The use of pedotransfer in soil hydrology research in Europe

workshop proceedings

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A. Bruand
O. Duval
H. Wösten
A. Lilly
Editors
The use of pedotransfer
in soil hydrology research
in Europe

Proceedings
of the second workshop of the project
'Using existing soil data to derive hydraulic parameters for simulation
modelling in environmental studies and in land use planning'
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Preface

The workshop entitled 'The use of pedotransfer in soil hydrology research in Europe' is the second workshop of the project on 'Using existing soil data to derive hydraulic parameters for simulation modelling in environmental studies and in land use planning' which is funded by the European Commission under the Human Capital and Mobility (DG XII) program (CHRX-CT94-0639).

As this workshop marks a transition into the third phase of the project (data analysis and presentation of results) it was considered to be beneficial to use the workshop as a platform to draw on the experience of all project partners in the actual use of pedotransfer functions and rules. Thus giving a number of European scientists an opportunity to report and exchange their research findings on the use of pedotransfer in soil hydrology research in Europe. Section 1 of these proceedings contains a number of these papers highlighting previous work in this area of research.

During the first year of the project (1995), the emphasis was on developing a flexible database structure to hold a wide diversity of data related to measured soil hydraulic properties. This database is known as HYPRES; HYdraulic PRoerties of European Soils, the structure of which is described in Section 2.

The second year of the project (1996) was largely devoted to collating the data from the project partners across the whole of Europe and entering these data into the database. Section 3 contains a report on progress made during the year and on the subsequent workshop discussions. Now that the soil hydraulic properties of some 3000 soil horizons are stored in HYPRES, the emphasis during the last year of the project (1997) will be on deriving pedotransfer functions from these data for European soils. These functions will find application in a wide variety of research projects related to both agriculture and environment at the European scale.

Henk Wösten,
Project coordinator
Opening address

In the name of the members of the Soil Science Department of INRA, and particularly of the Soil Survey Staff of France in Orléans, we are very pleased to welcome all the participants to the workshop on the use of pedotransfer in soil hydrology research in Europe.

The main mission of the Soil Science Department is the scientific knowledge of soils and especially their physical, biochemical and biological functions as influenced by agricultural production. The three priority topics of our Department are:

- Soil and agriculture effects on pollutant behaviour and transfer,
- Soil use for sustainable agriculture,
- Soil-quality evaluation and protection.

The main research programmes are thus in the fields of:

- Hydrology and water quality,
- Biogeochemical cycles and pollutant behaviour in soils,
- Soil as a support of life: microbial ecology and soil/plant interactions,
- Soil as a natural resource: constitution and quality,
- The pedological cover: space organization, functioning, use, and protection.

These two last programmes cover research and applied activities which are:

- Relationship between soil structure, porosity and physical properties,
- Estimate of soil properties and their variability,
- Modelling soils distribution,
- Modelling soils functions at different scales (space and time),
- Development of new methodologies of soil survey for different purposes,
- Coordination of soil survey at the national level: scale 1:100.000 - 1:250.000,
- Management of the soil national database,
- Contribution to European equivalent activities.

The main objective of Orleans Research Unit, which specification is spatialization of soil, is to analyse the nature and structure of pedologic organizations at different levels of investigation, and to study their role in the functioning of specific systems selected for their scientific interest, scale transfer being studied for generalization possibilities.
The Orleans Research Unit consists of three groups which develop research activities as following:

- Researches on the role of mineral constituents (nature and fabric) on physical properties of soils and their behaviour (group ER1),
- Researches on soil spatial organization and modelling, and on functioning processes in landscape units (group ER2),
- More applied researches to elaborate management tools for space and natural resources at national and European levels, with help of computerizing (group ECG).

Each of those groups are working in their own domain, with specific methods, technics and collaborations. However, a great part of unit’s works is common to the three groups.

One of the most important activities of our staff since some years now is to work on the European Geographic Soil Database, in the framework of the European Soil Bureau, under the leadership of JRC Ispra. The present workshop deals with pedotransfer rules or functions deriving from a well structured database of hydraulic properties. We hope that it will be possible in the future to combine the two databases in order to rationally manage European lands.

As members of the Organizing Committee of the next World Congress, which will take place within 2 years now in Montpellier, we hope that this meeting will be a good preparation for the different Symposia that have been scheduled on those themes.

We wish a real success to the present Workshop, and hope that the numerous exchanges which will take place will be very fruitful for the future.

Finally, we thank Henk Wosten, Allan Lilly, Ary Bruand and the members of their respective groups who have organized this Workshop, and welcome all of you.

Pierre Stengel, Head of the Soil Science Department

Marcel Jamagne, Director of the Orleans Soil Science Research Unit
Section 1:

Workshop proceedings
The European Soil Bureau

Luca Montanarella

European Commission, Joint Research Centre, T.P. 440, 21020 Ispra (VA), Italy

Soil is one of the essential elements of the biosphere which necessitates a global policy for management, evaluation and conservation (Borlaug & Dowswell, 1994). To implement such a policy, it is necessary to have information harmonized both in space and time (ISSS, 1988).

The Commission is the originator of several programs aiming to acquire soil data (CEC-JRC, 1995). Associated with other sources of information (water, air, land management) these data are a valuable aid for decision support processes, in particular for the control of agricultural production (Vossen & Meyer-Roux, 1995), land management and environmental protection (Blum, 1990).

The program MARS (Monitoring Agriculture by Remote Sensing) initiated the development of a geographical database from the European Soil Map (Meyer-Roux, 1987). The Support Group "Soil & GIS", bringing together experts from different EU countries, has proposed a methodology and constitutes a scientific network for the acquisition and exchange of information (Burrill & King, 1993). The work was based on the material available from archives of the EC soil map (CEC, 1985) and previous FAO activities (FAO, 1965, 1975; CEC-ISSS, 1986). The computerisation of the map made in 1986 by the CORINE program was improved thanks to new contribution of all European countries. The final product is the 1:1,000,000 soil geographical database of Europe (King et al., 1997).

The development of this database was a good initiative to increase contacts between soil scientists, to exchange information across national borders and to create a first platform for decision makers. However this project also highlights the absence of strong co-ordination not only between countries, but equally between different Directorates-General of the Commission.

In order to remedy this lack, the Joint Research Centre (JRC) created in 1994 a Soil Information Focal Point (SIFP). Following the work and initiatives stimulated by the EEA Task Force, its mission was, on the one hand, to manage information elaborated...
at the 1/1,000,000 scale and on the other, to organize thinking on the Commission's future needs for soil data.

Three initiatives have been identified:

1. The creation of a coordination group from the Directorates-General of the Commission (Inter DG Group) which includes the European Environment Agency (EEA).

2. Support for a second meeting of Heads of Soil Survey and those responsible for management of databases in the EU (CEC, 1991a).

3. The creation of a working group termed "Soil Information System Development" (SISD) bringing together experts in soil science and information systems.

The Inter-DG Group has produced a report identifying the demand for soil information from the Commission (CEC-JRC, 1995). The report highlights the large requirement for soil information, both within the Commission and in external institutes and organizations. The requirement is presently expanding due to an increased focus on environmental issues and sustainable planning. However, much of this need is presently unmet. The required information is either non-existent, exists only at an unsuitable resolution, or is available only as incompatible and/or incomparable datasets from national (or regional) organizations.

The second meeting of the Heads of Soil Survey and those responsible for management of databases in the EU was held in Orléans in December 1994. Main recommendations of the meeting were (CEC-INRA, 1996) (1) the support for the ongoing process of updating the European geographical and analytical soil database corresponding to the 1:1,000,000 scale, (2) the establishment of the Soil Information System Development working group, (3) the need for a more detailed database in Europe at scale 1:250,000 and (4) the creation of a European Soil Bureau.

The Soil Information System Development working group produced in 1996 an important policy paper titled “European Soil Information Policy for Land Management and Soil Monitoring” (King & Thomasson, 1996) that sets guidelines for the future European soil information policy. It recommends the creation of a European Soil Bureau.

In June 1996, it was officially launched with the approval of delegates from the EU countries. Its functions were defined and working groups were carried out in the continuity of previous studies of the already active groups (Soil&GIS, SIFP, SISD).

The Bureau is established at the JRC Space Applications Institute within the Agriculture Information System Unit (AIS). The activities of the ESB are of an horizontal nature, but are located within the Environment and major natural hazards sector. The capacities of the Bureau will be build up over several years with the intention to reach full capacity by 1997/98. Participation of detached National experts within the ESB should be encouraged. By 1997/98 the Bureau will be a substantial centre of excellence capable of undertaking an extensive range of scientific and technical activities.
The major tasks assigned to the Bureau are:

- To serve as a point of contact for coordination of soil data needed for numerous purposes by the Commission or other external bodies.
- To respond to the needs of the Commission furnishing information necessary for programs of the DGs.
- To develop and implement a policy and guidelines for the production of harmonized, and therefore compatible soil data.
- To develop and implement a policy for the distribution of information concerning soils, with the objective of favoring exchange of data without compromising the interests of the producers.
- To develop and distribute the tools facilitating the exchange and use of soil data
- To establish links with international bodies, such as FAO and UNEP, in order to assure a reciprocal flow of information.

The Bureau is still evolving his organizational structure (Fig. 1).

At the end of 1996 it is organized as follows:

- A small Secretariat to co-ordinate and catalyze the activities of the Soil Bureau, providing technical support as required. It also provides logistic support for the other elements of the Bureau.
- An Advisory Committee composed of National representatives of each EU and EFTA Member State, observers from neighboring countries and International bodies. It is charged with evaluating and advising on the Bureau activities.

**Organization of the European Soil Bureau (status end 1996)**

![Diagram of the European Soil Bureau's organization structure]

Fig. 1. Organization of the European Soil Bureau.
• An Inter-DG Coordination Group on Soil Information representing the European Commission's services concerned with soil information. It collects the needs of the Commission for soil information and conveys these to the Secretariat for subsequent action.

• A Scientific Committee nominated by the Commission according to its specific needs and the objectives specified by the Advisory Committee. This committee operates by small Working Groups.

Currently active working groups are:

• Soil Geographical Database of Europe at scale 1:1,000,000 working group.
• Information Access working group.
• Georeferenced soil database of Europe at scale 1:250,000 working group.
• Soil Hydraulic Parameters working group.

This Advisory Committee is composed of one (Full Member) representative for each EU Member State carrying particular responsibilities for soil surveys and soil related policy. EFTA countries are also represented. Representatives from EU neighboring countries and International bodies are considered as observer Members. The Advisory Committee meets yearly. The following objectives are set for the Advisory Committee of the European Soil Bureau: evaluate the activity of the European Soil Bureau as a whole and then indicate formally that it is content with the achieved results, advise the Secretariat on the objectives to be achieved, indicate formally as a whole that it is content with the guidelines or resolutions prepared by the Secretariat, advise on strategic issues related to the implementation of the European Soil Bureau and the coordination and cooperation with National and international organizations, assure efficient communication between the European Commission/European Soil Bureau and the relevant National political bodies, assure the spreading of information to the interested parties in the Member States. The first meeting of the Advisory Committee was held the 13th of June 1996. The representatives of the EU Member States, from the EFTA Member States and from International Organizations reviewed the activities of the newly established European Soil Bureau. The policy documents (CEC-JRC, 1995) (King & Thomasson, 1996) where approved. Major recommendations of the Advisory Committee where: continuation of the on-going work on the updating the European geographical and analytical soil database corresponding to the 1:1,000,000 scale, importance of close collaboration with the newly established European Topic Centre on Soil, priority of the information access issues for data distribution, endorsement of the project for a future 1:250,000 soil geographical database of Europe.

The Inter-DG Coordination group on soil information collects the specific needs for soil information within the Commission. The European Commission is active in many fields involving soil information issues within the European Union and also outside the EU. The main EU policies that have an impact on soil information are the Common Agricultural Policy (CAP), the Environmental Action Programme (EAP), the Regional Policy and the Framework Program for research and technological development (RTD). The last meeting of the Inter-DG Coordination group finalized the document
«Soils information for Europe», published by the Commission (CEC, 1995; Burrill, 1996), which identifies the main priorities as follows:
(1) Increased accessibility of data.
(2) Increased usability of existing data.
(3) Standardization of methods and quality assurance.
(4) Development of new datasets at more detailed scales.
(5) Relation with the Member States

The Scientific Committee of the ESB is formed by European soil scientists nominated by the Commission. Chairman of the Committee is Dr. D. King of the INRA-France. The Committee meets regularly and is in charge of all the scientific and technical activities of the ESB. It translates the requirements and needs of the Member States and of the Commission into projects. It operates through small ad hoc working groups that are in charge of each single project. The Scientific Committee ensures that the work accomplished by the ESB is of high scientific standard. It evaluates regularly the scientific work carried out by the working groups. It approves the documents and guidelines to be submitted to the Advisory Committee.

The Secretariat of the ESB is located in Ispra within the Joint Research Centre (JRC). It is formed by a small nucleus of permanent staff and a number of non-permanent staff members, as National experts, Post-Doc's, Ph.D. students, etc.. The Secretariat is in charge of co-ordinating the various activities of the ESB. It gives the necessary technical and logistical support to the various committees and working groups of the ESB. It prepares the relevant documents, guidelines and resolutions to be submitted to the Advisory Committee.

The two policy documents recently prepared by the Secretariat and submitted to the Advisory Committee are:

Four working groups are currently active within the ESB:
- The 1:1,000,000 European soil database group has been operating for many years, well before the creation of the ESB. It has been the driving force of an European joint effort by many soil scientists from different countries. Chairman of the group is Dr. M. Jamagne (INRA - SESCPF).
- The Information Access Working Group (IAWG) turned out to be one of the most important within the ESB, as it is in charge of the development of an European policy for the access to soil databases. The issue of data ownership is one of the most delicate, as it touches relevant interests of each contributing institute of each country. The general aim of the group has been to develop guidelines that insure the maximum protection of the data ownership together with regulated access for all the potential data users. Chairman of the IAWG is Dr. R.J.A. Jones (Silsoe College, Cranfield University).
- The 1:250,000 working group represents the future of the ESB. It works at the design and construction of the new European soil database at scale 1:250,000. It has
been established following a feasibility study by the DG XI (Environment) 1993, that recommended the creation of such a database for future environmental applications within the EU. Chairman of the group is Dr. P. Finke (SC-DLO, Wageningen).

- The soil hydraulic parameters working group has been established independently of the ESB, financed through a Human Capital and Mobility Network. Only during its second year of work it applied for being included in the activities of the ESB, as it is concerned with a soil hydraulic parameters database linked to the 1:1,000,000 soil database of Europe. The database will be distributed in its final version through the ESB according to the same data access procedures. Chairman of the group is Dr. H. Wösten (SC-DLO, Wageningen).

![Map of Europe](image)

Fig.2. Extension of the Soil Geographical Database of Europe at scale 1:1,000,000 Version 3.2. In hachures are countries to be included by 1998.
The soil geographical database has presently four parts: (1) the meta-database, (2) the so-called geographical database, (3) the soil profile database, and (4) the knowledge database. The geographical extension (Fig. 2) covers currently (Ver. 3.2) the EU Member States (excluding Sweden, Finland and Austria) and the Central and Eastern European countries (Poland, Czech Republic, Slovakia, Hungary, Romania and Bulgaria). It can be accessed (read-only) on the World Wide Web through a GIS-WWW gateway and is reachable via the following address

http://taws08.jrc.it/gis-gateway/gateway_main.html

New EU countries and neighboring countries are expected to be included during the next years. A major challenge is to integrate the various databases (profile, pedotransfer rules, meta-database, reference catalogue, etc.) into a single European Soil Information System (EUSIS). It is expected to complete such a system by 1998 covering the complete EU and the Central and Eastern European countries (CEEC).

The continuation of studies at the 1/1,000,000 scale for the Eastern European countries (NIS) and the Southern and Eastern Mediterranean countries (SEMC) is foreseen after 1998 in close collaboration with FAO.

The Information Access working group developed the guidelines (Jones & Buckley, 1996) that are a major breakthrough in European data access policy. The key statement is that data ownership and copyright remain with the Contributor. This means that the data supplied to the ESB by the Contributors for the creation of the European soil database are owned by the Contributors and not by the Commission. On the other hand the principle of regulated access to the data by everybody is reinforced. The combination of these two statements produces a data access policy that maximizes database access and use and safeguards the intellectual property by the Contributors.

Licencier of all the soil data is the European Commission through its European Soil Bureau that becomes focal point for data licensing and distribution. Data are leased for a limited time and not sold. Pricing is according to a price matrix. Data to be distributed beginning 1997 are the Soil Geographical Database of Europe Ver. 3.2 and the Soil profile Database of Europe Ver. 1.0. The adopted price matrix differentiates the cost of lease of data according to the use. Minimum charge (cost of handling) is applied to Contributors and non-profit organizations for internal use. Charging is required in the case of external use by these organizations. Maximum charging is applied to full commercial uses by private organizations.

The 1:250,000 Georeferenced Soil database of Europe project started after a feasibility study by the Directorate General XI (Environment) prepared by R. Dudal, A. Bregt and P. Finke in 1993. This study was commissioned to meet the still growing demand for soil parameters in environmental context - for which assessment on levels of regions or watersheds seems most appropriate - and to support the databases already developed by CORINE, e.g. on land cover and biotopes at a 1:100,000 scale. Direct contact to national soil surveys and land research centres of the former 12 EU Member States demonstrated that the national coverage of soil mapping at scale appropriate for a more detailed soil map ranged from 10% to 100%. However in all countries, some areas where found with coverage sufficient to be converted into a 1:250,000 soil map through generalization, eventually complemented with some additional fieldwork.
Special attention was paid to soil and terrain attributes which need to be recorded in term of environmental protection. Given the low availability of soil data suitable for preparing a more detailed soil map of Europe, it was determined that “a wall to wall soil map” or soil database could be accomplished only in the long term, but a recommendation was maid to carry out studies in small pilot zones with a high coverage of data, with the aim to develop a methodology, a common legend and a common database useful for the final database at scale 1:250,000. This principle was endorsed also by the European Environment Agency (Scoping study on establishing a European topic centre for soil, DGGU Service Report no. 47, 1995). In order to start the project, a working group was created within the ESB. It is charged with the preparation of the Manual of Procedures, the delineation of the pilot areas and the overall scientific supervision of the project. From the operational point of view the database will be created in selected pilot areas coordinated by regional co-ordinators for territorial correlation of each project (Fig. 3). The selection of the first pilot area already started with the delineation of an area covering the North-Italian quaternary plains. Project leader for that area is R. Rasio (ERSAL-Lombardia).

**Fig.3. Organization of the 1:250,000 soil database of Europe project.**

The preparation of the Manual of Procedures (tentative title: “Georeferenced soil database at scale of 1:250,000, towards a rational use of soil resources”) will proceed with the compilation of a first draft by February 1997. At the same time a draft soil regions map of Europe at scale 1:5,000,000 will be prepared. This map will be the basis for the delineation of the pilot areas of the project. A revised second version of the manual will then be submitted to the Scientific Committee of the ESB. The incorporation of the comments by the Scientific Committee will lead to the third draft edition to be submitted to the Advisory Committee. After approval by the Advisory Committee the Manual will be published as Version 1.0. At this stage regional co-ordinators will be nominated and the first pilot areas finally delineated. Experience gained during implementation of the Manual of Procedures will be incorporated in subsequent versions of the manual.
The general concepts and the structure of the database are still under discussion. Preliminary proposals suggest a relational structure being composed of objects: soil bodies (themselves subdivided into horizon bodies), soilscape and soil regions. Soil bodies are defined by the FAO 1990 classification, the parent material, the depth to obstacle to roots and the dominant texture. The soilscape should be a grouping of contiguous soil bodies in a watershed subbasin. This means that a soilscape containing a characteristic grouping of soil bodies may be split on a map when the soilscape covers more than one bordering watershed subbasin. Soil regions are delineated on a 1:5,000,000 map of Europe on the basis of parent material for the definition of major classes of soil regions, and subsequently a combination of texture, parent material and main relief to define and delineate soil regions.

The 1:250,000 project presents several aspects of great interest to National, Regional and Local administrations. Therefore already one pilot area (the quaternary plains of Northern Italy) generated some interest by the Regional administrations. Preliminary discussions showed great interest by the concerned administrations for the creation of a consortium of North Italian Regions for such a project. This could be a demonstration case for similar actions in other parts of Europe.

The last working group established within the ESB is the Soil Hydraulic Parameters working group lead by Dr. Henk Wosten. This working group has been originally established in the frame of the HCM (Human Capital and Mobility) program as a research network aiming at the establishment of a database of soil hydraulic parameters for the major European soils, linked to the 1:1,000,000 database. As this project is closely related to the activities of the ESB, the members of the group joined the ESB as a new working group with the main purpose of a better integration of the two databases.

In conclusion, the European Soil Bureau, established in Ispra at the JRC in 1996, can now be considered operational. It essentially collects soil information needs by the Member States through its Advisory Committee and by the European Commission through the Inter-DG Coordination Group on Soil. It transfers these needs and requirements to its Scientific Committee. The Scientific Committee translates these requirements into structured projects and establishes specific working groups charged with the scientific and technical tasks required. The resulting products (databases, guidelines, etc.) are then distributed to the European user community through appropriate information access procedures.

