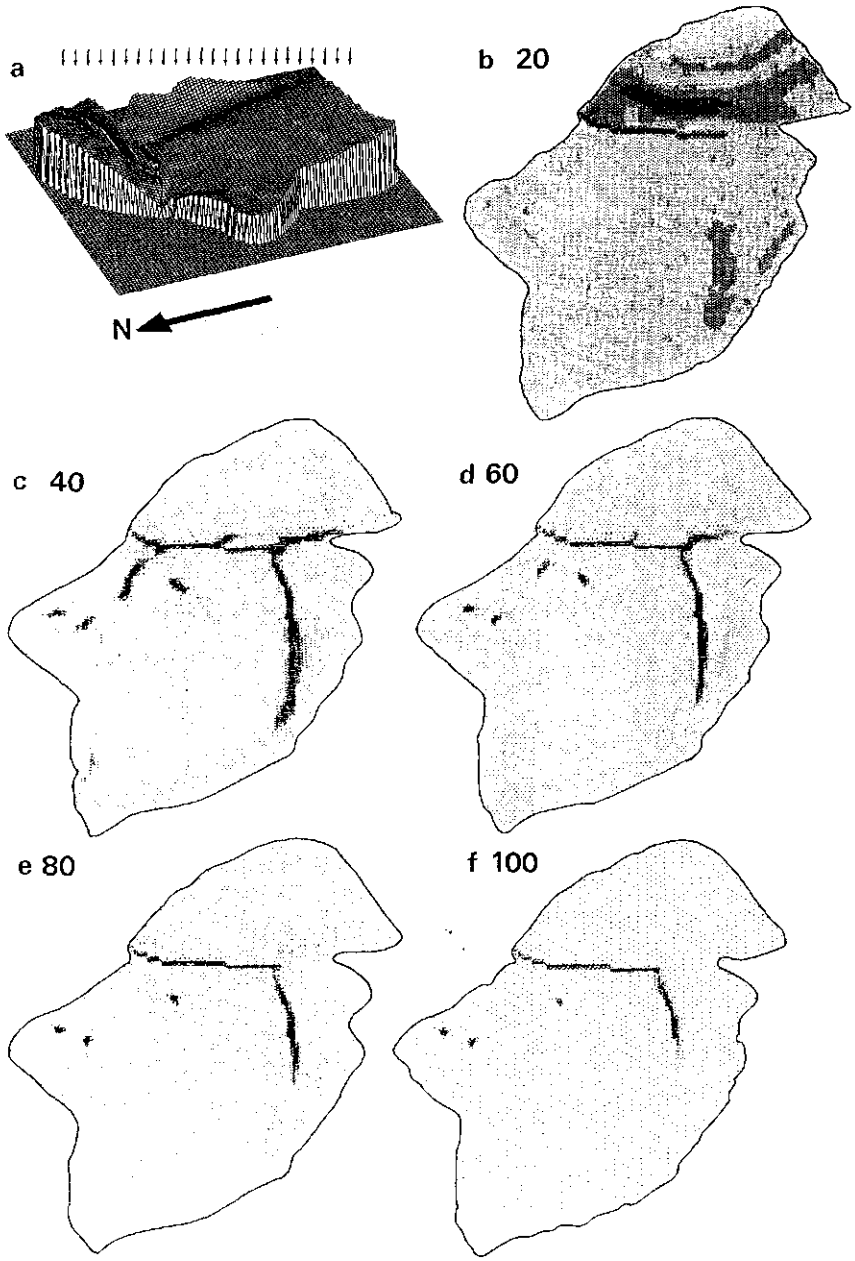


Fig. 6. Variation of land qualities in time can be visualised by stopping a dynamic model at intervals and displaying intermediate results with the GIS. a). Digital elevation model of a catchment. b) - f) show the distribution of surface water at 20 minute intervals after a heavy storm rains uniformally over the catchment. Modelling using the ANSWERS runoff/erosion model as adapted by A. de Roo (University of Utrecht).

The previous paragraph conjures up an ideal picture of a 'super GIS' with which a land use planner could model any process and compare any set of scenarios at will, displaying the results as high quality, multi-colored maps or even as three-dimensional block diagrams. In practice, it will not be easy to link GIS and models in such a way that a planner can work successfully with such a system independently of expert advice. There are many reasons why this is so, and it is important to know why.

Many distributed models of runoff and groundwater flow have a good scientific base. The distributed, finite element approach is sound providing that the models are supplied with data that describe spatial variation as accurately as the models can describe the process. This means that for a process model to yield consistently good results, each finite element in the substrate needs to be provided with its own location-specific data. Clearly, if the finite elements are large in relation to the spatial variation in the landscape, then the model results are likely to be unsatisfactory. Choosing small elements and filling them with the same values taken from already classified data brings no further intrinsic improvements, but only a dangerous illusion of accuracy resulting from the improved graphical quality of the resulting maps.

A major problem then for accurately modelling land qualities in space and time is the degree with which reliable location-specific estimates of the values of land qualities can be made. The full use of a distributed system based on a cubic raster for modelling movement of pollutants, for example, means that each cell in the raster needs to have its own values for permeability, hydraulic head, absorption and exchange of pollutants and so on. For each element a runoff model needs to have data on rainfall, evaporation, infiltration, lateral sub-soil movement and drainage, slope, soil type, land use and so on. These large, detailed data sets defining the substrate need huge computer memories for handling the large amounts of data, particularly for the three dimensional situations. We have arrived at a state of affairs that has been termed **"the parameter crisis"** - as models get increasingly realistic they need more and better data to control them and to drive them. But even with GIS, the data are not always available and the solutions are not always easy. They are:

a) Collect more data
b) Make better use of the data we have by using them for interpolating the values of attributes to a suitable grid instead of generalizing and lumping
c) Use existing data and knowledge about the geohydrology, physical geography, soil science and climatology of an area in such a way that better models of substrates can be generated.

So, in order to link land quality models and GIS usefully it is essential to pay careful attention to the following points:

a) From the point of view of the model:
   - What are the basic assumptions and methods?
   - At what scale or organisational level is the model designed to work?
   - What kinds of data are needed for the control parameters?
   - What kinds of data are needed to feed the model?

- Under which conditions are certain control parameters or input data more important than others?
- How are errors propagated through the model?

b) From the point of view of the GIS.
- Are the right input data available at the correct spatial scale and level of generalization?
- Are there sufficient good data to create a finite element substrate when required?
- Are data available for calibrating and validating the model?
- If certain data are not available can surrogates be used instead? How should they be transformed?
- How should model results be displayed as spatial and temporal patterns?
- How should the user be made aware of the intrinsic quality of the results of modelling?
- Is information available on data quality and errors?
- If the results are not good enough, should the GIS suggest alternative data, or alternative models to the user?

These are all questions that need to be answered properly before it will be possible to use GIS and models together in anything other than the present ad hoc ways. No current state-of-the-art GIS is capable of linking all kinds of models and GIS as suggested here. Improved GIS will require technological advances in data structures, in the availability of parallel processing, in the use of expert system shells, error propagation studies and improved user interfaces; finite element models, in particular, will require better ways of constructing the substrates needed to run them. An important complementary study concerns costs and benefits in order to ascertain just when and where the increased investment in data and computing power is justified by the application. These are all important topics for research in the coming years.

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# DIRECT AND INDIRECT METHODS FOR ESTIMATING THE HYDRAULIC PROPERTIES OF UNSATURATED SOILS

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## Summary

This paper reviews current methods for estimating the hydraulic properties of unsaturated soils. Numerous direct methods, including parameter estimation techniques, are now available for measuring the hydraulic properties. A large number of indirect methods also exist for predicting the unsaturated hydraulic conductivity from more easily measured soil water retention, soil texture, or other data routinely available from soil surveys. Specific areas in need of further research and development are outlined.
Keywords: soil water retention, unsaturated hydraulic conductivity, soil texture, pore-size distribution, particle-size distribution.

## Introduction

There is increasing evidence, and public concern, that the quality of our soils and waters is being adversely affected by agricultural and industrial activities. In efforts to better monitor and manage the migration of chemicals in the subsurface environment, scientists and engineers over the past several decades have developed increasingly complex computer models describing how water and chemicals move into and through the unsaturated zone. Computer models have now become indispensible tools in research for quantifying and integrating the most pertinent physical, chemical and biological processes operative in the root and vadose zones of agricultural soils. Similarly, planning, action, and extension agencies are increasingly resorting to the use of models for predicting the long-term impacts of alternative soil and water management practices on crop yield and groundwater quality. This trend of using models as tools in research and management will probably accelerate as computer costs decrease and the need for more realistic predictions further increases.

Unfortunately, reliable application of computer models to field-scale flow and transport problems requires considerable effort in quantifying a large number of model parameters, especially the unsaturated hydraulic properties. As our conceptual understanding and numerical expertise to simulate increasingly complex systems increases, the accuracy of future simulations may well hinge on the accuracy of parameters appearing in our computer models. Thus, there is a great need for more efficient and accurate methods for estimating model parameters.

The single most important parameter affecting water and solute movement in the vadose zone is the unsaturated hydraulic conductivity, K, which appears in the unsaturated flow equation:

$$C(h)\ \frac{\partial h}{\partial t} = \frac{\partial}{\partial z} K(h)\ [\frac{\partial h}{\partial z} - 1] \qquad (1)$$

where h is the soil water pressure head; $C(h) = d\theta(h)/dh$ is the soil water capacity, being the slope of the soil water retention curve, $\theta(h)$; $\theta$ is the volumetric water content, K is the hydraulic conductivity, t is time, and z is soil depth. A large number of laboratory and field methods have been developed over the years for measuring K as a function of h or $\theta$. These methods, nearly without exception, are extremely difficult to implement, especially for field situations. Enormous investments have and continue to be made by soil scientists and others in measuring the hydraulic properties of spatially variable field soils using methods that have remained costly and time-consuming. While a number of improved procedures have been introduced, notably those based on parameter estimation methods, our direct measurement technology has only marginally advanced over the last several decades.

In sharp contrast to direct methods for measuring the hydraulic properties, relatively little attention is being paid to developing improved indirect methods which predict the hydraulic properties from more easily measured data, including soil water retention data, particle-size distributions, or other data. This is unfortunate since indirect methods generally are much easier and far less costly to implement. Moreover, indirect methods often give hydraulic conductivity estimates which may well be accurate enough, or are close to being accurate enough, for a variety of applications (Wösten & van Genuchten, 1988).

Thus, in this paper we shall review both direct and indirect methods for estimating the unsaturated hydraulic properties. Among the indirect approaches are theoretical methods which predict the hydraulic conductivity from soil water retention data, and methods which correlate the hydraulic functions with soil texture and other data routinely available from soil survey data bases. We also include a brief discussion of the required accuracy of the hydraulic properties in terms of specific applications (land qualities).

## Direct methods for measuring the hydraulic properties

Recent inventories of direct methods for measuring the hydraulic conductivity, K, and the soil water diffusivity, $D=K(dh/d\theta)$, of unsaturated soils are given by Klute & Dirksen (1986) and Green et al. (1986) for laboratory and field methods, respectively. Most laboratory methods are steady-state procedures based on direct approximations of Darcy's equation. Popular transient methods include the Bruce and Klute (1956) method, and selected variations thereof, in which the diffusivity is estimated from horizontal water content distributions, and the sorptivity method of Dirksen (1975). Popular field methods include the instantaneous profile method of Watson (1966), various unit-gradient type approaches (Nielsen et al., 1973; Sisson et al., 1980), sorptivity methods following ponded infiltration (Clothier & White, 1981; Chong & Green, 1983), and the crust method of Bouma et al. (1971), the latter again based on steady water flow. Numerous variations of the above procedures also exist (Jones & Wagenet, 1984; van Grinsven et al., 1985; Green et al., 1986).

The above methods for measuring the hydraulic conductivity, $K(\theta|h)$, or the soil water diffusivity, $D(\theta)$, are typically based on Darcy's law, or on various numerical approximations or simplifications of Eq. (1) such that K or D can be expressed in terms of directly observable parameters. While relatively simple in concept, most of these direct inversion methods also have a number of limitations which restrict their practical use. For example, most methods are very time-consuming to execute because of the need to adhere to relatively restrictive initial and boundary conditions (e.g., free drainage of an initially saturated soil profile).

The need to impose simple boundary conditions often poses problems, especially for field experiments where accurate implementation of boundary conditions on a large scale may be very difficult. Methods requiring repeated steady-state flow or other equilibrium conditions are also very tedious. Other methods require the governing flow equations to be linearized or otherwise approximated to allow their (semi-)analytic inversion; this may also introduce errors. Finally, information about uncertainty in the estimated hydraulic parameters is not readily derived from direct measurement techniques. Recently introduced parameter estimation methods appear to alleviate at least some of those problems. Some of the main advantages of parameter estimation methods are briefly discussed below.

## Parameter estimation methods for measuring the hydraulic properties

A more flexible approach to solving the inverse problem is by using parameter estimation methods. A number of studies have recently shown the potential of such methods for simultaneously measuring the soil water retention and hydraulic conductivity functions from transient flow data (Zachman et al., 1981; Dane & Hruska, 1983; Hornung, 1983; Kool et al., 1987). In this approach the direct flow problem may be formulated for any particular set of initial and boundary conditions, and solved with any appropriate analytical or numerical method. One way to implement the parameter estimation method is to assume certain constitutive functions for the hydraulic properties, and then to estimate the coefficients in those functions by using an optimization algorithm which minimizes a given objective function (e.g., the sum of the squared deviations between observed and calculated water contents, pressure heads, water fluxes, or other attributes characterizing unsaturated flow). Frequently used expressions for the hydraulic functions are those developed by Brooks & Corey (1964) and van Genuchten (1980), denoted here by the BC and VG equations, respectively. The VG equations are based on Mualem's pore-size distribution model (Mualem, 1976a; see Eq. 8 below) for the unsaturated hydraulic conductivity, and can written in the form

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{(1 + |\alpha h|^n)^m} \qquad (m=1-1/n) \tag{2}$$

$$K = K_s \, S_e^{\ell} \, [1 - (1 - S_e^{1/m})^m]^2 \tag{3}$$

where $\theta_r$ and $\theta_s$ are the residual and saturated water contents, respectively; $\alpha$ and $n$ are shape factors, $m=1-1/n$, $K_s$ is the saturated hydraulic conductivity, and $\ell$ is an empirical parameter estimated to be 0.5 by Mualem (1976a) from an analysis of a large number of mostly disturbed laboratory soils. The effective degree of saturation, $S_e$, in Eq. (3) is given by

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}. \tag{4}$$

Note that the VG model contains a total of 6 unknown parameters: $\theta_r$, $\theta_s$, $\alpha$, $n$, $\ell$ and $K_s$.

We illustrate the flexibility of parameter estimation methods with one example in which the method was applied to the drainage of an initially

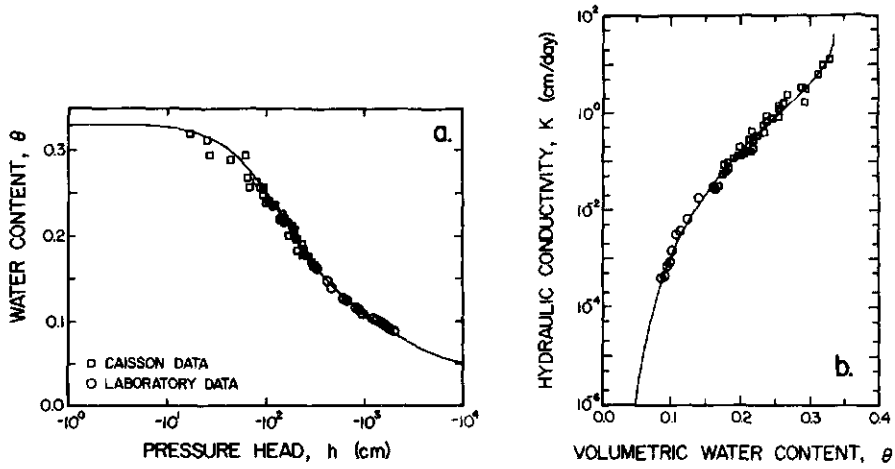


Fig. 1. Measured (data points) and predicted (solid lines) soil water retention (a) and hydraulic conductivity (b) properties of crushed Bandelier Tuff. The predicted curves were obtained with the Method 2 parameter estimates.

saturated 6-m deep, 3-m diameter lysimeter (caisson) filled with crushed Bandelier Tuff. The bottom boundary of the free draining lysimeter was maintained at saturation (h=0), while a no-flux condition was imposed at the soil surface. The inverse problem was formulated as a weighted nonlinear least-squares optimization problem that minimizes the objective function O(b)

$$O(b) = \sum_{i=1}^{5} \sum_{j=1}^{6} [\theta^*_{ij} - \theta_{ij}(b)]^2 + \sum_{j=1}^{6} W\,[h^*_j - h_j(b)]^2 \qquad (5)$$

where $\theta^*_{ij}$ represents measured water contents at 5 depths and 6 times, $h^*_j$ is the measured pressure head at z = 0.4 m and 6 times, and $\theta_{ij}(b)$ and $h_j(b)$ are the predicted water contents and pressure heads obtained with a finite element solution of Eq. (1) using the vector of unknown parameters $b = \{\theta_r, \theta_s, \alpha, n, K_s\}$. The weighting coefficient W was chosen such that the two composite terms of Eq. (5) attain roughly the same value (Parker et al., 1985). The unknown parameters in Eqs. (2) and (3) were also estimated directly (Method 2) from water retention and hydraulic conductivity data (Fig. 1) derived from the same drainage experiment using the instantaneous profile method (Abeele, 1984), and from independent laboratory experiments at low water contents (Abeele, 1979). The objective function for Method 2 was assumed to be

$$O(b) = \sum_{i=1}^{n_1} [\theta^*_i - \theta_i(b)]^2 + \sum_{j=1}^{n_2} V[\log(K^*_j) - \log(K_j(b)]^2 \qquad (6)$$

where $\theta^*_i$ and $\theta_i(b)$ are the observed and fitted water contents at $n_1$ pressure heads, $K^*_j$ and $K_j(b)$ are the observed and predicted conductivities at

$n_2$ values of the water content, and V is again a weighting factor whose value assures roughly equal values of the two composite terms of Eq. (6). In Method 2 all 6 parameters ($\theta_r$, $\theta_s$, $\alpha$, n, $\ell$ and $K_s$) were treated as unknowns.

Values for the fitted soil hydraulic parameters are listed in Table 1, while Figure 1 compares the fitted retention and hydraulic conductivity curves with the laboratory and caisson-derived data. The estimated curves for Method 1 (not shown) nearly duplicated those of Method 2 even though some of the fitted parameter values were quite different (notably $K_s$; see Table 1). Note the relatively wide 95% confidence limits on $K_s$ in Table 1 for both methods, indicating poor identifiability of $K_s$.

Figure 2 compares the observed (Abeele, 1984) and predicted water content profiles in the caisson for both methods. The observed data are somewhat underpredicted after 1 day of drainage, but are predicted very well at all other times, with Method 1 generating slightly higher water contents than Method 2. Additional details of this example are given by Kool et al. (1987) and van Genuchten et al. (1987). Other applications of the parameter estimation method to unsaturated flow are given in a recent paper by Kool and Parker (1988).

The above example illustrates several advantages of parameter estimation methods as compared to more classical direct measurement techniques: (1) there is no need to numerically invert (and hence approximate) the governing flow equation, (2) the method yields hydraulic properties over the full range of water contents, and (3) the method yields information about parameter uncertainty and model accuracy. Equally important, parameter estimation methods permit experimental conditions to be selected on the basis of convenience and expeditiousness, rather than by a need to simplify the mathematics. Thus, there is no reason to limit the approach to drainage (as in the above example), to non-hysteretic flow, to homogeneous soils, to experiments constrained by uniform initial conditions, or to experiments with time-invariant soil surface boundary conditions. While the parameter estimation methodology is clearly a promising approach, some problems related to computational efficiency, convergence and parameter uniqueness remain to be solved (Kool et al., 1987), especially when a large number of hydraulic parameters must be estimated simultaneously.

Table 1. Parameters in Eqs. (2) and (3) for Bandelier Tuff estimated from in situ drainage data (Method 1) and from previously measured hydraulic data (Method 2).

| Parameter | Method 1 | Method 2 |
|---|---|---|
| $\theta_r$ | 0.0[a] | 0.0255 (± 0.0185) |
| $\theta_s$ | 0.3308 | 0.3320 (± 0.0059) |
| $\alpha$ ($cm^{-1}$) | 0.0143 (± 0.0030) | 0.0154 (± 0.0022) |
| n | 1.506 (± 0.105) | 1.474 (± 0.744) |
| $\ell$ | 0.5[c] | 0.495 (± 0.371) |
| $K_s$ (cm/d) | 25.0 (± 12.6) | 33.7 (± 16.9) |

[a] Converged to zero; set to zero during estimation process
[b] Values in parenthesis indicate 95% confidence limits
[c] Assumed to be known

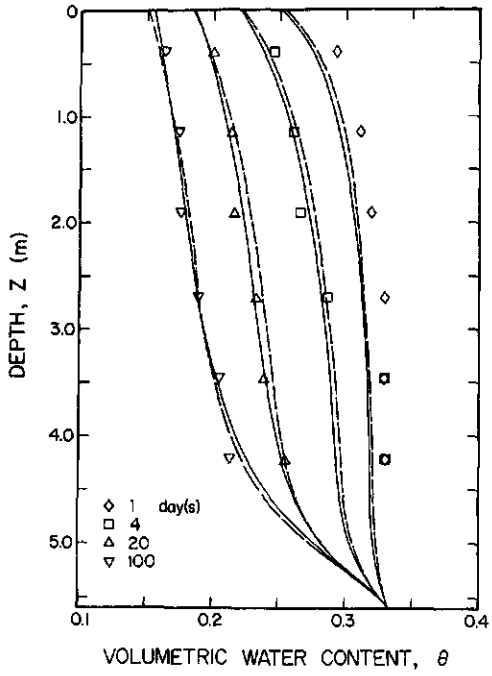


Fig. 2. Measured water content distributions during drainage in caisson A (data points), and predicted curves obtained with the Method 1 (dashed lines) and Method 2 (solid lines) parameter estimates.

## Estimating the hydraulic conductivity from soil water retention data

Direct methods for determining the hydraulic properties are time-consuming and expensive, and often subject to simplifying assumptions. One alternative to direct measurement is the use of theoretical methods which predict the hydraulic conductivity from more easily measured field or laboratory soil water retention data. Theoretical methods are usually based on statistical pore-size distribution models which assume water flow through cylindrical soil pores, and incorporate the equations of Darcy and Poiseuille. An excellent review of these methods is given by Mualem (1986). While numerous methods currently exist for predicting the unsaturated hydraulic conductivity from measured soil water retention data, we shall discuss only two different models. They are summarized by the equations:

$$K(S_e) = K_s S_e^{\ell} \int_0^{S_e} h^{-2}(x)dx \Big/ \int_0^1 h^{-2}(x)dx \tag{7}$$

and

$$K(S_e) = K_s S_e^{\ell} \left[\int_0^{S_e} h^{-1}(x)dx\right]^2 \Big/ \left[\int_0^1 h^{-1}(x)dx\right]^2 . \tag{8}$$

Equation (7) has been used extensively in the petroleum engineering literature. For example, Eq. (7) with $\ell=0$ leads to the model of Gates and Lietz (1950), and with $\ell=2$ to the model of Burdine (1953). Burdine's model was later used by Brooks & Corey (1964) to derive their classical functions for the unsaturated hydraulic conductivity. Equation (7) can also be shown (Mualem, 1976a) to represent the analytical version of numerical models developed by Childs & Collis-George (1950) and Marshall (1958) who assumed $\ell=0$, Kunze et al. (1968) and Jackson (1972) who suggested $\ell=1$, and Millington & Quirk (1961) who recommended $\ell=4/3$.

Equation (8) was derived by Mualem (1976a) from previous pore-size distribution models by including the effects of pore connectivity. Using $K(h)$ and $\theta(h)$ from 45 soils, Mualem concluded that the empirical coefficient $\ell$ in his model should be about 0.5. Because Mualem's data base (Mualem, 1976b) consisted of mostly repacked laboratory soils, the value of 0.5 for $\ell$ can only be a rough approximation and is not expected to hold for all soils. Our own experience indicates that $\ell$ may vary from less than -10 to more than 10 for soils of different texture (see also Wösten and van Genuchten, 1988).

The above brief summary shows that many predictive models can be formulated, with important differences between the models occurring in especially the quasi-empirical exponent $\ell$. These differences in $\ell$ appear to be caused mainly by the fact that different models were calibrated with different soils (usually a small number of soils). Thus, what is critically needed is a more comprehensive study involving the most promising predictive models, and using a soils data base which covers a very broad range of disturbed and undisturbed soils. The importance of model calibration in this context should not be underestimated. Pore-size distribution models give, by their very nature, an extremely simplified picture of actual soils, especially of undisturbed field soils. Soils simply do not consist of bundles of smooth, interacting or noninteracting parallel cylindrical pores, and hence any approximation with a pore-size distribution model must be suspect. The best one probably can do is to treat the oversimplified models in a pragmatic, semi-empirical manner by making sure that they at least accurately reflect the phenomenological properties of observed unsaturated hydraulic conductivity curves.

Application of the above pore-size distribution models requires independent estimates of the soil water retention curve. Measured input retention data for the predictive models can be given either as point values, or in terms of closed-form equations using parameters which are fitted to observed data. A recent inventory of analytical soil water retention functions is given by van Genuchten & Nielsen (1985). Unfortunately, only a few of the available retention functions can be easily incorporated into the above pore-size distribution models to yield relatively simple closed-form analytical expressions for the hydraulic conductivity. Notable exceptions are the BC and VG equations, and related models.

The use of analytical functions in general has a number of advantages. For example, they permit a more efficient comparison of the hydraulic properties of different soils and soil horizons. They are also more easily used in scaling procedures and, if shown to be physically correct over a wide range of water contents, provide a means for interpolation or extrapolation to parts of the retention curve for which little or no information is available. Analytical functions also allow for more efficient data handling in unsaturated flow models, especially for simulating water flow of multi-layered soils. Similar advantages of scaling and data handling are of course also important when setting up Geographical Information Systems involving the soil hydraulic properties.

Because of their simplicity and ease-of-use, predictive models for K(h) or K(θ) have become very popular in numerical studies of unsaturated flow. Results to date suggest that predictive models work reasonably well for most coarse- and many medium-textured soils, but that predictions for fine-textured and most structured soils remain suspect. In part because of inadequate calibration and validation with field-experimental data, we believe that the full potential of predictive methods has not yet been explored. Mainly because of the field-scale spatial variability problem, it appears nevertheless likely that predictive models, including those based on soil textural properties (to be discussed next), eventually will become the only viable means for characterizing the unsaturated hydraulic properties of large land areas, while direct measurement may prove to be economical only for site-specific problems.

## Estimating the hydraulic properties from soil texture and related data

Several attempts have been made in the past to statistically correlate the unsaturated soil hydraulic properties to soil texture and other soils data, including bulk density, organic matter content, and/or cation exchange capacity, clay minerology and soil structure. These studies include the work by Gupta & Larson (1979), Bloemen (1980), Brakensiek et al. (1981), De Jong (1982), Rawls et al. (1983), Williams et al. (1983), Rawls and Brakensiek (1985) and Puckett et al. (1985), among others. The resulting equations have been reasonably successful by giving approximate orders of magnitude of the hydraulic properties. Unfortunately, most studies have remained purely empirical by not taking advantage of past and recently developed pore-size and particle-size distribution theories. This again shows the need for a systematic and comprehensive study that integrates all available theoretical and experimental information about soil water retention data, the unsaturated hydraulic conductivity, particle-size distributions, organic matter, clay mineralogy, and soil structure.

Of considerable importance in this respect has been the study by Arya & Paris (1981) who presented a model for predicting the soil water retention curve from the particle-size distribution, the bulk density and the particle density. Their model first translates the particle-size distribution into an equivalent pore-size distribution model, which in turn is related to a distribution of water contents and associated pressure heads (the latter being inversely proportional to the pore radius). The Arya-Paris model was later modified by Haverkamp and Parlange (1986) to predict the soil water retention curve from soil textural and structural properties. Their study used the concept of shape similarity between the retention curve and the cumulative particle-size distribution. Theoretical results compared very well with measured data for 10 sandy soils. Unfortunately, the model was found to be less accurate for medium and fine-textured soils (Haverkamp, 1986; personal communication). Still, the importance of these studies is that continuous (cumulative) particle-size distributions are being used, rather than only three further undifferentiated particle-size classes (sand, silt, clay) typical of previous approaches.

Pertinent to the above approach are two recent studies which indicate additional promise in relating the cumulative particle-size distribution to the soil water retention curve. One of these is by Tyler & Wheatcraft (1988) who used the concepts of fractal mathematics and scaled similarities to show that the empirical constant α in the Arya-Paris model is equivalent to the fractal dimension of a tortuous fractal pore. The information was used successfully to predict soil water retention

data from measured particle-size distributions for 10 different coarse- and medium-textured soils. Finally, following a difference approach, Mishra et al. (1988) developed a statistical procedure based on the Arya-Paris model to estimate various hydraulic parameters and their uncertainty from measured particle-size distribution data.

## Required accuracy of the unsaturated hydraulic properties

Choice of a method for estimating the unsaturated hydraulic properties must depend upon the required accuracy of those properties. The required accuracy, in turn, should be commensurate with the type of application and/or the type of question being asked. As an example, Wösten et al. (1986) and Wösten and van Genuchten (1988) compared the accuracy of predicted and measured hydraulic functions in terms of three functional criteria thought to be typical of many other applications:

(1) the travel time, $T_r$, from the soil surface through the vadose zone to a water table at 1 m depth,
(2) the depth of the water table, $L_c$ which can sustain a certain upward flux of water to the soil surface or the bottom of the root zone, and
(3) the downward flux of water, $q_a$, corresponding to a minimum soil air content (taken to be 5%) needed to maintain adequate aeration for maximum root growth.

The predicted conductivity functions were obtained with the VG equations using parameter values which were correlated with soil texture and soil bulk density for a large number of surface and subsurface soil horizons in The Netherlands. Results for three different soils (Wösten & van Genuchten, 1988) showed that the predicted travel time $T_r$ had an accuracy of ± 1 month, which should be sufficient for most management problems on relatively detailed scales of about 1:10,000 or greater (Breeuwsma et al., 1986). Depth to the groundwater table, $L_c$, and downward flux density, $q_a$, also appeared accurate enough for most problems on detailed scales in the case of coarse-textured soils. However, the accuracy for medium and fine-textured soils only permitted answers on semi-detailed scales of 1:50,000 or smaller (van der Sluijs & de Gruijter, 1985). These observations are consistent with those of de Jong (1982) who concluded that water retention parameters of soil textural groups, as derived by the equations of Clapp and Hornberger (1978), were useful for simulating large areas of soils, but failed to closely approximate the soil water characteristics of specific sites.

Finally, we note that one purpose of the use of simulation models is to forecast future events, e.g., for predicting crop yields or estimating nutrient and pesticide loadings to groundwater. However, simulation models are also useful for comparing alternative management practices, the main objective then being to rank the performance of selected schemes relative to each other. Exact predictions in such cases are secondary to finding out which schemes or treatments produce the highest yields, or which are the most effective in limiting groundwater pollution. Accuracy of the unsaturated hydraulic properties for these types of applications is less of a concern than for applications requiring exact (absolute) predictions.

## Concluding remarks

This paper shows that a variety of direct and indirect methods are available for estimating the hydraulic properties of unsaturated soils. Direct measurement methods, including those based on recently developed parameter estimation procedures, are needed for most site-specific

problems. Indirect theoretical or statistical methods estimate the hydraulic properties from more easily measured soil properties, including soil water retention data, soil texture, bulk density, clay mineralogy, and/or soil structure. These extremely cost-effective indirect methods have proven to be useful for a number of applications, mostly for problems involving large areas of lands on semi-detailed scales of 1:50,000 or smaller. Their accuracy for site-specific applications on detailed scales of 1:10,000 or larger still needs improvement. Thus, a few innovate and comprehensive studies are needed to integrate all theoretical and experimental information relevant to the predicton of the unsaturated hydraulic properties from more easily measured soils data. A first and necessary ingredient for such a effort is the development of a large international data base of available soil water retention data, independently measured unsaturated hydraulic conductivity data, as well as soil texture and other data already available from soil surveys. A precursor for such a data base is given by the Dutch "Staring series" (Wösten et al. 1987). Additional initiatives in this area of work may well lead to large payoffs.

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# MODELLING IN THE LAND AND WATER DOMAIN WITH A VERSATILE GIS, ILWIS; EXPERIENCES FROM A LARGE TROPICAL CATCHMENT

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## Summary

Criteria for a versatile GIS are discussed in view of multifunctional tasks in the domain of watershed management and land use zoning. A main function of a GIS is to assist in preparing present-day and near-future scenarios for early warning and processing of remedial measures, based on biophysical criteria, socio-political considerations and cost effectiveness. A selection of application studies from South Sumatra are mentioned, related to modelling. They pertain to crop yield simulation using LECS to a comparison of prediction performance of a simple and a complex physical model (SWATR), and to erosion models.

## Introduction

The experiences will be discussed with developing and testing a GIS system for land use zoning and watershed management, termed ILWIS, Integrated Land and Watershed management Information System.

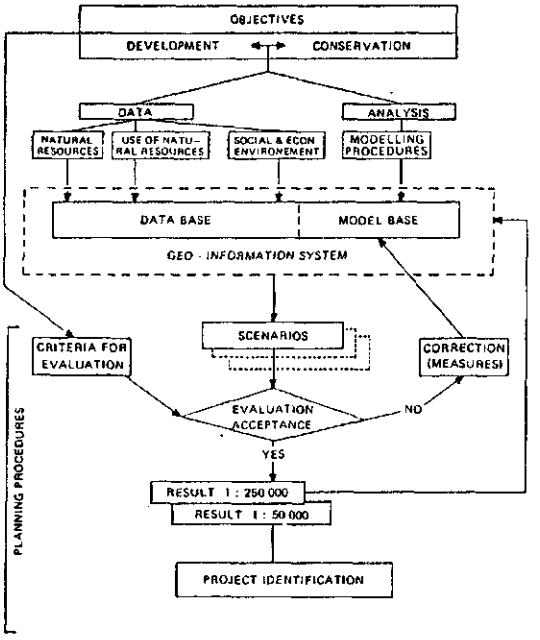
A leading principle for the design of the GIS was to enable interactions between biophysical simulations, notably crop production, on-site land degradation with corresponding off-site effects, and socio-economic considerations. The latter should on the one hand direct the choice of simulations in view of national policies, trends in population and agricultural production, and on the other hand input at detailed level, such as near-future erosion due to changes in farming systems.

The identification of the users' needs in Indonesia in the broad field of watershed management and agricultural development learned that indeed a multitude of tasks had to be performed. The first tasks were in the biophysical domain of monitoring land use, prediction of crop yield, estimation of erosion on slopes, sediment yields of subcatchments and the sediment transport in view of -then unknown- downstream problems. The reason for this priority is simple: no prescription without diagnosis.

It must be admitted that at the beginning of the project no clear concept could be formulated of the difficult interface between the socio-economical and biophysical domain. What emerged was anyhow the necessity to design a flexible system with transparent modules and easy exchange of data and results. It was decided to develop and test the rule base, with socio-economic criteria and transformation procedures, in an interactive, empirical way by working in the large test area of the Ogan Komering catchments in South Sumatra.

The structure to achieve the planning function may be visualized in Figure 1. Data base contents should be transformed with procedures and

Figure 1. Chart illustrating the planning function of ILWIS



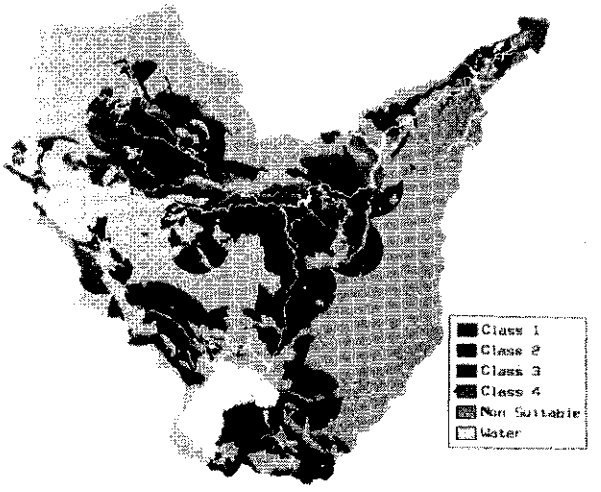




Figure 2. Example of a scenario; lands which are suitable, available and accessible for the dominant crop coffee (from colour screen).

models in the "rule base" to produce scenarios, for example of near-future erosion hazards or of other land degradations, coupled to expected land pressure. The scenario consisting of maps, tables or graphs may be judged and steps to reduce undesired developments can be iteratively evaluated with the GIS (V.d. Putte & De Meijere, 1987).

Such a scenario for the Upper Komering catchment is shown in Figure 2. It depicts the predicted near-future land use based on suitability for coffee -the dominant crop-, erosion hazard under coffee, availability of the land, accessibility and population pressure with present types of farming systems (De Meijere et al., 1988). In this text, the results in the biophysical domain will be discussed.

Specifications

With the above in mind, the following specifications are included:

1. The system should be capable of integrating vector data, raster data and table data. In this way, use can be made of the advantages inherent to each domain (Burrough, 1986): topology, geostatistical applications, digital terrain models, remote sensing processing, fast overlaying, communication with outside models.

2. Acceptance of mapping units and remote sensing data. Scarcity of data necessitates a methodology for acquisition and structured storage of data concerning terrain (geology, geomorphology, soil geography), cover (use type and cover type, divided into floristic composition, phenology and structure). This requires the integration of aerial photographic interpretations and remote sensing image processing and feature extraction in the system. For mapping units, aggregating natural associations (geomorphologically based terrain units, TMUs), an open-ended method for data storage in a relational data base is devised at three different levels of detail (Meijerink, 1988). The coupling to and structure of the soil data base are described by Valenzuela (1988). The method tries to compromise between what can be acquired rapidly (aerospace, field, existing data) and what input parameters are required for present and future simulations. The well-known problem of possible redundancy by systematic mapping and specific model input should be viewed in the perspective of conditional and relational "modelling" and of "what to do when a new model is adopted". The use of a relational data base has solved most of the problems so far in the applications, such as updating, estimation on non-direct input parameters by simple or complex transfer functions.

3. Outside models. The GIS should communicate with outside models in two ways:
- assist in preparation of data input, which may consist of spatial analysis first (see Bouma, 1988);
- preparation of spatial model results, for spatial combination with other maps.

4. Operators in GIS, interaction. Not all problems can be solved with existing simulation models. Hence, the system should be capable of translation of expert knowledge. This can be achieved by: (a) conditional operators and relational operators (see below), (b) these and other essential operators should address several data sources (spatial files) simultaneously and rapidly, to allow near real-time interaction. Of importance is

to realize that certain geographical entities, like a soil type, coupled to certain farming systems may mean more to an expert than the sum of selected attributes.

5. Operational efficiency, user friendliness. There will be a multitude of operations, which may be of different natures. In our experience, a complex system like a versatile GIS as ILWIS defeats its purpose if no care is taken to make modules and exchanges transparent, to hide cumbersome operations from the user, to have adequate utilities and make optimal use of colour.

## The system

With the above considerations, a system (ILWIS) was made and is still developed further. The writing of the software took place simultaneously with the development of transfer functions and model testing in the large Ogan-Komering catchments in South Sumatra to benefit from cross fertilization and have real world problems at hand.

Gorte et al. (1988) describes the integration of vector, table and raster base in the ILWIS software kernel. The system performance is discussed by Valenzuela (1988). Illustrations of both are provided elsewhere in these proceedings. Thematic map data, RS raster files and table data can be used as input. The programme TABCALC performs the communication tasks with the outside models and the data base(s) and with the large programme MAPCALC, where maps and attributes are processed.

There are conditional operators (If, Then, Else) relational (=, >, <, etc.), logical operators apart from the unary (Not) and the mathematical functions (+, -, /, *, sin, cos, atan, exp, log). A special feature is that all operators can be used simultaneously in a programming facility, addressing several maps (and thus also RS files). Operations may be done in the relational - attribute - data base or in the GIS software kernel, depending on convenience and nature of the problem.

The configuration of the system consist of a IBM-At level host computer, a 640x480, 8-bit graphics card (or larger) and input and output devices.

## Modelling

A structure which allows adoptation of virtually all types of models (geostatistical, empirical, distributed/finite element, stochastic, etc.) is shown in Figure 3.

In theory will always be better than opens offered on standard GIS

The outside models offer the state of the art approach. In practical work one is faced with the problem of selecting a model, which opens the following questions:

1. In what type of problems do complex models give improved accuracy, worthy of the increased effort of input parameters and calibration?

2. Since a GIS operates in the spatial domain, fully distributed models (cells, finite elements) seem an obvious choice. Are they available, practical and thrustworthy? Is it not advisable to select well-tested site models with or without routing functions?

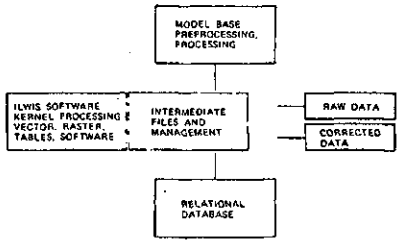



Figure 3. Structure showing coupling of main components of a comprehensive geo-information system.

3. Are there abstract parameters in the model, whose values can neither be measured in practice nor a-priori assessed. Even such a common parameter as infiltration should be regarded as a non-measurable input, because of its high spatial variability and temporal variability. Is it possible to obtain estimates of non-measurable parameters by transfer functions using parameters which can be acquired for use in a deterministic model? If not, probabilistic approaches, using density functions, should be selected. Of interest is to note that in our test area as in other tropical regions, there is no correlation between daily rainfall of stations as little as three km apart. This places a severe limitation on the selection of operational models.

Naef (1980) is one of the few compared results of simulations of hydrological models of different complexity, by measuring the mean difference between the observed and simulated outflows.

Considerable improvements were noted with the increase of complexity of very simple models, with the most significant difference occurring between the cases of no model and simplest possible model. If more sophisticated models were considered, the benefit from the rise in the degree of model complexity was small. In Figure 4 the hypothetical accuracy of results is given as a function of model complexity. Naef's findings would, for rainfall runoff models, be in support of the curve(d). The question is whether this holds also true for other domains, such as soil moisture, crop yields, or erosion. Our -limited- experience with comparison of soil moisture models suggest otherwise, but no generalisations can be made at this stage, as will be discussed below.

Nothing "the jungle of models in hydrological literature", ... "many of which increase the chaos in the jungle", Kundzewicz (1986) stresses the need for comparative analysis. In the Sumatra research, we have attempted to contribute -modestly- to this effort.

The modelling and incorporation in ILWIS in the Sumatra area, briefly discussed here comprise:
- testing and adjusting LECS (Land Evaluation Computerized System), Wood and Dent (FAO, 1983);
- a comparative study of results of a simple soil moisture model (Thornthwaite and Mather 1955) and a sophisticated model (SWATRE, Feddes et al. 1978). One of the objectives was to find an approach for application in

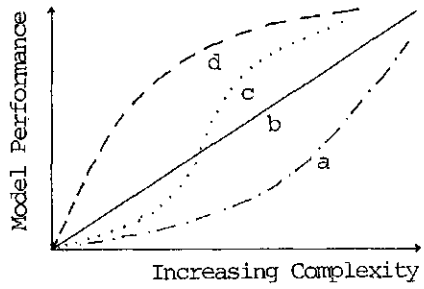



Figure 4. Hypothetical curves, relating complexity of simulation models (no. of parameters, equations, iterations) with model performance (difference between observed versus simulated results).

the spatial domain;
- a deterministic distributed (grid cells) erosion model (ANSWERS, Beasly et al. 1981);
- a stratified approach to erosion modelling, which includes the model of Morgan (1982) and an USLE based approach, made site specific for the Upper Komering catchment.

Land evaluation computerized system (LECS)

This method (op.cit.) was selected because of its low data requirement, its transparent adoption of the FAO method for land evaluation and because it was tried out in an area (Lampung), adjoining our test areas in South Sumatra. LECS makes use of the "law of the minimum". This law states that if one nutrient is deficient, the addition of other nutrients will not improve crop growth until that deficiency is improved. This applies both to land characteristics and to their aggregated form, the land qualities. Although LECS has components which need improvement, as mentioned by the original authors (Wood and Dent, 1983) and by Elbersen et al. (1988). The latter authors have obtained reasonable results with LECS in South Sumatra by changing the quality "nutrient availability", the amount of P in kg/ha for a plow layer of 20 cm by Bray's method (alkaline extraction) with a pH dependable liberation of P by organic compounds. They used the relationship in QUEFTS (Jansen et al. 1988), and an improvement in the predicted yields was noted. Actual yield estimates were carried out independently in several sample sites by UNSRI (Sriwijaya University, Palembang). Considerable improvements in predicted yields for several soils, with no inputs (LECS stage 1) were obtained particularly for cassava, groundnuts and wet rice. LECS found all of five soils unsuitable for maize; the P-corrected LECS left only 2 unsuitable, but predicted yields were generally too high (1.3 to 2.2 times, except one case with far too low yield).

In the area of study, according to Elbersen et al., the adjusted LECS is capable of producing realistic prediction of no-input crop yields (except for maize). Maps showing suitabilities for the important crops in the area have been prepared with ILWIS using the TMU data base, the WATER

data base and the P-adjusted LECS model. These products are input in scenarios of future erosion and conservation planning.

## Comparison of a simple and a sophisticated soil moisture model

One of the objectives of the study was to try out methods with which soil moisture changes in space and time could be captured in a GIS.

### Field observations

At five locations, soil moisture monitoring was done using gravimetric method. Samples were obtained by augering, at three depths (10, 30 and 90 cm) every three days. At each locality two or three sites were selected, close to each other and around a raingauge. One site at each locality was densily vegetated (forest) and the other site under cultivation. It must be remarked here that evaporation data could not be obtained directly at the sites, and estimates from stations several tens of kilometers away, had to be made. An adjustment was made for possible sunshine duration, using the Oldeman and Frere method (1982). Furthermore some moisture determinations are of doubtful quality because a kerosine oven had to be used. Prior to analysis of results, a data set was prepared for comparison with simulations. The field observation lasted for only 2 months (June-August 1987). The data of one locality could not be used because of the nature of the soil (hydrandepts).

### Simple method

The bookkeeping water balance method with the exponential dacay function for decrease of soil moisture as a function of accumulation water loss (Thornthwaite and Mather, 1955) was selected because of its simplicity and reported satisfactory use in some studies.

The time step of the model (T&M) was changed to 3 days. The means of the observed moisture content are compared with the means of those predicted by the T&M method, see Table 1. The observed and predicted values differ appreciably. Also, no satisfactory simulation of the time variations could be made. Adjustments by including loss by interception, overland flow and by using field capacity instead of saturation values, give some improvements, but not for all sites.

The average moisture contents at the three depths were considered. The means of the observed soil moisture content (every three days, for about two months) were compared with the corresponding T&M method predicted means. The results differ widely, as shown in Table 1. Careful examination of the graphs showing observed and predicted values over time indicated that the T&M method does not satisfactorily simulate time variations. Estimates of interception and overland flow could be included in the T&M method, and lower values for the water-holding capacity could be used (the T&M method uses saturation values). The overall difference between the means then becomes smaller, but in some cases, such as Batumarta XIII, the under-prediction will increase.

Table 1. Means of observed soil moisture and T&M results in percentage volume.

| Areas | Observed | T&M | Differences | |
|---|---|---|---|---|
| | | | Values | % Obs values |
| Pager Gunung | | | | |
| rubber | 40.5 | 42.5 | 2.0 | 4.9 |
| cultivated | 43.1 | 42.6 | 0.5 | 1.2 |
| forest | 45.6 | 52.5 | 6.9 | 15.1 |
| Batumarta XIII | | | | |
| cultivated | 44.0 | 37.5 | 6.5 | 14.8 |
| grass/cult | 41.0 | 37.5 | 3.5 | 8.5 |
| forest | 33.1 | 37.5 | 4.2 | 12.7 |
| Batumarta II | | | | |
| grass/alang | 36.4 | 45.1 | 8.7 | 23.9 |
| cultivated | 37.4 | 47.7 | 10.3 | 27.5 |
| Bl Umpu | | | | |
| shrub/grass | 22.6 | 30.2 | 7.6 | 33.6 |
| cultivated | 23.2 | 28.8 | 5.6 | 24.1 |

Complex physical model

Simulations of soil moisture profile and fluxes have been done by the E version of the SWATR model of Feddes et al. (1978) employing the following simplifications:
- values for fuction curves (pF) and hydraulic conductivity (K) of soil layers in the profile were estimated by using the functions of Cambell (1985), which require bulk density and grain size distribution parameters only;
- a sink term (water uptake by roots as a function of pressure head) recommended for grass was used for all sites.

In Table 2 the deviation of the mean of the predicted value from the mean of the observed value is expressed as percentage classes of the observed soil moisture content. As shown in Table 2, deviations were less than ± 5 percent in 15 cases out of the total 28. The larger deviations, of more than 5 percent (with a maximum of 10.4 percent), are about equally distributed.

The results were judged to be acceptable, considering the way the input values were determined. Particularly the ETO estimate and some of the field textural measurements should be improved.

Table 2. Number of observations which differ from the mean

| Depth | > -5% | > 5% | <¦5%¦ |
|---|---|---|---|
| 10 cm | 2 | 3 | 5 |
| 30 cm | 4 | 1 | 4 |
| 90 cm | 1 | 2 | 6 |
| All depths | 7 | 6 | 15 |

Model performance can also be expressed by two simple ways. A systematic, accumulated over- or underprediction was termed "divergence". This

happened only in 2 cases out of the total of 28. If the curve connecting the predicted soil moisture values intersected the curve of the observed values, this was noted as a "crossing". Table 3 shows that this did not occur often. The rather good results may be attributed to the fact that prediction of the course of soil moisture with time is less dependent on errors of input.

Table 3. Number of observations with crossing or divergence.

| Subject | 10 cm | 30 cm | 90 cm |
|---|---|---|---|
| Divergence | - | 1 | 1 |
| Crossing | 4 | 2 | 5 |

Note: 4 areas/10 sites/3 depths and ± 20 observations per site per depth.

The overall evaluation of the results led to the conclusion that the SWATR model seems to be suitable for studies concerning the spatial variability of soil moisture. For more information, we refer to Tepuk Iswadi (1987) and Meijerink et al. (1988).

Application of ANSWERS model

The model (op.cit.) was tried out for a small, hilly, volcanic catchment in Bali, for which good data sets of rainfall, runoff and sediment concentrations were available. Conditions are quite similar to some volcanic parts of the Upper Komering. Considerable effort was made to calibrate the model with observed hydrographs, without success. The reason is probably that most of the direct runoff response is caused by soil through flow (delayed flow, interflow) and only partly by overland flow. In only a few cases, the hydrograph shape allowed for an estimation of the overland flow response for several "normal" events. However, this calibration could not be used to predict more infrequent events, when most of the erosion occurs.

Our results should not be regarded as an evaluation of the ANSWERS model, but merely as an illustration of the difficulty of testing a model which describes only part of the runoff process. The complexity of modelling from hillslope runoff or small catchments is demonstrated by the work of Freeze (1980). The fact that there is unsufficient evidence to apply ANSWERS with confidence, made us look for another approach.

Erosion modelling, a stratified, assemblage approach

The preparation of erosion susceptibility maps (assuming bare, tilled, conditions) and erosion hazard maps (with crops or other vegetal cover) in such a large catchment as the Upper Komering (over 400 sq.km.), is in fact an impossible task if strict scientific criteria are adopted. However, the justification of the effort lies in the fact that (a) there are severe downstream problems, such as loss of hundreds of hectares of paddy land due to flooding, destruction of houses and roads, intake structures due to filling up and widening of the riverbed (Meijerink et al. 1988); (b) many soils are likely to give low yields when eroded and during the last 15 years, the undisturbed forest cover decreased from some 55% of the cathment area to some 15% only. Population increases are much more than the national -high- average because of influx of migrants. Hence

scenarios showing the present erosion hazard and the near future hazard are required to plan remedial measures. Furthermore, the instruments for remedial measures, such as reforestation programs, either by planting or regeneration of the forest (requiring unpopular measures), have proven their worth in parts of the catchment. Also, the Javanese migrants, who often occupy marginal lands, have started terracing. Such efforts deserve stimulation. Here, only the erosion modelling will be discussed.

Procedure

Essentially, stepwise decisions are applied to select the models and as is shown in Figure 5.

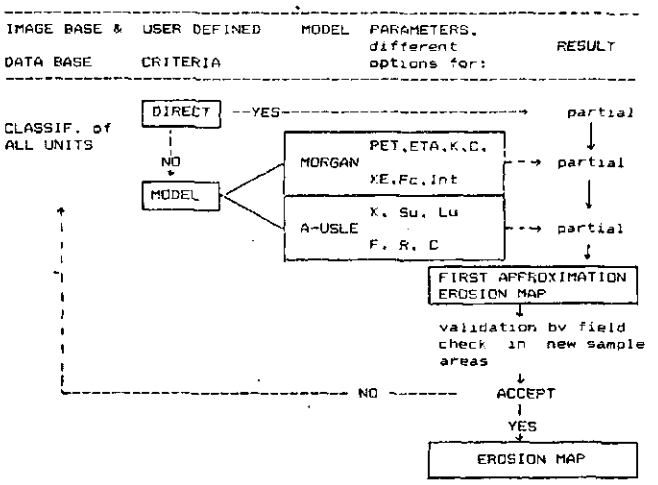



Figure 5. Scheme showing approach to erosion modelling for the Upper Komering watershed; segmentation, assemblage and iteration.

1. Direct classification

As in many areas, it is possible to apply certain decision rules with which units can be classified straight forwardly. This step forms the first stratification. In the Upper Komering with reasonable certainty it can be stated that no or insignificant erosion (< 0.8 t/ha) occurs, due to transport limitations for:

- Terrain Mapping Units (TMU data base), irrespective of cover:
  . non-dissected, flat units on Ranau Tuff, Fluvial terraces
  . young volcanic, Semingung units
  . recent Rhyolitic extrusions.
- Cover and Land Use Units, irrespective of soil, landform:
  . secundary forest less than 10 years old
  . terraced rice lands
  . rubber with dense undergrowth
  . non burnt grass (alang alang).
- TMU + CUMU + Altitude (overlay):
  . undisturbed rainforest with andosols above 800 m.

These criteria are based on "expert opinion" and can be processed partly in the relational data base and partly by the ILWIS kernel.

2. Model by Morgan et al.

For the remaining (80% of the area) units either the model described by Morgan et al. (1982), referred to as Morgan's model, is adopted or an adjusted Universal Soil Loss Equation (A-USLE) approach. Morgans model is selected in case the units have not been recently tilled and no rilling has been observed. In this way the cumbersome interactions between the soil erodibility factor of non-tilled soils and the vegetation factor (roots, litter, infiltration, etc.) are circumvented, because under such conditions, erosion is "transport limited". The model compares detachment rates with transport rates on an annual basis, and the least value is taken. The no-rilling criterion is used because in our experience Morgan's model underestimates erosion in such cases (data from rill volume measurements on fields). Parameters of Morgan's model are indicated in Table 4.

The overland flow estimate, as generated by the model is checked with a -as yet provisional- look-up table which contains hydrologic soil condition and hydrologic vegetation condition to estimate annual runoff coefficients. This table is based on data reported in literature of tropical areas. Model prediction should stay within the limits of the look-up table. If not, table values are assumed to be applicable.

In case the units (TMU) have incised drainage and straight or convex slopes, there is strong outflow of soil throughflow (exfiltration) at the lower part of the slope. In such cases the model prediction is increased arbitrarily by 20%.

3. Adjusted USLE

In all remaining units, an adjusted USLE method is adopted. The adjustments consist of:
- new site specific functions for slope steepness and slope length (see Table 5). These functions have been derived by regression analysis based on root exposure measurements on steep slopes with trees (rubber) or shrubs (coffee, tea) of uniform age (Komarsa, 1987). Slope steepness (S) and slope lengths (Sl), and those parts where erosion occurs (effective Se, Le) are derived from morphometric parameters Internal Relief (IR), drainage frequency (Df) and catena information, or is given as direct input;
- a method for estimating the cover (C) factor based on subfactors for canopy, groundcover, residual land use, reconsolidation (Kooiman, 1987);
- for those CUMU units with much upland cultivation, a normalized difference (b7-b5)/(b5+b7) MSS remote sensing image may be used to estimate the percentage of bare soil (Bs). An empirical transfer function is used to convert Bs in a C factor (see Kooiman, 1987);
- a lumped factor is used (F, form factor) to account for effects of slope form on deposition.

Empirical functions are used for the kinetic energy (Morgans model) and rainfall erosivity (A-USLE), because of a paucity of self recording rainfall stations. Iso-erodent maps are prepared to perform model calculations in the raster domain.

An overview in Table 4, column 2, is given of input parameters as derived from field (f) observations, topographic maps (m) or future digital

Table 4. List of input parameters and transfer functions for erosion modelling, Upper Komering, Sumatra (for abbreviation, see text).

| Terrain mapping units (TMU) image and attribute data | Data source | Symbol | Transfer function | (5) | (6) |
|---|---|---|---|---|---|
| TMU unit | | | | | D |
| Morphometry, direct input: | | | | | |
| Mean slope steepness | AP,f | Sm | or: f(IR,Dd) | n | M,U |
| Mean slope length | AP,f | Lm | or: f(Dd) or: f(Df) | n | U |
| Slope form | AP | Sf | | y | |
| Valley form | AP | Vf | | y | |
| Altitude | M | Alt | | y | |
| Internal relief | M,AP | IR | | y | |
| Drainage frequency | AP | Df | | y | |
| Drainage density | AP | Dd | | n | |
| Catena data: | | | | | |
| crest, slope valley | AP,f | c-s-v, cat | | n | |
| Input derived: | | | | | |
| Effective slope steepness | | Se | IR, Df, cat | n | M,U |
| Effective slope length | | Le | IR, Df, cat | n | |
| Slope form factor | | Fs | f(Sf), Vf) | y | |
| Drainage density | | Dd | f(Df) | n | |
| S factor USLE | | Su | f(TMU), f(Sm), f(Se) | n | U |
| L factor USLE | | Lu | f(TMU), f(Lm), f(Le) | n | U |
| Soil, direct input: | | | | | |
| Organic matter content | f | Om | | n | |
| Structure | f | Str | | y | |
| Texture | f | Txt | | y | |
| A-horizon | f | Ah | | y | |
| Soil type | f | So | | y | |
| K-factor field est. | f | Kf | | n | |
| Internal drainage | f | Di | | y | |
| Bulk density | f | Bd | | n | |
| Input derived: | | | | | |
| Soil erosivity-factor (nomogram) | | Kn | f(Om,Str,Txt), f(Ya) | n | M,U |
| Field capacity | | Fc | f(So) or: f(Txt) | n | M |
| Soil moisture holding capacity | | Sm | f(Txt) | n | M |
| **Cover land use mapping units (CUMU)** | | | | | |
| CUMU unit | | | | | D |
| Direct input: | | | | | |
| Cover type | f,AP | Ct | | y | |
| Structure type | f | Cs | | y | |
| Rooting depth | f | Dr | | n | |
| Canopy subfactor | f,AP | Cc | | y | |
| Groundwater & crop rotation subfactor | f | Cg | | y | |
| Residual land use subfactor | f | Ci | | y | |
| Reconsolidation subfactor | f | Cr | | n | |
| C-factor, field estimate | f | Cf | | n | |
| Input derived: | | | | | |
| C-factor | f | C | f(Cc,Cg,Ci,Cr) | n | M,U |
| C-factor (bare soil Cb) | RS | C | f(LAI) | n | M,U |
| Years after deforestation | RS | Ya | (see Kn parameter) | n | M,U |
| Water | | | | | |
| Direct input: | | | | | |
| Rain (time variable) | S | R | | y | U |
| Daily rain | S | Rd | | y | |
| Monthly rain | c | Rm | (Rd) | n | U |
| Annual rain | c | Ra | (Rm) | y | U,M |
| No. rainy days | c | Nr | | y | U,M |
| Max. daily rain | S | Rma | | n | U |
| Intensities | S | I | | y | M |
| Evaporation factors | | | (T,Hr,N,n,Ws) | n | M |
| Input derived: | | | | | |
| Pot. evapotranspiration | f | PET | T,Hr,N,Ws,Nr,R | n | M |
| Actual evapotranspiration | | ETA | Dr,Sm,R,PET | n | M |
| Erosivity | | Re | I,or:Ra or:Rm,Nr,Rma | n | U |
| Kinetic energy | f | Ke | I | n | M |
| Overland flow | | Of | model, f(Di,Str.Txt) | n | M |

Table 5. New slope functions for A-USLE method.

| Parent material | Functions: slope length | Functions: slope steepness |
|---|---|---|
| andesitic tuff | $E = (L/22.1)^{0.30}$ | $E = 4.268 \sin^{0.60} S \cos S$ |
| andes.strvolc. | $E = (L/22.1)^{0.31}$ | $E = 6.432 \sin^{0.77} S \cos S$ |
| Ranau tuff | $E = (L/22.1)^{0.30}$ | $E = 6.589 \sin^{0.75} S \cos S$ |
| basalt | $E = (L/22.1)^{0.30}$ | $E = 8.801 \sin^{0.90} S \cos S$ |
| Tert.sediment | $E = (L/22.1)^{0.70}$ | $E = 6.432 \sin^{0.77} S \cos S$ |

elevation models (Dem), aerial photographs (AP), MSS remote sensing (RS) and station data (s). Note that RS data is always applied with restriction. In fact masking operations turned out to be necessary for obtaining reliable data.

Input data for the erosion models, procedures and the parameters for the transfer functions are also listed (M is Morgan's model, U is adjusted USLE, D is direct classification, see column 6). The fifth column shows whether transfer functions are applied on a selective basis (n) or systematically to all units or to full map contents (y).

Persual of the list illustrates the "assemblage approach". Its practical application is made possible by the capabilities of the system described above. Work is in progress to expand the prediction with "morpho-erosion" (i.e. erosion by gullies, mass wasting, river networks) and sediment yield. After a second year of field validations, macros (command-series) will be proposed in order to allow modelling in similar regiona with less expert knowledge. By way of illustration, a second generation, tentative erosion map of the upper catchment is shown in Figure 6.

## Final remarks

- Time aspects: Research will be extended to relate spatial soil moisture maps using a physical model discussed above, with the outflow which is measured by the 'left alone' automatic recorders, installed in the field. Series of soil moisture maps will be made for varying but short time steps, by making use of the ILWIS kernel it will be attempted to establish relations with outflow parameters. A tank model will be used for converting TMU and CUMU data base contents into runoff, routed through the drainage network using the (probabilistic) concept of the Geomorphological Unit Hydrograph. We hope to learn from this to expand operational uses of the system.

- In building up the data base, we were caught in conventional patterns of thinking, by placing restrictions on the number of mapping units to some three hundred. Originally subdivided units, on the basis of aerial photo-interpretation, particularly morphometry, could have been entered in the image data base and the relational data base with ease. This would have saved time to later users of the data base.

- Attempts to use the system for comprehensive conservation planning suggests a two-stage approach:
1. analysis of trends using data of different domains in aggregated form, only partially geographically referenced;

A good db shd be considered a requirement, a model, db, accuracy + all level

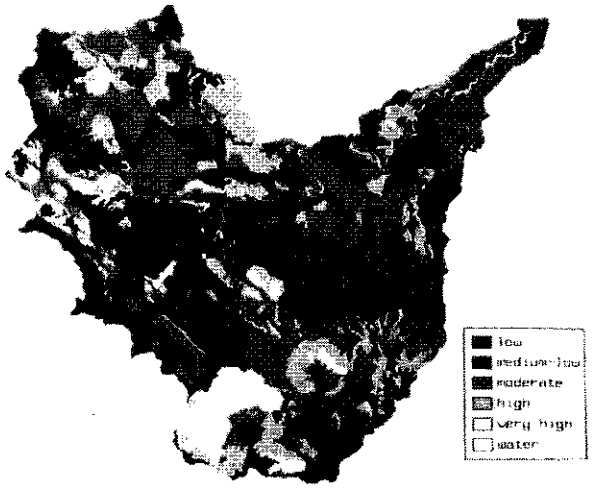



Figure 6. Map of the Upper Komering catchment, showing classes of erosion intensity (from colour screen).

2. operations whereby the results of (1) are translated in the spatial domain. The ILWIS facility of addressing several maps, in which pixel values can bepf entirely different value (input cost, erodibility, farmers attitude, suitability, etc.) and the variety of operators, opens hitherto unforeseen possibilities for interactive and thus iterative planning.

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# VARIABILITY IN SOIL DATA

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## Summary

When considering soil data, not only the detail but also the quality of the data is important. Identical soil samples analyzed in different laboratories, usually show different results due to within-laboratory variance and between-laboratory variance. Interlaboratory trials are used to check these variabilities. Results from the LABEX programme, an international interlaboratory trial, show that there is ample room for improvement on the quality of soil analysis.
Keywords: soil analysis, interlaboratory studies.

## Introduction

In his introductory paper Bouma mentioned the various levels of detail that can be used in land evaluation and land quality assessment. Each level requires the appropriate degree of detail in the needed data, ranging from rough estimates based on farmers experience to very detailed data needed for complicated dynamic simulation models. When judging data not only their detail, but also their quality is a feature that needs attention.

Until recently soil data were mainly stored in a descriptive form, as soil profile descriptions, e.g. according to the FAO Guidelines, supplemented with tables with analytical data.

The human mind cannot comprehend large masses of data and draw conclusions from them without making them accessible in one way or another. One way of making soil data accessible is the compilation of soil maps and derived 'special purpose' maps.

With the advent of electronic computers, and more in particular the relatively cheap personal computers, this has changed. We can now store, manipulate, retrieve etc. large masses of data and consequently data banks are emerging in all fields of science, including soil science. These data banks are useful for exchange of information and they allow statistical analyses in order to establish and to verify relationships between variables. They also provide the detailed information for the mentioned higher level data in land evaluation.

However, when trying to enter into databases the data, which until then were stored comfortably in drawers and files, the problems start: data sets are not complete, data are not comparable, units are different, methods of analysis are not the same, etc.

These difficulties are evident and clear. When transferring data from

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a written file into a computer system one encounters these problems and one is forced to find a solution.

Another aspect of the data however is the reliability. Very often the reliability of the data is not known, and once the data have been stored in a computerized databank they have an aura of credibility that can be very misleading.

Reliability is just one of the aspects of data quality.

## Data quality

Quality can be described very generally as: the degree to which prescribed specifications are met.

From this definition it follows that before judging quality, the specifications have to be established. The specifications should be in line with the intended use of the data. Quality is not a property by itself but should always be considered together with the use of the data and the criteria to be met.

Data quality depends on the analytical method employed to obtain the data, and on the performance of the actual analysis.

Quality aspects of an analytical method are amongst others the speed of analysis, the bias, the reproducibility and the repeatability.

In many cases there is a trade-off between the various quality aspects. For instance the speed with which the analytical results come available may have its price in the form of a lower accuracy. In the analysis of soil texture the hydrometer method is indicated when many samples are to be analyzed in a short time span. When more accurate data are needed, e.g. for special research purposes, the pipette method can be used but this method is more time consuming.

Very often quality requirements are only very vaguely described or even absent. Yet, we expect high quality work from the laboratory. Also it is important that when using 'old', existing data in new research one should be sure that the data quality is adequate, so that requirements imposed by this new research are met.

The mentioned quality aspects reproducibility and repeatability are defined as follows (ISO Handbook 3):

REPRODUCIBILITY, R, is the value below which the absolute difference between two single test results obtained with the same method on identical test material, under different conditions (different operators, different apparatus, different laboratories and/or different time), may be expected to lie with a specified probability; in the absence of other indications the probability is 95 %.

REPEATABILITY, r, is the value below which the absolute difference between two single test results obtained with the same method on identical test material, under the same conditions (same operators, same apparatus, same laboratories and a short interval of time), may be expected to lie with a specified probability; in the absence of other indications the probability is 95 %.

So repeatability refers to tests performed at short intervals in one laboratory by one operator using the same equipment, while reproducibility refers to tests performed in different laboratories, which implies different operators and different equipment.

These parameters can be checked by means of interlaboratory trials.

## Interlaboratory trials

When identical samples are analyzed in different laboratories generally different results are obtained. This variability in analytical data originates from various sources, as

(a) definition of the soil parameter
(b) the principle of the employed analytical method
(c) modifications of the analytical method
(d) skill of the technician
(e) errors in standard solutions/reagents
(f) tuning and calibration of instruments
(g) errors in the calculations
(h) random errors

The variability can be divided into two components: within-laboratory variability and between-laboratory variability. Each of the error sources mentioned may contribute to one or both of these components. Various techniques exist to check and control the within-laboratory variability (Bauer,1971; Kateman and Pijpers,1981; Massart et al.,1978). The application of these techniques can be realized by each laboratory independently. The between-laboratory variability can only be examined by cross-checking of results from different laboratories, in other words: interlaboratory trials.

An interlaboratory trial is a research effort in which a number of laboratories participate to serve a common goal. The objective of the research can be the evaluation of an analytical method, the evaluation of a test material, or the evaluation of laboratory performance. Each of these objectives can be subdivided as follows (Zwart, 1988):

I. Method evaluation
- a to establish repeatability, reproducibility and bias of the method to be studied (collaborative study)
- b to compare various methods and their results (comparative study)
- c to familiarize participants with new methods

II. Laboratory evaluation (proficiency study)
- a to compare the proficiency of laboratories in a given analytical method
- b to compare the proficiency of laboratories by comparing results obtained with their own method

III. Evaluation of test materials
- a to establish reference values of components or parameters of a reference material (certification study)
- b to establish characteristic values of components or parameters of a material for quality control purposes (consensus study)

Often various objectives are combined into one interlaboratory trial. This is also the case with the LABEX programme, an interlaboratory programme directed at soil laboratories.

## The LABEX programme

The Laboratory Methods and Data Exchange programme, conducted by ISRIC is an international interlaboratory programme to evaluate the proficiency of the participants.

The need for interlaboratory cross-checking was already recognized in 1935 by the International Society of Soil Science (ISSS). Since then various soil sample exchanges have been organized, mainly on a national or regional scale (Van Reeuwijk, 1984).

In 1978, the Second International Soil Correlation Meeting recommended that 'laboratory methods for soil characterization in various parts of the world be cross-checked, correlated and if possible standardized and that the then International Soil Museum (ISM), now International Soil Reference and Information Centre (ISRIC), assumes an active role in this matter'. To add reference to this recommendation ISRIC initiated its Laboratory Methods and Data Exchange Programme (LABEX). From 1980 to 1984 LABEX was run on an experimental scale, when 20 soil laboratories participated. A research grant from the Directorate-General for International Cooperation (DGIS) of the Dutch Government made expansion possible to a full scale project. During this phase the number of participating soil laboratories increased from 20 to over 90, from all over the world.

## Aims of LABEX

The aim of LABEX is a combination of the various goals for interlaboratory trials given above. Its objective is to reduce both the within- and the between-laboratory variability. In connection with this, it is understood that standardization of analytical methods is imperative. The International Standards Organization (ISO) has established a Technical Committee (TC 190) to standardize soil analytical methods. As standardization is a time consuming process, LABEX will establish a set of analytical procedures to be used in the programme. As ISO methods come available these will be used. By using standardized methods it is expected that eventually the between-laboratory variability will decrease. By providing soil samples as reference material LABEX makes the between-laboratory variability visible. Moreover, LABEX increases the awareness of the individual soil analyst of the need for quality control, which may result in the reduction of the within-laboratory variability.

## Operations in the period 1985-1987

During the phase 1985 - 1987 soil samples were mailed twice to the participants and the analytical data were collected three times. With the first set of samples, mailed in 1985, the participants were asked to do the analysis of: texture, pH, CEC, exchangeable bases, exchangeable acidity, base saturation and organic carbon. The analytical procedures were to be the participants' own 'best' methods. Details of these methods were collected with a questionnaire. The analytical results obtained then are referred to here as '85/1'.

After results had been received and reported, the participants were asked to repeat the analyses, but now using the analytical procedures that had been prescribed by the LABEX secretariat. The results thus obtained are here referred to as '85/2'.

With a second set of soil samples, sent in 1986, the LABEX analytical procedures were only slightly modified. This resulted in '86/1'.

The analytical results received were published shortly after each data collection round in LABEX Interim Reports (Pleijsier, 1985; 1986a; 1986b).