References


The use of pedotransfer in soil hydrology research in Europe.
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The 1:1,000,000 soil geographical database of Europe

D. King¹, J. Daroussin¹, M. Jamagne¹, C. Le Bas¹ and L. Montanarella²

¹ INRA-SESCPIC, Centre de Recherche d'Orléans Ardon 45160 France.
² JRC-ESB, Ispra 21020 Italy.

Abstract

This paper summarizes the different stages of the elaboration of the 1:1,000,000 soil geographical database of Europe. It focuses on the potential use of this information and its limits. This information is presently an important source of data for agriculture and environmental projects. However, the authors highlight the need for more precise spatial and temporal data. They also suggest increasing exchange of information within Europe as a whole. Finally, they present two new European bodies which should improve the harmonisation of soil activities in Europe.

Introduction

In Europe, as well as in the rest of the world, a thorough knowledge of soil use and soil protection is of vital importance. The European Commission, in particular its Directorates General of Agriculture (DG VI), Environment (DG XI) and Research (DG XII), has supported several programs with this objective in mind. The last major co-ordinated activity for soil information in Europe is the elaboration of the 1:1,000,000 soil geographical database. This information is now available thanks to many previous projects.

The first objective of this paper is to describe this database after a review of the previous work which brought it to its present status. The second objective is to summarize the activities following the elaboration of this database. Its use indicates the need for more precise information and the necessity to promote a better harmonisation of soil information in Europe. Considering the needs of the EU Commission and the
new European Environment Agency, two organisations were created in 1996 for the management of soil information. Their structure and aims are summarized in the last part of this paper.

Background

A knowledge of soil distribution within a given area is one of the basic requirements for natural resources evaluation. At a European scale, two main programs have required such knowledge:

- in the domain of agricultural production (DG VI): use of the 1:1,000,000 Soil Map of EC after an abortive attempt by the FAO;
- in environmental domain (DG XI): within the CORINE program.

Actions of FAO and EU Directorate VI (Agriculture)

From 1952, studies were made of the different soil classification systems in Europe, with a view to the eventual harmonisation and common usage. The first result was the publication of the FAO soil Map of Europe at scale 1:2,500,000 (FAO, 1965). During the seventies, work continued on the Soil Map of Europe at scale 1:1,000,000 under the auspices of the FAO. The legend was designed at the same time as that of the World Soil Map at scale 1:5,000,000 and was published in 1975 (FAO, 1975). Because of financial problems, the work was stopped by the FAO and the map was never published. In 1978, the European Commission decided, with the agreement of the FAO, to revive the work for the countries of the European Communities. The final Soil Map of the EC was published at scale 1:1,000,000 in 1985 (CEC, 1985). In 1986, the territories of Austria and Switzerland were added to the map on the initiative of UNESCO and the International Soil Science Society (CEC-ISSS, 1986).

Actions of EU directorate XI (Environment)

The main objective of CORINE (DG XI) was the creation of a Co-ordinated Information System on the state of the Environment and Natural Resources of the European Communities. This implied the setting up of an homogeneous framework for the collection, storage, presentation and interpretation of environmental data in EC countries (Briggs and Martin, 1988).

The CORINE program resulted in the digitisation of the EC Soil Map in 1986, constituting the first spatial soil database (version 1.0). This work consisted of digitising contours and indicating the number of the corresponding soil association and the nature of the possible phase for each polygon (Platou et al., 1989). No more data were used than were drawn on the map.

The first version of the database was soon applied to two major problems that required the use of multi-parameter combinations: a map of the Buffering capacity (Chadwick and Kuylenstierna, 1990) and a zonation of the southern part of the EC in terms of susceptibility of soil to erosion, associated with another zonation dealing with land quality (Giordano et al., 1995). Other uses of this information were attempted and
were not necessarily published but the number of studies remained few (Jamagne et al., 1994).

**Actions of the Joint Research Centre through the MARS project**

In 1987, the Commission launched a new program to estimate crop surfaces in Europe and to monitor them by using remote sensing (Meyer Roux, 1987): This is the MARS program of the DG VI (Monitoring Agriculture by Remote Sensing) which was set up by the Joint Research Centre in Ispra (JRC-Ispra). As it is important to have continuous monitoring of crop growth, it was decided to complement the remote sensing with agrometeorological models (Vossen and Meyer-Roux, 1995). Therefore, this methodology led to request soil and climate data.

The soil data contained in the digitised EC map were insufficient to supply values to the parameters needed by agrometeorological models. The Soil and Geographical Information System (Soil & GIS) support group was created to improve the database associated with the EC soil map (Burrill and King, 1993). The program was enlarged to encompass environmental needs in the framework of the European Environmental Agency Task Force of the DG XI.

**Method to elaborate the 1:1,000,000 Soil Geographical Database of Europe**

The first action of the Soil & GIS support group created by the MARS program was to list the parameters required by the main EU projects. After that, it investigated what type of soil parameters could be made available from existing soil maps or soil databases in Europe. For example, for the Soil Water Available for Plants, the so-called SWAP parameter, Thomasson (1995) reported different levels of information according to the level of complexity of the models used. Generally, the requested parameters for this range of models are not described in soil maps. This result is highlighted by Magaldi (1995) who described the state of progress of soil mapping in Europe. Furthermore, each country has developed different methods for soil surveys at various scales and objectives. Finally, the percentage of mapped areas in each country is very different from one country to another, and for many countries this percentage is less than 30%. The only common level for the European Communities was the 1:1M scale EC soil map.

**Available material at the EU level: the EC soil map**

The initial objective of the authors of the EC soil map was to have a basic common language for Europe. They wanted to harmonise pedogenetic concepts according to the FAO legend (1975) but they also wanted to define agronomic constraints (Tavernier, 1985). At that time, GIS techniques did not exist, and the task was oriented towards the publication of a conventional map. This led to many difficulties in extracting soil parameters for modelling.
The first problem was that the data on the paper map were limited to the "FAO soil name" and the "phase" i.e. the agronomic constraint coding; secondly, the main variable chosen to harmonise and publish this map was the FAO soil name of the predominant soil unit within soil associations. In using a soil taxonomy, all soil characteristics (e.g. texture, soil depth for the predominant soil unit and especially all the characteristics of the secondary soil units) were completely ignored. It has now become impossible to re-extract this information from the map for various purposes. Computerisation of the soil map in 1986 did not improve the information since only data found on the published map were digitised.

**Improvement of the version 1 by using archives and new information**

The Soil & GIS group suggested to going back to the primary information. The method is composed of three steps according to the facilities to get the data. The easiest data to obtain are the archives used to elaborate the EC Soil Map. The two other sources of information come respectively from the national experts and from the basic measured data of analytical soil profiles (JRC, 1995).

**Improvement from the FAO archives**

The archives of the EC soil map were stored in the University of Ghent in Belgium by R. Tavernier, co-ordinator of the work (table 1). Due to a good harmonisation of the preliminary mapping activities, it was easy to extract the main soil variables. This information was computerised and the digitised soil map was updated (King et al., 1994). The result is called version 2.0. 65 % of the soil mapping units were completely changed during this stage and all soil mapping units received new attributes. Very important variables were added in this second version such as parent material. Furthermore, data were added for each soil typological unit within soil associations over and above that of the dominant soil.

<table>
<thead>
<tr>
<th>Map Unit number</th>
<th>Soil Typological Unit (FAO)</th>
<th>% Area</th>
<th>Texture</th>
<th>Slope</th>
<th>Phase</th>
<th>Elevation (m)</th>
<th>Parent material</th>
<th>Land use</th>
</tr>
</thead>
<tbody>
<tr>
<td>42</td>
<td>Bd</td>
<td>90</td>
<td>2</td>
<td>c</td>
<td>Stony</td>
<td>300-600</td>
<td>Residual stony loam from schists</td>
<td>Forest, pasture, arable land</td>
</tr>
<tr>
<td></td>
<td>I</td>
<td>5</td>
<td></td>
<td></td>
<td>lithic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bgg</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>57</td>
<td>Lgs</td>
<td>75</td>
<td>4</td>
<td>c</td>
<td>Stony</td>
<td>250-400</td>
<td>Residual loamy clay of marl</td>
<td>Arable land, pasture, forest</td>
</tr>
<tr>
<td></td>
<td>Lo</td>
<td>10</td>
<td></td>
<td></td>
<td>lithic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Be</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>L, Ge</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>58</td>
<td>Qi</td>
<td>80</td>
<td>1</td>
<td>c</td>
<td>Stony</td>
<td>300-450</td>
<td>Residual sand of sandstone</td>
<td>Forest, arable land</td>
</tr>
<tr>
<td></td>
<td>Lo</td>
<td>10</td>
<td></td>
<td></td>
<td>lithic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pb</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Lo</td>
<td>75</td>
<td>2</td>
<td>c</td>
<td>Stony</td>
<td>250-380</td>
<td>Residual stony loam</td>
<td>Pasture, arable land</td>
</tr>
<tr>
<td></td>
<td>Be</td>
<td>25</td>
<td></td>
<td>c</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Updates by national experts

This first stage was still insufficient to obtain the required information for agrometeorological modelling. It was decided to go back to the soil scientists who gathered the basic data for the map. Two alternative approaches were suggested. The first one was the development of a soil knowledge database with the support of the DG XI (Van Ranst et al., 1995; Jones and Hollis, 1996). The idea was to formalise, as an expert system, the knowledge used to estimate unknown soil parameters from soil variables stored in the database. These estimations were called pedotransfer rules in reference to the concept of pedotransfer functions (Bouma and Van Lanen, 1986).

The second approach was to update the soil mapping units in order to improve the description of soil variables, because those that are stored in the archives and version 2.0 are very old. For this, version 2.0 was sent to all national correspondents asking for an update of the attribute values as well as of the graphic of soil boundaries. New attributes were added: depth of an obstacle to roots, depth to textural change, water regime, etc. (INRA, 1995) This final version is called version 3.1. The last task, which is in progress, is the harmonization across national borders.

Soil profile database

In order to have reliable data, the database was finally improved with basic soil profile data (Madsen and Jones, 1995). For each dominant soil unit, a representative soil profile was collected with main analytical data. Standard formats were developed for harmonising the various analytical methods in Europe.

Structure of the 1:1 M Soil Geographical Database of Europe

The soil geographical database has presently four parts (Fig. 1): (1) the meta-database, (2) the so-called geographical database, (3) the soil profile database, and (4) the knowledge database.

The meta-database is still under construction. The objective is to gather information on the references of pedological studies in Europe. The expected meta-database should provide a catalogue where users could find the localisation of detailed national maps. An earlier program was carried out (CEC, 1991) but no update has been made for ten years.

The geographical database lies at the heart of the system. It includes the list of the Soil Typological Units (STU) i.e. all soil types within the European Union which were identified within the FAO-UNESCO legend (1975) and revised by the CEC (1985). The non spatial attributes of STUs are described by an harmonized coding system: FAO soil name, parent material, slope, phase, topsoil texture class, textural differentiation, subsoil texture depth, depth to an obstacle to roots, presence of an impermeable layer, water regime, water management. From a geometric point of view, STUs generally are too small to be drawn on a map at the 1:1,000,000 scale. They are clustered in Soil Mapping Units (SMU) which are defined by contour lines and polygons. The "object SMU" is clearly related to the concept of soil association (Simonson, 1971).
The third part of the database contains soil profiles with physical and chemical analysis. The difficulties involved in the harmonisation of all the various analytical methods led to the adoption of two data formats. The first is for measured data which come directly from real georeferenced profiles. A code enables storage of the analytical methods used and missing values are accepted. The second format stores estimated data. The analytical methods are fixed for comparison of the values throughout the various countries of Europe. In this second format, all attributes must be estimated. About 300 soil profiles are currently available (table 2) but more are expected in the near future.
Table 2. Availability of soil profile proformas (Madsen and Jones, 1996)

<table>
<thead>
<tr>
<th>Country</th>
<th>Proforma 1 Estimated data</th>
<th>Proforma 2 Measured data</th>
</tr>
</thead>
<tbody>
<tr>
<td>UK including Scotland</td>
<td>64</td>
<td>90</td>
</tr>
<tr>
<td>Denmark</td>
<td>9</td>
<td>8</td>
</tr>
<tr>
<td>Belgium</td>
<td>34</td>
<td>34</td>
</tr>
<tr>
<td>France</td>
<td>118</td>
<td>0</td>
</tr>
<tr>
<td>Germany</td>
<td>69</td>
<td>50</td>
</tr>
<tr>
<td>Italy</td>
<td>21</td>
<td>17</td>
</tr>
<tr>
<td>Netherlands</td>
<td>20</td>
<td>19</td>
</tr>
<tr>
<td>Spain</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Luxembourg</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>Greece</td>
<td>0</td>
<td>19</td>
</tr>
<tr>
<td>Portugal</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ireland</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

The last part of the database contains the pedotransfer rules. These are simple deductive rules that help in estimating new soil parameters from the available data. This fourth part looks like an expert system constructed from expert evaluation by soil scientists and from literature (table 3). Rules are applied at the STU level and values are mainly qualitative. Such a knowledge database formalises the empirical interpretations that are always made by using soil maps. The main advantage of this system is the possibility of updating in the light of new knowledge.

Table 3. Standard table for describing a pedotransfer rule.
The columns on the left correspond to values taken by input attributes describing the Soil Typological Units. The central columns provide estimated values and their confidence level i.e. the expert uncertainty. The right-hand columns contain management attributes: author, date of last update, marker for access to explanatory notes. The lines indicate the possible occurrence of the rules, based on the values (or combinations thereof) for the input attributes in the geographic soil database.

<table>
<thead>
<tr>
<th>Input attributes</th>
<th>Output attributes</th>
<th>Reference attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regional Codes</td>
<td>Class</td>
<td>Confidence level</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>Authors</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>Date</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>Notes</td>
</tr>
<tr>
<td>....</td>
<td></td>
<td></td>
</tr>
<tr>
<td>n</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Recommendations for using the data

If spatial values for a soil parameter have to be estimated, then there are several ways of doing this. If the soil parameter is directly included in the description of the STU, the data can be directly extracted and used for modelling. If the soil parameter is not one of the STU attributes, it can be estimated from the knowledge database in many cases. If a representative soil profile exists within an STU, quantitative values can be estimated for this soil parameter. For example, if an agrometeorological model needs the SWAP parameter and there is no value for this parameter in the STU file, then one can use either the knowledge database to get a qualitative estimation per STU, or use the soil profile database to directly obtain a quantitative local value. Comparison between the two methods will help to highlight the largest discrepancies where it will be necessary to get more information from regional soil survey.

It was seen before that the main objective of such a database is to deliver parameters for modelling and also to produce derived maps. Most of the SMUs are complex associations and it is difficult to manage this variability on maps. However, it is easy to compute models at the level of the STUs. For example, by using all STUs within each SMU instead of only the predominant STU in a water balance mode, the errors involved decrease by 20% (Ngongo et al., 1993).

As a final stage, it is generally necessary to produce maps, either directly from the database (with or without the knowledge database), or indirectly as outputs of models. For example, in order to draw the SWAP parameter over the EU, three classes are chosen: high, medium and low. Only the dominant class within an SMU can be shown. However, in places, this dominant value is less than 50% of the total area of a SMU! In order to avoid erroneous interpretation, an automatic process draws a second map, called « purity map », showing the percentage of the area represented by the dominant STU on the first map (Fig. 2). Furthermore, attributes and rules needed to derive the SWAP attributes are the results of expert knowledge and are not necessarily 100% reliable. Therefore it was proposed to add confidence levels to each STU and each rule. Four classes are proposed, ranging from "high", via "medium" and "low" to "very low". To warn the users against improper use of pedotransfer rules, it was decided that the confidence level of an output value should be the lowest of the confidence level of the input attributes and their corresponding occurrences. The resulted confidence level can be mapped showing the reliability of the SWAP values (Fig. 2). For decision makers, these two kinds of maps (the purity and confidence level maps) will be as important as the primary requested map (here, the SWAP map).

Conclusion and perspectives

A usable Soil Geographical Database at 1:1,000,000 scale is available at the EU level and several projects currently require this information. The information in such a database is regularly updated when new knowledge becomes available or when new territories are added. Management of this information is undertaken by the European Soil Bureau which should ensure the quality control of the updates and will administer
the licensing of the data to users. Accessibility and usability of data are two important points for the future of this database.

![Map showing purity of mapping units for water storage capacity.]

![Map showing confidence level for water storage capacity.]

**Fig. 2. Examples of a purity map and a confidence level map**

The development of the 1:1,000,000 European Geographical Soil Database has helped to increase contacts between soil scientists, to exchange information across national borders and to create a first platform for decision makers. However this project also highlights the absence of strong co-ordination not only between countries, but equally between different Directorates-General of the Commission. In order to remedy this, the Joint Research Centre (JRC) created a Soil Information Focal Point (SIFP) in 1994. Following the work and initiatives stimulated by the EEA Task Force, its functions were to organise thinking on the Commission's future needs and to suggest initiatives for a better harmonization of soil science activities in Europe.
Four complementary initiatives were proposed: (1) the continuation of studies at the 1:1,000,000 scale for states bordering the EU, (2) the setting up of a geographical soil information system at 1:250,000 scale for technical exchanges with states and regions, (3) the setting up of a long term soil monitoring program within Europe and (4) the creation of a European Soil Bureau.

The European Soil Bureau was approved during the second meeting of Heads of Soil Survey (INRA-JRC, 1996). It was officially launched in June 1996 with the approval of representatives of the EU countries (Montanarella, 1997). Its functions were defined and working groups were established based on the activities of existing groups in order to ensure continuity.

The role of the European Soil Bureau has been extended to promote a better harmonization of EU soil programs. The various active groups (Inter-DG group, advisory committee, scientific working groups) acting within the ESB provide opportunities to exchange ideas and develop new programs. One of the priorities is to elaborate a 1:250,000 soil database. Although building on the work done for the 1:1,000,000 database it should use new methods in order to develop a more flexible and reliable information. Digital Elevation Model, Remote Sensing and Geographical Information System are the main techniques which would be integrated in this future project.

Soil monitoring will be the responsibility of the European Topic Centre on Soil. The objectives are limited to environmental problems, but this action will be complementary to the soil mapping activities. Coordination has already begun by the mutual exchange of representatives of both scientific working groups and administrative committees. The ESB and the ETC-Soil will provide a useful means of informing on and coordinating the activities within other EC programs.

The challenge for these two new European bodies is to organise the collection of ad-hoc soil information essential for the future needs. Basic data are certainly indispensable but currently lacking. It will also be necessary to increase the knowledge of soil processes in order to predict phenomena, this will certainly involve research programs on modelling.

Acknowledgements

The present paper is not the result of a personal activity but it is a summary of numerous activities on soil information in Europe thanks to a large collaboration. It will be too long to mention the names of the members of all working groups that have been acting for European soil information during the last years. The authors thank particularly the members of the Soil & GIS Support Group, the Inter-DG group and the SISD working group without forgetting the PHARE committee and the ESB advisory Committee. Many activities were financially supported by the EU Commission through the Directorates VI, XI and XII. The authors wish to express their sincere thanks to Dr P. Vossen, A. Burrill and J. Meyer-Roux of the MARS project in JRC-Ispra for support, help and advice.
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FAO. 1965. Carte des sols d'Europe au 1/2.500 000.

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A pedotransfer rules database to interpret the Soil Geographical Database of Europe for environmental purposes

J. Daroussin and D. King

I.N.R.A., Centre de Recherche d’Orléans, Unité de Science du Sol
45160 Ardon, France

Abstract

A Soil Geographical Database of Europe is established at the scale of 1:1,000,000 to be used mainly in contexts of crop monitoring or environmental protection. Such applications need specific soil attribute information (e.g. Soil Depth) which is not always directly available from this database. However this needed information can be derived from that available in the database (e.g. from Soil Name, Parent Material and Phase), by means of pedotransfer rules. These are based on expert judgement, mainly qualitative, and assume that a due weight is given to the confidence level of individual inferred attributes.

A set of tools was conceived within Arc/Info to manage and use a rules database for the inference of new information from that available within any Info database. These tools may be considered as a prototype of an expert system shell and were used in the above context. Several hundreds occurrences of rules were established by a European working group in the form of IF <condition> AND <condition> ... THEN <inferred value>. At this stage, although rules are applied to spatial objects (soil units), the system does not take spatial relationships between objects into consideration.

1. Introduction

Problems on land use and soil conservation require increasingly accurate information on soil properties and their geographical location. An important point is to obtain harmonized data over the diversity of the regions of concern. For the territory of the European Union, the Commission has suggested different approaches over the past twenty years. One of these has been the publication of the EC Soil Map at scale...
1:1,000,000 (CEC, 1985), and then its digitisation (Platou et al., 1989; INRA, 1990; King et al., 1993). The current Soil Geographical Database of Europe version 3 provides some answers to the above problems, thus helping in general decision making, but not sufficiently to answer some specific demands, particularly those concerned by environmental problems. Much of the needed information is missing although it is implicitly present into the actual data.

The Directorate General for the Environment of the European Union (DGXI) asked to draw up procedures to facilitate the use of the Soil Database. This paper presents a method based on the concept of pedotransfer function (Bouma and Van Lanen, 1986) but adapted to interpret the qualitative information available in the database to data needed for such environmental purposes. A European working group of soil scientists reached some consensus in the definition of a set of pedotransfer rules that are grouped into a knowledge database, and tools were developed to manage and make use of this knowledge to interpret the Soil Database. Advantages of the method are that interpretations are explicit and can themselves be updated whenever necessary either if the Soil Database or the interpretation knowledge are improved.

First, we will examine the attributes used for input to the system and those that are output from the system. Then, we will describe the typical structure of a rule, its computer-based implementation with details on the methodological choices adopted and the tools developed.

2. The input and output attributes

2.1 - Input attributes

Most of the attributes presently input to the pedotransfer rules are those of the Soil Geographical Database of Europe. Its structure is fully described in INRA, 1990. For simplicity we will only say that the soil map is made of polygons grouped into Soil Mapping Units (SMU) (Arc/Info "region" concept). SMUs are complex units of soils which in turn are semantically (not geographically) sub-divided into Soil Typological Units (STU) holding the full description of each soil type present on the map (King et al., 1994).

Pedotransfer rules are applied at this last STU level (table 1). One should note that this database structure implies that a mechanism be planned for to take into account the "complexity" of SMUs whenever a thematic map is to be displayed for attributes of the STU level (concept of "purity" of SMUs).

Moreover the internal spatial variability of typological units is described in the Soil Database for some of the attributes but is not considered in the present work. Only the dominant value over the STU is used. In a future work tests of pedotransfer rules' sensitivity to intra-unit variability could be made.

Some required input attributes to the rules could (elevation, slope, land use, ...) or must (temperature) come from external data sources. This implies the combination (overlay) of the Soil Database with the geographical database of such external attributes.
Table 1. List of attributes of the Soil Geographical Database of Europe and external sources used as input to the pedotransfer rules:

<table>
<thead>
<tr>
<th>Input attributes</th>
<th>Input classes</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAO Soil name (SN)</td>
<td>cf. (FAO, 1975) and (CEC, 1985)</td>
</tr>
<tr>
<td>Topsoil texture class (TEXT)</td>
<td>1 Coarse</td>
</tr>
<tr>
<td></td>
<td>2 Medium</td>
</tr>
<tr>
<td></td>
<td>3 Medium fine</td>
</tr>
<tr>
<td></td>
<td>4 Fine</td>
</tr>
<tr>
<td></td>
<td>5 Very Fine</td>
</tr>
<tr>
<td>Slope (SL)</td>
<td>a Level (0-8%)</td>
</tr>
<tr>
<td></td>
<td>b Sloping (8-15%)</td>
</tr>
<tr>
<td></td>
<td>c Moderately steep (15-25%)</td>
</tr>
<tr>
<td></td>
<td>d Steep (&gt; 25%)</td>
</tr>
<tr>
<td>Parent Material (PM)</td>
<td>cf. (CEC, 1985), (INRA-JRC, 1993)</td>
</tr>
<tr>
<td>Phase (PHASE)</td>
<td>cf. (CEC, 1985)</td>
</tr>
<tr>
<td>Land Use (U1)</td>
<td>cf. (INRA-JRC, 1993)</td>
</tr>
<tr>
<td>Elevation (ZMIN, ZMAX)</td>
<td>in meters</td>
</tr>
<tr>
<td>Surface percentage of STU within SMU (PC)</td>
<td>% STU/SMU</td>
</tr>
<tr>
<td>Regrouped accumulated mean annual</td>
<td>H: High (&gt; 3000°C)</td>
</tr>
<tr>
<td>temperature class (ATC) (source: JRC-MARS)</td>
<td>M: Medium (1800-3000°C)</td>
</tr>
<tr>
<td></td>
<td>L: Low (&lt; 1800°C)</td>
</tr>
</tbody>
</table>

2.2 - Output attributes

Output attributes were selected on the basis of the environmental parameters needed for the problems faced, e.g., hydrology of soil types for predicting catchment response to rainfall and standard percentage of run-off; location and sensitivity of wetlands; soil buffering capacity for predicting soil susceptibility; ecosystem and surface water deposition; vulnerability of ground- and surface-water to pollution by agrochemicals and farm waste; soil erosion potential, etc.

The output attributes selected for this work are listed in table 2. They are grouped into four classes that respectively correspond to attributes of biological, chemical, mechanical and hydrological nature. Some of them can be derived directly from the Soil Database via pedotransfer rules, others need previously derived attributes as input.

For each output attribute, we have indicated the necessary input attributes for making the estimates. We also indicate the values of the classes adopted at the output. They were fixed in a rather broad manner, in view of the low level of precision in the input attributes. The thresholds selected for class intervals are resulting from a compromise between currently established values in the Soil Science, and the possible level of precision at this scale. The adopted values may not correspond to the thresholds necessary for environmental problems. However, multiplication of the number of classes certainly would have reduced the reliability of the pedotransfer rules and thus the system would become unusable.
Table 2. List of selected output attributes from pedotransfer rules with their required inputs.

<table>
<thead>
<tr>
<th>Output attributes</th>
<th>Input attributes</th>
<th>Output classes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BIOLOGICAL ATTRIBUTES</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Topsoil organic carbon content (OC_TOP) (0 - 25 cm)</td>
<td>SN - FAO soil name</td>
<td>H(high): &gt; 6.0%</td>
</tr>
<tr>
<td></td>
<td>TEXT - Topsoil textural class</td>
<td>M(medium): 2.1-6.0%</td>
</tr>
<tr>
<td></td>
<td>USE - Regrouped land use class</td>
<td>L(low): 1.1-2.0%</td>
</tr>
<tr>
<td></td>
<td>ATC - Accumulated mean temp.</td>
<td>V(very) L(low): &lt; 1.0%</td>
</tr>
<tr>
<td>Presence of a raw peaty topsoil horizon (PEAT)</td>
<td>SN - FAO soil name</td>
<td>Y(Yes)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N(No)</td>
</tr>
<tr>
<td><strong>CHEMICAL ATTRIBUTES</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil profile differentiation (DIFF)</td>
<td>SN - FAO soil name</td>
<td>H(high) differentiation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>L(low) differentiation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>O: No differentiation</td>
</tr>
<tr>
<td>Profile Mineralogy (MIN)</td>
<td>SN - FAO soil name</td>
<td>(C)hemical or Geochemical</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(M)echanical or Physical</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(M)echanical or Physical</td>
</tr>
<tr>
<td>Topsoil Mineralogy (MIN_TOP)</td>
<td>PM - Parental material</td>
<td>KG: 1/1 minerals + quartz</td>
</tr>
<tr>
<td></td>
<td>MIN - Profile Mineralogy</td>
<td>KK: 1/1 minerals + oxides &amp; Hy.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MK: 2/1 and 1/1 minerals</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M: 2/1 and 2/1/1 non swelling m.</td>
</tr>
<tr>
<td>Subsoil Mineralogy (MIN_SUB)</td>
<td>PM - Parental material</td>
<td>MS: Swelling and non s. 2/1 m.</td>
</tr>
<tr>
<td></td>
<td>MIN - Profile Mineralogy</td>
<td>S: Swelling 2/1 minerals</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TV: Vertic materials</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TO: Andic materials</td>
</tr>
<tr>
<td>Topsoil Cation Exchange Capacity (CEC_TOP)</td>
<td>DIFF - Soil profile differentiation</td>
<td>L(low): &lt; 15 cmol(+)/kg−1 soil</td>
</tr>
<tr>
<td></td>
<td>MIN - Profile Mineralogy</td>
<td>M(medium): 15-40</td>
</tr>
<tr>
<td></td>
<td>OC_TOP - Topsoil organic carbon content</td>
<td>H(high): &gt; 40</td>
</tr>
<tr>
<td></td>
<td>TEXT - Topsoil textural class</td>
<td></td>
</tr>
<tr>
<td>Subsoil Cation Exchange Capacity (CEC_SUB)</td>
<td>MIN_SUB - Subsoil mineralogy</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TD - Subsoil textural class</td>
<td></td>
</tr>
<tr>
<td>Topsoil Base saturation (BS_TOP)</td>
<td>SN - FAO soil name</td>
<td></td>
</tr>
<tr>
<td></td>
<td>USE - Regrouped land use class</td>
<td>L(low): &lt; 50%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M(medium): 50-75%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H(high): &gt; 75%</td>
</tr>
<tr>
<td>Subsoil Base saturation (BS_SUB)</td>
<td>SN - FAO soil name</td>
<td>L(low): &lt; 50%</td>
</tr>
<tr>
<td></td>
<td>MIN_SUB - Subsoil mineralogy</td>
<td>H(high): &gt; 50%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>MECHANICAL ATTRIBUTES</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depth to rock (DR)</td>
<td>SN - FAO soil name</td>
<td>S(shallow): 0-40 cm</td>
</tr>
<tr>
<td></td>
<td>PM - Parent material</td>
<td>M(moderate): 40-60 cm</td>
</tr>
<tr>
<td></td>
<td>PHASE - Phase</td>
<td>D(deep): &gt; 60 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>V(very) D(deep): &gt; 120 cm</td>
</tr>
<tr>
<td>Volume of stones (VS)</td>
<td>PHASE - Phase</td>
<td>0% stones - 10% stones</td>
</tr>
<tr>
<td></td>
<td>PM - Parent material</td>
<td>15% stones - 20% stones</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subsoil textural class (TD)</td>
<td>SN - FAO soil name</td>
<td>1 Coarse</td>
</tr>
<tr>
<td></td>
<td>TEXT - Topsoil textural class</td>
<td>2 Medium</td>
</tr>
<tr>
<td></td>
<td>DR - Depth to rock</td>
<td>3 Medium fine</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 Fine</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5 Very Fine</td>
</tr>
</tbody>
</table>
(table 2: continued)

<table>
<thead>
<tr>
<th>MECHANICAL ATTRIBUTES (continued)</th>
<th>HYdroLOGICAL ATTRIBUTES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subsoil structure (STR_SUB)</td>
<td>Parent material PM</td>
</tr>
<tr>
<td>SN</td>
<td>- FAO soil name</td>
</tr>
<tr>
<td>H(umic) or Peaty soil</td>
<td>- Parent material R, C, S, L, H, M (INRA et al., 1993)</td>
</tr>
<tr>
<td>Topsoil Packing Density (PD_TOP)</td>
<td>Depth to a gleys horizon (DGH)</td>
</tr>
<tr>
<td>STR_TOP</td>
<td>SN</td>
</tr>
<tr>
<td>TEXT</td>
<td>- Topsoil structure type</td>
</tr>
<tr>
<td>USE</td>
<td>- FAO soil name</td>
</tr>
<tr>
<td>L(ow): 0.6-1.4 g/cm³</td>
<td>V(ery deep): &gt; 120 cm</td>
</tr>
<tr>
<td>M(edium): 1.4-1.75 g/cm³</td>
<td>S(hallow): &lt; 40 cm</td>
</tr>
<tr>
<td>H(igh): &gt; 1.75 g/cm³</td>
<td>D(eep): 40-80 cm</td>
</tr>
<tr>
<td>Subsoil Packing Density (PD_SUB)</td>
<td>Depth to permeable layer (DIMP)</td>
</tr>
<tr>
<td>STR_SUB</td>
<td>TEXT</td>
</tr>
<tr>
<td>TD</td>
<td>- Topsoil textual class</td>
</tr>
<tr>
<td>SN</td>
<td>- FAO soil name</td>
</tr>
<tr>
<td>S(hallow): &lt; 80 cm</td>
<td>D(eep): &gt; 80 cm</td>
</tr>
<tr>
<td>Hydrological class (HG)</td>
<td>HG1: soil with permeable substratum, remote from groundwater; seldom wet</td>
</tr>
<tr>
<td>ATC</td>
<td>HG2: lowland soil affected by groundwater, seasonally or permanently wet, or artificially drained</td>
</tr>
<tr>
<td>PMH</td>
<td>HG3: soil with permeable layers within 80 cm depth, seasonally or permanently wet</td>
</tr>
<tr>
<td>SN</td>
<td>HG4: soils of the uplands and mountains</td>
</tr>
<tr>
<td>ALT</td>
<td></td>
</tr>
<tr>
<td>DIMP</td>
<td></td>
</tr>
<tr>
<td>Topsoil Available Water Capacity (AWC_TOP)</td>
<td>Depth to rock</td>
</tr>
<tr>
<td>TEXT</td>
<td>TD</td>
</tr>
<tr>
<td>PD_TOP</td>
<td>- Topsoil textual class</td>
</tr>
<tr>
<td>Topsoil Easily Available Water Capacity (EAWC_TOP)</td>
<td>Subsoil packing density</td>
</tr>
<tr>
<td>TEXT</td>
<td>PD_SUB</td>
</tr>
<tr>
<td>PD_TOP</td>
<td>- Topsoil packing density</td>
</tr>
<tr>
<td>Subsoil Available Water Capacity (AWC_SUB)</td>
<td>Depth to rock</td>
</tr>
<tr>
<td>TD</td>
<td>- Subsoil textual class</td>
</tr>
<tr>
<td>PD_SUB</td>
<td>- Subsoil packing density</td>
</tr>
<tr>
<td>Subsoil Easily Available Water Capacity (EAWC_SUB)</td>
<td>Depth to rock</td>
</tr>
<tr>
<td>TD</td>
<td>- Subsoil textual class</td>
</tr>
<tr>
<td>PD_SUB</td>
<td>- Subsoil packing density</td>
</tr>
</tbody>
</table>

In our work, we limited ourselves to estimating the soil parameters necessary for environmental problems. We did not draw risk (or vulnerability) maps; such work would require the combination of soil attributes with physical (climate, relief), agronomic (agricultural exploitation structure) and industrial (type and place of polluting emissions) variables. Each case would also require a fine analysis of the problem, modelling of the processes, selection of the tolerance threshold, and validation through experimental field work. The development of pedotransfer rules is a preliminary work for such investigations; it should facilitate a general application to such studies for the whole of Europe, providing a first estimate of the soil parameters needed for environmental models.
3. Structure and options for application of pedotransfer rules

This section describes the structure that was adopted for implementation of the system, and defines the retained options.

3.1 - Choice of the computer system

Implementation of the system takes place within the Arc/Info Geographical Information System (GIS) software package, using its macro-programming language AML (Arc Macro Language). The reasons for this choice are: 1) the database of available information (soil descriptions) is stored and managed within Arc/Info; 2) the resulting data (environmental parameters) have to be stored and managed within Arc/Info for mapping display purposes; and 3) this implementation had to be made within time and means limits that did not allow for the acquisition of - and staff training in - a specialized software.

The implementation is tailored for use within the general context of deriving new information from existing one via expert knowledge and could be used in any field of interest. But in our case, it was primarily meant to provide the European Environmental Agency with spatialized environmental indicators that could possibly be derived from the Soil Database.

3.2 - Dataset, objects, attributes, values, NODATA:

All the information available in the field of interest is stored in a so-called "dataset", e.g. the Soil Typological Units (STU) dataset. The dataset is physically stored as a dataset Info file, and holds information on a number of "objects", e.g. a number of soil types such as Luvisols, Cambisols, etc. Each object is physically stored as a line or record in the dataset Info file.

The objects in the dataset have a number of characteristics called "attributes", e.g. soil types have a soil name, a texture, etc. Each attribute is physically stored as a column in the dataset Info file. Each object in the dataset has a particular "value" for each of its attributes, e.g. such soil has a soil name Luvisol, a coarse texture, etc. Each value is physically stored at the intersection of the object's record and the corresponding column in the dataset Info file.

Values generally follow a coding scheme before being physically stored in the dataset, e.g. the soil name Luvisol is encoded and stored as "Lo", coarse texture is stored as "1", etc. Some objects might not be fully described when some of their attributes are unknown, e.g. unknown texture of a soil. An unknown value for an attribute is called a "NODATA" value. As there is no pre-defined way of coding and physically storing NODATA values in Info files, each attribute coding scheme has to make provision for a NODATA value code, e.g. # means unknown texture.
3.3 - Rules, occurrences, input attributes, output attributes, facts

Soil Science experts of the working group provide the system with pedotransfer rules. These rules, using expert knowledge, permit to derive new needed information from the existing factual information, "fact", describing an object of the dataset; e.g. the soil depth of a particular soil type can be inferred from both its known soil name and its parent material. A rule is physically stored as a rule Info file. The whole of rules composes a set of rules and is physically stored as a rules Info database.

A rule can be seen as a statement of the form:
- IF <available information is ...> THEN <new information is ...>
- ELSE IF <available information is ...> THEN <new information is ...>
- ...
- ELSE IF <available information is ...> THEN <new information is ...>

Each line in this statement is called an "occurrence" of the rule. An occurrence is physically stored as a line or record in the rule Info file.

An occurrence can be seen as a statement of the form:
- IF (or ELSE IF)
  - <factual value for attribute i is w
  - and factual value for attribute j is x
  - ...
  - and factual value for attribute n is y>
  THEN
  - <inform the object with value z for a new attribute m>

where attributes i to n provide the factual information (values w to y of an object), and attribute m provides the new -inferred- information (with value z). Attributes providing the factual information are the "input attributes" to the rule. The attribute providing the new -inferred- information is called the "output attribute" from the rule. Input and output attributes are physically stored as columns in the rule Info file.

Example:
- IF <soil name is "eutric Cambisol" and parent material is "450">
  THEN <soil depth is "Medium">
- ELSE IF <soil name is "eutric Cambisol" and parent material is "700">
  THEN <soil depth is "Medium">
- ELSE IF <soil name is "dystric Cambisol" and parent material is "500">
  THEN <soil depth is "Deep">

As with the dataset, "values" are physically stored at the intersection of each record and the input and output attributes in the rule Info file.

Therefore pedotransfer rules tables are describing the link, established through expert knowledge, between input attributes from the Soil Database and output attributes. The structure of a typical table is given in Table 3. The columns on the left correspond to values taken by the input attributes; the central columns provide estimated values and
their confidence level (see section 3.6); the right-hand columns contain management attributes and the references of rule occurrences (see section 3.9). The lines indicate the possible occurrences of the rule, based on the values (or combinations thereof) for the input variables in the Soil Database.

Table 3. Standard table for describing a pedotransfer rule.

<table>
<thead>
<tr>
<th>Regional Codes (see 3.8)</th>
<th>i</th>
<th>j</th>
<th>...</th>
<th>n</th>
<th>Class</th>
<th>Confidence level</th>
<th>Authors</th>
<th>Date</th>
<th>Notes</th>
</tr>
</thead>
</table>

Input attributes in a rule must have the same definition (name, type, size, etc.) and coding scheme as their corresponding attribute in the dataset.

3.4 - Inferences

An "Inference" is the action of producing a new derived information to an object according: a) to the available information it provides, and b) to the rule that is activated. It proceeds in 5 steps:

1. The input attributes are identified in the rule.
2. The values for these attributes are retrieved from the object in the dataset and constitute a fact.
3. Occurrence of the rule that matches the fact is searched for by sequentially skimming the rule's occurrences.
4. The output attribute definition and value are retrieved from the matching occurrence.
5. and are added to the object in the dataset.

When a rule is activated on a dataset, inference will occur for each object of the dataset, one after the other. The result will be a new attribute in the dataset, one for the whole dataset, to hold the new inferred values, one for each object. An attribute of the dataset that has been previously inferred using a rule is further considered as storing available information. It can thus be used as an input attribute to other rules.

3.5 - Wild cards

It is difficult, if not impossible, for an expert to foresee all cases that can possibly occur in a set of available data. Furthermore, in some cases many different values of a fact will lead to the same conclusion, e.g. [IF <texture is sandy or loamy or ...> THEN ...]. A "wild card" mechanism allows the expert to define occurrences of rules that will match different facts.
For example:

IF <soil name is "eutric Cambisol" and parent material is "450">
   THEN <soil depth is "Medium">
   ELSE IF <soil name is "eutric Cambisol" and parent material is "any other parent material">
      THEN <soil depth is "Deep">

The "any other" wild card will, by convention, be denoted as a star character (*). A fact for which an exact matching occurrence can be found will receive this occurrence's output attribute value. A fact for which an exact matching occurrence cannot be found, will receive the output attribute value of the last occurrence of the rule that matches, if it can be found with the wild card convention. This assumes that an expert will construct a rule by refining its occurrences, considering the most general cases before the most particular cases.

When no matching occurrence at all can be found for a fact, no value is provided to the output attribute, thus leaving it "blank" (or "0" (zero) depending on the output attribute's type). This can lead to confusion if blank (or 0) are possible normal output values. Therefore, having a fully "wild carded" occurrence as header of a rule, will "pick up" all facts for which no valid occurrence can be found and force the output value to, say, the NODATA value.

Using these specifications, the above example will become:

IF <soil name is "any soil name" and parent material is "any parent material">
   THEN <soil depth is "unknown">
   ELSE IF <soil name is "eutric Cambisol" and parent material is "any parent material">
      THEN <soil depth is "Deep">
   ELSE IF <soil name is eutric Cambisol and parent material is "450">
      THEN <soil depth is "Medium">

It has been agreed that the last occurrence examined in the rule, will be the one to retain. As the occurrences are sequentially skimmed in the order of the lines of the table, i.e. from top to bottom, the construction of rules is designed to list the occurrences from the most general to the most detailed expert evaluations. For instance, if the input variable is "FAO Soil Name", the STU noted "Bge" will accept all following occurrences: "B**, "Bg", "*g", etc. The order of occurrences would be "B**, "Bg", "Bge". If the STU soil name only contains code "B", the first occurrence will be applied; if it contains detailed information of the type "Bge", the third occurrence will be applied.