## The soil samples used

The soil samples used include salt-afected soils from Syria, Kenya and Hungary, acrisols from Malaysia, vertisols and nitosols from Kenya, ferralsols from Brazil, luvisols and fluvisols from the Netherlands, spodosols from Canada and the USA, and a mediterranean soil from France.

## Analytical methods

For 85/2 and 86/1 the LABEX methods were to be followed. These procedures are summarized as follows:
Texture:
The sample is pre-treated with $H_2O_2$ to oxidize organic matter and with Na-Acetate buffer to dissolve carbonates, if present. As dispersing agent Na-pyrophosphate is used.
The fraction > 50 $\mu$m is separated by wet sieving, the silt and clay fractions are determined by the pipette method .
pH:
The pH is measured in a 1/2.5 (mass/volume) suspension in $H_2O$ or KCl (1 M).
CEC and Exchangeable Bases:
The soil is extracted or percolated with ammonium acetate and the exchangeable bases are measured in the extract/percolate. The excess salt is washed out with ethanol and the adsorbed ammonium is exchanged by potassium. This ammonium is determined after distillation and titrated. This is a measure for the CEC.

For exchangeable acidity and organic C no procedures were distributed as these parameters were omitted from 85/2 and 86/1.

## Results

The analytical results were initially published in the LABEX Interim Reports (Pleijsier, 1985; 1986a; 1986b). In the following paragraphs a summary will be given of these data and the relationship between the MEDIAN and the ABSOLUTE DEVIATION from the MEDIAN.

For the parameters clay%, pH and CEC, special attention, is given to two samples that were entered as hidden replicates under different numbers in 85/2 and 86/1.

A matching of the analytical results from 85/1 with the outcome of the questionnaire survey of the analytical methods did not prove to be successful. Differences in methods did not significantly explain differences in results, as the residual variance was too high.

## The median (MED) and the median of absolute deviations (MAD)

For each soil parameter the data reported by the participating laboratories form a discrete distribution. To identify the location and scale of the distribution the median (MED) and the median of the absolute deviations (MAD) are calculated. The median is the 'half-way' value. This means that the number of laboratories reporting a lower value equals the number of labs reporting a higher value for that particular soil and soil characteristic.

This median is subtracted from all the values in the distribution and of these so-called residuals the absolute value is taken. The median of these absolute residuals is the 'median absolute deviation' or MAD.

MED and MAD are preferred here rather than 'mean' and 'standard deviation' because they are less sensitive to extreme outlying values.

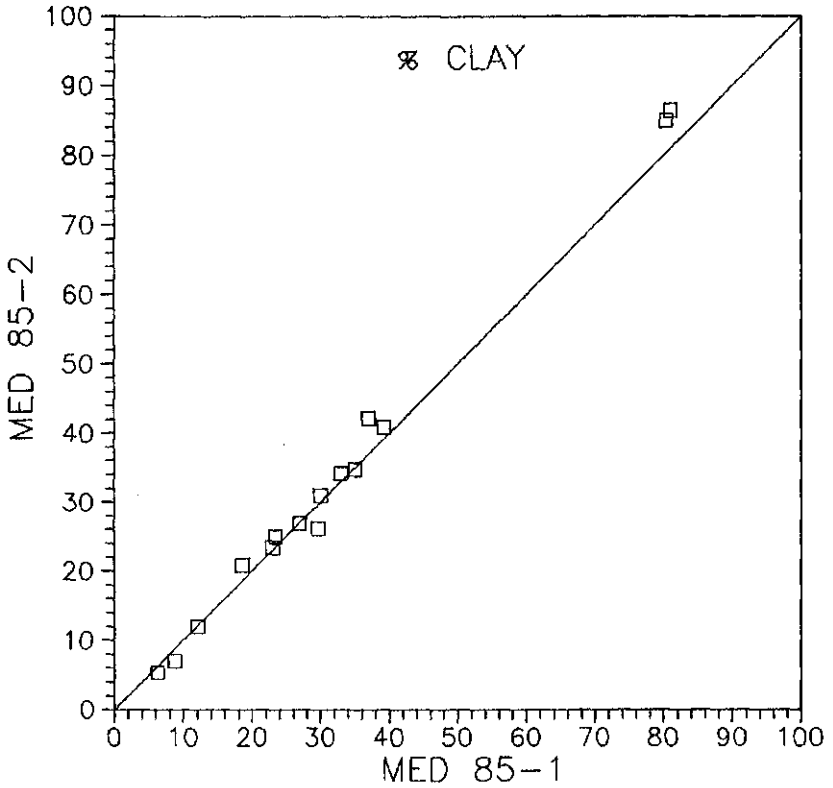


Figure 1. Plot of MED-85/1 with MED-85/2, Clay %

Comparisons of MEDs and MADs from 85/1 and 85/2

For 85/1 and 85/2 the same set of samples was used, the only difference being the analytical methods. So the question arises, what has been the effect of this change in analytical method?

In figure 1 the MED of the clay% of each sample in 85/1 is plotted against the MED of the same sample in 85/2. Also the diagonal is drawn.

As the plots for the 15 samples do not deviate much from the diagonal it can be concluded that the estimation of the Clay% from the whole set of data, is not much affected by the conversion from participants' own method to the LABEX method.

A plot of the MAD of 85/1 against MAD of 85/2 is given in figure 2. This figure shows a considerable spread. As most plots lie below the diagonal it can be concluded that generally in the Data-85/1 the MAD is larger than in the Data-85/2. This indicates that the change from participants' own method to LABEX method has reduced the spread in the clay

figures in the whole set of data. Apparently participants' own methods are so heterogeneous that the results produced are not very uniform.

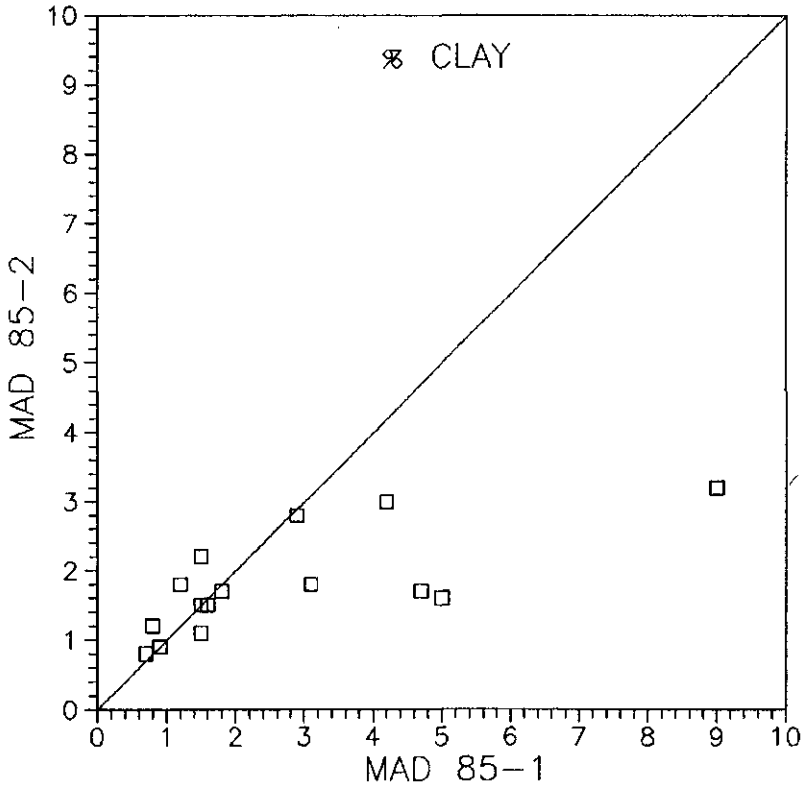


Figure 2. Plot of MAD-85/1 with MAD-85/2, Clay %

For the other soil parameters corresponding plots can be made. From these the conclusions are similar to that for clay. For the other parameters also the change of method has no effect on the estimate of the true value, but it has reduced the spread in the data. This reduction in spread may partly be attributed to the uniformity of the employed Labex method. It is however thinkable that it is also caused by the not-submitting of data in 85/2 by those participants who performed weakly in 85/1. By the omission of these 'weak' data the performance of the other data has increased relatively.

Relations between MED and MAD from 85/1 and 85/2

The relation between MAD and MED is also interesting. It shows how the 'spread' in the data varies with the value of the 'true value'.

In figure 3 MADs of 85/1 and 85/2 are plotted against the corresponding MEDs, for Clay %.

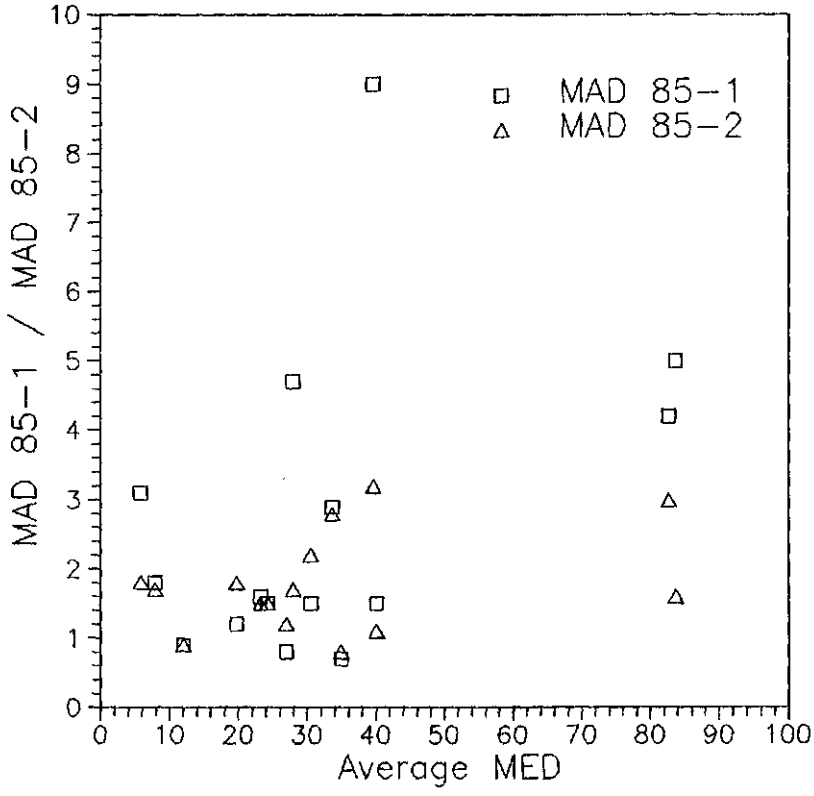


Figure 3. Plot of MAD with MED, 85/1 and 85/2, Clay %

The general trend in this figure is that with increasing MED the MAD also increases. This means that, as the 'true value' increases, the spread in the data also expands, at least in absolute terms.

Another general observation is that the 85/2-plots are below the 85/1-plots. This indicates that in 85/2 the spread is less than in 85/1, which had become clear already in the previous paragraph.

For the other soil parameters corresponding plots can be made. From these the conclusions are similar to that for clay.

The scatter of the points in the figure prohibits the accurate description of the functional relationships.

To get an approximate 95% 'confidence interval' around the MED, the MAD values have to be multiplied by a factor, which depends on the number of observations on which the calculations are based (Van Montfort, Math. Dept. Agric. Univ. Wageningen, pers. comm.). Calculations on the LABEX data result in the intervals as given in table 1.

Table 1. Estimated confidence intervals.

| | level | interval different methods | interval same methods |
|---|---|---|---|
| Clay | 10 % | 4 % - 16 % | 4 % - 16 % |
| | 80 % | 58 % -100 % | 70 % - 90 % |
| CEC(meq/100g) | 10 | 4 - 16 | 5 - 15 |
| | 70 | 40 - 100 | 55 - 85 |
| pH-$H_2O$(pH-unit) | 5 | 4.4 - 5.6 | 4.7 - 5.3 |
| | 9.5 | 8.9 - 10.1 | 9.2 - 9.8 |
| pH-KCl | 4.5 | 4.2 - 4.8 | 4.2 - 4.8 |
| | 8.5 | 7.9 - 9.1 | 8.1 - 8.9 |

These intervals indicate the 'resolution' of the analysis. This resolution is apparently low. But it should be kept in mind that calculations are based on analyses made in different laboratories, and therefore they are related to the reproducibility. However the above calculations are only approximations.

Replicated samples

Two samples in 86/1 were identical to two samples in 85/1 and 85/2. In this way hidden replicates were introduced.

Estimates of the reproducibility and repeatability can be made more accurately with the replicated samples.

The terminology and the calculations are based on the ISO standard ISO-5725, as given in the ISO Standards Handbook 3.

The reproducibility and repeatability are calculated from Data-85/2 and Data-86/1. The test material was identical and replicates were made in the same laboratory. However, the time interval between the replicates is quite long, so operators or equipment might not be the same. This implies that the definition of repeatability is stretched somewhat and that the 'true repeatability' is better (has lower value) than the values calculated below.

The results are summarized in table 2.

These data are not in complete agreement with Table 1, but it should be kept in mind that Table 2 has been based on data from 2 replicates only.

## Discussion and conclusions

The data reported by the Labex participants for the soil characteristics considered, show a large spread. Interpretation of calculated parameters such as Median, Median of Absolute Deviations, Reproducibility and Repeatability should therefore be done very cautiously. Still, the figures obtained thusfar show a low level of accuracy and precision.

LABEX started as a laboratory proficiency study to compare results obtained with participants own methods. As results showed a large variability, standardization of analytical methods was considered necessary.

Table 2. Reproducibility and Repeatability, estimated from two replicated samples.

| | level | Reproducibility(R) | repeatability(r) |
|---|---|---|---|
| Clay | 35 % | 9 % | 8.5 % |
| | 85 % | 20 % | 17 % |
| CEC(meq/100g) | 3 | 3.5 | 3.3 |
| | 80 | 27 | 22 |
| pH-$H_2O$(pH-unit) | 5 | 0.7 | 0.7 |
| | 9 | 0.7 | 0.6 |
| pH-KCl | 4 | 0.6 | 0.4 |
| | 7 | 0.75 | 0.7 |

Methods were prescribed in anticipation of ISO standards. Familiarization with these methods is necessary. Because of this combination of the effects of a proficiency study and a method evaluation, the values obtained for reproducibility and repeatability can not be interpreted solely as being the properties of the used analytical method. When in future the methods are established, and made familiar to the participants, LABEX can restrict its objective to be a proficiency study for soil laboratories.

Still, even if soil laboratory performance is increased, the soil scientist who submits his soil samples to a soil laboratory, should be aware of the levels of accuracy and precision, that are acceptable for him. Acceptability may vary according to the purpose of the analysis and the use of the data. In many cases the level of required accuracy has not been established. Ideally this level should meet both the demands from the user and the possibilities and skills from the producer of the data.

May the LABEX programme contribute to a better understanding, so that a researcher should know what he can expect from a soil laboratory, and the soil analyst knows what is expected from him.

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# ON THE CHARACTERIZATION OF BELGIAN SOILS

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## Summary

An information system for the characterization of Belgian soil series is described. It is a front end application based on a statistical summary of soil profile data and on pedotransfer functions. It provides information on the characteristics of soil series such as textural composition, organic carbon, calcium carbonate and hydrated ferri oxyde-content, Cation Exchange Capacity (CEC), soil water retention and hydraulic conductivity. Necessary input for the system are the soil series and some regional information. A two stage characterization approach has been adopted. Soil series are primarily described as sequences of morphological horizons which are subsequently characterized according to their properties.
Keywords: information system, soil database, soil profile.

## Introduction

A detailed soil map at a scale of 1/20.000 is published for almost the whole Belgian territory. It is based on a systematic soil survey with an augering density of one to two per hectare. Concurrently with the soil survey, thousands of profile pits were made, described, sampled and analysed. Morphological horizons were examined on texture, organic matter content and a number of chemical properties. Physiographic information was recorded for the different sampling locations. Most of the analytical data were mecanographically coded on Hollerith punch cards at the end of the sixties. Recently these and additional soil profile data have been integrated in a database which contains information on 8,962 profiles or 48,311 horizons. Fifty three variables are stored for the different horizons (Van Orshoven et al., 1988).

Soil series are mostly characterized by means of 'reference' or 'typical' profiles. Class limits are often seen as an indicator of variability. Foregoing characterization approach of soil series does not reveal a quantitative picture of the central behaviour and dispersion of soil properties. Therefore, an alternative characterization approach, based on the statistical analyses of multiple observed soil series, is presented for Belgian conditions.

## Soil horizon sequences

Vertical variation in characteristics is an important feature of most soil series. The Belgian soil survey project followed the 'classical' pedological approach by distinguishing different morphological horizons. To remain in line the same discretization of the soil profile has been used in the information system.

In many cases different horizon sequences have been described for a

given soil series. For every horizon of a sequence depth of occurrence and thickness are computed. Differences in horizon sequences are explained by (i) actual differences in the occurrence of non-diagnostic horizons, (ii) effects of erosion and management practices and (iii) judgement differences between soil surveyors. As a consequence the characterization of series according to horizon sequences should be done in a probabilistic way. An illustration is given in Table 1 where 17 different sequences are observed for a well drained Luvisol in the 'Haspengouw' region of eastern Belgium.

Table 1. Observed horizon sequences (extended national Belgian legend (Van Orshoven et al., 1988)) and their frequency for the Abal soil series in the loamy region of 'Haspengouw' (72 profiles described)

| Number | Sequence | Number of Observations | Number | Sequence | Number of Observations |
|---|---|---|---|---|---|
| 1 | Al AB Bt BC | 1 | 10 | Ap Bt BC Ca | 1 |
| 2 | Al Bt BC D | 1 | 11 | Ap Bt BC Q D | 1 |
| 3 | Ap A2 Bt BC | 1 | 12 | Ap Bt C | 6 |
| 4 | Ap A2 Bt BC C Ca | 1 | 13 | Ap Bt C Ca | 1 |
| 5 | Ap AB Bt BC | 4 | 14 | Apc Cc Bt BC | 2 |
| 6 | Ap AB Bt BC C | 2 | 15 | Apc Cc Bt BC BCa C | 1 |
| 7 | Ap Bt BC | 12 | 16 | Apc Cc Bt BC C | 1 |
| 8 | Ap Bt BC C | 31 | 17 | Apc Cc Bt C | 1 |
| 9 | Ap Bt BC C Ca | 5 | | | |

When the information system is used for the characterization of soil series, the most frequent occuring horizon sequence is activated by default. If however extra information is available, with evidence for a specific sequence, other sequences can be selected by the user.

Soil horizon characteristics

Textural composition, organic carbon, calcium carbonate and hydrated ferri oxyde content are available in the basic database. Mean value, standard deviation and the non parametric 10 and 90 percentiles were computed for different horizons. An example (Table 2) is given for the properties of the textural Bt horizon of the well drained Luvisol which was descibed for its horizon sequences in Table 1.

Table 2. Example of statistical information on some properties of the textural Bt horizon of the well drained Luvisol'(Abal map unit) of the 'Haspengouw' loamy region (based on 143 observations)

| | sand % | silt % | clay % | organic carbon % |
|---|---|---|---|---|
| mean | 4 | 72 | 24 | 0.3 |
| standard dev | 2 | 4 | 3 | 0.1 |
| 10 percentile | 2 | 67 | 21 | 0.1 |
| 90 percentile | 6 | 76 | 28 | 0.4 |

Attention is focused on the different number of observations as analyses on horizon sequence and horizon characteristics are concerned. The number of observations for calculating the statistics of the textural Bt horizon is 143 while 72 profiles are described. This is due to the occurrence of multiple horizons (Bt1, Bt2 or Bt3) which are pooled when calculating horizon properties. Further, the information system considers statistics of horizon properties the same for equally named horizons of different sequences of the series. As a consequence horizons are mostly characterized on a higher number of observations than the series are. This distinction between series and horizon characterization forms the core of the information system and is a logical consequence of the soil horizon considered as a basic carrier of information (Bouma, 1987).

Pooling of soil series

Each profile in the basic database is located in a soil zone. This regional concept has been taken over in the information system. Whenever possible soil series/horizons are characterized per soil zone. By doing so regional differences are taken into account. However, often not enough observations are available for the characterization per zone. In these cases observations are pooled by soil zone. This can be done at different levels according to the necessities and/or the regional information status as specified by the user. Together with this regional grouping soil series are pooled according to their similarity. Evaluation of this similarity is essentially done on the basis of soil surveyor's expertise.

It should be stressed that this procedure is a constant balancing between the number of observations for characterization, needed for prediction accuracy, and observation pooling, which causes possible inflation on characteristics' dispersion.

Pedotransfer functions

At the time of the soil survey attention was mainly focused on morphological, granulometrical and soil chemical properties. No data on mechanical and physical properties have been systematically measured. As described by Vereecken et al. (1988) several soil properties and parameters can be reasonably well related to basic information available in the database. Relations, called pedotransfer functions, for estimating the soil water retention, the hydraulic conductivity and the CEC have been implemented in the information system. These properties are estimated from data on textural composition and organic matter content, which need sometimes to be amended with additional information on bulk density and saturated conductivity.

Conclusions

The information system on Belgian soils enables the characterization of soil series according to several properties of the constituting horizons. Soil map information is used as basic input. A strict distinction between the characterization according to horizon sequences and horizon properties is made. The properties considered are textural composition, organic carbon, calcium carbonate, hydrated ferri oxydes, Cation Exchange Capacity (CEC), soil water retention and hydraulic

conductivity. Some of these properties are estimated from basic soil information using pedotransfer functions

The system enables (i) the statistical characterization with central values and measures of dispersion, (ii) the characterization of less frequent soil series, (iii) to account for regional differences when the soil series has been described more frequently. Due to the integration of pedotransfer functions, for estimating non systematically measured properties, a powerfull tool for soil series characterization and an essential basis for quantified land evaluation has been established.

The soil information system is implemented on personal computer in a dBASE III+ environment. It is modular of nature and intended to be extended for land evaluation purposes.

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# SISTAN: A SOIL INFORMATION SYSTEM FOR TANZANIA

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## Summary

This paper describes the main features of a computer system developed in Tanzania for the storage and retrieval of soil data. The system was developed on an IBM computer using the dBASE III PLUS data base management system. The system includes facilities for storage of soil survey information and its stratified retrieval as well as printouts of soil profile descriptions.

Key words: soil information system, data base, data storage, information retrieval, Tanzania, SISTAN.

## Introduction

In order to cope with the storage of an infinitely growing pile of soil survey data and at the same time facilitate fast retrieval of such information, a soil information system for Tanzania is being developed under the acronym SISTAN. The main objective of the system is to store field and laboratory data and make it available in raw or semi-processed form to end users while at the same time ensuring that the standards of field data collection are maintained according to the established national format. Moreover, in order to avoid turning the data bank into a museum, another objective is to provide answers to basic questions from the data base.

One of the main uses to which a land information system can be put is the production of thematic maps of the country at various scales permitted by the data base, e.g. rainfall pattern maps, growing season onset maps, etc and experimentation with existing models. The immediate future for SISTAN is the linkage to a soil-crop-climate water balance model which could be used for land evaluation studies in regular soil survey studies and in improving the agro-ecological zones map of Tanzania.

The present version of SISTAN (version 1.0) has modules for handling the full profile descriptions and the accompanying analytical data. The data base is stored in three files on the disk: the first file contains the environmental data at the soil profile site, the second file the soil morphological descriptions and the third contains the routine analytical data.

## The system tools

SISTAN was developed on the IBM XT/286 personal computer using dBASE III PLUS (Ashton-Tate Inc., 1985) as the supporting data base management system. In order to run SISTAN the MS-DOS operating system is required. Though it was developed with MS-DOS 3.20, SISTAN uses very few of the operating system commands and functions and it has been found to work with lower DOS versions as well (e.g. 2.11).

The principal storage medium for the system programs and all data is the integral hard disk. SISTAN is also adaptable to use on floppy

diskettes with a minimum formatted capacity of 360 Kbytes.

dBASE III PLUS requires at least 256 Kbytes user memory in the computer to function but SISTAN does not seem to work efficiently on IBM-compatible computers with this minimum of memory capacity; 512 Kbytes and higher give better results.

SISTAN runs faster on computers with a Math co-processor than on ones without.

## The system design

Apart from a vast range of commands and functions for file management and data manipulation, dBASE III PLUS offers a programming language. By making use of this facility SISTAN has been designed as an interactive menu arrangement which enables use of the system without the need for any knowledge of the commercial data base management system (dBASE III PLUS). A menu as used here may be defined as a list of options, any of which may be selected by following the directions as specified in the prompts which appear on the screen. The option is selected by striking a key or a sequence of keys on the keyboard. This in turn may bring up another menu or a specific question or instruction, etc. The term **interactive** is used to describe such a rapport between operator and computer system.

SISTAN's menus lead to three system modules namely:

a. data storage
b. data base editing
c. data retrieval

Figure 1 is a flow diagram summarising the structure of SISTAN.

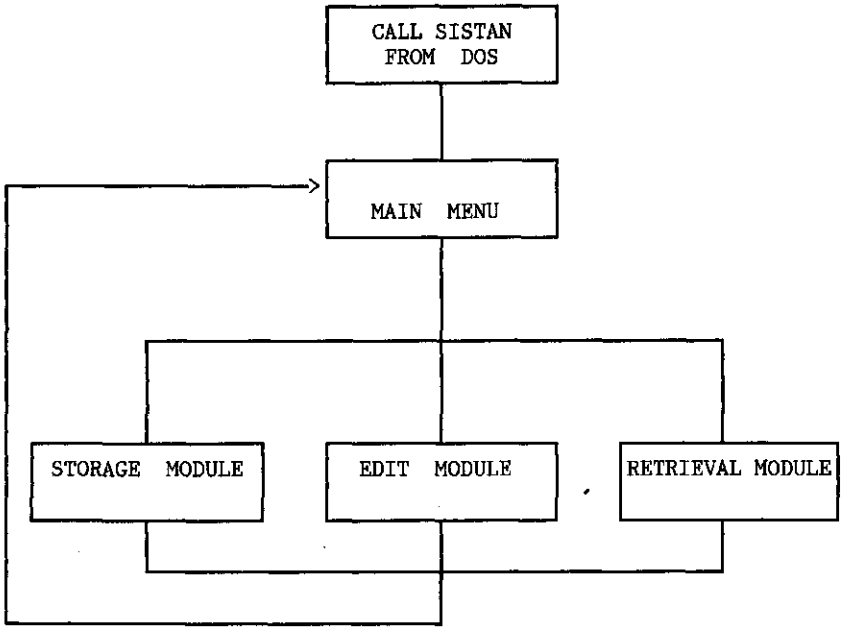


Fig. 1: Flow diagram of SISTAN's design structure

## The data storage module

The input screens in SISTAN are designed in such a way that they are similar to the Tanzania National Soil Service field forms. The positions at which entries are to be made are marked in reverse video. Control of the position for entry of each parameter is automatically effected at the end of each entry.

In principle the contents of each file are entered on one input screen but the form for the description of the profile environment is input on three screens. Apart from the edit option, SISTAN offers possibilities of forward and backward movements so that corrections in an input screen can easily be made.

Prior to storage in the information system, data need to be prepared in some way. All abbreviations and codes are checked against a conventional list and terminologies standardised according to a dictionary of terms. This helps to maintain uniformity and to ensure that all entries are those in convention. This is especially important since all translations and interpretations in the retrieval modules are based on the correct entry of symbols in the input screens.

In SISTAN the task of such data screening is simplified by avoiding the use of codes where the data are normally recorded as real numbers or in free text form. For other data variables, e.g. soil structure, soil color, etc which are normally recorded in coded form the same symbols are used in SISTAN's input and edit screens as are used on the National Soil Service field forms.

To improve the screening process, SISTAN has an in-built facility for automatically checking all the **coded** data. The results of these checks are reported on the screen and the erroneous entries rejected.

## The edit module

Being able to edit the data base is a desirable feature. Editing includes the addition of an entry, e.g. in the case where the first results of a laboratory analysis do not include all the determinations, as well as the actual correction of an entry already in the data base, e.g. re-classification of a soil profile.

SISTAN's menu for this feature leads through a process of specifying the record to be edited and results in the same input screens as used for the original entries. In addition, the original entries are displayed as well. The entries made in the edit mode are subject to the same checks as those made in the input mode.

## The retrieval module

The concept of information retrieval includes the acquisition of data from the bank in directly usable form as well as obtaining answers to simple questions concerning the contents of the data bases. These simple questions might be such ones as: "Are there any soils on map sheet 142/3 in the inventory?"; or, if one wanted to study soils with low CEC, "What soils have a CEC less than 16 meq/100 g?".

SISTAN's information retrieval module has a highly interactive menu for data selection. Selection of information is done on the basis of parameters stored in the same file. The definition of classes (which may be referred to as information stratification), e.g. pH between 5 and 6 and CEC < 16 meq/100 g of soil, is completed from this fully interactive menu showing a list of SISTAN's standard parameters which are available for class specification. The classes are defined by selecting one parameter

at a time. Where such a parameter contains numeric data the class is defined by entering a lower and upper limit; for alphanumeric data the required parameter code has to be specified (e.g. "sbk" for sub-angular blocky structure).

Non-standard selection for advanced users may also be made without the use of this interactive menu but by using the commands and functions of the data base management system.

SISTAN's results from the data selection menu are pre-processed prior to output. These preparations include decoding of abbreviations and the construction of substitute text or conversion to standard code for information interchange (e.g. ASCII). For example: a sub-angular blocky soil structure is recorded in the field and in SISTAN as "sbk". Prior to output this is decoded back to "sub-angular blocky".

The information output produced by SISTAN is routed to either the screen, a printer or into a file on disk. The present version of SISTAN includes features for production of hard copies of soil profile descriptions according to the format currently used in National Soil Service reports. The outputs written into a file are of two kinds. The first kind is basically an extract from the original data base file. Such files are useful because they reduce the size of the file to be handled and, by taking the selected data out of the main data bases, help to keep the original file intact and secure.

The second kind of files produced in SISTAN's output is an ASCII file. The data in such files are recorded free from the software codes of dBASE III PLUS and can thus be read by various other software systems including the operating system. (This statement must be taken within the limits of software and hardware compatibility). These files are of particular use for exporting data from the information system to other application software systems including word processors.

# LAND QUALITIES IN SPACE:COMPLEMENTARY USE OF SOIL MAPS AND TREND MODELLING FOR SPATIAL INTERPOLATION OF SOIL PROPERTIES BY KRIGING

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## Summary

Two approaches to removing or accounting for trends soil properties before spatial interpolating by kriging have been tried. The accuracy of predictions obtained after trend removal, in terms of residual sums of squares from observed values at selected target points were compared with predictions made by conventional soil survey output. The results of the comparison indicated that in most instances partitioning the trends by means of stratification of the data by soil mapping units was a simpler and slighthly more affective method, in terms of accuracy of predictions, than mathematical modelling of the trend by bicubic spline surfaces and kriging the residuals. The kriging estimates after trend partitioning by map units resulted also in most cases, in moderately better predictions than conventional soil survey outputs. The results also lead to suggest that trend modellingand soil maps may be used complementarily to deal with trends and to interpolate by kriging. These findings may be of pratical use to modern land evaluation procedures.
Keywords:bicubic spline, kriging, semi-variogram, stationarity, trend.

## Introduction

The matching of land qualities with alternative land-use requirements is fundamentalto land evaluation. Ideally, the assessment of soil/land potential should be made with ungeneralized data provided there are reliable means for interpolating the assessment into every point of interest within the area. Alternatively, soil point-data need to be interpolated first at every location of interest, then converted into land qualities and finally these are assessed by matching them with land use requirements (Beckett, 1984). Essentially, the problem is one of transforming "hard" soil/land point-data or their assessment into aereal data which is practically meaningful. Regionalized variable theory (Matheron, 1971) has as inportant role to play in providing tools, i.e the semi-variogram and kriging, for spatially interpolating the information needed for land evaluation. However, their application requires of stationarity assumptions being met by the variability of the soil property in turn. Fairly often in the field this does not occur due to the presence of strong trends or a changing drift. In order to interpolate by ordinary kriging then, the trend has to be accounted for or removed to comply with stationarity. Universal kriging is laborious and only profitable in exceptional circumstances of soil variability and sampling (Webster and Burgess, 1980).

## Procedures

Two precedures for removing trends in 4 soil properties, i.e. Total Carbonate, Exchangeable Potassium, Silt and Coarse Sand, and their effect on the accuracy of the kriging predictions obtained after trend removal are examined. On the one hand soil mapping units are used as a means to partition the trends. On the other hand, the trend is modelled mathema-

tically by bicubic spline surfaces. The trend was partitioned by grouping soil mapping units into calcareous and non-calcareous soils. Within -strata semi-variograms were calculated after trend partitioning. These showed structure and allowed interpolation by kriging at 16 selected target points. Trends in the data were also modelled by fitting bicubic spline surfaces to the variation of thé 4 properties. The presence of these trends was initially evidenced in the experimental semi-variograms. The residuals from the trends and their semi-variograms were computed. These semi-variograms were used to predict values of residuals from trend at the target points by kriging and later added to the surface at the same locations. This yielded the predicted values of the four soils properties from both de-trending approaches. Then these were compared with those from conventional soil survey output, i.e, class means, mapping unit means and the mapping unit typicalprofile at the same locations. These comparison was made in terms of the residual sums of squares of predictions (RSS) from the observations at the target points.

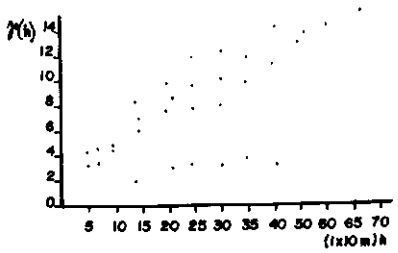
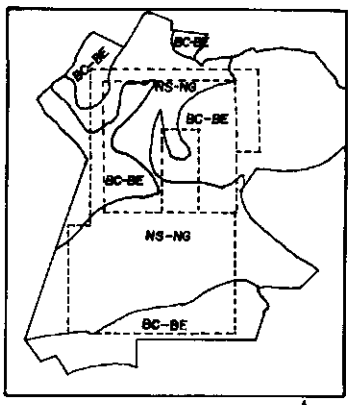


Fig- 1. CARBONATE. 50m GRID, YELFORD



---- SAMPLING GRID
—— MAPPING UNIT GROUPINGS
BC-BE Brown calcareous soils and brown earths
NS-NG Non-calcareous soils
Fig-2. MAPPING UNIT GROUPINGS.

## Results and Discussion

The strong anisotropy showed in figure 1 is caused by the trend in the same direction. The rest of the properties studied showed similar behaviour. Geology and local landscape explain the trends as their alignement coincides with the direction of the geological drift (Ponce-Hernandez, 1987).

The boundaries of strata resulting from grouping mapping units are shown in figure 2and the within-strata semi-variogram for Carbonate is shown in figure 3. Similarly to this property the rest of within-strata semi-variograms also showed spatial stucture and were also isotropic. This indicated that the stratification made sense to the effect of removing trends and their resulting anisotropic variations. On the other hand, the bicubic spine surfaces fitted to data represented well the trends. Figures 4a and 4b show the raw data Carbonate and its corresponding surface fit. The trend is quite evident. Except Potassium, all

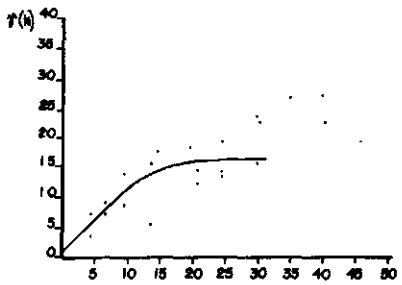



Fig-3 SEMI-VARIOGRAM of DATA IN MAP UNITS BC-BE, CARBONATE.

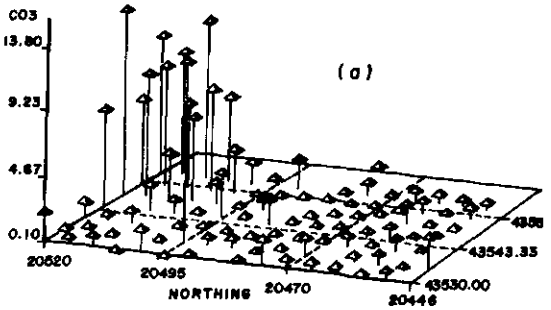



Fig-4. CARBONATE

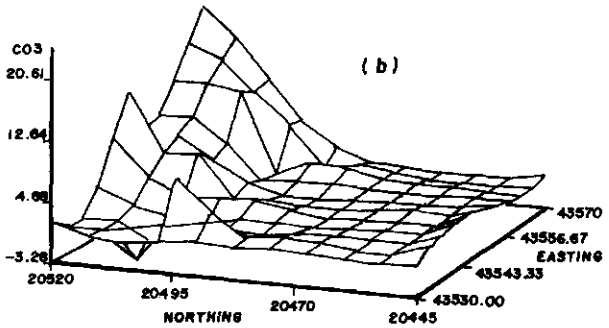



Fig-4. CARBONATE BICUBIC SPLINE SURFACE

semi-variograms of residuals from the trend did not show spatial structure. Their scatter of points indicated random variation. The best predictor in these cases was taken to be the mean values. The spherical model fitted to the experimental semi-variogram of residuals from trend of Potassium is showed in figure 5.

RSS of predictions from class means, map unit map unit means and map unit's typical profile were also calculated and compared with kriging estimates from both de-trending approaches. The results are summarized in table 1 and figure 6.

Table 1: Comparison of the success in predicting values of soil properties by kriging after de-trending the data by map units and modelling against conventional soil survey output. The predictive success is in terms of RSS.

| Soil Property | Predictive Tool | | | | |
|---|---|---|---|---|---|
| | class means (cm) | Map Unit means (mum) | Values from typical profile (typ) | Kriging Krg (mu)** | Kriging Krg (surf)* |
| Potassium | 1.08 | 0.84 | 2.12 | 1.30 | 0.75 |
| Carbonate | 101.50 | 114.16 | 167.88 | 87.24 | 449.25 |
| Silt | 344.0 | 370.19 | 828.00 | 191.73 | 265.69 |
| Coarse Sand | 239.19 | 396.87 | 1161.75 | 1520.66 | 2431.28 |

** (mu) kriging at target point after partitioning the trend with soil mapping units.

*(surf) kriging after modelling trends with bicubic spline surfaces.

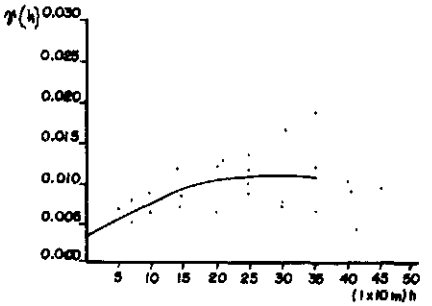



Fig-5. SEMI-VARIOGRAM of RESIDUALS from TREND, POTASSIUM.

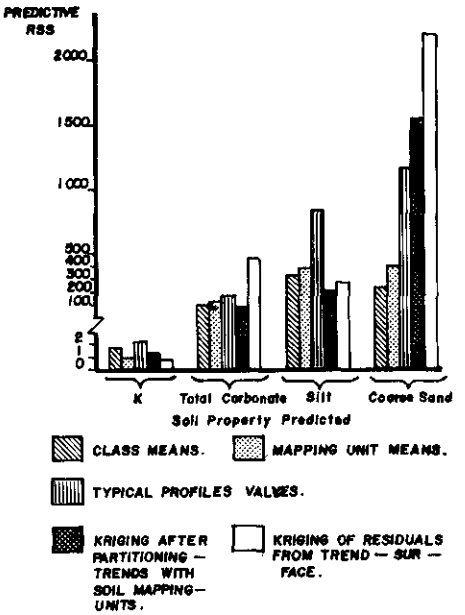



Fig-6. COMPARISON OF PREDICTIVE METHODS.

## Conclussions

Accounting for the trends to comply with stationarity assumptions allowed for spatial interpolation by kriging in situations where otherwise this would not have been possible. In that sense trend removal was a sucessful and useful practice. The results of the comparison indicated that, in terms of success of prediction by kriging, using a map to partition the area into strata was a better approach to account for the trend than modelling by fitting bicubic spineline surfaces. Except of coarse sand spatial interpolation by kriging after trend removal was a marginally better predictor of soil properties than conventional soil survey output. Using a map to partition the trends was a simpler and more reliable approach to account for them than modelling by trend surface fitting. However, both approaches can be used complementary when the resulting data after stratification are found insufficient for computationof reliable within-strata semi-variograms.

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# ALES: A MICROCOMPUTER PROGRAM TO ASSIST IN LAND EVALUATION

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## Summary

ALES is a computer program that allows land evaluators to build models that can be used to compute both physical and economic suitability of land map units, in accordance with the FAO Framework for Land Evaluation.
Keywords: land evaluation, microcomputers, expert systems.

## Introduction

The Automated Land Evaluation System, or ALES, is a computer program that allows land evaluators to build expert systems to evaluate land according to the Food and Agriculture Organization methodology (FAO 1976). It is intended for use in project or regional scale land evaluation.

Three classes of people interact with ALES. First, *model builders* construct and validate land evaluation models; second, *model users* enter land data and request that the program compute an evaluation; third, *end users*, such as land use planners, use the printed evaluation results. Results can also be used as data overlays in geographic information systems.

## The ALES program

ALES has five components: 1) a framework for a *knowledge base* describing proposed land uses, in both physical and economic terms; 2) a framework for a *database* describing the land areas being evaluated; 3) an *inference mechanism* to relate these two, thereby computing the physical and economic suitability of a set of map units for a set of proposed land uses; 4) an *explanation facility* that enables model builders to understand and fine-tune their models; 5) a *report generator*.

The program is highly interactive, and takes full advantage of the PC video display and keyboard. It is designed to be self-explanatory, with pop-up windows for menus, data entry forms, 'why?' explanations, and other dialogues, as well as context-sensitive help screens. Function keys control most operations. The program user can choose to interact with ALES in any human language to which the display text has been translated. Special attention has been given to the creation, editing, and display of decision trees (see below).

## The ALES knowledge base

Figure 1 shows an outline of the ALES knowledge base schema. Each evaluation model consists of a set of proposed land utilization types, a set of outputs, and a set of land characteristics.

Each land utilization type is specified in terms of its land use requirements and outputs. Each land use requirement within a land utilization type has a model-builder-specified number of severity levels

(i.e. levels of limitation of the corresponding land quality), and to each of these may be attached added costs of production. The model builder describes to ALES how to determine the severity of each limitation on the basis of land characteristics.

Land characteristics have a format defined by the model builder, thus allowing the use of any data in any form. Usually they are *discrete*, and have a user-defined number of classes, each with its own code and descriptive name. However, characteristics may be defined to have *continuous* values; these are then related to a commensurate discrete characteristic for further use in the knowledge base.

The model builder also constructs *data entry templates* which control how data can be entered by the model user or read from other data bases.

Figure 1: ALES knowledge base schema (simplified)

1 Evaluations
  2 Outputs
    - units of measurement, selling price
  2 Land Utilization Types
    - costs (annual & capital)
    - length of rotation
    - physical suitability decision tree (from LQ Severity Levels)
    3 Land Use Requirements (= Land Qualities)
      - severity level decision tree (from Land Characteristics)
      4 Severity Levels
        - additional costs (annual & capital)
    3 Outputs
      - number of crops per rotation
      - optimum yield
      - proportional yield decision tree (from LQ Severity Levels)
  2 Land Characteristics
    - number of classes, units of measurement, class limits

## Decision trees

Inferential knowledge is expressed by the model builder by means of *decision trees*, which are user-constructed hierarchical multiway keys. Inferential knowledge in ALES includes (1) how to determine severity levels of land qualities from land characteristics, (2) how to determine physical suitability and proportional yields of crops from severity levels of land qualities, and (3) how to infer values of land characteristics from other land characteristics. Figure 2 shows a simple severity level decision tree.

ALES decision trees can have an 'unknown' branch at any level in the hierarchy. This branch is followed if the datum being requested is not available for the map unit being evaluated. This allows the model builder to use alternative criteria in the case of incomplete data.

Decision trees are exponentially complex, i.e. the number of leaves is essentially the product of the number of classes of the entities used to build the tree. In practice, complete trees more than four levels deep are too time-consuming and confusing to build. Two techniques can be used in ALES to reduce the size of trees. First, early decisions can be made; this is facilitated by considering the most important criteria first when constructing trees. Second, related land characteristics can be grouped into intermediate trees, and the results of these trees can

then be used in (smaller) severity level trees.

Figure 2: A Decision Tree

This tree may be used to determine the severity level, on a scale of 1 to 4, of the land quality 'limitations for mechanization', for a land utilization type including intertilled crops.

```
slope class?
  - A or B (0-8%) -> stoniness class?
      - class 0 (<.01%) ............... --» 1 [no limitation]
      - class 1 (.01-.1%) ........... --» 2 [slight limitation]
      - class 2 (.1-3%) ........... --» 3 [moderate limitation]
      - class 3, 4, or 5 (>3%) ....... --» 4 [severe limitation]
  - C (8-15%) -> stoniness class?
      - class 0 (<.01%) ........... --» 2 [slight limitation]
      - class 1 (.01-.1%) ......... --» 3 [moderate limitation]
      - class 2, 3, 4, or 5 (>.1%) ... --» 4 [severe limitation]
  - D, E, F, or G (>15%) ........... --» 4 [severe limitation]
```

## The ALES database

The model user enters the list of map units to be evaluated. These can either be *homogeneous*, i.e. a single class value of each land characteristic expresses most of the variability in the map unit, or *compound*. In the latter case, the user specifies the map unit's homogeneous components and their proportions. Then the model user enters values for all land characteristics specified in data entry templates for each land unit in an evaluation area. Or, data can be input to ALES from relational tables in disk files.

## Computation and explanation

Once a model is built and land data is entered, the model user can request that ALES compute the physical and economic suitability of each map unit for each land utilization type. ALES computes these as in two stages, first the physical and then the economic. The computation proceeds by traversing decision trees, and querying the database for values of land characteristics as necessary. Economic suitability is determined on the basis of predicted gross margin, per hectare-year.

The results are displayed on the video screen as an *evaluation matrix*. While viewing this matrix, the ALES model user can request an explanation of any result. Explanations follow a backward chain, from the predicted returns and costs, to the severity levels of land qualities, and then to the values of land characteristics. Explanation screens show the actual paths traversed in decision trees. During the explanation, the model builder can adjust models, or the model user can correct land data, and then rerun the evaluation. This allows 'what if?' analyses and rapid comparison of alternatives.

## Reports

The results can be printed for the end user, sorted either by land utilization type (answering the question, 'Where is the best land for each land use?') or by land map unit (answering the question, 'What is

the best land use for each land area?').

The evaluation matrix may be written to a disk file in a format suitable for input into a relational database manager, for further processing, e.g. within a geographic information system.

## Spatial land qualities

ALES evaluates map units, not sites. Spatial land qualities can only be evaluated by assuming that all delineations of a map unit have the same spatial relation relevant to the land quality. For example, a land quality of 'accessibility' could only be handled by subdividing a landscape-based map unit on the basis of a diagnostic characteristic such as 'distance to roads', e.g. by map overlays.

## History and future developments

ALES version 1.0 (Rossiter et. al. 1988) was designed and written during 1987, released in January 1988; the current version 1.24 dates from June 1988. It may be purchased from the International Soils group, Department of Agronomy, Cornell University, Ithaca, NY 14853, USA.

Our main objective now is to develop useful ALES models, both as a proof of concept and as contributions to actual land evaluations. To this end, we want to cooperate with land evaluation teams and also conduct training courses at national institutions or international centers. We are soliciting cooperative projects to translate the program into Spanish, French, and other languages.

We also intend to start a clearing house for ALES models.

The program itself is being improved with a more sophisticated economic analysis, and will be integrated with other decision support tools for land evaluation, particularly with geographic information systems and economic optimization programs.

## System Requirements

ALES runs on the IBM PC microcomputer and successors such as the PC/AT and PS/2, and on 'PC-compatible' machines. It requires at least 384Kb of RAM and 1.65Mb of hard-disk space for the program, its support files, and a database sufficient for about five evaluations. ALES is written in the MUMPS programming language (Lewkowicz 1988), and requires the DataTree MUMPS language and database system (DataTree Inc., 1986), supplied with ALES.

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# FUTURE LAND USE MODELLING USING THE INTEGRATED LAND AND WATERSHED MANAGEMENT INFORMATION SYSTEMS (ILWIS)

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## Introduction

The need for improved methods for resource management and environmental hazard assessment is acute in many large watersheds in Asia. Thus, it would be useful to prepare a scenario of actual and estimated future erosion, taking into consideration the potential suitability of the land for a range of crops, the farming systems, the erosion susceptibility of the land, the availability of the land, and so on. The need for a versatile computerized system to handle such a vast amount of data has led to the development of an Integrated Land and Watershed Management Information System, termed ILWIS.

## The ILWIS system

The ILWIS system is based on an IBM-AT (or IBM-AT compatible) personal computer with a high-resolution monitor for colour display, a digitizer for data input and a colour plotter or printer for data output. A high-quality graphics board (MATROX) is used for efficient and fast manipulation of vector and raster data. Additionally a tape streamer can be connected for storage of large data sets or for retrieval of remote sensing data.

The overall structure of the ILWIS system, with the GIS functions of data gathering to data analysis and production of results, is shown in Figure 1. A connection is provided with models in the different scientific fields. These models are indicated on the right-hand side of the figure. This list is not exhaustive and should, in an ideal situation, represent the state of the art. Coupling to other systems is shown on the left-hand side of the figure. Although ILWIS has been designed primarily as a stand-alone system, it can also be used as a working station to a larger national GIS system.

An overview of the ILWIS software and data flows is shown in Figure 2. The communication between the three data bases (vector, raster and table) is indicated, as well as the connection between the relational data base (ORACLE, or others) and the models.

The coupling of the independently developed models and the relational data base with the graphics data base, through the table data base, is enabled by an interface called TABCALC. This interface allows flow of data in both directions and permits a choice by the user in models and data bases.

The program for manipulation of raster files (maps or images), called MCALC, takes a central place. Arithmetical (+, -, /, *), mathematical (sqrt, exp, log, sin, cos, atan), relational (>, >=, <, <=, =, <>), boolean (not, and, or, nor) and conditional (if ... then) operations can be

performed simultaneously on several maps or images.

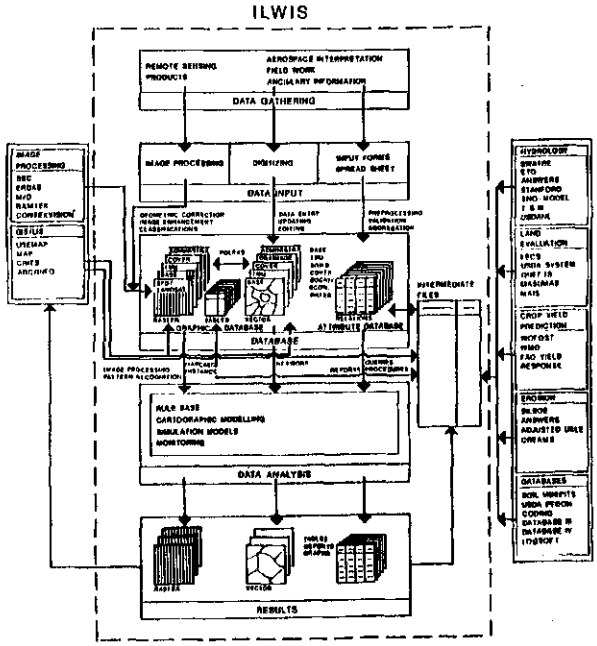


Figure 1. Schematic representation of ILWIS.

The remote sensing modules contain all the standard programmes for displaying, combining, enhancing, classifying and transforming remote sensing data.

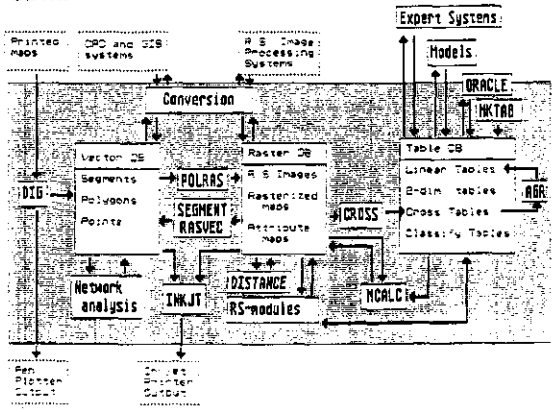


Figure 2. ILWIS software overview and data flow.

The land use model

An example is given on how the ILWIS system can be used for planning and resource management on a regional level. Social, economic and physical resource data are combined to project future development in land use. The land use model in the example deals with the expansion of coffee producing areas in the Upper Komering watershed, South Sumatra, Indonesia (over 4,000 km2).

In order to make a scenario of near-future developments the following procedure was adopted, assuming that no restrictive measures are taken.

1. Based on fieldwork, aerial photographs and satellite imagery, a map was made expressing the influence of the terrain and soil characteristics (soil erodibility, length and steepness of slope) on soil erosion.

2. A rainfall erosivity map was prepared. Used were station data, an empirical equation to estimate the erosivity of the rainfall, and an interpolation procedure considering orographic effects.

3. By combining the rainfall erosivity map with the map containing the factors soil erodibility and slope factors, a potential erosion map or erosion susceptibility map was prepared. This map indicates the erosion hazard when the protective vegetative cover is totally absent.

4. To evaluate the soil erosion hazard when the coffee plants provide the protective cover, a erosion hazard map was created using the erosion susceptibility map combined with a map containing the cover factor C for coffee (Figure 3).

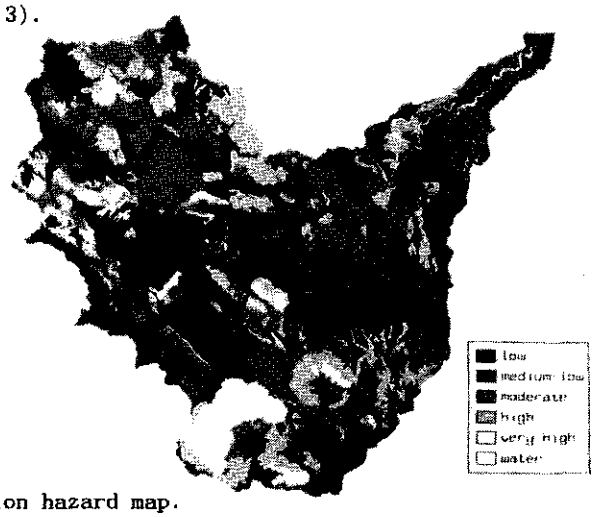


Figure 3. Erosion hazard map.

5. The ecologic suitability of the different terrain/soil units in the Upper Komering watershed for coffee was assessed by employing the Land Evaluation Computerized System (LECS). This model has been developed by the FAO (Wood & Dent, 1983), but is calibrated for the area under consideration (Elbersen et al., 1988).

6. The combination of the erosion hazard map and the ecologic suitability map leads to a land suitability map which indicates the areas where coffee may be grown.

7. Using fieldwork and aerial photo interpretation, a map was made which shows where land for agricultural development is still available.

8. As was shown in a socio-economic survey, the development of new coffee producing areas will only take place in areas which are within 5 km from roads or villages. Taking this into account, an accessibility map was prepared.

9. The products of steps 6, 7 and 8 are combined to produce a map indicating all the areas which are suitable, available and accessible (Fig. 4).

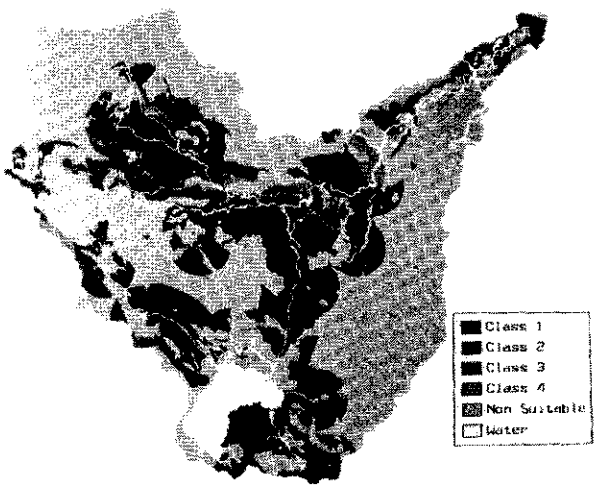


Figure 4. Suitable, available and accessible areas for coffee.

10. A forecast of the future land situation and an indication of the remaining available land in the year 2000 was made. The trend in population growth was assessed from statistics. When this is coupled to a dymanic farm model, the demand for coffee land in the near future can be expressed. The last map indicates all the suitable, available and accessible areas which will be utilized between 1986 and 2000.

The above example may indicate how a GIS like ILWIS can be used for land use planning. The projection of the future land use does not pretend to be fully realistic, but shows one of the capabilities of the ILWIS system in resource management.

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# DERIVING PEDOTRANSFER FUNCTIONS OF SOIL HYDRAULIC PROPERTIES

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## Summary

Pedotransfer functions (PTF) (Bouma, 1988) estimating the parameters of the simplified Van Genuchten equation. (Vereecken et al., 1988) for the moisture retention characteristic (MRC) and the parameters of the Gardner model (1958) for the hydraulic conductivity pressure head relation are presented. The derivation of these PTF is based on 40 Belgian soil profiles sampled per genetic horizon and analyzed for soil and hydraulic characteristics.

Information needed in the PTF are the granulometric composition, the carbon content, the bulk density and the saturated hydraulic conductivity. Depending upon the level of detail of the textural information, two sets of PTF are presented.

Keywords : Pedotransfer function, moisture retention characteristic, hydraulic conductivity.

## Introduction

In Land evaluation the need for quantitative soil information is growing constantly, particularly the demand for the soil's hydraulic properties. Quantification of simple and compound land qualities (Bouma, 1986) like pressure head or moisture availability requires information on the MRC and the unsaturated hydraulic conductivity. In most situations information is not readily available. Basic information sources, used in land evaluation, like soil maps do not contain this kind of properties. Functions relating this basic information with hydraulic properties are therefore needed.

Different methods are described in literature to estimate from basic soil data the MRC and the hydraulic conductivity (Vereecken et al. 1988a, 1988b). Two major methodologies can be distinguished. In the first approach points from the MRC and/or the hydraulic conductivity relation are estimated. Regression equations with soil characteristics as predictor variables are used. The second one parametrizes the measured data and estimates the parameters from basic data with statistical models (regression, ANOVA, ANCOVA).

The parametrization approach offers the largest perspectives, since it generates complete curves and facilitates mathematical operations. It allows easy comparison of the hydraulic properties between different soils. In this paper PTF are presented for the MRC and the hydraulic conductivity using the parametrization approach and regression analysis.

## Materials and methods

The MRC and the hydraulic conductivity were measured on 182 soil horizons of 40 soil profiles, representative for the Belgian territory north of the rivers Meuse and Samber. In addition the granulometric composition in nine fractions, the organic carbon content, the bulk

density and the saturated hydraulic conductivity ($K_{sat}$) were determined. The Geometrical Mean Particle Size (GMPS) and the Geometrical Standard Deviation (GDS) were calculated according to Shirazhi and Boersma (1984). Details on the measurement techniques are discussed by Vereecken et al. (1988a, 1988b). 182 MRC and 127 hydraulic conductivity curves were retained for the derivation of the PTF. The simplified Van Genuchten equation (1985) was used to parametrize the MRC :

$$S_e = [1 + (\alpha h)^n)]^{-1} \quad (1)$$
$$S_e = (\theta - \theta_r)/(\theta_s - \theta_r) \quad (2)$$

where $\theta$ is the soil moisture content ($m^3\ m^{-3}$), $\theta r$ the residual moisture content ($m^3\ m^{-3}$), $\theta s$ the saturated moisture content ($m^3\ m^{-3}$) and $\alpha$, n parameters describing the MRC shape.
The hydraulic conductivity was parametrized by the Gardner model (1958) :

$$K(h) = K_{sat}/[1 + (bh)^{n_1}] \quad (3)$$

where $K_{sat}$ is the saturated hydraulic conductivity (cm $day^{-1}$) and b, $n_1$ soil dependent parameters.

Performance of both equations in describing measured data was succesfully tested on a wide variety of soils (Vereecken et al. 1988a, 1988b). Parameters of both models were estimated using Marquardt's optimization algorithm which minimizes a least squares objective function (Van Genuchten, 1985). In case of the Gardner model, the values of the hydraulic conductivity were log transformed.

Regression techniques were used to develop relations between model parameters and soil characteristics. Two sets of PTF are discerned depending upon wether the granular composition is known in nine or three fractions. At the more detailed level the GMPS and GSD are included in order to account for distributional aspects. In order to avoid the problem of multicollinearity all textural information at the more detailed level is transformed in principal components.

## Results and discussion

Table 1 shows the PTF obtained from regression analysis. In order to estimate the MRC, information is needed on sand, silt and clay content, bulk density and organic carbon content. Prediction of $\theta_s$ can only be successful when the bulk density is known. Detailed information on the granulometric composition improves the estimates for the shape parameters of the MRC ($\alpha$ and n). Fig. 1 illustrates for a pedogenetic horizon the MRC estimated by the two information levels, in comparison to measured data and the fitted Van Genuchten model.
To estimate the hydraulic conductivity the measured $K_{sat}$ is needed. Textural information does not add to the explanation of the $K_{sat}$ model parameter but does for the b parameter. Silt and clay content are enough to estimate the $n_1$ parameter.

Further research is needed to examine the significance of the second level information in predicting hydraulic properties. Fig. 2 gives an idea of the performance of the PTF for the hydraulic conductivity.

## Conclusions

PTF estimating the hydraulic properties of the soil are valuable tools in quantified land evaluation. In this paper PTF are presented for the MRC and the hydraulic conductivity. These functions estimate the

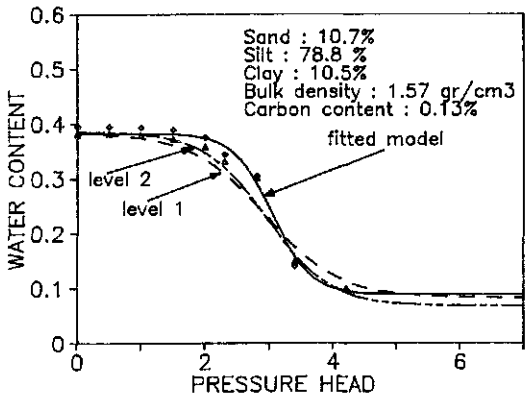


Fig. 1. Estimated and fitted MRC. The measured data are indicated with squares and triangles.

Table 1. Pedotransfer functions estimating the parameters of the Van Genuchten and the Gardner model. Two levels of soil information are distinguished. All predictor variables are significant at a 5% significance level.

level 1 Sand, (Sa), Silt (Si) and clay (Cl) content in %, organic carbon content (C%), bulk density (bd, gr $cm^{-3}$) and measured saturated hydraulic conductivity ($K_{satm}$, cm $day^{-1}$)

| | | |
|---|---|---|
| $\theta_R$ | = 0.015 + 0.005 Cl + 0.014 C% | $R^2adj$ = 70.3 |
| $\theta_s$ | = 0.810 + 0.283 bd + 0.001 Cl | $R^2adj$ = 84.8 |
| $\log(\alpha)$ | = -2.486 + 0.025 Sa - 0.351 C% - 2.617 bd -0.023 Cl | $R^2adj$ = 68.0 |
| $\log(n)$ | = 0.053 - 0.009 Sa - 0.013 Cl + 0.00015 $Sa^2$ | $R^2adj$ = 56.0 |
| $\log(K_{sat})$ | = -0.379 + 1.044 $\log(K_{satm})$ | $R^2adj$ = 92.7 |
| $\log(b)$ | = -2.640 - 0.019 Sa + 0.05 Cl + 0.506 $\log(K_{satm})$ | $R^2adj$ = 60.9 |
| $\log(n_1)$ | = 1.186 - 0.194 log (Cl) - 0.0489 log (Si) | $R^2adj$ = 55.3 |

level 2 textural information (nine fractions, GMPS, GSD) transformed in principal factors (F1-f11), organic carbon content (C%), bulk density (bd, gr $cm^{-3}$) and saturated hydraulic conductivity ($K_{satm}$, cm $day^{-1}$)

| | | |
|---|---|---|
| $\theta_r$ | = 0.068 + 0.333 f1 + 0.017 f3 - 0.015 f4 - 0.009 f8 + 0.015 C% | $R^2adj$ = 72.0 |
| $\theta_s$ | = 0.840 - 0.010 f1 + 0.004 f3 - 0.005 f4 - 0.288 bd | $R^2adj$ = 84.8 |
| $\log(\alpha)$ | = -1.538 - 0.994 f1 - 0.310 f6 - 0.147 f9 - 0.0092 f10 - 0.416 C% - 2.507 bd | $R^2adj$ = 78.3 |
| $\log(n)$ | = 0.10 - 0.323 f1 - 0.062 f6 + 0.066 f9 | $R^2adj$ = 60.0 |
| $\log(K_{sat})$ | = -0.379 + 1.044 $\log(K_{satm})$ | $R^2adj$ = 92.7 |
| $\log(b)$ | = -3.245 + 0.998 f1 + 0.188 f3 + 0.175 F7 - 0.207 F9 + 0.572 $\log(K_{sat})$ | $R^2adj$ = 68.6 |
| $\log(n_1)$ | = 1.186 - 0.194 log (Cl) - 0.0489 log (Si) | $R^2adj$ = 55.3 |

parameters of the simplified Van Genuchten and the Gardner model using continuous soil characteristics. Sand, silt and clay content, organic carbon content and bulk density are needed to estimate the MRC. More detailed information on the granulometric composition improves the estimate of the shape parameters. The saturated hydraulic conductivity is needed to estimate the hydraulic conductivity curve. Detailed textural information improves the estimate for the b parameter in the Gardner model but not for the $n_1$ parameter.

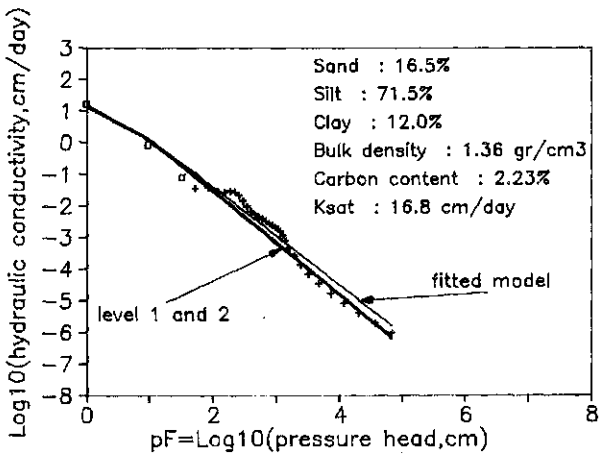


Fig. 2. Estimated and fitted hydraulic conductivity curves. Squares and crosses indicate the measured data.

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# BOTSWANA SOIL AND LAND EVALUATION DATA SYSTEM

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## Summary

This paper describes the establishment of a soil database and a computerized land evaluation system for Botswana, using micro computers and a relational database management system. General structure, user requirements and the implementation of the system are discussed.
Keywords: Soil database, computerized land evaluation system, coding system, micro computers.

## Introduction

The FAO/UNDP/Govt. of Botswana project "Soil Mapping and Advisory Services" started in 1981 to help improve the basis for médium and long term planning of agricultural and rural development in Botswana. Activities of this project include a systematic soil survey programme at reconnaisance scale and the development of a land evaluation system for arable farming for Botswana. At present soil maps at scale 1:250.000 are available for a considerable part of the country, and land suitability maps are produced for rainfed arable farming.
The main reasons for the establishment of a soil and land evaluation data system were:
(1) To acquire easy access to the large amount of field and analytical soil data for the construction of soil maps, land evaluation procedures and advisory services.
(2) To enable an effective production of land suitability data in useful formats for various purposes.

## General Structure of the System

The system comprises two subsystems that can be operated independently, a soil database (BSD) and a land evaluation system (LEDS).
The establishment of the soil database was the essential first step in the development of the system since the construction of soil maps and the subsequent land evaluations require the availability of a consistent set of field and analytical soil data.
On a planning level comprehensive information on the soil units is required. Therefore a second system (LEDS) was established. LEDS comprises a database containing land qualitity ratings for each soil unit and the procedures to determine and store the suitability classes of the soil units for different types of arable farming.
The design of BSD and LEDS was greatly influenced by the personnel situation. Since no permanent technically qualified staff is available to run and maintain the system, a user friendly interface had to be developed that can be operated by all staff, without the risk of destroying the databases or the software. In addition the system uses standard software (dBASE III) and hardware (IBM compatible micro

computers). Further it is important to realize that the Land Evaluation System for Arable Farming in Botswana is still in the proces of development. To allow for future modifications and additions the application programs have a modular structure. This structure in combination with extensive documentation and the use of a standard database management system makes it relatively easy to change or add modules and databases.

## The Botswana Soil Database (BSD)

BSD basically consists of a number of databases that contain site, profile and analytical information on the soils, and procedures to enter, edit and retrieve data. An extensive interactive selection facility allows for searches (on combinations) of almost all site, profile and analytical characteristics without forcing the user to approach the databases directly in dBASE. In this way the databases are protected against potential data loss due to inexpertly use.
Printouts of field information can be obtained in descriptive or tabular formats.
The data input comprises the encoding of data and the actual entering of these data in the computer. Both aspects are described below in more detail since they are key factors in the establishment of a useful database.

### Encoding of Data

Soil information is largely descriptive and consequently a good soil description annex coding system is a prerequisite. The main considerations in the construction of the so-called Botswana Guidelines for Soil Profile Description (Remmelzwaal & Van Waveren, 1988) were:
(1) The system had to be acceptable to all surveyors, i.e. it should enable the soil surveyor to make satisfactory soil profile descriptions and it should not complicate the work in the field.
(2) All existing soil profile descriptions would have to be incorporated in the database without a significant loss of information. This is a vital requirement, since the older profile descriptions form a significant part of the available soil information.
For these reasons a system was developed along the lines of the formerly used FAO Guidelines for Soil Profile Description (1977) and draft versions of the description system were extensively tested and discussed by all surveyors during a number of joint surveys.
These tests proved to be very useful and resulted in a comprehensive and efficient description system consisting of a description form (a single A4), a single plastic laminated sheet containing the coding system, and a separate report with the explanatory text, the Botswana Guidelines for Soil Profile Description.
In the field the soils are described immediately, into a coded format. This approach has the following advantages:
(1) The field data is entered directly from the sheets into the database, instead of being encoded later-on. This saves time and eliminates one potential source of writing errors.
(2) The surveyor is forced to follow the description system precisely and to make decisions in the field, rather then to use vague descriptive terms that in a later stage have to be fitted into the coding system. This eliminates the risk of interpreting the original information wrongly, especially when the transfer is not carried out by the surveyor personally.

## Entering of Data into the Computer

Input screens were designed with a layout similar to the description form. Entered codes are immediately checked on validity and the database does not accept the same profile number twice. These simple measures guarantee an effective and relatively error free input. However, since the database does not include a quality control, the results should always be checked afterwards by the surveyor.

## The Land Evaluation Data System (LEDS)

This system is based on 'A Land Evaluation System for Arable Farming of Botswana' (Rhebergen, 1988). LEDS generates land suitability classes for various land use types from the land quality ratings. The unit of evaluation is the soil unit. LEDS includes a number of databases, the main database contains the land quality ratings, secundary databases contain the suitability classes of the soil units for the various land use types. At present program modules are available for: (1) improved traditional dryland farming with the following main crops: maize, sorghum, millet, cowpea, groundnut, or dolichos lablab (fodder crop). (2) small scale irrigated farming with main crop maize.
The results are printed in a tabular format. The tables contain the land quality ratings, the suitability subclasses and the final suitability classes for the required land use types for each soil unit on a specific map sheet.
The land evaluation system is only partly computerized. The land quality ratings are determined manually by the land evaluator (in most cases the soil surveyor) and subsequently entered in the computer rather than to be derived directly from the soil database. This is done for the following reasons:
(1) For the rating of a number of land qualities, such as available soil moisture and drainability, comprehensive topographic information is required, which is at present only partly available in a digital format. Additional information is derived from surveyors records or from other sources, such as maps. Furthermore at reconnaissance scale the available soil site information may not be representative for the whole mapped area.
(2) To ensure the quality of the database. The manual step-by-step procedure allows the surveyor to compare the intermediate results with those of other soil units and with conditions as observed in the field. In this way unrealistic land quality ratings are more likely to be detected than when using a fully automated system in which basic data is directly processed into land suitability classes. This is especially important since the systematic land evaluation programme has only started recently, and reference information is still scarce.