3.6 - Confidence level

Expert knowledge is subject to evolution. Furthermore, the available data, and the inferences that can be made using that information and the expert knowledge, have a certain level of reliability. It is thus necessary to have a mechanism that allows all available information (or factual values) held in the dataset, and each inferred
information (or output value) held in the rule database, to be complemented with an evaluation of its reliability.

The reliability of information is called its "confidence level". Confidence levels are held by confidence level attributes, one for each attribute of the dataset, and one for the output attribute of each rule. Each object in the dataset thus has a confidence level value for each of its attributes, and each occurrence of each rule has a confidence level value for its output attribute.

Four classes are proposed, ranging from "high", via "medium" and "low" to "very low". When the definition of input attributes enables the direct evaluation of an output attribute, the level is "high". On the other hand, if it is known that a very strong variation exists in the values of an output attribute, the "low" level is retained. "Very low" is used in the case of missing input attribute values.

So as to warn the users against a too abusive use of pedotransfer rules, it was decided that the confidence level of an output value should be the minimum of the confidence levels of all the input attributes and its corresponding occurrence.

When an inference takes place, the following 4 steps complement those listed above in section 3.4:

6. The output confidence level attribute definition is retrieved from the matching occurrence,
7. and is added to the object in the dataset.
8. The minimum (worst) confidence level value is retrieved from the confidence levels of all attributes implicated in the inference process (input confidence levels of the object, and output confidence level of the occurrence).
9. The resulting confidence level value is added to the output confidence level attribute in the object.

We have seen that an attribute of the dataset that previously was inferred using a rule, can be used as an input attribute to other rules. Its confidence level will be used in the same way as for any other input attribute.

3.7 - Missing data

In many cases, data are missing from the dataset because there are unknown input values to some objects. Two options then are open: the first consists in not evaluating the output attribute, which then itself becomes a missing attribute. The second proposes to output the best value found using the wild card convention, but with an imposed "Very Low" confidence level.

Use of wild cards in the case of missing input data carries the risk that information is generated that has never existed. The two options proposed above make it possible to retrace for each mapping unit the origin of its estimates. Checks are especially possible through the making of maps of the output "Confidence Level".
3.8 - Regionalizing of rules

In general the rules are drawn up for all of the mapped European territory. For making estimates, no attributes were used that might cause a strong regional bias. To avoid any drift that, locally, might become dominant, a systematic input attribute called "Region" is planned. The selected geographical level is that of the European administrative regions, called NUTS II, but the stacked coding for administrative regions (NUTS 0 = country, NUTS I and NUTS II) enables the easy writing of a rule at the scale of a country. For instance, a rule that is specific for Italy will be noted "32*" in the "Region" column.

The rules can thus be completed by specific occurrences for countries, without modification of the initial general structure. As the occurrences are skimmed in a sequential fashion, displacement is always from the most general to the most specific case.

Although not used at present this option will enable revision or refinement of any rule with the help of regional experts. Its use will require the geographic combination of soil and administrative boundaries.

3.9 - Management and updating of rules

Three management attributes were added to the structure of the table describing a rule. The first gives a pointer to the author(s) of each occurrence. An authors' references table is kept up to date. The second attribute defines the date of establishing the occurrence. The third attribute gives a pointer to explanatory notes, defining the reasons for selecting a certain estimate (not used up to now).

Such management attributes give insight into the origin of the proposed estimate. Moreover, in case an occurrence is updated, it is avoided that an old occurrence has to be eliminated in order to be replaced with a new one. The new one will rather be placed sequentially behind the old one. During application of a rule, the last occurrence accepted is the one retained, which will enable to keep trace of the subsequent updates effected.

3.10 - Expert and class type rules

The rules described above are called "expert type rules" as opposed to "class type rules". The latter are simple reclassification or recoding rules. They are used in any of the following cases:

1. convert the Info data type of an input attribute in the dataset from an unauthorized to an authorized type (e.g. binary to clear numerical);
2. reduce the number of different values for an input attribute (e.g. reclass detailed land use classes into less detailed land use classes);
3. recode the values of an input attribute (e.g. change codes to a more "speaking" coding scheme);
4. any combination of the above cases.
Class type rules accept only one input attribute and produce one output attribute. The input attribute has no limitation as to its Info data type. The output attribute follows the same limitations as those applicable to expert type rules.

Class type rules do not follow the wild card convention. Wild cards may not be used there.

Class type rules do not make use of the confidence level of the input attribute if it exists in the dataset, whereas expert type rules use all available confidence levels to compute an output confidence level.

Class type rules may or not produce a confidence level attribute together with the output attribute, but expert type rules always produce a confidence level attribute.

3.11 - Tools

A toolbox was developed on the basis of these specifications for the creation, deletion, editing, management, description, report and inference of rules. The tools also maintain a dictionary for the rules database, legends for input and output attributes, and a last rule edit historical file.

A tracing mechanism allows the detection of forward and backward dependencies. This means that when a rule is inferred, the tree of rules that are depending on its results can be traced forward in order to be fired in the correct sequence. Conversely backward tracing chases all the rules on the results of which one rule is depending.

Other utilities run compatibility controls between rules and the dataset, i.e. check input attributes in the rules against their corresponding in the dataset. This includes historical compatibility, i.e. date of last inference must be checked against date of last edit of a rule.

Plotting tools make use of the dictionary of the database, its legends, its controls for historical compatibility, and of the rules' output confidence levels. It also provides a mechanism for the proper generalization of the attributes describing STUs -which is the level of the Soil Database at which the rules are run- to the SMUs -which is the level that can be plotted on a map- (see 2.1). Therefore, each map of the results of a rule inference represents the dominant value of the output attribute over the polygons and can be provided together with both its corresponding confidence level and purity maps.

Finally a "WHY" tool is provided to allow the user to interactively point to a location on the map and ask why a rule has provided such a result. It will then give a full explanation of the inference that lead to the result.

These tools are provided as a command line language. They should be considered as a prototype that could be fully implemented at a future stage using an appropriate expert system development software and an ad-hoc interface to Arc/Info.

Figures 1 to 3 show the maps produced by this procedure for an attribute inferred by a pedotransfer rule.
SOIL DATABASE OF EUROPE
version 3.21, 30/10/1996 & Pedotransfer Rules version 2.0

Fig. 1. Depth to rock (DR) interpreted from the Soil Database by rule 411, and generalized to SMUs. This means that only the value of depth to rock which is dominant over each polygon is represented.

Fig. 2. Associated confidence level of the dominant depth to rock represented on figure 1.
4. Conclusions

The Soil Geographical Database of Europe represents a knowledge potential that is based on many years of map-data collection and compilation in Europe. Such data have already been used in applications related to agriculture and environment, thus showing the interest and importance of this knowledge as well as its limits. The main limitation is the difficulty in obtaining accurate data on soil parameters needed for environmental studies, when based only on synthetic attributes such as the soil name according to the FAO classification used.

The objective of our work is to propose an automatic interpretation of the data present in the Soil Database, leading to estimates for environmental use that are as reliable as possible. This means that it is necessary to formalize the interpretations made empirically by a well-versed reader when faced with a soil map.

This is done by means of so-called pedotransfer rules that link the standard soil characteristics to more complex properties, such as hydrodynamic properties. The rules appear in a standardized format which facilitates their use and management. They are created by expert judgement based on a general knowledge in Soil Science and can be associated to a region.
The results provided by the application of these rules are only qualitative estimates. At the 1:1,000,000 scale it is difficult to provide accurate information from the few data contained in the Soil Database, and care is taken to point out the methodological limitations of our approach. This is done by attaching a confidence level to each output value, which can highlight those areas for which the results are not so reliable. Moreover rules are applied to Soil Typological Units (STU) and when their results have to be displayed as maps, purity of the Soil Mapping Units (SMU) has to be accounted for. This can be computed from an indicator of the surface percentage of STUs within each SMU which is provided in the database.

The improved version of the Soil Database -version 3- is now available. It provides some means of validation of the methodology because some of the new attributes in version 3 where instead derived by pedotransfer rules from version 2 of the database at the time of development of the system. Soil profile databases and larger scale regional soil geographical databases are other means by which tuning or validation of the rules can be done.

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Development of soil data sets for global environmental modelling

N.H. Batjes

International Soil Reference and Information Centre (ISRIC).
P.O. Box 353, 6700 AJ Wageningen, The Netherlands

Introduction

Earth and atmospheric scientists require up-to-date and geo-referenced data on the world's natural resources, including climate, geology, landforms and soils, as well as socio-economic factors for their modelling studies. ISRIC, in collaboration with a number of other institutes, is meeting this demand by developing digital databases on the geographic distribution and characteristics on soil resources that can be used at different scales of operation.

Development and applications of the databases

The database development activities at ISRIC started in the mid-eighties when the information held in its World Soil Reference Collection was computerized. This pedon database, with the acronym ISIS, now holds over 600 fully described profiles representative of the soil units of the FAO-Unesco Soil Map of the World (FAO-UNESCO, 1974).

Although remaining the best available source on world soil resources, the 1:5 million scale FAO-Unesco Soil Map of the World, initially published in the 1970s, is partly out-dated. Thus a second thrust has been to develop a methodology for updating both the "area" and "attribute" data on the soils of the world. This is SOTER, the World Soils and Terrain Digital Database project, the development of which was endorsed by ISSS during its 13th International Congress at Hamburg. After testing of a methodology and software in parts of South and North America, the revised procedures for soil data description and handling were endorsed by ISSS, FAO, UNEP and ISRIC (Tempel et al., 1996).
The SOTER system handles input for a range of applications, including land evaluation, studies of crop production potentials and population supporting capacity. SOTER databases, linked to models and GIS, permit a geographic quantification and characterization of areas of concern (e.g., desertification, land degradation, soil pollution), permitting identification of areas for follow-up studies at larger scales and policy formulation.

A practical limitation to a 1:5 M SOTER is that world coverage will require up to 10 years, largely depending on the available funding. During this period, the need of global modellers for comprehensive and geo-referenced soil profile data representative for the main soil units of the world will remain. This led to the creation of the World Inventory of Soil Emission Potentials (WISE) database, the development of which started in 1991. WISE consists of: (1) a file with data on the type and relative extent of the component soil units of each ½° latitude by ½° longitude grid cell of the world, derived from the 1:5 M scale Soil Map of the World (FAO, 1995); and (2) selected morphological, physical and chemical data for over 4300 soil profiles considered representative for the respective soil units of the world. Associated files list the analytical methods used and source of primary data (Batjes and Bridges, 1994). Since its completion in December 1994, WISE has been used, amongst others, to calculate available water capacity using pedotransfer rules (Batjes, 1996) and to present median values for selected soil properties (Batjes, 1997). These derived data by FAO-Unesco soil unit can be linked to the ½° x ½° raster map, permitting the generation of GIS image files for global environmental applications, such as an assessment of areas at risk from water erosion. A data file with 1,125 georeferenced profiles derived from WISE is available in the public domain (Batjes, 1995). This subset, with its technical documentation, formed an ISRIC contribution to the activities of the Global Soils Data Task Group of IGBP-DIS (Scholes et al., 1995). As a sequel to the WISE activities, ISRIC and FAO plan to combine the best elements of their respective soil databases on a single CD-ROM which is to be presented as a unified product to the global modelling community in the near future.

In a separate activity, ISRIC has been contracted by IGBP-DIS to develop a point data set specifically for pedotransfer function (PTF) development. This non-georeferenced data set includes profile descriptions derived from the CD-ROM of the Natural Resources Conservation Service (USDA-NRCS) and ISRIC's ISIS (Tempel et al., 1996). As both organisations use similar analytical procedures and produce comparable results (L.P. van Ruijwijk and J.M. Kimble, pers. comm.), records from the two data sets can be easily merged into one single file, thereby avoiding the critical, yet often overlooked, issue of data comparability between disparate databases (Batjes et Bridges, 1994; Pleijier, 1989). Contrary to the European Data Set on Soil Hydraulic Properties (Lilly, 1995), the PTF data set developed for IGBP-DIS does not include data on hydraulic conductivity, as these were not routinely included in the source databases. Members of the IGBP-DIS Global Soils Data Task first intend to use the data set to develop PTFs for water retention, heat capacity and conductance.
Conclusions

Soil science has long recognised the strong links between soil and terrain, a relationship that can be expressed through the compilation of physiographically based soil maps. In using physiographically defined map units, as opposed to essentially taxonomically defined soil mapping units, a better geographical basis will be provided for studies of global change than has been the case so far with the Soil Map of the World. ISRIC, FAO, UNEP and ISSS are in the process of updating the information on the world’s soil resources in SOTER, the World Soil and Terrain Database programme (Van Engelen and Wen, 1995), which is to supersede the current Soil Map of the World (FAO, 1995) upon its completion. Although this work is complementary to other soil data base compilation activities at the regional or continental level (Arnold, 1995; Madsen and Jones, 1995), the need remains for better collaboration on the uniformisation of methods and data transfer protocols.

References


Predicting soil properties over a region using sample information from a mapped reference area

M. Voltz, P. Lagacherie and X. Louchart

Laboratoire de Science du Sol, INRA, place Viala, 34060 Montpellier Cedex 1, France

Introduction

Predicting soil behaviour at regional scales requires to determine the spatial variation of soil properties. The two most common approaches to deal with this have serious disadvantages for routine use. One uses information from conventional soil maps and assumes that soil properties vary little within each mapping unit and that the average values of the properties can represent the whole soil class. Its precision depends on the mapping resolution (Webster & Beckett, 1968; Marsman & De Gruijter, 1986; Leenhardt et al., 1994). For example, Leenhardt et al. (1994) showed in a case study in Southern France that only detailed soil surveys, producing maps at scales of 1:10 000 or at 1:25 000, enabled the spatial variation of a range of soil physical properties to be mapped with adequate precision. Unfortunately in most countries detailed soil maps are available only for small areas (Zinck, 1990).

The other approach uses numerical interpolation techniques. Among these kriging seems to be the most reliable (Laslett et al., 1987; Voltz & Webster, 1990; Voltz & Goulard, 1994). Ordinary kriging predicts the values of a variable at unsampled sites as weighted averages of observed values of the same variable at neighbouring sites. To determine the weights assigned to the observed values optimally kriging takes account of the spatial dependence between the observation and prediction sites and among the observation sites. This in turn requires a knowledge of the spatial covariance function and fairly intense sampling to estimate it. This is usually beyond the available resources when the soil property is expensive to measure.

Consequently whichever approach is used mapping soil properties at regional scales remains demanding. To improve this situation we propose a method that combines soil
classification and interpolation, and uses sample information from a reference area and simple soil observations over the region. The performance of the method is evaluated in a small physiographic region in south France.

Description of the classification with interpolation method

The classification with interpolation method requires a detailed soil survey in a chosen reference area which encompasses all of the soil classes of the region. The method for choosing reference areas is described and discussed by Favrot (1981, 1989) and Lagacherie et al. (1995). Our starting point here assumes that the reference area has been chosen already and that a detailed survey has identified the soil classes of the region as well as the criteria for recognizing them from auger samples. Then the prediction procedure consists of two main stages.

Predicting the soil properties by classification at observation sites. First the soil is observed at a set of \( n \) sites distributed over the region, and each site is assigned to one of the soil classes identified in the reference area. This can be done by an inexperienced surveyor provided that the soil classification and prescribed criteria have been defined clearly initially. Once the soil class has been determined at each observation site, the procedure follows that of conventional soil classification. The value of a property \( Z \) at the site is predicted by the mean of the soil class occurring there; the class means having been estimated by sampling at representative profiles in the reference area. In other words, by classification, we have a predicted value \( z_c(x_i) \) of \( Z \) at any observed location \( x_i \) within the region, with \( i = 1, 2, ..., n \).

Interpolating between the observation sites. To predict the value of \( Z \) at any unobserved location \( x_0 \) we use a linear combination of the data \( z_c(x_i) \), namely

\[
\hat{z}(x_0) = \sum_{i=1}^{n} \lambda_i z_c(x_i).
\]

In principle, the weights \( \lambda_i \) should be chosen to ensure unbiasedness and minimum variance of the prediction. To this aim, the geostatistical theory shows that the actual variogram of \( Z \) must be known (see Voltz et al., 1997). In the classification with interpolation procedure we only have predicted values of \( Z \) and can therefore only compute a biased estimate of the variogram of \( Z \). The solution we propose is to use the latter variogram in the ordinary kriging system for computing the \( \lambda_i \). As this solution is approximate, we also investigated two other weighting schemes. The first is inverse squared distance, in which the weights assigned to the observation points are proportional to the inverse of the squared distance between the prediction point and the observation points. The second is the nearest neighbour, in which all weights are set to zero apart from that of the nearest observation site which is set to 1.
Fig. 1. Soil map of the reference area, test area and sampling locations. (---) boundaries of the reference area, (-----) soil boundaries, (------) boundaries of the test area, (●) grid samples, (○) random samples, (■) River Hérault, (■) urban areas, and (□) scrublands and forests.

Case study

In the following we evaluate empirically the classification with interpolation procedure in its three versions (classification with kriging, classification with inverse squared distance, and classification with nearest neighbour), and compare it with conventional methods, namely ordinary kriging with actual data and prediction from a soil map at a scale of 1:100 000.

The test area and its sampling

The prediction methods were used to map the soil water content at wilting point in a small region, the central valley of the river Hérault. This region is a part of the Mediterranean coastal plain of the south of France and covers nearly 400 km². A soil map of the region at 1:100 000 was made by Bonfils (1988), and a reference area of 800 ha covering the main geological units was surveyed in detail. The methods were evaluated on a test area of 1736 ha surrounding the reference area (Fig. 1). We sampled it in two ways: at the nodes of a square grid with a 200-m spacing, giving 374 sampling points, and by selecting 52 additional sites probabilistically. Three square sampling grids were extracted from the main grid to evaluate the method of prediction for a range of sampling intensities; they were 200 m, 282 m and 400 m respectively. For each of these grids of observations we used the observations of the remaining sampling points for independent validation.

At each sampling site in the test area, soil type was identified following the criteria defined during the soil survey of the reference area, and water content of the soil at wilting point was measured on soil samples taken at a depth of 0.4 m.
Table 1. Prediction mean square errors of water content at wilting point in g kg\(^{-1}\)

<table>
<thead>
<tr>
<th>observation sites</th>
<th>prediction method</th>
<th>distance between prediction sites and closest observation sites</th>
</tr>
</thead>
<tbody>
<tr>
<td>400 m grid</td>
<td>number</td>
<td>100 - 141 m</td>
</tr>
<tr>
<td>&quot;</td>
<td>ordinary kriging</td>
<td>34</td>
</tr>
<tr>
<td>&quot;</td>
<td>classification-kriging</td>
<td>627</td>
</tr>
<tr>
<td>&quot;</td>
<td>classification-inverse distance</td>
<td>763</td>
</tr>
<tr>
<td>&quot;</td>
<td>classification-nearest neighbour</td>
<td>1168</td>
</tr>
<tr>
<td>Representative profiles</td>
<td>classification at 1:100 000</td>
<td>1258</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1032</td>
</tr>
</tbody>
</table>

Summary of the results

A full account of the results is given by Voltz et al (1997). In this abstract, only a representative sample of the results is described. Table 1 lists the mean square errors of prediction at the validation sites for all methods in the case of the 400 m observation grid. Comparing the mean square errors shows that, as expected, ordinary kriging always performed best. The performance of classification with interpolation differs largely according to the method of interpolation. Furthermore, differences in precision between the three classification with interpolation procedures are often larger than the differences between these predictors and the traditional methods. Classification with kriging performed the best, and in addition the results were close to those from ordinary kriging for those prediction points at a short distance from the observation points. This suggests that the approximate procedure we used for optimizing the kriging weights in classification with kriging introduced only a slight bias on the estimated vector of weights. The $MSE$s of classification with nearest neighbour were always larger even than those of conventional soil classification. The performance of classification with inverse squared distance was intermediate between those of classification with kriging and of classification with nearest neighbour.

Last, for the large distances between the observation sites and the prediction sites, the difference in the performance of classification with kriging and that of conventional classification decreased greatly, although classification with kriging remained slightly better. Yet, the performance of classification with inverse distance and classification with nearest neighbour became worse than that of conventional classification at large distances, which means that in this instance there is no clear advantage in using the former methods instead of the latter.

Conclusions

This study shows that combining detailed soil classification and interpolation is a promising procedure for predicting soil properties at unobserved sites in a region from sample information in a reference area of the region. This procedure is cost effective...
since it requires samples only at representative profiles within the reference area. This is especially advantageous, in comparison to methods such as kriging, when mapping soil properties that are expensive to measure.

The precision of classification with interpolation depends largely on the method of interpolation used. Classification with kriging performed the best.

Acknowledgements

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References


The Wind’s evaporation method: a standard laboratory method adopted by the French INRA laboratories

P. Bertuzzi¹ and M. Voltz²

¹ Institut National de la Recherche Agronomique, Unité de Science du Sol, Domaine Saint Paul, Site Agroparc, 84914 Montfavet Cedex 9, France.
² Institut National de la Recherche Agronomique, Unité de Science du Sol, 2 Place Viala, 34060 Montpellier Cedex 1, France.

Wind (1969) developed a simple method for determining both the water retention and the unsaturated hydraulic conductivity relationships of soil samples in the laboratory and under evaporation conditions. For the past three years, four INRA laboratories (Soil Science laboratories of Avignon, Montpellier and Orléans, Agronomy laboratory of Laon) have been determining the soil hydraulic properties using the Wind method. All the laboratories use the same experimental equipment and computer programs that were designed by the Soil Science Laboratory of INRA in Avignon.

Undisturbed soil cores were sampled in the field with sharpened inox cylinder having 70 mm of height and 150 mm of internal diameter (Fig. 1).

![Fig. 1. The field sampling of core cylinder](image1)

![Fig. 2. The micro-tensiometer](image2)
Six micro-tensiometers can be inserted into the soil (one at depths of 5, 10, 20, 30, 45, 60 mm. These arc (1) 20 mm long and 2 mm in diameter porous cups (Fig. 2). Each arc connected by a plastic capillary (2) to differential pressure transducers (3). These are piezo-resistive sensors having a linear calibration relationship between 0 to -10 m (electrical range 0-100 mV). But sensors are sensible to temperature which influences the slope and the offset value of the linear calibration. Both of these temperature dependencies are also described by a linear model. The accuracy of the soil potential measurements is near +/- 2 mm.

The output signal (mV) of the pressure transducers are recorded by a data logger. The weighing device and the data logger are linked to a PC microcomputer by two serial ports (Fig. 3). A program written in Basic manages the data recording at a constant time step (10 or 15 minutes for example). The variation with time of soil pressure heads are automatically displayed on the screen of the micro-computer. This is very helpful to visualize the effect of the evaporation process and to verify the intensity of pressure head gradients.

![Fig. 3. The laboratory setup](image)

![Fig. 4. An example of graphical tool associated to the computer program](image)

A program was developed to calculate the soil hydraulic properties. The program was written in FORTRAN 77 on UNIX system and used SPLUS graphical analysis system for the graphical tools (Fig. 4).

The soil hydraulic properties of over three hundred samples were routinely determined by the Wind method. This database will constitute the French contribution to the HYPREs European database.

Tamari et al. (1993) compared the water retention and the unsaturated hydraulic conductivity relationships determined with this method to that obtained from a reference method. The hydraulic properties obtained with Wind’s method agreed well with those obtained with the reference method which required the pressure head and water content profiles at several time steps. But the author showed that when tensiometric measurement errors were taken into account, estimation of the water retention curve using the evaporation method was not very sensitive to experimental
errors, but small uncertainties in tensiometric data greatly influenced the hydraulic conductivity determined under wet conditions. Mohrath et al. (1996) have investigated thoroughly the properties and accuracy of the Wind method. By using a numerical model for unsaturated flow, several questions related to the consequences of errors in the measurements on hydraulic property estimates were solved. When different cases of measurement error were taken into account, estimation of the water retention curves using the Wind method was not very sensitive to experimental errors, except when the soil was heterogeneous. On the other hand, small uncertainties in the position of the tensiometers and in the calibration curve of the transducers used for the pressure head measurements had a great influence on the estimated hydraulic conductivity of soil samples. The hydraulic conductivity vs water content relationship were generally greatly biased. Thus, it is necessary to place of tensiometers only 10 mm apart and with typically a plus or minus 1-2 mm accuracy. We think that these stringent specifications are more or less achievable in practice using micro-tensiometers which are horizontally located in the soil column into small cylindrical guides. Nevertheless, the measurement of the exact distance between porous cups of the tensiometers must be done at the end of the experiment by destroying of the sample. Results also showed that it was important to correct thermal effects related to liquid water viscosity when calculating hydraulic conductivity.

References


The use of pedotransfer in the development of a hydrological classification of UK soils (HOST)

A. Lilly\textsuperscript{1}, D.B. Boorman\textsuperscript{2} and J.M. Hollis\textsuperscript{3}

\textsuperscript{1} Macaulay Land Use Research Institute, Craigiebuckler, Aberdeen, AB15 8QH Scotland
\textsuperscript{2} Institute of Hydrology, Wallingford, England
\textsuperscript{3} Soil Survey and Land Research Centre, Cranfield University, Silsoe, Bedfordshire MK45 4DT England

Introduction

Soils have a major influence on catchment hydrology through the storage and transmission of water. When combined with the chemical properties of the soil, the pathways of water movement through the soil impact on its ability to act as a chemical or biological buffer. The aim of the HOST project (Hydrology of Soil Types) was to develop a hydrologically based classification of UK soils capable of predicting hydrological indices for ungauged catchments and as input into environmental assessments.

Development of the classification

While it is recognised that soil hydraulic conductivity, soil water storage capacity, the pathways of water movement through the soil and the temporal variability in soil moisture content greatly influence catchment hydrology, these variables are only available for a limited number of British soils. However, there are two extensive databases comprising approximately 24,000 soil profile descriptions which give spatial and temporal qualitative information on the hydrological conditions of the soils. A series of pedotransfer rules and expert knowledge were applied to these profile data to derive a set of semi-quantitative attributes that could be used in multiple regression analyses against two hydrological indices to develop the classification. These attributes were: the presence or absence of an organic surface layer, substrate hydrogeology, the depth to a slowly permeable layer, the depth to gleying and air capacity values. Information on the spatial distribution of soils within catchments was also obtained from existing 1:250 000 scale soil maps.

The presence or absence of an organic surface layer was obtained directly from the soil
profile description while the substrate hydrogeology was derived from a simple
recording of the recorded soil parent material. The parent materials were grouped
according to their general permeability, the notional depth to an aquifer (if present) and
general mechanisms of water flow through them. Pedotransfer rules based on the soil
colour and the degree of mottling were used to determine which soil horizons were
gleyed and thus the depth at which this occurred (Avery, 1980; MAFF, 1988 and
Hollis, 1989). A similar rule-based approach using information on the grade, size and
type of soil structure in conjunction with the soil texture and consistence was used to
ascertain whether a soil horizon should be classed as slowly permeable, that is, having
a lateral hydraulic conductivity < 10 cm day\(^{-1}\) (Thomasson, 1975; Avery, 1980; MAFF,
1988). A dataset of approximately 4000 soil horizons were used to develop class
pedotransfer functions based on soil texture and packing density in order to estimate
the air capacity of the soil (that is, the volume of air-filled pores when the soil moisture
content is at field capacity).

Interrogation of the soil profile database established a modal sequence of soil horizons
for each taxonomic unit and a list of soil profiles which belonged to each taxonomic
unit. The pedotransfer rules were applied to each soil horizon within the soil profiles to
establish their porosity, whether they were gleyed or were slowly permeable. From
these data, a database containing the average porosity, average depths to gleying and to
a slowly permeable layer, the presence of an organic surface layer and the substrate
hydrogeology for all taxonomic units was established.

The hydrological indices used in the regression analyses were derived from archives of
daily mean river flows for approximately 1000 catchments and of flood event data
containing observations of rainfall and flow for 220 catchments (Institute of
Hydrology, 1980; Boorman, 1985).

Quantification and validation of the classification was an iterative process involving
some preclassification of the soil taxonomic units into one of 11 conceptual classes.
The proportions of soils falling into each conceptual model within the catchments used
in the analysis were calculated and multiple regression analyses were used to
determine the influence of the soils on the Base Flow Index and on the Standard
Percentage Runoff. These parameters describe the volume of baseflow and the runoff
under standardised rainfall events and antecedent moisture contents respectively. The
results of the regression coefficients and their standard errors were used to further
subdivide the 11 conceptual models on the basis of the soil attributes leading to the
development of a 29 class system.

Conclusions

This new hydrologically based classification was developed by applying a series of
pedotransfer rules and functions along with expert knowledge to soil survey data and
then validating the assessments against measured hydrological indices via a series of
multiple regression analyses. The HOST classification is capable of predicting river flow levels of ungauged catchments ($r^2 = 0.79$, s.e.e $= 0.089$ in the case of Base Flow Index) and is applicable for predictions of water quality and in land suitability assessments.

Acknowledgements


References


Development of neural network models to predict soil water retention

E.J.W. Koekkoek and H.W.G. Boolink

Department of Soil Science and Geology, Wageningen Agricultural University, Duivendaal 10, 6701 AR Wageningen, The Netherlands.

Introduction

Soil water retention curves are needed to describe the availability of soil water to plants and to model movement of water through unsaturated soils. Measuring these characteristics is time consuming, labour-intensive and therefore expensive. Several attempts have been made to estimate either the function that describes the soil water retention curve for a range of matric potentials, or to predict the water content at certain potential values. Pedo-transfer functions (Bourma and Van Lanen, 1987) are functions which use relatively easily measurable soil characteristics as input variables and which have the water retention curve or the hydraulic conductivity curve as output variable. This study was conducted to develop and evaluate pedo-transfer functions based on neural network models to predict soil water retention characteristics.

Materials and methods

Neural network

Neural networks exhibit certain analogies with the way in which arrays of neurons function in biological learning and memory. The fundamental building blocks are units ("nodes") which can be likened to neurons, and weighted connections which can be likened to synapses. Nodes are simple information processing elements. The number of nodes and the connection patterns of the nodes can vary. The most widely used connection pattern is the three-layer neural network. This pattern has proved to be useful when modeling input-output relations (Elizondo et al., 1994; Schaap, 1996) and was also used in this study.
Data

Two data bases were available for research: (i) a Dutch and (ii) a Scottish data base. The Dutch data base contained the following variables on 178 soil horizons, described in 890 records: either the clay or sand content (%), bulk density (kg m$^{-3}$), organic matter content (%), and the volumetric water content (%) at five different matric potentials (hPa). These water contents were calculated using the Van Genuchten parameters. Furthermore the data base contained information on the type of horizon, being either a structured topsoil (A horizon) or a less structured subsoil (B and C horizons). This data base was provided by the DLO-Winand Staring Center.

The Scottish data base contained information (704 records) on horizon, clay-, silt-, and sand content (%), bulk density (kg m$^{-3}$), organic matter content (%), structure, and measured water retention characteristics on 165 soil horizons located in Scotland. This data base was kindly provided by the Macaulay Land Use Research Institute.

Description of neural network models

A series of 20 models were developed, based on various combinations of input and output soil variables. All neural network models were tested against independent data sets which were extracted from the original sets. Accuracy of the models’ predictions was quantified by the root of the mean squared error (RMSE) between the measured and the predicted retention characteristics, and the coefficient of determination ($R^2$).

From the 20 models the three most accurate models were chosen for optimization. In the optimization procedure the internal parameters (learning rate, momentum, activation function, and number of hidden nodes) of the neural networks were varied. All three models (A, B, and C) had topsoil as input variable. This attribute had the value 1 if the soil was a topsoil, and -1 if the soil was a subsoil. Furthermore, bulk density, organic matter content, clay-, silt-, and sand content were used as inputs for model A. The volumetric water contents at matric potential values of 0, -100 and -15000 hPa were used as output variables for A. Model B used matric potential (being either 0, -10, -100, -2000, or -15000 hPa), bulk density, organic matter content, clay-, silt-, and sand content as inputs. Model C used the inputs of model B and pedsize as inputs. Both model B and C had volumetric water content as output variable.

Results and discussion

For model A the RMSE varied from 2.64 to 4.76 %, and $R^2$ varied from 0.80 to 0.93 for the three matric potentials. Models B and C had an RMSE of 4.35 and 4.26 % respectively. For both models the coefficient of determination had a value of 0.89.

Comparison of the three neural networks with existing regression-type pedo-transfer functions (Gupta and Larson, 1979), using three independent tests sets, showed that the neural network models’ accuracy sets was better. Neural network A had a coefficient of
determination of 0.92, while the regression-models' $R^2$ was 0.72. The RMSE were 3.79 and 7.10 % for the network and the regression respectively. Network B had an $R^2$ of 0.87, and the regression model had an $R^2$ of 0.54. The RMSE were 3.15 and 5.91 % for subsequently the network and the regression. The coefficients of determination were 0.87 and 0.24 for model C and the regression's predictions respectively. The RMSE were 3.13 and 7.71 % for the network and the regression respectively.

Comparison of the three neural network models with regression-type pedo-transfer functions which were fitted to the previously described data sets, also showed that the neural network models' accuracy was better (Figs. 1, 2 and 3). However, the difference in accuracy between neural network models and these fitted regression models was not as large as the difference in accuracy between the neural network models and the original regression equations: the neural network's $R^2$ values varied from 0.84 to 0.91, while the regression models' coefficient of determination varied from 0.83 to 0.90.

![Graph showing predicted water content (%) as a function of measured water content (%).](image)

**neural networks:** $y = 0.8816x + 3.3921$

**regression:** $y = 0.9833x + 1.1123$

Fig. 1. Predicted water content (%), as a function of measured water content. Independent production-set data are shown; $R^2$ is 0.84 for the neural network A (black squares) and 0.83 for the regression model (white circles). Regression lines are drawn through the predicted points, and the regression equations are shown. Broken lines are drawn through the regression's predictions, regular lines through the neural networks' predictions.
Fig. 2. Predicted water content (%), as a function of measured water content. Independent production-set data are shown; $R^2$ is 0.86 for the neural network B (black squares) and 0.84 for the regression model (white circles).

Fig. 3. Predicted water content (%), as a function of measured water content. Independent production-set data are shown; $R^2$ is 0.91 for the neural network C (black squares) and 0.90 for the regression model (white circles).

Conclusions

1. While classical statistical regression techniques always require an a-priori model type (e.g. linear, exponential, or logarithmic), neural networks do not need such an a-priori model. The lack of this a-priori model and the organization structure...
of a number of strongly interconnected nodes, make neural networks extremely useful when non-linear input-output relations have to be described.

2. As neural networks learn input-output relations from training data, representative training sets of adequate size are crucial for the accuracy of the networks output.

3. Though previously developed pedo-transfer functions, based on neural networks and regression analysis did not employ the input variable \textit{matric potential}, usage of this input seem to improve the accuracy of the pedo-transfer functions’ predictions.

4. In this study neural network models performed somewhat better than previously developed regression-type pedo-transfer functions. The neural network models’ coefficient of determination varied from 0.89 to 0.92, while the regression-models’ $R^2$ varied from 0.24 to 0.72. Comparison of the three neural networks with regression models which were fitted to the data that were used during this study, also showed that the neural network models’ accuracy was better: the neural networks’ $R^2$ values varied from 0.84 to 0.91, while the regression models’ coefficient of determination varied from 0.83 to 0.90.

\section*{Recommendations}

Neural networks seem to provide good opportunities for modeling all kinds of input-output relation e.g. in predicting weather forecasts, especially if strongly non-linear relations among the dependent variables exist.

As the neural network models were developed and tested for a limited number of soils, further research on the applicability of neural network models as well as comparison with existing pedo-transfer functions is needed.

In order to be able to further explore neural network modeling for the development of pedo-transfer functions, the availability and accessibility of data on basic soil properties, hydraulic conductivity characteristics, and soil water retention characteristics needs to be improved. EG-projects like “Using existing soil data to derive hydraulic parameters for simulation models in environmental studies and in landuse planning”, in which the soil data base HYPRES (Hydraulic Properties of European Soils) was developed, should be encouraged.

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References


Regionalization of soil property functions in a highly variable soilscape

A. Scheinost¹, W. Sinowski² and E. Priesack³

¹ Agronomy Department, Purdue University, West Lafayette, IN 47907, U.S.A.
² GSF - National Research Center for Environment and Health - PUC - Ingolstädter Landstr. 1 - 85764 Neuherberg - Germany
³ GSF - National Research Center for Environment and Health - Institut für Bodenökologie - Ingolstädter Landstr. 1 - 85764 Neuherberg - Germany

Introduction

Regionalized soil buffering functions are a prerequisite to modelling the fluxes of water and ions in terrestrial ecosystems. To generate three-dimensional maps of these functions for a 1.5 km² research farm (Long. 09° 11' E, Lat. 48° 30' N) with a high variability in relief, parent material and land use, soils were sampled at the nodes of a 50x50 m grid in five depths. The samples were analysed for the basic soil properties texture, pH, bulk density, and nutrient concentrations. These basic properties were interpolated by using geostatistical methods that incorporated the soil forming factors. Following the grid sampling 19 additional sites were selected to develop pedotransfer functions, which predict buffering functions like the water retention curve and the K/Ca exchange curve from these basic properties.

PTF for water retention curves (WRC)

For predicting water retention curves (WRC) a new PTF had to be developed to account for the extreme variation in soil parameters: texture varying between gravel and clay, organic C content up to 81 g kg⁻¹, and bulk density from 0.80 to 1.85 Mg m⁻³ (Table 1).
Table 1. Selected soil properties of the two different data sets of the study area.

<table>
<thead>
<tr>
<th>Data set: n</th>
<th>&quot;Grid&quot; 2448 Mean (Min - Max)</th>
<th>&quot;PTF&quot; 87 Mean (Min - Max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil Property</td>
<td>Unit</td>
<td>(0.80 - 1.85)</td>
</tr>
<tr>
<td>Bulk density</td>
<td>Mg m$^{-3}$</td>
<td>1.49</td>
</tr>
<tr>
<td>Corg</td>
<td>g kg$^{-1}$</td>
<td>9</td>
</tr>
<tr>
<td>Clay</td>
<td>kg kg$^{-1}$</td>
<td>0.21</td>
</tr>
<tr>
<td>Silt</td>
<td>kg kg$^{-1}$</td>
<td>0.38</td>
</tr>
<tr>
<td>Sand</td>
<td>kg kg$^{-1}$</td>
<td>0.41</td>
</tr>
<tr>
<td>Gravel</td>
<td>kg kg$^{-1}$</td>
<td>0.10</td>
</tr>
<tr>
<td>log($d_g$)</td>
<td>log(mm)</td>
<td>(-3.0 - 11.3)</td>
</tr>
<tr>
<td>$\sigma_g$</td>
<td>-</td>
<td>16</td>
</tr>
</tbody>
</table>

When using texture for the prediction of WRC parameters describing the entire particle size distribution seems more useful than combinations of single texture classes. Therefore the particle size distribution was parametrized using the geometric mean diameter, $d_g$, and its standard deviation, $\sigma_g$, according to Shirazi et al. (1988). In contrast to Shirazi et al. (1988), the upper limit of the distribution was extended to 63 mm to account for gravel, an the lower limit was assumed to be 0.04 $\mu$m to account for a log normal distribution within the clay fraction.

The parameters of a van Genuchten-type function (van Genuchten, 1980), $\theta_s$, $\theta_r$, $\alpha$, and $n$, were substituted by linear equations relating these parameters with soil properties in a physically meaningful way (equations 1). That is, the particle-size distribution parameters $d_g$ and $\sigma_g$, were assumed to be related to the pore-size distribution parameters $\alpha$ and $n$. Compared with other PTF, the new PTF improved the prediction of WRCs by 60 % within the study area. This improvement was mainly caused by accounting for skeletal soils and soils with low density and high organic matter content.
\[ \theta_s = 0.85 \left( 1 - \frac{bd}{2.65} \right) + 0.13 \text{ clay}_s \]

\[ \theta_r = 0.51 \text{ clay}_s + 0.0017 \text{ Corg} \]

\[ \alpha = 0.00023 + 0.00023 \ d_g \]

\[ n = 0.33 + \frac{2.6}{\sigma_g} \]

bd: bulk density [Mg m^{-3}]
clay$_s$: clay content of the total soil [kg kg$^{-1}$]
Corg: organic carbon content [g kg$^{-1}$]
d$_g$: geometric mean diameter [mm]
\( \sigma_g \): standard deviation of d$_g$ [-]

Additionally a bimodal model of the van Genuchten function was derived to cope with differences between the total pore volume and \( \theta_s \). For the macro pores model part the following assumptions were made: \( \theta_{sm} = \) total pore volume; \( \theta_{rm} = \theta_r; \ alpha_m = 1 \ \text{hPa}^{-1}; \ n_m = 5. \ \theta_s, \ \theta_r, \ \alpha \) and \( n \) of the matrix pore model part were fitted with the same combinations of basic soil properties used in equations 1. Then, the monomodal and the bimodal PTF models were compared by deriving the unsaturated hydraulic conductivity curves using the program "SHYPFIT" (Durner, 1993) and an data set of measurements independent of the data set used to build the PTFs. Nevertheless, the bimodal model showed much higher deviations between predicted and measured hydraulic conductivity and therefore the monomodal model was used for further calculation (Schinist & Auerswald, 1995).

During the workshop the problem of negative van Genuchten parameter \( \alpha \) and \( n \) of many PTFs, which are trying to predict the van Genuchten parameters directly was discussed. For the PTF described above this problem could not be observed when applied to the basic soil properties measured for the 50x50 m grid. The reason might be on one hand the very wide range of values of the calibration data set for fitting the PTFs and on the other hand the physically oriented design of the PTFs, which uses the \( d_g \) and \( \sigma_g \) for the prediction of \( \alpha \) and \( n \).