## Present Status and Future Developments

The soil database is fully operational since one year. At present approximately 1000 profiles have been stored, of which a considerable part consists of older profile descriptions. The transfer of the old descriptions into the new format proved to be time consuming, but worthwhile since the information is simultaneously checked and updated.
It is to be expected that by the end of the year LEDS will contain

information at reconnaisance scale for a significant part of the country. The future developments will include the extension of the system for other major land use types, such as forestry and extensive grazing. The quantification of the relations between soil characteristics and land qualities, as well as the incorporation of topographic and climatic data will allow for further automation and integration of the systems.

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# Data use and simulation modelling

# CONSIDERATIONS ON THE USE OF IBSNAT MODELS TO PREDICT SOME LAND QUALITIES AND ITS EXTRAPOLATION

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## Summary

IBSNAT simulation models can predict several land qualities, totally or partially, in a realistic way, provided they are validated and their minimum data set is gathered. To be applied to a farm or to a new survey area, a grid sampling at distances derived from nested sampling for the appropiate input parameters, seems appropiate. For past surveys nested sampling within and between selected mapping delineations can be use to establish the adecuate level of prediction and valid management scenarios for the area.

## Introduction

Quantified Land Evaluation for specified systems of management is becoming the goal for Land Evaluation elsewhere (Beek,Borrough and MacCormack,1987). Land Qualities will have to be assessed quantitatively, and this could be done by: inexplicit ways like guessing, analogy or more explicit means like statistical or by simulation models. Each of those have a place and a time, advantages and disadvantages in Land Evaluation. Specially in developing countries of tropical and subtropical latitudes, the large variability in physical factors that affect the type of crops to be grown, and the large variety of farming systems, are demanding many "matching rules" to judge land qualities versus land utilization types. If we add to the above the insufficient and non-detailed knowledge of natural resources, and agricultural experimentation we can visualize the need to improve the number and quality of the predictions. Ideally the combination of a comprehensive model (physical,biological and socio-economic factors been considered) coupled with a data base of the resources variables, could provide the quantitative predictions for many specific alternatives with high efficiency. But these models are not complete in the factors involved, or have not bee extensively tested or the resource data bases are incomplete or too general to accomplish the ideal situation.

## Data required and outputs of IBSNAT models

IBSNAT (International Benchmark Soils Project for Agrotechnology Transfer) is an international effort to try to use simulation models to assess crop performance at any location. At present there are two operational models, CERES (Maize and Wheat) and SOYGRO (Soybean). These models have the capability to predict the performance of crop production system at any location and season depending on the provision of a specific minimum set of data on soils, crop, weather, and management (IBSNAT, 1985). The minimum data set for soils includes the following soil propierties as a function of depth: horizon thickness, upper and lower limits for water retention, water saturation, initial soil water contents, bulk density, pH, organic carbon, total nitrogen, initial contents of nitrates and ammonium. Other special features like root distribution in the profile and a coefficient expressing the drainage

rate are also included. The minimum set for weather includes the daily radiation, precipitation, maximum and minimum temperature. The crop minimum data requires specific coefficients for each cultivar related to its maturity types, photoperiod sensitivity, and yield components needed to evaluate optimum efficiencies within the constraints of weather and soil. The management data required, that one can set, is on sowing date, plant population, irrigation amount and dates, fertilizer amounts and dates, residue managment and plowing depth. Some models like SOYGRO, also include pest control factors.

Among the best technological elements that these models can analyze, at present, and for a given locality we have: the best adapted cultivar with respect to yields or to stability of yields for a long term; the best planting time and best population of plants as judged by average yields, risk analysis on long periods, and for crop combination in time; the most efficient rates and ways of application of nitrogen, also judged by yields and/or economic benefits; and finally the best irrigation strategies to use in that locality.

These outputs may serve to evaluate the best strategies of managment, or in other words some land qualities of the F.A.O. Framework for Land Evaluation (FAO,1976) like: radiation, temperature, moisture availability, partly nutrient availability and retention, rooting conditions and partly conditions affecting germination. Other factors like oxigen deficiency, P and K, salts, Al toxicity, risk of erosion, etc, are been studied to be incorporated into the models or to be handled through other means like Expert Systems.

## Pre-requisites to use simulation models

Before simulation models are used to predict land qualities, there are certain steps that have to be taken.

The first condition is that they are validated. Validation implies (Dent, 1986) that we have enough confidence in the predictions the models are doing. To obtain this a comparison between field results, experimental or not, and model predictions for the same site and period of time have to be made.

Some results from Venezuela (Comerma and Guenni, 1986,1987) show that in the validation we may find good fit for certain aspects of the model and not so good for others. Such is the case of CERES-maize with good correspondence in phenological events in all sites where tested; with water balance, although not when comparing with soil layers, but for the whole profile, and a poor relation with nitrogen balance was found (Delgado,1988).

In general we can not expect that simulation models will provide an exact fit for all circumstances and environments. Generally, model components have been built only considering certain ranges of environments, and the minimum data set never can cover all aspects of the environment or crop that may affect the results.

To improve the above situation, a process of calibration or fine tuning will be necessary before applying the model. The objective will be to minimize discrepancies between the model output and real system performance (Dent,1986). The most sensible parameters of each model will be varied within certain bounds until the discrepancy criteria are reduced to a minium.

Finaly, and after the validation of the model, is the process of sensitivity analysis. In assence it comprises the evaluation of how sensible are the model outputs (ex. yields) to the different input variables. Questions could be: are yields more affected by a variation in

the values of soil water retention parameters, or of initial nitrate values or of amounts of residue incorporated?. From this analysis we will know which are the most important input parameters and can derive recommendations for special considerations and methods in the collection of the minimum data set. Once we have enough confidence in the predictions the model can do for an area, provided with the necessary data set, we can go in the process of model application.

Considerations on the application phase

As has been mentioned before (Nix, 1987) the ideal situation for the transfer of Agricultural Technology would be to couple a validated comprehensive simulation model to a detailed data base of point data of the resource variables needed to run the model components.

With a reasonable effort many countries can test, validate, and calibrate available crop simulation models. But a very important problem, specially in developing countries in the application of the ideal situation, is the absence of a detailed data base of the resource variable needed by the models to run.

The ideal data base should contain point data of all the soil, weather, terrain, land use and socio-economic input variables. But most developing countries only have small scale maps of territories and only small proportions with semi or detailed level basic surveys. Moreover, weather data is point data but soil information is mostly areal. In these circumstances and if we want to apply simulation models there are several questions that have to be answered. Among these we have:

- Can we operate simulation models with available information derived from our basic past surveys? and What limitations would they have?
- Are there reliable methodologies to increase or derive information on certain variables through time and space?
- What kind and what level of confidence can predictions have when done at different levels of detail of our resources variables?

In Venezuela the plan has been to test the correspondence between the level of detail in the model prediction and the level of detail of natura resources, specially the soil component. The hypothesis is that with an increasing level of information on natural resources there is an increase in the number and precision of reliable predictions. In broad scale maps, prediction would be more related to climatic variables, with less spatial variability, like the selection of cultivars; at intermediate scales, with more homogeneous soil units, the predictions would be related to better water balances, including then predictions like planting time and plant population; then at detailed levels, the delineations could be homogeneous enough in organic matter so to be able to predict aspects related to nitrogen fertilization. At parcel level the data set can be gathered, and consequently a full use of the models could be accomplished including predictions on various management strategies (Comerma and Guenni, 1987). A similar approach has bee used by Dutch scientists (Keulen and de Wit, 1984; Driessen and van Diepen,1987) relating scales of maps, detail of information to gather, and production situations or type of predictions in a hierarchical fashion.

In relation to the question whether past surveys provide all the minimum data set to run the models, the answer is generally no. Specially soil water retention properties and nitrate-ammonium values of each layer are usually not collected in soil surveys. We will have to look for transfer functions (Bouma and van Lanen, 1987) to predict those properties from characteristics such as particle size distribution, bulk density, percent organic matter, etc. For water retention there are

functions (Cassel, Ratcliff and Ritchie,1983) to calculate them, but still need validation and adjustments if applied to new areas (P. van Leeuwe)*. For the N components we still have not found a good function to predict their values in time and space.

In relation to weather information there are several aspects to consider. The ideal situation of having a high density of meteorological stations with daily records during many years is far from reality, specially in developing nations. But there are methods (Richardson, 1981) of generating daily records from monthly values, provided we have long records. The length of the records can also be extended through various methods either using the information of that station or from neighbour ones; the low density of weather information can also be partly solved by krigin or other interpolation methods (Hutchinson, 1987). We are also convinced that at all levels, but more with an increase in detail, that to apply models we should have information about spatial variability. This is specially true for soils been the most variable element. Application of models may lead to unknown, and in some cases substantial errors, if spatial variation is not recognized (Brinkman and Stein, 1987).

To obtain the necessary information at farm level in Turen, Venezuela, geostatistical study was carried out (Mateos,1987). The technique of nested sampling was employed to identify the scale of variation of important soil variables for the model, and to predict the best sampling interval. Through a regular grid, at the previously determined interval of sampling, a map of quantitative soil properties was done, complemented with kriging optimal interpolation techniques. The parameters studied in the field were: depth to mottles, to plowpan, drainage class, depth to horizon boundaries, and for each horizon, the particle size analysis, percent organic carbon, electrical conductivity and pH. With some of the above parameters all th necessary soil water inputs, to run the water balance of IBSNAT models, were calculated, with the exception of the initial soil water content. To do the calculation, a transfer function developed for that purpose (Cassel, Ratliff and Ritchie, 1983) was used. The spatial distribution o the calculated soil water parameters was also determined and mapped. Afterwards the CERES-maize model was applied to each of the point data gathered to predict yields, and with kriging a map of yields for the whol parcel was obtained (Mateos, Burrough and Comerma,1988). An additional output of this methodology was to give unbiased estimates with minimum variance and the estimation variances, allowing to know the relative error of the output map estimated from the kriging estimate error of the input data.

The above mentioned methodology seems appropiate for a farm level, as was the case described, or for an area where a Soil Survey is going to be initiated. But could we use this approach for areas where large, medium, and small scale soil surveys have already been done, and we want to apply simulation models? and moreover, What would be the objectives of such a complementary soil characterization with this methodology?.

In our plans of using past soil survey information to apply simulation models and predict some land qualities, we feel that part of the described methodology could accomplish some important objectives.

The main objectives of complementing the soil characterization of past soil surveys for a better use with simulation models would be: (1) to obtain a measure of soil variability within delineations, and between delineations of the same mapping units, its purpose being that of setting a "confidence limit" to the prediction within a delineation, and to the

* Personal comunication

process of extrapolation to the same mapping units, and (2) to gather special information that is not given by the survey report but that is essential to run the model.

We feel that to accomplish these objectives we could use only the portion of the methodology related to the nested sampling. After selecting the most important mapping units of a survey report, we could at random, select a few ( three or more )relatively large delineations of each mapping unit we want to study. To each delineation we could apply a fixed nested sampling scheme, like starting from the center of the delineation and move 1,5,10 and 20 mm in the longest direction of the delineation, but with established routes in relation to N, S, E or W. This example of fixed distances could work well for quite variable alluvial plains; for more uniform areas other distances should be set. Once established for a region it could be applied independently of the scale of the map giving consequently different distances in the field according to its scale. At each point we would gather the field data and samples needed to fulfill the necessary information as inputs for the model under consideration. To reduce the number of samples we could use an unbalanced nested sampling (Oliver and Webster,1986) which could give after its analysis the information about spatial variability within and between delineations, as well as some information on the range of variation of certain properties.

With the above information we can run the models on all these points and discover the most appropiate level of prediction for that scale of survey, judged from the degree of variability of the outputs within and between delineations of the same mapping unit, that we are willing to accept. At the same time we can use the range of various properties, characterized in the nested sampling, to establish different scenarios and management strategies that are valid for each soil mapping unit.

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# QUANTIFIED LAND EVALUATION: CONSISTENCY IN TIME AND SPACE

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## Summary

Quantified Land Evaluation (QLE) expresses land qualities and land utilization requirements as numerical variables with values that depend on the momentary state of the entire land use system. Realistic descriptions of land use systems would have to be dynamic and consider biotechnical and socio-economic processes in one integrated analysis. In practice, the complexity and massive data needs of such models are prohibitive. A two stage approach in which physical production potentials are calculated for simplified 'production situations' and serve as input in a subsequent socio-economic analysis, is the best alternative. Such an overlay approach evades the problem that land unit oriented biotechnical and region oriented socio-economic data have different temporal and spatial resolutions by coupling the two analytical stages in an interfacing structure. Here, alternative stage-one output sets, found satisfactory on agronomic grounds, are aggregated to conform to stage-two data specifications before being input in the socio-economic analysis. Concatenating QLE analyses of individual crop cycles or years harbours the danger that low-intensity side effects, unnoticed over one year but lethal in the long run, are overlooked. Long-term QLE projections must be interpreted against the background of long-term global projections as produced by the International Institute for Applied Systems Analysis, and not against the levels and trends in yesteryear's statistics.

## Introduction

The essence of land evaluation lies in the comparison of relevant (land utilization) requirements with corresponding (land) qualities, and in translation of the outcome of this comparison into an expression of the suitability of the considered tract of land for a specific land utilization type. The main difference between Quantified Land Evaluation (QLE) procedures and most other, traditional, land evaluation methods is that requirements and qualities are expressed in numerical variables with values that depend on the momentary specifications of the entire land use system. In line with the dynamic nature of land use systems, QLE procedures entail frequent updating of the values of all system-dependent (or 'state') variables. The frequency of parameter value adjustment or, alternatively, the time interval over which variable values can be considered invariate, depends on the dynamics of the system. It follows that also the resolution of the basic data which are processed, and the level of generalization of the functional relations which translate basic data into quantified land qualities and land utilization requirements, must tally with the dynamics of the system.

If basic data and algorithm are in order, sets of matching quality and requirement specifications, assumed to hold for the duration of one, sufficiently short time interval, can be compared. Next, all dependent variable values are adjusted, in agreement with the outcome of the

interval calculations, and assumed invariate for the duration of a next interval, and so on. A sequence of such individual matching operations will show, for a longer period of time, when and to what degree the evaluated land qualities meet the corresponding land utilization requirements.
Note that one full sequence of interval calculations describes the dynamic behaviour of one land use system, with one land unit definition, one crop/variety, and one set of management and technology specifications over one season or year. It still is a point analysis.
Extending the analysis of points to an analysis of land adds an extra problem in that it introduces the aspect of the spatial variation in land qualities and land utilization requirements to the analysis. In analogy to a minimum temporal resolution, imposed by system dynamics, the basic data input must have a minimum spatial resolution, dictated by the scale and purpose of the evaluation.

Evidently, the suitability of a tract of land for a certain use is not merely a matter of the biophysical environment but depends also on the prevailing socio-economic conditions. For example, if the application of fertilizers is a requirement for realizing a set production target, not only the fertilizer must be available but also the labour and the means to apply this fertilizer to the crop in the proper manner at the proper time. It follows that QLE must also quantify the availability, quality and price of labour (and other socio-economic assets and limitations) at any moment to be able to assess whether what is needed from the biotechnical point of view is socially acceptable and economically viable.
As biotechnical and socio-economic qualities act simultaneously and in interaction, an 'integrated' analysis of land use system performance is needed in which quantified biotechnical and socio-economic information is processed simultaneously and in interaction. This requires all basic information to be of uniform temporal and spatial resolution, despite fundamental differences in the nature of the data. The temporal resolution, for all practical purposes the permissible length of individual intervals in a simulation run, depends on the most dynamic process in the system. (An interval length of 1 day proved satisfactory in many cases, but there are situations thinkable in which interval lengths must be shorter or can be longer.) The spatial resolution, i.e. the dimensions of the individual land use systems in an area, depends on the homogeneity of the area in terms of physical characteristics and management/cropping practices. By definition, land use systems extend over one land unit or one management unit, whichever is smaller, so that, in practice, integrated (biotechnical and socio-economic) analysis seems feasible only for areas with the size and complexity of one farm.

Note that in this reasoning A FARM IS CONSIDERED TO BE A SELF-CONTAINED ENTITY with one or only a few land use systems in operation at the same time, a limited number of qualities and/or limitations that need to be considered in the quantification of physical production, and a limited number of factors or incentives which prompt the producer (farmer) to take certain action. The picture that emerges is that of a capital-intensive, highly mechanized family enterprise in which (1) a limited number of commodities is produced for a stable market, (2) physical limitations such as nutrient shortages, weeds infestation, pests and diseases are considered minor inconveniences, easily eliminated with comparatively inexpensive commercial fertilizers, herbicides, pesticides, and other production means, and (3) the producer's overriding motivation is making a maximum profit within the law.

Such farms/producers may exist, perhaps, in Holland or elsewhere in the EEC, but they are certainly not representative of the farming community in developing countries where physical limitations cannot be straightened out without straining the (very limited) budget, and where farmers are not so much motivated by maximization of income as by more pressing and more complex worries such as self-reliance in food, risk aversion, social status, etc.

Production situations and production potentials

The small farmer's production environment, with its multitude of physical and socio-economic limitations, is too complex to be handled in an integrated and quantified analysis. If, however, most or all amendable limitations were assumed eliminated or corrected (so that they can be ignored in the analysis), a less complex production environment would evolve for which a production figure could be calculated. The generated production figure would be higher than the actual production realized by the farmer in his real environment: it is a production potential and refers exclusively to the newly defined production environment. The more constraints are (assumed) eliminated, the higher the calculated production potential will be, until only such physical land qualities and/or limitations remain that cannot be manipulated.
The 'Production Situation' (PS) with the lowest possible complexity, PS-1, pertains to a hypothetical land use system with a 'biotechnical production potential' that is solely determined by the crop choice and by the temperature and the availability of solar irradiance at any moment in the crop cycle. All other land qualities are assumed optimum under PS-1.
If, besides temperature and irradiance, also the actual availability of water were a possible limitation to crop performance, a slightly more complex production situation would result (PS-2) with a 'water-limited production potential' that is equal to the production potential of PS-1 (if there is no water limitation) or lower.
One level deeper, in PS-3, one could introduce the land quality 'availability of nutrients' in the analysis, in addition to all qualities and limitations considered at the PS-2 level, and calculate a 'water and nutrients-limited production potential'. However, practice has shown that the complexity of a so-defined production situation is already prohibiting; massive data needs and inaccuracy of the generated production figures frustrate the calculation of dependent production potentials in PS-3 and lower. Instead, one could calculate the input requirements needed to eliminate a certain limitation (i.e. the input requirements for realizing a set production target). At the PS-3 level, the fertilizer requirement is quantified; at the PS-4 level the need for weeding is added, and so on.

Evidently, there always will be a gap between production potentials that can still be calculated with satisfactory accuracy (PS-1 and PS-2 levels) and the actual (PS-n) production of 'the small farmer'.
Figure 1 illustrates this; calculated production potentials for PS-1 and PS-2 (i.e. Y1 and Y2 respectively) are plotted against the summed inputs (X1 and X2) that are required to realize these potentials. The reference base is the production situation of the small farmer (Yn) whose production environment comprises all possible limitations and who can afford only a low level of inputs (Xn, mainly labour) to correct some of these limitations.

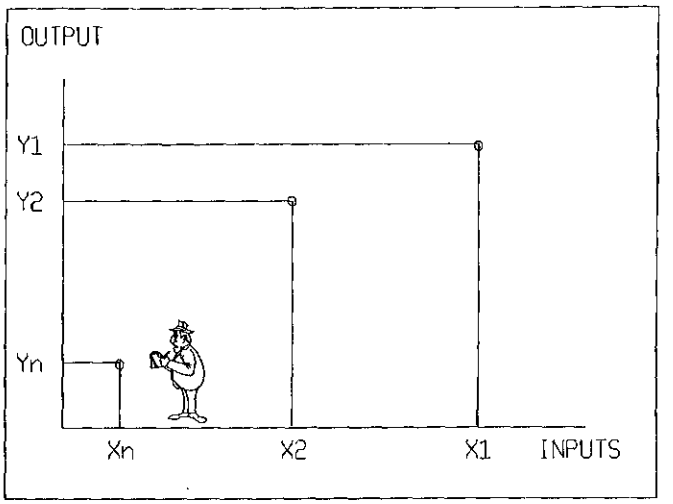


Fig. 1. Schematic presentation of input-output relations in various production situations.

If the hypothetical small farmer of Figure 1 were able to invest the equivalent of (X2-Xn) dollars in material inputs and labour, he could eliminate such limitations as pests, diseases, weed infestation and nutrient shortages and his output would increase to Y2, the 'water-limited production potential' of PS-2. For realizing the biotechnical production potential', Y1, the required investment would total the equivalent of (X1-Xn) dollars.
The production potentials of PS-1 and PS-2 are calculated in kg (dry product) per hectare; these figures are based on the known and quantifiable response of a well documented variety to sets of well documented dynamic land qualities/limitations. The corresponding estimate of all required inputs (expressed in dollars per hectare) is less well predictable. Although physical input requirements are quantified in unmistakable terms such as the number of kilos of a certain nutrient that the crop must take up per hectare, or the number and timing of weedings, there often is more than one way to meet such requirements. In a certain situation, a broadcast application of several tons of rock phosphate and a banded application of a few hundred kilos of superphosphate might well result in the same (required) phosphorus uptake, but at different prices. In many systems, there is substitution possible, between herbicides and manual weeding, between different implements, between machine traction and animal traction, etc. How a certain requirement will be met (and at what price) depends on the state of the entire system at the time when measures are required. It is for this reason that integrated analysis is so often advocated; it remains to be seen, however, if it is also practicable.

So far, the discussion focussed on a hypothetical production unit, the 'self-contained farm'. This might be a realistic concept as far as the physical aspects of crop production are concerned; the production

environment could indeed be defined in such a way that crop performance depends solely on the crop, soil and atmosphere conditions on-farm, without any influence from outside (no seepage, no runoff/runon, etc). We would go overboard, however, if we would assume the same of the socio-economic context; no sane farmer ignores production incentives from outside, e.g. from the local, regional, national and even international market situation. There is a fundamental difference in scale between the biotechnical and the socio-economic land qualities and limitations in a land use system. One consequence is that the temporal and spatial resolution of the basic data required to describe the physical plant production process differ from that of the information required for optimum describing relevant socio-economic influences on the physical on-farm production. The growth and development of a crop can be approximated by analysing the growth and development of one individual plant, representative of tens of thousands similar plants in a field. When that plant senses water stress it will close its stomatal openings to curb its water consumption, and if stress surpasses a system-specific tolerance limit, the plant will die. One may trust that all other plants that, together, constitute 'the crop' will die with it. If a farmer is in need of water, he will not just wither and die but he will find, buy, swap, steal, acquire the needed water within the possibilities that his environment offers, or move out. There is much greater deviation between the behaviour of individuals and groups in the case of 'people' than in the case of 'crops', if only because the uniformity among the individual plants in a crop is greater and the individual's freedom to take an independent course is less.

Descriptions of the physical crop performance can be experimentally verified on an area the size of an experimental plot. (Agricultural research stations do their experiments under conditions which conform to PS-specifications; in a fertilizer experiment for instance, weeds, pests and diseases are eliminated and irradiance, temperature and water supply are 'as in PS-2'.) In contrast, describing 'the producer' cannot be done by describing one or a few farmers in isolation; we must handle (interacting) groups of people with basic specifications that have a higher level of aggregation than the specifications of other constituents of the land use system (crop, soil, atmosphere). The conclusion must be that realistic/reliable dynamic land use system descriptions which integrate agronomic and socio-economic aspects of actual production in one balanced model are distant future. For now, we must proceed differently.

## The two stage approach: how the twain shall meet

Information on land use system characteristics and performance is collected in agricultural censuses and recorded in statistical reports. Unfortunately, this information often is limited to general levels and trends and disaggregation to producer-specific data with a higher resolution is not possible. One cannot 'make' basic information.
Quantification of production potentials requires basic data of a system-specific minimum resolution and cannot, therefore, rely very much on region-oriented statistics. 'Normalizing' all basic data, biotechnical and socio-economic, to one level of generalization (the temporal and spatial resolution of the socio-economic data) would bring consistency to the basic data set but is out of the question for reasons mentioned.

Clearly, there are two complementary but fundamentally different parts in land use system analyses:

(1) the analysis of physical production potentials based on specific information regarding (hypothetical) but rigidly described production situations, and
(2) the analysis of the socio-economic feasibility of production, including potential production, based on information with a higher level of generalization.
Since the feasibility of potential production cannot be judged before the potential and all required inputs are known, the analysis of production potentials comes first. The results of individual PS-simulation runs (point analyses) can then be input in a subsequent socio-economic evaluation. This 'two stage approach' is the only alternative left where integrated QLE is a technical impossibility. This overlay technique is theoretically inferior to the integrated approach in that only interactions of physical land qualities and limitations are accounted for in a dynamic analysis, and not interactions between physical and socio-economic land qualities and limitations. An advantage of the two stage approach is, however, that the analysis is divided into two clearly distinguishable parts that can conveniently be implemented by separate multidisciplinary teams, covering the broad fields of 'Agronomy' and 'Socio-economics', each with their own data requirements and analytical strategy.

A serious analytical difficulty of the two stage approach is in the 'interfacing module', i.e. the structure through which scores of alternative sets of generated production potentials and associated input requirements are introduced in the socio-economic analysis. The problem is essentially an aggregation problem. Each of the sets generated in the first stage covers one production situation, unique in space and time; many sets are needed for a regional analysis. Direct input of the sets in the second (socio-economic) stage will rapidly overload the capacity of any (manageable) input module. The output of stage one must therefore be brought to the level of spatial and temporal resolution observed in stage two before it is further processed. In other words, point data must be aggregated to represent administrative units rather than (physical) land units or farm areas, and administrative (e.g. fiscal) periods rather than crop cycles. That idea is impopular among agronomists because aggregation of calculation results leads to loss of detail, on occasions perhaps to the extent that calculating production potentials seems no longer worthwhile. However, there is no alternative to dynamic crop production modelling. For one, aggregation of stage-one results will not produce the 'general production levels' or, less conspicuous but equally suspect, 'production indices', that are 'found' with a quick-and-easy procedure in which land characteristics are lumped to parameters with rather arbitrary weights, and in which complex interactions are mutilated to simple one-time addition or multiplication. Econometrics with a 'green rim' of so-fabricated general production levels and input requirements is a poor substitute for quantified land evaluation. Dynamic analyses of alternative production situations are indispensible.

## QLE in wider perspective

Land qualities (and land utilization requirements) are dynamic by nature; interactions between different land qualities are affected by the (differences in) land use system dynamics but it is not always possible to account for that in a two stage approach. An example: if weeding is done in time interval (x), the effects of this measure on crop performance, e.g. a higher assimilation rate, are first noticed in simulation interval (x+1). Recall that the length on one interval is normally one

day. In a two stage approach, the need for weeding and the effects of weeding are evaluated in the first stage whereas the land quality 'availability of labour', instrumental in the decision to apply hand-weeding, or herbicides, or a mixture of the two, or not to weed at all, is considered only in the second stage and based on data of much lower temporal resolution than one day. The stage-two analysis can only endorse or reject, in retrospect, the production situation specifications used in the first stage. If alternative production situation definitions are used the 'best' alternative can eventually be selected from multiple stage-one runs. This solution may be less than elegant but is satisfactory in practice.

Superimposed on short-term developments are long-term trends which cannot always be included in the analysis. Soil degradation, soil salinization and erosion are such developments; they are seldom noticeable over one time interval or even one crop cycle and are not normally considered in QLE procedures. Yet, they have caused the decline of powerful empires in the past and eat away at the resources of many of today's nations. It is an alarming circumstance that increased population pressure, but also modern agro-technology have considerably increased both the intensity of land degradation and the areas that are involved. An example: an important part of Dutch agricultural exports are based on intensive livestock keeping and the use of imported animal feeds. Soil fertility is transferred from the U.S. corn belt, the French wheat region and the cassava fields of north-eastern Thailand to Holland from where a small part of it is re-exported in meat, eggs, etc. A large part of all imported nutrients remains behind in chicken dung and pig slurry and is dumped on the fields where it upsets the balance between the land quality 'nutrient availability' and the nutrient requirement of the crop. Related problems such as groundwater pollution and acid atmospheric deposition develop faster and over larger areas than ever before and indicate that land quality dynamics are not what they used to be.
That being the case, we should not continue as if nothing happened. The International Institute for Applied Systems Analysis (IIASA) in Laxenburg, Austria, studies global developments in the fields of industry, politics, finance, environment, etc that are beyond the horizon of land evaluators; its long-term projections, however, are a background against which prospective land utilization types (the subject of 'our' QLE) can be placed. Definitions of realistic land use alternatives in today's world must be made and tested with today's tools and not based on vague notions that stem from levels and trends in yesteryear's statistics.

# INTEGRATING AND ANALYZING SPATIALLY VARIABLE SOIL PROPERTIES FOR LAND EVALUATION

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## Summary

A project combining simulation modeling of water and chemical movement, use of the Cornell Supercomputer, and techniques of Geographic Information Systems (GIS) is underway to integrate, condense and summarize the behavior of spatially variable soils at the large scale (order of km). A one dimensional, convection-dispersion based solute transport model was used to simulate the movement of four classes of solutes through layered soils for a 7 by 10 km site near Albany, New York. The site was divided into a 163 by 112 grid (0.4 hectare/cell), and multiple model executions at each cell were used as a means of incorporating the influence of spatial variability of soil hydraulic properties into the study. Regression equation-based pedotransfer functions were used to relate soil physical properties to the mean and variance of hydraulic properties within each cell. Each model execution used hydraulic properties selected from frequency distributions derived from these parameters. Land use, soil, and slope maps were overlaid with a GIS to select and group the grid cells appropriate for modeling. Maps of solute mass, concentration, and residence time are being produced for 1 and 25 year simulations using local climatic data. "Hazard maps", or maps depicting the probability of a given concentration or mass being attained at 0, 50, 100 and 150 cm depths, at selected times, are also being produced.
Keywords: convection-dispersion, GIS, leaching, simulation modeling, spatial variability.

## Introduction

The increased use of fertilizers, pesticides and herbicides, in conjunction with the growing number of leaking underground tanks and unavoidable chemical spills, has produced a need for greater understanding and quantification of the processes relevant to solute movement in soils. A review by Hallberg (1986) reports that at least 17 commonly used pesticides have been detected in the groundwater of 23 states as a result of routine agricultural practices, a 50% increase since 1984. Only a handful of these pesticides have been observed under field conditions with sufficient detail to accurately assess the migration potential of such compounds. Furthermore, the high cost of chemical analysis, intensive labor requirements of field studies, and restrictions on hazardous substance dispersal outside the laboratory environment all hinder additional data acquisition. As a result of these limitations, predictions of pesticide movement based on solute transport model simulations are being relied upon more frequently to serve as guidelines during the development of pesticide regulatory policies.

Highly detailed, research-oriented simulation models such as the LEACHM (Leaching Estimation and CHemistry Model) series developed by Wagenet and Hutson (1986), can be used to provide data required for short-term policy development as well as to provide baseline estimates of solute movement

as a first step in the model validation process. As the magnitude of ground-water contamination grows, the capability to examine the impact of altering the policies governing pesticide application rates, for any irrigation, precipitation, and soil combination, without actually contaminating the environment is becoming more desirable, and hence the use of a simulation modeling approach is becoming more widespread.

In the broadest sense, this study attempts to relate land properties and characteristics (FAO, 1976) which are accessible in existing soil surveys and databases, to environmental land qualities which are not as easily identified, such as the leaching potential of agricultural chemicals, through the use of simulation modeling. The primary objective of the study is to develop a procedure similar to that of Green et al. (1988) which can be used to produce detailed maps of the leaching potential or hazard to groundwater of agricultural chemicals, which also considers the influence of spatial variability in the analysis. The maps are intended to be used by growers, policy developers, and researchers as an aid to identify discrepancies between land use and suitability which could potentially produce groundwater pollution. The focus of this paper is upon the methods being used, with a more complete presentation of the final results at the Symposium on Land Qualities in Space and Time, Wageningen, The Netherlands, August 22-26, 1988.

## Methods

The project consists of three main phases: (1) site selection and data acquisition, (2) model execution, and (3) generation of maps.

### Site selection

The site chosen for the study was based on several factors, including the availability of soils information and the existence of a non-point source of pollution which could potentially impact a local population. A 7 by 10 km region near Albany (Figure 1) was chosen because it was

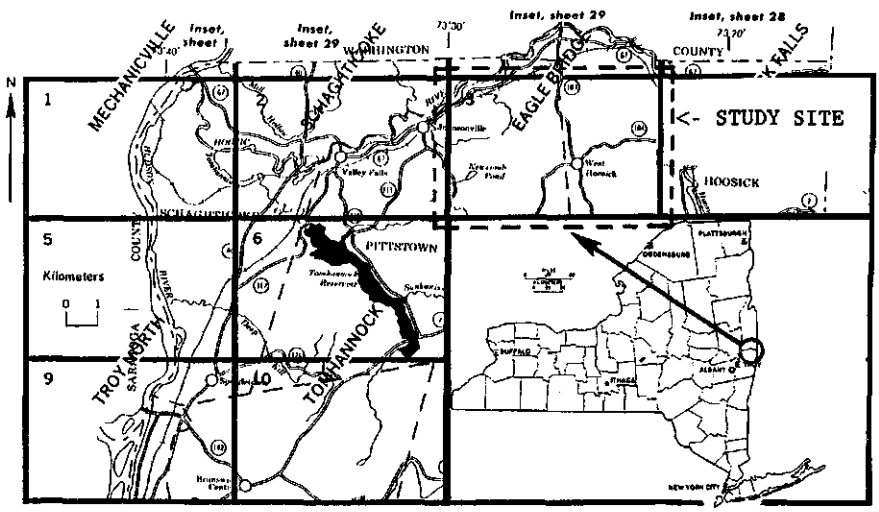



Fig. 1. Location of study area within New York State.

(1) within the boundary of the first soil survey update in New York to be completed on an orthophotomap base, and (2) a large fraction of the land was used for agriculture (Work, 1988). Residues from agricultural chemicals used in the region could potentially migrate to the nearby Tomhannock Reservoir which serves as the water supply for Troy, a city of 70,000. The updated soil survey corrected errors produced by relief displacement (Forbes et al. 1987) and is now based on maps which can be geo-referenced by a geographic information system (GIS). The boundaries of survey map sheet 3 defined the limits of the study site (Figure 1).

The soils map for the study site was obtained from the Soil Conservation Service in a digital line graph format. This was converted into a grid of 163 by 112 cells (18256 total) with the GRIDPOL program in the ERDAS (Earth Resources Data Analysis System) geographic information system. Each cell, or pixel, was 63.61 by 63.61 meters on a side or about 0.4 hectares. The dominant soil class in each cell was recorded to produce a pixel-based soils map. One desirable feature of pixel-based, or raster maps, is that several maps can be simultaneously overlaid in computer memory with a GIS (Figure 2), and new maps based on the intersection of properties at each pixel can be produced quite rapidly (Burrough, 1986). All pixel maps used in the study were produced with the same number of grid elements and the same pixel size.

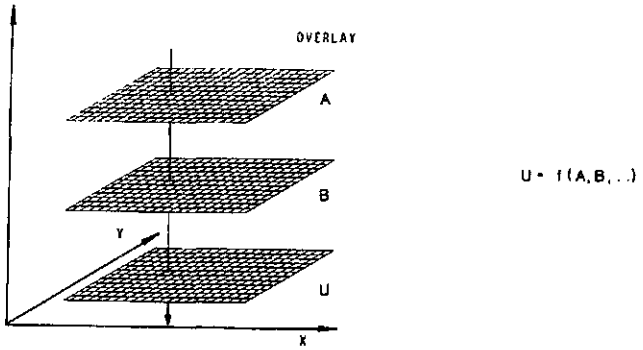



Fig. 2. Representation of a digital map overlay procedure to produce a composite map.

Due to the fact that the portions of the study site were not devoted to agriculture, further selection of those pixels in the study site which would be modeled was required. This was accomplished with data available from the Land Use and Natural Resources (LUNR) inventory of New York and a GIS map overlay technique.

The LUNR data for the study site were obtained from the CLEARS (Cornell Laboratory for Environmental Applications of Remote Sensing) library in the form of 1:24000 scale acetate maps which delineate the land use or crop cover present at the time the map was produced. The inventory, based on interpretation of aerial photographs, was completed in 1968 and includes multiple categories for agriculture, forestry, residential, industrial, and other specialized land use classes. The LUNR map sheet corresponding to the study site was manually digitized and converted to a pixel map with the ERDAS GRIDPOL program. Then, by overlaying the soil map and the land use map, it was possible to produce another map which consisted of all soils which were used for agricultural purposes in the 1968 era.

A final set of overlays was used to complete the selection process. Because the LEACHM model does not include a runoff or erosion component,

only areas on slopes less than 10% were modeled. An overlay of a slope map produced from remotely sensed DEM (Digital Elevation Model) data, obtained from the Defense Mapping Agency, was used to exclude areas with a slope greater than 10 percent. This soils map of agricultural areas on shallow slopes, defined the pixels in which the model was executed, and accounted for about 45 percent of the original study area.

Soil hydraulic properties

The soil hydraulic properties required by the LEACHM model include the saturated hydraulic conductivity, the slope of the logarithm of matric potential versus normalized water content, the intercept of the logarithm of the matric potential versus normalized water content (i.e. the shape of the soil water characteristic curve from Campbell, 1974), and the bulk density for each layer of the profile. A continuous pedotransfer function approach described by Bouma and van Lanen (1987) was used to relate soil physical properties of each pixel to be modeled to the soil hydraulic properties of each layer of the soil profile at that location. These transfer functions were obtained from regression equations developed by Cosby et al. (1984) and Rawls and Brakensiek (1982) which describe relationships between the mineral fractions of soils and the mean and variance of soil hydraulic properties, based on a sample of 1448 U.S. soils (Table 1).

Table 1. Regression equations used in developing the hydraulic parameters for this solute modeling project (from Cosby et al. 1984).

| Parameter | Regression Equation | $R^2$ |
|---|---|---|
| Mean b | 0.1570*(% clay) - 0.0030*(% sand) + 3.10 | 0.966 |
| Mean log $\Psi_s$ | -0.0095*(% sand) - 0.0063*(% silt) + 1.54 | 0.850 |
| Mean log $K_s$ | 0.0126*(% sand) - 0.0064*(% clay) - 0.60 | 0.872 |
| Mean $\theta_s$ | -0.1420*(% sand) - 0.0370*(% clay) + 50.50 | 0.785 |
| S.D. b | 0.0492*(% clay) + 0.0144*(% silt) + 0.92 | 0.584 |
| S.D. log $\Psi_s$ | -0.0026*(% silt) + 0.0012*(% clay) + 0.72 | 0.111 |
| S.D. log $K_s$ | 0.0032*(% silt) + 0.0011*(% clay) + 0.43 | 0.403 |
| S.D. $\theta_s$ | -0.0805*(% clay) - 0.0070*(% sand) + 8.23 | 0.574 |

b = slope of the logarithm of matric potential ($\Psi$) versus normalized water content ($\theta/\theta_s$), i.e. b from the equation:
$\Psi = \Psi_s[\log(\theta/\theta_s)^{-b}]$
$\Psi$ is the matric potential
$\Psi_s$ is the intercept of the logarithm of matric potential ($\Psi$) versus normalized water content ($\theta/\theta_s$)
$\theta$ is the volume water content at the matric potential $\Psi$
$\theta_s$ is the saturated volume water content
$K_s$ is the saturated hydraulic conductivity (in/hr)
S.D. is the standard deviation

The particle fractions of the soil profiles at the study site were obtained through the New York State soils database which augments the soil survey. Frequency distributions based on the mean and variance of each property were used to generate a population of hydraulic parameters

for each pixel. Cosby et al. (1984) determined that the values of $\theta_s$, b, and the logarithm of $\Psi_s$ were approximately normally distributed, while $K_s$ was log-normally distributed.

Soils from different taxonomic classes which had a similar sequence of hydraulic properties through the profile were grouped. For example, soils with a relatively high conductivity and water holding capacity in the first layer, low in the second, and high in the third produced one group. Various other combinations produced the remaining groups. Similar land use classes were also grouped (Table 2), the original 53 soils classes and 22 LUNR classes thereby reduced to 6 hydraulic groups and 7 land use groups for the next step of execution of the simulation model.

Table 2. Grouped land use classes and grouped soil hydraulic classes used for model simulations. Values represent the number of pixels in the study area.

| | LUNR CLASS | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| HYDRAULIC CLASS | 1 Ag | 2 Br | 3 Fo | 4 Ot | 5 Re | 6 Wa | 7 We | TOTAL |
| 1 | 3729 | 1389 | 2431 | 22 | 4 | 20 | 163 | 7758 |
| 2 | 79 | 16 | 13 | 4 | 3 | 3 | 4 | 122 |
| 3 | 313 | 83 | 106 | 10 | 0 | 0 | 70 | 582 |
| 4 | 2326 | 672 | 800 | 18 | 3 | 12 | 209 | 4040 |
| 5 | 376 | 246 | 213 | 53 | 1 | 26 | 57 | 972 |
| 6 | 7 | 5 | 0 | 0 | 0 | 0 | 0 | 12 |
| OTHER | 1396 | 1083 | 1517 | 288 | 2 | 191 | 293 | 4770 |
| TOTAL | 8226 | 3494 | 5080 | 395 | 13 | 252 | 796 | 18256 |

Description of classes:

| LUNR | Description | LUNR | Description |
|---|---|---|---|
| Ag: | All agriculture | Re: | All residential |
| Br: | All brushland | Wa: | All water |
| Fo: | All forestry | We: | All wetlands |
| Ot: | All other classes | | |

Hydraulic classes are based on the order and magnitude of hydraulic properties through the profile

Due to the fact that field measured hydraulic properties are highly variable in space (Nielsen et al, 1973), multiple model executions for each pixel were used as a method of reflecting the expected variability of hydraulic properties within that pixel. For any one execution at any one pixel, hydraulic properties were selected from the population of values for the group which included that pixel. This was repeated up to one hundred times for each of the six hydraulically different groups in the study area, in an ordered fashion, so that the complete range of the hydraulic parameters from each group was used. The method of treating the output of these multiple executions is described below under the section Model execution, output, and map generation.

## Model description

The LEACHM model is designed to simulate the movement of water and solutes through both layered and non-layered soil profiles. Darcy's law is used as the fundamental approach which when combined with the continuity equation, produces a description of transient vertical water flow as:

$$\frac{\partial \Psi}{\partial t}(\theta) = \frac{\partial}{\partial z}\left( K(\theta) \frac{\partial H}{\partial z} \right) - U(z,t) \qquad [1]$$

where $C(\theta)$ is: $C(\theta) = \partial\theta/\partial\Psi$ [2]

and $K(\theta)$ is the hydraulic conductivity at the water content $\theta$, H is the hydraulic head, U is an uptake term, and z and t are depth and time respectively. Water contents and fluxes calculated with this equation are used in conjunction with the convection-dispersion equation to describe the movement of solutes which can adsorb, volatilize, and degrade. Expressed mathematically:

$$\frac{\partial c}{\partial t}(\rho K_d + \theta + \epsilon K_h) = \frac{\partial}{\partial z}\left[ (\theta D(\theta,q) + \epsilon K_h D_{OG}) \frac{\partial c}{\partial z} - qc \right] \pm \phi \qquad [3]$$

in which c is solute concentration, $\rho$ is the bulk density of the soil, $K_d$ is the pesticide partition coefficient between sorbed and solution phases, $\theta$ is the volumetric water content, $\epsilon$ is the gas filled porosity, $K_h$ is a modified Henry's Law constant, $D_{OG}$ is a the vapor diffusion coefficient (Jury et al, 1984), $D(\theta,q)$ is the diffusion-dispersion coefficient, q is the convective water flux, $\phi$ is a first order decay term, and t and z are time and depth respectively. Four different solutes can be modeled independently, but subject to the same water flow regime, during any one execution of the LEACHM model. The finite difference forms of these differential equations are solved numerically.

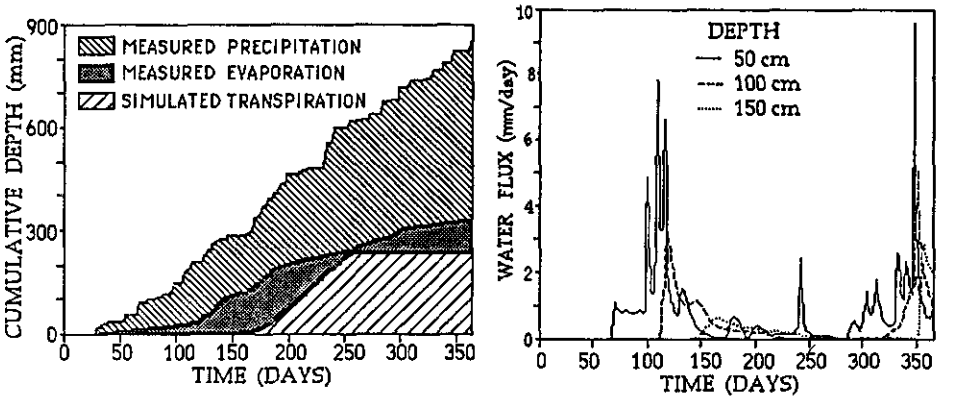
The time step interval used in the model is controlled by the infiltration rate, therefore, during precipitation and irrigation events, small time steps are required to insure numerical stability and produce accurate water flux calculations. The smallest time step can span several seconds and the largest is generally one-tenth of a day. For each time step, new water contents, pesticide concentrations and mass balances are calculated in an iterative process for all layers. As a result of the numerically intensive iteration process, the large number of time steps produced during multiple year simulations, combined with the large number of simulations required to produce county-scale maps which reflect the influence of spatial variability, the Cornell National Supercomputer was used for the model simulations.

Subroutines that allow for growing plants which can act as sinks for both solutes and water have also been included in the model. Data for typical corn planting and growth patterns, as well as pesticide application rates for the Albany region were obtained from the New York State crop recommendation handbook (1987) and were based on climatic patterns for the 1967 to 1986 period.

## Previous model applications

The LEACHM models have been used in a variety of applications, both for validation and as a predictive tool (Wagenet & Hutson, 1986, Hutson et al., 1988, Wagenet et al, 1988). These studies have established the

approach as a reasonably reliable predictive tool for the cases studied, which include aldicarb, diazanon, and simazine in field leaching situations. The model has also been used as an interpretive tool to analyze DBCP movement in carefully controlled leaching plots. The model has been shown to be quite flexible in its ability to consider variable surface applications of water and solute, allowing for simulations that represent climatic variability and its effect on transient conditions of water and chemicals in the soil profile. Examples of preliminary model output for the study area are shown in Figure 3 for a 1967 test case.




(a) (b)

Figure 3. Model output for a 1967 test case, (a) measured cumulative precipitation and evaporation, with simulated transpiration, and (b) simulated water fluxes at 50, 100, and 150 cm depths.

Initial and boundary conditions for this project

The maximum depth modeled in this exercise was 150 cm, which corresponded to the minimum depth of the water table present in most of the region (Work, 1988). Each soil profile was modeled as a set of 15 layers, each layer 10 cm thick, with a water table of constant (zero) potential at the 150 cm depth. Initially, the matric potential of the soil profile was set to a value of -100 kPa. The surface water flux was calculated from measured precipitation and class A pan evaporation data which was collected daily at the agricultural experiment station at Valatie, New York.

Two sets of simulations were accomplished. Each set was executed as described above, but the sets differed in the boundary conditions for precipitation. Precipitation patterns corresponding to (1) the mean monthly totals for the 1967 to 1986 period, and (2) for the 90th percentile of the same data set were used for the simulations. This provided a means of analyzing the impact of high precipitation years on regional solute leaching.

Pesticide properties

In this project, four classes of solutes were modeled which spanned a range of sorption and volitization properties. Table 3 lists the properties (Jury et al., 1984) for the cases simulated.

Table 3. Solute properties used in simulations (from Jury et al, 1984).

| Saturated vapor density (mg/l) | Aqueous solubility (mg/l) | $K_{oc}$ ($m^3/kg$) | Example compound |
|---|---|---|---|
| $7.5 \times 10^{-6}$ | $9.0 \times 10^{+2}$ | $2.0 \times 10^{-2}$ | 2,4-D, Atrazine |
| $2.0 \times 10^{-3}$ | $3.0 \times 10^{-1}$ | $7.3 \times 10^{+0}$ | Trifluralin |
| $2.2 \times 10^{-1}$ | $3.7 \times 10^{+2}$ | $2.8 \times 10^{-1}$ | EPTC |
| $1.0 \times 10^{-8}$ | $5.0 \times 10^{+6}$ | 0 | Nitrate |

Model execution, output, and map generation

The bulk of the modeling exercise is currently in progress and results will be reported orally. The procedure being followed is presented below. Day one was declared for the modeling exercise as January 1, 1967. During each model execution the four classes of solutes described above were applied on day 146 (May 10) at a concentration determined by routine agricultural practices in the area. For each of the six hydraulic groups in the study area, the model was executed 100 times. For each execution, hydraulic parameters were selected randomly, based on conventional Monte Carlo techniques, from the frequency distributions for that group. This produced a set of frequency distributions for each of the model output parameters (mass, concentration, surface matric potential), which will be used to generate maps.

After the precipitation simulations are complete, raster maps will be generated that present the probability of a given output condition occurring. Each of these maps will be subject to the same boundary conditions. Maps depicting solute behavior will be produced in the following manner: for the desired pixel, and for the desired output parameter (e.g. mean solute concentration at the 50 cm depth after 250 days elapsed time),

(1) determine which hydraulic group the pixel belongs to,
(2) select the concentration from the frequency distribution of concentrations generated during the 100 model executions for that soils group, (values at the 50th percentile will be used for the mean case maps, and at the 90th percentile for the extreme cases, however, once the distributions have been generated, any value appropriate for the intended map use could be selected),
(3) repeat steps 1 and 2 for all pixels in the study area until the map is complete.

Maps will be produced for the following cases:

(a) mean precipitation case
  (i) mean mass of solute remaining in profile
    at 0, 50, 100, 150 cm depth
      at 0, 50, 100, 150, 200, 250, 300, 350 days, 25 years
        for each of the four solute's modeled
  (ii) mean concentration of solute in profile
    (same depth, time and solute series)
  (iii) 90th percentile mass of solute remaining in profile
    (same depth, time, and solute series)
  (iv) 90th percentile concentration of solute in profile

(b) high precipitation case
    (same sequence as above).

The purpose of this approach is to avoid maps which identify a single magnitude for any point in space, and rather to produce maps which could be used to answer such questions as "What regions within the study area have a 90 percent probability of exceeding the national health standard for solute X given an initial surface application rate Y?".

Other possible products include maps of near-surface matric potential and corresponding regional/seasonal trafficability maps, as well as animation loops of the maps described above. The supercomputer generated output and maps can be animated to produce "movies" with the facilities at the Cornell Center for Theory and Simulation, which can be displayed either on a computer or video screen.

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# CONVERTING SOIL SURVEY CHARACTERIZATION DATA INTO IBSNAT CROP MODEL INPUT

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Summary

Many of the variables needed for describing soil properties in crop simulation models are not contained in traditional soil classification data. Although the accuracy of crop model predictions is best when soil properties needed in the simulation run are measured in the field, most model users do not have the needed measurements available and must resort to estimations for the soil properties. This paper presents the steps for estimating the soil properties as part of the minimum data sets needed to run the crop simulation models being used by the International Benchmark sites Network for Agrotechnology Transfer (IBSNAT) project.

Keywords: Soil survey, soil description, soil classification, field capacity, soil water balance, root growth, soil texture.

## Introduction

A major function of the soil is to provide a reservoir for plant water and nutrients and to anchor the plant to the ground. The supply of water and nutrients throughout the life cycle of a plant influences the expansion rate of the growing organs and ultimately their economic yield. Thus for functional models of plant growth, we seek to describe the soil as a source of water and nutrients. When these resources are available in sufficient quantities, plant growth is controlled by above ground atmospheric factors. When the soil-supplied factors are not adequate, plant growth is reduced below the amount determined by the atmospheric conditions. Because soils vary greatly in their capacity to hold water and nutrients, the soil properties that influence the plants of these resources are important.

This paper discusses the minimum number of soil related properties that we believe are necessary to provide a relatively general description of the soil-water supply to plants. The prediction of nutrient supply is not discussed but it parallels in several ways that of the water supply. However the nutrient supply of interest in agricultural decision making is often most strongly influenced by the amount and type of fertilizers used than it is by soil properties.

The soil properties to be discussed are those approximated for use in the functional models adopted by the IBSNAT project (Uehara, 1985) which presently include maize, rice, wheat, and soybean; and when sufficiently validated, potato, sorghum, millet, barley, peanut, and field bean. The models are limited to these crops because it is a prototype project. The goal of the developers of the IBSNAT crop models is to predict the performance of a particular cultivar sown at any time on any soil in any climate for agrotechnology transfer. Models help to accomplish this goal by defining soil, weather, management, and genetic information that should be collected in practically all experimental

trials to help explain outcomes and thereby transfer the technology beyond the site and year of the trial.

Types of crop production models

Before presenting details of the soil properties needed for the IBSNAT crop models, we wish to clarify the approach used in the models. Because models of the important processes involved in crop production have different purposes and are approached from different levels of organization, it is possible to categorize them for discussion. They can be described as deterministic or stochastic, mechanistic or functional, and rate or capacity types (Addiscott and Wagenet, 1985). Deterministic models produce a unique outcome for a given set of events. However, due to the spatial variability of the mediating processes there will be some degree of uncertainty associated with the results. Stochastic models have been developed to accommodate this spatial variability and to quantify the degree of uncertainty. Stochastic models produce an uncertain outcome because they include one or more parameters that are random variables with an associated probability distribution. While stochastic models are rightfully gaining in popularity, they have been applied little in crop production analysis.

Most models used for evaluating crop production systems can be further categorized as mechanistic or functional. Mechanistic models are usually based on dynamic rate concepts. They incorporate basic mechanisms of processes such as Darcy's Law or Fourier's Law and the appropriate continuity equations for water and heat flux, respectively. Functional models are usually based on capacity factors and treat processes in a more simplified manner, reducing the amount of input required. They usually contain no less than daily time steps and can run through computers quite rapidly to evaluate outcomes over large space and time.

Perhaps the most important difference between mechanistic and functional models is their usefulness as either research or management tools. Mechanistic models are useful primarily as research tools for better understanding of an integrated system, and are usually not used by non-authors due to their complexity. The functional models have modest input requirements making them useful for management purposes. Because of their simplicity, functional models are more widely used and independently validated than their mechanistic counterparts.

Every model of the plant-soil-atmosphere system, whether mechanistic or functional, uses some level of empiricism in order to reduce the need for input information. Thus it may be somewhat difficult to distinguish between mechanistic and functional models. The IBSNAT crop models are all deterministic and functional.

Soil information considered to be uniform for all soils

The models do not use the physical properties of soil matric potential or conductivity as direct inputs. The input values are approximated through generalizations of measured values. This approach is used considering the high variability of the real values in space and time. The two variables approximated are the unsaturated hydraulic conductivity for all soils near matric potentials of -2 MPa and a

constant for second stage evaporation that is also related to water flow at low water content.

The hydraulic conductivity, K, is approximated on the assumption that all soils have a constant conductivity of $5 \times 10^{-6}$ cm day$^{-1}$ at the lower limit of water availability to the plant (LOL, volume %) or at a matric potential about -2 MPa. The relationship used is

$$K_{SW} = 5 \times 10^{-6} * e^{C_T(SW-LOL)} \quad [1]$$

where $C_T$ is a texture dependent coefficient that is approximated from LOL, and SW is the actual soil water content. All water contents in this paper are expressed in volume percent. The value for $C_T$ is obtained from the equation

$$C_T = 1.2 - 0.025 * LOL \quad [2]$$

This relationship is used primarily to determine the maximum possible daily uptake rate by plant roots as used in a single root radial flow model (Ritchie, 1985).

The second stage evaporation rate of soils begins when the water content at the soil surface approaches air dry conditions (Black et al, 1969). After this stage is reached there is a gradual decrease in the evaporation rate until the soil surface is wetted again. Probably because the diffusivity of all soils near the surface is about the same value for the first few days in second stage drying when the evaporation rate is relatively large, the constant $C_e$ in the evaporation equation

$$\Sigma E_{S2} = C_e t^{-1/2} \quad [3]$$

has proven to be about 3.5 mm day$^{-1/2}$ for many soils. In equation [3] $\Sigma E_{S2}$ is the cumulative evaporation rate at time (t) in days from the beginning of stage two evaporation until soil is re-wetted.

Soil factors needed in the model

The factors considered can be categorized into those that influence (1) water entry and retention in soil, (2) loss of water by the evaporation process, (3) the limits of water retention capacity, and (4) the environment for root growth. They can be further categorized into single properties needed for the whole soil profile and those that vary with depth.

Single profile properties

Infiltration and runoff

Infiltration of water into the soil is calculated as the difference between precipitation and runoff. Runoff is calculated using the USDA-Soil Conservation Service (SCS) procedure known as the "curve number technique" (Soil Conservation Service, 1972). The procedure uses total precipitation in a calendar day to estimate runoff. The relation excludes duration of rainfall as an explicit variable, so rainfall intensity is ignored. Runoff curves are specified by numbers which vary from 0 (no runoff) to 100 (all runoff). The SCS handbook provides a list of runoff curve numbers for various hydrological soil groups and

soil-cover complexes. The SCS technique considers the wetness of the soil, calculated from previous rainfall amount, as an additional variable in determining runoff amount. The technique has been modified for layered soils. The wetness of the soil in the layers near the surface replaces the SCS antecedent rainfall condition. This modified procedure is considered by hydrologists to be one of the most conservative models of runoff when only daily precipitation is known.

To determine the runoff curve number for cropland soils, it is necessary to decide which of four hydrologic soil groups best describes the soil. Description of the groups is given in Table 1. The curve number (CN2) is determined from the slope of the site using information in Table 2. The curve number is modified for the degree of conservation practices followed as indicated on the lower part of Fig. 2.

Table 1. The soil hydrologic groups needed for selection of a runoff curve number for croplands.

| Hydrologic group | Description |
|---|---|
| A | Lowest Runoff Potential. Includes deep sands with very little silt and clay, also deep, rapidly permeable loess. |
| B | Moderately Low Runoff Potential. Mostly sandy soils less deep than A, and loess less deep or less aggregated than A, but the group as a whole has above-average infiltration after through wetting. |
| C | Moderately High Runoff Potential. Comprises shallow soils and soils containing considerable clay and colloids, though less than that of group D. The group has below-average infiltration after thorough wetting. |
| D | Highest Runoff Potential. Includes mostly clays of high swelling percent, but the group also includes some shallow soils with nearly impermeable subhorizons near the surface. |

Table 2. Runoff curve numbers (CN2) for various hydrologic conditions, slopes, and conservation practices.

| % Slope | Hydrological Condition A | B | C | D |
|---|---|---|---|---|
| 0-2 | 61 | 73 | 81 | 84 |
| 2-5 | 64 | 76 | 84 | 87 |
| 5-10 | 68 | 80 | 88 | 91 |
| >10 | 71 | 83 | 91 | 94 |

Modifications for conservation practices

| | |
|---|---|
| Good | CN2 * 1.0 |
| Fair | CN2 * 1.04 |
| Poor | CN2 * 1.08 |

Once the daily infiltration is determined a "tipping bucket" approach is used to distribute the water in the soil, or if there is no capacity for it, to increase drainage. It is assumed that water flowing through the soil at a faster rate than the drainage calculation discussed in the following section does so through connected macropores.

Drainage

Because water can be taken up by plants while drainage is occurring, the drained upper limit soil water content is not always the appropriate upper limit of soil water availability. Drainage rates among soils vary greatly. Many productive agriculture soils drain quite slowly, and may thus provide an appreciable quantity of water to plants before drainage practically stops.

The drainage formula assumes a fixed saturated volumetric water content (SAT) and a fixed drained upper limit water content (DUL). Drainage takes place only when the water content is between these two limits. The daily drainage (DRAIN) from any depth (i) is

$$DRAIN_i = SWCON\ (SW_i - DUL_i) * DLAYR_i \qquad [4]$$

where SWCON is a drainage coefficient (unitless), SW is the soil water content and DLAYR is the depth of the layer (cm). The coefficient SWCON varies between 0 and 1 and represents the fraction of water between the actual water content and the DUL that drains in one day. Thus for a coefficient of 0.5 with the soil water at SAT, the water content would decrease to half of the difference between the two limits in one day. On the second day, half of the remaining water between the limits would drain, etc. Further details of this procedure are available in Ritchie (1985).

When field values of SWCON are not available, the values are approximated from soil descriptions based on the permeability classification as given in Table 3.

Table 3.

| Permeability class | SWCON |
|---|---|
| Very Rapid | 0.85 |
| Rapid | 0.75 |
| Moderately Rapid | 0.60 |
| Moderate | 0.40 |
| Moderately Slow | 0.25 |
| Slow | 0.05 |
| Very Slow | 0.01 |

Albedo

Soil albedo (SALB) is the reflectance of solar radiation from the soil surface. It is input to the model because of its variability between soils. Under most circumstances, precise albedo values are not very important nor is it very sensitive in influencing the water balance. The soil albedo varies with surface roughness and wetness, usually being lower for wet and rough conditions. For the models, the soil albedo is used to calculate potential evaporation from the soil surface. Therefore, the approximations that are made are based on wet surface conditions. The color of the upper horizon is used to approximate the albedo as shown in Table 4.

Table 4. Color modifiers

| Color | Albedo* |
|---|---|
| Brown | 0.13 |
| Red | 0.14 |
| Black | 0.09 |
| Gray | 0.13 |
| Yellow | 0.17 |

*Add .01 for lighter modifiers and subtract .01 for darker modifiers. If the modifier "very" is present, add or subtract .02.

Upper limit stage one evaporation

The upper limit constant (U, mm), like the albedo, is usually not very sensitive in affecting crop productivity, but it can have an important influence on the amount of soil evaporation during period when the soil surface is frequently wetted by rainfall. The equations for U are as follows:

$$U = 8. + 0.08 * CLAY \qquad SAND < 80,\ CLAY < 50 \qquad [4]$$

$$U = 5. + 0.15 * (100. - SAND) \qquad SAND > 80 \qquad [5]$$

$$U = 5. + 0.06 * (100. - CLAY) \qquad CLAY > 50 \qquad [6]$$

where CLAY has a particle size less than 0.002 mm, SILT is between 0.002 and 0.05, and SAND is between 0.05 mm and 2 mm, as defined by U.S. Soil Classification System. For poorly drained soils, the above value for U is increased by a multiplier equal to (3. - 13. * SWCON), when SWCON value is less than 0.23.

Depth dependent soil properties

Extractable soil water limits

The soil water limits needed as inputs to the IBSNAT crop models are defined as: (i) drained upper limit (DUL), the highest field-measured water content of a soil after it had been thoroughly wetted and allowed to drain until drainage became practically negligible; (ii) lower limit (LOL), defined previously in this paper; and (iii) potential extractable soil water (PLEXW), the difference in water content between DUL and LOL. Procedures for determining the field-measured limits are presented in Ritchie (1981). Data for determining estimates of these parameters were taken from a survey conducted in the U.S.A. on this subject (Ratliff et al., 1983). They demonstrated significant departures between field-measured and laboratory-estimates of extractable water. This point is illustrated in Fig. 1 where laboratory estimates of extractable soil water limits, plotted against field measured values are compared with a line representing a 1:1 correspondence. The nature of the departure from the 1:1 correspondence line depends on soil texture (Ratliff et al., 1983).

Empirical equations from the field data collected in the Ratliff et al. study should be applicable to most mineral soils if direct field measurements are not available. The equations should not be used for organic or volcanic soils. Details of the derivation of the empiricisms used in this section along with the detailed data collected in the Ratliff et al study are available in a special report (Ritchie et al, 1987). The report also provides comparisons of the estimated water limit values with field measurements.

Separate equations are used for various ranges of soil textures in order to best approximate the extractable water limits. For soil with sand percent greater or equal to 75 percent, the following equations estimate LOL and PLEXW:

$$LOL_m = 18.8 - 0.168 * SAND \qquad SAND \geq 75\% \qquad [7]$$

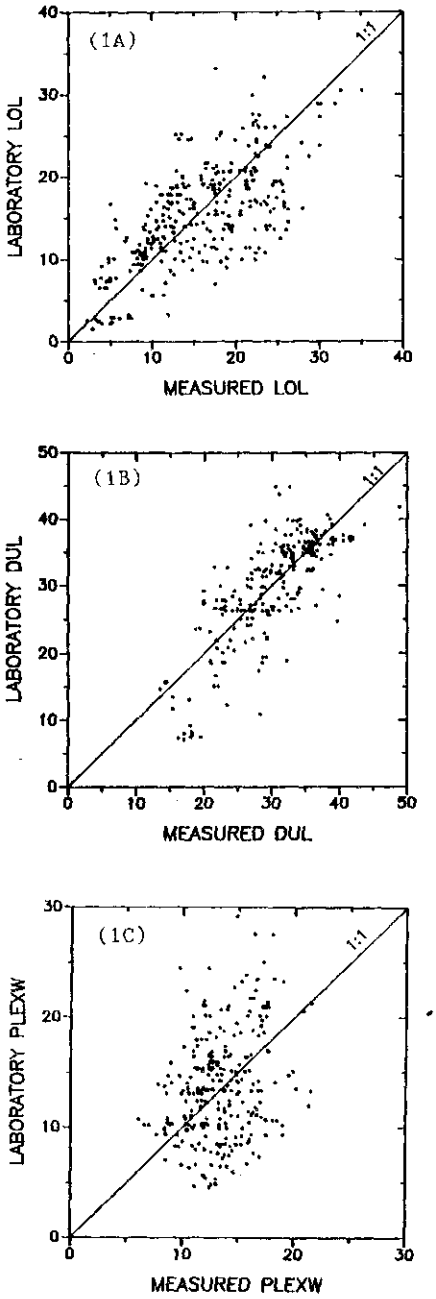
$$PLEXW_m = 42.3 - 0.381 * SAND \qquad [8]$$

where the subscript m is used when estimating water content limits for mineral soils. For sand less than 75%, soils are separated into two groups according to their silt content for $LOL_m$:

$$LOL_m = 3.62 + 0.444 * CLAY \qquad SAND < 75\%,\ SILT < 70\% \qquad [9]$$

$$LOL_m = 5.0 + 0.0244 * CLAY^2 \qquad SAND < 75\%,\ SILT \geq 70\% \qquad [10]$$

Fig. 1. Comparison of laboratory estimates of LOL (A), DUL (B) and PLEXW (C) with field-measured limits. Laboratory estimates of LOL and DUL based on water retention at -0.33 and -15 bar potentials, respectively.



For both silt groups,

$$PLEXW_m = 10.79 + 0.05004 * SILT \qquad SAND < 75\% \qquad [11]$$

For all soil textures,

$$DUL_m = LOL_m + PLEXW_m \qquad [12]$$

Approximating the Influence of Bulk Density, Organic Matter, and Rock Fragments on Extractable Soil Water Limits

The field measured limits of extractable soil water reported in the survey of Ratliff et al. (1983) did not contain samples with large variations in bulk density or organic matter. Thus the data did not provide sufficient information to develop relationships needed to account for the influence of bulk density and organic matter on the extractable soil water limits.

For most deep soils, the water extracted by roots of annual crops decreases at depths greater than about 1.3 m, indicating a lack of complete extraction. However, because some roots reach deeper soil, some water is extracted from there. Thus, the LOL water content for those depths must be estimated in order to calculate PLEXW for use in soil-water balance evaluations.

Many soils have relatively high bulk densities within part of the profile which often limits the ability of roots to penetrate uniformly throughout the soil volume (Jones, 1983).

Rawls (1983) used 2721 samples from various horizons to develop a bulk density contour map based on percentages of sand and clay. The measured density data, for the -0.03 MPa water potential, were adjusted for organic matter using a published formula so that the results were for mineral soil bulk density.

It is assumed that mineral soils of any specific texture combination have a mean mineral bulk density ($D_m$) such that DUL, LOL and PLEXW are constant. Further, soils with densities higher than $D_m$ have lower than average PLEXW and higher than average DUL and LOL and vice versa for those with densities lower than $D_m$.

Information from literature and from the Ratliff et al. (1983) survey were used to develop empirical equations to approximate $D_m$ for mineral soils with less than 8% organic matter (OM). The three equations for various textural ranges are:

$$D_m = 1.709 - 0.01134 * CLAY \qquad SAND > 80\% \qquad [13]$$

$$D_m = 1.118 + 0.00816 * SAND + CLAY * [0.008340-0.3606/(100-SAND)] \qquad 20\% < SAND < 80\% \qquad [14]$$

$$D_m = 1.453 - 0.004330 * SAND \qquad SAND < 20\% \qquad [15]$$

Voorhees et al. (1975) and Asady et al. (1985) reported data from compaction studies where the soil density for the same soil texture varied considerably. In each case, soil cores were brought into an equilibrium water potential in the -0.01 to -0.1 MPa range. In both studies, the water content at pressure potentials near DUL indicated

that there was an increase in the water content of approximately 17 volume percent per unit density change ($g/cm^3$).

Further, assuming that organic matter (OM) increases the DUL by 0.23 volume percent for each one percent of OM, the following equation is used to modify the $DUL_m$ value as calculated in equation [12]:

$$DUL_c = DUL_m - 197 * (D_m - D_f) + 0.23 * OM_f \quad [16]$$

where $D_f$ is the measured -0.03 MPa bulk density from field samples, $OM_f$ is the measured OM and $DUL_c$ is the estimated DUL when corrected for OM and density.

No suitable laboratory-measured data were available to determine the change in PLEWX for soils with unusually high or low densities or with contrasting OM contents. The following equation was used to approximate how density and OM influence PLEXW:

$$PLEXW_c = PLEXW_m + 3.5 * (D_m - D_f) + 0.55 * OM_f \quad [17]$$

$LOL_c$ follows as:

$$LOL_c = DUL_c - PLEXW_c \quad [18]$$

Figure 2 compares the estimated values for LOL, DUL, and PLEXW in the field-measured extractable soil water limits. Departures of estimated PLEXW from the observed PLEXW values seem smaller in Fig. 2C than in Fig. 1C. Thus, results produced by equations [7] to [18] are at least as good as those where laboratory procedures are used to estimate LOL, DUL and PLEXW.

If measured $D_f$ values are not available for use in equations [16] and [17], default values can be approximated by the equation:

$$D_f \text{ (default)} = [OM_f * 0.224 + (100 - OM_f) * D_m]/100 \quad [19]$$

If rock fragments (particles greater than 2 mm diameter) are a significant quantity in soil, there should be a correction made in the estimation of extractable soil water. The rock fragments are usually reported as a weight percentage (RFW). Assuming the density of rock fragments to be 2.65 $g/cm^3$, the following equation converts weight percent to volume percent (RFV):

$$RFV = 1/[1 + 2.65 * (100 - RFW)/(RFW * D_f)] \quad [20]$$

The soil volume percentage (SV) excluding rock fragments is

$$SV = 100 - RFV \quad [21]$$

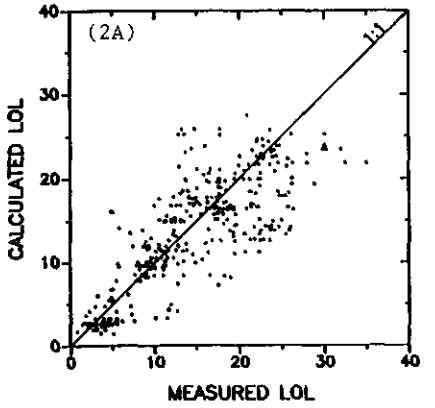
Assuming the rock fragments hold negligible water for plant use, the corrected soil water extraction limits are:

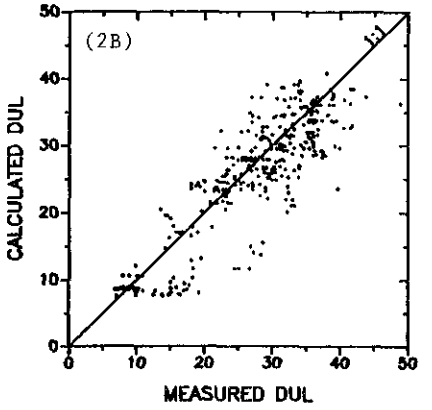
$$LOL_e - LOL_c * SV/100 \quad [22]$$

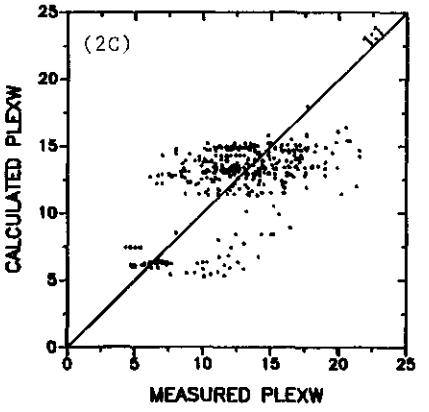
$$DUL_e = DUL_c * SV/100 \quad [23]$$

$$PLEXW_e = PLEXW_c * SV/100 \quad [24]$$

Fig. 2. Comparison of calculated LOL (A), DUL (B), and PLEXW (C) with field-measured values. Calculations are based on equations [7] to [18].



where the subscript e represents estimated water content limits that have been corrected for rock fragments, density and organic matter.