**The use of PTFs for WRC in simulation models**

One of the motifs to derive pedotransfer function is their use in water flow simulation models. Many of these models are based on numerical solutions of the Richards equation:

\[ \frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[ K(h) \frac{\partial h}{\partial z} - K(h) \right] + S \]
where $\Theta$ is the volumetric water content, $h$ is the soil water suction head, $t$ is time, $z$ is depth positive downward, $K$ is the hydraulic conductivity, and $S$ represents a sink, which for example considers root water uptake. To account for the non-linearity $\Theta(h)$ in the numerical solution schemes of the Richards equation the slope of the retention curve $C(h)$ has to be calculated. Using the representation of the retentivity curve as proposed by van Genuchten (1980)

$$
\Theta = \begin{cases} 
    \Theta_s & \text{for } h \geq 0 \\
    \Theta_s + (\Theta_r - \Theta_s) \frac{1}{(1 + |zh|^{n})^m} & \text{for } h < 0
\end{cases}
$$

the slope is given by

$$
\frac{\partial \Theta}{\partial h} = C(h) = \begin{cases} 
    0 & \text{for } h \geq 0 \\
    (\Theta_r - \Theta_s) \frac{mn^{m-1} |zh|^{n-1}}{(1 + |zh|^{n})^{m+1}} & \text{for } h < 0
\end{cases}
$$

Since the pedotransfer function as given above may predict values of $n<1$, this leads to a difficulty in evaluating $C(h)$ near saturation as $C(h)$ tends to infinity if $h$ takes negative values approaching zero. Therefore in a next step we will try to derive a pedotransfer function limited to values of $n>1$. Usually the goodness of fit does not decrease significantly by this limitation, since its effect is largely compensated by changes in $m$ if we remove the limitation $m=1-1/n$.

**PTF of K/Ca exchange curves**

To predict K/Ca exchange curves a pedotransfer function was developed that generates a Freundlich-type exchange curve based on two basic properties: the clay concentration accounts for the amount of exchange sites, and the Ca-acetate-lactate-extractable K ($K_{\text{CAL}}$) accounts for exchangeable K (equation 3, Scheinost et al., 1997).

**Regionalization of the PTFs**

The regionalization of soil buffering functions with a PTF can be performed in two different ways: (1) Interpolate first the fundamental properties, and apply then the PTF to the interpolated data to predict the WRCs. (2) Predict first the WRCs by applying the PTF on to the point-wise measurements of the fundamental data, and interpolate then the WRCs. Both procedures have been tested. Using procedure (1), the spatial variability of each fundamental property could be individually analysed and accounted for in the regionalization process and, thus, reduce the root mean squared differences.
(RMSD) compared to procedure 2. Due to the improved spatial patterns and the
decrease in the regionalization error, procedure (1) was clearly superior to procedure
(2) for the PTFs predicting soil buffering functions. Additionally, external factors
controlling the spatial variability can be analysed and considered into regionalization
individually for each basic soil property. Thus, each regionalized basic soil property
might be useful for several PTF and the external factors considered in the basic soil
properties will influence the spatial variability of the output property according to its
relations in the PTF.

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Statistical and geostatistical analyses of soil water retention characteristics estimated by pedotransfer functions

Nunzio Romano

Institute of Agricultural Hydraulics, Univ. of Naples "Federico II"
Via Università 100, 80055 Portici, Napoli - Italy

Accurate knowledge of soil hydraulic properties (essentially, the soil water retention and hydraulic conductivity functions) is of crucial importance for reliable applications of recently developed distributed models to environmental studies and land-use planning. To provide such information in a cost-effective way, indirect estimation of water transport parameters from easily measurable or already available soil data using pedo-transfer functions (PTFs) is becoming increasingly popular. However, distributed hydrological modeling requires that soil hydraulic characterization also takes account of the description of spatial variability.

The objective of this study was to evaluate some published PTFs in the light of their ability to quantify the spatial structure and variability of soil water retention adequately. Four PTFs were tested: two provided only values of water content at specific pressure potentials (PTF Group A), whereas the remaining two estimated the parameters of closed-form relations describing the water retention function (PTF Group B).

The data analyzed were obtained on a hillslope of the Sauro River catchment, the main tributary of the Agri River. The catchment is located within the Middle Agri Valley and represents an interesting area for site-specific studies on surface erosion and land degradation. The sampled area was close to the village of Guardia Perticara, and represented a hillslope orientated in the N-NW/S-SE direction, running from the mountain-top called "Serra Dievolo", at about 1073 m above mean sea-level, down near the Sauro River, at about 458 m above mean sea-level. Undisturbed soil samples were collected from the surface layer of soil at 100 sites, spaced 50 m apart, along a 5-km long transect parallel to the main slope. The samples were taken from 5 to 12 cm soil depth using steel cylinders with an inside diameter of 7.2 cm and 7.0 cm high. Each sample was subjected to standard laboratory analyses to determine soil physical and chemical properties such as texture, bulk density, particle density, and organic carbon content. The collected samples represented a relatively wide range of soil texture classes. There are somewhat large variations from sand-rich soil samples to
clay-rich soil samples, while the silt contents are contained in a narrower range from about 24% to 54%. Sand-kaolin box and membrane plate apparatuses were used to measure soil water retention data points, which for each sample were fitted with the well-known van Genuchten's analytical relation (van Genuchten, 1980) using a nonlinear least-squares curve-fitting procedure based on the Marquardt method, as developed in the RETC software package (van Genuchten et al., 1991). In this study the parameter $\theta$, was fixed at zero throughout, as this value was considered acceptable by some authors (Wösten and van Genuchten, 1988).

The PTFs that belong to the first group (PTF Group A) and are chosen for testing are the PTF of Gupta-Larson (Gupta and Larson, 1979) and the PTF of Rawls (Rawls et al., 1982). The PTFs that belong to the second group (PTF Group B) and are chosen for testing are the PTF of Rawls-Brakensiek (Rawls and Brakensiek, 1989) and the PTF of Vereecken (Vereecken et al., 1989).

Fitted and estimated water retention data sets were subjected to standard exploratory data analysis to describe the nature of the frequency distributions by traditional summary statistics (such as mean, median, interquartile range, standard deviation, and coefficient of variation). Data were tested for normality at 95% significance level using the procedure proposed by D’Agostino et al. (1990). This test is based on the $K^2$ statistic which accounts for the combined effects of skewness and kurtosis.

Water content estimates from each pedo-transfer function were evaluated using the maximum error (MXE), the mean error (ME), and the root mean square error (RMSE) statistics defined as:

$$MXE = \max_{i=1,N}[\text{abs}(f_i - e_i)], \quad ME = \left(\frac{\sum(f_i - e_i)}{N}\right) \times 100, \quad \text{and} \quad \text{RMSE} = \left(\frac{\sum(e_i^2)}{N}\right)^{1/2} \times 100.$$ 

where $N$ is the number of observations, and $(f_i - e_i)$ is the error between fitted value, $f_i$, and estimated value, $e_i$. These three statistics were employed to measure the power of the performance of the different PTFs: the MXE may be considered as a local indicator of the goodness of the estimates provided by a certain PTF, the ME reveals the presence of a possible bias (i.e., a systematic overestimation or underestimation of the fitted values), while the RMSE gives an overall idea of the dispersion between RETC-fitted water contents vs. PTF-estimated water contents and therefore quantifies the scatter around the 1:1 line in a plot depicting these two different data sets.

Geostatistical analysis of the spatial data sets was then performed to evaluate the structure of spatial variability exhibited by the retention characteristics along the study transect, and the classical estimator was employed for the experimental semivariance, $\gamma$, as a function of the distance $l$ between the sampled locations (Journel and Huijbregts, 1978). Visual inspection of plots of the spatial series versus distance along the transect was used to identify spatial outliers as well as trends in the variables. The lack of outliers did not make it necessary to use more robust estimates of the function $\gamma(l)$, namely more resistant to the effects of outliers (Cressie and Horton, 1987). Also, no presence of trends was observed in the examined data sets. The maximum lag distance considered for semivariance calculations was 30 (equal to a maximum separation distance of 30×50m=1500 m), so as to meet the empirical criterion which
suggests stopping the estimation of the semivariance function for lag distances exceeding values between $N/4$ and $N/3$. All the experimental semivariograms were fitted to the spherical model (Journel and Huijbregts, 1978). The spherical model performed well in all of the cases considered in this study, but the selection of a unique theoretical model was also made to allow an easy and direct comparison among the geostatistical model coefficients of the four PTFs. Therefore, cross-validation techniques were not used to judge the validity of the fitted theoretical model. All geostatistical analyses were carried out using the GEOPACK software package (Yates and Yates, 1990), which employs a non-linear least-squares fitting procedure for estimating the coefficients of the semivariogram function.

Comparisons between descriptive statistics for the fitted and PTF-estimated soil water retention characteristics are carried out with reference to water content $\theta$ at the selected pressure potentials of -10 and -100 kPa for PTFs of Group A, and to water content $\theta$ at the selected pressure potentials of -1, -10, and -100 kPa for PTFs of Group B (Table 1).

Table 1. Statistical properties of fitted and PTF-estimated variables used for evaluation and relevant statistical comparisons.

<table>
<thead>
<tr>
<th>PTF</th>
<th>Variable</th>
<th>Min</th>
<th>Max</th>
<th>$\bar{x}$</th>
<th>$\sigma$</th>
<th>CV</th>
<th>$K^2$</th>
<th>MXE</th>
<th>ME</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fitted Water Retention Data</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\theta_{-1}$</td>
<td>0.313</td>
<td>0.526</td>
<td>0.418</td>
<td>0.0412</td>
<td>9.85</td>
<td>5.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\theta_{-10}$</td>
<td>0.286</td>
<td>0.493</td>
<td>0.390</td>
<td>0.0463</td>
<td>11.9</td>
<td>0.15</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\theta_{-100}$</td>
<td>0.157</td>
<td>0.427</td>
<td>0.286</td>
<td>0.0482</td>
<td>16.9</td>
<td>0.58</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PTF-estimated Water Retention Data</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A1</td>
<td>$\theta_{-10}$</td>
<td>0.301</td>
<td>0.545</td>
<td>0.432</td>
<td>0.0576</td>
<td>13.3</td>
<td>4.1</td>
<td>0.154</td>
<td>-4.26</td>
<td>5.95</td>
</tr>
<tr>
<td></td>
<td>$\theta_{-100}$</td>
<td>0.121</td>
<td>0.554</td>
<td>0.255</td>
<td>0.0517</td>
<td>20.3</td>
<td>0.87</td>
<td>0.148</td>
<td>5.09</td>
<td>5.91</td>
</tr>
<tr>
<td>A2</td>
<td>$\theta_{-10}$</td>
<td>0.269</td>
<td>0.538</td>
<td>0.425</td>
<td>0.0552</td>
<td>13.0</td>
<td>2.1</td>
<td>0.173</td>
<td>-3.54</td>
<td>5.83</td>
</tr>
<tr>
<td></td>
<td>$\theta_{-100}$</td>
<td>0.150</td>
<td>0.404</td>
<td>0.288</td>
<td>0.0512</td>
<td>17.8</td>
<td>0.12</td>
<td>0.148</td>
<td>-0.274</td>
<td>4.95</td>
</tr>
<tr>
<td>B1</td>
<td>$\theta_{-1}$</td>
<td>0.361</td>
<td>0.521</td>
<td>0.429</td>
<td>0.0375</td>
<td>8.73</td>
<td>4.4</td>
<td>0.0880</td>
<td>-1.08</td>
<td>2.34</td>
</tr>
<tr>
<td></td>
<td>$\theta_{-10}$</td>
<td>0.242</td>
<td>0.463</td>
<td>0.372</td>
<td>0.0441</td>
<td>11.9</td>
<td>2.1</td>
<td>0.0970</td>
<td>1.77</td>
<td>3.79</td>
</tr>
<tr>
<td></td>
<td>$\theta_{-100}$</td>
<td>0.146</td>
<td>0.376</td>
<td>0.279</td>
<td>0.0507</td>
<td>18.2</td>
<td>1.3</td>
<td>0.121</td>
<td>0.755</td>
<td>4.95</td>
</tr>
<tr>
<td>B2</td>
<td>$\theta_{-1}$</td>
<td>0.353</td>
<td>0.501</td>
<td>0.422</td>
<td>0.0293</td>
<td>6.94</td>
<td>3.9</td>
<td>0.097</td>
<td>-0.415</td>
<td>3.12</td>
</tr>
<tr>
<td></td>
<td>$\theta_{-10}$</td>
<td>0.286</td>
<td>0.462</td>
<td>0.376</td>
<td>0.0334</td>
<td>8.89</td>
<td>0.56</td>
<td>0.098</td>
<td>1.33</td>
<td>3.87</td>
</tr>
<tr>
<td></td>
<td>$\theta_{-100}$</td>
<td>0.142</td>
<td>0.400</td>
<td>0.294</td>
<td>0.0494</td>
<td>16.8</td>
<td>0.92</td>
<td>0.135</td>
<td>-0.800</td>
<td>4.87</td>
</tr>
</tbody>
</table>

* Min, minimum value; Max, maximum value; $\bar{x}$, mean; $\sigma$, standard deviation; CV, coefficient of variation (%); $K^2$, $K^2$ statistic for normality test computed from the data ($K^2_{0.05} = 5.96$). MXE, maximum error; ME, mean error; RMSE, root mean square error.

Overall, in terms of sample means and standard deviations the PTF of Rawl-Brakensiek and Vereecken (Group B PTFs) provide better estimates than the PTFs of Gupta-Larson and Rawls (Group A PTFs). The standard deviations are generally
greater for the PTFs pertaining to Group A than for PTFs of Group B. The highest $\sigma$ is observed at $\theta_{10}$ as estimated by PTF A1, whereas the smallest $\sigma$ occurs for $\theta_{1}$ as estimated by PTF-B2. Although the individual mean and standard deviation values for the PTF-estimated variables are in some cases rather different from those computed for the reference variables, the CVs of the PTF-estimated water contents compare closely with the CVs determined for the fitted water contents, thus indicating a high similarity in relative dispersion between the water retention data sets. As shown in the literature, the CVs reported in Table 1 increase moving from wetter to drier regions of the water retention curve. It is also worth noting that the range of variation (i.e., Max-value minus Min-value) for Vereecken’s PTF is always significantly smaller than the range of variation for the fitted water contents, and this indicates a sort of smoothing effect with respect to the reference data caused by the use of this PTF. In contrast, for most of the remaining test cases the ranges of variation are greater than those of the fitted water contents.

One shortcoming that becomes apparent in using the PTFs A1, A2, and B1 is their inability to provide reliable mean values of the retention characteristics along the transect, despite an overall good estimation of the deviations from the means. On the other hand, while the analysis of variance has confirmed even analytically that Vereecken’s PTF tends to generate smoother patterns of spatial data, this analytical function offers the best efficient indirect estimation of the soil-water retention curves along the transect. Especially from a broader point of view of employing hydrological models at large scales, the choice of a method which enables the mean values of a certain soil hydraulic variable to be determined accurately is of primary importance. The main consequences of a different magnitude of the spread around the mean, with respect to the behavior of the original retention data, exhibited in some cases by the tested PTFs will be discussed further on in this section through the geostatistical analysis of the transect data.

In Table 1, if $K_{c}^{2} > K_{0.05}^{2}$ the hypothesis that the set of data is derived from a normal distribution should be rejected. All the fitted water retention data employed as spatial variables for comparison can be considered as normally distributed and all the sets of PTF-estimated data behave similarly. In a comparison of $K_{c}^{2}$ statistic for the fitted and PTF-estimated variables, only $K_{c}^{2}$ values for PTF-B2 are very similar to the corresponding values of the fitted variables and therefore the frequency distributions of these data sets have practically the same skew and thickness of the tails as those of the fitted data. The ME values show an overall tendency of the PTF Group A towards a systematic overestimation of the fitted retention data. With respect to this problem, the PTF Group B behave in a rather neutral way within the range of pressure potentials considered. The generally good assessment provided by the PTFs B1 and B2 is confirmed if one examines the computed values of the RMSE statistic. A qualitatively summary of the above comments can be found in Figure 1 that shows, as an example, the plots of fitted vs. PTF-estimated water contents at the selected pressure potential of -10 and -100 kPa for PTF-A1 of Gupta-Larson and PTF-B2 of Vereecken. For the variables estimated by PTF-B2, most of the points fall close to the 1:1 line with very
few outliers. In contrast to the results on PTF-B2, the plots related to the expression PTF-A1 clearly show the presence of biases in estimating the retention characteristics.

The predicted retention values at selected pressure potentials for the 100 sampled locations along the transect are shown in Figure 2 for PTF-A1 and PTF-B2. In each of these plots, open circles indicate the fitted water contents obtained from the experimental water retention curves. None of the spatial series reveal trends along the transect or the presence of spatial outliers. In the case of PTF-A1, the estimated spatial series of $\theta_{10}$ show evident differences from the fitted series within the first half of the transect, and then the two series run rather closely. There are no significant differences between the two spatial series of the variable $\theta_{100}$, except at approximately $d=1000$ m and for distances ranging from about 2300 to 3000 m. Similar results are observed for the case of PTF-A2, although now the two series under comparison are much closer and follow somewhat similar patterns (plots not shown). In the case of the PTFs of Group B, except for a few locations, the correspondence between fitted and estimated retention values at $h=-10$ kPa is much more satisfactory. For $h=-100$ kPa, discrepancies between the two sets of spatial data become more evident. As already discussed when presenting the statistics of the variables considered, the PTF of Vereecken tends to smooth out the variability of the fitted retention characteristics along the transect. It is therefore important to see whether this behavior of PTF-B2 can cause any evident consequence for the geostatistical analysis.
Fig. 2. Spatial series of soil-water retention variables $\theta_{10}$ and $\theta_{100}$ as estimated using PTF-A1 and PTF-B2. Open circles indicate the fitted retention data.

The results of the geostatistical analysis are presented in Table 2, which reports the sample variances together with the geostatistical parameters which appear in the spherical model as computed using either the fitted or the PTF-estimated water retention data considered in this study. In this table the close correspondence between variance and total semivariance is evident in most of the cases, thereby practically confirming the absence of trends in the spatial series. However, two points are worth noting. First, the distance of spatial correlation, as expressed by the range $R$, is comparable for all of the spatial series, except for those relating to the variable $\theta_{100}$: the range for the fitted $\theta_{100}$ values is significantly less than the ranges of the PTF-estimated $\theta_{100}$ values. Secondly, all the fitted water retention variables show a rather weak spatial correlation, with percent ratio between nugget semivariance and total semivariance being on average equal to about 60%. With the exception of the variable $\theta_1$ as estimated by PTF-B1, the water retention characteristics predicted by the pedo-transfer functions tested here show a more evident spatial structure and the percent ratio between nugget semivariance and total semivariance is about 35%.
Table 2. Parameters for semivariogram models for fitted and PTF-estimated retention characteristics.

<table>
<thead>
<tr>
<th>PTF</th>
<th>Variable</th>
<th>Variance</th>
<th>Model</th>
<th>Nugget</th>
<th>Structural</th>
<th>Total</th>
<th>Range</th>
<th>m</th>
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</thead>
<tbody>
<tr>
<td></td>
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<td></td>
<td>Semivariance</td>
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<td></td>
<td></td>
<td>Fitted Water Retention Data</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>θ₁₀</td>
<td>1.696 · 10³</td>
<td>0.9679 · 10³</td>
<td>0.4993 · 10³</td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Spherical</td>
<td></td>
<td>1.356 · 10³</td>
<td>0.6854 · 10³</td>
<td>2.041 · 10³</td>
<td>378.73</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td>θ₁₀₀</td>
<td>2.144 · 10³</td>
<td>1.322 · 10³</td>
<td>1.124 · 10³</td>
<td>2.446 · 10³</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Spherical</td>
<td></td>
<td>2.324 · 10³</td>
<td>1.322 · 10³</td>
<td>1.124 · 10³</td>
<td>2.446 · 10³</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>PTF-estimated Water Retention Data</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>θ₁₀</td>
<td>3.314 · 10³</td>
<td>1.128 · 10³</td>
<td>2.497 · 10³</td>
<td>3.625 · 10³</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Spherical</td>
<td></td>
<td>2.677 · 10³</td>
<td>1.183 · 10³</td>
<td>2.192 · 10³</td>
<td>3.375 · 10³</td>
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<td></td>
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<td></td>
<td></td>
<td>θ₁₀₀</td>
<td>3.053 · 10³</td>
<td>1.076 · 10³</td>
<td>2.548 · 10³</td>
<td>3.624 · 10³</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Spherical</td>
<td></td>
<td>2.623 · 10³</td>
<td>1.134 · 10³</td>
<td>2.183 · 10³</td>
<td>3.317 · 10³</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>B1 θ₂</td>
<td>1.404 · 10³</td>
<td>0.8023 · 10³</td>
<td>0.5972 · 10³</td>
<td>1.399 · 10³</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Spherical</td>
<td></td>
<td>1.948 · 10³</td>
<td>0.8518 · 10³</td>
<td>1.493 · 10³</td>
<td>2.345 · 10³</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>θ₁₀₀</td>
<td>2.568 · 10³</td>
<td>1.157 · 10³</td>
<td>2.068 · 10³</td>
<td>3.225 · 10³</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Spherical</td>
<td></td>
<td>2.444 · 10³</td>
<td>1.161 · 10³</td>
<td>1.938 · 10³</td>
<td>3.099 · 10³</td>
</tr>
</tbody>
</table>

To facilitate the comparison of the shapes of the functions \( \gamma(l) \), normalized semivariograms are plotted with the dimensionless vertical axes representing the ratio between the semivariance \( \gamma \) and the relevant sample variance \( \sigma^2 \) of each spatial series. Figure 3 presents the normalized spherical semivariogram models for the fitted retention variables \( \theta_{1} \), \( \theta_{10} \), and \( \theta_{100} \) as well as the normalized spherical semivariograms associated to the same variables as predicted by the pedo-transfer functions. The form of the normalized spherical models for the PTF series seems to remain relatively constant. These semivariograms show rather greater relative sills than that of the fitted series and tend to exhibit similar relative nugget effects. The relative position of the normalized semivariograms for the fitted and PTF-estimated variables is such that it could result in kriged retention values rather insensitive to the type of method employed to determine the water retention characteristics. However, this last statement should be carefully verified and the degree of insensitiveness tested with reference to the problem under study.
Fig. 3. Normalized spherical semivariograms for the soil-water retention variables $\theta_{1}$, $\theta_{10}$, and $\theta_{100}$ as fitted to the original retention data and as predicted by the PTFs.