Saturated soil water

For this calculation we assume that for most cases the saturated water content (SAT) is equal to 0.85 of the total porosity. Thus the value is calculated from the equation

$$SAT = (1 - D_f/2.65) * 85 \qquad [25]$$

where 2.65 is the assumed bulk density of the mineral particles. The exception to equation [25] is when (SAT - DUL) is less than 1%. In that case we assume that

$$SAT = DUL + 1.0.$$

Root weighting factor

The root weighting factor (WR) is needed for determining the root distribution for new growth each day. By definition, the depth of soil used as model input is to contain the full grown rootzone of the crop. The WR value is the weighting that each depth of soil will receive relative to the total WR values for depths where root growth is occurring, assuming good aeration and sufficient soil water content. Poor aeration and low soil water information from the crop models modifies the WR value. Because root growth is always more dominant near the surface under optimum water contents, a value of WR between 0 and 1 is calculated for each depth increment, i, from

$$WR_i = 1. * e^{(-0.02 * Z_i)} \qquad [26]$$

where Z is the depth of the center of layer i.

The value of $WR_i$ is modified by a constant factor based on the qualitative descriptions for the presence of roots in the soil. The modifiers are given below with the multiplier constant for WR shown in parenthesis:

No roots seen (0.1)
Roots between peds (0.4)
Roots between horizontal planes (0.4)

Concluding remarks

No doubt several improvements can be made in the estimation of soil parameters used in functional crop models. Research is continuing not only to improve the soil parameters but also to provide more general and accurate relationships within the model. The models in this present state, however, are proving to be quite valuable for several applications. Further experience in model testing and use will continue to contribute to the improvements.

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# QUALITY OF REPRESENTATIVE PROFILE DESCRIPTIONS FOR PREDICTING THE LAND QUALITY MOISTURE DEFICIT AT DIFFERENT SCALES

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## Summary

A soil map on a scale of 1 : 10 000 was used to derive soil maps on scales of 1 : 25 000 and 1 : 50 000. The representative profile descriptions of the mapping units of the three soil maps were physically interpreted and were used thereafter to simulate moisture deficits.

Moisture deficits were also calculated for individual borings within the area. The simulated values of the representative profile descriptions were compared with simulated values of the individual borings.

For the whole area, the mean error was used as a quality measure. No difference in quality was found between the representative profile descriptions of the three maps. As a quality measure for point predictions, the mean absolute error and the mean square error were used. The calculated errors are quite large. Variation of the attribute within the mapping unit forms a large proportion of this error. The best predictions at point locations were obtained with the representative profiles descriptions of the 1 : 10 000 map.
Keywords: moisture deficit, soil mapping, quality control.

## Introduction

Soil maps are used and interpreted for a variety of purposes. Interpretations of soil maps are generally based on descriptions of representative profiles for each mapping unit. The quality of these interpretations depends entirely on the quality of the representative profile descriptions. A wrong representative profile description will automatically lead to wrong interpretations. Therefore, knowledge of the quality of these descriptions is very important. In this study, it was investigated whether the quality of representative profile descriptions enabled correct predictions for the entire area or for specific locations within the area. The influence of the map scale on the quality of the predictions was studied as well.

The soil map interpretation was focused on predicting moisture deficits.

## Materials and methods

### Soil survey and interpretation

The soil was mapped on a scale of 1 : 10 000, with an average observation density of 1.5 borings per hectare. For each mapping unit of the soil map the soil surveyor defined a representative profile description (RPD) based on the borings in that unit. From the soil map on a scale of 1 : 10 000 and its associated RPD's, a soil map on a scale of 1 : 25 000 with RPD's was derived through generalisation, without new fieldwork. In the same way, a soil map on a scale of 1 : 50 000 with RPD's was derived from the soil map on a scale of 1 : 25 000. Only one experienced

soil surveyor was involved in delineating and in composing representative profile descriptions.

The soil map interpretation in this study was focused on the sensitivity of soil to a drawdown of the water-table. The sensitivity was calculated with a simulation model developed by De Laat (1980).

The separate soil horizons of the representative profile descriptions are soil-physically characterized (Wösten et al., 1985). When pedologically different horizons behave physically identically, they are combined into one soil-physical horizon. To allow estimation of the quality of the RPD, a similar soil-physical interpretation of all the borings in the study area was made. With meteorological data of the study area and the soil-physical and hydrological parameters of the RPD and borings, the simulation model calculated a water balance for successive ten days' periods. Calculations were made for the period 1956-1985, assuming the presence of a grass vegetation with a growing season of 180 days, viz. from April 1 to October 1.

In this study the average moisture deficit (mm) in a thirty years period under the present hydrological situation was used, which I refer to in this article as the moisture deficit.

## Statistical analysis

The quality of the representative profile description (RPD) was estimated by comparing its value of a mapping unit with the values of the individual borings in that mapping unit.

As a quality measure for the RPD for estimating an average value for the total study area the mean error (ME) was used. The ME is of particular interest for agencies interested in results related to the total study area, e.g. water extraction companies and provincial water boards. They want to know the quality of the map for predicting a correct average value for the entire area.

As a quality measure for the RPD for estimating values at specific locations within the area, the mean absolute error (MAE) and the mean square error (MSE) were used. The value of MSE is more influenced by outliers in the dataset. The MAE and MSE are of particular interest to the local user, e.g. the farmer.

Both a large variation within mapping units and a high error in the representative profile descriptions will lead to high MAE and MSE values (Fig. 1). The error due to variation is determined by soil variation and the definition and delineation of the mapping units. The error due to the RPD is determined by the way of describing the mapping unit. Therefore, separation of these two effects is meaningful. This can be done by splitting the MSE into two parts (Kempthorne and Allmaras, 1986):

$$MSE = MSEs + MSEr$$

where:
MSEs = contribution in mean square error due to systematic errors;
MSEr = contribution in mean square error due to random errors.

The systematic error (MSEs) is caused by the difference between the value of the RPD and the mean value of the mapping unit, and a systematic component in the measurement error. The random error (MSEr) is caused by variation within the mapping unit, and a random component in the measurement error.

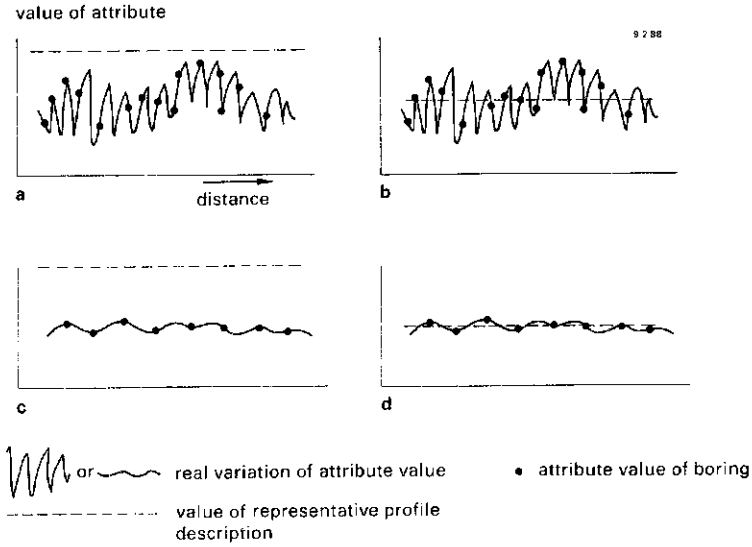


Fig. 1. Notional examples of attribute variation in mapping units and values of associated representative profile descriptions (RPD).
a) large variation and large error in RPD results in high MAE and MSE values.
b) large variation and small error in RPD results in high MAE and MSE values.
c) small variation and large error in RPD results in high MAE and MSE values.
d) small variation and small error in RPD results in low MAE and MSE values.

## Results and discussion

In Table 1 the ME, MAE and MSE values are given for the moisture deficit calculated for the scales 1 : 10 000, 1 : 25 000 and 1 : 50 000. The ME varies from 2.8 mm for the 1 : 10 000 map to 1.6 mm for the 1 : 50 000 map, indicating an overall overestimation of the average moisture deficit by the RPD on all scales. The scale of the map hardly influences the prediction of the average moisture deficit of the whole area. This means that someone who is only interested in an average value for the whole area can use the 1 : 50 000 soil map.

The MAE gives an indication of the quality of the RPD for making predictions at specific locations. The MAE values range from 5.5 mm for the 1 : 10 000 map to 7.2 mm for the 1 : 50 000 map. This means that for the 1 : 10 000 map predictions for a particular spot in the area based on representative profiles are on an average 5.5 mm too low or too high. The transition from scale 1 : 25 000 to 1 : 10 000 gives only a small benefit in terms of decrease in the mean absolute error. The MSE shows a similar pattern as the MAE. The random component (MSEr) in the MSE is quite large for the three scales.

The MSEs can be reduced by improving the quality of the RPD. With an improved RPD it is, for instance, possible to reduce the MAEs on a scale

Table 1. Mean error (ME), mean absolute error (MAE) and mean square error (MSE) values for the average moisture deficit (mm) in a thirty year period under the present hydrological situation for three scales. The 95% confidence interval for ME, MAE and MSE is given between brackets.

| Scale 1 : | Mean value (MV) | Mean error (ME) | Mean absolute error (MAE) | Mean square error | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | total (MSE) | systematic component | | random component | |
| | | | | | (MSEs) | % of MSE | (MSEr) | % of MSE |
| | (mm) | (mm) | (mm) | ($mm^2$) | ($mm^2$) | | ($mm^2$) | |
| 10 000 | 11.4 | 2.8 (1.9-3.8) | 5.5 (4.7-6.4) | 103 ( 74-132) | 13 | 13 | 90 | 87 |
| 25 000 | 11.4 | 2.9 (1.9-3.9) | 6.1 (5.2-7.0) | 120 ( 89-151) | 13 | 11 | 107 | 89 |
| 50 000 | 11.4 | 1.6 (0.4-2.8) | 7.2 (6.2-8.2) | 155 (116-194) | 65 | 42 | 90 | 58 |

of 1 : 10 000 with 13% (Table 1). The remaining 87% is a result of random errors and can not be resolved by improvement of the RPD.

For all scales the contribution of the random component in the MSE is quite large. Due to this random component, studies with very detailed simulations that are based on data for one point and that are casually extrapolated to a large area of land, have to be considered with great scepticism. Large errors can be made.

The individual farmer is often not interested in the moisture deficit on a particular spot, but more in the moisture deficit of a field. In this study, we have no information about the 'real' moisture deficit values for fields to check the quality of the RPD in this respect. We expect, however, that the error made in predicting the value for a field will be less than the error in predicting for points, because:
i) on all the scales a large proportion of the MSE is caused by random erros, of which soil variability forms a large component. For a field, the differences in change in yield due to spatial variability, are likely to be averaged;
ii) the growth of crops does often not reflect all the spatial variability as observed in soil. The extent of the rooting system has the effect to average variability patterns.
In order to translate soil variability into practical management procedures, more attention has to be paid to this aspect.

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# A FIELD METHOD FOR ESTIMATING MOISTURE CHARACTERISTICS OF SOFT CALCIC HORIZONS

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## Summary

A field method was developed to estimate available moisture in soft calcic horizons from bulk density, liquid limit and consistency. The method was tested against pF data obtained from ring samples. In total 23 samples from different sites and different parent materials in Malaga province, Spain were treated. By means of multiple regression, equations were devised which were able to explain 62% of the variation observed.
Keywords: available moisture, calcic horizons, liquid limit.

## Introduction

The present study deals with moisture characteristics of soft calcic horizons in soils of the Antequera area, Malaga Province, Spain. These horizons are encountered in a variety of soils but tend to be dominant in Inceptisols (Calcixerollic Xerochrepts) and Alfisols (Calcic Haplo/ Rhodoxeralfs). As conventional methods for the determination of moisture characteristics of calcic horizons are tedious, a field method was calibrated against laboratory methods with regard to available moisture.

## Materials and methods

The materials were collected from 23 sites where continuous soft calcic horizons were developed in soils on three different parent materials: Jurassic limestone and marls (J), Triassic marls (T) and calcareous Miocene sandstones (S). Depth of sampling ranged between 45 and 175cm, while samples were collected from the most homogeneous part of the horizon. All materials have a silt loam field texture and were slightly moist.
The "field methods" covered the following determinations: bulk density, liquid limit (ASTM, 1954), plasticity and stickiness (FAO, 1977). To obtain the bulk density in the field a horizontal plateau was made in the selected part of the calcic horizon of about 20x50cm. A small hole was made by Edelman auger (ø 7cm) of 15-20cm depth. The material was collected in a plastic bag. The volume of the hole was measured by lining it with a thin polythene bag, which was than filled with water up to the rim of the plateau. The bag was then removed and its contents were poured into a measuring cylinder to obtain the volume. The collected soil was weighed. Its moisture content was determined from satellite samples. In the laboratory the following analyses were performed by the International Soil Reference and Information Center (ISRIC): pF and bulk density on ring samples taken from the same sites.

## Results (see Table 1)

### pF and Available Moisture

The full range of pF values was established. Only the values for pF4.2 and pF2.0 are represented here. For pF2.0 the range is from 27.4-47.8

vol%. For pF4.2 values range from 4.6-17.6 vol%. For available moisture the difference of these two values is taken. It ranges from 160 mm/M to 387 mm/M The average is 291 mm/M which is in excess of what most common soil materials can store. The highest variation and lowest average is obtained in soft calcics on "S" (average 223 mm/M, range 160-387 mm/M), followed by those on "J" (average 311 mm/M, range 245-351 mm/M) and those on "T" (average 317 mm/M, range 299-336 mm/M).

Bulk densities: BDL(lab.)/BDF(field)

BDL(lab.) varies from 1.02 to 1.65 $g/cm^3$ the average being 1.33 $g/cm^3$ BDF(field) varies from 1.06 to 2.01 $g/cm^3$ the average being 1.55 $g/cm^3$. BDF(field) is consistently higher. This may be due to a systematic error in either of the two methods: The rings used for BDL(lab.) may consistently underestimate the weight of the material due to the disturbance caused in the sampling especially in indurated calcics. The field method may consistently underestimate the volume due to an imperfect fit of the plastic bag in the hole. The results for bulk density are in general in line with those published by Elbersen (1982).

Liquid Limit

The values observed are low in general. They vary from 15-47% with an average of 29.8. This is in line with the Liquid Limits found by Elbersen (1982) for soft calcics of the Merida area. He explains the low values because of the crystalline character of the soft lime: Low amounts of water in the planar voids between the sparite crystals act a lubricant. Two processes tend to interfere with this lubricating effect: admixture of clay sized impurities and growth of micrite on the sparite due to chemical redistribution on lime. Both will lead to higher liquid limits.

$CaCO^3$ content

The contents found are very high. They vary from 54.5 to 96.6% with an average of 85.9%. Similar values are reported by Elbersen (1982).

Relations

In the following the relations existing between some of the mentioned properties and the values for pF2.0 and pF4.2 will be discussed to evaluate their usefulness as predictors for the available moisture derived from these pF- values. (See correlation matrix Table 2.)

Bulk density

Both BDL(lab.) and BDF(field) show a high negative correlation with the moisture content at pF2.0. This is to be expected since pore space is related with bulk density. The correlation with watercontent at pF4.2 is poor however since it is not the packing but the constitution (type) of the material which determines this content.

Liquid Limit (LL)

LL has a fair positive correlation with both pF2.0 and pF4.2 values. For pF2.0 this positive correlation may be derived from the indirect negative correlation which exists between LL and bulk density. For pF4.2 the positive correlation presumable depends on the degree up to which higher liquid limits indicate clay admixture as discussed before. The cases

where higher liquid limits do not derive from clay admixture but from micrite growths on the crystals, will form a disturbing factor.

$CaCO^3$ content

The negative correlation between $CaCO^3$% and watercontent at pF2.0 is fair since there is a good positive correlation between bulk density and $CaCO^3$%. For pF4.2 values the correlation is poor since $CaCO^3$% is a poor indicator for the kind of admixtures to the horizon.

Multiple regression (See Table 3.)

For pF4.2

Bulk Density and LL are about equally poor predictors individually but their combination improves the prediction. $CaCO^3$ content contributes little and can be omitted. Considerable improvement is obtained by including S (Stickiness) or P (Plasticity) as dummy variables provided their values are defined as follows: S = 1 if the material is Slightly Sticky or more sticky. P = 0 if the material is nonplastic. For all other cases its value is 1. The relation selected for the field method is the one containing BDF, LL and S. It explains only 38% of the total variation observed and has a standard error of 2.64.

For pF2.0

Bulk Density is a major indicator for watercontent at pF2.0. It is superior to LL in this respect. Addition of LL to Bulk Density does not improve the prediction. Some improvement is obtained by the addition of $CaCO^3$%. Inclusion of Stickiness or Plasticity as dummy variables (as defined above) can make the inclusion of $CaCO^3$% largely superfluous. As such the relation recommended for the field method is the one containing BDF, LL and P. This relation explains 75% of the total variation and has a standard error of 2.66.

Available Moisture

Making use of the equations selected, available moisture was estimated:
pF2.0 : 59.88-13.86*BDF+0.16*LL-3.10*P
pF4.2 : -9.23+5.90*BDF+0.39*LL-2.01*S
In Fig. 1. The available moisture calculated by the ("field method") is plotted against the value obtained from the pF data. The result is reasonable since 62% of the total variation is explained. (Standard error is 2.52). This is possible despite the poor prediction of the moisture content at pF4.2 since these values are low compared to the values at pF2.0 anyhow. It is assumed that these equations have validity for soft calcic horizons in other areas too.

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Table 1. Results of field- and laboratory determinations.

| Samp.nr. | Moist Col. | Par.Mat. | Depth | pF 2.0 | pF 4.2 | Av.Moist. | BD.lab. | BD.field | $CaCO^3$% | Liq.Lim. | Stick. | Plast. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.5Y 7/4 | S | 100-105 | 38.40 | 9.48 | 28.92 | 1.44 | 1.49 | 83.70 | 23 | NS | SP/P |
| 2 | 7.5YR8/4 | J | 120-125 | 42.05 | 17.60 | 24.45 | 1.27 | 1.47 | 93.10 | 30 | SS/NS | P |
| 3 | 7.5YR6/6 | S | 100-105 | 33.52 | 4.58 | 28.94 | 1.55 | 1.79 | 83.90 | 15 | NS | SP |
| 4 | 2.5Y 7/4 | S | 075-080 | 34.70 | 15.01 | 19.69 | 1.44 | 1.96 | 74.60 | 39 | S/VS | P |
| 5 | 10YR7/4 | S | 060-065 | 27.38 | 11.37 | 16.01 | 1.62 | 2.05 | 54.50 | 22 | NS | SP |
| 6 | 10YR7/4 | S | 080-085 | 36.70 | 13.71 | 22.99 | 1.59 | 1.85 | 75.90 | 30 | SS | P |
| 7 | 10YR8/3 | J | 120-125 | 41.59 | 8.66 | 32.93 | 1.20 | 1.41 | 91.50 | 35 | S | P |
| 8 | 10YR8/2 | J | 085-090 | 43.87 | 12.11 | 31.76 | 1.21 | 1.55 | 93.00 | 32 | NS | SP |
| 9 | 10YR8/3 | S | 055-060 | 40.29 | 14.79 | 25.50 | 1.28 | 1.53 | 90.40 | 33 | NS | SP |
| 10 | 10YR8/2 | S | 110-115 | 44.96 | 12.04 | 32.92 | 1.18 | 1.43 | 71.20 | 37 | NS | P |
| 11 | 10YR8/3 | S | 050-055 | 42.85 | 12.14 | 30.71 | 1.31 | 1.55 | 87.90 | 33 | SS | SP |
| 12 | 10YR8/2 | S | 045-050 | 42.39 | 7.88 | 34.51 | 1.36 | 1.65 | 96.60 | 26 | NS | NP |
| 13 | 2.5Y 8/2 | J | 150-155 | 47.01 | 12.98 | 34.03 | 1.02 | 1.03 | 88.90 | 47 | SS | SP |
| 14 | 2.5Y 8/2 | J | 120-125 | 45.01 | 12.02 | 32.99 | 1.07 | 1.31 | 92.50 | 37 | SS | SP |
| 15 | 7.5YR7/4 | J | 090-095 | 40.09 | 14.02 | 26.07 | 1.24 | 1.36 | 92.80 | 31 | NS | SP |
| 16 | 7.5YR7/4 | T | 110-115 | 42.94 | 9.37 | 33.57 | 1.32 | 1.61 | 87.30 | 29 | SS | SP/P |
| 17 | 5YR7/6 | T | 120-125 | 37.49 | 7.60 | 29.89 | 1.44 | 1.87 | 88.50 | 22 | SS | P |
| 18 | 5YR6/6 | S | 120-125 | 34.48 | 11.80 | 22.68 | 1.34 | 1.74 | 85.20 | 22 | NS/SS | SP |
| 19 | 7.5YR8/2 | S | 100-105 | 47.81 | 9.08 | 38.73 | 1.26 | 1.50 | 96.00 | 28 | NS | NP |
| 20 | 2.5YR8/2 | S | 130-135 | 40.13 | 6.58 | 33.58 | 1.20 | 1.48 | 94.10 | 30 | NS | NP |
| 21 | 7.5YR7/4 | J | 120-125 | 41.80 | 6.74 | 35.06 | 1.29 | 1.52 | 90.80 | 31 | S | P |
| 22 | 7.5YR7/4 | J | 170-175 | 42.63 | 11.42 | 31.21 | 1.26 | 1.50 | 88.20 | 32 | NS | NP |
| 23 | 7.5YR6/6 | S | 055-060 | 33.81 | 10.65 | 23.16 | 1.65 | 1.80 | 74.00 | 22 | SS | P |

Table 2. Correlation matrix: R for pF values and properties.

| | BDL (rings) | BDF (field method) | Liquid Limit | $CaCO^3$ |
|---|---|---|---|---|
| pF 2.0 | - 0.84 | - 0.82 | 0.62 | - 0.69 |
| pF 4.2 | - 0.16 | - 0.10 | 0.50 | - 0.15 |

Fig. 1. Relation available moisture (pF2.0–pF4.2) and field method.

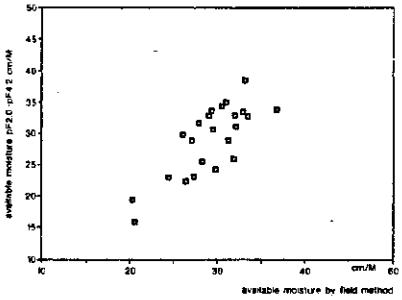


Table 3. Results of multiple regression with different combinations of variables to predict moisture content for pF 2.0 and pF 4.2.

| For pF 2.0 | | | For pF 4.2 | | |
|---|---|---|---|---|---|
| Variables(t) | R^2 | ST.ERR | Variables(t) | R^2 | ST.ERR |
| LL (3.63) | 0.39 | 3.95 | LL (2.57) | 0.24 | 2.79 |
| BDF (6.54) | 0.67 | 2.89 | BDF (0.56) | 0.015 | 3.17 |
| BDL (6.89) | 0.69 | 2.79 | BDL (0.73) | 0.025 | 3.16 |
| BDF (4.42)LL (1.09) | 0.69 | 2.87 | BDF (1.28)LL (2.83) | 0.30 | 2.75 |
| BDL (4.49)LL (0.19) | 0.69 | 2.85 | BDL (1.57)LL (2.96) | 0.32 | 2.70 |
| BDF (2.18)LL (2.10)CA (2.87) | 0.78 | 2.46 | BDF (0.56)LL (2.45)CA (0.66) | 0.31 | 2.79 |
| BDL (1.74)LL (1.38)CA (2.43) | 0.77 | 2.56 | BDL (0.84)LL (2.37)CA (0.32) | 0.33 | 2.76 |
| BDF (1.96)LL (1.88)CA (2.80) | 0.78 | 2.53 | BDF (1.02)LL (2.95)CA (0.53) | 0.39 | 2.70 |
| S (0.16) | | | S (1.51) | | |
| BDL (1.50)LL (1.07)CA (2.26) | 0.77 | 2.63 | BDL (1.75)LL (3.24)CA (0.22) | 0.45 | 2.56 |
| S (0.04) | | | S (2.00) | | |
| BDF (4.11)LL (0.90)S (0.10) | 0.69 | 2.95 | BDF (1.78)LL (3.35)S (1.60) | 0.38 | 2.64 |
| BDL (4.26)LL (0.17)S (0.63) | 0.70 | 2.89 | BDL (2.41)LL (3.81)S (2.07) | 0.45 | 2.50 |
| BDF (4.31)LL (1.50)P (2.07) | 0.75 | 2.66 | BDF (1.03)LL (2.64)P (1.45) | 0.37 | 2.67 |
| BDL (3.97)LL (0.58)P (1.49) | 0.73 | 2.77 | BDL (1.14)LL (2.58)P (1.26) | 0.37 | 2.66 |
| BDF (6.45)S (0.59) | 0.68 | 2.93 | LL (2.77)S (1.03) | 0.28 | 2.78 |
| BDL (6.81)S (0.65) | 0.70 | 2.83 | LL (2.58)P (1.66) | 0.33 | 2.67 |
| BDF (6.65)P (1.81) | 0.70 | 2.74 | | | |
| BDL (6.73)P (1.41) | 0.72 | 2.72 | | | |

Behind each variable the t value is given between brackets.
In addition R^2 (squared value of the regression coefficient) and ST.ERR (standard error of the estimate) are given. BDF = bulk density determined by field method, BDL = bulk density determined by ring sampling, LL = Liquid limit, CA = $CaCO^3$ %, S = Stickiness (0 or 1), P = Plasticity (0 or 1).

# TEMPORAL VARIABILITY OF WORKABILITY, AND PLANTING AND EMERGENCE DATES IN RELATION TO CROP YIELD FOR TWO CONTRASTING SOILS IN THE NETHERLANDS

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## Summary

Soil water flow and crop production simulation is used to evaluate the variability of workability, planting/sowing and emergence dates and the related crop yield for two Dutch soils. Workability is derived from the simulated pressure head of the topsoil and a threshold value. Probability of occurrence of workable days is presented. Planting and emergence dates of a potato crop are calculated as well as the actual yield and yield reduction caused by a shortening of the growing season.
Keywords: workability, timeliness, yield reduction, simulation.

## Introduction

Workability in spring is an important land quality defining suitability of land for a spring-sown crop. When sowing or planting takes place earlier in spring, the final crop yield may be higher because the growing season is longer.

Workability depends largely on soil characteristics and the moisture condition of the topsoil. The soil moisture status itself differs from day to day depending on weather, soil characteristics and water-table. The moisture regime and the crop production are simulated with the model SWACROP. The workability is related to the pressure head at 5 cm depth and a soil-specific threshold value. The planting and emergence dates of a potato crop are calculated as well as the actual tuber yield and its reduction due to retarded planting and emergence. The aim of this paper is to show the temporal variability of workability and emergence (timeliness) and the related crop yield reduction, as a part of a quantitative land evaluation procedure.

## Methods and materials

### Model description

The model SWACROP consists of a soil water flow model (SWATRE) and a crop production model (CROPR). One-dimensional, transient, unsaturated water flow in a heterogeneous soil-root system is described by SWATRE using the Darcy flow equation and the continuity equation (Belmans et al., 1983; Feddes et al., 1988). The combination of these equations is solved numerically with hydraulic properties, boundary conditions for the top and bottom of the schematized soil profile and initial conditions. For the top boundary condition daily meteorological data are used. As a bottom boundary the water-table can be used or a known potential or flux through the bottom of the profile.

The crop production model CROPR (Feddes et al., 1978) computes daily actual and potential dry matter productions under optimum conditions of fertilization and without harmful effects of weeds and diseases. The

output of the integrated SWACROP model contains all the terms of the soil-water balance, the pressure head distribution, and the crop yield.

Workability

The workability of the soil is related to the moisture regime of the topsoil. Van Wijk & Feddes (1986) derive the workability of the topsoil from the pressure head at 5 cm depth and a threshold value (workability limit). When the soil-specific threshold value below which fieldwork can take place without deterioration of the soil structure is known, workability on a daily basis can be derived from simulated pressure heads. This implies that the results show the temporal variability for this land quality from day to day. Workability, however, also differs from year to year. For that reason calculations are carried out with thirty years' meteorological data, so that the variation due to weather conditions is obtained.

Planting/sowing and emergence dates

Knowing the occurrence of workable days, the earliest possible planting date for each of the thirty simulation years can be predicted. For potatoes four workable days are considered to be necessary for planting activities on an average Dutch farm (Van Wijk & Feddes, 1986). The emergence date is calculated with a required heat-sum. The daily heat-sum increment is a function of temperature and pressure head ($h$) at 5 cm depth. Germination is retarded when the topsoil is too wet ($h > -100$ cm) or too dry ($h < -500$ cm). With these methods the long-term variability of planting and emergence dates can be predicted.

Yield reduction

The crop yield reduction ($R_s$) caused by retarded planting and emergence is called the spring effect and is expressed as:

$$R_s = 1 - Q_{act1}/Q_{act2}$$

where:
$Q_{act1}$ = actual yield (kg/ha),
$Q_{act2}$ = actual yield without moisture limitations in spring (kg/ha).

The actual yield $Q_{act1}$ is calculated using the planting and emergence dates that are simulated as discussed above. For $Q_{act2}$ the planting date used is the first possible one for potatoes in the Netherlands (1st April) and germination is considered to be only depending on the heat-sum and moisture regime is assumed to be optimal. The earliest possible emergence date is calculated, followed by the yield that can be obtained, when in spring no workability or germination restrictions occur.

Sites

The sites used are the Sinderhoeve and Lelystad experimental stations. At the Sinderhoeve site a coarse, sandy, fluvioglacial soil is found with a deep water-table, which can be classified as a Plaggeptic Haplohumod. The soils at the Lelystad site are Typic Fluvaquents (clay loam with shallow water-table). For modelling purposes the soil profiles have to be divided into physically different layers for which water retention and hydraulic conductivity characteristics were measured.

## Results and conclusions

The derivation of workable days is illustrated in Figure 1. In the graph the course of the pressure head at 5 cm depth for the Sinderhoeve is plotted together with the threshold value ($h$ = -70 cm). Values below the horizontal line in the figure represent non-workable days. Probability of occurrence of workable days for all the ten days' periods of the year can be calculated, knowing workability for each day of the thirty years (Bouma & Van Lanen, 1987). In Figure 2 these probability graphs are drawn for both sites. The threshold value for Lelystad is $h$ = -90 cm. It is obvious that this land quality can be quite restrictive for the Lelystad soil. Figure 3 shows the calculated planting and emergence dates for potatoes at the Sinderhoeve and Lelystad. Yield reduction due to timeliness problems will be greater at the Lelystad site.

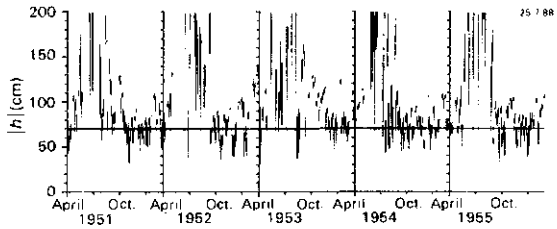


Fig. 1. Pressure head ($h$) at 5 cm depth at the Sinderhoeve site (1951-1955).

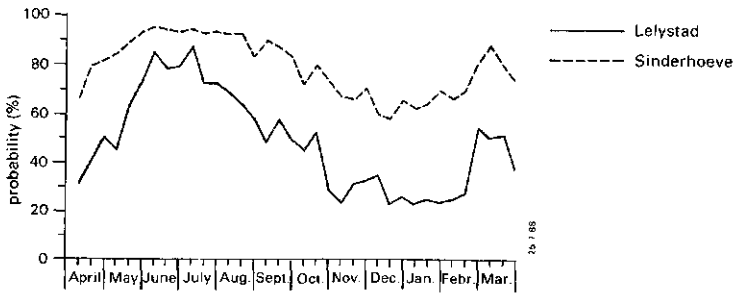


Fig. 2. Probability per ten days of occurrence of a workable day.

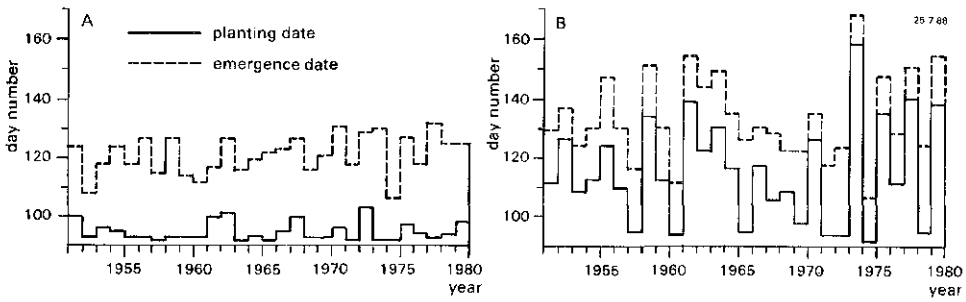


Fig. 3. Planting and emergence dates for potatoes at the Sinderhoeve site (A) and the Lelystad site (B) from 1951 to 1980, 1st April (day 91) to 30th June (day 181).

At the Sinderhoeve no significant reduction is found. The results of the relative tuber yield reduction calculations are shown in Figure 4. The variability of the values can be very high, e.g. for Lelystad the relative yield reduction can range from 0 to 36 %.

The results show that the approach used can describe land qualities in a more quantitative way. The parameters, characterizing land qualities (such as the number of workable days characterizing workability), can be obtained by simulation models. As a part of quantitative land evaluation procedures, simulation can be used to estimate the temporal variability of land qualities, such as workability, and related crop yields.

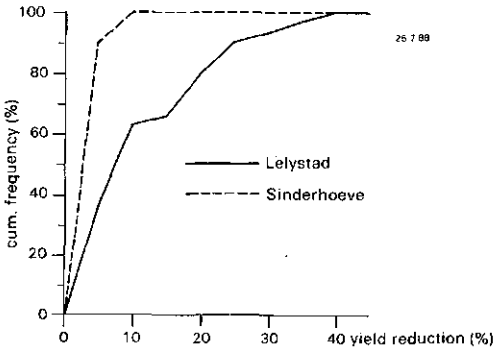


Fig. 4. Cumulative frequency of yield reduction ($1 - Q_{act1}/Q_{act2}$) for the Lelystad and Sinderhoeve sites.

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# APPLICATION OF SCALING TECHNIQUES AT A WATERSHED SCALE

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## Introduction

In hydrology values of parameters and variables are usually inferred from measurements at a small number of points. The question then arises how well the limited number of observations will represent the property to be investigated, taking into account that soil properties may have a large natural variability. It is therefore that techniques have to be found that describe the spatial variability of soil properties (Hopmans, 1986a). Since the study of unsaturated soil-water transport requires knowledge of soil hydraulic properties, the objectives of this investigation were (i) to describe the variability of soil physical properties and (ii) to study the influence of this variability on plant transpiration and other water balance components. Also, before conclusions can be drawn with respect to the transport of solutes through the soil, it is of immediate concern that the transport of water through the unsaturated zone is characterized first. Evaluation of simulation results (transpiration and water balance) is done by comparison with values of transpiration and other water balance components, measured at the experimental hydrological study-area "Hupselse Beek" near Eibergen (Gld).

## Methods

A soil map of the catchment area (650 ha) was made by STIBOKA (Wösten et al., 1983). Forty profile characteristics were described at 2 borings per ha; a sampling density based on a study by Burrough et al. (1983). Consequently, approximately 1300 locations were sampled. The soil data make, together with the sampling location coordinates, a soil morphological database.

Soil physical properties (soil-water characteristic curve and unsaturated hydraulic conductivity curve) were measured according to 3 scenarios or sampling schemes; each scheme being different by the area of the sampled region. In the first sampling scheme, 7 profiles across the 650 ha study area were examined. These 7 sites were chosen in such a way that they included most of the characteristic soil profiles and horizons in the watershed. The results of the soil physical measurements were reported by Wösten et al. (1983). The second sampling scheme comprised an area of 0.5 ha and was chosen such that the 7 sampled sites within this area were all from the same and most important soil map unit. Duplicate samples were taken in the A and B horizon. Finally, the highest sampling density was achieved in the third sampling scheme, where 6 sites were sampled in triplicate within 2 $m^2$, and in the A, B, and C horizon. This sampled area was located within the second scheme.

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Before analyzing the soil physical data, the soil water characteristic and hydraulic conductivity curves were both fitted to an analytical model. All soil physical data for each soil sample were thereby characterized by only 5 parameters (Hopmans and Overmars, 1986).

The variation in soil hydraulic properties was determined by a normalization or scaling procedure, by which a number of soil-water characteristic or hydraulic conductivity curves is described by a reference curve and a set of scale factor values (Hopmans, 1987a). After measurement of soil hydraulic properties at 20 locations (sampling scheme 1, 2 and 3) and at different depths, and after statistical analysis of the scale factor values, it was concluded that a representative soil profile in the watershed consists of a A-horizon with fixed thickness and a BC and D-horizon with variable thickness (Hopmans and Stricker, 1987). Such a reduction in the number of horizons which are distinct from the soil physical point of view was also found by Wösten et al. (1985).

The transport of water was partly simulated with an existing deterministic computer model (SWATRE). Assuming variability in soil hydraulic properties, this model was modified such that soil hydraulic properties were generated from the frequency distribution, the mean and standard deviation of the set of scale factor values for each distinct horizon (Hopmans, 1987b). A stochastic-deterministic 1-dimensional model is proposed that simulates soil-water flow with both variable soil hydraulic properties and a variable lower boundary condition. Since groundwater levels were measured at approximately 85 locations within the watershed it was also possible to normalize the discharge (q)-groundwater level (h) relationships and to calculate the corresponding set of scale factor values with its frequency distribution, mean and standard deviation (Hopmans, 1987c). From the statistical properties of the sets of scale factor values for the soil hydraulic properties of the various horizons and the lower boundary condition, one realization of output variables is obtained with the deterministic model. Through Monte-Carlo simulations, by which a series of realizations are simulated, a frequency distribution of output variables (transpiration, discharge and groundwater levels) is obtained. With the statistical properties of the soil physical characteristics from the second sampling scheme as input, Cislerova (1987) compared the results of such a Monte-Carlo analysis with the 7 deterministic simulations using the measured values of soil hydraulic properties of the second sampling scheme. The statistical properties of output variables of both types of simulations agreed fairly well.

## Main results

Application of the stochastic-deterministic model (Monte-Carlo analysis) with a stochastic input of soil hydraulic properties and lower boundary condition, determined from all available soil physical and groundwater level data, will be closer to reality (Hopmans, 1987d). It should be noted, however, that the analytical model for the soil physical characteristics in combination with the normalizing procedure will yield soil hydraulic properties that may deviate somewhat from the original measured values.

A Monte-Carlo analysis was carried out for 5 characteristic profiles, each profile being representative for a specific starting depth to clay (D-horizon). After statistical analysis of the measured groundwater levels, it was found that also the q(h)-relationship was dependent on starting depth to clay. Therefore, two normalized q(h)-relations were

defined, based upon whether starting depth to clay was above or below the 1.2 m soil depth. The simulation model was validated by comparing measured and simulated transpiration values and groundwater level depths. There was close agreement in transpiration values for the growing season of 1982, however, the simulation results for 1976 were significantly larger than measured. This difference may be caused by the calibration procedure of the sink-term. The sink-term, which simulates the water uptake by plant roots, was calibrated in another study for only one typical soil profile. A correct calibration should take into account the measured variability in soil horizon thickness and soil physical properties. Further validation included the comparison of the statistical properties of groundwater levels at the end of the growing season. The mean simulated and measured groundwater levels were very close, but the simulated variation was only 40-60% of the measured variation. Most likely, most of the smaller than actual variation was caused by assumptions regarding the variability of input variables. From calculation of the statistical properties of each set of output variables, it was then possible to characterize the Hupselse Beek watershed by 3 soil profile classes. This classification was based on distinct values for simulated transpiration values during the growing seasons of 1976 and 1982 for each class.

## Conclusion

Through scaling it is possible to describe the spatial variability of soil physical or hydrological variables. Using the statistical properties of sets of scale factor values, the variation in soil-water transport can be simulated with a one-dimensional soil-water transport model. Monte-Carlo simulations resulted in a frequency distribution of plant transpiration for various soil profile classes within the watershed.

Differences between measured and simulated values for the mean and variation in output variables may be minimized by a recalibration of the sink-term and by making variation of input variables as potential transpiration (different landuses), precipitation or rooting depth possible.

Future research will make it possible to compare the 1-dimensional results with a 2-dimensional soil-water system. For the latter problem, it will be necessary to take into account the spatial structure in soil hydraulic properties in the horizontal direction. Another study will investigate whether it is possible to estimate soil physical characteristics from soil morfological information. A technique to be used for that purpose is co-kriging.

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# A SYSTEM FOR QUANTITATIVE EVALUATION OF SOIL FERTILITY AND THE RESPONSE TO FERTILIZERS

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## Summary

A system is presented that calculates the yield of maize on unfertilized tropical soils and the yields than can be expected upon application of fertilizers. Required soil (0-20 cm) data are: pH($H_2O$), org. C., P-Olsen, exch. K. Relations between yield and the uptake of N, P and K, and the balance between these nutrients form the basis of the model. The system indicates the nutrient(s) in shortest supply and the most economic combinations and rates of fertilizers.

## Introduction

In the course of some projects on soils and crops in Kenya and Suriname a simple model has been developed for quantitative evaluation of the fertility of tropical soils. Preliminary versions (of parts) of this so-called QUEFTS system are given by Guiking et al. (1983), Janssen et al. (1986) and Smaling & Janssen (1987), and the final version by Janssen et al. (1989a, b).

Chemical soil fertility is conceived as the capacity of a soil to provide plants with nutrients. In many unfertilized soils crop growth is limited by a low supply of one or more of the major nutrients N, P and K while there is a relatively ample supply of secondary and trace elements. Therefore the QUEFTS system is as yet restricted to an appraisal of the status of N, P and K. It calculates yields of maize as a function of the availability of these nutrients. The system is meant for well drained deeply rootable soils of which the values of chemical properties lie within the ranges: pH($H_2O$) 4.5-7.0; organic C less than 70 g/kg, P-Olsen less than 30 mg/kg, exchangeable K less than 30 mmol/kg.

## Main concepts used in the system

The pivot of QUEFTS is formed by the relations between nutrient uptake and yield. Such relations might vary considerably.

When a nutrient is poorly available compared to the other nutrients and growth factors, it is diluted in the plant and its content goes down to a minimum value; the ratio of yield and nutrient uptake has then its maximum value.

On the contrary, when a nutrient is abundantly available, it accumulates in the plant till its content reaches a maximum value; the ratio of yield and nutrient uptake has then its minimum value.

Given a certain uptake of N, P or K the possible yields range between the yields that correspond with maximum accumulation and maximum dilution, respectively, which are denoted by YNA, YND, YPA, YPD, YKA and YKD.

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In the soil, nutrients are made available to crops by processes like mineralization of organic matter and weathering of minerals. Often the supplies of the different nutrients are not in balance with the needs of a crop. When the supply of a particular nutrient is small compared to those of other nutrients, the whole supply of that nutrient will be taken up by the crop. When the supply of a particular nutrient is large compared to those of other nutrients, crop growth is limited by the low availability of these other nutrients and the crop cannot make use of the whole supply of the particular nutrient. Then the actual uptake is less than the potential supply.

The potential supply of a nutrient is enlarged by application of fertilizers. A part of the applied nutrient is made unavailable to crops by processes like microbial immobilization and chemical precipitation, and a part is lost by e.g. leaching and volatilization. The fraction that is recovered by the crop might vary from zero to about 0.8. Under otherwhise comparable conditions the recovery of a fertilizer nutrient by the crop is the higher, the lower the supply of that nutrient by the soil is. The maximum recovery fraction for a fertilizer nutrient is a function of soil, weather and crop properties.

## Scheme of calculations

The QUEFTS system comprises a number of calculation steps.

First the potential supplies of N, P and K are calculated using empirical equations that have been established on the basis of field-trial results (Table 1). In the equations at least two soil properties are included; this proved necessary to account for their mutual relationships.

The actual uptake of a nutrient is calculated as a function of the potential supply of that nutrient in relation to the potential supplies of the other nutrients. The curve of actual uptake against potential supply of a nutrient consists of three parts. At low values of the potential supply actual uptake equals supply, at medium values the curve is parabolic, and at high values the actual uptake reaches a maximum value that is determined by the potential supply of the other nutrients.

The data for actual uptake are used to calculate the yields that correspond with maximum accumulation and maximum dilution of a nutrient (Table 2). To produce any grain, plants must have a minimum size for which the required uptakes per ha are 5 kg N, 0.4 kg P and 2 kg K. Therefore these values are subtracted from UN, UP and UK in the equations of Table 2.

Next the yield ranges found for the three nutrients are combined to one yield estimate. Principles for this combining are that the estimated yield lies in the overlap if yield ranges overlap, and that it can never exceed the upper limit of the lowest yield range if there is no overlap. For the calculation of the yield within an overlap

Table 1. Equations for calculating the potential supply of N, P and K by a soil. Potential supplies (SN, SP and SK) are expressed in kg/ha, org. C in g/kg, P-Olsen in mg/kg and exch. K in mmol/kg; pH is pH($H_2O$). Sample depth is 0-20 cm .

| |
|---|
| $SN = 1.7 \times (pH-3) \times org\ C$ |
| $SP = 0.35 \times (1-0.5\ (pH-6)^2) \times org\ C + 0.5 \times P\text{-}Olsen$ |
| $SK = 100 \times (8.5-pH) \times exch.\ K/(2 + 0.9 \times org\ C)$ |

Table 2. Equations for calculating grain yields of maize (kg/ha) corresponding with maximum accumulation (YNA, YPA, YKA) and maximum dilution (YND, YPD, YKD) of N, P and K in the crop. UN, UP and UK stand for actual uptake of N, P and K in kg/ha.

| | |
|---|---|
| YNA = 30 x (UN- 5) | YND = 70 x (UN-5) |
| YPA = 200 x (UP-0.4) | YPD = 600 x (UP-0.4) |
| YKA = 30 x (UK-2) | YKD = 120 x (UK-2) |

parabolic equations have been established. First yield ranges are combined in pairs (N and P, N and K, P and K) and then the yields for paired nutrients are averaged. This average is the final yield estimate. Table 3 shows the combining of yield ranges for N and P.

The increase of the potential nutrient supply due to fertilizer application is found by multiplication of the rate of fertilizer and the maximum recovery fraction. The value for the maximum recovery fraction might be obtained from appropriate fertilizer trials. If such data are not available a fraction of 0.5 is used as standard for N and K fertilizers, and of 0.1 for P fertilizers.

Once the potential supply upon fertilizer application has been calculated the procedures outlined above are applied again to estimate the yield of a fertilized crop.

If the prices of fertilizer N, P and K are known, or at least their ratios, the most economic combinations of fertilizers can be determined. First the most limiting nutrient should be applied till the yield reaches a level where the second nutrient becomes most limiting. By applying these two nutrients in a balanced ratio the yield can further increase till the third nutrient becomes limiting. For still higher yields a balanced application of all three nutrients is required. This procedure follows Liebig's Law of the Minimum.

What the most profitable rates of fertilizers are depends on the price ratio of produce and fertilizers, and on yield limitation by other growth factors like water availability and solar radiation.

Table 3. Combining of yield ranges for N and P. Actual uptake of P is 10.9 and the corresponding yield range 2100-6300 kg/ha. Actual uptake of N varies as indicated. All data in kg/ha.

| N uptake | Yield range for N | Overlap with range for P | Combined yield for N and P |
|---|---|---|---|
| 35 | 900- 2100 | 2100 | 2100 |
| 65 | 1800- 4200 | 2100-4200 | 3383 |
| 95 | 2700- 6300 | 2700-6300 | 4278 |
| 125 | 3600- 8400 | 3600-6300 | 4988 |
| 155 | 4500-10500 | 4500-6300 | 5553 |
| 185 | 5400-12600 | 5400-6300 | 5989 |
| 215 | 6300-14700 | 6300 | 6300 |

## An example

Table 4 shows the calculated results for various fertilizer treatments on a soil where P is severely limiting. Application of N or K alone results in an increase of their supply but not of their uptake and the yield does not change. Upon application of P, however, the uptake increases for all three nutrients, although the supply of N and K remains the same as in the unfertilized soil, and there is a

considerable increase in yield. When P has been applied, it is profitable to apply also N or K or both. The most economic N-P-K rates to spend 400, 500, 600 or 700 units on fertilizers are 0-50-0, 9-58-0, 17-62-18 and 28-69-18 with corresponding yields of 2818, 3043, 3263 and 3483 and net returns of 1428, 1553, 1673 and 1793.

Table 4. Calculated potential supply (SN, SP, SK) and actual uptake (UN, UP, UK) of N, P, and K, maize yield estimate (YE) (all in kg/ha) and returns (in units of the price of 1 kg of maize) for various fertilizer treatments on a soil with pH($H_2O$) 4.7, org. C 23 g/kg, P-Olsen 1.6 mg/kg and exch. K 4 mmol/kg. Prices of maize, N, P and K are in the proportion of 1 to 4 to 8 to 2. Maximum recovery fractions are 0.5 for N and K, 0.1 for P.

| Nutrients applied with fertilizer (kg/ha) | | | | | | | |
|---|---|---|---|---|---|---|---|
| N | 0 | 50 | 0 | 0 | 50 | 0 | 50 |
| P | 0 | 0 | 50 | 0 | 50 | 50 | 50 |
| K | 0 | 0 | 0 | 50 | 0 | 50 | 50 |
| SN | 66.5 | 91.5 | 66.5 | 66.5 | 91.5 | 66.5 | 91.5 |
| SP | 2.1 | 2.1 | 7.1 | 2.1 | 7.1 | 7.1 | 7.1 |
| SK | 67.0 | 67.0 | 67.0 | 92.0 | 67.0 | 92.0 | 92.0 |
| UN | 38.0 | 38.0 | 62.5 | 38.0 | 81.5 | 62.5 | 81.5 |
| UP | 2.1 | 2.1 | 6.9 | 2.1 | 7.0 | 6.9 | 7.0 |
| UK | 35.0 | 35.0 | 61.0 | 35.0 | 61.0 | 79.2 | 79.2 |
| YE | 990 | 990 | 2818 | 990 | 3114 | 3006 | 3290 |
| GR[1)] | - | 0 | 1828 | 0 | 2124 | 2016 | 2300 |
| Costs | - | 200 | 400 | 100 | 600 | 500 | 700 |
| NR[1)] | - | -200 | 1428 | -100 | 1524 | 1516 | 1600 |

[1)] GR, NR = gross return, net return.

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# ASSESSMENT OF SOIL MOISTURE DEFICIT AND SOIL AERATION BY QUANTITATIVE EVALUATION PROCEDURES AS OPPOSED TO QUALITATIVE METHODS

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## Summary

Qualitative and quantitative land evaluation procedures are applied to assess the land qualities moisture deficit and aeration for two soil types and several water-table classes. As a part of quantitative procedures, the use of dynamic simulation models allows a more extensive quantitative expression of land qualities, including temporal variability, and a more comprehensive evaluation of potential situations than the qualitative methods.
Keywords: qualitative and quantitative land evaluation methods, dynamic simulation models, soil moisture deficit, soil aeration.

## Introduction

Dutch agriculture is now facing problems of surplus production. Furthermore, intensive cropping, which mainly includes wheat, potatoes and sugar beets in rotation, has resulted in a deterioration of soil structure and too high a population of nematodes and soil fungi. Policy is changing and farmers have to adapt their production systems. More market-oriented production systems have to be developed that have no adverse effects on nature and environment (e.g. reduction in nutrient losses). This new policy will alter land use (e.g. zoning of production, set-aside of land, and timber production). Conflicting situations may arise. Policy-making, therefore, should be based on objective and scientifically developed land evaluation methods. Descriptive, qualitative evaluation systems produce quick but general answers. As a first approximation they are helpful, but more quantitative information is generally needed. This may be provided by quantitative procedures. A large number of crops and a wide range of site conditions, both actual and potential, can be evaluated quantitatively.

The aim of this paper is to show differences between quantitative and qualitative land evaluation procedures. The land qualities moisture deficit and aeration will be used as examples. Emphasis is laid on temporal variability, expressing the range in weather conditions at a specific location.

## Methods and materials

The simplest qualitative land evaluation procedures are purely descriptive. Land qualities are expressed in classes, such as good, moderate or bad. The more sophisticated qualitative methods, sometimes called 'semi-quantitative', already provide quantitative expressions for some land qualities, which have been derived from measured data, such as moisture retention and climatic data. This can be seen as a gradual transition to quantitative procedures. The essential difference between qualitative and quantitative procedures is that the latter comprise the application of dynamic simulation models.

### Qualitative land evaluation procedures

This paper only deals with land qualities associated with water shortage or water excess. Moreover, only temporal variability will be discussed and no spatial aspects. Plant-available water (-5 kPa to -1600 kPa), moisture supply capacity (plant-available water plus capillary rise), and soil droughtiness (plant-available water minus potential precipitation deficit) will be calculated as measures for drought susceptibility. Air capacity (0 to -5 kPa), drainage status (related to water-table), and wetness class (integration of number of field capacity days, gley features and depth of impermeable layer) will be used for susceptibility to water excess. For a more detailed description of the assessment of the land qualities the reader is referred to McKeague et al. (1984).

### Quantitative land evaluation procedures

Simulation of water flow and evapotranspiration by dynamic simulation models (e.g. Belmans et al., 1983) plays a prominent part in determining the land qualities moisture deficit and aeration. Land characteristics are either directly used as model input (e.g. horizont thickness and rootable depth) or converted by pedofunctions into land properties (e.g. moisture retention and hydraulic conductivity data) to feed the model. Moreover, non-land data, such as crop and weather information, are needed to perform the simulation. Variability in weather conditions is taken into account by using a thirty years' record of meteorological data. The model computes, among other things, potential and actual transpirations on a daily basis as well as air-filled porosities at various depths. Moisture deficit occurs when actual transpiration is smaller than potential transpiration. Inadequate aeration occurs when the air-filled porosity at a certain depth is lower than a soil-specific threshold value (Bakker et al., 1987). Land qualities are described with a probability distribution. Probability of occurrence of a moisture deficit or an adequate aeration is derived from an analysis of the daily results of the simulation of thirty years. This procedure is widely discussed elsewhere (Bouma & Van Lanen, 1987; Van Lanen et al., 1987).

### Crop, soils and water-table classes

The land qualities moisture deficit and aeration are determined for two soil types, which are classified as Typic Fluvaquents. The soils are located in the south-western part of the Netherlands and are mainly in use as arable land. Therefore, a potato crop is used to illustrate the procedures. The first soil type (indicated by A) consists of 60 cm of sandy loam overlying sand and the second type (indicated by B) consists entirely of sandy loam. Both soils are calcareous and have topsoils of about 30 cm with organic matter contents of about 2%. Water-table classes are distinguished, which are charaterized by the mean highest (MHW) and the mean lowest water-tables (MLW). In these soils three classes occur, namely IV, VI and VII. These classes have MHWs of 50, 75 and 110 cm and MLWs of 120, 160 and 190 cm below soil surface respectively.

## Results and discussion

The results of the qualitative land evaluation procedures are listed in Table 1. In the upper part, land qualities related to drought susceptibility are given and in the lower part those related to water excess.

The results of the quantitative procedure are presented in Figures 1a (moisture deficit) and 1b (aeration). The assessment of the land qualities is carried out for both soil types A and B and several water-table classes. The land qualities related to water shortage are determined for water-table classes VI and VII, and those related to water excess for classes IV and VI.

Table 1. Assessment of some water-associated land qualities for two soil types (A and B) and several water-table classes (IV, VI and VII) by qualitative methods.

| Water shortage land qualities (mm) | A | | B | |
|---|---|---|---|---|
| | VI | VII | VI | VII |
| plant-available water | 100 | 100 | 115 | 115 |
| moisture supply capacity | 100-150 | 100-150 | > 200 | 150-200 |
| soil droughtiness | 30 | 30 | 45 | 45 |

| Water excess land qualities | A | | B | |
|---|---|---|---|---|
| | IV | VI | IV | VI |
| air capacity (vol.%) | 7 | 7 | 8 | 8 |
| drainage status | 2 | 2 | 2 | 2 |
| wetness class | III-VI | III-VI | III-VI | III-VI |

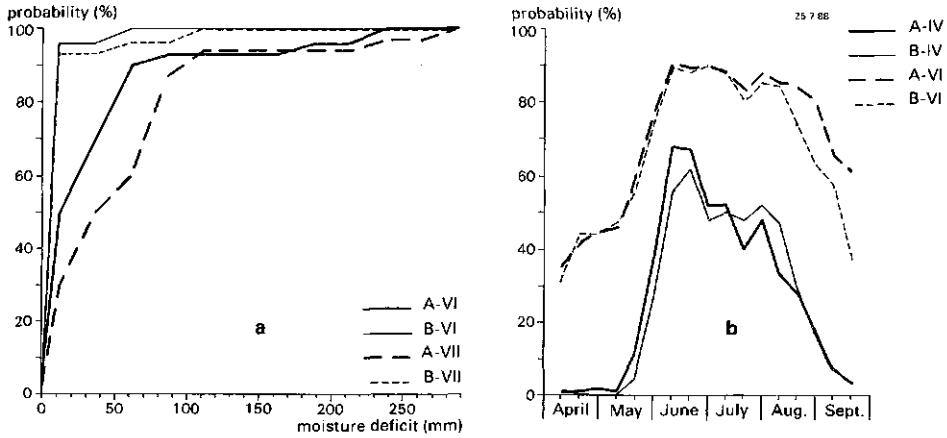


Fig.1. Probabilities of occurrence of a moisture deficit (mm) for the entire growing season (a) and adequate soil aeration (days per ten days) (b) for two soil types (A and B) and several water-table classes (IV, VI, and VII).

In 9 out of 10 years the moisture deficit of the potato crop grown on soil type B is less than 20 mm. Hardly do any differences occur between the water-table classes (Fig. 1a). The moisture deficits in soil type A are higher than those in B; in 9 out of 10 years the deficits are less than 70 mm for water-table class VI and 110 mm for class VII. The maximum deficits are about 120 mm in soil type B and about 250 mm in A. Temporal variability, as induced by variable weather conditions, is not accounted

for by the qualitative methods (Table 1). Plant-available water is used without taking into account climatic differences. The moisture supply capacity and soil droughtiness are in a way adjusted to soil, crop and climate. In comparison with the quantitative procedures, the results of qualitative methods only refer to one specific, usually an average or a typically dry, climatic situation. Furthermore, the approximation is much simpler. For instance, irregular rainfall distribution (time step equals one growing season) and increasing rooting depth for spring-sown crops are not taken into account.

Between the soil types A and B no great differences in aeration occur. Significant differences occur, however, between the water-table classes IV and VI. From June to September aeration is adequate in 9 out of 10 days in soils with water-table class VI (on an average), but this is not more than 5 out of 10 days in soils with class IV (Fig. 1b). At the start and the end of the growing season, aeration is less than in the mid-season. The land qualities defined by the qualitative methods do not supply temporal variability. Moreover, the distinct differences between the water-table classes are not characterized (Table 1). Therefore, potential situations, such as drainage measures, cannot be properly evaluated by the land qualities assessed by qualitative methods. Quantitative procedures as opposed to qualitative methods allow: (i) a more extensive quantitative expression of land qualities, including temporal variability; (ii) a more comprehensive evaluation of potential situations, and (iii) no arbitrary weighing of land charateristics to derive land qualities.

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# USE OF A SMALL-SCALE SOIL MAP TO ASSESS REGIONAL VARIABILITY OF TRAFFICABILITY AND ITS CONSEQUENCES FOR LIQUID ANIMAL MANURE APPLICATION

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## Summary

Animal manure surplus causes environmental pollution in some regions of the Netherlands. Recently, a ban on applying manure during some winter-months and periods with frozen soil was imposed by the Dutch government. Initially, land with trafficability problems, unless frozen, was considered to be exempted from this ban, if their area and regional variation would be small. To inform policy-makers quickly about this, a small-scale soil map was used. About 40% of Dutch rural land proved to have trafficability limitations, which mainly coincides with susceptibility to surface water eutrophication. This percentage being too high, no land is exempted from the ban. A ban on applying animal manure for some time obliges farmers to construct manure storage facilities and to improve trafficability of non-frozen soil. How simulation models and soil survey and weather data can be used to give a quantitative expression of trafficability, is briefly discussed here.
Keywords: trafficability, soil map, animal manure surplus, simulation.

## Introduction

The last three decades livestock densities have enormously increased in the Netherlands. Pig and poultry farming in the sandy regions mainly caused this increase, although the number of cattle also increased by about 60%. Increased use of imported concentrate feeds greatly contributed to this development. Pig and poultry production systems that were more or less land-independent could be established. This development has resulted in a manure production of about 99 million tons per year (Van Boheemen, 1987). Manure production has reached such a level that application of minerals through manure exceeds the crop's nutrient uptake capacity, even if the manure would be uniformly distributed over all the Dutch rural land. In some areas animal manure surplus already causes pollution of soil, groundwater, surface water, or air by leaching, surface run-off, or volatilization of ammonia. Recently, various legal restrictions were imposed by the Dutch government to reduce detrimental environmental effects.

One of these restrictions is a ban on applying animal manure during some winter-months (October and November) and periods with frozen soil (January - 15th February). Because it is difficult to check quickly and at many spots whether soil is frozen or not, the law controversially assumes that a snow cover is a good indicator for a frozen soil. In a preliminary draft the Dutch government intended to exempt grassland regions with low trafficabilities from this ban (Commissie Uitrijverbod, 1986). For dairy farmers in these regions, periods with frozen soil offer the only opportunity to apply animal manure during winter. Before the Dutch government would include such

an exemption in a law, they wished to be informed on the area and the regional variability of land with trafficability limitations. The aim of this paper is to show how a small-scale soil map, stored in a geographical information system, was used to derive information on regional variation in trafficability at a national scale and to discuss the consequences of trafficability limitations and animal manure application possibilities at dairy farms.

## Methods and materials

The weather-independent component of the land quality trafficability can be determined by soil charateristics (e.g. texture, organic matter content, bulk density) and the mean fluctuation of the water-table. This information can readily be extracted at different scales from a geographical information system. For this study at a national scale, the soil map of the Netherlands 1 : 250 000 was used (Steur et al., 1986).

Trafficability is correlated with penetrometer measurements, which have to be performed on grassland soils during a dry time in winter when the water-table equals the level of the mean highest water-table. Distinct differences in penetrometer resistances of the upper soil horizons were measured between different textural classes (Table 1). Trafficability of grassland is assumed to be adequate if the penetration resistance is higher than 0.6 MPa (class I). A resistance

Table 1. Number of plots (*n*), mean penetration resistance and standard deviation (after: Van Wallenburg & Vleeshouwer, 1987).

| Texture | *n* | Resistance (MPa) | |
|---|---|---|---|
| | | winter 1981 | spring 1981 |
| peat, sandy peat, clayey peat | 22 | 0.38 ± 0.15 | 0.51 ± 0.20 |
| clay over peat | 39 | 0.54 ± 0.16 | 0.66 ± 0.19 |
| clay loam and clay | 42 | 0.36 ± 0.10 | 0.63 ± 0.25 |
| sandy loam and loam | 27 | 0.39 ± 0.15 | 0.56 ± 0.20 |
| sand | 49 | 0.67 ± 0.26 | 0.70 ± 0.25 |

between 0.3 and 0.6 MPa (class II) means a moderate trafficability. Land with a penetration resistance less than 0.3 MPa (class III) has an inadequate trafficability. Based on measured penetration resistances and knowledge of field soils, each mapping unit was assigned to one of the three trafficability classes. A geographical information system was used to draw maps and to compute the area of land with trafficability limitations. The weather-dependent component, which causes a temporal variability in trafficability, has not been considered in this reconnaissance study.

## Results and discussion

Regional variation in trafficability is shown in Figure 1. About 4% (143 000 ha) of Dutch rural land has inadequate trafficability and 38% (1 277 000 ha) moderate trafficability. If land would be exempted from a ban on applying animal manure to frozen soil, 40 % of rural land, predominantly at dairy farms, should be considered. The great extent, scattered over the entire country and often located in areas where

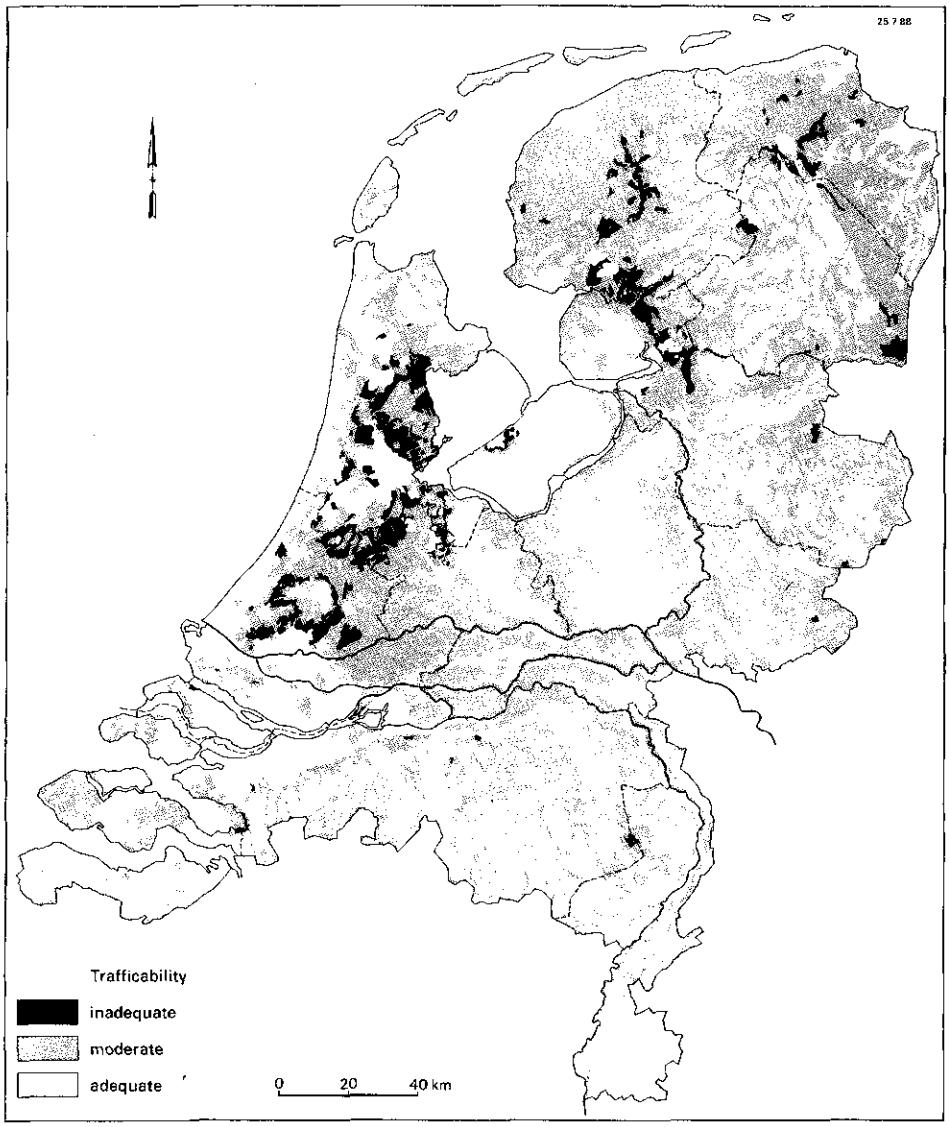


Fig. 1. Regional variation in trafficability.

surface water eutrophication has to be diminished, has finally resulted in a decision not to exempt any land.

In areas with trafficability limitations, a ban on applying animal manure during some winter-months and periods with frozen topsoil results, among other possible solutions (Van Boheemen, 1987), in a necessity to construct extra manure storage facilities and to improve trafficability, if possible. The required storage capacity depends on manure production, time and period that manure application is prohibited, and on trafficability. A qualitative description of trafficability at a national scale, as presented above, is

insufficient for determining the required storage capacity at farm scales. At this detailed scale, the probability of days with adequate trafficability in certain periods has to be known. Models simulating the moisture content of the topsoil offer a sound approximation to determine these probability graphs (Bouma & Van Lanen, 1987; Wosten & Bouma, 1985; Van Lanen et al., 1987). These models use soil survey, crop, and a record of 30 years' weather data as input. The probability of having an adequate trafficability for the current situation but also for potential situations, such as after a drawdown of the water-table by drainage, can be simulated.

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# MODELLING WATER EROSION HAZARD AS A LAND QUALITY

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## Summary

The use of a distributed model to assess erosion hazard as a land quality is very practicable in land evaluation. Several scenarios with proposed patterns of different land utilization types with or without erosion control measures can be evaluated.

## Introduction

In land evaluation, the most satisfactory methods of erosion hazard assesment are based on predicted soil losses by modelling the determinants of climate, soil erodibility, slope and vegetation factors (FAO 1983). Soil erosion models such as the Universal Soil Loss Equation (USLE) and the Soil Loss Estimator for Southern Africa (SLEMSA) model are used for the assesment of erosion hazard by sheet wash. The need of models for predicting soil loss from watersheds or other large areas resulted in modificated versions of e.g. the USLE, which originally was designed for predicting soil loss from single fields.
At present, recently developed models are available to assess surface runoff and soil erosion from watersheds. When a distributed deterministic model is used, information concerning the areal distribution of all spatially variable, non-uniform processes incorporated into the model is preserved and utilized.
The advantages of using distributed models are described in De Roo & Hazelhoff (1988) and Burrough (1988). This paper discusses the applications of the distributed erosion model ANSWERS in land evaluation.

## ANSWERS

The distributed parameter model ANSWERS (Areal Nonpoint Source Watershed Environment Response Simulation), developed by Beasley et al. (Beasley & Huggins, 1982) is used for modelling surface runoff and soil erosion. The model is intended to simulate the behaviour of watersheds having agriculture as their primary landuse, during and immediately following a rainfall event. Its primary application is planning and evaluating various strategies for controlling surface runoff and sediment transport from intensively cropped areas.
A watershed to be modelled is assumed to be composed of square elements of a desired magnitude (e.g. 5 or 10 m square). Raster maps of about 20 variables with values for each element are stored in a geographical information system (GIS). Variables such as slope, aspect, porosity, moisture content, initial and

saturated infiltration capacity, soil erodibility, crop coverage, interception capacity and soil roughness are included. A rainfall event is simulated with increments of one minute. The continuity equation is used to accomplish the composite response of the single elements. Several mathematical relationships are used to describe the processes involved (Beasley & Huggins 1982, De Roo & Hazelhoff 1988). A major advantage of this model is the incorporation of spatial variability of land characteristics and the realistic simulation of a rainfall event.

Case study Catsop

In 1987, a study was carried out in cooperation with the Department of Hydrology at the Agricultural University in Wageningen in a watershed of 42.7 hectares near Catsop (Stein, Limburg, the Netherlands).
The Catsop research project is designed to provide information on possible erosion control measures and at the same time to provide data for the validation of the ANSWERS-model. The impact of possible erosion control measures was assessed during several simulations.
The watershed was modelled by constructing 4275 elements of 10 m square (0.01 ha.) (De Roo & Hazelhoff 1988). A Digital Elevation Model (DEM) (figure 1) was constructed by digitizing a contour map, which was rastered to cells of 10*10 m. The data used for the simulations are described in De Roo et al. (1988).
In order to evaluate some erosion control measures, and determine the best possible locations for them, several land-use scenarios were developed. The following scenarios were used for the Catsop watershed:

1. BASELINE — Landuse and management as in March 1987. 88.0% of the surface is simulated as fallow with crop residuals, 10.7% as grassland and 0.5% as lynchets, which are forrested terrace-borders on slopes.
2. FALLOW — The grassland is converted to fallow land with crop residuals, and the lynchets are removed.
3. GRASSLAND — All fallow land is converted to grassland.
4. CONTOURING — The fallow land is ploughed on the contour.
5. LYNCHETS — At several locations, lynchets are constructed as forrested flat terraces.
6. CONTOUR-GRASS-STRIPS — Strips of grass, constructed on the contour, are left unploughed between bands of cropped land. This erosion control measure is a standard option in ANSWERS: the Best Management Practice no. 4).