References


Significance of the soil fabric on the water retention properties: Example of clayey soils and consequences on PTFs.

A. Bruand, P. Quétin, O. Duval, H. Gaillard and L. Raison

INRA - Centre de Recherche d'Orléans - Unité de Science du Sol - SESC PF
Avenue de la Pomme de Pin - 45160 Ardon - France

Introduction

Pedotransfer functions (PTFs) have been developed to predict soil properties such as hydraulic properties from other more easily available soil characteristics (Bouma, 1989). The ability of PTFs to predict the soil behaviour is related to the number and availability of soil data which are required and to the accuracy of the estimation. Water retention properties of clayey soils have been studied for several years at the Soil Science Laboratory in Orléans in order to investigate the variation in water retained at each value of matric potential according to the clay mineralogy, fabric and content. In this paper, we present briefly the results of these different studies.

Material

The soils which were studied were located mostly in the Paris Basin and developed on marl, sedimentary clays, limestones and alluvial deposits (Bruand et al., 1996). 220 subsoil horizons were collected. The clay content ranged from 30 to 98 % and the bulk density from 1.1 to 1.8. The organic carbon content ranged from 2 to 10 g kg$^{-1}$ except for a few horizons which exhibited a higher carbon content.

Methods

Undisturbed samples 50 - 100 cm$^3$ in volume were collected in winter when the soil was near to field capacity because in moist conditions, porosity is more homogeneous
and there is less risk of a change in sample volume during equilibration at high water potential (Hall et al., 1977). The samples were stored at 5°C in sealed plastic containers to avoid water loss, and clods 5-8 cm$^3$ in volume were separated from them by hand. The field bulk volume ($V_b$ in cm$^3$ g$^{-1}$, reciprocal of the bulk density) of the clods was measured using the kerosene method (Monnier et al., 1973). Water contents ($\theta_m$, g of water per g of oven-dried soil) at -1, -3.3, -10, -33, -100, -330, -1 000 and -1500 kPa matric potentials were measured using pressure membrane or pressure plate apparatus. Clods were placed on a paste made of <2μm particles of kaolinite to establish continuity of water between the clods and the membrane or the porous plate of the apparatus (Tessier et al., 1992; Bruand et al., 1996). Water contents were expressed with respect to the dry mass of the sample after oven-drying at 105°C for 24h, then converted with respect to the soil volume near to field capacity ($\theta_n$, in g of water per cm$^3$ of soil) by correcting $\theta_m$ as follows:

$$\theta_n = \theta_m / V_b$$  \[1\]

Fifteen clods were used for each sample to determine the mean values of $V_b$ and water retained at the different values of matric potential.

## Results and discussion

### Development of PTFs using a single soil characteristic

The results showed that PTFs which use a single soil characteristic can be established to predict the water retained for a matric potential ranging from -1 to -1500 kPa (Bruand et al., 1996). A close linear relationship was established between the water retained ($\theta_m$) and the bulk volume ($V_b$) of the soil when it is near to field capacity (Table 1). These relationships were used to predict the value of $\theta_m$ within the same range of matric potential without any distinction of clay content, clay mineralogy or pedological origin. The mean error on the calculated water content ranged from 0.02 to 0.03 g g$^{-1}$ for the matric potentials which were investigated (Table 2). Water content expressed with respect to the soil volume can be estimated with the relationships given in Table 1 by correcting $\theta_m$ using Eq. [1].

The close relationships which were established showed the importance to refer both the amount of water retained and the soil properties to the same basis, i.e. the oven-dried mass of soil and not the soil volume as usually done. By using the oven-dried mass of soil, the results were referred to a constant mass of solid phase whatever the bulk density of the soil or its water content. Thus, it was possible to relate in a simple way the water retained to a soil characteristic such as $V_b$ which expresses numerically and globally the soil fabric.
Table 1. Regression equations which were established for the clayey horizons at different matric potentials between the gravimetric water content ($\theta_m$, in g of water per g of oven-dried soil material) and the bulk volume ($V_b$, in cm$^3$ per g of oven-dried soil, reciprocal of the bulk density) of the horizons near to the field capacity (after Bruand et al., 1996).

<table>
<thead>
<tr>
<th>Matric potential (kPa)</th>
<th>Regression equation</th>
<th>$r^2$ corr. coeff.</th>
<th>n number of horizons</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1</td>
<td>$\theta_m^{\cdot1} = 0.949 \left( V_b \right) + 0.339$</td>
<td>0.87</td>
<td>43</td>
</tr>
<tr>
<td>-3.3</td>
<td>$\theta_m^{\cdot3} = 0.914 \left( V_b \right) + 0.324$</td>
<td>0.89</td>
<td>35</td>
</tr>
<tr>
<td>-10</td>
<td>$\theta_m^{\cdot10} = 0.871 \left( V_b \right) + 0.312$</td>
<td>0.89</td>
<td>24</td>
</tr>
<tr>
<td>-33</td>
<td>$\theta_m^{\cdot33} = 0.869 \left( V_b \right) + 0.313$</td>
<td>0.91</td>
<td>106</td>
</tr>
<tr>
<td>-100</td>
<td>$\theta_m^{\cdot100} = 0.763 \left( V_b \right) + 0.361$</td>
<td>0.88</td>
<td>50</td>
</tr>
<tr>
<td>-330</td>
<td>$\theta_m^{\cdot330} = 0.725 \left( V_b \right) + 0.261$</td>
<td>0.88</td>
<td>34</td>
</tr>
<tr>
<td>-1 000</td>
<td>$\theta_m^{\cdot1000} = 0.629 \left( V_b \right) + 0.204$</td>
<td>0.89</td>
<td>26</td>
</tr>
<tr>
<td>-1 500</td>
<td>$\theta_m^{\cdot2500} = 0.527 \left( V_b \right) + 0.152$</td>
<td>0.78</td>
<td>107</td>
</tr>
</tbody>
</table>

Table 2. Mean error on the estimation of the gravimetric water content ($\theta_m$) for the clayey horizons (after Bruand et al., 1996)

<table>
<thead>
<tr>
<th>Matric potential (kPa)</th>
<th>Mean error (g g$^{-1}$)</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1</td>
<td>0.034</td>
<td>42</td>
</tr>
<tr>
<td>-3.3</td>
<td>0.027</td>
<td>39</td>
</tr>
<tr>
<td>-10</td>
<td>0.028</td>
<td>24</td>
</tr>
<tr>
<td>-33</td>
<td>0.027</td>
<td>104</td>
</tr>
<tr>
<td>-100</td>
<td>0.027</td>
<td>54</td>
</tr>
<tr>
<td>-330</td>
<td>0.031</td>
<td>39</td>
</tr>
<tr>
<td>-1 000</td>
<td>0.020</td>
<td>24</td>
</tr>
<tr>
<td>-1 500</td>
<td>0.028</td>
<td>105</td>
</tr>
</tbody>
</table>

Significance of the clay content and clay fabric

The capability of $V_b$ to express the soil fabric results from the close relationship between the bulk volume and both the clay content and clay fabric. The clay fabric, which is defined as the spatial assemblage of clay particles (Brewer and Sleeman, 1960), was expressed numerically using the pore volume associated with the clay phase ($v_p^c$, volume of pores within the clay phase in cm$^3$ of pore per g of oven-dried
clay). This was done by calculating the pore volume \( V_p \) inside the soil as follows (Bruand et al., 1994):

\[
V_p = V_b - V_s^{cl+sk}
\]  

[2]

with \( V_b \) : the field bulk volume in cm\(^3\) per g of oven-dried soil,

\( V_s^{cl+sk} \) : the volume of the solid phase in cm\(^3\) per g of oven-dried soil (0.377 cm\(^3\) g\(^{-1}\), reciprocal of 2.65 g cm\(^{-3}\)).

Results showed that \( V_p \) ranged from 0.179 to 0.532 cm\(^3\) g\(^{-1}\). For clayey soils and when they are near to field capacity, it was demonstrated that the pore volume due to cracks and biological activity can be neglected against the pore volume due to the clay fabric \( (V_p^{cl}) \), i.e. the pore volume which results from the packing of elementary clay particles within the clay phase (Bruand et al., 1994). Thus:

\[
V_p^{cl} = V_p
\]  

[3]

Then, \( V_p^{cl} \) was calculated by correcting \( V_p^{cl} \) for the clay content \((C, \text{ in g of particles < 2 \( \mu \)m per 100 g of oven-dried soil})\) as follows:

\[
V_p^{cl} = \frac{V_p^{cl}}{(10^2 C)}
\]  

[4]

The values of \( V_p^{cl} \) which were calculated in that way ranged from 0.39 to 0.99 cm\(^3\) g\(^{-1}\).

![Graph](image)

Fig. 1. Clay fabric expressed as the clay pore volume \( (V_p^{cl}) \) versus the clay mineralogy expressed as the cation exchange capacity of the clay phase \( (\text{cccl}) \).

Clay mineralogy was characterized by the cation exchange capacity of the clay phase \((\text{cccl}, \text{ in cmol}^+ \text{ per kg of oven-dried clay})\) as follows:

\[
\text{cccl} = \frac{CEC}{(10^2 C)}
\]  

[5]
with CEC, the cation exchange capacity of the bulk sample. cec$^{cl}$ was smaller than 25 cmol$^+$ kg$^{-1}$ for 22 horizons, ranged from 25 to 45 cmol$^+$ kg$^{-1}$ for 110 horizons and was greater than 45 cmol$^+$ kg$^{-1}$ for the remaining horizons. The relationship between $\nu_p^{cl}$ and cec$^{cl}$ indicates the clay fabric as being related to the clay mineralogy ($r = 0.73$, $n = 86$) (Fig. 1, Bruand and Zimmer, 1992).

Studies by transmission electron microscopy on clays extracted from the studied clayey soils have shown that cec$^{cl}$ is related to the number of sheets which constitute the elementary clay particles (Robert et al., 1991). This result is consistent with those from other works on elementary particles of illite, interbedded illite-smectite and smectite extracted from soils (Nadeau et al., 1984a and b). By referring to these studies that proposed a new conceptual model for interbedded clays, we proposed a morphological model for the fabric of elementary particles that is consistent with the relationship between $\nu_p^{cl}$ and cec$^{cl}$ (Fig. 2).

![Morphology of the fabric of the clay phase that takes the clay pore volume ($\nu_p^{cl}$) and the cation exchange capacity of the clay phase (cec$^{cl}$) variations into account.](image)

**Use of a pedological stratification**

Among the whole set of clayey horizons which were studied, three much smaller sets (sets I, II and III) were considered to discuss the interest to stratify the clayey horizons prior the establishment of PTFs (Bruand, 1990). Set I consisted of 18 horizons originating from various contrasting French soil families. A soil family is defined as a group of soil having the same pedogenic origin, and developed from a particular type of parent material (Jamagne, 1967). Set II consisted of 13 horizons originating from Chromic Luvisols (FAO, 1988) which were developed in a formation resulting from the weathering of Jurassic limestones (Baize, 1972). Set III consisted of 9 horizons originating from Gleyic Cambisol (FAO, 1988) which were developed in a Miocene sandy-clay alluvial deposit (Arrouays, 1987; Lamotte et al., 1988).
With horizons originating from a number of contrasting locations, we showed that it was necessary to take $V_b$ into account, i.e. both clay content ($C$ ranging from 31 to 93%) and clay fabric ($\nu_p$ ranging from 0.551 to 0.911 cm$^3$ g$^{-1}$), in order to explain the differences in $\theta_m$ (Table 3). There was a strong decrease in the closeness of the relationships when $C$ was used as soil characteristic instead of $V_b$.

Table 3. Regression equations between the water retained at -33 kPa ($\theta_{m}^{33}$) and -1 500 kPa ($\theta_{m}^{1500}$) matric potential and (i) the clay content ($C$, expressed as the percentage of particle size <2 µm) and (ii) the bulk volume ($V_b$ in cm$^3$ g$^{-1}$) (after Bruand, 1990).

<table>
<thead>
<tr>
<th>Regression equations</th>
<th>Variance accounted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sets I, II and III (n = 40)</td>
<td></td>
</tr>
<tr>
<td>$\theta_{m}^{33} = 0.408 \times (10^2 C) + 0.050$</td>
<td>67</td>
</tr>
<tr>
<td>$\theta_{m}^{33} = 0.873 \times (V_b) - 0.321$</td>
<td>89</td>
</tr>
<tr>
<td>$\theta_{m}^{1500} = 0.362 \times (10^2 C) + 0.014$</td>
<td>82</td>
</tr>
<tr>
<td>$\theta_{m}^{1500} = 0.701 \times (V_b) - 0.266$</td>
<td>89</td>
</tr>
<tr>
<td>Set I (n = 18)</td>
<td></td>
</tr>
<tr>
<td>$\theta_{m}^{33} = 0.385 \times (10^2 C) + 0.072$</td>
<td>57</td>
</tr>
<tr>
<td>$\theta_{m}^{33} = 0.946 \times (V_b) - 0.360$</td>
<td>95</td>
</tr>
<tr>
<td>$\theta_{m}^{1500} = 0.350 \times (10^2 C) + 0.024$</td>
<td>76</td>
</tr>
<tr>
<td>$\theta_{m}^{1500} = 0.730 \times (V_b) - 0.279$</td>
<td>90</td>
</tr>
<tr>
<td>Set II (n = 13)</td>
<td></td>
</tr>
<tr>
<td>$\theta_{m}^{33} = 0.400 \times (10^2 C) + 0.043$</td>
<td>86</td>
</tr>
<tr>
<td>$\theta_{m}^{33} = 0.917 \times (V_b) - 0.376$</td>
<td>87</td>
</tr>
<tr>
<td>$\theta_{m}^{1500} = 0.367 \times (10^2 C) + 0.008$</td>
<td>90</td>
</tr>
<tr>
<td>$\theta_{m}^{1500} = 0.821 \times (V_b) - 0.362$</td>
<td>87</td>
</tr>
<tr>
<td>Set III (n = 9)</td>
<td></td>
</tr>
<tr>
<td>$\theta_{m}^{33} = 0.581 \times (10^2 C) + 0.026$</td>
<td>94</td>
</tr>
<tr>
<td>$\theta_{m}^{33} = 0.935 \times (V_b) - 0.346$</td>
<td>95</td>
</tr>
<tr>
<td>$\theta_{m}^{1500} = 0.390 \times (10^2 C) + 0.004$</td>
<td>92</td>
</tr>
<tr>
<td>$\theta_{m}^{1500} = 0.633 \times (V_b) - 0.220$</td>
<td>94</td>
</tr>
</tbody>
</table>

For horizons originating from a single soil family (Sets II and III), a high percentage of variance was explained by $C$. $V_b$ did not significantly increase the percentage of variance that was explained. The close relationship between $\theta_m$ and $C$ was attributed to the low variation of $\nu_p$ within sets II and III ($0.534 < \nu_p < 0.657$ cm$^3$ g$^{-1}$ within set II and $0.467 < \nu_p < 0.604$ cm$^3$ g$^{-1}$ within set III). Thus, in contrast to set I, the clay fabric did not change greatly within sets II and III.
After pedological stratification, $V_s$ depends primarily on clay content since when soils result from the same pedogenesis on a particular parent material, their clay fabric does not change greatly (Bruand, 1990). Consequently, differences in water retained can be explained by variations in clay content alone and PTFs can be established with the clay content alone, i.e. a soil characteristic which is more easily available than the bulk volume. The relationships established for set III were used for prediction of water retained for soils originating from the same soil family. The results showed no difference in the prediction accuracy of water retained using $C$ and $V_s$ (Bruand et al., 1994).

**Conclusion**

Our results showed that it is possible to establish simple PTFs to estimate the water retained at particular values of matric potential. Such relationships were established using a single soil variable such as the bulk volume when the soil is near to field capacity, or a more easily obtained variable such as the clay content for sets of clayey soils originating from the same soil family. For clayey soils, our results also showed that it should be possible to establish an equation for the water retention curve using a single variable which could be the clay content after an appropriate pedological stratification, or the bulk volume when there is no such a stratification.

**References**


Interest of class pedotransfer functions and soil distribution models for water quality studies: the case of nitrate in armorican catchments

P. Curmi, C. Walter, C. Gascuel-Odoux and P. Durand

Unité de Science du Sol et de Bioclimatologie INRA-ENSAR
65 rue de Saint Brieuc, 35042 Rennes cedex, France

Introduction

The modernisation of agriculture in Brittany over the last 30 years has made it one of the most productive regions of both France and Europe for pigs, dairy products and vegetables. The environmental consequences of such a development have been underestimated: a significant part of the area is in structural excess of nitrogen due to the density of indoor farming (Cann, 1990). In humid temperate zones with large areas of hydromorphic soils, the denitrification in waterlogged areas is thought to be the main sink for the nitrogen leached from the cultivated soils. The importance of this process will depend on the space and time extension of waterlogged areas and on water pathways within the landscape at different scales. This led the investigations conducted at a hydrological and landscape unit level, within a catchment, and focussing on the description of the spatial structure of the processes governing the water transfers (Curmi et al., 1995). The present paper shows how the pedological approach enables the landscape compartmentalisation into several pedological volumes. The use of this compartmentalisation for hydrological and water quality purposes is then illustrated.

The pedological system in the silty cover of the armorican massif

In the silty loam cover which is spread over schist and granite substrates, soil distribution can be modelled as a soil system comprising a well drained domain and a poorly drained one. Three dominant processes occur: leaching of clay particles, hydromorphy and degradation which produce seven pedological horizons with a determined spatial arrangement and genetic relationships (Curmi, 1993).
In the well drained domain, acid conditions lead to the development of a microgranular structure in the Sal horizon of the « Alocrisol » (Arousseau et al., 1985). Clay migration causes the development of eluvial E and illuvial BT horizons in the loamy cover when it is thick enough and produces a « Luvisol » (Curmi et al., 1994). In the poorly drained domain, iron redistribution due to hydromorphy follows clay particles translocation in Eg and BTg horizons of the « Luvisol Rédoxisol ». The degradation process in acid and reducing conditions occurs afterwards in the « Luvisol Rédoxisol dégradé ». This phenomenon covers geochemical, mineralogical and morphological aspects simultaneously (Roussel, 1982), resulting in: (i) geochemically, a loss of iron and clay mineral hydrolysis; (ii) mineralogically, a relative increase of quartz in the clay fraction and an aluminisation of clay interlayer spaces (Arousseau et al., 1983); (iii) morphologically, the bleaching and the loss of structure of the reduced volumes. This structure loss leads to an important macroporosity when non degraded volumes are still present and maintain the global architecture. This is the case of the illuvial and degraded horizon BTgd where the resulting macropores are the center of preferential flow (Diab et al., 1988). On the contrary, when degradation concerns the whole horizon, structure collapse is total and leads to a compact massive structure, as the result of the silty texture of the material. This is the case of the eluvial albic horizon Ea, a horizon of very low permeability (Widiatmaka, 1994) that induces hypodermic subsurface flow.

Fig. 1. Horizon distribution along a typical toposequence

Detailed studies of catenas show that hydromorphy, increasingly accompanied by degradation, appears from upslope to downslope starting at the basis of the silty horizons and gradually reaching the outer surface (Fig. 1). Therefore an increasing

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1 Soil and horizon denominations are made according to the « Référentiel Pédologique » (Baize et Girard, 1995).
development of hydromorphy and degradation in originally well drained horizons seems to be caused by an excess of water of topographical origin. The detailed survey of the stream banks reveals a second type of system in a colluvio-alluvial material, not yet well understood. In the case of schist bedrock, as far as the hydrodynamic properties are concerned, this colluvio-alluvial system can be assimilated to the hydromorphic and degraded domain.

Hydrodynamic characteristics of the pedological horizons of the soil system

The pedological approach identified a small number of horizons and their topological relationships. The next step was to test the interest of this stratification to predict the hydrodynamical properties of the soil. For this purpose saturated hydraulic conductivity (Ksat) and water retention curves θ(Ψ) of the seven horizons were determined and an attempt was made to group these horizons (Widiatmaka & Curmi, 1994) following the "building blocks" concept (Bouma, 1989).