The ANSWERS-model was run several times with several rainfall-events of different magnitude to determine how the watershed may possibly react under normal and extreme rainfall conditions. The results of the simulations of an 28.5 mm event are summarized in table 1.

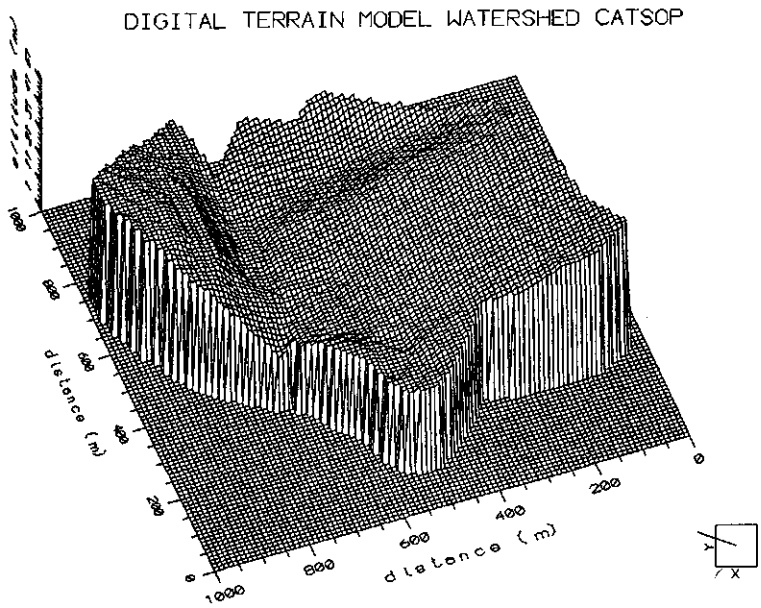


Fig. 1. Digital elevation model of the Catsop watershed (South-Limburg, the Netherlands).

Fig. 2. Surface runoff simulated with ANSWERS in the Catsop watershed (South-Limburg, the Netherlands).

Fig. 3. Soil erosion simulated with ANSWERS in the Catsop watershed (South-Limburg, the Netherlands).

Table 1. Simulation results for several scenarios for the Catsop watershed for event no. 1.

| scenario | runoff ($m^3$) | % | average soil loss (kg/ha) | % | max. runoff (l/s) | % |
|---|---|---|---|---|---|---|
| BASELINE | 1300 | - | 194 | - | 92 | - |
| FALLOW | 1498 | +15.2 | 316 | +62.9 | 101 | + 9.5 |
| GRASSLAND | 813 | -37.5 | 0 | -100.0 | 5 | -94.1 |
| CONTOURING | * | | 160 | -17.5 | * | |
| LYNCHETS | 1253 | - 3.6 | 188 | - 3.1 | 78 | -15.4 |
| GRASS-STRIPS | 914 | -29.7 | 56 | -71.1 | 28 | -69.2 |

From the results it could be concluded which scenario is the most effective in reducing soil erosion.
Maps of runoff (figure 2), soil erosion (figure 3) and sedimentation of the scenarios were compared by subtraction, resulting in maps of change erosion and sedimentation after the introduction of certain control measures in the watershed.

## General applications in land evaluation

The general applications in land evaluation are clear: erosion hazard of several landuse-scenarios with one or more Land Utilization Types (LUTs) can be evaluated using the ANSWERS model. Several standard rainfall events can be used to predict runoff and sediment transport from a watershed in which a land evaluation is carried out. A comparison can be made between different watersheds. Also it can be assessed whether a storm at the start of the growing season results in a different erosion risk than the same storm at the end of the growing season.

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# ASSESSMENT OF REPRESENTATIVE SOIL DATA FOR PHOSPHATE LEACHING

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## Summary

The phosphate sorption capacity of soils can be derived from oxalate-extractable aluminium ($Al_{ox}$) and iron ($Fe_{ox}$) by a pedo-transfer function. In a pilot area of 4800 ha, values of $Al_{ox} + Fe_{ox}$ vary significantly with soil type and soil class. The predictive value of these data was studied for two important soil types. For most soil horizons the data of the study area reasonably predict the phosphate sorption capacity in other areas.
Keywords: Al, Fe, phosphate sorption capacity, pedo-transfer functions.

## Introduction

A substantial increase in manure production in Dutch sandy districts has caused high manure applications on agricultural land. This in turn leads to phosphate leaching from phosphate-saturated soils (Breeuwsma & Schoumans, 1987; Schoumans et al., 1987). The saturation time depends on the application rate and the phosphate sorption capacity (PSC) of the soil. The correlation between the PSC of non-calcareous sandy soils and oxalate-extractable aluminium ($Al_{ox}$) and iron ($Fe_{ox}$) contents in the soil can approximately be described by:

$$\text{massic PSC} = 0.5 * (Al_{ox} + Fe_{ox}) \quad \text{(mmol P per kg)} \qquad (1)$$

$$\text{aeric PSC} = 0.355 * d * \rho * (Al_{ox} + Fe_{ox}) \quad \text{(kg } P_2O_5 \text{ per ha)} \qquad (2)$$

with:
$Al_{ox}$ = oxalate-extractable aluminium content (mmol $kg^{-1}$)
$Fe_{ox}$ = oxalate-extractable iron content (mmol $kg^{-1}$)
$d$ = depth (m)
$\rho$ = bulk density (kg $m^{-3}$)

The coefficient 0.5 in equation (1) is found in phosphate-saturated samples (Schoumans et al., 1986).

The utility of the soil map in predicting the phosphate sorption capacity of soils was studied by investigating:
- the relations ("pedo-transfer functions" as defined by Breeuwsma & Bouma, in prep.) of $Al_{ox} + Fe_{ox}$ to soil horizons and soil types respectively in a study area;
- the values of these relations in predicting $Al_{ox} + Fe_{ox}$ in other areas.

## Methods

### Collecting representative soil data

Representative soil data were obtained from a geostatistical study in a sandy district of 4800 ha near Wesepe (Fig. 1). Sampling sites were selected by systematic grid and stratified random methods using soil type

and soil horizon as sample strata. $Al_{ox}$, $Fe_{ox}$, thickness and bulk density were determined for each horizon.

Validation

The predictive value of the data of the study area (Wesepe) was tested for two important soil types (Typic Haplaquods and Plaggepts). For this purpose all the available data outside the study area were used (Fig. 1).

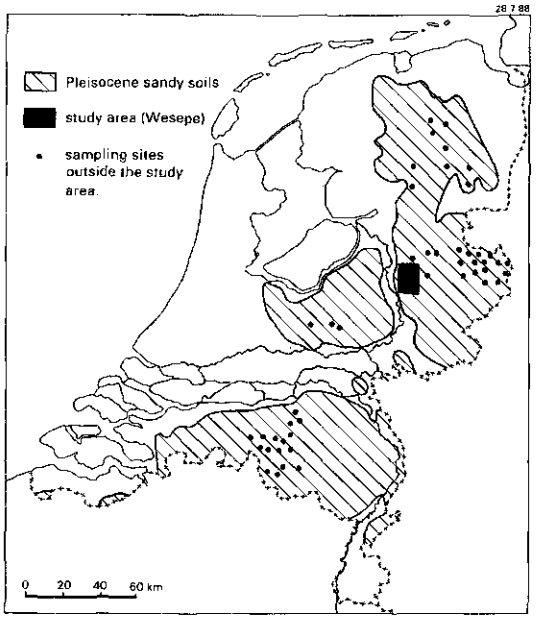


Fig. 1 Location of the study area and sampling sites outside the study area.

## Results

Data on soil horizons and soil types

To reduce the number of soil horizons distinguished by the soil surveyor, horizons were clustered into horizon classes. Each horizon class is defined in terms of major soil horizons (A, B, C and G) and phosphate sorption capacity classes. The mean values and standard deviations of the oxalate-extractable aluminium ($Al_{ox}$) and iron ($Fe_{ox}$) contents of three important horizon classes are presented in Table 1. The mean values of $Al_{ox} + Fe_{ox}$ of the three horizon classes differ significantly ($p = 0.001$). The B horizon has significantly higher values than the parent material (C horizon) in accordance with pedogenetic processes.

Depending on depth, soil types may also vary in $Al_{ox} + Fe_{ox}$ and, therefore, in phosphate sorption capacity. For example, the total amount of $P_2O_5$ (t $ha^{-1}$), as calculated to a depth of 1 m, differs significantly for Typic Haplaquods and Plaggepts (Table 2). These results indicate that sample stratification based on soil type and soil horizon (horizon class) can be important in assessing the phosphate sorption capacity of the soil.

Table 1. Three examples of horizon classes and their associated mean values and sample standard deviations for $Al_{ox} + Fe_{ox}$ (mmol $kg^{-1}$).

| Horizon | | | Mean value | Sample standard deviation |
|---|---|---|---|---|
| code | class | number | | |
| Ap, Aap, A(p)b | 1 | 204 | 76.2 | 25.6 |
| Bhs, Bws | 9 | 15 | 133.8 | 64.1 |
| C, Ce | 13 | 179 | 35.7 | 21.7 |

Table 2. Two examples of soil types differing in total phosphate sorption capacity ($P_2O_5$ in t $ha^{-1}$) to a depth of 1 m.

| Soil type | Number of soil profiles | Mean value | Sample standard deviation |
|---|---|---|---|
| Typic Haplaquod | 63 | 25.7 | 9.8 |
| Plaggept | 16 | 47.1 | 10.7 |

Validation

Data on horizon classes of the Typic Haplaquods and Plaggepts (Table 3) were used to predict $Al_{ox} + Fe_{ox}$ of the same classes outside the study area (Fig. 2).

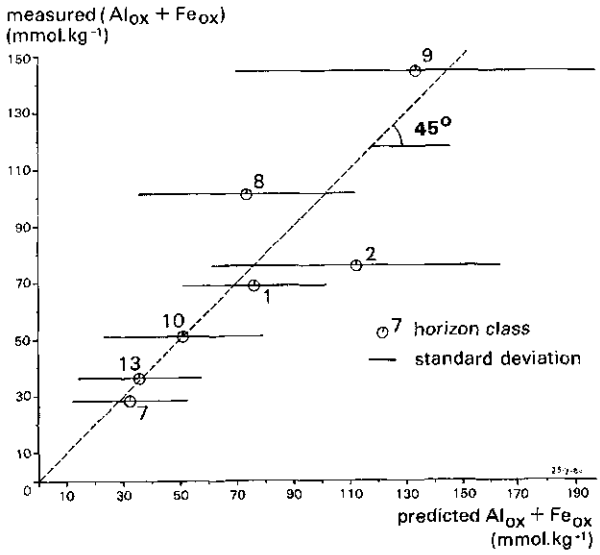


Fig. 2. The relation between the predicted and measured values of $Al_{ox}$ + $Fe_{ox}$ for the horizon classes mentioned in Table 3.

Table 3. Assignment of soil horizons to horizon classes for representative profiles of a Typic Haplaquod and a Plaggept.

| Typic Haplaquod | | | Plaggept | | |
|---|---|---|---|---|---|
| depth (cm) | horizon | horizon class | depth (cm) | horizon | horizon class |
| 0- 20 | 1Ap | 1 | 0- 25 | 1Aap | 1 |
| 20- 30 | 1E | 7 | 25- 60 | 1Aa1 | 2 |
| 30- 50 | 1Bhe | 8 | 60- 80 | 1Aa2 | 2 |
| 50- 75 | 1BCe | 10 | 80- 90 | 1Apb | 1 |
| 75-120 | 1Ce | 13 | 90-105 | 1Bhgb | 9 |
| | | | 105-120 | 1BCb | 11 |

Except for horizon classes 2 and 8, there are no significant differences ($p = 0.05$) in the predicted and measured values of the mean $Al_{ox} + Fe_{ox}$ of the horizon classes. The exceptions are most likely due to regional effects. Horizon class 2 includes the horizon of the oldest man-made material of Plaggepts. The composition of this material varies in different parts of the Netherlands. The effect of the use of different materials may therefore prove to be mappable. The difference between the predicted and the measured values of horizon class 8 is probably related to the presence of clay or glacial till in the subsoil of some profiles outside the study area. This occurrence is indicated on the soil map and can also be used for further differentiation of the existing horizon classes.

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COMBINING SOIL CLASSIFICATION WITH (CO-)KRIGING OF MOISTURE DEFICITS.

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Summary

Predictions of 30-year average moisture deficits (MD30) were carried out by means of kriging and co-kriging in a stratified survey area. Major soil map delineations, as distinguished by a soil survey, showed different internal variability. Stratification resulted in an increase of precision of predictions in strata with low MD30 variability and a decrease in strata with high MD30 variability. Use of co-kriging resulted in an average increase of precision of MD30-maps of about 10%. This study illustrates use of available soil survey information for stratifying a survey area to enhance precision of predictions.
Keywords: Geostatistics, Moisture Deficit, Co-kriging, Spatial variability, Stratification.

Introduction

The quality of predictions obtained by (co-)kriging is directly related to the quality and the variability of the basic data being used and to the selected pattern of observations (McBratney & Webster, 1983). Much variation is likely to be found when a preselected sampling grid is placed over an area with contrasting soil types, not taking into account geological or pedological differences. It may be postulated therefore that sampling within major soil delineations would result in a reduction of the overall variability, leading to a new use of existing maps.

The purpose of this study was to test the feasibility of using sample stratification in creating predictive soil maps on the basis of soil-map delineations.

Materials and Methods

In 1985 a soil survey was carried out in the Mander area in the eastern Netherlands by the Dutch Soil Survey Institute (Stiboka) to study the influence of groundwater extraction on the production of

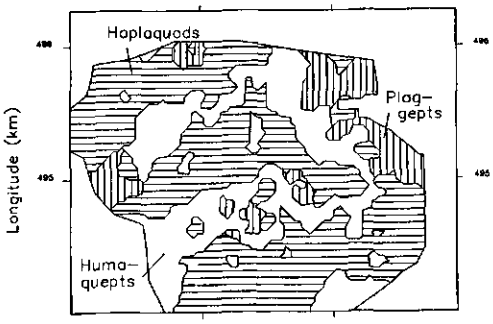


Fig. 1. Soil map of the Mander area.

grassland. In the 404 ha study area, which consists of Haplaquods, Humaquepts and Plaggepts, 500 soil borings were made (Fig. 1). Lowering of water tables results in a change in production. Hydraulic conductivity and moisture retention data for major soil horizons were measured and averaged. Simulation calculations for moisture deficit (MD30) were carried out for each boring location for a 30 year period. To evaluate predictions, 100 borings were selected at random from the data set to serve as a test set for which predictions were carried out.

The statistical prediction techniques kriging and co-kriging (Journel & Huijbregts, 1978) are used to provide predictors for the values of MD30 as well as for the variances of the prediction error in the test points. In co-kriging the variable Mean Highest Watertable (MHW) was used as a co-variable (Stein et al., 1988). For the prediction of MD30 in any point of the test set 8 neighbouring MD30 observations were used.

Two measures were used to obtain insight in the performance of the predictors, the Mean Variance of the Prediction Errors (MVPE) and the Mean of Squared Errors of Predictions (MSEP):

$$MVPE = (1/n) * \sum_{i=1}^{n} Var(t_i - y_{0i}) \qquad (1)$$

$$MSEP = (1/n) * \sum_{i=1}^{n} (t_i - y_i)^2 \qquad (2)$$

with for every point i, i=1,..,n, in the test set: $t_i$ = the predictor provided by (co-)kriging, $y_{0i}$ = the variable under study, $t_i$ = the prediction and $y_i$ = the observation.

Within each stratum every variable is considered to follow the intrinsic hypothesis and to be isotropic. For every point in the test set the predictor is entirely based on observations belonging to the same stratum whereto the test point belongs.

Stratification of the region is based upon the three soil types. For the semi- and cross-variograms a linear model without sill, g(h) = a+b*h, was fitted for every stratum by means of weighted linear regression, with weights based upon the number of pairs of points in a distance class.

## Results and discussion

The strata differ with respect to MD30 according to the estimated mean values, the standard deviations around the mean (Table 1) and the fitted

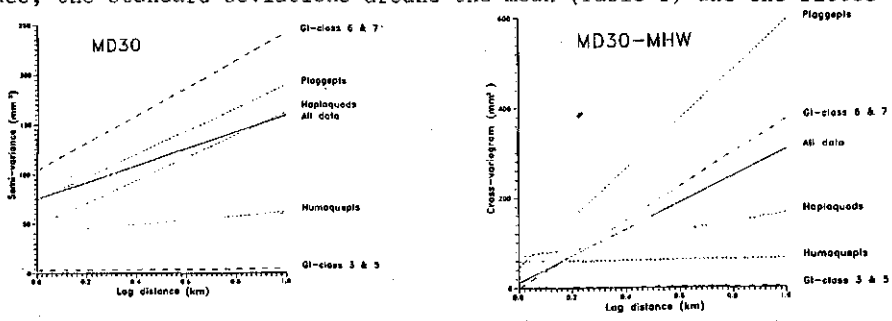


Fig. 2. Semi-variograms for MD30 (left) and cross-variograms for MD30 with MHW (right) according to different strata.

Table 1. Descriptive statistics of MD30 and the correlation coefficient of MD30 with MHW in different strata.

| | # Observations | Mean | S.d. of the mean | Corr.coeff. with MHW |
|---|---|---|---|---|
| All data | 399 | 10.1 | 3.2 | .587 |
| *Humaquepts* | 121 | 9.9 | 3.4 | .387 |
| Haplaquods | 227 | 4.9 | 1.3 | .453 |
| Plaggepts | 51 | 25.1 | 5.5 | .604 |

Table 2. The MVPE and MSEP values according to kriging and co-kriging for the stratified region.

| | MVPE | | MSEP | |
|---|---|---|---|---|
| | kriging | co-kriging | kriging | co-kriging |
| Unstratified | 93.0 | 90.7 | 68.1 | 61.2 |
| Stratified | 79.8 | 68.3 | 75.7 | 70.0 |
| Humaquepts | 101.3 | 97.3 | 48.6 | 48.2 |
| Haplaquods | 67.3 | 48.5 | 53.6 | 57.3 |
| Plaggepts | 51.5 | 41.9 | 273.1 | 207.6 |

variograms (Fig. 2).

Co-kriging generally resulted in more precise preditions than Kriging (Table 2). The increase in precision varied from 1 to 25%. The combination of stratification and co-kriging was succesful, in that the MVPE decreased after stratification. The MSEP increased after stratification, probably due to the fact that observation points used in the predictions were located further away.

The predictive MD30 soil map (Fig. 3) obtained without stratification is of more or less uniform precision as compared with a map with stratification (Fig. 4). Strata showing high spatial variability are the less precise parts of a predictive soil map as compared with the strata

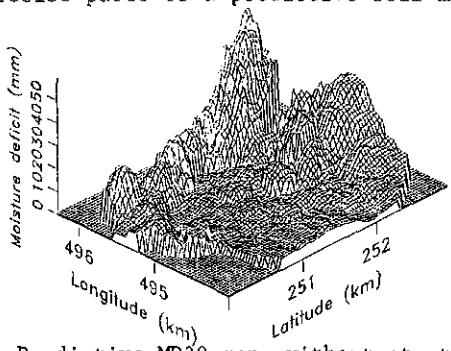


Fig. 3. Predictive MD30 map, without stratification.

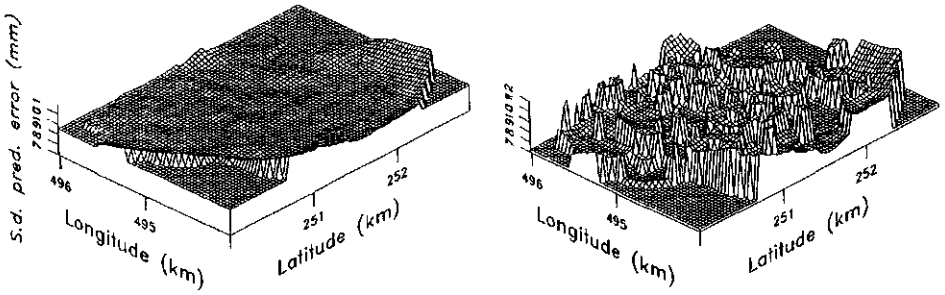


Fig. 4. Map of the standard deviation of the prediction error without stratification (left) and with stratification (right).

with low spatial variability. When strata are ignored, average MVPE and MSEP values are obtained, which in fact are lower, but which mask the fact that variability is characteristically lower in certain strata and higher in others.

The results can lead to interesting consequences for soil survey. When a uniform degree of precision is required it is feasible to decrease the number of observations in strata showing relatively low spatial variability and to increase the number of observations in strata showing relatively high spatial variability. A possible future activity would be to allow statistically founded quantitative predictions of relevant land qualities rather than qualitative estimates based on "representative" profiles.

Maximizing the accuracy of predictions and, at minimum cost, dealing with variability aspects as a function of different land units is an important task for soil scientists in future.

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# A STUDY ON THE LIMITATIONS TO MAIZE PRODUCTION IN ZAMBIA USING SIMULATION MODELS AND A GEOGRAPHIC INFORMATION SYSTEM

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## Summary

Grain yields are calculated for maize growing on the main land units of Zambia which are defined along agro-ecological criteria. Four levels of maize production are distinguished with an increasing number of constraints to crop production:
1. the potential yield, not limited by water availability, nutrient availability, weeds, pests, and diseases;2. the water-limited yield; 3. the nutrient-limited yield;4. the actual yield.
For the calculations of the different yield levels a crop growth simulation model and a soil fertility evaluation system are used.

From the calculation results for Zambia it can be derived that the water-limited yields are only lower than potential yields, if rainfall during the crop growth cycle is less than 800 mm, that the gap between nutrient-limited and water-limited yields is very large and that as a consequence, large increases in maize production can be realized by increasing fertilizer application. For different farming systems corresponding with different levels of fertilizer application and crop protection, actual yields are calculated for the main land units of Zambia.
Keywords: evaluation system of soil fertility, geographic information system, maize, nutrient-limited yield, simulation model, water-limited yield, Zambia.

## Introduction

The Centre for World Food Studies has developed a methodology for making quantitative estimates of the yield levels of annual crops under various constraints and of the inputs that are needed for their realization. The main tools for this approach are a crop growth simulation model, accounting for crop, climate and soil characteristics and their interactions, and a quantitative evaluation system of the soil fertility.

This methodology is applied for calculating grain yields of the principal food crop in Zambia, i.e. maize. The relevant soil and climate data used in the simulation model, are stored in a geographic information system which allows geographic representation of these input data but also of the calculated yields. The resulting maps and the complete description of this study on the limitations to maize production in Zambia are reported by Wolf et al. (1987).

## Methodology

The simulation model for the calculation of potential and water-limited crop production

The principles underlying this agronomic model are treated in detail by van Keulen and Wolf (1986) and the complete documentation of the model is given by van Diepen et al. (1988). The growth of a crop is simulated from emergence to maturity on the basis of physiological processes as determined by the crop's response to environmental conditions. The major processes are $CO_2$ assimilation, respiration, partitioning of assimilates to various plant organs, and transpiration. The model follows a hierarchical approach. At the highest level solar radiation and temperature are the only environmental conditions considered. At the second level, moisture availability is introduced as a possible growth-limiting factor.

The basis for the calculation of dry-matter production is the rate of gross $CO_2$ assimilation of the green canopy. A part of the assimilates is used for respiratory processes to provide energy for its own maintenance. The remainder of the assimilates is available for increase in structural dry matter. The increase in total dry weight of the crop is partitioned over the plant organs, roots, leaves, stems and storage organs, whereas the partitioning is a function of phenological development stage.

Within the optimum soil moisture range for plant growth transpiration losses are fully compensated, and transpiration and assimilation proceed at their potential rates. Outside that range the soil can be either too dry or too wet. Both conditions lead to reduced water uptake by the roots, desiccation of the plant and hence reduced growth: in a dry soil due to water shortage, in a wet soil due to oxygen shortage. The soil moisture content in the root zone follows from a quantification of the water balance based on rainfall, runoff, soil surface evaporation, transpiration, and percolation beyond the root zone.

Quantitative Evaluation system of the Fertility of Tropical Soils (QUEFTS) for the calculation of the nutrient-limited crop production

Soil fertility was evaluated according to the so-called QUEFTS system. This system comprises a number of successive steps. First, the quantities of nitrogen, phosphorus and potassium that are potentially available for uptake by a maize crop during one growth cycle, are estimated using empirical relationships between chemical soil properties and nutrient uptake. Relationships between actual and potential uptake are used to calculate the actual nutrient uptake by maize. From the actual uptake of N, P, and K and the yield-N uptake, yield-P uptake, and yield-K uptake ratios at minimum and at maximum nutrient concentrations, the ranges in yields can be calculated. From the three ranges in crop yield for the nutrients N, P, and K the actual yield can be calculated by weighing the effect on crop yield of the availability of the three nutrients. More information on the QUEFTS system is given by Janssen et al. (1988).

The response of maize to fertilizer application is also calculated with the QUEFTS system. But in this case, data on the fraction of fertilizer nutrient taken up by the crop (recovery fraction) have to be collected from fertilizer trials. The amount of fertilizer nutrient applied is multiplied with the recovery fraction to find the additional uptake and in the QUEFTS system this additional nutrient uptake is added to the potential uptake of the unfertilized soil. The successive steps are just the same as described above.

## Data base

For this study the soil map has been digitized to allow the selection of relevant soil and climate data combinations for the dynamic simulation model, the calculation of hectarage, and the geographic representation of data and results of computations. The digitization comprises transformation of the irregularly shaped mapping units into a rectangular grid pattern by assigning to each grid cell the number of its dominant map unit.

Crop data representing the maize HYV cultivar MM752 with a growth duration of about 150 days, have been used for all maize production calculations.

The agro-climatic zonification is depending on two components, i.e. mean annual temperature and mean annual rainfall. For Zambia 9 agro-climatic zones have been derived from the map of mean annual rainfall via intersection by the map of mean annual temperature. For each agro-climatic zone a representative weather station has been selected for the calculations of the crop production.

Soil information includes the geographical distribution of soils and their chemical and physical properties. For this study the 1:2 500 000 scale Soil map of Zambia has been used. It is of a rather general nature, with a small number of soil units distinguished. This causes a large variability in soil characteristics within one soil unit. For the kinds of soil that are of importance for maize production representative soil data have been collected from various soil reports and maps. They consist mainly of the soil moisture characteristic, the effective soil depth, and the hydraulic conductivity of the soil for use in the simulation model and of soil chemical data for use in the QUEFTS system.

## Computed results

### Potential and water-limited crop production

Potential yields have been calculated for nine climatic zones in Zambia, and vary from 10000 to 14000 kg/ha of grains (air dry). The differences in yield level between zones are largely related to differences in temperature. The cooler zones allow longer growth cycles and higher yield levels.

Water-limited yields of maize have been computed for 21 climate-soil combinations. In most cases yield reductions due to water shortage are small, i.e. less than 10 percent, and also the yield variability is small, even though the interannual variability of the rainfall is usually as high as 20 percent.

In zones receiving on an average less than 800 mm of rainfall during the crop growth cycle, the average yields are reduced to about 8000 kg/ha of grains (airdry) and the yield variability increases to about 25 percent, as water stress becomes more pronounced. In years with low rainfall grain yields are reduced more strongly, and particularly if the rainfall distribution is unfavourable and the water-holding capacity of the soil is low.

### Nutrient-limited and actual yields

For the different soil types in Zambia, chemical soil data are collected that are used to calculate nutrient-limited yields with the QUEFTS system. The yields range from about 800 kg/ha of grains (airdry)

on Barotse sands in the Western province to about 1400, 2000 and 3800 kg/ha on Sandveldt soils, Red brown loams and Red clays, respectively that are found mainly in the Central, Eastern and Southern provinces. According to these calculations phosphorus is the nutrient that mainly limits the maize yields. In the leached soils in the Northwestern and Northern provinces the pH is so low that maize production is almost impossible. This also applies to the remaining soil units that are unsufficiently drained and/or flooded during the wet season, are saline, rocky, swamp, etc. Comparison of the nutrient-limited yields with the water-limited yields indicates that large increases in maize production can be realized by increasing fertilizer application.

Actual yields obtained in agricultural practice are the result of intricate interactions among the availability of water and nutrients, competition by weeds, occurrence of pests and diseases, and actual management practices. Because the availability of nutrients appears to be the most constraining factor in Zambia, the actual yields of maize are mainly a function of the natural soil fertility. The nutrient-limited yields will practically always be higher than the actual yields, because part of the yields may be lost.

The average amount of fertilizer used per hectare of maize is still small, because a large part of Zambia is used for traditional subsistence farming. Only commercial farmers apply large amounts of fertilizer. A classification of management levels and amounts of fertilizer applied per management level are derived from a study by Admiraal (1981). Besides subsistence farming three more advanced levels of farming are distinguished, i.e. small-scale emergent, medium-scale commercial and large-scale commercial farming, which are mainly found in the Central, Eastern, and Southern provinces of Zambia. For these four management levels the amount of fertilizer nutrients applied, the level of crop protection and the resulting loss fraction are specified. These data are used to calculate for the main soil units in Zambia the actual yields of maize with and without fertilizer application at the four management levels (Wolf et al., 1987). The same approach can also be used for studying the limitations to the production of other crops than maize, as the methodology is universally applicable.

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# RELATION BETWEEN THE QUESTIONS BEING ASKED AND THE SCALES AND COSTS AT WHICH LAND EVALUATION IS PERFORMED

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## Introduction

In The Netherlands, soil maps are increasingly used for environmental interpretations in the context of new laws on soil protection. Such interpretations have to be quantitative in order to allow reliable estimates of soil properties in relation to critical levels that are being defined in soil protection laws. These critical levels may, for example, relate to chemical contents of heavy metals and phosphates or to physical characteristics such as the density of compacted soil horizons and associated physical land qualities.

Environmental interpretations are needed at different levels.

At a national level, broad information is needed, for example as to the location of soils that have a low trafficability or a low capacity to adsorb phosphates. The new 1 : 250 000 soil map of The Netherlands (Steur et al., 1985) is successfully applied in this context. Interpretations at a regional or provincial level are usually more detailed, and standard 1 : 50 000 soil maps are being used here. Quite specific interpretations at farm level are made using 1 : 10 000 maps that are compared for all land reallotment plans in The Netherlands.

This study focuses on the benefit-cost relation of soil surveys at different scales. Small-scale surveys are less costly than large-scale ones but the information provided is less specific, at least in principle. Ideally, a user should consider the degree of detail he needs to answer his questions. Then, in turn, the number of observations to be made during mapping and the associated map scale can be chosen. So far, this benefit:cost analysis has not been available for our soil survey users. This study was made, therefore, to compare application of soil surveys at four different scales: 1 : 10 000, 1 : 25 000, 1 : 50 000 and 1 : 250 000. The application was focused on predicting the sensitivity of soils to lowering of the water-table following water extraction for drinking-water supply.

## Materials and methods

An area of 400 ha with sandy soils was surveyed at a scale 1 : 10 000. Because this soil survey was to be used for hydrological interpretations it included data on those subsurface soil horizons expected to be important for the soil physical behaviour of the profile. For further details, the reader is referred to Wösten et al., 1987. For every mapping unit of the 1 : 10 000 soil map, the soil surveyor defined a 'representative profile' on the basis of the borings in that unit. From the 1 : 10 000 soil map a soil map on scale 1 : 25 000 was derived, by the same soil surveyor, through generalisation without new fieldwork. The 'representative profile' for every mapping unit of the 1 : 25 000 soil map was assumed to be identical to the 'representative profile' of the mapping unit occupying the

largest area on the 1 : 10 000 map, within the particular 1 : 25 000 mapping unit being considered. In the same way a soil map on scale 1 : 50 000 was derived from the soil map on scale 1 : 25 000 and a soil map on scale 1 : 250 000 was derived from the soil map on scale 1 : 50 000. When deriving the smaller-scale maps, the surveyor used his field experience, assuming availability of fewer borings as map scales decreased. The number of mapping units was greatly reduced as the map scale decreased.

The separate soil horizons of the 'representative profiles' of the 1 : 10 000 soil map are characterized by measured soil physical characteristics (Wösten et al., 1985). When pedologically different horizons behave physically identically, they are combined into one soil physical horizon or 'building block'. The soil physically interpreted soil map together with data of the water-table depth, thickness of the rootzone, precipitation, evaporation from a free water surface and a crop coëfficient to relate potential evapotranspiration and evaporation from a free water surface are used to simulate the moisture deficits of a grass vegetation for successive 10-day periods. Calculations were made for the period 1956-1985 with a growing season of 180 days from April 1 till September 30. Calculated moisture deficits are transformed to yields by making use of the established relation between yield per mm moisture and potential production (Van Boheemen, 1981).

Water extraction may also lead to yield increase. This is the case for soils that were originally too wet. Increase in yield is derived from existing curves that relate changes in yield to the water-table depth. Calculations were made for the former hydrological situation without water extraction and the present hydrological situation with water extraction.

Final results are presented as an average change in yield, expressed as a yearly percentage, due to lowering of the water-table. Negative percentages indicate a dominant effect of a lower water supply during the growing season. Positive percentages indicate a dominant effect of lower water-tables during the wet periods of the year.

## Results and discussion

The soil maps of the area on four different scales show that the number of mapping units decreases strongly with decreasing scale. As a consequence also the costs to calculate changes in yield decrease strongly with decreasing scale. For the area studied costs per hectare on scale 1 : 10 000, 1 : 25 000, 1 : 50 000 and 1 : 250 000 are Dfl. 120, Dfl. 60, Dfl. 37 and Dfl. 3 respectively. These values indicate the importance of choosing the right scale for specific problems.

The average change in yield for the area as a whole is Dfl. 130 on all four scales. This figure indicates that for the area as a whole, lowering the water-table has a positive effect on the yield. The fact that the average change in yield is the same on all four scales means that the relatively cheap 1 : 250 000 scale is, in this case, the most appropriate scale to work on. This average change in yield for an area as a whole might be sufficient information for the planning activities of, for example, a water extraction firm or a provincial waterboard.

The influence of scale on the accuracy of the calculated changes in yield for separate parcels of land was investigated by at random selection of 20 parcels in the area. For every parcel the change in yield expressed in Dutch guilders per year, was determined using maps on the various scales. Results were compared with those of the 1 : 10 000 map because larger scale maps are not economically feasible, and this map was

therefore considered to be the reference. It is shown that changes in yield of individual parcels can differ quite significantly depending on the scale of the map being used. Differences of Dfl. 300 per parcel per year are possible. The average absolute change in yield, expressed in Dfl. per parcel per year, increases strongly with decreasing scale. As a consequence financial losses per parcel are, for example, settled in the most appropriate way by working on a scale 1 : 10 000.

It is not possible to recommend any one particular scale. For every problem an evaluation is necessary, considering the desired accuracy of data and the associated costs. This application focused on predicting the sensitivity of soils to lowering the water-table. Comparable studies, however, are relevant for evaluating effects of scale on detail and costs of other environmental interpretations. In all cases, optimal spending of resources should be determined by defining the degree of detail of required data considering the problem being studied.

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# Studies at regional scale

# MACROSCALE LAND EVALUATION USING CROP GROWTH MODELS AND COMPUTERIZED INTEGRATED DATA BASES

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## Abstract

Macroscale land evaluations focus on assessments of regional potentials and long term trends. Successful applications depend on properly scaling the data base, model(s) and output to the problems being addressed. The criteria of average soil and climate during the growing season, simulation of basic physiological processes with a seasonal time step, and output in terms of comparative performance are appropriate for regional and continental evaluation. Examples for crop yield and land use analysis are provided.

## Introduction

Land evaluation procedures involve matching land use requirements with information on the soils and climates of an area (Beek, 1978). Results are expressed in terms of physical suitability classes (FAO, 1976) or economic feasibility if yield and associated economic data can be derived. Smit et al. (1984) differentiate between physical land evaluation which identifies agronomic potential in terms of biophysical parameters, and integral land evaluation which integrates agronomic potential with economic supply/demand data to identify alternate production possibilities.

Land evaluation must be tailored and properly scaled to the applications envisaged. In Canada, because of the large land areas and low intensity agriculture, land evaluation schemes have generally been broadscale. Of the approaches tried in the past the most sucessful has been the Canada Land Inventory program (CLI). In this scheme all potential agricultural lands were rated into one of seven classes of soil capability.

Capability classifications, however, do not provide estimates of crop yield, and it has been demonstrated that yield is the single most important and most easily understood measure of agricultural potential (Dumanski and Onofrei, in press). Statistically derived comparative yield indices for capability classes were developed to overcome this deficiency (Hoffman, 1971; Shields and Ferguson, 1975), but these could not be used to define yield potentials, because they were based on historical yield records, with varying levels of management and they were regionally biased. The Agroclimatic Resource Index (ACRI), based on growing season length, moisture deficit and summer heat, and correlated against forage yields across Canada (Williams, 1983) eliminated some of the regional biases and facilitated the first national comparisons of agricultural productivity. However it also could not be used to evaluate yield potentials. Obviously better procedures were necessary, and a project was initiated to achieve this.

The project focussed on providing long term yield estimates over large land areas, and consisted of three objectives:

a) to develop and use a systematic methodology to provide reliable estimates of crop production potentials. This implied not only unit area yields for specific crops, but also location and extent of areas where these crops could be produced economically.

b) to provide estimates of the degree of residual production potential for the various regions of Canada, so as to identify areas with the highest future production opportunities. This implied comparing actual (currently achieved) yield with estimates of potential yield to identify residual potentials.

c) To complete the analyses in a manner compatible with the FAO Agroecological Zones Project (FAO, 1978), so as to contribute to the global assessment of agroecological crop yield potentials.

This paper outlines the experience gained in attempting to address the first and third objectives of the project.

Procedures

When the project was initiated crop modeling techniques were being used regularly for research on experimental sites in Canada and elsewhere, but rarely for broad regional studies. The exceptions were the studies conducted by FAO (1978) on global evaluation of agroecological crop yield potentials.

The procedures used in this study were adopted from FAO (1978), with modifications to reflect the requirements of the project and the types of data available in Canada. The procedures are described in detail elsewhere (Dumanski and Stewart, 1981; Stewart, 1981; Stewart et al., 1984), but in general terms the steps are as follows:

1. develop an integrated data base of unique (homogeneous) polygons, each with its suite of described soils and long term climate records, and containing the necessary input data for the model or models being used.

2. develop or adapt a suitable crop growth model that is properly scaled to the applications envisaged, with input requirements that match the data base.

3. develop a set of crop suitability decision tables describing the optimal edaphic conditions for each crop, as well as the range in conditions.

4. use the crop model to calculate the yield potential for each crop in each polygon; use the suitability decision tables to calculate location and extent of land where the crops could be produced economically.

The production potential for each polygon is then calculated as the product of yield and the area of the polygon suitable for the crop. Summing this for all polygons where the crop can be grown defines the production potential for that crop in any region and for the country, assuming no competition for land from other crops.

A comparison of the procedures developed by FAO (1978) and those employed in the Canadian study are shown in Table 1. The same crop

Table 1. Comparison between procedures developed by FAO (1978) for calculation of agroecological crop yield potentials, with those used in the Canadian study.

| | Number of Crops in Study | Source of Soil Data | Climate Integration | Criteria for Growing Season Length | Calculation of Potential (Constraint free) Yield | Calculation of Anticipated Yield (yield reducing factors) | Expression of Results | Level of Management Input |
|---|---|---|---|---|---|---|---|---|
| FAO (1978) | 11 | Soils of the World (1:5m) | Overlay of climate isolines, giving agroecological zones | Moisture/ temperature rainfall >½ PE plus number of days to evaporate 100 mm of moisture reserve, mean min. temperature > 6.5°C | Simplified mechanistic model modified from de Wit (1965) | Semiqualitative estimates of moisture stress, disease, pests, weed, etc. | Suitability classes agroclimatic suitability compared to constraint free yields, modified by soil suitability | Low<br>High |
| Dumanski and Stewart (1981) | 5 initially, expanded to 8 | Soils of Canada (1:5 m) | Calculate climate per map unit, giving agroecological areas | Temperature: mean minimum temperature >5°C | Same | Quantitative calculations of effects of moisture stress, harvest probability and adverse soil conditions | Suitability classes based on per cent of maximum anticipated yield for country | High |

growth model was used for both projects, but Dumanski and Stewart (1981) used only quantitative estimates of soil moisture stress, fall workday probability and a soil index to calculate anticipated yields. In the Canadian study, long term (30 year) climatic normals were derived for each polygon in the Soils of Canada map (Clayton et al. 1977), whereas in the FAO (1978) study climate isolines were physically overlayed onto the Soils of the World map with the resultant subdivision of many of the polygons in the creation of unique areas. The two procedures, although seemingly different, in fact provided similar results, because of the finer subdivisions originally built into the Soils of Canada map. The final suitability classes according to FAO (1978) were calculated as the ratio of anticipated to constraint free yield in each agroecological zone, whereas in the Canadian study (Dumanski and Stewart, 1981), suitability classes were derived as the ratio of the anticipated yield in each polygon to the maximum anticipated yield for that crop in the country. The difference is that in Canada, comparative ratings of the resource base both regionally and for the entire country are possible, and this is often very useful for policy analyses.

Validation of output in macroscale studies involving crop growth models is one of the most difficult steps in the procedure, but it is extremely important. Constraint free yields, which are based primarily on heat, radiant energy and growing season length in each polygon, were validated by using data from available irrigation trials and the "best years" from controlled experiments. In these situations it was assumed that management inputs were optimal and moisture stress was minimal, and that yields obtained would be approaching the genetic potential of the crop in question. Experience has indicated this to be generally valid for most crops in Canada (C. Onofrei, R.A. McBride, personal communications).

Validation of anticipated yield was more difficult. Detailed experimental sites were found not to be useful because the values represent a microplot, they are generally too short term, and they often measure

factors other than those being simulated by the model. Data from long term programs such as soil testing were ultimately used for validation, particularily where values from a given location could be matched to a specific polygon. The final criteria that were developed to judge the acceptability of a model run were that the modelled yields be within one standard deviation of mean yields for that area, for a time period approximately similar to the climate normals used as input. Under these criteria the overall performance of the FAO model was judged to be acceptable overall, although it was not sufficiently accurate to predict yields for individual polygons. Considering these constraints, then, output procedures were based on comparative evaluation classes (suitability, etc.) rather than absolute prediction.

The soil and climate (input) data for each polygon were integrated with the predicted yield (output) data and with actual yield (from Crop Reporting Districts) and land use data (from Statistics Canada), to form the Land Potential Data Base (LPDB) (Kirkwood et al., 1983). These data have subsequently been used for a variety of studies. Selected examples are outlined in the following section.

## Applications of the methodology and results

### 1. Yield analysis, land suitability and production potentials.

Constraint free and anticipated yields for specific crops (non irrigated) were calculated for all polygons where the crops could be grown. Constraint free yields (CFYi) were obtained from simulated net biomass production, as controlled only by temperature, radiant energy and growing season length, by applying an appropriate harvest index. These yields were interpreted as representing genetic potentials for individual areas, and they have been used in maximum yield experiments (Stewart et al., 1984).

Anticipated yields (Yi) were calculated by reducing constraint free yields (CFYi) by soil moisture stress (SMS), fall workday probability (WP) and unfavourable soil conditions (SI), using a multiplicative function:

$$Yi = CFY_i \cdot SMS \cdot WP \cdot SI \qquad 1)$$

Values derived from equation 1) were interpreted as representing field potential yields under ideal management. They were grouped into land suitability classes by comparing the anticipated yield for each polygon where the crop could be grown with the maximum anticipated yield for that crop in the country. The distribution of land suitability classes for spring wheat in Canada is shown in Fig. 1.

The national production potential (Pi) for each crop was then derived by accumulating the product of anticipated yields (Yi) and variously suitable cropland area ($S_i$):

$$P_i = \sum_{i=1}^{n} S_i \cdot Y_i \qquad 2)$$

where n is the number of polygons where the crop can be grown. These

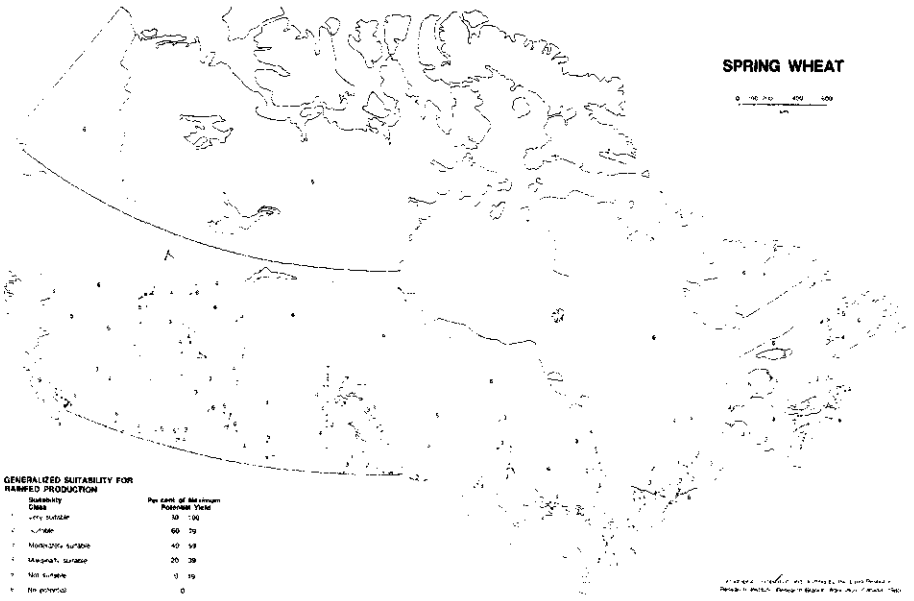


Figure 1. Suitability classes for spring wheat in Canada derived from modelled growth yields.

data have been used for policy analyses to identify market potentials and opportunities for land use adjustement (Acton et al., 1980; Nowland et al., 1982).

The crop production potential in western Canada under various land use scenarios and using spring wheat as the indicator crop is shown in Table 2. In the first case, scenario I, it is assumed that all land suitable for wheat is used for that crop. This gives a total long term production potential of 100 million tonnes. This, however, assumes no competition from other land uses and is quite unrealistic. Scenario II is an adjustment to 1976 land use and management conditions (Agriculture Canada, 1980). This resulted in projections of 42.5 million tonnes produced on 18.5 million hectares, which compares favourably to the 37.9 million tonnes actually produced in 1978 on 19.6 million hectares. Adjusting the land use to achieve some soil conservation objectives, scenario III, and recalculating the potentials, gave estimates of 51.7 million tonnes on 22.6 million hectares, which are quite similar to current production levels.

Data from the Land Potential Data Base were used to estimate the area of agricultural land reserves in Canada i.e. areas suitable for field crop cultivation but not yet utilized (Dumanski et al., 1984). Results suggested that by using integrated crop potential studies the estimated reserve was only 12.1 million hectares, almost 45% less than estimates available from soil capability data (sum of classes 1 to 4). It is likely that this figure would have been further reduced if economic constraints to production had been used.

Table 2. Prairie crop production potentials estimated for various land use scenarios.

| Scenario | Summer fallow | Land use distribution (millions of hectares) Hay, fodder and pasture | Cropland reserve | Seeded area | Estimated production (Millions) tonnes |
|---|---|---|---|---|---|
| I | 0.0 | 0.0 | 0.0 | 43.5 | 100 |
| II | 10.7 | 5.8 | 7.6 | 18.5 | 42.5 |
| III | 6.7 | 5.8 | 7.6 | 22.6 | 51.7 |

2. Sensitivity Analysis on Yield

The crop growth model and data base were used to assess the possible effects of climate change on selected crop yields (Bootsma et al. 1984). Temperature change scenarios of up to ± 3° C and precipitation changes of 60-140% of normal were imposed on a climatic normals data base (30 yr. means for 1941-70), and yields estimated for each scenario for selected agricultural areas (Fig. 2). Results indicated that an increase in temperature of up to 3° C with no concurrent increase in precipitation could result in yield depressions of up to one tonne/ha. The analysis also suggested that an increase in precipitation of approximately 40% above normal would be required to maintain yields at current levels given a temperature change of that magnitude. Other climate change analysis involving these procedures are discussed by Williams et al. (1987) and Stewart (1986) for spring wheat production in Saskatchewan, and by Smit et al. (1988) for selected field crops in Ontario.

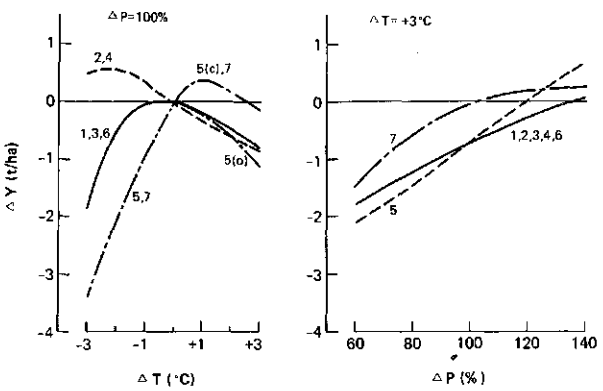


Figure 2. Changes in estimated dry matter yields from normal (ΔY) for cereals(c) and oilseeds(o). ΔT: change in temperature (°C) from normal; ΔP: percentage of normal precipitation. Locations are 1) southern Saskatchewan, 2) Okanagan Valley, 3) northern agricultural fringe, 4) southern Ontario, 5) Peace River area, 6) Annapolis Valley, 7) northern Ontario.

Data in the LPDB were used to evaluate temporal variation in corn yields in Ontario, relative to technology trends, weather variability, fertilizer applications and soil suitability (Dumanski et al., 1986). Results indicated that yield increases resulting from technology improvements (assuming normal weather) averaged 2, 1 and 0.3% per year in the most suitable, intermediate and marginal areas respectively. Decreased yields and increased yield variability observed in many areas in the mid-1970's were related to a period of weather instability. The effects of this variability, however, were greatest in the least suitable areas, and least in the most suitable areas. This demonstrated the capacity of high quality soil areas to "buffer" against outside stresses such as increased weather variability, and demonstrated their long term strategic value to agriculture.

3. Land Use Analyses

Data in the LPDB has also been integrated with the agricultural census, and used for several studies on agricultural land use. One study using clustering techniques characterized the spatial relationship between agriculture and the soil resource in Canada, (Dumanski, et al. 1982). Good spatial relationships were found with land based activities, demonstrating that soils and climates have major influence on farm configuration and crop distribution. This study confirmed the strong regional specialization in Canadian Agriculture.

A further more detailed study (Huffman, 1988) demonstrated that farmers have made considerable adjustment in management practices and farming patterns in relation to different soil/climate areas, and that investments to optimize regional production opportunities have been made. Farm size decreases and crop diversity increases as the physical environment for production improves, resulting in higher capital investments and total sales, but also higher operating expenses per cultivated hectare. This results in gross margins that are relatively similar over a range of environmental conditions, reflecting the practice of farmers to reduce inputs in regions where the probability of adequate return is less.

The data in the LPDB were also used to develop an index of physical land flexibility (PLF) for the Canadian prairie region, to identify inherent opportunities for land use diversification and land use adjustment (Dumanski et al. 1988). It incorporated estimates of anticipated yield ($Y_i$) with estimates of how much land considered as suitable ($S_i$) could be used for the 8 crops used in the study (spring wheat, oats, barley, canola, corn, soybeans, sunflower, phaseolus bean). The equation was:

$$PLF = \sum_{i=1}^{n} S_i . Y_i/Ym \qquad 3)$$

where Ym is maximum anticipated yield for the region to be evaluated, and n is the number of crops in the study. Results indicated that the highest potential for land use diversification occurs in the Black Chernozemic area followed by Dark Gray, Dark Brown and Brown Chernozemic soils (Fig.3). PLF values in the Black Chernozemic were four times higher than the Brown, two times higher than the Dark

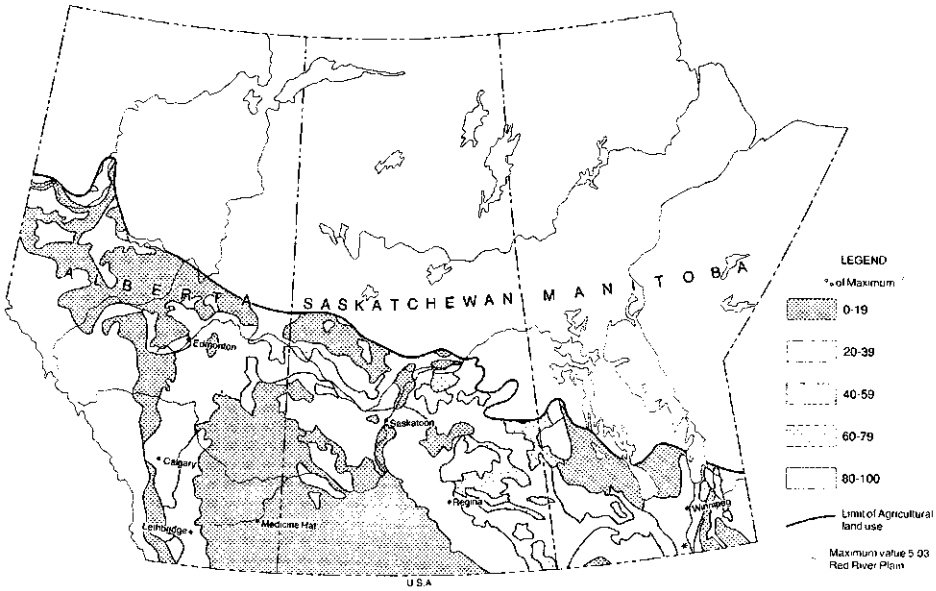


Figure 3. Physical land flexibility (diversification potential) for the prairie region of western Canada.

Brown, and 20% higher than the Dark Gray Chernozemic, and they increased directly with clay content in the soils. Analyses revealed that sandy soils in all areas and loamy soils in the Brown soil zone were being over utilized, whereas some intensification of production could be envisaged in Black Chernozemic areas.

Spatial and temporal scaling of data for macroscale land evaluations

The objective of macroscale evaluations is to provide long term comparative assessments of large geopolitical areas, for the economically most important land uses (crops). This requires proper scaling of input data, models and output, in relation to the spatial and temporal variability associated with the area to be evaluated.

Macroscale evaluations differ from site research in that they require assessments for areas which in space scale are continental and regional (100's to 1000's km$^2$), and in time scale are long term (30 years or more). By necessity this approach focusses on broad regional differences, and deemphasizes microvariations in weather, topography, soils and management, and interyear variability.

The problem is approached most practically by first of all selecting a model that simulates only the most important physiological processes that control crop growth and uses a seasonal time step, then creating a data base to match the input requirements of the model. Temporal variations in weather can further be controlled by defining climate in terms of long term mean monthly conditions during the growing season. In doing this several climatological variables become available for large areas which are not available on shorter time scales, e.g. solar radiation, vapour pressures, wind speed, etc. Variations in soils are

expressed as percentage distributions of existing soil conditions in each polygon. Under these conditions the data input requirements (soil, climate and crop information) became more easily available and manageable, and costs and time frames for carrying out simulation are kept realistic. However output procedures must also be scaled to be in balance with the assumptions built into the model and the input data (Allen et al. 1984). Consequently the more realistic approach is to estimate comparative production potentials and crop suitability rather than simulating specific crop growth processes or yield at a particular site. These criteria of average soil and climate during the growing season, simulation of basic physiological processes with a seasonal time step, and output in terms of comparative ratios are judged to be appropriate spatial and temporal scales for continental application.

The reliability of macroscale evaluations depends to a large extent on the validity of assumptions that are made along the way (Strand, 1981). Long term modeling results based on climate normals are not easily validated, because crop yield data are not generally available on such scales. Also the use of long term average data tends to minimize the effects of important weather dependent events such as hail, drought, frost, pests and diseases and local soil conditions such as moisture availability at specific phenological stages, fertility, salinity, water tables and so forth. Technological advances in terms of improved management, new varieties and so forth are not easily accomodated in such models. Also, often some of the mandatory input variables are found to be inadequate in terms of temporal or spatial representation, and techniques must be developed to estimate missing values or to extrapolate from a limited number of sites to large areas. Consequently the information generated tends to be limited in scope and applicability; results relate to long term growing season conditions only and are unidimensional in time. The structure of the models used and the scaling of the input data are such that results are best suited for comparative assessment of yields over broad areas. They have little applicability for studies such as interyear variability or for producing yield estimates at any given location.

## Conclusions

Macroscale land evaluations are difficult and challenging excercises because of the dual problems of interpolation over time and space, and because results are difficult to validate. On the other hand, if treated within the limits of an entire geopolitical unit, these kinds of studies provide very useful input for policy development and other studies. Recently developed procedures of applying mathematical and statistical methods to land evaluation have improved the capability for undertaking macroscale evaluations, but in the final analysis the quality and dependability of the results depends on the validity of the assumptions that have to be made along the way.

Successful macroscale land evaluations depend to a large extent on properly scaling the data base, model(s) and output to the types of problems being addressed. This implies ensuring that the modeling procedures and input data are in good balance in terms of detail and frequency, and that the output data are classified properly so as to reflect the scale of the models and the problems being researched. For example, models using long term, mean climate data and average

soil conditions cannot be used to provide reliable estimates of yield at the level of a site, nor to study interyear variability. The scale of the model in terms of the processes simulated and the time step involved, the scale and frequency of input data and the classification of the output data must be carefully matched to the requirements of the evaluation.

In macroscale evaluations ratings of comparative performance (yield for example) have been more useful than estimates of absolute performance. The criteria of average soil and climate conditions during the growing period, simulation of basic physiological processes with a seasonal time step, and output in terms of comparative ratios are the most appropriate for regional and continental evaluation.

Validation of the results of macroscale land evaluation is a serious problem and it will remain so in the foreseeable future. This arises because of the scarcity of long term experimental data, and the wide variety and range of management practices possible, but it is also related to the problem of scaling. Detailed, experimental plots, with several kinds and levels of management, are of limited use in validating models that run on long term climatic means. To be useful the validation data should be similar in detail and frequency to the scale of the model, i.e. the types of input data, the physiological processes simulated and the time step of the model. The possibility of achieving this, however, is remote, given the rapid changes in technology that are occurring.

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# LAND EVALUATION AT REGIONAL SCALE

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## Summary

This paper describes the development, during the last 10 years, of land evaluation procedures in the UK for application mainly at regional scale. These procedures involve the use of land information systems and automated cartography. Multiple output of interpretive assessments for a range of users having different needs is now accepted.

Key words: land quality, crop suitability, risk assessment, soil datasets, climatic datasets, pixels.

## Introduction

'Regional scale', for the purposes of this paper, will be considered as the range 1:200,000 to 1:2M, broadly a level at which differences between individual fields and farms are obscured, but differences between regions, counties, provinces, major river catchments or hydrologic zones are readily observed. For most purposes a resolution, minimum mapping area or pixel of 2 x 2 to 5 x 5 km has proved acceptable to express information at regional scale.

Land evaluation is defined generously to include interpretations of soil maps such as:

- Crop suitabilities
- Land management techniques
- Hydrologic processes
- Amenity and ecological suitabilities
- Environmental risks
- Civil engineering suitabilities
- Soil trafficability and drought risk

## Methodology

The methodology for land evaluation at regional scale is not sharply differentiated from that needed at farm, field or 'site' level. Indeed, the aim is to develop systems which are workable at all levels. The main differences relate to the precision of the data required and the need to compile national and regional datasets with large volumes of soil, climate, land use, crop production and other information. If we ask for large spatial replication of point observations or measurements, then we may need to be less demanding about the amount and quality of data for each point. This problem was, in the 1960's and 1970's, taken to mean that land evaluation methodology (usually assumed to be mainly for agricultural purposes) should require only 'low quality' point data, e.g. auger observations of soil morphology, field textures etc. Similarly, climatic data should be 'off the shelf', e.g. mean annual rainfall, winter and summer mean temperatures (MAFF 1966; Bibby & Mackney 1969; Klingebiel & Montgomery 1961). The resulting systems of land evaluation required a great deal of individual judgement, and were often inconsistent or imprecise for decision making purposes.

During the 1970's in UK (Hall et al 1977; Robson & Thomasson 1977), in the Netherlands (Bouma 1977; Beek 1978) and in Germany (Renger 1971) the idea began to evolve that more sophisticated soil and climatic parameters

could be used to support more precise and useful land evaluation systems. It is clearly uneconomic to make expensive, time-consuming measurements in every parcel of land. However, if for example, a representative dataset of available water measurements for texture classes, with adjustments for structure (density) and horizonation (Table 1) can be acquired, we have a basis to upgrade simple point observations and hence map delineations. The Dutch concept of 'transfer functions' has a similar aim (Bouma et al 1986). To the purist these procedures may appear reprehensible (even immoral), but for land evaluation we must be pragmatic in designing systems to run on available data, rather than ideal data. Our systems must be directed to solving real problems. Upgrading climatic data should have been a simpler task than handling soil data. However, we have found that it is necessary to work very closely with meteorologists, and to do a great deal of data manipulation ourselves to obtain the requisite climatic parameters in a form to interface with soil characteristics for land evaluation. Our national maps of meteorological parameters (Figures 1 and 2) required a lot of effort from the Soil Survey staff.

## UK Experience

The 1970's saw a considerable build-up of data on soil water retention and field water regimes. These had little effect on our national systems of land evaluation until the initiation of the 1:250,000 national soil mapping programme (1979-84). During the early part of this programme, it was intended to publish a Land Capability Map in parallel with the soil map at 1:250,000 scale. This latter project was aborted, for administrative reasons, in England and Wales, but carried to completion in Scotland. A new initiative was needed to demonstrate the practical applications of the soil map in England and Wales. It was decided in 1981 to use a quantitative system of suitability assessments for the main arable crops and grass for each major soil series, with climatic adjustments for different locations. These were not portrayed cartographically. However, regional descriptions of the soil series and specification of their distribution in soil association map units, allowed the system to be used to interpret the National Map. In addition, land qualities such as droughtiness (crop-adjusted) workability, trafficability and poaching risk were presented for constituent soil series in each map unit. A system of grassland suitability and 'hill grazing value' (for unimproved pastures) was also presented (Harrod, 1979). Land drainage design, soil water regime before and after drainage, suitability for mole drainage and the need for subsoiling were specified for some 200 soil series, in their regional context. A critical part of this exercise was the compilation of climatic datasets, resolved to 10 x 10 km (Jones and Thomasson, 1985):

| | |
|---|---|
| Field Capacity Duration (return and end dates) | FC days (Figure 1) |
| Maximum potential soil moisture deficit | Max PSMD (grass) |
| Crop adjusted soil moisture deficits for winter wheat, spring barley, potatoes, and sugar beet | MD (Wheat) (Figure 2)<br>MD (Spring Barley)<br>MD (Potatoes)<br>MD (Sugar Beet) |
| Month-end potential soil moisture deficits | MD-April<br>MD-May<br>MD-June<br>MD-July<br>MD-August<br>MD-September |

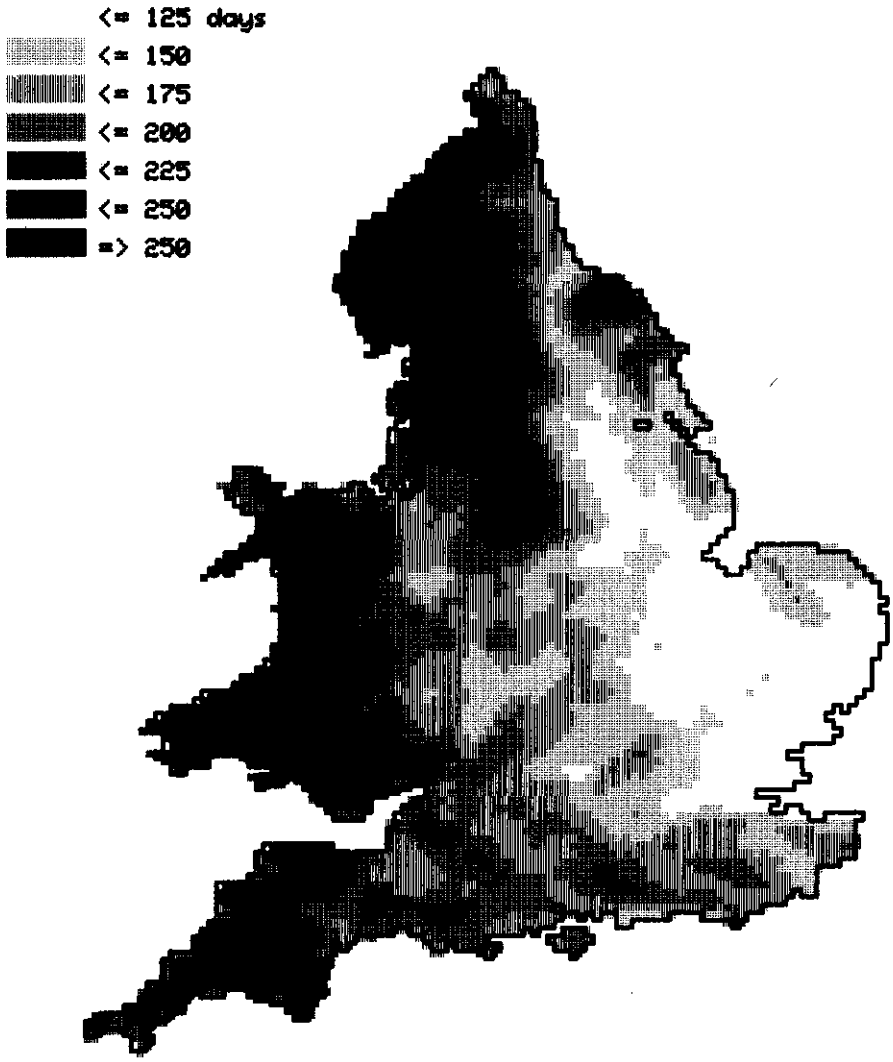


Figure 1. Median duration of field capacity, defined from meteorological data as zero moisture deficit; 5 x 5 km pixels (days)

Table 1 Estimation of available water from texture class, horizon and bulk density

| Texture class | A Horizons Total available water %[1] (easily available %)[2] | B and C Horizons Total available water %[1] (easily available %)[2] Low density | Medium density | High density |
|---|---|---|---|---|
| Clay | 17 (10) | 21 (15) | 16 (8) | 13 (7) |
| Silty clay | 17 (10) | 21 (15) | 15 (8) | 12 (7) |
| Sandy clay | 17 (11) | 19 (14) | 15 (10) | 13 (8) |
| Sandy clay loam | 17 (11) | 19 (14) | 15 (10) | 13 (8) |
| Clay loam | 18 (11) | 21 (14) | 16 (10) | 12 (7) |
| Silty clay loam | 19 (10) | 21 (12) | 17 (10) | 12 (6) |
| Silt loam | 23 (15) | 23 (17) | 22 (14) | 15 (9) |
| Fine sandy silt loam | 22 (14) | 22 (16) | 21 (15) | 15 (9) |
| Medium sandy silt loam | 19 (11) | 19 (13) | 17 (11) | 15 (9) |
| Coarse sandy silt loam | 19 (11) | 23 (17) | 19 (11) | 15 (7) |
| Fine sandy loam | 18 (13) | 22 (17) | 18 (13) | 17 (11) |
| Medium sandy loam | 17 (11) | 17 (13) | 15 (11) | 11 (8) |
| Coarse sandy loam | 19 (12) | 22 (15) | 16 (11) | 11 (8) |
| Loamy fine sand | 18 (14) | 15 (13) | 15 (13) | – |
| Loamy medium sand | 13 (9) | 12 (9) | 9 (6) | – |
| Loamy coarse sand | 11 (7) | 11 (7) | 8 (6) | – |
| Fine sand | – | 14 (12) | 14 (12) | – |
| Medium sand | 12 (8) | 7 (5) | 7 (5) | – |
| Coarse sand | – | 5 (4) | 5 (4) | – |

[1] Water held between 0.05 and 15 bar suction (% vol)
[2] Water held between 0.05 and 2 bar suction (% vol)

Table 2 Allocation of Suitability Classes[1] for Sugar Beet[2]

| Machinery work days 1 January–30 April plus 1 September–31 December | | Droughtiness[3] (AP–MD) mm Over 40 | >20 to 40 | 1 to 20 | 1 & below |
|---|---|---|---|---|---|
| Over 120 | Increasingly restricted workability | Well | Moderate[4] | Moderate[4] | Marginal[4] |
| >90 to 120 | | Well | Moderate | Marginal | Marginal |
| >60 to 90 | | Moderate | Moderate | Marginal | |
| 60 & less | | Marginal | Marginal | | |
| | | | | Increasing droughtiness | |

[1] The full names for these classes are well suited, moderately suited, marginally suited and unsuited.
[2] Land is classified as unsuited for sugar beet where the accumulated temperature is less than 1600 day °C above 5.6°C (whole year), or the maximum PSMD is less than 100 mm, or where slope is more than 7° or where the soil within 25 cm depth has more than 15 per cent stones (more than 6 cm diameter).
[3] Crop-adjusted value
[4] Well suited with irrigation

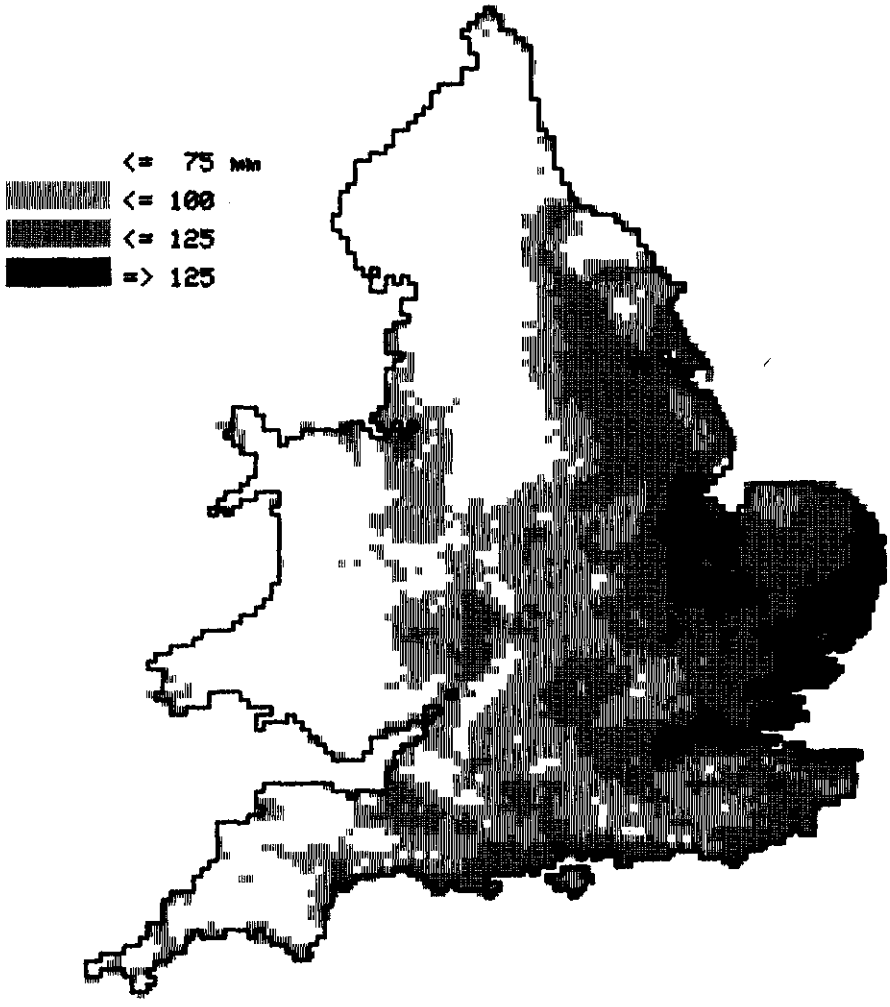


Figure 2. Mean crop-adjusted moisture deficit for winter wheat, defined from meteorological data, adjusted for crop cover and growth period; 5 x 5 km pixels (mm)

| | |
|---|---|
| Accumulated temperature Day°C | |
| Above 0°C, January to June | AT0 |
| Above 6°C, whole year | AT6 |
| Above 10°C, whole year | AT10 |

Table 2 shows the type of suitability matrix for sugar beet devised from soil, site and climatic data. After excluding wholly unsuitable land - steep, very stony, cool or wet climate, remaining land is graded from the interaction of drought risk [profile available water (AP), minus adjusted moisture deficit (MD)] with workability [field machinery work days (MWD)]. The latter is calculated from meteorological data defining the period of zero soil moisture deficit (FC days) together with water retention and permeability data (Figure 3). In UK it is considered sensible to grade land assuming that appropriate field drainage measures have been applied, insofar as these affect workability. For sugar beet and potatoes, adjustments for irrigation may be applied to permeable, well drained land. For cereals and grass, irrigation is excluded (Jones and Thomasson, 1987).

The whole system is now mounted on a VAX mini-computer so that, for any point portrayed on the National Soil Map, local soil and climatic data can be interrogated to give drought risk for individual crops; field machinery work days for spring and autumn periods; suitability for arable crops and grass; poaching risk under intensive grazing. Clearly such interpretations depend heavily on the quality of the soil mapping. To leave opportunity for the user to add improved soil data, the interpretations are given for up to four soil series likely to occur within the designated association. For automated cartography, the dominant soil series in each 5 x 5 km (or 2 x 2 or 1 x 1) pixel is used.

The overall approach may be described as semi-quantitative and non-mechanistic. There are, however, some stochastic features. As well as mean or median climatic variables, the distribution of wet or dry years (quartiles and standard deviations) can be appraised for both workability and drought risk. Our research effort is partly directed at designing an improved, mechanistic system, which would use more precise dynamic soil parameters, rather than capacities and morphology as currently employed. It must be said that the task of mounting an entirely new usable, national system would be formidable. A more likely scenario is that we will use the new modelling procedures on well documented sites to test and 'tune' the existing system. This point may need further emphasis. Sophisticated modelling procedures applicable only to closely monitored experimental sites, and not applicable through the medium of the general purpose soil map, have only limited value for decision-making, advisory or policy purposes. Such modelling may be of greater value for research purposes or to 'improve understanding'. These are separate issues.

## Lessons from this experience

As described earlier, our system of land evaluation was developed and implemented quite quickly (1981-1984) because the earlier land capability approach was rejected by our funding ministry. It was to some degree fortuitous that the research effort to provide adequate data on soil physical properties and water regimes had reached a fruitful stage. Understanding of the climatic parameters needed for crop suitability was also fairly advanced. The massive effort needed to build a national database was only barely appreciated. At this time, it was considered that crop suitability was a more detailed system than land capability, and therefore better applied at farm or field level. We were still thinking of advisory use and the farmer or farm manager as the main customer. It was only after the publication of the National Soil Map and the

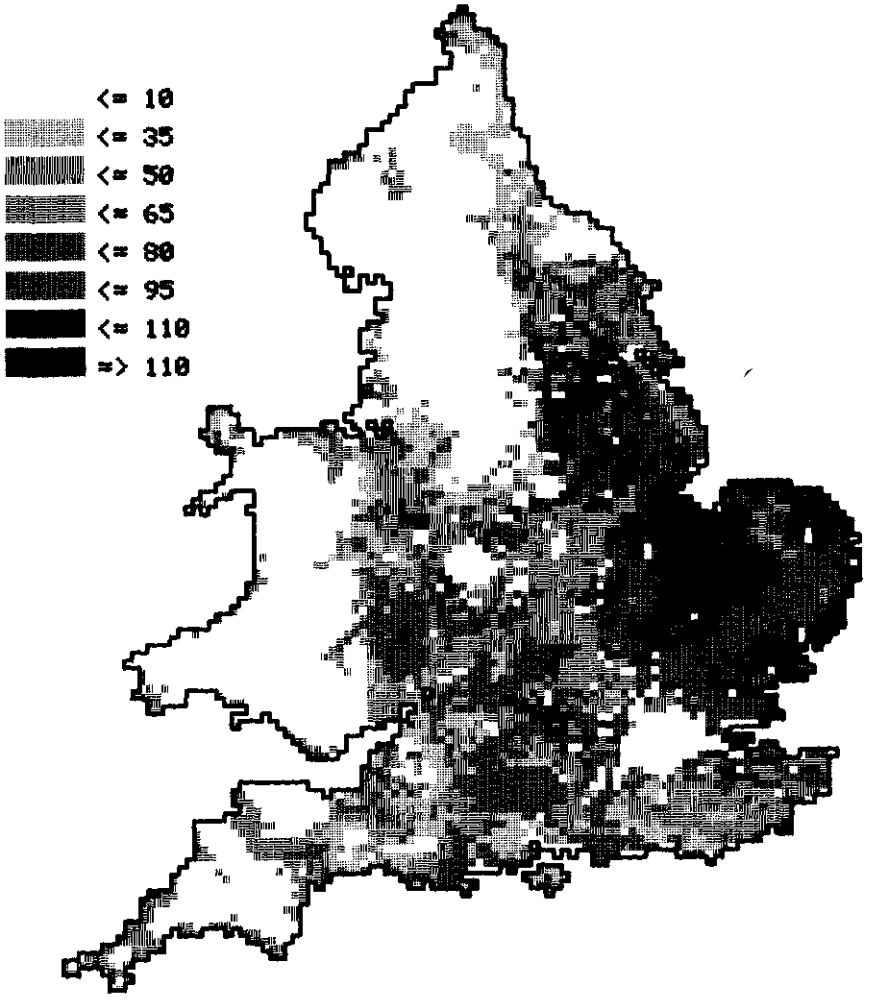


Figure 3. Average Machinery Work Days (MWD) in Autumn (1 September to 31 December) defined from soil and meteorological data; 5 x 5 km pixels

accompanying Regional Bulletins (Soil Survey Staff, 1984) and as the system became computerized that the potential to address new problems, and provide information for broader land use policy, was appreciated.

The need for derived interpetive maps is also worth considering. At the time of publication of the National Soil Map in 1983 it was decided to use an advanced system (Laserscan) to digitise all soil boundaries to a resolution of 100 m. This would enable new interpretive 'vector' maps to be drawn automatically. The system has only been used for one simple, soil-based interpretation. Apart from cartographic problems, it is now clear that very large computer capacity is needed to interface vector soil boundaries with other data such as climate, topography or land use. Most advanced interpretations require such interfacing. Layers of spatial data are much easier to handle using 5 x 5 or 2 x 2 km pixels.

At the outset of the 1:250,000 mapping programme, much emphasis was placed on the need to have an element of grid-controlled (statistical) sampling. This was considered necessary to evaluate the content of map units, to make statistically sound statements on the frequency of occurrence of various land and soil attributes and to test operating systems of soil and land classification. A 5 x 5 km grid, yielding some 6000 points in England and Wales and 4000 points in Scotland was chosen, and considerable efforts devoted to collecting soil profile data and a topsoil sample from each point. This project was termed the 'National Soil Inventory' (NSI dataset).

These data have not yet been fully absorbed into the system and apart from trace element analyses on the topsoils there have been difficulties in exploiting it for land evaluation. With hindsight, a smaller number of randomly located sample areas e.g. 1 x 1 km would have been much more useful to form a dataset where soil, land use and environmental properties could be recorded and re-visited to monitor change in relation to land type (Bunce & Heal 1984).

## Who are the customers for land evaluation?

Ten years ago, the customer was perceived as 'the advisory and farming community'. The object was more production from land, assuming that 'more' would mean more efficient and more profitable. The land scientist's objective was to provide information for advisers and farmers to make more informed judgements about their land to improve productivity. Policy makers in government, industry or professional organisations were assumed to have much the same information needs as the farming community.

Certainly for studies at regional level the chief customer is likely to be the policy-maker rather than the farmer. Emphasis is now on reducing crop surpluses, finding alternative land uses, and protecting the general environment. A derived map of erosion risk or nitrate leaching risk (to groundwater supplies) is not of much interest to a farmer, but it could be a vital base for policy, legislation or major capital investment. Suitability for a crop such as winter wheat could be of interest to a farmer at 1:10,000 scale but possibly it would tell him little he does not already know. A series of maps at 5 x 5 km pixels, is useless for the farmer, but could be a good basis for discussion on price levels in an EEC context. A comparable set of maps showing suitability for other crops would be an aid to decide how critical wheat price is for regional farming communities. There is an important point here, that comparative land suitability between crop options may be more important than single suitabilities. Similarly, suitability for any crop should consider the

environmental risks as well as production and profitability. If top yields of sugar beet on a particular piece of land require annual losses of more than 100 kg/ha $NO_3$-N to groundwater supplies, then the suitability of that land for beet production must be questioned.

## Conclusions

The main changes in land evaluation over the past ten years may be summarised as:

1. Recognition of the need for large cartographic and tabular datasets which are easily manipulated.

2. The acceptance of land qualities, e.g. droughtiness and workability, which are strongly interactive between climate (weather) and soil.

3. The change from single to multiple assessment systems - e.g. Land Capability is replaced by Crop Suitabilities and Environmental Risk Assessments.

4. The change of customer from farmer/adviser to policy-maker.

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# LAND EVALUATION IN HUNGARY - SCIENTIFIC PROBLEMS, PRACTICAL APPLICATIONS

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## Summary

The main achievements and limitations of soil inventory, soil mapping and land evaluation in Hungary on different scales are reviewed and discussed in the present paper. A short outline is given on soil functions, soil and land characteristics, properties and on their control. Soil maps always represent a good scientific basis in Hungary for the development, planning and organization of agricultural production and for the various activities ensuring normal soil functions on national (1:500 000), regional (1:100 000), farm (1:25 000) and field (1:10 000) level, in each phase of their realization. Based on a critical evaluation of the scientific problems and inadequacies in mapping and monitoring of land qualities in space and time, conclusions are drawn on the actual and future tasks aiming rational land use, efficient soil fertility control and environment protection.
Keywords: soil inventory, soil mapping, soil information system, soil fertility control, land evaluation.

## Introduction: soil functions, soil properties, land characteristics and their control

Soils represent a considerable part of the natural resources of Hungary, consequently, their rational utilization has particular importance in the national economy.

The main functions of soils in the biosphere can be summarized, as follows (Várallyay, 1987):

a. Soil as reactor, is the transformator and integrator of the combined influences of various natural resources, as solar radiation, atmosphere, surface and subsurface waters and biological resources. Soil represents the "life media" for microbiological activities and the ecological environment (standort, landsite) for natural vegetation and cultivated crops.

b. Soils are the most important means of production in agriculture, the most important media for crop production.

c. Soils are the most significant - conditionally renewable - natural resources. During crop production they do not change irreversibly, their quality does not decrease necessarily, radically and fundamentally. This renewal does not go on automatically: the maintenance and increase of soil fertility requires permanent activities. In most cases this is the aim of agrotechnics and amelioration.

d. Soils represent a high capacity buffer media of the biosphere, which - to a certain limit - may buffer and can moderate the various stresses caused by:

- environmental factors, as climatic droughts or too humid conditions, air pollution, frost, etc. and/or
- human influences, as intensive, fully-mechanized and chemically controlled crop production; liquid manure of large-scale animal husbandry farms; wastes and waste waters originating from industry, transport,

civilization, urbanization, recreation; pollution from various sources, etc.

Unfortunately, the human-induced stresses gradully increase in their probability, intensity, frequency and territorial occurrence, and their consequences are becoming more and more threatening.

Land qualities - in accordance with the definitions formulated by FAO (1976) and Bouma (1988) - are objective-dependent terms, expressing the ability of land to fit the requirements of one (or more) of the above-listed soil functions. Land qualities are determined by land-site characteristics: relief, geological, hydrological and meteorological conditions, among which soil characteristics ("directly available static attributes being obtained during soil survey"), soil properties ("static attributes that can be related to soil characteristics or that can be measured directly") and soil regimes (time dynamism of soil characteristics and properties) have particular significance. The most important and unique, complex soil property is fertility: the specific feature that water, air and available plant nutrients may occur simultaneously in this four-dimensional, four-phase, polydisperse system and may cover - to a certain extent - the main soil ecological requirements of natural vegetation or cultivated crops. Soil fertility depends on the integrated influences of various soil characteristics and properties, which are the result of soil processes, the mass and energy regimes, abiotic and biotic transport and transformation processes of soils, or more exactly, the geological strata - soil - water- - plant - near-surface atmosphere system.

Consequently, any soil-related activity, as land use, crop production, agrotechnics, amelioration, waste-disposal, etc. influences land qualities, land-site characteristics, soil characteristics and properties through these processes. The influences can be purposeful or undesirable, "favourable" or "non-favourable". "Favourable" is again an objective-dependent term without a definitive, general(izable) meaning. The final aim is to control these processes in such a way, which simultaneously guarantees

- normal soil functions;
- the renewal of soil as natural resource
  - maintenance or increase of soil fertility,
  - prevention of harmful soil degradation processes;
- the satisfaction of soil ecological requirements of various crops, as well as soil technological requirements of various agrotechnical operations;
- the prevention of undesirable environmental consequences, e.g. pollution of surface and subsurface waters; landscape deteriorations, etc.

To ensure the effectivity, rationality and efficiency of any soil-related action, a d e q u a t e soil information are needed. These are exact and quantitative territorial data on well-defined soil and land characteristics and properties, as well as, on single and compound land qualities, including pedotransfer functions; with statistical characteristics on their spatial and time variabilities. These information are required on global, regional, national, micro-regional, farm, field levels and in different phases of these actions: necessity-evaluation → selection of necessary elements → planning → implementation → maintenance → utilization.

Hungarian soil science and soil survey - soil analysis practice have always paid special attention to land evaluation at different scales and continuously gives significant help in the development, planning and organization of agricultural production. For the discussion of the achievements, results and problems of the quantified evaluation of land qualities in space and time, Hungarian experiences represent a good case study, due to the following facts:

- the relatively small size of the country (93 000 $km^2$);
- highly variable physiography: meteorological, geological, hydrological conditions, relief, etc., and, consequently, the occurrence of a wide range of different soils with high spatial and time variabilities;
- wide range of land-use problems: highly mechanized, large-scale farming with intensive chemization; concentrated animal husbandry; flexible cropping pattern, appropriate for the given ecological conditions; amelioration of various soils with limited fertility; prevention of various soil degradation processes; agricultural water management; rural and urban development; environment protection; etc.
- particular importance of agricultural production in the national economy;
- high amount of data and information, as a result of long-term meteorological and hydrological observations, detailed geological and soil survey and mapping.

The main results and limitations of soil inventory, soil mapping and land evaluation on different scales in Hungary are summarized and discussed in the present paper, and conclusions are drawn on the possibilities, actual and future tasks in the scientific research and practical application of the quantified evaluation of land qualities towards rational land use and efficient soil fertility control and environment protection.

## Soil mapping in Hungary

In Hungary soil maps always represented an up-to-date and comprehensive synthesis of soil information according to the given level of soil science, soil survey and soil analysis practices. The main etaps of Hungarian soil mapping can be summarized as follows:

1. The first agro-geological map, including some soil information, as parent material, texture, organic matter status, was prepared by J. Szabó in 1858 for Békés-Csanád county in the scale of 1:576 000.

2. Large-scale agro-geological maps were prepared between 1890 and 1910 by eminent geologists of the Agrogeological Department of the Royal Hungarian Geological Institute:
- on 1:25 000 scale cartographic sheets for physico-geographic regions;
- in the scale of 1:14 500 or even 1:3 500 for large farming units.

On the maps the parent material, texture, organic matter status and land use were indicated, and schematic soil profiles were illustrated for the "representative" soil varieties.

3. I. Timkó had drawn up the first soil map of Hungary (1:900 000) in 1914, indicating genetic soil types (!)

4. P. Treitz compiled the climazonal soil map of Hungary (1:1 000 000) in 1918. On the map the main classes of soils and soil forming factors (climate, geology, natural vegetation) were indicated simultaneously.

5. In 1935 a national programme was initiated by L. Kreybig for a systematical, 1:25 000 scale, practical soil mapping. Such maps had been prepared on cartographical sheets for the w h o l e country between 1935 and 1955. The Kreybig soil maps indicate soil reaction and carbonate status, as well as salinity-alkalinity status by colours; physical-hydrophysical properties and soil depth by symbols. Their categories are delineated by contours. For the "representative" soil profiles additional soil characteristics and properties: organic matter content, total $P_2O_5$ and $K_2O$ content; depth of humus horizon, depth of water table were given, expressed by coded categories defined by numerical limit values. The location of "representative" and "additional" soil profiles and supplementary borings were indicated on the map, but their "validity areas" were not delineated by contours. The maps were supplemented with a data-base, including the field description of soil profiles, data of field observations and labora-

tory analyses; and with a short explanatory booklet, including the characterization of physiographic conditions and soil formation processes, recommendations for rational land use, cropping pattern and agrotechnics. This material was unique at that time on the World and still represents a valuable treasure of soil information.

6. As the synthesis of Kreybig soil maps, Stefanovits, Szücs and their co-workers compiled the genetic soil map of Hungary in 1954 and 1961 in the scale of 1:200 000 and 1:500 000, respectively (Stefanovits, 1968, 1981). On these maps, in addition to the soil taxonomy units according to the Hungarian soil classification system, parent material was also indicated and delineated by contours. The 1:500 000 scale map was the basis of numerous tematical soil maps on organic matter resources, C:N and $C:P_2O_5$ ratios, hydrophysical properties, salt affected soils, soil erosion status, limiting factors of soil fertility, possibilities of soil tillage, necessity of soil amelioration, etc.

7. Within the scope of the programme of the Hungarian Academy of Sciences entitled "Assessment and evaluation of the agro-ecological potential of Hungary" (Láng et al., 1983), a 1:100 000 scale map was prepared at the Research Institute for Soil Science and Agricultural Chemistry (RISSAC) on the soil factors determining the agro-ecological potential (Várallyay et al., 1979, 1980a, 1985). The map was based on all available physico-geographical and soil information. The following characteristics were indicated on the map, using an 8-digit code-system:

1. and 2.: Soil types and subtypes (31 units);
3.: Parent material (9 categories);
4.: Soil reaction and carbonate status (5 categories);
5.: Soil texture (7 categories);
6.: Soil water management properties (9 categories) (Várallyay et al., 1980b);
7.: Organic matter content (6 categories);
8.: Depth of the soil (5 categories).

The map's complete data-base was computer-stored, according to contoured elementar soil mosaics.

8. The above-mentioned information - completed with two more codes:
- clay mineral associations (Stefanovits and Dombóváriné, 1985), and
- soil bonitation value (Szücs, in MÉM OFTH, 1974)

were printed on 1:100 000 scale topographical sheets and published as "Agrotopographical Map" (Várallyay, 1985a).

9. Based on maps (7) and (8), the following tematical maps were prepared for Hungary, in the scale of 1:100 000:
- main types of soil moisture regime (Várallyay, 1985b, 1986);
- main types of substance regime in soils (Várallyay, 1985b, 1986);
- hazard of waterlogging due to soil conditions;
- susceptibility of soils to acidification (Várallyay et al., 1987);
- susceptibility of soils to physical degradation (structure destruction, compaction) (Várallyay, 1987).

10. 1:10 000 scale genetic soil maps were prepared for farming units (state farms and collective farms), mostly between 1960 and 1970 (Szabolcs, 1966). These maps, covering about 60% of the agricultural land of Hungary, consist of four main parts:
- genetic soil map, indicating soil taxonomy units - types, subtypes and varieties - according to the Hungarian soil classification;
- tematic soil maps on the most important physical and chemical soil properties, as: soil reaction and carbonate status; texture and depth of soil; hydrophysical properties; salinity-alkalinity status; depth of humus horizon and organic matter content; plant nutrient status for N, P and K; depth of water table, salt content and salt composition of the groundwater;

- maps indicating recommendations for rational land use; erosion control, reclamation, irrigation, drainage; tillage practice and fertilization;
- data base with explanatory booklet.

These maps were widely used in Hungary and became the easily applicable scientific basis of intensive, large-scale agricultural production. The correction and up-dating of available maps, and preparation of new maps for the missing 40% of the country started again in 1985 within the framework of the National Land Evaluation Programme.

11. Special 1:25 000 scale tematic soil maps were prepared for the territory of the Tisza-II. (Kisköre) Irrigation System. These maps consist of 6 tematic sheets: soil map; texture and hydrophysical properties; salinity-alkalinity status; groundwater conditions; "critical depth of water table"; possibilities, preconditions and recommendations of irrigation. The maps serve as a scientific basis for efficient irrigated farming in the given area without any harmful environmental side-effects, as secondary salinization/alkalization, waterlogging, secondary peat formation, etc. (Szabolcs, Darab and Várallyay, 1969).

12. For the farm- and field level planning, implementation and follow-up of various agrotechnical and ameliorative measures towards the optimation of soil moisture regime, a special 1:100 000-1:25 000 scale mapping system was elaborated by Várallyay in 1986. It consists of the preparation of 4 tematical maps, with the application of a digital code system, in which the various categories are defined by the limit values of measured or calculated soil and groundwater characteristics and properties:

- the soil map indicates soil type and subtype; pH, texture, $CaCO_3$ and organic matter content and their distribution within the soil profiles; depth of humus horizon and the productive soil layer;
- the map of salinity-alkalinity status shows the average and maximum salt content; depth of maximum salt content; pH in the $B_1$ horizon; thickness of A horizon; ESP in the A and B horizon; cation and anion composition;
- the map of hydrophysical properties gives information on texture; water storage capacity (pF 0), field capacity (pF 2.5), wilting percentage (pF 4.2), available moisture range; saturated and unsaturated hydraulic conductivity; layering of soil; moisture regime and waterlogging hazard;
- the map of groundwater conditions indicates the average, minimum and maximum depth of water table; average salt content, cation and anion composition, Na% and SAR of the groundwater.

As it can be seen from this short review of soil mapping in Hungary, the following levels of "decisions", and consequently soil maps, can be distinguished:

| | | |
|---|---|---|
| - national level | 1:500 000 scale | with relevant content (number of parameters and categories with their limit values) data base, accuracy and "fidelity". |
| - regional level | 1:100 000 scale | |
| - farm level | 1:10 000 - 1:25 000 scale | |
| - field level | 1:5 000 - 1:10 000 scale | |

The rational scale and relevant content of a soil map depends on the main purpose of mapping and its accuracy-probability requirements, and the database must be in accordance with these requirements.

The main data sources of soil maps are as follows:

a. Field survey information: e.g. relief characteristics; density and species spectra of natural vegetation; state of crop canopies; parent material and bedrock; rockiness, stoniness, drainage conditions; colour, compaction, structural status of soil surface; sequence, thickness and morphological features of various horizons, etc.

b. Data of field measurements: e.g. depth of humus horizon, appearance

of carbonates and alkalinity against phenolphthalein; pH; moisture content; salt content; infiltration rate; hydraulic conductivity; etc.

c. Data of laboratory analyses.

d. Calculations and estimations on the basis of verified models expressing some existing relationships: e.g. calculation of moisture retention curves on the basis of measured data of particle-size distribution, saturation percentage, bulk density, organic matter content and salinity-alkalinity status; calculation of unsaturated conductivity from measured or calculated moisture retention curves and saturated conductivity; etc.

e. Modelling of different soil processes, i.e. the development and formation of various soil properties.

f. Remotely-sensed data: aerial photographs; multispectral satellite imagery; infrared or false-colour photographs; radar or microwave observations, etc.

g. Estimations on the basis of geostatistical analyses.

These potential information sources become available and practically applicable according to the (a) → (g) chronological order and may considerably contribute to the solution of the main problems of soil mapping;

(i) to indicate three- or four-dimensional characteristics, as soil properties with their vertical, horizontal and time variabilities;

(ii) to extend point information (data on soil profiles or on individual soil layers) into spatial ones;

(iii) to establish categories for various properties defined by limit values or other criteria, based on measurements, calculations, estimations or special interpretations.

Classical soil survey and mapping

- select various morphological, physical and chemical soil parameters, e.g. diagnostic horizons with their characteristic sequence and properties for the definition of various soil classes at different taxonomic levels of soil classification;
- use visible or easily detectable attributes (see a. point earlier) for their preliminary delineation during the field survey; use physiographic information, indicated on the basic topographical maps (contours; water-network; land use pattern → moisture conditions, etc.) during the final drawing of the soil map contours;
- use - in most of the cases - soil taxonomy units as the "carrier" of one or more soil properties.

This was the only, and quite acceptable approach for a long time in soil survey, and it has considerable grounds in the present, modern soil mapping, as well, especially when there are close casual relationships between the registered and the derivated soil characteristics. If such relationships are missing, or the correlation is not appropriately close, other approaches are required. Their necessity is emphasized by two more facts:

- the rapidly increasing accuracy requirements for soil maps as a scientific basis of expensive, complex technical measures;
- the rapid development in analytical methods which do not limit the accuracy of soil information.

The two most promising from these new approaches are remote sensing with computerized digital pattern recognition analysis and the application of various geo-statistical procedures. They have to be used not instead of, but in addition to the "classical" soil survey and mapping.

In Hungary, the researches on the further development of soil mapping or soil information system are carried out in the following main directions:

1. Modelling of various soil processes: e.g. salinization/alkalization (Kovda and Szabolcs, 1978).

2. Correlation analysis between microrelief - natural vegetation - soil

characteristics - moisture regime - surface and groundwater conditions. Such studies are going on in the salt affected areas of the Hortobágy and Kiskunság National Parks.

3. Study of the relationships between the reflectance properties and the physical, mineralogical, physico-chemical and chemical characteristics of salt affected soils. A joint USA (National Science Foundation, Purdue University) - Hungary (Hungarian Academy of Sciences, Research Institue for Soil Science and Agricultural Chemistry) Project began on this topic in 1988.

4. Study of the applicability of various remotely-sensed data for soil mapping; regional monitoring of soil moisture regime, natural ecosystems, moisture and nutrient stresses in various crop canopies.

5. Application of various geo-statistical methods for the characterization of spatial variability of soil properties
- in a very heterogeneous salt affected land under extensive grazing;
- in a heterogeneous sand-hill area with poor grassland;
- on a "homogeneous" chernozem soil with high productivity under intensive agricultural use.

For the mapping of various soil properties - in most of the cases - it's necessary to create categories and class characteristics have to be defined by single values. This is a rather subjective, purpose- and scale-dependent task, because categories (groups, classes) have to be established according to the actual objectives, scale and the given conditions. Because these are not constant, the classes, and their limit values are also not generalizable. If it is so, the maps have to indicate not only the class characteristics, serve as a basis for delineation of mapping contours, but the registered (described, observed, measured, calculated, estimated) single values as well. In such cases the rearrangement of classes according to new limit values, appropriate for a new task, or for changed conditions, is a relatively simple computational procedure, especially if the data base gives opportunities for the application of geo-statistical procedures. Without the indication of registered single values and their exact location, such contour-rearrangement according to new class limits is almost impossible, or at least irrationally expensive and decreases the accuracy and fidelity of the indicated soil information.

In Hungary - as it was discussed earlier - numerous category-systems were elaborated during the 50-year history of soil mapping (Baranyai, Fekete, Kovács, 1987; Földértékelési Szabályzat, 1982; Sarkadi, Várallyay, 1988; Stefanovits, 1968; Szabolcs, 1966; Várallyay, 1985b, 1986b; Várallyay et al., 1979, 1980a, 1980b, 1985). The development of the computerized geographic soil information system (Hun SIS) was a great step forward in this direction, making possible the simultaneous storage of point data and maps of class characteristics and the rearrangement of delineated contours according to given class limits (Csillag et al., 1986, 1988). The results of all soil investigations were and are back-feeded to Hun SIS and used for the improvement of the existing soil mapping practice and advisory system.

## Soil and land evaluation in Hungary

Soil and land qualities are objective-dependent dynamic attributes, which can be divided into two main groups (Bouma, 1988):
- single land qualities: characterizing measurable state-variables of the land, and
- compound land qualities: have to be derived using calculations, simulation models or pedo transfer functions and various soil and land characteristics, and models.

In addition to soil and land characteristics and properties, soil maps

may represent single and compound land qualities, as well, as it was discussed earlier in the review of Hungarian soil mapping. Therefore, here only three additional examples are briefly summarized from Hungarian experiences:

1. Rating of soil fertility

Soil fertility or, alternatively, yielding capacity or productivity includes its "fitness" for plant growth and its suitability as a rooting medium.

The final expression of soil fertility or site fertility, including the contributions of climate, relief and water supply, is the yield, the quantity of dry matter per unit area, its quality, and their year to year variation. Potential soil fertility can be defined as maximum attainable yield with optimizing of all factors; actual soil fertility is the present status under ruling unimproved conditions. The difference between potential and actual soil fertility can be used as a good and sensitive indicator of the e f f i c i e n c y of the agricultural utilization of soils. Potential soil fertility can be improved by soil amelioration, by the elimination or moderation of unfavourable influences and consequences of limiting factors. Actual soil fertility can be raised up to potential soil fertility by proper agrotechnics, and accurate production technologies. An ideal fertility rating system has to express:

- both soil fertility and site fertility;
- both potential and actual soil fertility;
- both natural and economic "values" of a soil or land site.

In addition to these, the system has to be:

- specific enough for various crops (land capability classifications and suitability ratings) and various objectives (agricultural land use, environment protection, landscape planning, planning of urban and rural development, etc.);
- general (or generalizable) enough for special, mostly financial-oriented purposes (price, tax, etc.);
- complex enough to express integrated relationships as soil fertility itself;
- simple enough for quick and easily computerizable data handling and data processing.

All the existing numerous land and soil evaluation systems on the World, including the Hungarian system, are far from being able to satisfy all these requirements, and have some more or less significant limitations.

In the Hungarian system (Földértékelési Szabályzat, 1982), where the rating is 0-100, the basis of the evaluation is the genetic soil type. "Unfavourable" soil properties, as extreme, too acidic or alkaline soil reaction; extreme, too coarse or too heavy texture; too high carbonate content; salinity-alkalinity; quantity of coarse fragments; shallow depth due to various factors; depth of humus horizon and organic matter content, as well as land-site characteristics, as relief, slope gradient and exposure, climatic index are taken into consideration as limitations of the maximum (potential) fertility of a given soil type. These ecological limitations are expressed as "minus" points and must be substracted from the initial value. The system - according to our opinion - overemphasizes the importance of genetic classes in soil fertility, which is not fully correct because:

- the exact and precise definition and determination of the applied soil genetic classification units are sometimes rather subjective, based not only on measured, or measurable parameters;
- in the case of the most important and most widespread soil types of Hun-

gary (e.g. brown forest soils, chernozems, meadow soils, alluvial soils) there is no direct relationship between genetic type and fertility, because these soil types show great variations in various soil properties, and, consequently, in fertility, as well.

Under the conditions of intensive agriculture, the response of soil to various influences (e,g. tillage, fertilization, irrigation, etc.) has much greater significance than "original" soil fertility. This is still missing from the system, as well as crop specification. In spite of these inadequacies, the system was officially accepted and a National Land Evaluation Programme started in 1981 on old "cadastral" basis and has been followed from 1986 on an up-to-date large-scale (1:10 000) soil map basis. The Programme will be completed in the early nineties. Until then, the "preliminary" soil bonitation values are available on the printed sheets of the 1:100 000 scale agrotopographical map.

2. Soil and land evaluation for fertilizer recommendations (Sarkadi and Várallyay, 1988)

In the system, Hungarian soils were classified into 480 elementar soil mosaics. Each mosaic was characterized by a 4-digit code. The 1st digit of this code expresses the main types of water and substance regimes of soils, coded as follows: (1) Migration type; (2) Leaching type; (3) Hydromorphic type; (4) Skeletal soils; (5) Salt affected soils; (6) Shallow soils; (7) Organic soils; (8) "Human made soils". The 2nd, 3rd and 4th digits indicate the most important soil characteristics from the viewpoint of the evaluation of plant nutrient regime and efficiency of applied fertilizers, such as: texture; soil reaction and carbonate status; organic matter; or other properties. The 480 mosaics were aggregated into 6-6 land-site categories. This aggregation was - naturally - different for the various major nutrient elements N, P, K, Ca, Mg , consequently, the "land-site categories" contain different "collections" of elementar soil mosaics in each case.

Measured plant nutrient contents are converted into 5-5 "nutrient supply classes", according to these land-site categories. These "nutrient supply classes" are mapped (generally in the scale of 1:10 000) and serve as a basis of fertilizer recommendations. For the mapping of plant nutrient status, the sampling unit is a plot or a max. 6 ha area, from which "average" soil samples are taken for laboratory analyses. The sampling and analysis is repeated every third year. Data are stored in the Agrochemical Information System (AIIR) (Baranyai et al., 1987).

3. Land evaluation for recultivated spoil banks (Szegi et al., 1988)

The system, elaborated by Várallyay et al. (1988), is based on the following principles:

a. The system does not take into account genetic soil types, because they cannot be developed here during the short recultivation period.

b. "Soil quality value" (SQV) is calculated as a sum of "balls", based on the partial evaluation of the various factors that contribute to fertility: i.e. microrelief; amount of coarse fragments on the surface and within the profile; texture and stratification; pH and $CaCO_3$ content; "humus" content.

c. Because in most cases heterogeneity is the limiting factor of land suitability and fertility of recultivated spoil banks, we introduced a heterogeneity factor (HF) and developed a procedure for its calculation. To obtain "land quality value" (LQV) of a field, SQV values, calculated for the appropriate soil profiles, have to be averaged ($\Sigma$ SQV/n) and multiplied by HF:

$$LQV = \frac{\Sigma\ SQV}{n} \cdot HF$$

d. Substracting a "climatic factor" (CF) from LQV, "land-site quality value (LSQV) can be obtained.

According to my opinion, the additive procedure and the introduction of a "heterogeneity" factor may be successfully applied in the fertility and land suitability rating of agricultural lands, as well.

Computerized cartographic soil information system in Hungary (HunSIS=TIR)

For the systematically controlled processing, for a comprehensive, up-to-date synthesis and, for the multi-purpose practical use of all the earlier mentioned soil information, a computerized cartographic soil information system (HunSIS=TIR) was developed in RISSAC (Csillag et al., 1986, 1988). TIR consists of two main parts:

(i) "bank" of soil data and contours;

(ii) information system.

There are three main types of input information:

a. "Point information". Measured, coded or calculated data on the various characteristics of soil profiles or their diagnostic horizons, different layers. Their locations are accurately defined by geographical co-ordinates. At present the data on more than 30 parameters are stored in the system.

b. Territorial (cartographical) information. 1:25 000 scale tematical maps on various environmental factors: geomorphology, relief, groundwater conditions and soil properties. At present more than 20 territorial parameters are stored, digitized as polygons.

c. Special inputs can be various equations, formulated relationships and models established for the description and characterization of soil processes, soil - water - plant relationships, regimes of various soil constituents as moisture, plant nutrients, pollutants, etc. A good example for this is the preparation of contour maps on the "optimum depth" and on the "critical depth" of the water table. The maintenance of water table at "optimum depth" ensures the moisture-supply of plants from the good quality groundwater. The stabilization of water table under the "critical depth" prevents soil salinization-alkalization from the poor-quality, stagnant groundwater. Based on the simultaneous input of our four-step model, describing the transport of water and soluble constituents in the unsaturated zone of the stratified soil, profiles with fluctuating water table (Várallyay, 1974), and its required basic parameters, soil and groundwater characteristics, the contour maps were direct outputs of the System, and were efficiently used for the forecast of probable ecological consequences of the Danube (Gabcikovo-Nagymaros) and Tisza (Kisköre) irrigation systems in Hungary.

The system itself may formulate such relationships and develop models on the basis of the evaluation and analyses of the large number of input data, This opens up new output possibilities, and may extend the data and contour "bank" into a real information system.

The digitizer - computer - plotter distributed system, including SZATIR software, is operational to search for either location or attributes and to display results in digital, tabular, graphical or cartographical form (data, categorized data, results of model calculations, tematical maps, etc.).

Current system development is focused upon the enhancement of local (i.e. work-station) modelling and editing functions, as well as to make this quadtree-based tematic GIS compatible with other gridded data sources.

## Practical applications

Soil information (data, maps, HunSIS, etc.) are widely used in Hungary, mainly in the following fields:

- in the planning and implementation of rational land use and cropping pattern, according to ecological conditions, i.e. delineation of ecologically favourable regions for certain crops;
- in the determination of the preconditions and possibilities of adaptive agriculture that can promptly and flexibly respond to "stress situations" as frost, drought, excess moisture, etc;
- in estimating the necessity, the predictable impact and efficiency of various measures required to ensure good crop yields and the maintenance or increase of soil fertility, e.g. amelioration: erosion control, soil reclamation, increase of water-use efficiency; agrotechnics: tillage, nutrient control, etc.;
- in the implementation and control of the above measures on national, regional, farm and field levels;
- in the prediction and prevention of unfavourable soil degradation processes due to natural factors or antropogenic activities, as acidification, salinization-alkalization, structure destruction, waterlogging, etc.;
- in land and soil evaluation, for the determination of real "fertility values" and indices expressing the sensitivity and responses of soils to different treatments;
- in the elaboration and selection of rational territorial variants of non-agricultural land use, e.g. industrial, urban and rural development; landscape planning, etc.;
- in the protection of the environment and nature conservation;
- in educational activities.

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# REGIONAL MODELLING OF SALT LEACHING

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## Summary

Regional models of salt-leaching have been developed which simulate every measured point in a field. Based on these point values, maps were obtained using geostatistical methods. The relative error (simulated minus measured) as percentage of the mean was in the range of up to 50%. Nevertheless, the maps of the simulated values represented the essential features of the maps of the measured values correctly.
Keywords: salinity, leaching models, spatial variability

## Introduction

One method to reclaim salt-affected soils is the leaching of the soluble salts below the root zone. Simulation models of the leaching process can help to determine the amount of water needed for a desired level of desalinization or, vice versa, to give an estimate of the extent of leaching accomplished by a given quantity of water. - As soils are generally heterogeneous, regional models (in contrast to point models) were developed. In that way not only the average response of a whole field can be investigated, but also that of specific sites in a field. Dividing a field into subplots of equal leaching requirement can help to save irrigation water.

## Materials and methods

### Field experiments

Two field leaching experiments were conducted in Haryana, Northern India: a 20 x 20m plot was selected (site I, saline soil) and 49 observation points were marked on a 2.5 m regular grid. Before the experiment infiltration tests were carried out at each of the 49 points. Soil samples from 3 depths (0-20, 20-40, 40-60 cm) were taken before the experiment and after the infiltration of 10, 20 and 30 cm of irrigation water from a nearby canal. The samples were analyzed for water content, EC, Ca+Mg, Na and Cl; all measured in a 1:2 soil-water extract. The average infiltration rate was 5.2 cm/day. - A similar experiment was carried out on a saline-sodic soil after the application of gypsum (site II). The size of the field was 15 x 25m, samples were taken at 45 points on a 2.5 m regular grid. The average infiltration rate was 2.3 cm/day. Table 1 shows some characteristics of the two soils.

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Table 1: Composition of the soils at the experimental sites (all values measured in 1:2 soil-water extract.)

| | Site I | | | Site II | | |
|---|---|---|---|---|---|---|
| depth(cm) | 0-20 | 20-40 | 40-60 | 0-20 | 20-40 | 40-60 |
| pH | 7.5 | 7.8 | 7.6 | 9.9 | 10.0 | 9.9 |
| EC(mmho/cm) | 2.6 | 2.4 | 3.1 | 2.0 | 1.8 | 1.6 |
| Ca+Mg (meq/l) | 17.8 | 15.0 | 19.1 | 2.8 | 2.8 | 3.6 |
| Na (meq/l) | 6.3 | 11.5 | 15.0 | 20.6 | 16.8 | 14.4 |
| Cl (meq/l) | 17.0 | 12.1 | 15.1 | 3.4 | 2.8 | 2.6 |

The models

Two basic models were applied: a model based on the convection-dispersion equation (CDM) and a model based on plate theory (PTM; Burns, 1974). Both models include transport of water and solutes, cation exchange (Gapon equation), and the dissolution/precipitation of gypsum (solubility product). They are described in detail in Anlauf (1988). The PTM is mathematically simple, calculation is fast and easily determinable input data are needed (such as field capacity). The CDM is more complex and some input parameters (such as the dispersion coefficient) are difficult to measure and must be estimated.

The spatial heterogeneity of the transport parameters is assumed to be one of the main factors for the difficulties of transport models to describe leaching at field scale. One method to account for this variability is the use of Monte-Carlo-simulations (e.g. Amoozegar-Fard et al., 1982, Anlauf & Richter, 1987): the model was run for each sampling point several times with infiltration rates randomly taken from a given lognormal frequency distribution. The average of these simulations describes leaching at a particular point.

Geostatistical methods

Anisotropic variograms (Journel & Huijbregts, 1978) were calculated for the solute concentrations at the various stages of leaching. Based on these variograms, values at non-recorded points were interpolated by block-kriging at a distance of 0.625 m and with a block size of 1x1 m, and maps were drawn from these values.

Results and discussion

Solute transport at every point in the field was simulated with both the PTM and CDM. Because the results of the PTM and CDM were very similar, only those simulated with the more simple PTM are displayed here. The quality of the simulation has been evaluated by the following methods: 1. calculation of the mean error (which should be close to zero) and the mean absolute error, and 2. comparison of the measured and simulated maps of Cl, Na and EC for 0-60 cm depth as a

measure for the total salt removal from the root zone.

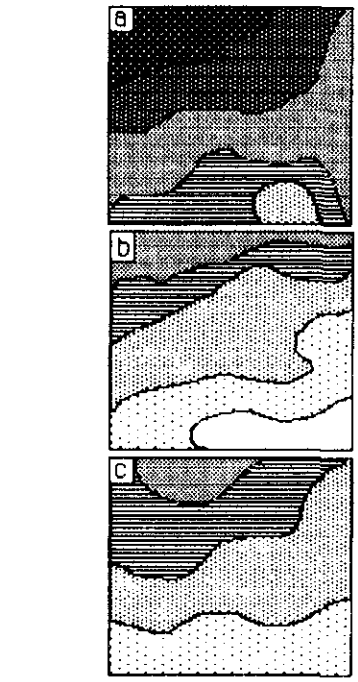
The agreement at site I (saline soil) was poor in the sense, that the simulated values were always much lower than the measured, i.e. the modelled leaching efficiency was much higher than the observed one. The reason is the different structure of the two soils: site I had large pores and shrinking cracks and, thus, the infiltration rates were high and log-normally distributed. At site II (saline-sodic), the soil was very compact without large pores and, therefore, the infiltration rates were normally distributed. Site I could only be modelled satisfactorily with Monte-Carlo-simulations and the assumption of a log-normal distribution for the infiltration rates (CV = 100%). One reason for the difference between this assumed CV of 100% and the measured CV of 50% possibly is, that the infiltration rates measured for few hours in the topsoil do not necessarily represent the rates after days of infiltration.

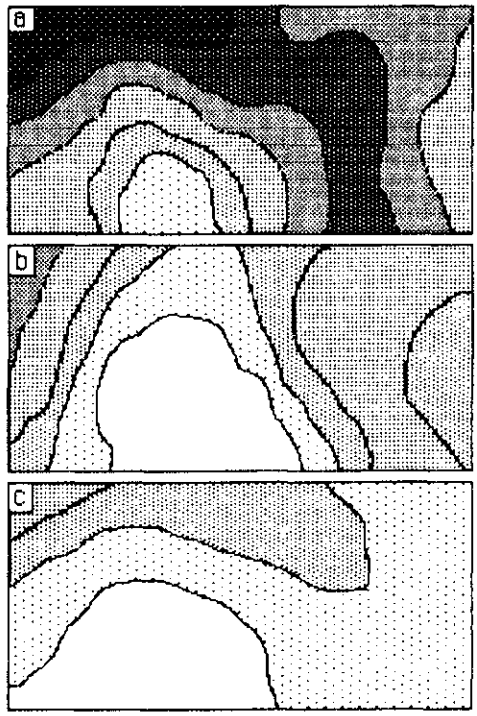
Table 2 gives the mean error (simulated minus measured values), the mean absolute error and the relative absolute error (mean absolute error in percent of the mean value) for both sites. A paired t-test has been applied to test the hypothesis that the mean error is zero. The relative absolute error ranges from 10 to 58 % for Cl, 14 to 31% for Na and 18 to 40% for EC. Figs. 1 and 2 show maps of the simulated and measured values after 30 cm of irrigation together with the maps of the initially measured values. In spite of the high relative absolute errors in the range of up to 50%, the maps of the simulated values represent the essential features of the measured values correctly. The maps of the simulated Na and EC values are of similar quality.

Table 2. Quality of the simulation.

| | site I | | | | site II | | | |
|---|---|---|---|---|---|---|---|---|
| irrigation | ME | MAE | Mean | RAE% | ME | MAE | Mean | RAE% |
| | | | | Chloride | | | | |
| 10 | 0.40* | 0.56 | 2.51 | 22.3 | -0.81 | 2.42 | 13.23 | 18.3 |
| 20 | -0.18 | 0.72 | 2.16 | 33.3 | -0.58 | 2.71 | 9.40 | 28.8 |
| 30 | -0.45* | 0.64 | 1.11 | 57.7 | 0.12 | 2.23 | 6.16 | 36.2 |
| | | | | Sodium | | | | |
| 10 | 0.92 | 2.42 | 17.04 | 14.2 | -1.78* | 3.09 | 11.40 | 27.1 |
| 20 | 0.20 | 2.67 | 15.29 | 17.4 | -1.36* | 2.65 | 8.70 | 30.5 |
| 30 | -0.11 | 3.06 | 10.85 | 28.2 | -0.12 | 1.21 | 5.63 | 21.5 |
| | | | | Electric conductivity | | | | |
| 10 | 0.28* | 0.33 | 1.80 | 18.3 | 0.10 | 0.42 | 2.40 | 17.5 |
| 20 | 0.22* | 0.32 | 1.63 | 19.6 | 0.16 | 0.51 | 1.80 | 28.3 |
| 30 | 0.25* | 0.45 | 1.13 | 39.8 | -0.09 | 0.41 | 1.66 | 24.7 |

An asterix (*) indicates a significant difference from zero. ME=mean error, MAE=mean absolute error, RAE%=relative absolute error in percent of the mean.



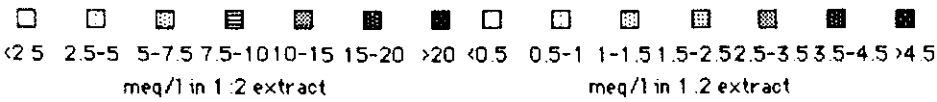




Fig. 1. Site I (17.5 x 17.5 m): Cl concentrations in meq/l. a) initially measured b) measured, c) simulated after 30 cm of irrigation.

Fig. 2. Site II (12.5 x 22.5 m): Cl concentrations in meq/l. a) initially measured b) measured, c) simulated after 30 cm of irrigation.

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# JAMPLES: A COMPUTERIZED LAND EVALUATION SYSTEM FOR JAMAICA

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## Summary

JAMPLES is a software package designed to determine land suitability of areas targeted for agricultural use. It matches climate, soil and topographical data with agro-ecological requirements of specific crops, indicating possible limitations. Following this "matching" process the final suitability is determined at three levels of management. The system generates semi-quantitative results which have been used for rural planning in Jamaica. JAMPLES is the agricultural interface of the Jamaica Geographical Information System (JAMGIS). JAMGIS is being developed to provide a nationally consistent capability for land use planning at scale 1:25,000 to 1:50,000.
Keywords: land evaluation, geographical information system, Jamaica.

## Introduction

The Rural Physical Planning Division of the Ministry of Agriculture continues to develop JAMGIS, the Jamaica Geographical Information System. The development of JAMGIS is part of the Government's policy to develop a nationally consistent computer capability allowing for large scale agricultural planning. Parallel to this programme the bilateral Soil Survey Project, co-funded by the Governments of Jamaica and the Netherlands, was established in 1983. Its objective is to upgrade the national soil data base with a view to provide comprehensive information on the soil resources and their potential for crop production. The latter task has been addressed by developing a computerized land evaluation system referred to as JAMPLES (Batjes, Bouwman & Sinclair, 1987).

JAMPLES matches requirements of selected crops grown under broadly defined levels of management with the agro-ecological qualities of the land indicating existing limitations. This information is then used to determine the land unit's suitability for a projected agricultural use.

The development of JAMPLES is according to the guidelines proposed by FAO (1976) and Beek (1978). The system forms the physical part of a "two-stage" approach, presently focussing on agro-ecological aspects of land evaluation. In a later stage it will be supplemented with a socio-economic evaluation.

## Land qualities and crop requirements

Most land qualities are composed of one or more land characteristics (FAO, 1976). Both the agro-ecological requirements of crops and the environmental characteristics of land are rated according a rating system. Version 3.0 of JAMPLES is based on the second approximation of this rating system (SSU, 1987d). Successive approximations will be prepared as insight into soil-water-crop yield relations further increases.

JAMPLES groups land qualities into those relating to the agro-ecological environment and land and water management. The former includes: soil moisture regime (MR); air temperature regime (TR); soil reaction (PH); nutrient retention (NR); nutrient availability (NA); calcium carbonate toxicity

(CC); aluminium toxicity (AL); salinity hazard (SA); sodicity hazard (SO); availability of oxygen in the rootable zone (OX); rooting conditions (RC); and the latter: long term erosion hazard (E); ease of cultivation (W); irrigability of the land (I).

Most agro-ecological requirements of specific crops were derived from a research of local and international literature.

## The matching procedure

Data on soil and terrain conditions are analyzed by the matching module (MATMOD; SSU, 1986b). The user selects "land units" which are characterized by major soils (series), slope gradient and slope length. Relevant crops are selected next. The pertinent information from the soil and crop data bases is accessed during the matching process which involves:

a) Matching of the crop's temperature requirements with the air temperature regime to indicate possible limitations for growth. Linear regression is used to calculate the land unit's temperature regime from elevation above mean sea level (SSU, 1986c).

b) Matching of crop water requirements with the minimum amount of rainfall that can be expected during the growing period in 75 percent of the years (SSU, 1986a).

c) Matching of the erosion index with the tolerable soil loss. This index is calculated according to a modified version of the Universal Soil Loss Equation (SSU, 1985; Bouwman, 1986).

d) Matching of specific "soil" requirements of crops with the remaining land qualities (SSU, 1987d).

MATMOD generates a table showing the degree to which each land quality is limiting for a given crop. The degree of each limitation is rated into three classes, viz.: no/slight, moderate and strong limitations which correspond respectively with less than 20 percent, 20 to 50 percent and over 50 percent reduction as compared with optimal (target) yields. MATMOD also creates a computer file for the LANDEV module.

LANDEV converts ratings of limitations into a final suitability class. At this stage three broadly defined levels of management are considered (i.e. low, medium and high). This differentiation is made to take into account the effect of management practices on the suitability of a land unit for a given crop.

LANDEV recomputes the degree of each limitation under the considered level of management into an I-index. This index is assigned a value of 100 when a land quality is not/slightly limiting, 80 when it is moderately limiting and 40 when it is strongly limiting. The final suitability INDEX is calculated by multiplying the I-index of the most limiting land quality by the average of the I-indices of the remaining land qualities. Wood & Dent (1983) used a similar approach when developing a Land Evaluation Computer System for Indonesia. The value obtained for INDEX is interpreted according to Table 1.

Table 1. INDEX values and corresponding suitability classes

| INDEX value | code | suitability class |
|---|---|---|
| 80 and over | S1 | highly suitable |
| 60 - 80 | S2 | moderately suitable |
| 35 - 60 | S3 | marginally suitable |
| 25 - 35 | S4 | poorly suitable |
| less than 25 | N | not suitable |

At present suitability classes cannot be related to achievable yields due to a lack of site specific information on soil-water-crop yield relations.

## The JAMPLES software

The JAMPLES software package is written in BASIC release 3.0 and can be operated on an IBM PC/AT or compatible micro and mini computers with MS-DOS 2.1 or later versions. Required peripherals are a monochrome monitor and a line printer with 85 column capability. SSU (1987b) describes the installation procedure.

JAMPLES is a menu driven system which facilitates the understanding of each operation. Accompanying technical bulletins discuss data requirements, aspects of data management and include technical information on the assumptions and procedures (SSU, 1985; SSU, 1986 a & b; 1987 a, b & d).

Subroutines for management of climate, soil and crop data can be accessed through submenus. POWSTAT (SSU, 1986a) makes a statistical analysis of monthly rainfall totals. RAINSTAT uses files generated by POWSTAT to calculate the dependable growing period at the 75 percent level of statistical confidence. CROPRISK (SSU, 1987a) simulates crop-water-yield relations giving the probability of having a pre-specified departure from optimum yields under rainfed conditions. SODEMOD (SSU, 1985) determines the required soil conservation practices based on a modified version of the Universal Soil Loss Equation. It includes COSTMOD which calculates the costs of proposed soil conservation practices.

The modules which assess the land suitability for a specific use have been discussed in detail under the heading of "matching procedure".

Output of LANDEV can be off-loaded to the GIS. The GIS facilitates mapping of areas of similar agro-ecological potential for specific forms of land use. It calculates further the hectarage of land that can be earmarked for rural development taking into consideration additional features such as land ownership, present land use and infrastructure.

## Present applications

Modules of JAMPLES are tested, validated and calibrated on a routine basis resulting in updated versions of the software. Release 2.0 has been used for land evaluation producing encouraging results (SSU, 1987c). Release 3.0 has been applied during the Cocoa Pilot Study, the testing ground for the ARC/INFO based Jamaica Geographical Information System (ESRI, 1987; RPPD, 1988). Other applications of JAMPLES include the assessment of recommended soil conservation practices (Bouwman, 1986) and agro-climatic zoning (SSU, 1987e).

## Ongoing and future work

A crucial stage in the development of the software is model validation and calibration. An important restriction for testing JAMPLES is the limited availability of site specific information on soil-water-crop yield relations under Jamaican conditions. As a result the feasibility of using agricultural data from other Caribbean and Latin American countries is being investigated.

A possible future development is the linkage of JAMPLES with a comprehensive soil data base management system such as ISIS (Van Waveren, 1987).

## Discussion

It was envisaged that JAMPLES could provide a user service within two years from its conceptualization in November 1985 (see Batjes, Bouwman & Sinclair, 1987). A semi-quantitative version of JAMPLES is now fully operational. It is most suited for land evaluation studies at a scale of 1:25,000 to 1:50,000. At present suitability classes cannot be correlated with yields and hence economic returns. This limitation will be addressed when developing release 4.0. The linkage of JAMPLES with the GIS has produced encouraging results. It is anticpated that JAMGIS will play an important role agricultural planning and decision making in Jamaica in the near future.

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# CALCULATING THE RESIDUAL SUITABILITY OF AGRICULTURAL LAND BASED ON ROUTINE LAND RESOURCE SURVEYS

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## Summary

A methodology is proposed for the assessment of the impact of land degradation on the suitability of land. The 'residual suitability' is defined as the time it would take for the intrinsic productivity of land to degrade down to a level which makes it unsuitable for the land utilization type considered. The residual suitability can be calculated using the results of routine land resource surveys and simple modelling techniques. The methodology can accommodate different levels of sophistication. An example from the communal areas of Botswana is given.
Keywords: land evaluation, land degradation, residual suitability, modelling.

## Introduction

The purpose of land evaluation is to predict the performance of specific land use systems as conditioned by the constraining influence of land properties (BEEK, 1978). The performance of the land use system is expressed in actual suitability classes when the present condition of land is considered; the potential suitability of land refers to the suitability after improvement of (some of the) characteristics of the environment.

The attributes of the environment, however, are not constant: land qualities change with time and lead to a reduced potential to produce - a process referred to as land degradation.

The present paper proposes a general procedure for the integration of the assessment of land degradation within the exercise of land evaluation through the definition and calculation of the residual suitability of agricultural land.

## The intrinsic productivity and residual suitability of land

The residual suitability of agricultural land is defined as the time (in years) it would take for the intrinsic productivity of land to degrade down to a level which makes it unsuitable for the land utilization type considered and is equivalent to the Soil Life concept of ELWELL and STOCKING (1984).

The productivity of land is defined after BEEK (1978) as a 'super' land quality and encompasses a number of qualities giving the potential for producing specified plants or a sequence of plants under defined sets of management. BIOT (1986) has defined the intrinsic productivity of land as being composed of the set of irreplaceable land qualities which are responsible for the long-term potential of land to produce.

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## Calculation of the residual suitability of land: a general procedure

The residual suitability of agricultural land can be calculated in three steps: the identification and calibration of a productivity index, the expression of the land use system in a mathematical model and the integration of the land use model between the present day and minimum allowable productivity levels.

### Identification and calibration of the productivity index

BIOT (1988 a and b) has discussed the different kinds of productivity indices currently used in the fields of land evaluation and erosion/productivity research. Three main categories are identified: measured crop yields, modelled crop yields and land qualities or characteristics.

A number of land characteristics and qualities are used as productivity index: soil depth and topsoil thickness (ELWELL and STOCKING, 1984 and TODOROVIC et al., 1987) and various rating systems such as the one developed by KINIRY et al., (1983).

Two main requirements have to be fulfilled by a productivity index: its relationship with crop yields must be calibrated for the land utilization type considered, and it must encompass all land qualities which are potentially affected by land degradation processes.

Once calibrated, it is possible to calculate the present day productive potential of the land using current values of the land properties. The minimum allowable productivity level is derived from economic considerations on the one hand and the relationship between the productivity index and crop yields on the other (see for instance the method proposed by STOCKING and PAIN, 1983).

### Modelling of the Land Use System

The second step involves the expression of the land use system in a mathematical model which incorporates the productivity index and the ways in which this index is potentially affected by the land degradation processes. Different levels of sophistication are possible: EPIC (WILLIAMS et al., 1984) is a complex model of the land use system used in the United States; a number of empirical models exist based on land characteristics and qualities, e.g. LARSON et al. (1983) and ELWELL and STOCKING (1984); TODOROVIC et al. (1987) use a stochastic model of crop production and land degradation processes to assess the effect of soil erosion on the productive potential of land.

### Integration of the Land Use Model

Two main methods of integration are recognised: both EPIC and most empirical models calculate losses due to land degradation in annual increments: each year the condition of the soil is re-assessed and both the productivity and rate of degradation of the degraded soil are re-calculated on the basis of soil profile data; ELWELL and STOCKING (1984), BIOT (1988 a and b) and TODOROVIC et al. (1987) use mathematical algorithms for the integration of the land use model.

## A case study: calculating the residual suitability of communal rangeland in the Hard Veld of Botswana

A case study involving the forecasting of future productivity trends of the communal rangelands of Botswana illustrates the above methodology.

Given the semi arid climate and the importance of water availability in the context of the long term productive potential of agricultural land, the available water storage capacity (AWSC) was selected as productivity index. A routine resource survey was conducted to assess the effectiveness of this productivity index and it was found that AWSC is positively related to the characteristics of the primary production. The present day productivity level was calculated using the average soil depth and the AWC. The minimum allowable productivity was derived from the relationship between the productivity index and grass standing biomass at the end of the season and standard guidelines concerning cattle nutrition.

A simple input - output model involving productivity gains from topsoil and subsoil formation and losses caused by erosion was considered. The input (figure 1) and output (figure 2) flow equations were calibrated using the results of a survey of rates of erosion, enrichment ratios of clay and organic carbon, AWC of the topsoil and humification and mineralisation rates of organic matter on sites which are representative of the different stages in the erosion process.

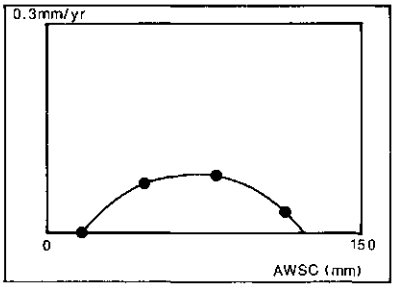


Figure 1: Input flow equation

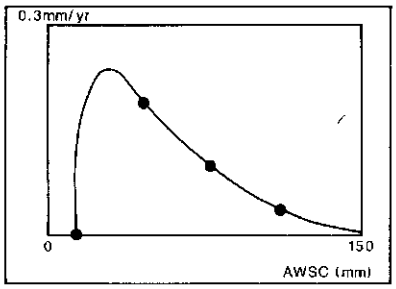


Figure 2: Output flow equation

Integration of the land use model using the above calibrated input and output flow equations is illustrated in figure 3. The residual suitability is derived by plotting both the present day and minimum allowable productivity levels on this graph. In the case of communal rangeland in the study area, a residual suitability of 400 to 500 years has been predicted.

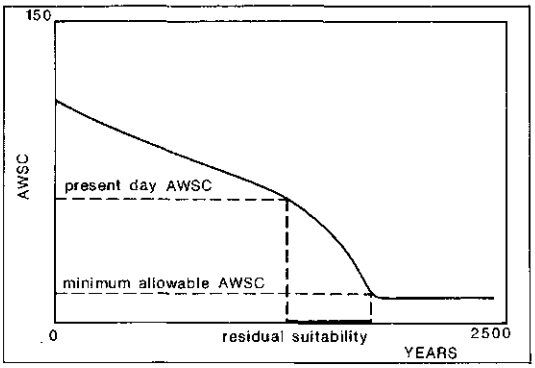


Figure 3: Integration of the land use model and the residual suitability.

## Discussion and conclusions

A number of recent efforts in erosion/productivity research and quantitative land evaluation have opened the way to a quantitative assessment of the suitability of land in the future and a general methodology is proposed. The method makes use of the results of routine land resource surveys and simple modelling techniques and can accommodate a wide range of productivity measures and levels of sophistication of the modelling component.

Given the present (low) level of accuracy of erosion and crop yield forecasting, the predictions are best interpreted as a relative measure. Guidelines for such interpretation are proposed in table 1.

Table 1: Guidelines for the interpretation of the residual suitability of agricultural land.

| Residual Suitability | Interpretation | |
|---|---|---|
| 0 to 10 years | Very poor | N2 |
| 10 to 20 years | Poor | N1 |
| 20 to 50 years | Moderate | S3 |
| 50 to 100 years | Good | S2 |
| ≥ 100 years | Very good | S1 |

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THE SOIL RESOURCE EVALUATION SYSTEM (SRES) IN THE PEARL RIVER DELTA

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Soil resource evaluation is an integrative analysis based on main properties and fertility of soil. It involves two major tasks: the identification of advantage and disadvantage factors affecting soil productive potential, and the classification of suitabilities, limitations and productive potentials of soils for agriculture. In short, soil resource evaluation is the classification and assessment of soil quality. The basic purpose of soil resource evaluation is to advance a set of practical and effective measures for agricultural planning and soil improvement in order to develop fully productive potentials of soil resources.

The soil resource evaluation system (SRES) in the Pearl River Delta was developed in 1986. It is based on the outcomes of the 2nd National Soil Survey in 1979-84. The basic data include 1:50,000 county-level series maps (land use maps, soil type maps, and varied soil nutritional content maps), 1:200,000 region-level series maps and soil survey data in field and labratories. SRES is directed at the special conditions of the Pearl River Delta, Southern China, but its methods may be available for studies in other agricultural regions.

## Outline of study area

The Pearl River Delta, taking up 25,012 $km^2$ land, lies in the southern sub-tropical zone of China (see Fig.1). The agro-climatic characteristics of the region refer to a mean annual temperature of 21-22°C (minimum 10-15°C in January; maximum 28-32°C in July), an annual (not less than 10°C) cumulative temperature of 6,700-8,500°C, mean annual solar radiation hours of 1,700-1,900 hrs and an annual rainfall of 1,700 mm. The main landform

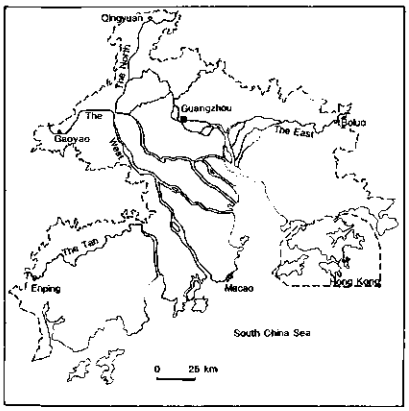


Fig.1. Outlined map of the Pearl River Delta, Southern China.

types in the Pearl River Delta are deltaic alluvial plains, river alluvial plains, short mountains and hills, and "base-pond system" - a kind of artificial geomorphology or landscape. The soil in the Pearl River Delta can be divided into eight great groups, 16 subgroups, 32 families and 72 species according to China's Soil Taxonomy. Of these, paddy soils take 1,317,066 ha or 55.65% of total soil area, and lateritic red soils cover 851,345 ha or 35.97% of total soil area.

## Principles of soil resource evaluation

Soil is a natural object, whose natures and fertility properties are affected by natural factors as well as by artificial factors. Therefore, the evaluation of soil resources should be not only based on soil natures and fertility levels, but also regarded with those as follows: (1) combining an integrative evaluation with leading factors; (2)combining soil uses with resource conservation; and (3)combining the yield criterion with fertility factors. The soil resource evaluation in the Pearl River Delta is based on soil species by the way to combine a fertility analysis with an integrative assessment. According to ecological environment and structural characteristics of soils covering in the region, natural pastures are not suitable to develop in large scale. Thus, to assess soils for agriculture and for forestry becomes the main content of soil resource evaluation in the region.

(1)Evaluative items. Because of different requirments of soil and ecological environment for different soil uses, items and criteria of evaluation are different. Firstly, some stable fertility factors which can reflect the productive potentials and fertility levels of soils are selected such as effective depth of soil, texture, content of organic matter, degree of alkalinity-acidity, slope, water conditions, degree of erosion, salinity, and so forth. For Jishui soils (soils in base-pond system, Chinese term "Jishui" means "base and water"), width and height of bases, and area ratio of base to water are also considered. Secondly, soil nutritions, and yield and quality of crops are selected as unstable factors of the soil resource evaluation.

(2)Classing criteria and indexes. The soil resource evaluation in the Pearl River Delta has a set of special systems of classing criteria. A given range of criteria is described with an index (0, 1, 2 or 3).

(3)The hierarchy of soil resource evaluation. According to the character of soil resources in the region, soil resources are divided into two levels - groups and classes - to evalue. The basis of groups is soil-use ways and that of classes is effective degrees of limits on soil fertility. The group of soil resources includes paddy soil (P), dryland soil (D), Jishui soil (J) and natural soil (N). The class of any soil species can be defined by calculating the sum of indexes, and given ranges of the index sum correponds respectively to different classes. A type is used to describe different limits in same classes. For a soil species, there would be several limits but only the mainest limit is considered. For example, the paddy soil of class 4 have "drought" and "waterlogging" types, which can be respectively symbolized as P4m and P4h. Any class 1 soils are not subdivided.

## Techniques for soil resource evaluation

SRES is aided by a computer system, which is mainly composed of three

blocks - database, classification subsystem and mapping output subsystem.

(1)Grid sampling system and database

A sampling grid of 0.25 $km^2$ (1 $cm^2$ on 1:50,000 maps) is superimposed over the entire study area. Thus, the whole study area is divided into about 100,000 cells. Each cell can have a set of variables. In this project, different cells have alternative numbers of variables, e.g., 12 variables in a cell of paddy soils, 9 in a cell of natural soils, and 3 in a cell of water (river or lake). The total database includes near 1,000,000 data items. The data structure is a relational database structure.

(2)A computer package for soil resource classification and evaluation

A computer algorithm is depicted in Fig.2. The program uses simple identification structure with FORTRAN-77 in order to transplant itself easely to different facilities and for different users.

(3)Computer mapping and result output

Output of classing and evaluating results uses a graphic package and produces a series of small-scale plotting symbol maps. Another output is an area statistics of varied soil resources with a computer. These steps are described in Fig.2. also.

For this project, indeed, data input needs a large work. However, the database set up not only makes this project produce a satisfactory result but also becomes a basis of further research on soil resources in this region. For example, the division of soil uses for agriculture in the Pearl River Delta has been completed on the basis of SRES database.

## Conclusion

Compared with existing land evaluation schemes, SRES has an obvious character - putting the current ways of land-use on the premise of evaluation. This character makes SRES more practical in soil utilities, especially in the soil improvement because most of land uses will be not changed although there would be a good land use proposal and because farmers are even concerned with limits to their cropping and how to improve their lands. Therefore, the essential aim of SRES is a guide to soil improvement and utilization rather than a prediction of soil uses. This point is very important and necessary for agricultural development in most developing countries.

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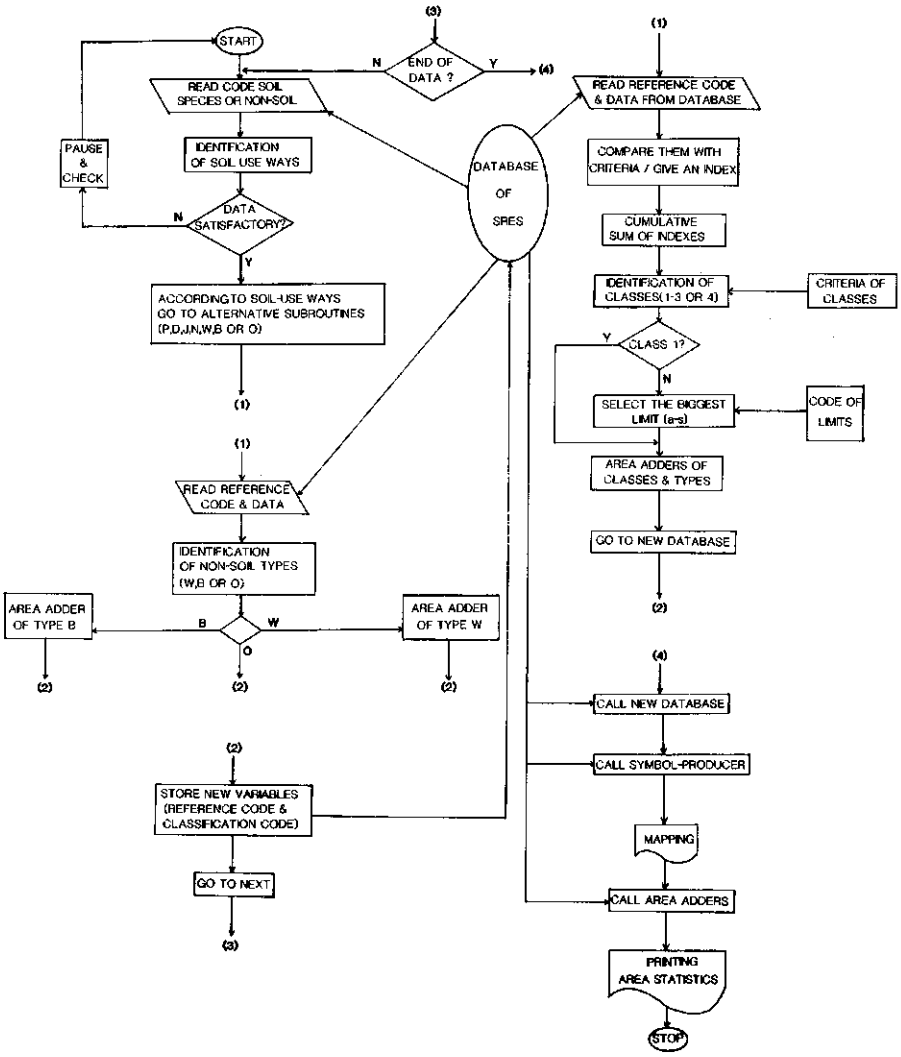


Fig.2. The general flow chart of computer-aided SRES.

# APPLICATION OF A DISTRIBUTED CATCHMENT MODEL FOR THE SIMULATION OF THE WATERTRANSPORT IN AGROECOSYSTEMS

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## Summary

The physical deterministic model SHE (Systeme Hydrologique Europeen) was chosen to simulate the watertransport of a catchment. The applicability of the system was tested by simulating single rainfall events with runoff and also by simulating the watertransport during a longer period of time (6 months).
Keywords: distributed models, simulation, applicability of models

## Introduction

SHE is a distributed catchment model for the simulation of water transport in agroecosystems. This deterministic model is based on differential equations and consists of the following parts:

1) two-dimensional groundwater model
2) two-dimensional overlandflow model
3) one-dimensional waterflow within the unsaturated zone
4) one-dimensional waterflow within the drainage channels
5) one-dimensional calculations of evapotranspiration, interception and snow melt.

SHE is described in detail by Abbott et al. (1981) and Beven (1985). The model has been applied several times to simulate the runoff of different catchments (DHI 1984a, DHI 1984b, Rohdenburg et al. 1986).

The investigated catchment is situated 40 km south of Braunschweig, FRG. The catchment was choosen since is has the following properties:

1) numerous different soils and sediments
2) slopes up to 8 %
3) an impermeable layer of clayey marl in depths greater than 3-7 m.

The heterogenity of the catchment offers excellent conditions to test model concepts. Bork et al. (1985) give a full description of the catchment. Bork (1988) summarizes the data which are necessary to validate a distributed model and points out ways to regionalize these data.

## Results and discussion

The areal discretisation of the catchment is shown in Fig. 1. It demonstrates clearly that the rigid discretisation which is created by using finite differences is only of limited value. The main cause is the land use pattern (50 fields are situated in the catchment of 1 $km^2$). Fig. 2 compares the simulated and measured runoff at the basin outlet. The measured and predicted heights of the peaks correspond remarkably well. The simulated runoff event lasted only about ten hours. Is it possible to

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get such excellent results also if longer periods of time are simulated?

The application of a simulation model compromises between the input (data collection, computer time) and the output (result). The simulation of a long period of time cannot be calculated with the same short time steps (6 min) as the simulation of the single runoff event. The catchment properties are further complicated by the rapid reaction of the groundwater table to the infiltration of greater amounts of surface water. The other properties are characterized by high spatial variability of small scale. The model inherent seperation of groundwater and unsaturated zone and the properties mentioned above make it necessary to choose very short time steps for the simulation - this is not relevant for single events. The spatial distribution should be detailed enough because of the horizontal and vertical variability. A main frame (Amdahl 470) uses about 1 hour of cpu time to simulate a period of 6 months. These calculations have to be repeated several times to calibrate the parameters. In addition several scenaries have to be calculated for analysation. So much computer time is often not available. The consequence is that this model concept is of limited use for the investigated area.

The successful application of a distributed model on single rainfall events can only prove that the model is applicable. But this is by no means a validation. During single runoff events the following variables are extremely important: the soil water suction near the surface, the saturated hydraulic conductivity at the surface, the flow resistance coefficient at the surface. These variables are not constant in time. The conditions at the beginning of the event are of essential importance for the runoff although the values of the variables are usually not measured at that time. Repeated simulations with varied sets of data minimize the differences between the simulations and measurements. The calibrated data set is not transferable - neither in space nor in time. If the results of the simulation can only be compared to measurements of the runoff at the basin outlet there is no point in applying a distributed model.

## Conclusions

A model concept like SHE is a suitable tool to simulate the water transport processes of a catchment. But not all simplifications of the model are in every case tolerable. The model concept is not suited for all research areas. The problem of the rigid discretisation can be solved by using the method of integrated finite differences (Springer 1983). The problems caused by the heterogenic catchment - especially the calculation of the thin bodies of groundwater - can be avoided if single sites are calculated ( for example with the site model DESIM, cf. Rohdenburg et al. 1986) and if the lateral transport of water between the sites is considered.

Simulations of single events, especially if there are only few measurements available for comparison are useless for the validation of the model. The use of calibrated parameters (e.g. saturated hydraulic conductivity, flow resistance coefficient of the surface) in other simulations is very limited. The main problem of the application of model systems is the regionalization of starting and boundary conditions as well as of model parameters (Bork 1988).

The application of physical stochastic models should be investigated more intensively than that of physical deterministic models. In physical stochastic models the parameters are not represented by one single value but by a probability function. The results of such models are also probability functions (Gelhar,1984).

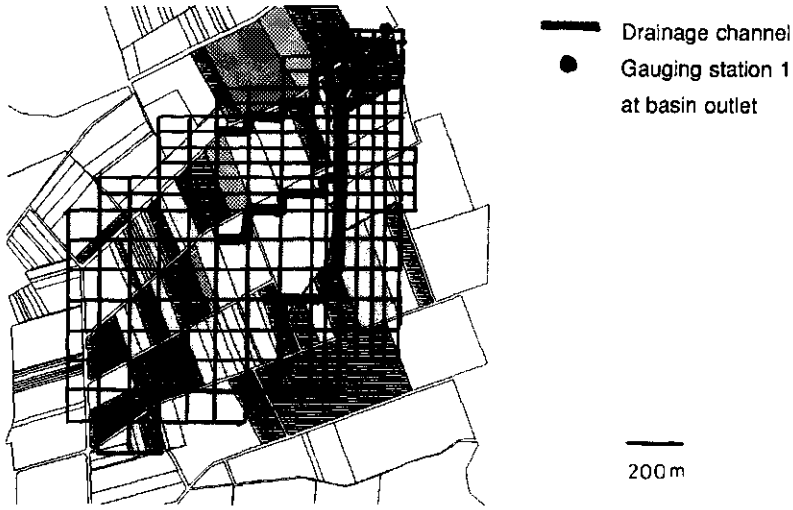


Fig. 1: Application of the SHE-Model:
Land use pattern and discretisation of the research catchment

Acknowledgements

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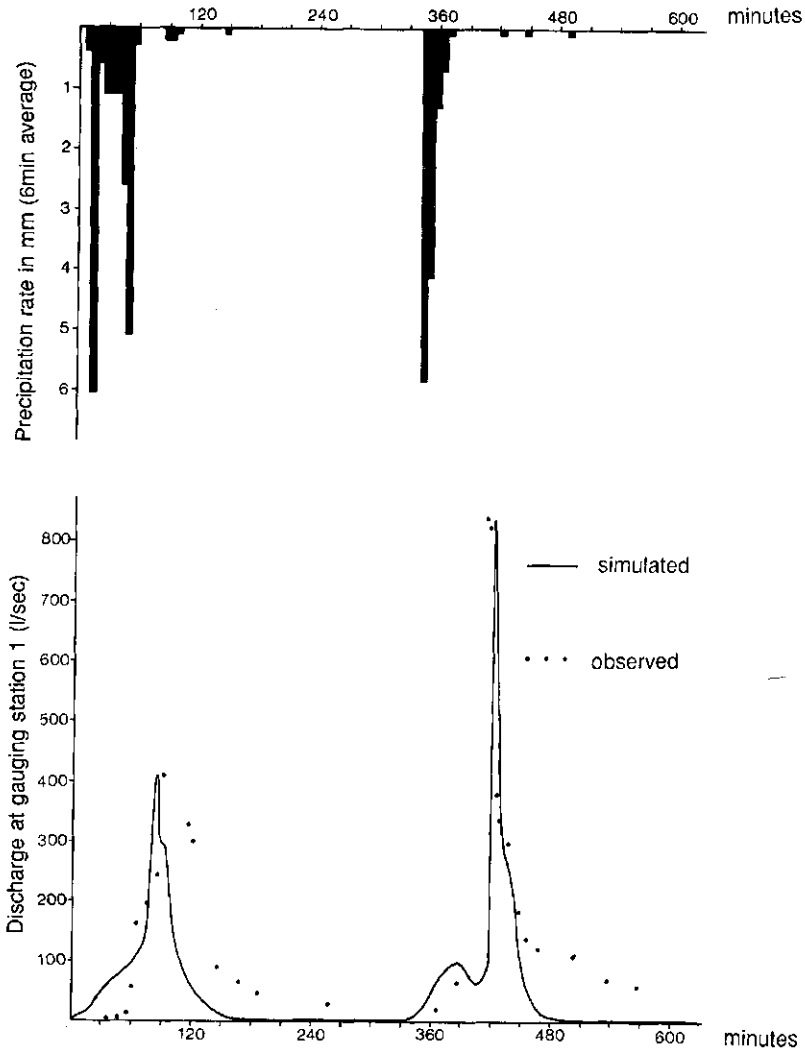


Fig. 2: Application of the SHE-model: Measured precipitation rate and comparison between simulated and observed hydrograph

# LAND QUALITIES USED IN SUDANESE LAND EVALUATION SYSTEM

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## Summary

The land suitability classification system used by the Soil Survey Administration, Sudan Ministry of Agriculture and Natural Resources is extracted from the FAO land evaluation system. The system consists of orders, classes, subclasses and units. The subclasses are determined by evaluated land qualities which are combinations of individual land characteristics.
Keywords: land suitability classification, FAO land evaluation system, land qualities, land characteristics.

## Introduction

The Soil Survey Administration used a soil survey interpretation system (Tahir and Robinson, 1969) based on the American land capability classification system (USDA, 1961). the system now in use (Kevie, 1976), which replaced the old one, is called the land suitability classification system which is modified from the F.A.O. Framework for Land Evaluation (FAO, 1974) to Suit Sudan Conditions.

## Categories of the system

Our system, now in use, recognizes four categories according to a decreasing level of generalization. These are briefly described below.

### Orders

Reflecting kinds of suitability; suitable land (S) and unsuitable land (N).

### Classes

Reflecting degree of suitability within orders: four classes in the suitable order and two classes in the unsuitable order.

### Subclasses

Reflecting kinds of major limitations within classes and the general direction of required improvements.

### Units

Distinguishing lands with minor differences in production capacity.

## The land limitations

These are the land characteristics which are rated according to their effect and limitations to profitable agricultural land use. Accordingly

the suitability subclass is determined, then the class and the order respectively.

Some of the limitations used in our system according to designated alphabetical symbols are:

a - alkalinity: limitations due to alkaline soil reaction and high exchangeable sodium percentage.
c - climate: limitations caused by adverse climatic conditions (climate too wet or too dry or adverse temperature regime).
d - depth and stoniness: limitations due to shallowness or stoniness or both, restricting root development.
e - erosion: limitations casued by erosion hazards or past erosion damage.
f - fertility: limitations due to low chemical fertility (soils have low content of plant nutrients).
g - surface gravel or stones: limitations due to the occurrence of gravel or stones covering the surface, hampering cultivation and seedling establishment.
i - inundation: limitations casued by inundation (flooding) of the land from rivers.
m - moisture deficiencies: land with moisture deficiencies due to soil conditions.
p - physical soil deficiencies: limitations due to adverse physical soil properties (other than mentioned under v).
s - salinity: limitations due to high content of soluble salts.
t - unfavourable topography: limitations due to unfavourable relief or relative elevation limiting use.
v - vertisolic: limitations due to the high content of swelling clay.
w - wetness: limitations due to waterlogging caused by a high water table, slow permeability or slow surface drainage, or a combination of these.
x - pests and crop diseases: limitations casued by the occurrencce of pests and crop diseases.

## The land qualities

The suitability of a tract of land is determined by a number of land qualities which are combinations of individual land characteristics, and are distinct from other land qualities in their influence on the suitability of land for a specific kind of land use. The land characteristics determining a land quality show specific limitations to profitable use of the land. For instance, moisture availability for plants is a land quality that is determined by rainfall, potential evapotranspiration, soil depth, runoff and water holding capacity of the soil material and related to either a climatic limitation (c) of caused by too low rainfall, or a moisture limitations (m) if caused by a very low water holding capacity of the soil material, high runoff or other unfavourable characteristics, or a depth limitation (d) of caused by shallowness of the soil.

The land qualities cannot be directly measured such as most of the individual land characteristics, but they can be rated as good, moderate, poor and very poor, based on the measured land characteristics which determine them. By rating the land qualities one can determine the land subclass, class and order thus accomplishing the land suitability classification for the tract of land under consideration.

A list of land qualities that are used by the Soil Survey

Administration in assessment of land suitability is given below (Table 1).

Table 1. Major land qualities for agricultural production with the major individual land characteristics and related limitations.

| Land quality | Major land characteristics | Limitation symbol |
|---|---|---|
| Moisture availability for the plants | Soil depth, available water capacity, degree of runoff, & climate moisture regime | d, m, c |
| Chemical soil fertility | Content of N, P and K, micro-nutrients, CEC, base saturation and pH | f |
| Conditions for seedling establishment | Texture, structure, aggregate stability, consistence, bulk density, stoniness, surface gravel | p, g |
| Drainage conditions in growing season | Drainage and ponding | w |
| Flooding hazards | Depth and current of flood water and period and frequency of inundation | i |
| Possibities for mechanization | Slope, relief, consistence stoniness, shallow pans | t, v, p, g, d |
| Salinity | Electrical conductivity and content and kind of soluble salts | s |
| Sodicity (alkalinity) | Exchangeable sodium percentage, soil reaction | a |
| Erosion hazards | Slope, infiltration rate | e |
| Capability of maintaining surface water (padly rice only) | Slope, microrelief, drainage, subsoil permeability | t, m |
| Adequacy of topography for gravity irrigation | Slope, microrelief, slope complexity, elevation in regard to supply level | t |
| Climate regime | Temperature regime, air humidity, storm hazards | c |
| Trafficability and | Slope, relief, drainage pattern, bearing capacity content and type of clay rainfall | t, w |
| Possibilities for rational layout of farm plots | Slope, relief, drainage pattern | t |
| Occurrence of pests and crop diseases | Frequency and severity of pests and diseases caused by birds, insects, nematodes etc. | x |

For each soil mapping unit recognized in the Survey Area ratings are given to the land qualities, using tables, by the different ranges of the individual land characteristics which in combination determine the land quality rating.

A number of land qualities such as trafficability and accessibility, possibilities for rotional layout of farm plots soil toxicity, occurrence of pests and crop diseases, cannot be easily rated on the basis of quantitatively expressed land characteristics, and have to be rated for the time being in a general qualitative way.

The system recognizes several kinds of land suitability classification. It distinguishes between current suitability and potential suitability and in both classifications suitability classes may be expressed in either qualitative or quantitative terms. The potential classification deals with classifying land for a defined land use after major improvements of the land be carried out. One of the possibilities this classification tackles is the potential land suitability with partial amortization of non-recurrent inputs which takes into account costs and difficulties involed in overcoming non-recurrent soil limitations such as leaching of salts, removal of gravel and stones, grading and levelling or provision of drainage.

The land qualities that can be changed and improved through time are chemical soil fertility, conditions for seedling establishment, drainage conditions, salinity, sodicity, erosion and occurrence of pests and diseases.

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# LAND EVALUATION USING TUSCAN LAND INFORMATION SYSTEM (TULIS)

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## Summary

The Land Information System of Tuscany (TULIS) is based on Tuscan Forest Inventory (IFT) data base and Land System Project (PLS) data base. It was initiated in 1985 and now covers about one third of the region (approx. 800,000 ha). Procedures for data handling and editing are developed using SAS software.
Keywords: land information system, soil information system, land evaluation.

## Introduction

Whitin the comprehensive Land Information System of Tuscany (TULIS) the Land System Project (PLS) is a basic element for the knowledge of land resources and for land evaluation. The main purpose of this land evaluation is land use planning at regional level, therefore for the selection of project areas (with peculiar problems) and for the evaluation of the extensibility of more detailed information. The land information gathered is at reconnaissance level, corresponding to a map scale of 1:100,000.

## The PLS survey

Land resources are described by an integrated survey, mainly based on the 'Land System Method' developed by the CSIRO (Christian & Stewart,1968). The environmental factors surveyed are climate, lithology, physiography, (land form, slope, erosion), land cover/vegetation and soil; they are organized in the three levels of land system, land unit and land site. The system developed for the tuscan region differs from the original one because of two main reasons:

- the more detailed scale due to a higher variability of the land and to the anthropization processes that historically condition the landscape;
- a structure directly setted up as a data base connected with the preexisting data base of the Tuscan Forest Inventory.

The Land System Project comprises four working phases:

1) collection and preparation of literature and base material (air photos, geological, climatic, land use maps, etc.);
2) air photo interpretation, using b&w, panchromatic photos (approx. scale of 1:33,000) with the 400x400 mt IFT regular grid overlayed; the land sites are identified and described (quali-quantitatively) and the land units are also mapped;
3) field survey; the photointerpretation is checked and the soil characteristics are surveyed in sample areas (grid cells of 400x400 mt) in at least 1% of the land;
4) data storage; the data are recorded in two different data base, the photointerpretation data base (working phases 1 and 2) and the soil data base (working phase 3). For maps production the land unit boundaries are stored in poligonal form then converted in grid cell data.

## Data handling and land evaluation

The soils of the sample areas are assigned to all the land sites, identified in the photointerpretation phase, in which a similar set of characteristics occurs.

Appropiate procedures for statistical analysis, graphic outputs and for the interaction with the IFT data base have been developed using SAS software, version 5.16 (SAS Institute Inc., 1985) on IBM 3083 mainframe under MVS/TSO operating system.

For land evaluation purposes the interpretation of the data collected needs a 'sieve treatment'; in this procedure are first identified the land characteristics that represent per se major limitations, which determine the assignation to definite classes of land capability or land suitability (e.g. badlands, rock outcrops = VIII land capability class). In the next phase, for the remaining land sites also the soil characteristics are examined with a parametric approach.

The examples presented in the poster session refer to various kinds of interpretation implemented.

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# LANDEVALUATION ON A REGIONAL BASIS: AN APPLICATION TO THE GROSSETO REGION (ITALY)

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J.V. Witter
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## Summary

Suitability of soils within the Grosseto region with respect to irrigation has been analyzed by simulating the waterbalance of different soils for particular combinations of crops and irrigation methods. The simulation model uses locational as well as non-locational data from a Geographical Information System (GIS). For planning purposes such combination of a simulation model with a GIS is particularly effective.
Keywords: GIS, irrigation, land evaluation, simulation.

## Introduction

The Landscape and Environmental Research Group of the University of Amsterdam has executed a soil survey and a land evaluation of the Grosseto region in Italy (Figure 1). This region is about 80,000 has large, and consists of a wide coastal plain, surrounded by hills and mountains. The results of the soil survey and land evaluation have already been published in Sevink et al. (1988) and Sevink (1988). This paper investigates whether the combination of GIS and simulation studies can contribute to the land evaluation. As pointed out by Burrough (1986), this combination has wide perspectives in land evaluation. We choose as study area the Northern part of the Grosseto region (appr. 10,000 has), indicated in Figure 1. The central part of the area forms the inland continuation of the coastal plain and is dominated by fluvial terraces and alluvial fans of different age. Sediments are often gravelly and stony, in particular close to the surrounding hills, which have a steep relief and are mostly under forest or shrubs. Soils in the older alluvial deposits tend to have a slowly permeable argillic B-horizon, while soils in the hills generally are shallow and weakly developed. Climatic conditions are such that additional irrigation is necessary during the growing season. In this paper we will briefly discuss the GIS software and the simulation model. Thereafter, the results will be presented. Finally, some conclusions will be drawn.

## The geographical information system and the simulation model IRRSIM

By using SQL/Oracle relational database software, a database has been constructed containing the soil data: digital maps in vector format, and tables with information on the soil units considered. The way the digital maps are stored in the database is based on the work by Denneboom et al. (1985). The information on soil units includes: (1) texture; (2) structure top soil; (3) drainage conditions; (4) terrain slope; (5) rock outcrop classes; (6) storage topsoil and subsoil, based on pF data; (7) evidence for the precense of toxic levels of trace elements as deduced

from the vegetation; (8) soil depth. Items (1) to (5) have been classified according to Doorenbos & Pruitt (1977). Apart from the soil data, datafiles with respect to plant growth, rainfall (daily data) and evaporation are available.

IRRSIM simulates the daily waterbalances for all soil units and for all considered combinations of crops (tomato; pepper; maize; sunflower; apricot; peach; apple; olive) and irrigation methods (surface irrigation; trickle irrigation (25mm/d); sprinkler irrigation (50, 75, or 100 mm/d)). Before simulating the waterbalance, each soil unit is evaluated for its suitability for the selected combination of crop and irrigation method. The simulation part of the model may also be omitted. Rainfall input consists of historical daily records. The rainfall that moistens the soil profile beyond pF 1.7, is considered to be uneffective. Evapotranspiration is derived by multiplying monthly values of reference evaporation (Sevink, 1988) with a crop factor (Doorenbos & Pruitt, 1977), and expressing the result on a daily basis. As soils are assumed to be irrigated at pF 3, stress is assumed not to occur. Therefore, a depletion factor (Doorenbos & Kassam, 1979) has not been used. It is further assumed that directly after irrigation the pF is equal to 1.7, and that all soil moisture in the rooting zone at pF values in the range 1.7 - 3 is available to plant growth. Because of rainfall it may occur that the pF value is lower than 1.7. Then, percolation and, eventually, runoff will take place. However, other percolation losses are not considered. Further, overall efficiency is negatively affected by a variety of other factors. Thus, the water requirements as calculated by IRRSIM should be readjusted, based on overall irrigation efficiency. It is well-known, that this efficiency may be rather low.

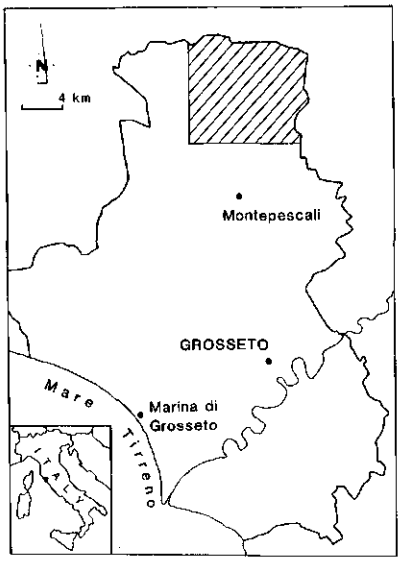


Figure 1. The Grosseto plain and the study area.

## Results

The model has been run by using rainfall data for the years 1959, 1967,

and 1969, with annual rainfall equal to 816 mm, 511 mm, and 716 mm, respectively. These values should be compared to the long-term mean for Grosseto, 606 mm. The years 1967 and 1969 are characterized by dry summers. The study area appears to be well-suited to the growth of fruit crops (most notably, olive), which need little water and can stand gravelly and stony soils. There may be problems, however, due to groundfrost. Trickle irrigation is the irrigation method best suited to the conditions in the Grosseto region, particularly because of the low infiltration capacity of most soils. Both conclusions are illustrated in Table 1. The conclusions coincide with those by Sevink (1988).

Table 1. Number of soil units suitable for a given combination of crop and irrigation method (total number of soil units considered: 35).

| Crop | Irrigation method | | | | |
|---|---|---|---|---|---|
| | Surface | Sprinkler 100mm/d | Sprinkler 75mm/d | Sprinkler 50mm/d | Trickle 25mm/d |
| Tomato, pepper sunflower, maize | 0 | 0 | 0 | 2 | 5 |
| Peach, apricot apple, olive | 0 | 0 | 0 | 8 | 13 |

Considerable differences in irrigation requirements for a particular year may occur between different soil units, because some soil units need an irrigation gift shortly before the end of the growing season. Also, because of year-to-year differences in rainfall, irrigation requirements for a particular combination of crop and irrigation method fluctuate considerably between years. Thus, irrigation requirements should be based on long-term means. As a side-effect, the simulation model yields insight into variability of yearly irrigation requirements. Table 2 gives mean irrigation requirements for tomato and olive under trickle irrigation, for the years considered.

## Conclusions

The practical conclusions with regard to the suitability of the study area for irrigated agriculture do not deviate from those derived by Sevink (1988). Thus, in this respect, the combination of GIS and simulation does not add something new. Of course, it facilitates the evaluation, makes assumptions explicit as well as facilitates the inclusion of different assumptions, and gives readily interpretable graphical output. Also it is possible to find the optimum combination of crop and irrigation method for a given soil unit. The basic strength of the approach, however, is that it yields insight into the spatial and temporal variability of the evaluation outcomes.

The simulation model still needs a better foundation with regard to:
- the estimation of net rainfall;
- the distribution of soil moisture over the profile;
- the estimation of irrigation losses.

When the model is used for planning purposes, it must be stressed that it needs calibration as well as verification.

Table 2. Mean net irrigation requirement and irrigation interval for tomato and olive under trickle irrigation, for the years 1959, 1967 and 1969.

| Soil Unit* | Tomato | | Olive | |
|---|---|---|---|---|
| | Net irrigation requirement [mm] | Irrigation interval [days] | Net irrigation requirement [mm] | Irrigation interval [days] |
| A1a | | | 259 | 26 |
| A1b | 386 | 17 | | |
| A1d | 405 | 18 | | |
| A2c | 382 | 9 | 288 | 18 |
| F2a | | | 261 | 19 |
| F2b | 380 | 14 | 275 | 30 |
| F2c | | | 275 | 30 |
| I2a | | | 281 | 54 |
| I2b | | | 281 | 54 |
| I3a | | | 267 | 30 |
| I4 | 367 | 26 | 244 | 70 |
| K1b | | | 273 | 21 |
| R2 | | | 277 | 19 |
| R3 | | | 270 | 28 |
| V2 | | | 292 | 13 |
| others | not suitable | | | |

* Soil mapping units according to Sevink et al., 1988.

Acknowledgement

The analysis has been performed on a IBM 6150 computer, made available in the context of the cooperation between the Dutch IBM branch, and the University of Amsterdam.

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# KENYAN PHYSICAL LAND EVALUATION SYSTEM

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## Abstract

The Kenya Soil Survey of the Ministry of Agriculture is developing and testing a land evaluation system suitable to the Kenyan conditions. It follows closely the FAO Framework. This paper discusses the methodology which has been developed over the years while considering mainly physical and chemical constraints. Land qualities that are likely to limit the suitability of each mapping unit for a defined land utilization type are identified and rated. This is followed by a formulation of land suitability criteria and preparation of conversion tables for each land utilization type. Finally an exercise of matching of criteria with land requirements and land qualities to arrive at land suitability classification is executed.

## Introduction

Soil is one of the most widely occuring natural resource of any country. In Kenya, soil is very important since the mainstay of the economy almost wholly depends on agriculture. In order to utilize this natural resource to the best advantage, the various soil types in a country have to be identified. The process of soil survey has been executed in Kenya at different intensities and for various purposes since the beginning of this century.

In early 1970's, the Kenya Government having realised the importance of accerelating the process of inventory of the natural resources, it requested for assistance from the Government of the Netherlands. The resulting bilateral agreement led to the establishment of the Kenya Soil Survey whose objective was to conduct soil and land investigations in order to produce soil maps and other related resource maps and interpret them for rational land use and sustained high level of productivity while at the same time conserving the natural resources. One of the aims of the Kenya Soil Survey is to develop a land evaluation system which could be used in assessing the suitability of various land mapping units for various land use alternatives.

## Methodology

The system of land evaluation that has been so far developed by Kenya Soil Survey closely follows the principles of the FAO Framework for land evaluation (FAO 1976) somewhat modified to suit Kenyan conditions (Muchena 1987). Over the years, Kenya Soil Survey has made attempts to develop a scheme for ratings of land qualities (Weg van de and Braun 1977, Muchena 1981, Weeda 1987). Also proposals have been made to develop conversion tables for land suitability ratings (Weg van de 1978). In this system, the relevant land utilization types (LUTs) i.e. kinds of land uses that are physically possible and also socially and economically

promising are identified in the early stages of the soil survey. For each survey area, a background study is made of the essential attributes that are used to define the relevant LUTs. The most important attributes are produce, capital and labour intensity, farm power, farm size, technical know-how of land users and related management practices (Beek 1978). Each LUT has its own requirements in terms of land qualities. A land quality is a complex attribute of land which acts in a distinct manner in its influence on the suitability of land for a specific kind of land use (Sys 1980). Each land quality is rated for all mapping units identified in the area being evaluated. The ratings are "matched" with specifications set in conversion tables for each LUT to arrive to a suitability classification. The end results are presented in a Land Evaluation key.

This system has been applied in Kenya mainly for rainfed agriculture and to some extent for irrigation purposes. Due to scarcity of necessary economic data, land suitability classification has been primarily based on physical and chemical constraints.

The following stages are adopted for land evaluation:

Stage I

Identification and definition of the relevant Land Utilization Types (LUTs). At this stage, an analysis of key attributes is carried out.

Stage II

Compilation of the specifications of the land requirements (LR) of each LUT. These include ecological requirements, management requirements, conservation requirements and improvement requirements. At this stage, the land qualities (LQ) that are likely to limit the suitability of each mapping unit for the defined LUT are identified and rated.

Stage III

Formulation of land suitability criteria and preparation of conversion tables for each LUT.

Stage IV

Matching of criteria with land requirements and land qualities to arrive at land suitability classification.

The above approach is illustrated diagrammatically in figure 1.

Specific criteria used

For each land utilization type (LUT) under consideration, land suitability criteria is set depending on the land quality requirements. In the process of selection of land qualities to be considered and the specifications of the criteria for land suitability evaluation for each LUT, any assumptions made are expressly defined.

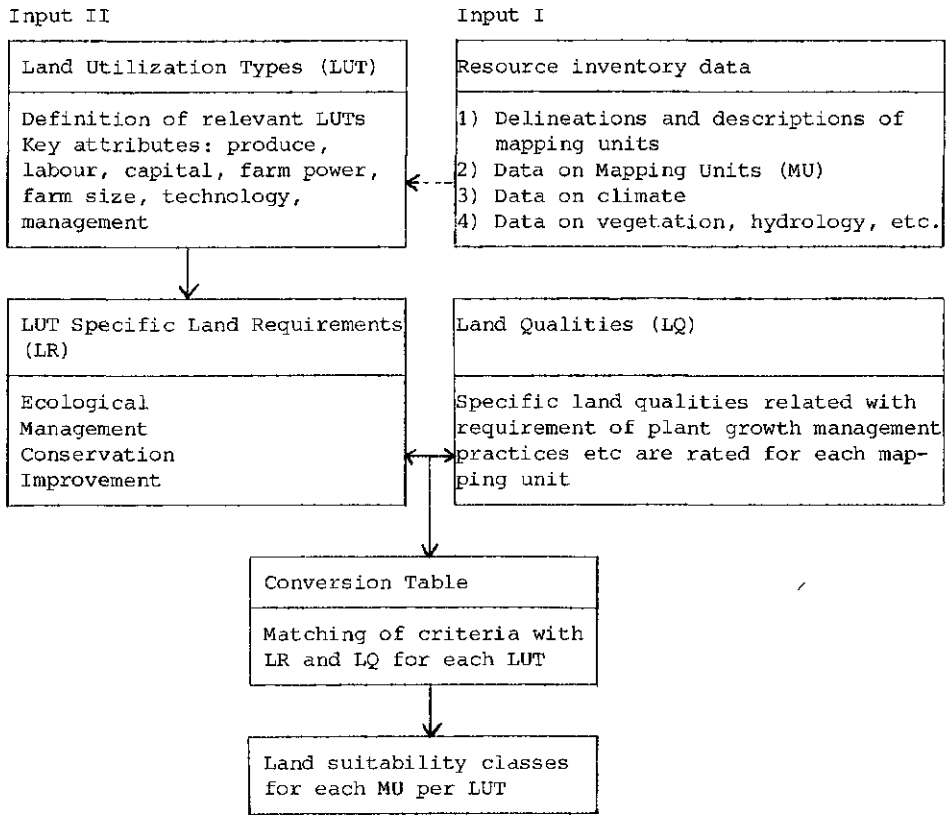


Fig. 1. Schematic presentation of the land evaluation approach (adapted from Muchena 1987)

Table 1. Land qualities and their land characteristics that are commonly used in the process of land evaluation.

| Land Quality | Land characteristic(s) |
|---|---|
| Capacity for water retention | Soil texture, type of clay, organic matter<br>Soil depth (effective rootable depth)<br>Calcium carbonate content. |
| Absence of salinity | Electrical conductivity of saturation extract (ECe) in mmhos/cm. |
| Absence of sodicity | Exchangeable sodium percentage (ESP)<br>(soil reaction-pH) |
| Availability of oxygen for root growth | Drainage class. |
| Conditions for germination (seedbed) | Structure of topsoil<br>Susceptibility to crusting. |

| Land Quality | Land characteristic(s) |
|---|---|
| Availability of nutrients | Cation Exchange Capacity of soil (CEC). Available nutrients. pH-$H_2O$. |
| Availability of foothold for roots | Soil depth to limiting layer. |
| Workability (ease of tillage) | Dry and moist consistence. |
| Ability for drainage | Natural drainage conditions<br>Infiltration rates<br>Presence of impermeable layers<br>Texture (type of clay minerals). |
| Ease of land clearing (sparseness of vegetation cover) | Physiognomic vegetation types. |
| Freedom for layout of field plans | Topography and slope. |

## Land suitability classification

The land suitability classes are established for each of the LUTs by considering the land quality requirements of the various land mapping units. The land qualities of the land mapping units are compared "matched" with the limits set for each LUT to arrive at the suitability classes. The most limiting land quality of the land mapping unit under consideration determines the final suitability.

Suitability classes used in Kenya have been adopted from FAO (1976) and modified to suit Kenyan conditions (Muchena and van der Pouw 1981). Five land suitability classes have been identified according to the degree of limitations. The five suitability classes are coded as $S_1$, $S_2$, $S_3$, $NS_1$ and $NS_2$ which are briefly defined as highly suitable, moderately suitable, marginally suitable, provisionally suitable and permanently not suitable respectively.

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# Studies at field scale

# REGIONALIZATION OF SOIL DATA MEASURED AT SITE SCALE

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## Summary

Comprehensive validations of deterministic and distributed catchment models are an important requirement for the prediction of the water and matter dynamics in landscapes. For such validations it is necessary to know the initial soil moisture conditions (soil water content, soil water potential, ground-water level) as well as the soil moisture parameters (pF- and k-functions) for each discretized element. This paper presents procedures capable of the regionalization of these data with the aid of soil and land characteristics (ecologically relevant morphographic parameters calculated with the Digital Relief Model DRM and basic soil data interpolated with the digital Sediment and Soil Model SESOM) and a sample of soil moisture data measured at site scale.
Keywords: regionalization, digital relief model, digital soil and sediment model, soil water flux, distributed models

## Introduction

Environmental problems such as the pollution of surface water and ground-water have become a major issue of public interest. Other acute world-wide problems of agricultural land quality are the changes of physical, chemical and biological properties of soils as a result of soil management practices, cover effects, overland flow, erosion, and deposition of soil material.

In order to be able to evaluate these problems and to offer potential solutions, it is often necessary to know the water and matter dynamics of an ecosystem, differentiated both in time and space. The knowledge gained has to be valid for large areas. One instrument to analyse environmental problems is the description of ecosystems by models (cf. Rohdenburg et al. 1986).

For this purpose transferable, i.e. physically and chemically consistent dynamic models are needed, which have to be developed and evaluated. Numerous models are already available which can be used to calculate specific parts of the hydrologic cycle at specific sites and in heterogeneous catchments (soil water flux models, ground-water flux models). Recently, a few models have been developed, which are able to simulate the complete hydrologic cycle (e.g. DESIM and OPUS for sites, cf. Rohdenburg et al. 1986, Bork 1988; SHE for catchments, cf. Beven 1985, Diekkrüger 1988). These comprehensive models differ from each other not only with regard to the respective way of discretization in time and space, but also in the degree of approximation of a correct description of the transport processes.

As long as a model has not been validated, however, it cannot be used for routine applications. The questions still to be answered are: Can a model so complex in structure be validated at all when there are so many

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simultaneous processes which, depending on the condition of the ecosystem, vary considerably in their effects? Is it possible to isolate individual processes in specific experiments in the laboratory and in the field so that, under controlled boundary conditions, their causes and effects can be quantified? The boundary conditions have to be changed so far as to include the spatial variability occurring in the field. A validation under more or less invariable ecosystem conditions would be of no use. Under these conditions the model would work satisfactorily. Yet, under conditions differing from those which the model was tested on great differences between measurements and predictions may be observed. Therefore, model validations should be based on the simulation of periods which cover considerable variations in the ecosystem conditions. When validating physically based water flux models, for example, periods with slow and fast wetting and drying, with Hortonian overland flow, saturated surface and subsurface runoff should be included. These conditions of the ecosystem are dependent on the weather conditions; they do not occur every year though. Longterm measurements of the boundary and system conditions are thus indispensable. Furthermore, the changes of parameters which vary in time must be taken into account, e.g. parameters describing the dynamics at the soil surface and in the ploughed layer.

One consequence of the facts mentioned above is that a vast number of data is necessary for the validation of distributed catchment models. To start with, data of the initial conditions are required for every discretized element and the respective simulation periods. In addition to that, it is necessary to know the upper, the lower and the lateral boundary conditions and the model parameters for every discretized element.

## Methods Applied and Area of Investigation[2]

The extensive data required for small heterogeneous catchments as well as for every field in a larger area can be obtained, with a justifiable amount of energy and time, in the following manner: First, basic soil and land characteristics (cf. Bouma 1988) which can easily be obtained in the field or from topographic maps are processed for the complete research area.

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[2] The methods described have been utilized successfully at the Technical University of Braunschweig (FRG) within the scope of the Special Collaborative Program (SCP) 179 "Water and Matter Dynamics in Agroecosystems". Eight departments of the Technical University of Braunschweig, the Federal Center for Agricultural Research, the Federal Biological Research Center, the Central Research Institute of Agricultural Meteorology of the German Weather Service, the Geological State Survey of Lower Saxony, and the Department of Soil Science of the University of Hannover are participating in this major research program since January 1st, 1986. This interdisciplinary program was initiated and coordinated until his early death by Heinrich Rohdenburg.

The main objective of the SCP 179 is the analysis and forecasting of effects which farming and natural properties have on energy and water fluxes, matter dynamics, microclimate and soil organisms. Physically and chemically based models are developed and validated and will be applied to describe and forecast the water and matter dynamics of ecosystems.

The aims of the subprojects "A6: Soil Hydrology" and "B1: Regionalization and Remote Sensing" of this program are the measurement, parameterization and regionalization of soil moisture conditions and parameters. Results of the subprojects A6 and B1 are represented in this paper.

Second, the conditions of soil variables (e.g. soil moisture suction, soil moisture content, ground-water level) are measured at a few dissimilar sites. The relations between these measured data and the basic soil and land characteristics are described by pedotransfer functions. These functions are then applied to regionalize the conditions of the soil variables. The results of this procedure are the initial conditions for each discretized element.

The measurements were made in the research catchment Krummbach of the Special Collaborative Program 179, an area of about 15 $km^2$ in the northern foothills of the Harz mountains, 40 kilometers south of Braunschweig (Lower Saxony, FRG). The catchment is characterized by a large variety of sediments (loess, marlaceous solifluction layers, gravel, various glacial deposits, silty, loamy and clayey colluvial and alluvial materials), soils (Orthic Luvisols, Luvic Phaeozems, Gleyic Phaeozems, Vertic Cambisols, Gleysols, Fluvisols, Regosols) and relief structures. Impermeable marls underlay the quarternary deposits.

## Results

### Digital Relief Model DRM and Digital Sediment and Soil Model SESOM

Our path leading to a regionalization of the soil moisture conditions is shown in Figures 1 and 2. The soil and land characteristics necessary for this procedure are regionalized with the Digital Relief Model DRM and with the digital Sediment and Soil Model SESOM I (Fig. 1).

The DRM is used to determine slope, drainage direction, curvature, horizontal and vertical distances from divide and drainage channel, position on the slope (cf. Fig. 3), size and slope of the drainage area for each discretized grid element (cf. Fig. 4) from regularly distributed elevation values (cf. Bauer et al. 1985, Bork & Rohdenburg 1986). The sizes of grid elements used vary from 6 m to 250 m. The DRM is made use of successfully in operational applications.

For the application of SESOM I the existence and the results of many drill cores (in heterogeneous areas at least 200 per $km^2$) are required. A simple procedure interpolates the boundaries of the classified sediments and soil horizons. This procedure calculates weighted means, taking into account the spatial distribution of the drill cores (cf. Hensel et al. 1985, Bork & Rohdenburg 1986). The interpolated boundaries are transformed into a regular grid. The basic characteristics of the sediments and soils (e.g. texture, structure, specific gravity, humus content, cf. Fig. 1) are interpolated separately for each sediment or soil horizon.

The applicability of SESOM I is very much restricted by the necessity to have a high drill density. For this reason, we are at present developing SESOM II for the 15 $km^2$ area of the Krummbach catchment, which should be transferable to a large extent. SESOM II will take into account the causal relationships between the spatial distribution of sediments and the relief. If these are known, the data needed for routine applications of SESOM II will be provided by the soil survey and the DRM.

### Parameterization and Regionalization of the Soil Moisture Conditions

With DRM and SESOM applications the required basic soil and land characteristics of the central part of the Krummbach catchments were calculated for the whole area in a 6 m or 25 m grid respectively.

Fig. 1: Regionalization of soil and land characteristics

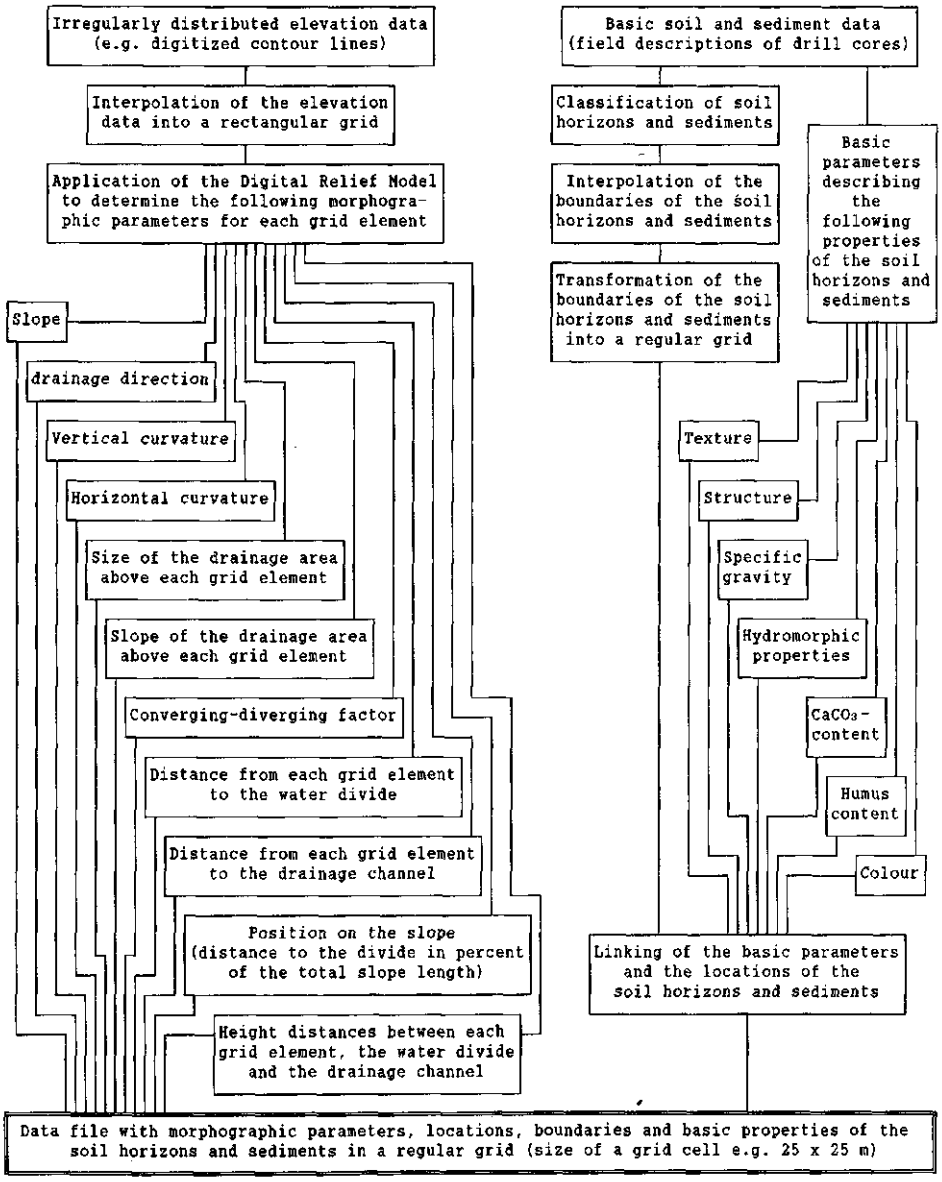
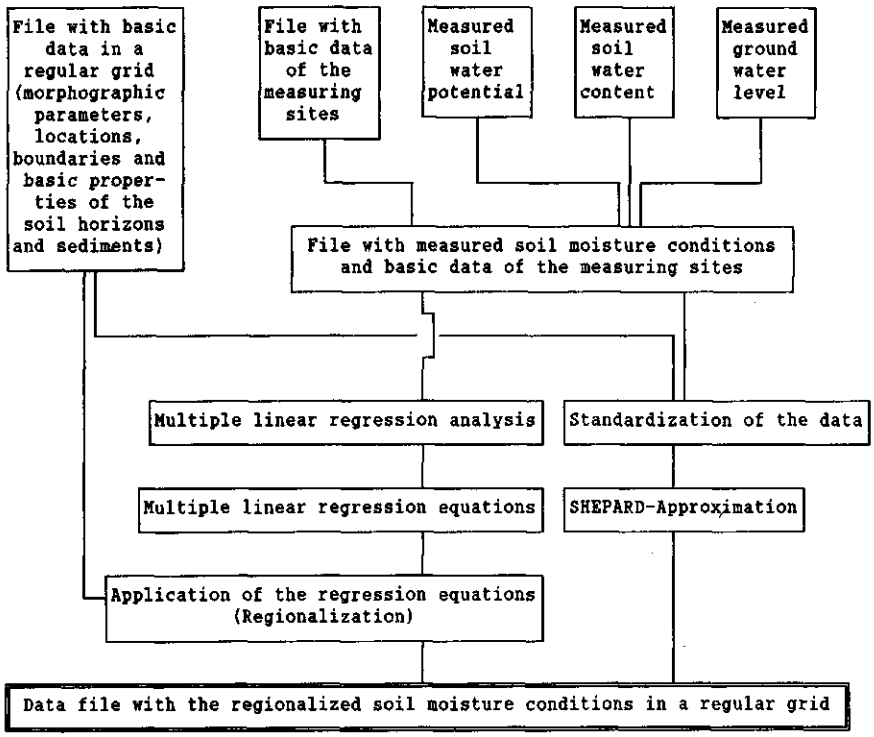


Fig. 2: Parameterization and regionalization of soil moisture conditions using pedotransfer functions




In order to be able to regionalize the soil moisture data required as initial conditions for model validations, measurements are necessary of the soil water content, the soil water potential and the ground-water level (Fig. 2). In the example given here these soil water conditions were measured by Urland (1987) at many sites in the central part of the Krummbach catchment. The soil water contents were determined gravimetrically at 22 sites in distances of 10 cm down to a depth of 100 cm below the soil surface (220 samples were taken). The soil water potentials were measured with about 150 tensiometers at 25 sites down to a depth of 180 cm below the surface. The depth of the ground-water level below surface was measured at about 100 sites.

The regionalization of the soil moisture conditions can be achieved by multivariate interpolation and approximation methods. Apart from the soil moisture data measured at sites, these methods use the soil and land characteristics processed by DRM and SESOM I as additional information, which are used to explain the variance of the variables to be processed to a high degree.

Then, a data set including the basic land and soil characteristics and the measured soil moisture data is prepared for the samples from the measurement sites (cf. Fig.2). This data set is used to compute the pedotransfer functions. One pedotransfer function is determined for every date and,

where soil water contents and soil water potentials are concerned, for every depth to be discretized. This parameterization is obtained by multiple linear regression analysis and the use of the Shepard-approximation method (Gordon & Wixom 1978).

In the samples tested by multiple regression analysis, between 8 and 13 soil and land characteristics explain 70 to 87 per cent of the variance of the soil moisture conditions (Urland et al. 1985, Bork & Rohdenburg 1986, Urland 1987). The mean errors in the estimated volumetric soil water content amount to 1.5 to 2.5 per cent. A mean error of 20 to 50 cm waterhead was calculated for the soil water potential while the mean errors in the estimated ground-water level range from 20 to 40 cm. The regression equations were applied to the central part of the Krummbach catchment utilizing the basic soil and land characteristics. Regionalization results are given in Figures 5 (soil water potential on June 4th, 1984) and 6. The ground-water levels measured on Dec. 11th, 1985 vary from 40 to 450 cm below surface (mean error of the estimated ground-water level: 40 cm). The basic soil and land characteristics which had been incorporated into the regression equation were used to compute the Shepard-approximation. The fitting parameter p was fixed to be 0.25. Low values of the fitting parameter lead to a description which is characterized by a fairly smooth ground-water surface while with higher values outlayers are possible. A comparison of Figures 6 and 7 shows that with the fitting parameter of $p = 0.25$ the Shepard-approximation leads to a ground-water surface which is smoother than the one predicted by the regression equation. However, the results of the two methods are very similar (cf. Urland 1987). The pedotransfer functions mentioned above are adjusted to the special conditions of the Krummbach catchment. Therefore, they are not transferable or, if so, with considerable limitations only.

## Parameterization and Regionalization of the Soil Moisture Parameters

The relations between soil water potential and soil water content were measured in the laboratory and in the field for the sediment and soil horizon types respectively. As expected, depending on the sediment or soil horizon type, the field data were slightly to significantly lower than the soil moisture retention curves received from measurements in the laboratory. As a consequence, the laboratory functions were corrected and attached to the individual sediment and soil horizon types (cf. Urland 1987).

The saturated hydraulic conductivities of the sediments below the ground-water level were determined by pumping tests and tracer experiments. The computed saturated hydraulic conductivities which are log normal distributed vary from one cm per day in the matrix of the marlaceous solifluction deposits to about 100 cm per day in the macro pores.

Above the ground-water level the saturated and unsaturated hydraulic conductivities were determined in the field as well as in the laboratory by rainulator experiments. In the laboratory undisturbed samples with about 14,000 $cm^3$ were analyzed. The measurements were attached to the respective sediments and soil horizons. The hydraulic conductivities of the surface crusts and the ploughed layers were determined at various dates in the year (cf. Bork 1988). These surface-near measurements were attached to two different sediments (silty material derived from loess soils and clayey material derived from marlaceous solifluction deposits and clayey soils).

As a result of the research work the soil moisture conditions and soil moisture parameters processed for a continuous area of about one $km^2$ are available in digital form and in maps (Figs. 5-7).

Fig. 3: Digital Relief Model: position of the grid elements on the slopes of the Krummbach research catchment (distance to the divide in percent of the total slope length; view to southwest; size of a grid element: 25 x 25 m)

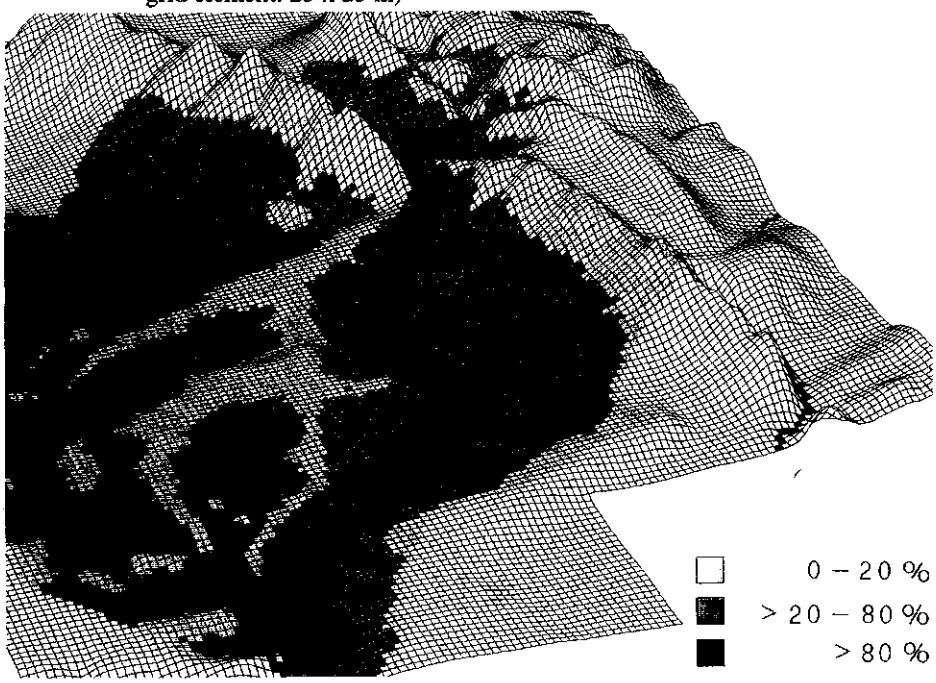



Fig. 4: Digital Relief Model: size of the catchment of each grid element in the Oker catchment (northern foothills of the Harz mountains; size of a grid element: 250 x 250 m)

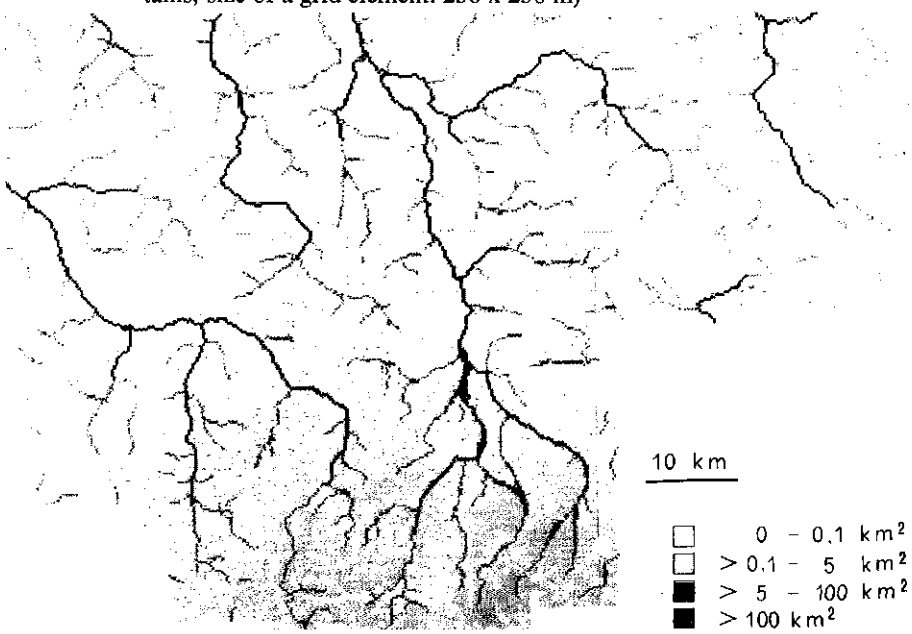


Fig. 5: Soil moisture data processing using regression techniques: soil water potential (cm waterhead) in the central part of the Krummbach catchment in a depth of 40 cm below surface on June 4th 1984

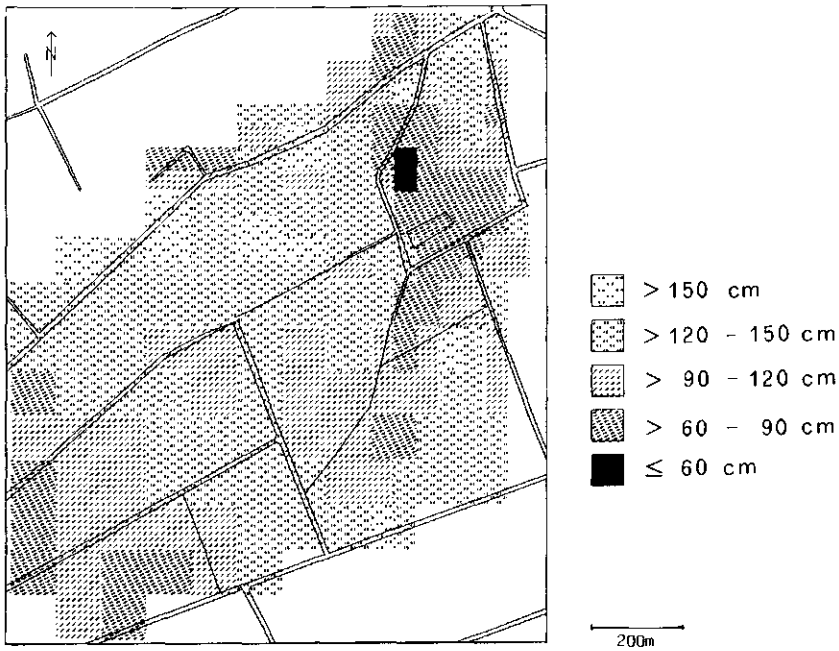



Fig. 6: Soil moisture data processing using regression techniques: ground water level (depth below surface in m) in the central part of the Krummbach catchment on Dec. 11th 1985

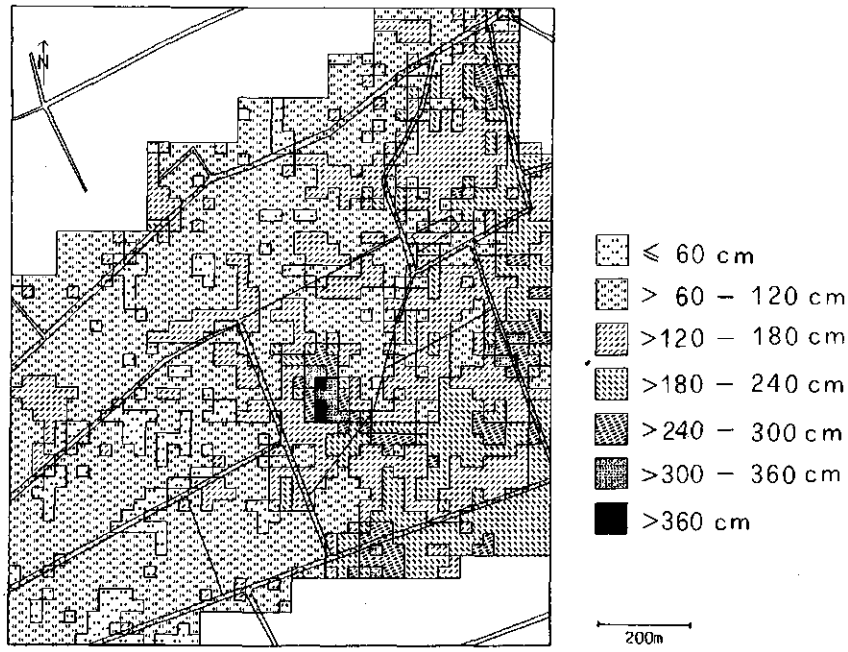
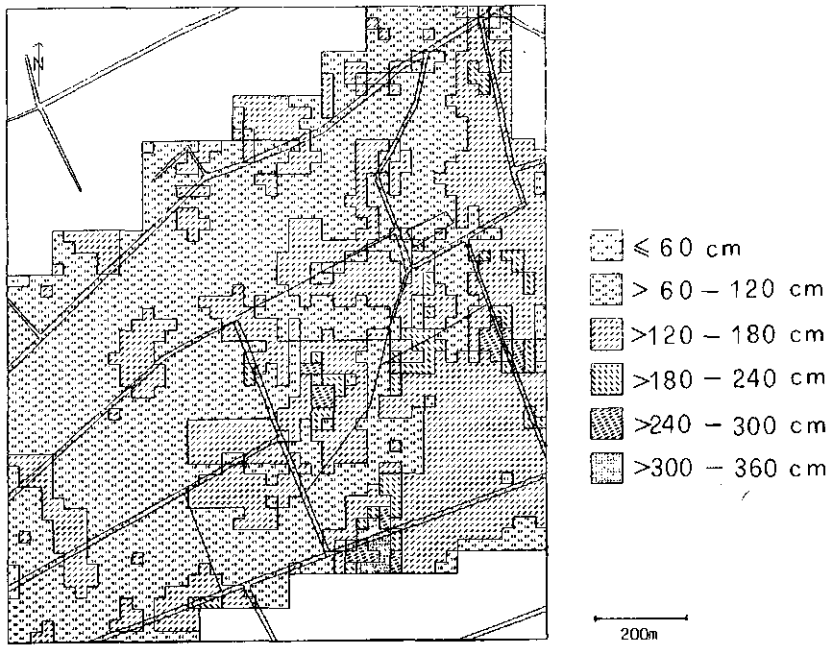


Fig. 7: Soil moisture data processing using Shepard approximation: ground water level (depth below surface in m) in the central part of the Krummbach catchment on Dec. 11th 1985




The soil moisture conditions and soil moisture parameters that have been parameterized and regionalized successfully with the methods described above were used for the validations of distributed catchment models and for other tasks. Results of model validations are described by Rohdenburg et al. (1986), and Diekkrüger (1988).

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# LAND EVALUATION AT FARM LEVEL USING SOIL SURVEY INFORMATION SYSTEMS

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## Summary

County soil surveys of the United States National Cooperative Soil Survey program include detailed soil maps, soil descriptions, soil characteristics, and various soil interpretations. This information can be used for a variety of applications including land evaluation at the farm level. In Minnesota, a user-friendly and menu-driven soil survey information system (SSIS) was developed to help users access the information very easily and quickly for land assessment, farm management, land use planning, soil conservation programs, and education. Application software using the SSIS soil map database was developed for specific uses. PRODEX software is a tool developed for land evaluation. It evaluates relative productivity potential of land parcels using the Crop Equivalent Rating (CER). A soil survey information system can also help evaluate soil conditions for farming by soil. Conventional agricultural management uses one fertilizer and pesticide application rate for an entire field based on a single yield goal determined by dominant soil and climatic conditions. This management creates inefficiencies in application and product effectiveness by overtreating or undertreating some areas. This results in increased field management costs and the potential for surface and ground water pollution. County detailed soil surveys used with emerging modeling techniques, remote sensing technologies, geographic information systems, and computerized field applicators offer great opportunities for farming soil more efficiently in the agricultural ecosystem.

## Introduction

Minnesota, and most agricultural lands of the United States of America will have a detailed soil survey by 1990. The objective of the National Cooperative Soil Survey (NCSS) program is to obtain through soil surveys, an inventory of the Nation's soil resources, record the location of soils, predict soil performance under defined use and management, facilitate the transfer of soil information from one location to another, and contribute to the knowledge, understanding, and proper use of our land resources (U.S.D.A., 1988). Initially, soil surveys had as objectives not only to identify, classify and map soils but also to interpret them for various applications. Emphasis was on using detailed soil maps for their practical predictive values for farming, ranching, and forestry (U.S.D.A., 1984). Later, the use of soil survey progressively increased and new, more specific, or broader interpretations were added for engineering, soil conservation, residential and industrial developments, and land appraisal. Soil use predictions usually give a soil limitation ranking such a slight, moderate, severe.

Although soil surveys can be developed for one specific purpose, they are normally made to cover a broad range of interests and needs. They are used for farm management as well as land-use planning. Modern detailed soil surveys made for counties with predominant agricultural land use have common scales of 1:15840 or 1:20000. This is a compromise between the level of details needed for intensive land use and farm management, and the cost of mapping. This level of mapping is termed a second order survey. It is made for intensive land uses that require detailed information about soil resources for making predictions of soil suitability and management. The information can be used in planning for general agriculture, construction, urban development and similar uses that require precise knowledge of the soils and their variability (U.S.D.A., 1984). Map unit delineations on soil maps represent areas dominated by one major kind of soil or several kinds of soils. A map unit is identified and named according to the taxonomic classification of the dominant soil or soils. Within a taxonomic class there are precisely defined limits for the properties of the soils. On the landscape, however, soils generally have a great variability in their properties. Consequently, every map unit has soils that belong to other taxonomic classes. These occupy small areas (1.5 to 10 acres, 0.6 to 4 hectares depending on survey scale) and cannot be shown separately on the soil maps at the selected mapping scale. They are called inclusions and are always noted in the map unit description (U.S.D.A., 1985). This is very important to emphasize when using soil surveys for land evaluation.

The county soil survey report is then commonly a large technical document with much information. The report is difficult to use by non-technical users, limiting utilization of the information. A few years ago the Minnesota Cooperative Soil Survey started a program to make county detailed soil surveys readily and easily accessible to users for a variety of applications at a farm level.

Soil Survey Information System

The Soil Survey Information System (SSIS) is a computerized county detailed soil survey (Robert & Anderson, 1987). SSIS can retrieve, sort, display, highlight, and print any soil survey data for an area of one section (1 $mi^2$, 640A, 259 ha) or a similar gridded area (e.g., 5000 $ft^2$ or 500 $m^2$ grid). SSIS, developed by the Department of Soil Science, University of Minnesota, has the following major objectives:

1. to provide easy, fast access to any soil geographic information (map, descriptions, characteristics, and interpretations) related to any tract of land. The software is truly user-friendly and menu-driven. Only a very limited training is needed for inexperienced microcomputer users.

2. to run on simple, inexpensive, and stand-alone microcomputer systems so that anyone can use SSIS anywhere, in any office, home or field, and anytime for day-to-day decision making.

3. to create a versatile system for easy and quick update of maps and data, addition of new soil interpretations for urban, rural and forest uses, and overlay of other geographic data bases.

4. to provide a base for the development of specific application

software using selected data of the information system. The software is user-friendly and menu-driven (Fig. 1). This is a prerequisite for software used in field, county offices, and on farms by users with very little computer experience.

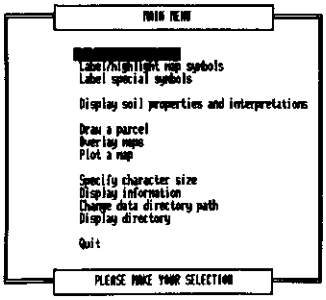



Fig. 1. SSIS MAIN MENU

Options are clearly presented and selected by pressing a few keys. Menus have pop-up HELP screens to assist in making selections. The computer program has routines to check menu selections and data entries. When an error is detected, a message indicates the correct procedure or the expected input. INFORMATION screens are provided upon request to define soil terms and procedures, to explain how the data were collected and analyzed and to specify data limitations for specific applications. A user guide is provided to configurate the software to the hardware. The system displays the soil survey data. The map unit soil symbols can be shown or highlighted (Fig. 2).

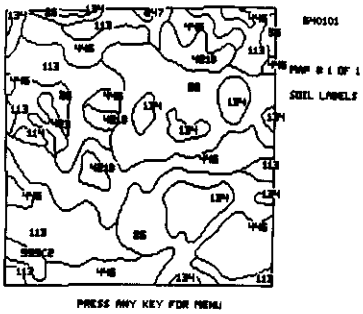



Fig. 2. SSIS Soil map with symbols

A summary table describes each symbol. For example, the soil symbol 86 is described as Canisteo clay loam and 421B is described as Ves loam, 1 to 4 percent slopes. SSIS can highlight soil features in color, e.g., all soil map units with soil reaction greater than 8 and give a corresponding total acreage (Fig. 3).

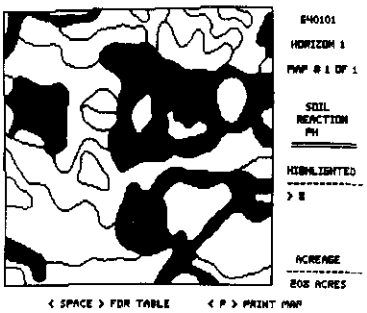



Fig. 3. Interpretive map showing map units with soil reaction greater than 8.

The soil properties and interpretations available with the current version (2.0) of the Redwood County SSIS are:

- Crop and pasture expected yields, soil productivity index (PRODEX), and prime farm land;
- Building site development;
- Construction materials;
- Water management;
- Sanitary facilities;
- Recreational site development;
- Wildlife habitat potential;
- Engineering properties;
- Soil and water features;
- Physical and chemical properties.

Each category has several options. For example, the Sanitary facilities submenu gives soil limitations for:

- Septic tank absorption fields;
- Sewage lagoon areas;
- Sanitary landfills - trench
  - area
  - daily cover

A new category - Ground water pollution susceptibility for nitrogen and some common pesticides - will be added soon.

The MAIN MENU has the option "Draw a parcel" to delineate a parcel of land using the arrow keys on the keypad or using a small digitizing tablet. In both cases, a menu displays options to draw straight lines between selected points, to draw continuously irregular lines, to correct and erase lines, to mask all features outside the parcel. The "Plot a map" option provides a submenu to plot a map at a selected scale. The system can also display and overlay other digitized maps such as land use, ownership, vegetation cover, roads, drainage, etc. A separate overlay routine, the Map Overlay System (MOS), displays in color the location of overlapping features selected from two different types of maps and calculates the acreage of combined attributes. A spreadsheet type screen shows the acreage of all possible combinations.

The Soil Survey Information System runs on IBM PC, PS/2 and compatibles with 512K RAM memory, two flexible disk drives or a combination of flexible drive(s) and firm disk drive(s), one graphics adapter and monitor (CGA, EGA, or VGA). A dot matrix printer, a desktop plotter, or a digitizing tablet are optional. SSIS works with digitized soil maps and optional overlay maps. The soil survey base map sheets on mylar are digitized using a high resolution scanner. Hand digitizing was found too slow, costly, and had the potential for considerable errors. Digitizing tablets are used to digitize simpler land features such as land use, cover types, and ownership parcels.

According to a recent survey (Finney & Paulson, 1986), the principal uses of the system were, in decreasing order, land appraisal, farm management, government and local programs, and education. The main uses of the software by county departments were for land assessment, federal and state conservation programs, and land use, planning, and zoning. On farms, the system is principally used to improve fertilizer and herbicide management (Ohm, 1985), select sites for soil sampling, design conservation plans, prepare cropping plans, and evaluate land for rental or purchase (Robert & Anderson, 1988). Extension agents are using SSIS to help farmers locate the most productive soils, to improve soil management (e.g., tillage and drainage) and crop management (e.g., agrichemicals) (Robert & Anderson, 1986). Maps of soil surface texture (Fig. 4), organic mater percentage, and pH levels are useful when selecting herbicide rates.

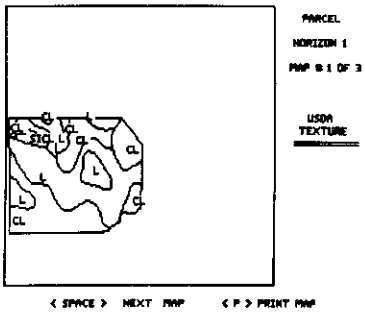



Fig. 4. USDA soil surface texture interpretive map (C: clay, CL: clay loam, L: loam, SICL: silty clay loam).

Several counties are using a land use overlay for land assessment, planning and zoning, and conservation programs. Four northern Minnesota counties have a forest cover overlay in progress for timber management.

Recently there has been a strong and growing interest in SSIS, as the use of the system has increased, from agribusinesses, agricultural cooperatives, appraisers, realtors and bankers. The SSIS data base is utilized in several application software packages developed for specific uses. The PRODEX software was developed for land appraisal and assessment.

PRODEX: land assessment for individual parcels.

County soil surveys provide detailed and unique information about the soil characteristics of land. Soil surveys can be interpreted specifically in terms of soil qualities that bear directly on soil potential productivity and land evaluation for assessment (U.S.D.A., 1984). One important attribute of soil survey is the fact that most soil characteristics do not change very much whereas other elements that determine the land value change with time. A land assessment index based on soil properties can easily be reinterpreted as economic or institutional conditions change.

A variety of productivity ratings have been developed to provide a common basis to compare one soil to another. Productivity comparisons are usually made for one or two levels of management. When used in combination with detailed soil surveys, potential productivity of soil mapping units or land parcels can be evaluated. Productivity ratings in general are numbers that reflect relative value of a soil for agricultural or forestry use (Miller, 1984). In many instances these ratings have been based on physical and chemical properties of soils and the effect that these properties have on productivity for the most commonly grown crops (Huddleston, 1982). In Minnesota, the productivity rating system that is used is the Crop Equivalent Rating (CER) (Rust et al., 1984). This system goes one step beyond relating soil properties to gross crop yields. Recognizing the importance of management in obtaining economic yields, the CER reflects the inputs necessary to obtain a given yield such as fertilizer, drainage, and irrigation. Therefore, net economic returns are calculated and indexed instead of just soil properties. CER's are indexed on a scale of 0 to 100. A relative ranking can be assigned to any soil of some extent.

The following procedures are used to provide the basis for equalized assessment:

1. data are obtained on the selling price, earning value, cash rent or appraised value of agricultural land in representative soil areas;

2. the relationship between the CER and one or more measures of dollar value are determined;

3. a schedule of adjustments for location of roads, special soil conditions, and other local conditions is prepared.

Adjustments can be made to the CER values for the following: lands

in pasture and timber, climate, drainage, and physical land constraints. A CER of about one third the cropland value is recommended where cultivated cropping is not a feasible alternative and the land is either in permanent pasture or timber production. Climatic adjustments are made on the basis of rainfall differences. If average rainfall of the county under consideration differs an inch or more from the geographical center of that soil, 3 percent is added to the CER for each additional inch of rainfall or subtracted for each inch of lower rainfall.

To relate the CER for specific soil survey mapping units to individual ownership parcels requires manipulation of large amounts of data. Before availability of microcomputers, this manipulation was done primarily by hand. This involved considerable time and effort on the part of individual county assessors and was a drawback to the use of CER's for land evaluation in the assessment process. For this reason computer software was developed to be used with the Soil Survey Information System (SSIS) to quickly and accurately assess relationships between land parcels and CER. This software, titled PRODEX (Productivity Index), also allows rapid changes and adjustments to both individual soil and parcel ratings.

The objectives of the software are to (Anderson & Robert, 1987):

1. allow the rapid use of detailed soil survey information to evaluate relative productivity potential of any size land parcel up to one section;

2. provide access to SSIS and evaluate the CERs for a parcel;

3. provide menu options to draw ownership parcels, change CERs for map units, and change the weighted average productivity rating;

4. print and/or save the results on disks.

The program operation of the PRODEX software is very simple. A detailed digitized soil survey map (one section) for the land parcel to be evaluated is first retrieved through menu options. An optional overlay grid of different sizes can be selected to assist in locating parcels. Land parcels can be drawn by two methods. Parcel boundaries can be drawn using the keyboard "arrow" keys or using a digitizing tablet. Once the land parcel has been identified, the rest of the soil map is masked to highlight parcel boundaries (Fig. 5).

Each soil map unit within the parcel is automatically measured to determine the number of acres according to the scale of the map. Soil series labels are then retrieved. Productivity ratings, in the form of the CER corresponding to each of the soil survey mapping units, are displayed in tabular form (Figure 6). A number code is assigned to each soil subarea on the map. Individual CERs are displayed by subarea with number of acres and weighted acreage CER value for the ownership parcel. The data can be changed and adjustments made to the CERs according to any previously prepared schedule of adjustments or as a result of any changes in total acreage.

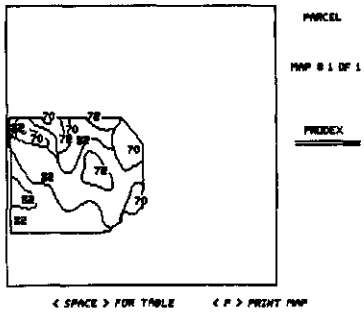



Fig. 5. Parcel boundary identified with each mapping unit CER value.

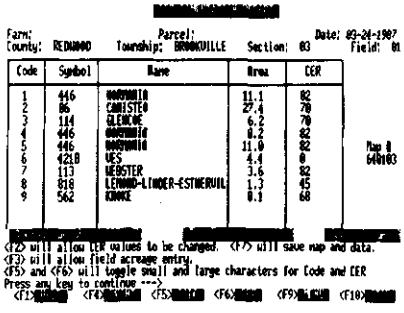



Fig. 6. Tabular display of data for each map unit and weighted average productivity rating.

Applications of PRODEX are multiple. CERs can be used to evaluate productivity of different land parcels. This information can aid producers and planners to make management decisions. When used with the Soil Survey Information System, the area and distribution of each soil can be measured and an evaluation of productivity can be made for an individual soil map unit or as a weighted average for a parcel. Some areas of application are:

1. Land management. A general assessment of the quality of the soil resource managed can be made. CERs as an index based on net economic returns provide an independent, objective and quantitative method to evaluate productivity.

2. Land rental and purchase. Graphs can be constructed for various geographic regions by correlating bona fide sales data with soil CERs. The weighted average CER by parcel can then be calculated to determine a fair market value or, if rental values are used, a fair rental price.

3. Equalized assessment.

4. Preservation of agricultural land. Weighted average CERs provide an objective indicator of overall parcel quality. (Fig. 7). High CER values would indicate that the parcel is high quality agricultural land and it should be dedicated to agriculture. This, of course, cannot be the only criteria on which these decisions are made, but it is a useful tool.

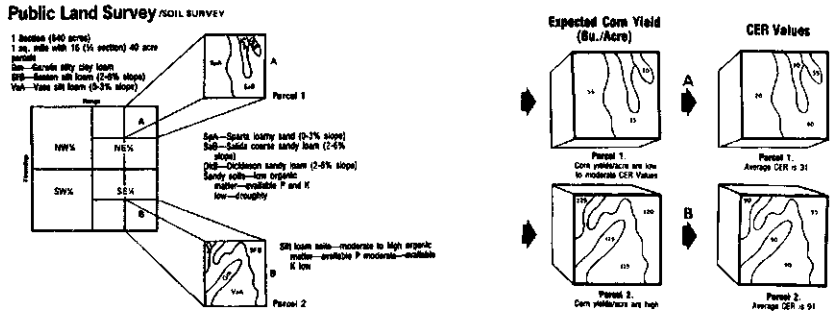



Fig. 7. Productivity ratings offer an objective method to evaluate parcel boundary.

PRODEX is an example of application software using the soil survey information system. A similar program was developed to evaluate parcel eligibility for state and federal conservation programs. Another program helps select locations and number of soil samples within fields to provide a good representation of soil variability. This software aids soil sampling for fertilizer recommendations. Development of this kind of software, used with a soil survey information system will continue to increase the use of soil survey information.

Land evaluation for soil specific farming.

A new application, at the farm level, of soil surveys and particularly soil survey information systems is farming by soil. Uniform field application of fertilizers, herbicides and seeds create inefficiencies by over-treating some soils and under-treating some others. This increases field management cost, decreases net return, and may contribute to surface and ground water pollution. County detailed soil surveys used with emerging modeling techniques, remote sensing technologies, computerized geographic information systems, and computerized field applicators offer great opportunities for farming soils more nearly according to their capabilities.

Detailed soil surveys or aerial photographs taken after plowing show that individual fields of any size have generally several different soil types (Robert & Rust, 1982). This varies with the type of landscape. Rolling moraine may have a much greater soil variability than flatter landscape developed from more homogenous parent material. In southwestern Minnesota, most fields have at least three contrasting soil types with variable texture, organic matter content, pH, available water-holding capacity, permeability, and nutrient content levels.

The following example comes from one 80 acre field in 1987 in Renville county, Minnesota.

| | Soil type 1 | Soil type 2 | Soil type 3 |
|---|---|---|---|
| Acreage (ha) | 50 (20) | 17 (6.8) | 13 (5.2) |
| <u>Soil characteristics</u> | | | |
| O.M. (%) | 6.3 | 3.2 | 2.2 |
| pH | 7.7 | 8.1 | 8.0 |
| Nitrogen. lb/ac (kg/ha) | 50 (56) | 32 (35.8) | 38 (42.5) |
| Phosphorus. lb/ac (kg/ha) | 15 (16.8) | 30 (33.6) | 8 (9.0) |
| Potassium. lb/ac (kg.ha) | 302 (338) | 304 (340) | 342 (383) |
| Zn (ppm) | 1.7 | .4 | .4 |
| <u>Soil management</u> | | | |
| Yield goal. bu/ac (kg/ha) | 160 (10750) | 140 (9406) | 110 (7390) |
| Fertilizer recommendation (N-P-K) | 155-95-50 | 135-50-40 (10 lb. Zn) | 85-85-0 (10 lb. Zn) |
| Cost/acre (ha) | $50.45 (20.2) | $45.59 (18.2) | $37.74 (15) |
| Herbicide recommendation Lasso, qt. (L) | 4 (3.8) | 3.5 (3.3) | 3 (2.8) |
| Cost/acre (ha) | $18 (7.2) | $16 (6.4) | $13 (5.2) |

Benefits of <u>farming by soil</u>:

| | |
|---|---|
| Increased yield: 7.6 bu./ac. x $1.65 = | $12.54 |
| Herbicide cost saving | 1.20 |
| Fertilizer | -6.10 |
| | $7.64 per acre |
| | ($3.06 per ha) |

Soil survey information systems or application software can be used to group soil map units in classes of fertility levels (Fig. 8) and

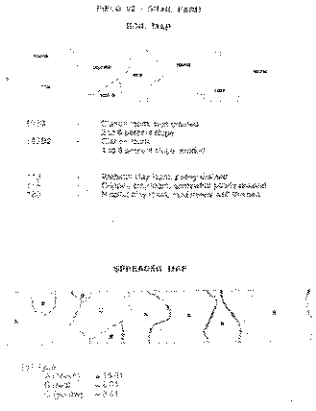
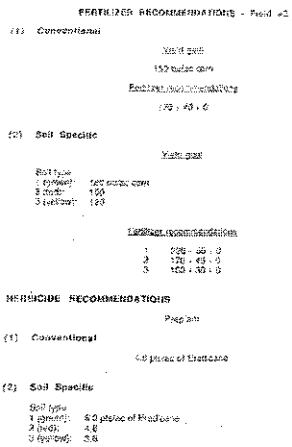


Fig. 8. Soil map and soil type spreader map of an experimental field (20 ac., 8 ha.) near the University of Minnesota SW Experiment Station.

create a field soil type map. When available, color infrared photographs can be combined with soil survey maps to increase the resolution of the field soil type map. When soil surveys and aerial photographs are not available, a systematic soil sampling can be used.

Kriging software is then used to create the field soil condition map using actual fertility levels. This technique is also preferred on coarse textured soils and on fields with some specific farming practices such as the use of manure. Fertilizer and herbicide recommendations are made for each soil condition (Fig. 9) instead of


FERTILIZER RECOMMENDATIONS - Field #2

(1) Conventional

Yield goal

150 bu/ac corn

Fertilizer recommendations

(2) Soil Specific

Yield goal

Soil type
1 (yellow): 150 bu/ac corn
2 (red): 100
3 (yellow): 120

Fertilizer recommendations

1 [illegible]
2 [illegible]
3 [illegible]

HERBICIDE RECOMMENDATIONS

Preplant

(1) Conventional

4.0 pts/ac of Bradicane

(2) Soil Specific

Soil type
1 (yellow): 4.0 pts/ac of Bradicane
2 (red): 4.0
3 (yellow): 3.0

Fig. 9. Fertilizer recommendations for the Figure 8 field.

one recommendation for the field using conventional techniques. The soil type maps are digitized and read by a small microcomputer equipped with graphics and guidance capabilities installed in the cabin of a computerized spreader (Fig. 10, 11). When driving across a field, types and rates of fertilizers and chemicals are automatically selected as a function of soil types, or conditions.

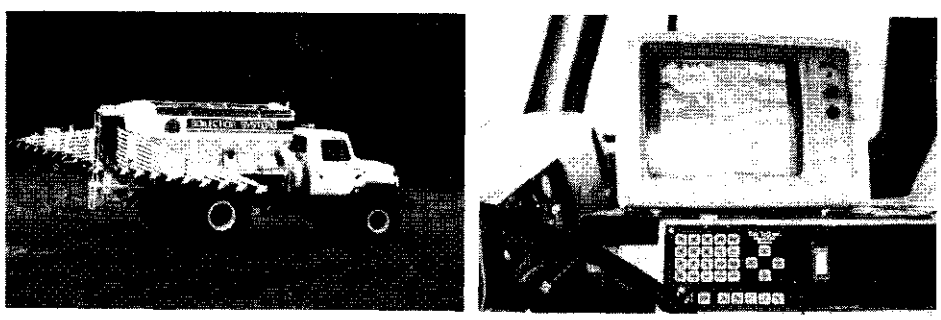


Fig. 10 and 11. Computerized spreader.

The benefits of new technologies of farming by soil are:

- Increase in farm profitability. Preliminary results indicate (current) improved net return by five to ten dollars per acre depending on field soil combinations. The improved net return is the result of more efficient fertilizer use, decreased herbicide cost, and increased yields.

- Optimization of soil productivity by selecting fertilizer rates and grades as a function of soil potential.

- Reduction in soil erosion by conserving or improving soil characteristics and fertility.

- Reduction in surface and ground water pollution by using rate of chemicals adapted to the soil conditions.

## Conclusions

At this moment, the second order soil survey (county detailed soil survey) is generally adequate for farm management. In the future, there will be a need for larger scale soil surveys, for improved land evaluation, to optimize the use of new technologies such as farming by soil.

## Acknowledgments

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# COMPARISON OF PHYSICAL LAND EVALUATION USING A PARAMETRIC METHOD WITH LAND CHARACTERISTICS AND WITH LAND QUALITIES. APPLICATION ON OIL PALM PLANTATIONS IN NORTH-SUMATRA (INDONESIA)

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## Summary

Fysical land evaluation using a parametric method with land characteristics and land qualities as a basis for land evaluation was carried out in North-Sumatra. Relationships were found between yield of oil palm, grown in estates, and various land indices. The most interesting correlation was found between oil palm yield and the index calculated using land characteristics. The land suitability classification was based on economical considerations.

## Introduction

In parametric (numerical) land evaluation the diagnostic criteria are rated numerically and the land classification is obtained by mathematical manipulation. Various parametric systems of land classification exist (Riquier & Schwaar 1972). Land suitability classification by a parametric system can be achieved by using either land characteristics or land qualities as a basis of the evaluation. In the present paper both methods are compared.

## Environmental setting

The study area is located in the Eastern part of the province of North-Sumatra (Indonesia) (latitude: 2° to 6°N; longitude: 97° to 101°E; altitude: sea level to 125 m; mean temperature: 24.4°C to 26.8°C; annual rainfall: 3950 mm in the South and 1640 mm in the North; no dry season in the South, < 3 months in the Northeast (February to April) (Poeloengan Zulkarnain, 1987).

Soil **parent materials**: 1) shales and sandstones of Tertiary age, 2) Quaternary marine and alluvial deposits and 3) rhyolitic Tertiary and 4) basaltic Quaternary volcanic ashes from Mount Toba. The soils (total=36) include 8 Entisols, 5 Inceptisols, 21 Ultisols and 2 Oxisols.

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## Materials and methods

The average monthly temperature and rainfall records of 22 **climatic stations** situated in selected estates and the complete climatic records over a 15 year period of 4 meteorological stations belonging to the national network were used for this study.

The site descriptions and morphological and analytical characteristics of 36 soil profiles located in existing oil palm plantations were used. The descriptions were carried out according to the FAO Guidelines.

A composite soil sample of about 0.5 kg was prepared of the surface 20 cm of the soil of the blocks where a profile pit (2 m) was described. The samples were taken in the fertilizer areas - the circumferance of a circle of about 7 m diameter around the stem of the oil palm tree - of 70 trees, i.e of about 1 tree on 2. Each sample was composed of 140 subsamples. The yield data used in this study are the ceiling yields, averaged over 5 years, of blocks of healthy trees of 6 to 10 years old plantations of Elaeis guineensis Jacq., var. tenera.

The **estate type of land utilization** of North-Sumatra was described in detail by Zulkarnain Poeloengan (1987).

The following **land characteristics** were used (Zulkarnain Poeloengan, 1987):

1. climate of the estate
2. topography at the profile site
3. wetness of the profile
4. physical soil conditions of the profile recalculated over 100 cm using depth correction factors (Sys, 1985).
5. chemical soil fertility of the top 15 cm of the profile (base saturation at 50 to 60 cm depth)

The following **land qualities** were considered (Embrechts & Zulkarnain Poeloengan, 1988):

1. foothold for roots of the profile
2. availability of nutrients of the top 15 cm of the profile or of compound surface samples
3. soil acidity conditions: pH water 1/1 of the top 15 cm of the profile or of compound surface samples
4. availability of oxygen of the profile
5. water availability of the profile (Sys, 1985)
6. temperature regime of the estate
7. soil workability of the top 15 cm of the profile (FAO, 1983)
8. resistence to erosion at the profile site

The **land index** is calculated by a simple multiplicative model:

$$LI = \pi_{i=1}^{q} Ri.100^{1-q}$$

With: LI : land index
Ri : rating of the $i^{th}$ land characteristic or quality
q : total amount of land characteristics or qualities

The ratings of the individual land characteristics or land qualities are determined according to a limitation scale. Each **limitation level** corresponds to a rating range. The following scale of limitations was used: Optimal (100-95), Slight (95-85), Moderate (85-60), Severe (60-40), Very severe (40-20).

For land evaluation with land characteristics the requirement

table developed by Poeloengan Zulkarnain (1987) was used. Land evaluation with land qualities was carried out using the requirement table of Embrechts & Poeloengan Zulkarnain (1988).

According to the Medan-Based Joint Marketing Office (1984) the **optimum yield** was 30 tons of fresh fruit bunches (ffb)/ha.year. The **marginal yield** was 10 tons of ffb/ha.year. The **suitability classification** according to the yield level was based on the following assumptions:

1. the boundary between classes S1 and S2 is 75% of the optimum yield, i.e. 22.5 tons of ffb/ha.year
2. the boundary between classes S2 and S3 is situated 40% above the marginal yield, i.e. 14 tons of ffb.ha.year
3. the boundary between class S3 and order N is 10 % below the marginal yield, i.e. 9 tons of ffb/ha.year

## Results

Sunshine duration, water availability and temperature regime are not limiting in the study area.

Relationships were found between yield of oil palm grown in estate plantations in North-Sumatra and land indices calculated using either land characteristics or land qualities as the basis of the evaluation. The coefficients of determination of simple regressions between the land index calculated with characteristics and with qualities are shown in table 1.

Table 1. Coefficients of determination of the relationships between yield and various land indices.

| Type of regression | Coefficient of determination (n=36) | | |
|---|---|---|---|
| | land characteristics | land qualities using | |
| | | profile data | compound samples |
| Linear | 0.79 | 0.50 | 0.72 |
| Exponential | 0.87 | 0.58 | 0.77 |
| Logarithmic | 0.73 | 0.52 | 0.72 |
| Power | 0.83 | 0.64 | 0.79 |

The simple regressions between yield and the land index are all highly significant. If land qualities are used the coefficients of determination are higher with compound surface samples than with profile data. The best correlations however are found between yield and the land index calculated with land characteristics. The coefficients of determination of the correlations between yield and land characteristics do not differ much from each other. Linear regressions are easier to handle than other single regressions. Therefore in this case preference is given to the linear regression. High values of the coefficients of determination indicate that the regression equation can be used for yield prediction purposes.

To calculate 'availability of oxygen' the water content of the soil at field capacity, the bulk density of the soil and eventually the particle density should be determined. 'Availability of nutrients' is best estimated using chemical characteristics of compound surface samples. 'Water availability'

depends on the water holding capacity of the soil and is calculated using Penman evapotranspiration. Many of these data are not found in most explanatory texts accompanying soil maps of North-Sumatra, are not available for the region concerned or are difficult to find. In oil palm estates of North-Sumatra land suitability classification based on land characteristics is therefore easier and more accurate then land suitability classification with land qualities. The linear relationship between yield of oil palm and the land index calculated with land characteristics and the resulting land suitability classification is shown in fig. 1.

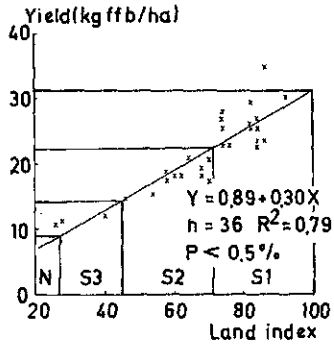


Fig.1.Relationship between yield and land index and land suitability classification.

## Conclusion

In oil palm estates of North-Sumatra correlations are found between yields and land indices. For practical reasons the linear relationship between yield and the land index calculated on the basis of land characteristics is the most interesting. The regression equation may be used for yield prediction.

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# AN OPTIMUM MODEL FOR LAND USE IN XIZHUANGGOU BASIN, CHINA

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## Summary

An optimum model for land use, including both economic and ecological consideration, is presented. By computer calculation, 5 scenarios of land use in Xizhuanggou Basin, Shaanxi province, China, are provided, and their economic and ecological effects are analysed. Finally, one model of optimum economic-ecological structure is developed. It can be seen from the calculation with the model that the natural resources will be fully exploited without disbalancing the ecological structure and soil loss will be reduced by 2/3. The results from the analysis indicate that yields and economic returns can be trebled.

## Introduction

The task of land use planning is to aid the selection of rational land use, according to physical, economic, and social conditions. The aim of this project was to develop within one year an optimum land use model for a Water and Soil Conservation Bureau of the Middle of the Yellow River. A small area - Xizhuanggou basin was selected to carry out land use planning, propose rational land use and control soil erosion. The objective of the project was to design an optimum model of land use to result in sound economic benefits and ecological balance.

## The project area

Xizhuanggou basin is located in the north-central part of the loess plateau in northern Shaanxi province in China. It is located between Mizhi and Suide and includes the 26 villages with a total population of 9016. The area of basin is 94.5 $km^2$. The river in the basin is a minor tributary of the Wuding river. The length of river in the basin is 14.3 km, and there are 27 smaller streams. The climate of the region is semi-arid, winters are bitterly cold and long, summers are hot and short. The annual rainfall is 450-480mm and concentrated in summer; climatic hazards are posed by intense rain storms, spells of dry weather, and incidences of hail. The soil is loessic and the parent material is thick and fertile. Erosion is widespread because of extensive deforestation in the past. Of considerable importance is the tendency of the loess to vertical cleavage. Intense storms can also cause considerable damage (Fu, 1983). The loss of soil is very serious with an annual erosion loss of 282,000 tons; this works out at an erosion rate of about 3000 tons $km^{-2}yr^{-1}$. The ecological environment deteriorates to pose serious problems to the area. Therefore, it is very important to work out a long term plan for rational use of land resource.

## Method and results

Linear programming provides a method for determining optimal solutions in order to achieve economic and ecological balance. A group of linear

equations, as a series of constraint conditions, expresses the needs of economic and ecological balance. A function expresses the optimal land use. An optimal model of land uses is made up of a group of linear equations and the objective function.

The standard form of linear programming can be expressed as: Max (Min) $Z=\underline{C}^t\underline{X}$ Subject to $\underline{A}\underline{X}=\underline{b}$, $\underline{X}\geqslant\underline{0}$, Where $\underline{b}\geqslant 0$, and $\underline{C}^t=(c_1, c_2,\ldots,c_n)$ is called the profit vector;

$$\underline{X}=\begin{pmatrix}X_1\\X_2\\\vdots\\X_3\end{pmatrix},\quad A=\begin{pmatrix}a_{11} & a_{12} & \cdots & a_{1n}\\a_{21} & a_{22} & \cdots & a_{2n}\\\vdots & \cdot & & \cdot\\a_{m1} & a_{m2} & & a_{mn}\end{pmatrix},\quad \underline{b}=\begin{pmatrix}b_1\\b_2\\\vdots\\b_m\end{pmatrix},\quad \underline{0}=\begin{pmatrix}0\\0\\\vdots\\0\end{pmatrix}.$$

The matrix A is the coefficient matrix.

In setting up the linear programming model, account is taken of rational use of land, potential carrying capacity of land, soil erosion, soil fertility, the basic requirements for food for present and future populations. These requirements are incorporated into constraint conditions to provide maximum benefits.

Constraint conditions

These are divided into six classes; the form of land use, the amount of water and soil loss, the balance of soil fertility, input of chemical fertilizers, the population growth rate, and per capita food requirement. The constraint conditions are made up of eleven constraint equations.

The variables of constraint equations are:

$X_1$: % of farmland with gentle slope (0-3°),
$X_2$: % of farmland with moderate slope (3.1-15°),
$X_3$: % of managed pasture, $X_4$: % of natural pasture,
$X_5$: % of economic forest, $X_6$: % of conservation forest,
$X_7$: % the population density (people per square kilometre),
$X_8$: the amount of applied chemical fertilizers to farmland (kg $ha^{-1}$).

The constraint equations are:

$$X_1+X_2+X_3+X_4+X_5+X_6=95 \quad (1)$$

According to the survey of land use and land evaluation (Liu and Yang, 1985), non-productive land makes up 5% of area of the basin. Land suitable for farming, forestry, and livestock make up 95% of area of the basin.

$$X_1+Y_2\leqslant 20 \quad (2)$$

According to the land classification and land evaluation (Liu and Yang, 1985), farmland is suitable on slopes less than 15 degrees. The land less than 15 degrees makes up 20% of the area of the basin.

$$X_1=5 \quad (3)$$

According to the county plan for agricultural development, during the stage of plan, the gently sloping land will constitute 5% of the basin.

$$3X_3-2X_4=0 \quad (4)$$

Grass should be grown on the steep land. Steep land currently cultivated should be abandoned and sown with grass. Therefore, if steep land currently cultivated is abandoned, the ratio between managed pasture and natural pasture will be 2:3.

For controlling water and soil loss, the area of forest must be over

27.7% of the basin. According to the current land use and the county plan for agricultural development, the area of economic forest during the stage of land use planning should be less than 10% of the area of the basin, Therefore,

$$X_5+X_6 \geqslant 27.7 \quad (5)$$

$$X_5 \leqslant 10 \quad (6)$$

For water and soil conservation, the loss of water and soil should be controlled within definite limits. The soil loss on gentle slopes farmland (1250 tons $km^{-2}yr^{-1}$) is taken as the limits, based on the average index of soil erosion for different land use (Chen et al, 1983). The effects on yields, because of soil erosion, can be expressed in the following equation:

$$15X_1+40X_2+5.2X_3+5.2X_4+5.2X_5+3.75X_6 \leqslant 1184 \quad (7)$$

According to the population census, the ratio of natural population increase is 1.4% in 1980-1983. Based on the policy of birth control, the predicted population density in the region for 1990 is:

$$X_7 \leqslant 105 \quad (8)$$

According to fertilizer experiments on rainfed agriculture, the amount of applied chemical fertilizers is less than 225 kg $ha^{-1}$ on farmland with gentle slopes and is less than 75 kg $ha^{-1}$ on farmland with moderate slope (Chen et al, 1983). The constraint condition about the amount of chemical fertilizer is:

$$-225X_1-75X_2 \quad +X_8 \leqslant 0 \quad (9)$$

The constraint about balance of soil fertility;

the inherent natural fertility of soil plus the additional fertilizers should satisfy the fertilizer needs of grain production. Therefore,

$$-2760X_1-1730X_2+1260X_3+68X_4+90X_5+113X_6+525X_7+285X_8 \geqslant 0 \quad (10)$$

where, the coefficients of $X_1$ and $X_2$ are derived from the fertilizer needs to produce a certain amount of grain. The coefficients of $X_3$ to $X_6$ are derived from the compost resulting from the stalks. The coefficients of $X_7$ and $X_8$ are derived from the manures and applied chemical fertilizers.

According to the county plan for agricultural development, grain production should satisfy food requirements. People require on average 400 kg grain per year. The annual yield of grain is 3000 kg $ha^{-1}$ on gently sloping farmland and 1880 kg $ha^{-1}$ on moderate sloping farmland. Therefore,

$$3000X_1+1880X_2-400X_7 \geqslant 0 \quad (11)$$

The objective function

Under these constraint conditions, the maximum economic benefit is specified.

$$Z=720X_1+450X_2+375X_3+135X_4+1200X_5+300X_6$$

where, the coefficient of $X_1$ to $X_6$ are the values of biological products.

The simplex method of linear programming was used and calculated by computer through many scenarios. The five scenarios are listed in table 1. They are optimal solutions under definite constraint conditions.

Table 1. Results from linear programming mathematical model (1990 year).

| scenario | gross output value (RMB Yuan) | average income per man (Yuan) | population | population density (people $km^{-2}$) | amount of soil erosion (ton) | yield of grain (kg) |
|---|---|---|---|---|---|---|
| 1983 | 1150442 | 127.6 | 9016 | 95.4 | 282000 | 2856173 |
| 1 | 3580384.8 | 383.3 | 9341 | 99.4 | 95920 | 3736630 |
| 2 | 3602817.9 | 368.3 | 9783 | 104.1 | 99968 | 3912944 |
| 3 | 3569471.4 | 373.8 | 9550 | 101.6 | 97810 | 3820000 |
| 4 | 3492062 | 440.3 | 7931 | 84.4 | 82860 | 3172731 |
| 5 | 3626534.1 | 372.8 | 9729 | 103.5 | 99462 | 3891757 |

| gentle slope | moderate slope | economic | conservation | managed | natural | livestock component | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | sheep | cattle | pig |
| farmland (%) | | | forest (%) | pasture (%) | | (head) | | |
| 2.48 | 28.3 | 1.6 | 18.9 | 6.6 | 24.1 | 4394 | 1104 | 1870 |
| 5 | 13.2 | 10 | 24.4 | 17 | 25.4 | 11985 | 2996 | 3995 |
| 5 | 14.2 | 10 | 20 | 18.3 | 27.5 | 12921 | 3230 | 4307 |
| 5 | 13.6 | 10 | 22.3 | 17.6 | 26.5 | 12693 | 3173 | 4231 |
| 5 | 10 | 10 | 38.3 | 12.68 | 19.02 | 8939 | 2235 | 2980 |
| 5 | 14.1 | 10 | 20.5 | 18.2 | 27.2 | 12789 | 3197 | 4263 |

By comparing the five scenarios, it can be suggested that scenario 1, 3, and 4 have advantages in some aspects. But, the gross output value is less and the livestock component is lower. This indicates that the natural resources are not fully used under the specified constraint conditions. In addition, it is not possible that the population growth rate decreases from 1.4% to 0.9% or 0.5%, even that total population in the basin decreases. Therefore, these scenarios are not feasible. The land use patterns of scenarios 2 and 5 are similar, but, the gross output value and average income per capita of scenario 5 are more than those of scenario 2. The amount of water and soil erosion is also less. The population growth rate of scenario 5 is 1.2%. It is possible that the population growth rate will decrease from 1.4% to 1.2% if the policy of birth control is strictly implemented. Therefore, according to physical, economic and social conditions, scenario 5 is an optimal one. It has the rational land use structure. The natural resources will be fully exploited without unbalancing the ecological structure; soil loss will be reduced by 2/3. The rate of gross output value increase will be 215%. The grain yield and economic returns can be trebled.

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# MORPHOLOGICAL FACTORS AFFECTING OVERLAND FLOW ON SLOPES

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## Summary

Many morphological factors affect overland flow namely: slope gradient, slope length, shape of the slope and slope exposure to prevailing winds. This paper contains a discussion of the effect of morphological characteristics of slopes on the overland flow process. The analysis of the different effects is presented through case studies.

Although the effect of the morphological factors on the overland flow process may be strongly reduced by soil properties, soil roughness, vegetation cover and effective rainfall patterns, it is believed that its effect can not be neglected.

Keywords: overland-flow, slopes, hillslopes, morphology, water-erosion.

## Introduction

Overland flow is affected by many factors such as soil characteristics, climate, vegetation, topography, geology, land use, man made constructions such as roads, etc. The size of a drainage basin and the areal distribution of all those factors also have a strong influence. Overland flow is the primary flow in urban runoff, in runoff from rock outcrops and in surface runoff from some small drainage basins.

Many morphological factors affect overland flow on slopes namely: slope gradient, slope length, shape of the slope and slope exposure to prevailing winds. The degree to which morphological aspects influence overland flow is closely related to other factors such as soil characteristics, climate, vegetation, etc. For example in semi-arid areas, where Horton overland flow is a fairly common phenomenon, topography seems to have a slight influence on the overland flow production (Dunne & Leopold, 1978). Most humid regions may experience saturation overland flow (Dunne & Leopold, 1978), and topography is of importance in determining where overland flow will occur. The removal of vegetation from a forest area can lower the infiltration capacity enough to generate large amounts of overland flow where previously runoff was a slow subsurface percolation.

This paper contains a discussion of the effect of morphological characteristics of short slopes on overland flow. Use is made of both numerical and analytical techniques, and laboratory and field experiments.

## Results

### Slope gradient

Slope gradient is one of the major factors affecting overland flow. The interdependence of slope gradient and water erosion hazard has been studied by various authors and shows that the intensity of the erosion process increases with growing tangential shear stress and velocity of the overland flow sheet both of which are closely related to the slope (Holy, 1980).

Slope gradient influences the amount of infiltration and consequently of overland flow. The greater the slope gradient, the greater is the portion of the rain that runs off as overland flow. As more water runs off, the velocity is increased both as a consequence of the steepness of the slope and the greater depth of overland flow. However for a vertical rainfall the amount of rain per unit area decreases with slope steepness, this effect being considerable for very steep slopes. For inclined rainfall the effect may be even more significant.
Fig. 1 shows hydrographs of overland flow obtained in a laboratory experiment in an impermeable concrete model with mounds simulating the cultivation of large root crops - like yam - in Africa. The rainfall intensity was approximately the same in the different cases. Slope affects the shape of the outflow hydrographs.

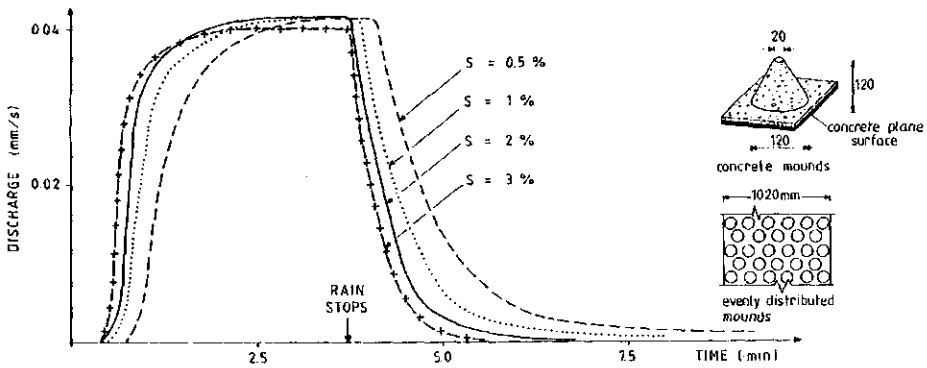


Fig. 1. Effect of slope gradient on overland flow hydrographs.

Slope length

For the same conditions, slope length will affect discharges and water depths and consequently overland flow hydrographs. This is particularly important with respect to water erosion problems.
Fig. 2 illustrates the effect of slope length on simulated overland flow hydrographs in a sandy loam. Use was made of the model KININF, that combines the kinematic wave equations for overland flow with an infiltrating model derived from soil moisture theory (Lima, 1987).

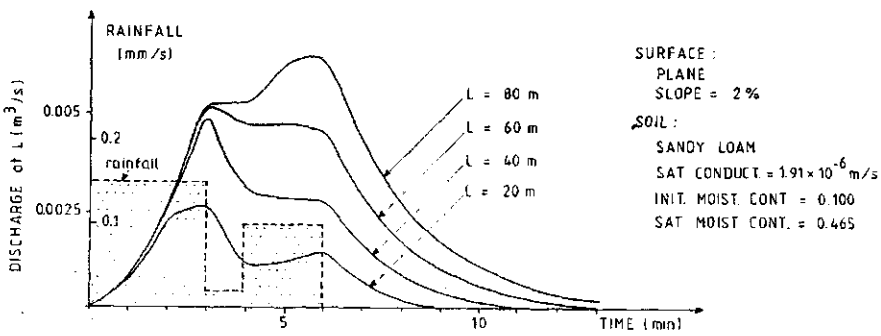


Fig. 2. Effect of slope length on overland flow hydrographs.

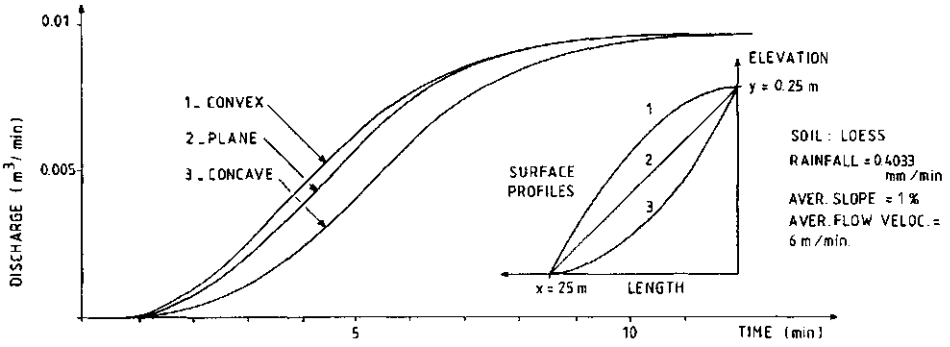


Fig. 3. Effect of slope shape on the rising limb of hydrographs.

Slope shape

Many are the shapes used to represent real slopes in overland flow studies: planes, cascade of planes, convex and concave surfaces, segments of cones etc. The overland flow process is strongly affected by the shape of the slopes. This is not only because of the overland flow process itself but also because of the effective rainfall rate at the surface.

Fig. 3 gives the overland flow hydrographs for strips of concave, convex and plane surfaces using the analytical kinematic model of Lima & Molen, 1988. The shape of the slope is determinant in the assessment of the shape of the rising limb of the overland flow hydrographs.

In convex slopes both steepness, drainage area, and depth of overland flow increase towards the foot of the slope. Comparisons made of erosion intensity on different slopes (Holy, 1980) have shown that the highest intensities are reached on convex slopes, and the lowest on concave slopes for the same length and elevation. These results are in accordance with the form of the rising limb of the hydrographs (Fig. 3).

Slope exposure

In an experimental station located in Alentejo (semi-arid region of Portugal), 15 standard field plots of 20x8.33 $m^2$ with slopes ranging from 10 to 20% were studied with respect to rain water erosion. It was found that fields with slopes of around 20% showed less erosion than slopes of 10% for the same amount of runoff, which is attributed, to the orientation of the fields with respect to the dominant direction of the winds.

Lima (1988) showed the influence of wind intensity and prevailing wind direction with respect to the position of the slope on both the effective rainfall intensity and the mechanics of the overland flow process on slopes. They affect overland flow in the following ways: angle and velocity of impact of raindrops, splash shape, tangential shear stress in the water-air boundary, and effective rainfall pattern at ground level.

Consider two impermeable slopes approximated by two impermeable planes of different orientations with respect to the inclined rainfall. Assuming equal slope characteristics and an angle of incidence of the rain of $45^0$, the overland flow hydrographs at the bottom of the two slopes are compared for two different rainfall patterns measured with horizontal raingauges (Fig. 4). The hydrographs for the two slopes have remarkable differences, as expected.

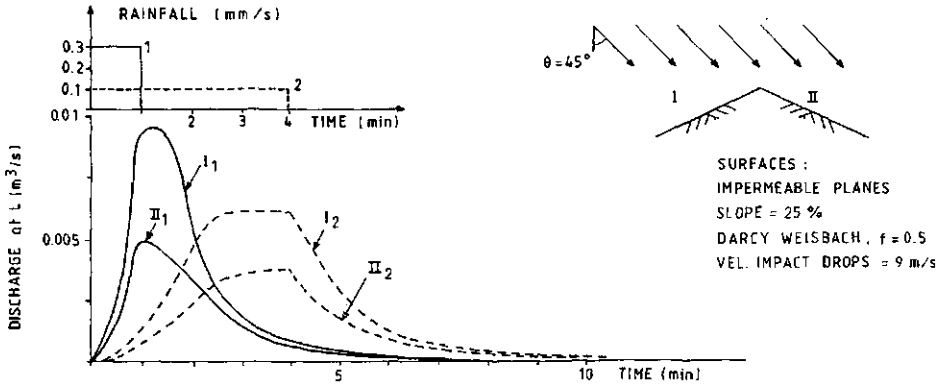


Fig. 4. Effect of slope exposure on overland flow hydrographs.

## Conclusion

The major morphological factors affecting overland flow are: slope gradient, slope length, shape of the slope and slope exposure. Although the effect of the morphological factors on the overland flow process may be strongly reduced by soil properties, soil roughness, vegetation cover and effective rainfall patterns, it is believed that it cannot be neglected. Slope gradient and length are presumed to be factors that more strongly affect overland flow process. The shape of the slope is determinant in the assessment of the time to peak and of the shape of the rising limb of the overland flow hydrographs. The slope exposure is also of great importance in case of slopes exposed to strong winds from some prevalent direction.

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# PROCESSING OF RAINFALL DATA: MULTI-PURPOSE COMPUTER PROGRAMMES AN EXAMPLE ON RAIN EROSIVITY

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## Summary

We hereby propose a fast and simple automatic system for storing and processing rainfall data. Two distint programmes have been worked out, the first for storing the rainfall data and the second for processing it. The structure of these programmes has been thought out in such a way as to obtain data which can be used both for statistical-type processing and for the identification of the singular parameters necessary for analysing the rainfall events. In this specific case rain erosivity data, calculated on the basis of the USLE (Universal Soil Loss Equation, Wischmeier and Smith, 1978), are processed.

## Introduction

The main objective of this work, carried out as part of the P.F.-IPRA (Special grant, Increase Productivity Agricultural Resources) supported by CNR, is the evaluation of rain erosivity and the drawing up of the isoerosivity map for the area under examination. Erosivity in fact is one of the fundamental factors in enabling us to forecast erosion with the use of the statistic-parametric model mentioned above (USLE).
It is well known fact that the breaking away action of the soil particles depends on the intensity and therefore on the energy, developed by the rain. Since variations, at times considerable, in intensity and therefore in energy (which is correlated to the intensity by a logarithmic type function), occur within each rainfall event, it is necessary to know the intensity variations relating to each individual event.

The distribution of the intensities for each event has been obtained from the rain gage data recorded continually on weekly strips by specially designed instruments (recording rain gages).

The two programmes presented in this work are named REDS (Rain Erosivity Data Storage) and REDA (Rain Erosivity Data Analysis).

## Methodologies

Rain erosivity, as a numerical datum, is calculated with algorithms which take into consideration the energy developed in each individual rainfall event.

The unitary energy relating to each intensity is calculated with:

$$KE = 12.13 + 8.9 \log I$$

where KE = unitary kinetic energy in ton per m/ha per mm of rain
I = intensity in mm/h

The sum total of the unitary energy values multiplied by the height of

rain relating to each intensity enable us to determine the total KE of each event.

This total energy multiplied by the maximum intensity in 30 minutes, transferred to intensity in hours, relating to each event, allows us to evaluate the $EI_{30}$ which is equal to 100 times the R factor, expressed in ton per m per mm/ha per h.

The sum of the $EI_{30}$ (or of the R factors) of the single events of each year gives the annual erosivity value.

Besides calculating the $I_{30}$ value, the REDA programme also calculates other three intensities, namely the maximum intensities relating to 15, 45 and 60 minutes. Consequently we can obtain index $EI_{30}$ values (or R) relating to these four different maximum intensities. These values will then be analyzed by means of statistical procedures in order to identify possible correlations with some already known local rain gage characteristics.

If such relations were found to exist it is possible to derive the erosivity value without having to go on the long and laborious stage of digitizing and direct processing of the recording rain gage data.

Steps in the programmes

The two programmes have been made in such a way as to store the digitized data in weekly files (REDS programme); these data are then recorded in pairs in sequential files. Each data pair represents the time of the rainfall datum and the increase in rain with respect to the previous datum.

The data recorded in this way can then be recalled and processed by the second programme (REDA).

REDS programme

It begins with the keyboard input (T) of the address data and continues with the input of the boundaries of the strip by means of digitizing (D) in order to determine the reference axis system and then dimension it to correct any possible errors (V). After having transformed the coordinates of each point, it checks them and stores them in a temporary file.

When the digitizing of the data strip is finished, the data are transferred to a final file and recorded on disc (see sketch 1).

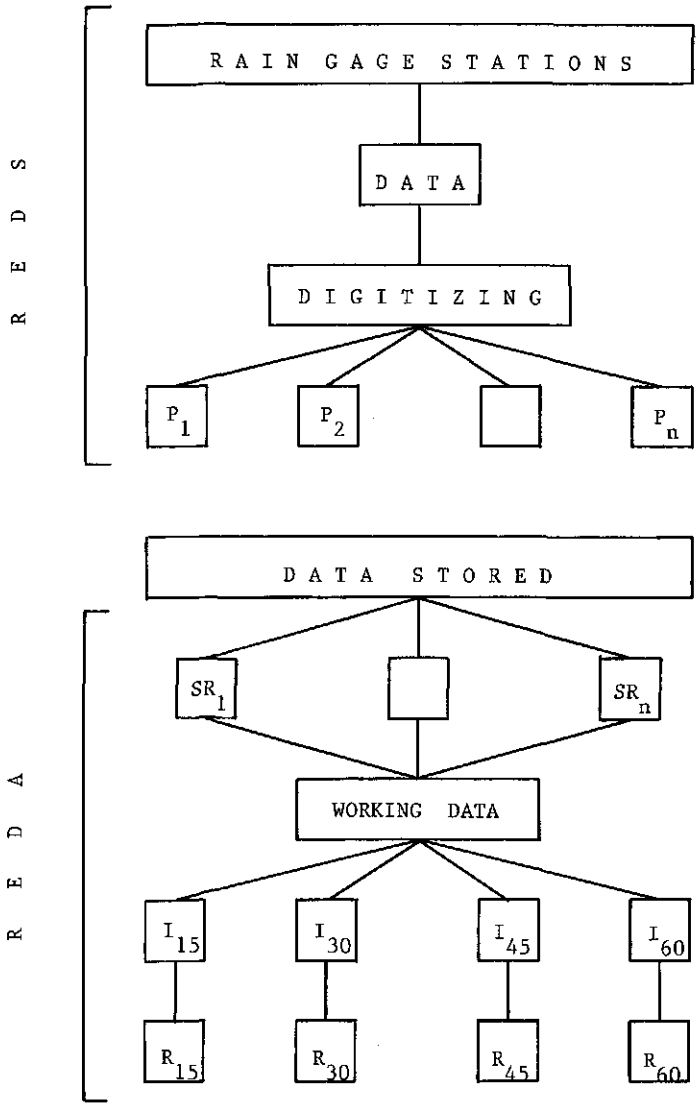
REDA programme

The programme begins with the keyboard input (T) of the addresses to find the file to read. After having read the data it calculates and then records the rainfalls of the week, therefore it links two files in sequence and picks out each rainfall event with previously set duration and rainfall quantity limits (threshold).

Once each event has been singled out the intensities, the total rainfall and all the parameters necessary for the relative erosivity calculation are computed.

The checks are carried out on the defined rainfall threshold and on the division between the events, the latter is determined by the interval of time in which no rainfall is recorded.

Another kind of check is carried out at the moment of the coupling of two consecutive files in order to determine whether or not an event straddles two weeks, months or years.




P = weekly precipitations
SR = single rainstorm
$I_{15}$ = maximum intensity in 15 minutes
R = rain erosivity factor

Sketch 1

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# LAND EVALUATION AT DIFFERENT SCALES IN LOMBARDY (ITALY)

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## Summary

The possibility of giving useful cognitive tools for land use planning procedures, forecasts this knowledge would be adequate for contents and levels of decisions; the typical levels are reconnaissance, semi- detailed and detailed ones. The land evaluation examples at different scales drawn up in Lombardy, give the possibility of planning, starting from the semi-detailed one which takes priority, effective methodologies of land use designing and a multidisciplinary approach for decisions.
Keywords: soil, mapping, evaluation, Lombardy.

## Introduction

Soil survey and land evaluation are recent tools for land use planning procedures in Italy. Lombardy is going forward regarding to survey and interpretation stage for application; on the contrary the contacts between soil scientists and decision-makers for soil survey implementation in land use planning procedures are at the beginning.

A very delicate moment in designing an operational model concretely useful for monitoring and leading interacting land use dynamics, above all in areas with strong competition for environmental resources use such as Lombardy plain, is in understanding of information requirements and in suggesting adequate tools for consequent decisions. In short, soil scientists are involved in suggesting, facing to different land use and management problems, maps and evaluation tools operational at different decision levels.

Later on the state of the art in soil mapping at different scales is presented (reconnaissance, semi-detailed, detailed level), the deriving land evaluation, the applications carried out in Lombardy for land use and soil management.

## Semi-detailed level

This is the representative soil survey scale in Lombardy; in fact, a survey of Lombardy plain is a work in progress (125000 ha have already been mapped), with the purpose of giving a sistematic and reliable inventory of soil resources useful for planning at district level.

The examples drawn up enable to forecast a considerable use of soil information at this scale, with an operational value for problems of rural planning, water protection, environmental designing. There are problems in land use connecting different users of soil resources, such as single farmers producing milk for the cheese factories and having problems of slurry spreading, or municipalities in partnership for a natural park, or members of an irrigation or reclamation society.

Land capability classification is the most immediate tool for evaluating agricultural potentials of a tract of land; these maps are usually used for leading the choices of urban destination toward areas with lower fertility: one of these options has been occurred for a waste disposal,

which has been placed in a III class area, in alternative to a I class one. In another example, soils belonging to the I class in a first time assigned for urban use, have been in a second time classified again only for agricultural use.

The planning of pigs slurry spreading is easier know thanks to soil evaluation for this purpose, relating to potential risk of pollution for surface water and groundwater. The semi-detailed maps allow to plan, on different and sometime distant plots, the optimum quantity of slurry, following the season, soil type and crops.

In the field of crops pattern planning, is very interesting the example of a soil suitability for vineyards, drawn up in an area where this land utilization type shows market potentials, allowing protection of traditional rural landscape; the suitability shows that only few vineyards are placed on very suitable soils. This map gave the input for another one application of semi-detailed land evaluation, that is the choice of representative sites for experimenting relations between crop and soil type, looking for reliability of white wine qualities (Tokai, Lugana) with soil characteristics. Having benchmark soils in the most intensively cultivated plain, resulting from semi-detailed land evaluation, we have in this moment a lot of data from a five years experimentation, related to phosphorus and potassium asportation for most important crops (maize, winter wheat, barley, alfalfa, fescue).

The use of water for irrigation is becoming a limiting factor for intensive production on most permeable areas, where an high consumption of water resources is connected with vulnerability of groundwater to pollutants; there are districts where more tracts of land are planned to become irrigated: for both cases, a land evaluation for irrigation is required, to reduce water use where economical and environmental costs are too high and to plan this use in soil with higher suitability. This evaluation is often joined to a water balance for actual or future crops, with an estimation of water needs to reach appointed production levels.

At semi-detailed level is possible to locate more diffused soils where planning a farm fertility monitoring, on representative farms, regarding to soil type, organizing disposition, cropping pattern; these farms, which are about ten in Lombardy, are the support of an advisory service, for rural development, energy and environmental costs moderation (fertilizers, drainage, deep ploughing, water management).

Regarding to land evaluation for recreation purposes, landscape planning, forestland, in the Lombardy plain there are interesting examples in regional park management. Semi-detailed soil suitability maps allow to subdivide the protected land in areas suitable for suggested uses: there are exaples in suitability for chestnut-woods in areas where is looked for a new balance between deciduous and coniferous forests; for protecting tracts of land less suitable to transformation in the sense of anthropic use; for restoring peatlands, where intensive farming is now prevailing, favouring grassland and swamp vegetation.

## Reconnaissance level

An impulse for production of maps at this scale came by questions posed in regional and infra-regional land use planning.

A national law (431/85) about landscape planning, gave the input to draw up interpretative maps showing broad soil associations and distribution of typical soil-landscape relationships. These maps are useful above all because show "closed" delineations, relatively homogeneous and so reliable from a regional point of view, thanks to reference outlines. The apparent monotony of Lombardy plain has been overcomed looking for

interactions between soils and landscape, and typical "pedo-environment units" may be identified and classified for landscape conservation plans.

This soil-landscape evaluation is joined, at reconnaissance level, to a land capability classification,connecting environmental value with agricultural potential. These maps are particularly useful for decision-makers when public works with high environmental impact are proposed, such as new highway lay-out; there is the possibility of a preliminary assessment for agricultural potential and aesthetic value of different tracts of land involved in the project.

Land evaluation at reconnaissance level, in terms of homogeneity of soil-cropping pattern associations, allowed a different and more active planning of single advisory and rural development districts, designed for the first time on a provincial framework. The first subdivision was made on social and economical basis; the second one had the input of environment and soil survey, optimizing knowledge and information acquired on typical soils, and favouring an agricultural management connected with natural resource availability.

## Detailed level

A detailed level land evaluation was made when very specified purposes were imputed, and only for limited tracts of land in Lombardy.

There are maps of land evaluation for forestry drawn up in Ticino Natural Park woodland (9000 ha), derived from detailed soil survey and vegetation maps. A comparable analysis was made on a relict tract of native forest of the plain of the Po, extending 250 ha on stony soils nearby Mincio river: the detailed soil map and land evaluation show areas with different rooting possibilities, where a hardened horizon (a pan rich in lime) is a limiting factor for oaks rooting. An experimental study about poplar cultivation, diffused in the plain not only nearby main river Po, shows the delineation of low potential areas in a single plot, because of lime richness limiting growth after six years of cultivation.

A study at detailed level has been executed for a Common of Milan hinterland, Vignate, 850 ha large; land capability classification, soil suitability for grassland and maize, are basic tools for model land use planning of Commons, and for diffusion of agricultural productivity guideliness less contrasting with environmental quality.

A survey with precise purpose was made in Valtellina flooded areas during August and September 1987: for a tract of land 2000 ha wide we can have now a set of maps delineating soil characteristics, soil drainage, depth and texture of alluvial deposits, limitations for agricultural use in different areas, struck with variable intensity. The reclamation project and agricultural planning used these documents and information for designing the drainange system and implementing good agricultural management in advisory service.

## Conclusions

Mapping for land evaluation, at different scales, is not a conceptual exercise, but allows of experimenting the flexibility of procedures improving qualitative level of decisions for present or future land use. The value of decisions on land use may be hardly influenced by quality of available information, and by better relationship between soil scientists and planners, politicians or decision-makers: the relationship may improve more and more if land evaluators will look for a modulation of informative contents following requests, time and available financial

resources.

Experiences being conducted in Lombardy allow to plan an operational methodology, at different levels and for most urgent problems connected with environmental resources utilization; persevering tests of outputs will give the possibility at least of acquiring evaluation criteria and suitability classification outlines more and more provided of previsional effectiveness.

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# GEOSTATISTICAL EVALUATION OF THE SIMULTANEOUS INTRINSIC RANDOM FIELDS OF SOIL SODICITY, TREE GROWTH AND LEAF NUTRIENTS

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Three simultaneous continuous random fields of soil sodicity, growth of tree and leaf nutrients concentrations have been analysed as regionalized variables by considering definite correlations rather than independence among the neighbouring observations.

## Experimental

A sodic soil (Natric Haplustalf) was sampled in the depths of 0-30 ($d_1$), 30-60 ($d_2$), 60-90 ($d_3$) and 90-120cm ($d_4$) at 6x6m grid pattern from a 3 year old plantation of Dharek (Melia azedarach Linn.) raised under uniform silvicultural practices at 3x6m spacing (33 rows and 8 columns). Four cores (7.5cm diameter), drawn from the corners of a 1x1m square centered at the tree trunk in the alternative rows of trees, were composited for each of the depths. They were analysed for pH in the saturation paste ($pH_s$), sodium adsorption ratio (SAR) and DTPA-ammonium acetate (Soltanpour & Schwab, 1977) extractable elements. Ten eight months old leaves were sampled from all round of each of the 264 trees and analysed for their nutrients by wet digestion. The third random field consisted of tree height recorded after 1, 2 and 3 years of the growth.

## Results and discussions

### Statistical analysis

Mean and variances of rows and columns were statistically different (non-stationarity) with an overall trend in their means. Since realizations of spatially stochastic processes, are generally true over small distances, the long range deterministic variation (drift) was accounted for by the non-parametric median polish technique of Hamlett et al. (1986). Median of each row was subtracted from the observations of that row and distributions of the residuals examined. Then median of each column of the residuals was subtracted from them, new residuals obtained and their statistics studied. Distributions (at original scale) of pHs, SAR, and extractable Na, P, K, Zn and Mn and leaf nutrients were generally significantly positively skewed. And the distributions became symmetrical and peaked after their median polishing. Same was true for the growth data except that the distributions were negatively skewed. Coefficients of variation (CV) of SAR, extrac-

table Na, P, K, Zn and Mn varied from 86-94, 100-168, 68-80, 19-25, 55-66, and 26-44% depending upon the soil depth, respectively. CVs of the tree height at 12, 24 and 36 months were: 28, 28 and 27%, respectively. Similarily leaf Na, P, K, Ca, Mg, Zn, Mn and Fe CVs were: 27, 21, 29, 19, 34, 30, 25 and 81 %, respectively. Variation in all the three random fields was definitly excessive by the agronomic standards. Variography analysis of the residuals was done by the methods of Journel and Huijbregts (1978):

$$\gamma_{kk'} = (Z_k(xi+h)-Z_k(xi))\ (Z_{k'}(xi+h)-Z_{k'}(xi))$$

where $\gamma_{kk'}$ is the cross variogram between the two simultaneous random fields $Z_k(xi)$ and $Z_{k'}(xi)$ and "h" is the separation distance. When k=k' then it gives auto variogram. Analysis was done in eight directions with an angle tolerance of $\pm 11.25^{o}$. Spherical models were fitted to the semi-variances by the weighted least square methods.

Regionalization

Variability in soil sodicity, extractable elements, growth and leaf nutrients was anisotropically spatially distributed (Fig. 1 & 2). Spatial patterns in the growth at 12 & 36 months

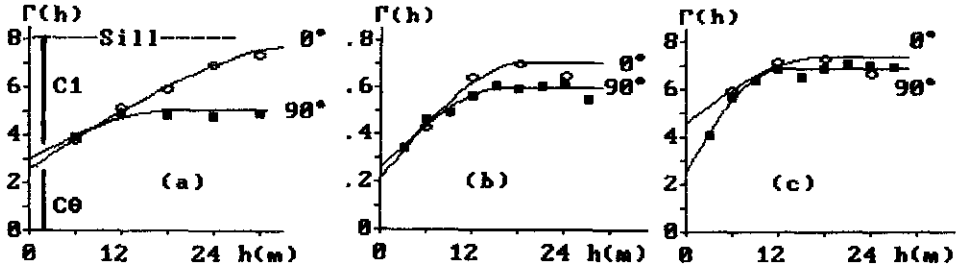


Fig. 1. Semi-variograms of soil $pH_s$ in $d_2$ (a), height of two year old tree (b), and leaf sodium (c).

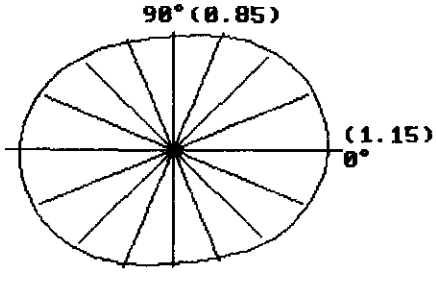


Fig. 2. Variation in the sill of three years old tree height as a function of direction (sill was greatest in 6.3° direction).

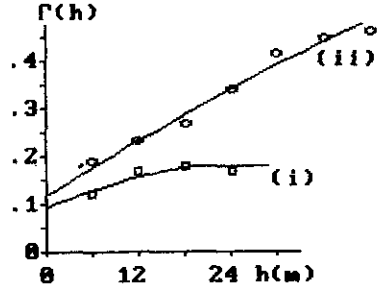


Fig. 3. Variograms of the 1st (i) and 2nd (ii) annual increment in the tree height (0° direction).

were similar to those at 24 months. Soil heterogeneity was of higher magnitude in 0-60cm as compared to lower layers. Sill of the three random fields was maximum in 0° (NW-SE) direction (at right angle to a 200 year old unlined canal about 50m away). Variability was minimum but nested along the 90° orientation (models for this direction were fitted to the first nest i.e. from 20 to 24m). In order to know spatial variation in the growth entirely due to soil ( over and above the other causes as genetic and damages by wind, insect and diseases etc.), variograms were computed on the annual increments in the height. Figure 3 confirmed that variation in the growth was due to soil heterogeneity. Structural component ($C_1$) of soil variation as a percentage of sill in the 0° direction is given in table 1. The proportion of ordered variation ($C_1$) of height ranged from 70-77% in 0° and 54 to 63% in 90° direction depending upon the age. Results were similar for the leaf Na, P and K. Spatial patterns were not so well defined for rest of the tissue elements. Models fitted to the data were validated by jack knifing. Error (e(xi)) was defined:

$$e(xi) = Z(xi)-Z^*(xi)$$

where Z(xi) are the measured and $Z^*(xi)$ are the kriged values, respectively. Normal distributions of e(xi) with zero mean satisfied the hypothesis of the estimation variance.

Table 1. Structural component (in 0°) of soil variation (% of sill)

| Depth | $pH_s$ | SAR | Extractable elements Na | P | K | Zn | Mn |
|---|---|---|---|---|---|---|---|
| d1 | 88 | 51 | 50 | ub* | 50 | 46 | 30 |
| d2 | 66 | 60 | 51 | 52 | 49 | 63 | 50 |
| d3 | 70 | 37 | 55 | 36 | 72 | 41 | 45 |
| d4 | 88 | 53 | 59 | 42 | 56 | ub | 37 |

*ub= sem-variance was unbound

Coregionalization

Transfer of the soil variation ($pH_s$) in to the growth of Dharek is evident from figure 4. Negative cross variograms

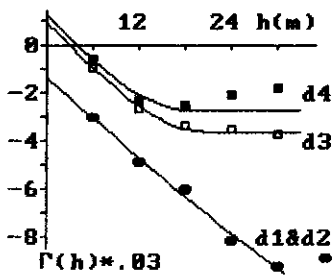


Fig.4 Relative cross-variograms of three year old tree height with $pH_s$ in four depths of soil (0° direction).

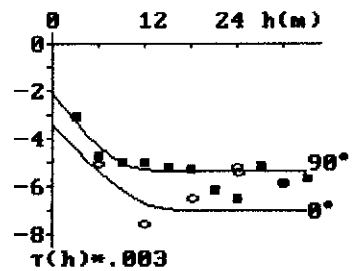


Fig.5 Anisotropic cross-variogram between leaf sodium and potassium.

revealed the adverse effect of soil sodicity on the tree height. Growth was relatively more sensitive to the soil variation in the upper 60cm layers as compared to lower depths. Cross variability between $pH_s$ and height was anisotropically spatially structured in all the four depths. Results were similar with the SAR and extractable Na over all the three years. Interpretable part of covariation of $pH_s$ ($d_2$) with height recorded at 12, 24 and 36 months in $0^o$ direction was of the order of 82, 81 and 91%, respectively. Anisotropic cross variation among the distributions of leaf nutrients is shown in figure 5. From the negative scale of the crossvariograms it could be infered that high concentrations of sodium lowered the uptake of P as well as K. Cross variograms between leaf P and K were positive. Cauchy-Schwarz's condition of inequality of cross variograms was satisfied by all the data sets.

It could be seen from the above discussed results that variation in the growth as well as leaf nutrients was almost a mirror image of the natural variation of soil sodicity. There are several implications of these observations. Naturally occuring soil variation can be exploited to study the relative tolerance of the generally deep rooted tree species to sodicity - a task which is relatively difficult to do in pot culture experiments. Genetic potentials of different tree species also vary considerably and, therefore, scaled analysis would be the choice for comparing their relative tolerance. Other applications are in the forest resources evaluation by the optimal kriging estimator. For improving the precision of treatment comparisons during field trials, special statistical approaches like that of Künsch (1987) which can account for the ordered part of variation are required especailly for the heterogenous salt affected soils.

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## CONCLUSIONS AND RECOMMENDATIONS OF THE DISCUSSION GROUPS

During the Symposium three discussion groups were formed to make specific recommendations on three themes as follows:

Theme 1 : Spatial and Temporal variability: consequences for land evaluation.
Chairman : D.R. Nielsen, University of California, USA.

Theme 2 : Working at different scales: implication for data acquisition and modeling.
Chairman : J. Bouma, Agricultural University, the Netherlands.

Theme 3 : Predicting land qualities: the role of information technology.
Chairman : J. Feyen, University Leuven, Belgium.

Conclusions and recommendations of the three discussion groups were integrated as follows:

### On data gathering

The level of detail of acquisition of soil and land data should correspond with the level of detail of the objectives of the study and of the technology to be used. Detail and scale of the problem to be studied should always be analyzed in close consultation with the user. Scale

Guidelines for data gathering are available for some existing land evaluation methodologies (e.g. TSBF*, FAO**). Introducing models requires a re-orientation of future data gathering, for which guidelines will have to be provided.
* Tropical Soil Biology and Fertility Handbook (IVBS/UNESCO). J.M. Anderson (Ed.). (Dept. Biol. Sciences, Univ. of Exeter, Devon U.K.).
** FAO (1983). Guidelines: land evaluation for rainfed agriculture. FAO Soils Bulletin 52.

Remote sensing techniques should be more widely applied to obtain basic data and to monitor spatial and temporal variability in a given region. Variability patterns, thus obtained, may help to select appropriate scales for any particular study. Determination of groundtruth at appropriate periods to be selected during the year is essential for proper interpretations of remote sensing images.

Information technology allows storage of a large body of data at the greatest level of detail. Indiscriminate use of such data may yield erroneous results. Reliability and accuracy of data must therefore always be included as well. Data to be gathered should not only include measured data but also "groundtruth" to be obtained by talking to farmers and other users of the land.

Data for modeling should preferably be measured in the field. Pedotransfer functions can be derived or used when no measured data are available. These functions should, however, be used with caution because: (1) the applicability is limited to range and conditions for which they were developed, and (2) extrapolation and generalization of functions requires sound validation. To promote their proper use, a catalogue providing a review of existing functions and their limitations, should be established.

## On modeling

Process-oriented deterministic simulation models, which facilitate transferability of results obtained, should be further developed and tested for different purposes and scales. Accuracy of input parameters is often unknown. To demonstrate the effects of input variability on model output, Monte-Carlo techniques can be used. Such a stochastic approach, within a deterministic context, provides an attractive expression for land qualities in terms of probabilities rather than in terms of single values.

## On use and presentation of soil survey information

Land qualities can best be calculated for point data, using results of borings. (Geo)statistical methods and information technology permit clustering of results afterwards. Clustering within units of the soil map may result in lower variability of predictions as compared with clustering within arbitrarily defined areas of land. Further studies are needed to evaluate this type of use of existing soil maps.

Mapping units shown on soil maps at different scales, based on Taxonomy, are suitable as carriers of information on land evaluation, provided a measure is included for internal variability and its effect on the level of detail of predictions being made. There is a need to visualize degrees of variability to indicate the different nature of boundaries. One boundary may be discrete, while another may be completely different, or almost identical. It is recommended to use colors, line types, and other (printing) techniques which visually convey information on the degree of variability.

More research is needed on procedures and techniques for determination of optimal sampling which recognizes spatial and temporal variability. Soil survey programs should be initiated in this context to (1) apply nested sampling techniques within major mapping units on different scales, and (2) use of simulation modeling for expressing temporal variability in terms of the effect of considering different time periods.

## On variability

An understanding of the spatial and temporal variability of land qualities, defines limits of scientific acceptability. No commercial studies should be made which fall below what is scientifically acceptable.

The term variability often has a somewhat negative connotatien. However, variability of land qualities in space and time is crucial for some types of land use where variability in space helps to overcome effects caused by variability in time (e.g. multiple cropping farming systems, where many animals need a heterogeneous environment). Sometimes, this may imply that the suitability of a given area depends on the suitability of another area quite far away. Also, effects of variability in time can sometimes be overcome by effects of variability in space. Although these aspects of variability have been recognized, research is needed to develop a methodology to incorporate such variability effects into land evaluation systems.

On application of information technology

Cost effectivitess of information systems should be considered over a sufficiently long period to bridge the implementation phase and to allow a realistic definition of direct and indirect benefits.

On training

The gap between the level 2-3 and 4-6 approaches to determine land qualities appears to be particularly large and pressing in some developing countries. To bridge the gap, functional documentation of models, of associated data needs and of GIS are needed, preferably by non-commercial agencies.

All over the world land evaluators and field workers should be made familiar with information technology. Continuous training is required for proper and beneficial use of information systems in land evaluation. UNESCO-education service can help to provide such training programs.

On communication

Modern information technology easily generates excessive output. It is the responsibility of the land evaluator to critically screen this output and communicate results to the user in such a way that his requirements are satisfied. This should, however, always include a measure for the variability and the associated reliability of these results.

Non formalized knowledge and subjective information within land evaluation procedures may well be captured, in principle, within expert systems. However, creative use and expansion of existing data bases and interpretive systems may provide a simpler and cheaper means towards integrating non formalized knowledge and subjective information. Further exploration of the latter procedure should be encouraged.

# CLOSING REMARKS

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It is clear from the recommendations of the three working groups that much work remains to be accomplished on describing, analyzing, integrating and predicting land qualities in space and time. However, it has become obvious over the last few days that there is an optimistic, and even excited, perception among the individuals at this symposium that soil scientists, working in conjunction with computer scientists, geographers, statisticians and others can help design effective and meaningful solutions to both agricultural and environmental problems. Indeed, the excitement seems to arise from the realization that our message is getting through that soil science and the evaluation of land qualities must play a central role in environmental management as well as agricultural management. The problems and challenges that we face in estimating land qualities with space and time are obviously exciting to us, as they represent very clear opportunities to contribute to societal needs at all scales, and to be recognized and respected for that contribution.

As we respond to these opportunities, and face the associated challenges, there are a few particular issues I would like to raise for consideration. My own biases obviously color these remarks, but I have tried to develop them from objective reflections on the content of this workshop. I hope you keep a few of these issues in mind as you attempt to respond to the recommendations of the working groups in your future endeavors.

First, it is clear that we are going to continue to be confronted with problems at all spatial and temporal scales, from the global to the micro. In any particular case, our initial approach must be a careful definition of the problem, and the scale at which we wish to provide a response. It is especially important that we remain intellectually flexible in designing this response. We must recognize that different tools should be used to address different problems. In this context, we must weigh the relevance of our previous experience as each new problem is attacked. Experience at the microscale may in some cases be irrelevant at the larger scale, and vice versa. Each one of us should identify the limits of his/her own experience, and when venturing outside that experience recognize that some alteration of any previous approach may be necessary, be it the soil sampling methodology, pedotransfer function or type of simulation model. Intellectual flexibility in our approach is going to insure that we use the right tools for each task, and will insure as well that we provide useful and accurate answers.

Second, with respect to the attractive opportunities offered by geographic information systems, I offer a word of caution. I came to this meeting partially to learn more about GIS and its capabilities. While this objective was satisfied, I noted in a number of cases that GIS and its glorious graphical capabilities were perceived as ends in themselves, rather than as means to an end. If I attend the next meeting of this group a few years from now and see color maps of input data presented as the end product of the scientific endeavor, I will be

disappointed. I think we should all keep clearly in mind that GIS techniques are only tools, and while these techniques allow us to better communicate the results of our scientific analyses, it should be results of analyses that are presented, whether these results be modeling analyses, map overlay or some other synthesis and integration of data. Then, when we use the attractive GIS display to sell our scientifically-derived product, or to more effectively present complex answers, we are presenting a unique contribution of soil scientists, and not just a graphical engineering of the data base. Given the rapidly developing complexity of GIS systems, and the increasing opportunities for data analyses (e.g. fuzzy clustering, simulation modeling, geostatistical techniques), it is clear that no one of us will be able to do everything required. Team efforts are the only way to address such problems in the future. More is said about this below.

A third area worthy of mention is that of simulation modeling. There has been much discussion, and at times disagreement, about the role modeling can play in land evaluation efforts. Several comments have come to my mind during such discussions. First, it must be recognized that there are different models for different purposes. If we clearly define the (a) problem we wish to solve, (b) scale at which we will have to work to solve the problem, and (c) scale at which data can be available, then and only then will it be possible to consider the use of a model, and to select an appropriate model. We should accept the fact that simple models are not always the best. At times, no model should be used, and at times a very complex model can be used, depending upon the nature of the question asked and the availability of data and computer expertise. Second, it is important that we not compromise our science in the use of models. While we may wish to serve the needs and desires of our customers, we must make sure that they recognize that there is both an economic cost (in terms of developing data input) and a risk (in terms of uncertainty of prediction) inherent in the use of any model. We should not necessarily choose to use a simple model only because our client is unwilling to pay the cost associated with developing adequate input information required for the use of an appropriate model. Conversely, we must be responsible professionals, and identify modeling approaches that provide with minimum data requirements a quantitative estimate of system behavior with some indication of the uncertainty of the predictions. It is probable that a wide variety of modeling approaches will be needed to cope with the variety of problems that we wish to address. Reconciling the diverse needs of model users and the capabilities and interests of model builders is a challenge to us all.

Fourth, data is needed. This is perhaps the one point on which we all agree. Where soil surveys are available and accurate, they must be digitized. In other areas of the world, data gathering or the translation of existing soils data bases into transferrable and usable formats must be accomplished. Innovative sampling designs should be adopted to minimize the number of samples needed to characterize areas. Attention should be given to the development of pedotransfer functions that allow basic soil characteristics to be translated into estimations of soil properties for the next step of estimation of land quality. This development must be through a regular interaction between those individuals with field experience and the modelers and GIS specialists. That interaction and the exchange of ideas between these two groups is one of the strengths of this symposium, and is the only way that field truth and the exotic mathematics/computer science will be married. I congratulate each person here on their patience in dealing with the

"other side" during this symposium. I personally look forward to the interaction continuing.

Finally, it is incumbent upon all of us, whether we are involved in agricultural development activities in the third world, or environmental management issues in the developed world, to participate in and contribute to the evolution of land evaluation methodology. We all have different needs and capabilities, and simultaneously we all have a responsibility as soil or agricultural scientists to explore new methods of addressing our problems. There is need for input and guidance from all directions in the development of land evaluation methodologies. Only in this way will methodologies evolve which are flexible enough to meet all our needs, in both the developing and the developed world. Clearly there will need to be compromises. For example, modeling procedures must be developed that are appropriate for the limitations of a third world environment. Similarly, it may be necessary for everyone involved in land evaluation programs, because of the complexity of the problems, to have access to, and know how to use, a microcomputer.

In closing, I want to reiterate my good feelings at this time. The symposium has been extremely valuable in all respects, and provides a very sound and logical basis for us to move forward. The interactions I have had here have been open, honest and valuable exchanges. We owe a great thanks to Johan Bouma for conceiving and organizing this effort. We also should recognize the substantial energy expended by Arnold Bregt and the other Dutch scientists involved in organizational activities. Thanks to all, from all of us.

Finally, I would like to say thanks to all who attended. I look forward to meeting with you all again, and until then, I wish you well.

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