The Ksat data followed a lognormal distribution. But Ksat of the well drained horizons were significantly greater and more scattered than Ksat of the poorly drained horizons which led to define two « building blocks » (Fig. 2A). θ(Ψ) data were obtained from undisturbed cores at six potentials. Discriminant factor analysis on the θ(Ψ) data led to the creation of three « building blocks », each block being defined by the mean values and standard deviations of the water contents at the six potentials (Fig. 2B).
These first results obtained on a reference site were validated at the catchment level of 1200 ha (Walter et al., 1996). They show that the seven soil horizons of our pedological system can be grouped in a smaller number of building blocks depending on the parameter considered (Table 1). These groupings illustrate that in a soil cover relatively homogeneous in texture, the structure variations induced by the pedological processes are dominant. The hydrodynamic properties of the horizons worsen with the pedological development. When iron and clay are lost in silty soils, the structure collapses.

Table 1. Groups of horizons according to their hydrodynamic properties

<table>
<thead>
<tr>
<th>Domains</th>
<th>Soil types</th>
<th>Horizon types</th>
<th>$K_{sat}$ « building blocks »</th>
<th>$\theta(\Psi)$ « building blocks »</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well drained</td>
<td>Allochrisol</td>
<td>Sal</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>Luvisol</td>
<td>E</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BT</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Poorly drained</td>
<td>Luvisol</td>
<td>Eg</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>Rédoxisol</td>
<td>BTg</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>Luvisol</td>
<td>Ea</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>Rédoxisol</td>
<td>BTgd</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

According to these « building blocks » and to the soil distribution model, two main domains with specific behaviour can be identified along the slope at the catchment scale: a highly permeable homogeneous upslope domain and a poorly permeable multilayered downslope one.

**A two dimensional multilayer water transfer model**

The development of temporary shallow perched water tables above the eluvial albic horizon Ea, in the poorly drained domain, was observed from tensiometric measurements (Zida et al., 1996). To test the hydrological behaviour of the poorly drained soils in the valley bottoms and to separate the specific contributions of the different soil layers, the Hillslope mechanistic model (HM-Model) (Taha & Gresillon, 1994) which simulates the two dimensional hydrodynamics of a layered section of hillslope was used. To describe a typical bottomslope of the area, three horizons have been distinguished: $L_g$, an old ploughed horizon with pseudogleicy features which now supports a grassland; Ea and BTgd.

The HM-Model uses the classical equation of mass transfer, using the measured saturated hydraulic conductivity of the horizons only, in a first stage. The model uses the finite difference method to solve the two dimensional transient saturated-unsaturated Richard’s flow equation. The application of the model was only a
simulation exercise. The general trends obtained agreed well with in situ observations and with the shape of the hydrographs at the outlet of the catchment.

Different rainfall events have been tested, showing that the contribution of the upper layer rises rapidly after the beginning of the shower and stops relatively quickly after its end (Fig. 3). These results suggest that the importance and dynamics of the stormflow response depend strongly on the development of the shallow perched water table above the eluvial albic horizon Ea. At least two compartments corresponding to two different flow paths contribute to the streamflow.

![Fig. 3. Simulated contribution by application of the HM-model of the perched water table (triangles) and the deep groundwater (squares) to the total hydrograph (continuous line) of a single flood event, (observed hydrograph = filled circles).](image)

**The influence of water pathways on water quality**

The next step of the study was to analyse the influence of the physiographic structure and of the hydrology on water quality, especially for the nitrate transfer. The hydrochemical variations in streamwater at the outlet of a 4.9 km² subcatchment during storm events were interpreted using a four endmember conservative mixing model to separate the hydrograph (Durand & Juan Torres, 1996).

The four endmembers were defined following the converging conclusions of the studies in pedology, hydrology and biogeochemistry. The first endmember has a chemistry close to that of the streamwater before the flood event: it was identified as the groundwater located in the weathered bedrock and the deep soil horizons. The second endmember is the overland flow, whose composition was assimilated to that of the rainwater. The third endmember is the perched aquifer located above the eluvial
albic horizon Ea of the bottomland soils. It is composed of denitrified waters seeping in the stream mainly during the storm events, due to piston flow. The fourth component comprises the free soil water of the upper horizons of the cultivated soils. This quickly circulating water can reach the stream without flowing through the bottom land saturated zone due to ditch and underground drainage networks.

![Graph showing hydrograph separation](image)

Fig. 4. Hydrograph separation for a storm event obtained by application of a four endmember mixing model (total flow = bold line; groundwater = continuous line; overland flow = triangles; perched aquifer = dashed line; cultivated zone water = circles)

The results of the hydrograph separation (Fig. 4) show that overland flow and riparian zone seepage are responsible for the beginning of water level rising, while water from the cultivated zone comes generally later. The nitrate dilution observed during the flood is nearly equally due to the overland flow and to the seepage of denitrified water. The relative contribution of each endmember varies between the events due to the antecedent conditions of the catchment and to the rainfall pattern. These results were tested using the data on the chemical parameters not used in the separation computation and the model was able to reproduce the variations of most of the parameters.

**Conclusion**

Water transfer and nitrate fate were tightly dependent on the soil distribution within the landscape. Armorican catchments with a silty cover were characterized by a soil system constituted by seven pedological horizons which could be grouped in two or
three «building blocks» depending on the hydraulic parameter (Ksat and θ(Ψ) respectively). This resulted in the identification of two main domains with specific behaviour according to the topography: (i) an upslope homogeneous well drained domain highly permeable where water and solute transfers were mainly vertical; (ii) a downslope multilayered poorly drained domain with a shallow perched water table developed above the impervious eluvial albic horizon Ea in an organic rich horizon. In the latter denitrification and lateral transfers during the storm periods might occur.

References


Effect of soil tillage on the hydraulic properties of tilled layers: Consequences for pedotransfer functions

G. Richard, J.F. Sillon and O. Marloie

I.N.R.A., Unité d’Agronomie, 02007 Laon Cedex, France

Abstract

The effect of soil tillage on the hydraulic properties of the tilled layer and its consequences for soil drying was investigated in the Spring of 1995 (March-June) in a silt loam soil (Typic Hapludalf) with 150 g clay kg\(^{-1}\) in the ploughed layer (0-30 cm). The two areas compared were a fully compacted ploughed layer resulting from severe soil compaction in wet conditions (bulk density 1.6 g cm\(^{-3}\), very low structural porosity) and a ploughed layer with a very high porosity (bulk density 1.1 g cm\(^{-3}\)) resulting from deep soil tillage in March. Soil moisture/soil water potential relationships were established from gravimetric and tensiometric measurements in the field, and by using Richards and Wind methods in the laboratory. Soil moisture/soil hydraulic conductivity relationships were established from disc permeameter measurements in the field and by the Wind method in the laboratory. The effect of soil structure on its hydraulic properties depended on the water potential and on the methods used. Soil water was restricted to the textural pore space at low water potentials and the soil water content, expressed on a mass basis, was similar whatever the soil structure. Soil water was in the textural and structural pore spaces at high water potentials, and the soil water content was lower in the compacted soil. Hydraulic conductivity, at a given water content expressed on a mass basis, was higher in the compacted soil. Discrepancies between methods are discussed and the difficulties of establishing pedotransfer functions in cultivated soils are illustrated.
Introduction

Soil bulk density varies greatly from one soil type to another and it is a major variable for predicting the hydraulic properties of a soil unit using the pedotransfer functions (see the paper by Bruand et al. in this book). But the bulk density of a tilled layer is not a permanent characteristic of cultivated soils, it changes after each soil tillage operation. Indeed, one of the aims of soil tillage is to modify the structure of the ploughed layer to control soil water balance: to facilitate soil drying (for example to increase the number of workable days in a given period), to limit soil drying (for example to favour seed germination in the seed bed), or to increase water infiltration at the soil surface. However, the effect of soil structure on soil hydraulic properties and its consequences for the soil water balance are not well quantified (Horton et al., 1994). Soil tillage also produces aggregate and clods of very different sizes, and this is the second component of the structure of a tilled layer for a given soil texture. The heterogeneity of the ploughed layer structure at one centimetre scale produced by the tillage is a great problem for building a model of water transfer and to establish pedotransfer functions in cultivated soils.

Our first step was therefore to work with a single soil having ploughed layers that were as uniform as possible under field conditions. The objective of the work was to establish the relationship between the soil structure, which is mainly described by its bulk density under uniform conditions, and the hydraulic properties of the soil. Few data have been published on the effect of soil structure on soil hydraulic properties, and those that have were mostly obtained under laboratory conditions using artificial soil samples (Reicosky et al., 1981; Tamari, 1994). In contrast, we have tried to compare methods of estimating the soil hydraulic properties under field and laboratory conditions using natural soil samples.

Material and methods

The field experiment was carried out during March-June 1995 in the North of France in Mons en Chaussée (Sonne) in a silt loam soil. The soil (Typic Haplustalf, Luvisol Orthique) contained an average of 150 g clay kg\(^{-1}\), 780 g silt kg\(^{-1}\), 50 g sand Kg\(^{-1}\), 20 g organic matter kg\(^{-1}\) and 5 g CaCO\(_3\) kg\(^{-1}\), and it had a pH of 7.6. Two treatments were tested. One was a fully compacted ploughed layer resulting from severe compaction in wet conditions under tractor wheel tracks. The bulk density was 1.63 g cm\(^{-3}\) on average in the ploughed layer which corresponded to a structural porosity, as defined by Stengel (1979), of less than 0.05 m\(^3\) m\(^{-3}\). This was a Δ layer according to the classification of Manichon (1987). The other was a fragmentary ploughed layer resulting from deep soil tillage in March. Fine earth and aggregates of less than 2 cm diameter accounted for 700 g per kg dry soil in this layer. The bulk density was 1.16 g cm\(^{-3}\) on average in the ploughed layer, the structural porosity was 0.30 m\(^3\) m\(^{-3}\).
It was a Γ layer according to Manichon (1987). The CV of the bulk density was low for the two treatments (2 and 4%) indicating a uniform soil porosity in the ploughed layer (30 cm depth). The two treatments are the extremes of a range of soil structural porosities which can be obtained by soil tillage.

Several measurements were made to obtain the soil hydraulic properties for each treatment (Table 1). The matric potential was measured in the field with mercury tensiometers installed at depths 5-25 cm in the ploughed layer. Three tensiometers were used at each depth. The water content of the ploughed layer was determined gravimetrically 3 times a week with six replications in each plot.

Table 1. Range of matric potential (in absolute values) of the field and laboratory methods used to estimate soil hydraulic properties in each ploughed layer

<table>
<thead>
<tr>
<th></th>
<th>Matric potential/ water content</th>
<th>Hydraulic conductivity/ water content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tensiometer (mercury)</td>
<td>5-80 kPa</td>
<td>-</td>
</tr>
<tr>
<td>Gravimetric soil moisture</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Infiltrometer</td>
<td>0.5 and 1 kPa</td>
<td>0.5 and 1 kPa</td>
</tr>
<tr>
<td>Laboratory</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Richards pressure plate (2-3 mm or &lt;2 mm)</td>
<td>10-100 kPa</td>
<td>-</td>
</tr>
<tr>
<td>Suction table (100 cm³)</td>
<td>1-5 kPa</td>
<td>-</td>
</tr>
<tr>
<td>Wind method (1200 cm³)</td>
<td>5-90 kPa</td>
<td>5-90 kPa</td>
</tr>
</tbody>
</table>

Matric potentials measured at 5, 12, 17 and 25 cm were plotted against the soil water content measured in the layers at 4-6 cm, 10-15 cm, 15-20 cm and 20-30 cm. The hydraulic conductivity was measured using the multiple disc infiltrometer TRIMS (Clothier and White, 1988). Hydraulic conductivity was calculated according to Scotter et al. (1982). Measurements were done for matric potentials of -0.5 and -1 kPa with two discs (10 cm and 30 cm diameter) at five locations per disc and per matric potential.

Richards pressure plates were used to measure the soil water content for water suction between 10 and 100 kPa on either aggregates of 2-3 mm diameter, or on fine earth with particle diameters less than 2 mm. The aggregates with diameters of 2-3 mm were assumed to reflect the textural pore space of the soil (Monnier et al., 1973). The fine earth with particles >2 mm is commonly used to obtain the relationship between the matric potential and water content. A suction table was used to measure soil water content for water suction of 1 and 5 kPa on 100 cm³ cylinders. The Wind method was used on cylinders with a volume of 1200 cm³. Six cylinders in each plot were taken.
from depths of 5-12 cm, or from 15-22 cm. The methodology and the analytical software were those developed by the INRA Science du Sol, Avignon (Morath et al., 1997).

**Results**

The relationships between matric potential and water content obtained in the compacted and fragmentary ploughed layers are shown in Figure 1. The water content was calculated on a mass basis because this better reflects the water retention properties of a soil.

The results for the compacted ploughed layer varied a great deal (Fig. 1a), both in the field measurements and in the data from the Wind method. The difference in soil moisture varied from 0.02 to 0.04 g g\(^{-1}\) at a given matric potential. There was a rather good agreement between the various methods, except for the infiltrometer which indicated low values of soil moisture near saturation.

The results for the fragmentary ploughed layer were less variable (Fig. 1b) than those for the compacted ploughed layer for a given method. But there was a discrepancy between the field measurements and the Wind data in the fragmentary ploughed layer:

![Fig. 1. Relationships between matric potential and soil water content in the compacted (a) and fragmentary (b) ploughed layer](image)

- **a:** Field, Infiltrometer, Wind method
- **b:** Suction table, Richards pressure plate (2-3 mm), Richards pressure plate (<2 mm)
the soil water content estimated from the Wind method was higher than that obtained from the field measurements. The difference was about 0.04 g g\textsuperscript{-1} at a given matric potential. On the other hand, the laboratory measurements agreed well with each other. The discrepancy between the Wind method and field measurements may be due to the method used to saturate the soil core with water in the Wind method. The soil core was placed under water for several days to obtain a water saturation close to 100%. This method of saturation could be too far removed from conditions in the field, inducing a higher water content at a given water potential such as hysteresis. Further measurements are needed to test this.

Comparison of the water retentions of the two ploughed layers shows that (1) the fragmentary ploughed layer had a higher water content from saturation to a matric potential of -50 kPa with the Wind method or -10 kPa with the field measurements and (2) that the two ploughed layers had similar water contents at lower matric potentials. The trend is in agreement with the partition of the pore space between textural and structural pore space: at low matric potential, water is located only in the textural pore space and the soil water content, expressed on a mass basis, does not depend on soil bulk density. At high matric potential, near saturation, water is also located in the structural pore space, which is a smaller fraction in the compacted ploughed layer. The water content is therefore lower in the compacted ploughed layer. However, the value of the matric potential at which the retentions were similar, whatever the structural pore space, seemed to be low (-10 or -50 kPa).

The relationships between hydraulic conductivity and water content obtained in the compacted or fragmentary ploughed layer are shown in Figure 2. The water content is given on a mass basis, as for the matric potential.

![Graphs](image)

**Fig. 2.** Relationships between hydraulic conductivity and soil water content in the compacted (a) and fragmentary (b) ploughed layer.
The various experimental curves obtained from the Wind method for a given situation were similar although the y-axis in Figure 2 is on a log scale. There was slightly more variation in the compacted ploughed layer than in the fragmentary ploughed layer, in spite of a more uniform bulk density. Strange experimental curves were obtained, within a very low range of soil moisture, below 0.02 g g$^{-1}$, indicating the difficulty of estimating soil hydraulic properties.

The hydraulic conductivity of the fragmentary ploughed layer was lower than that of the compacted ploughed layer, at a given water content. This was verified up to the point of saturation of the compacted ploughed layer (which was approximately 0.24 g g$^{-1}$ water). When the bulk density of a soil increases, the area of contact between aggregates increases and the hydraulic conductivity increases at a given water content when there is no water in the inter-aggregates porosity. The ratio between the hydraulic conductivity of the fragmented ploughed layer and that of the compacted ploughed layer was about 20% in the range of water content 0.20-0.24 g$^{-1}$. Tamari (1994) found similar results for artificial soil samples whose bulk densities were in the range 1-1.55 g cm$^{-3}$.

The trends were different near saturation. The highest matric potential for which we obtained an assessment of the hydraulic conductivity was about -5 kPa. The water content at -5 kPa was about 0.23 g g$^{-1}$ in the compacted ploughed layer and 0.28 g g$^{-1}$ in the fragmentary ploughed layer (Fig. 2) and the hydraulic conductivity was higher in the fragmentary ploughed layer than in the compacted ploughed layer (Fig. 2). The hydraulic conductivity obtained at a matric potential of -0.5 kPa with multiple disc infiltrometer were 1.5e$^{-7} \pm 1.2e^{-7}$ m s$^{-1}$ in the compacted ploughed layer and 2.8e$^{-6} \pm 7.8e^{-7}$ m s$^{-1}$ in the fragmentary ploughed layer. The hydraulic conductivity was higher near saturation in the fragmentary ploughed layer than in the compacted ploughed layer. Water is probably transferred to the structural pore space near saturation. Structural pore space was very low in the compacted ploughed layer, leading to lower hydraulic conductivity in this situation than in the fragmentary ploughed layer.

**Conclusion**

It is still difficult to determine the hydraulic properties of a soil and to explain the discrepancies between the various methods. The method used to saturate soil samples with water in the laboratory could cause differences between the field and laboratory methods. Nevertheless, the experiment shows that the ploughed layer structure has significant effect on soil hydraulic properties. These results will have to be carefully compared with several models for predicting soil hydraulic properties, such as those of Van Genuchten or Mualem. The change in the soil hydraulic properties with soil tillage shown in this experiment also corresponds to the variability of the soil hydraulic properties in a given field, as a function of wheel track positions for example. It is therefore difficult to assess the hydraulic properties of a cultivated field and to establish pedotransfer functions in cultivated soils. It depends on the objective and scale of the study in which pedotransfer functions will be used.
References


Effects of uncertainty in major input variables on simulated functional soil behaviour

P.A. Finke¹, J.H.M. Wöstena¹ and M.J.W. Jansen²

¹ DLO Winand Staring Centre for Integrated Land, Soil and Water Research (SC-DLO), P.O. Box 125, 6700 AC Wageningen, Netherlands
² DLO Agricultural Mathematics Group (GLW-DLO), P.O. Box 100, 6700 AC Wageningen, Netherlands

Introduction

Uncertainties in major input variables in water and solute models were quantified and their effects on simulated functional aspects of soil behaviour were studied using basic soil properties from an important soil mapping unit in the Netherlands. The major sources of uncertainty were: (i) spatial variability of basic soil properties such as soil profile composition, soil texture combined with spatial variability in water-table depths and (ii) uncertainty associated with the use of pedotransfer functions (Bouma and Van Lanen, 1987) to predict soil hydraulic functions. The two different sources of uncertainty were quantified and their respective contributions to the explanation of variability in modelling results for five functional aspects of soil behaviour were statistically evaluated by an analysis of variance (Vereecken et al., 1992). Additionally, regression analysis was used to evaluate the role of spatial variability in water-table depths only. Two of the five functional aspects were of a physical nature (i) days with a good workability and (ii) days with sufficient aeration while the remaining three functional aspects were of a chemical nature (iii) chloride breakthrough, (iv) cadmium breakthrough and (v) Isoproturon breakthrough (Wöstena and Van der Zee, 1993).

Uncertainty due to spatial variability of basic soil properties

The study focuses on a soil mapping unit of the Soil Map of the Netherlands scale 1:50 000 which occurs in the northeastern part of the country (Fig. 1). The soil mapping unit Hn21-V/V*, occupying 115 km², is defined as a sandy, siliceous Typic Hapludoll with a mean highest water-table (MHW) shallower than 40 cm and a mean lowest water-table (MLW) deeper than 120 cm. Statistical analysis of sampled profiles (Finke et al., 1996) showed, that the soil-part of the definition is met in 93% (SEM 3%)
of the area. The water-table depths were consistent with the definition in 41% (SEM 8%) of the area only.

The dataset analyzed in this study was obtained following a stratified two-stage random sampling design (Cochran, 1977). Eleven map sheets, in some cases extended with adjoining areas containing the soil mapping unit, served as sampling strata. In each stratum two map polygons belonging to the soil mapping unit were drawn at random with replacement, where the drawing probability of a polygon was proportional to its acreage. In each polygon four sampling locations were allocated randomly. The resulting dataset comprised $11 \times 2 \times 4 = 88$ profile descriptions. As a set these profiles expressed the variability of the considered mapping unit in a statistically representative way.

Information was available on the profile descriptions consisting of general properties such as rooting depth, $MHW$ and $MLW$, and further for each soil horizon its depths and the properties percentage clay + silt (CS), percentage organic matter (OM) and the median of the sand particle size ($M_{50}$).

**Uncertainty of pedotransfer functions**

The continuous pedotransfer functions used in this paper were established by describing all individually measured hydraulic functions for sandy soils in the Netherlands with the analytical equations of Van Genuchten (1980). This description resulted in the establishment of a set of five parameters (i.e. $K_s$, $\alpha$, $n$, $I$, $\theta_r$) in the Van Genuchten equations for each individually measured hydraulic function. To comply with a number of physical boundary conditions the original model parameters were transformed to five new parameters (i.e. $K_i^*$, $\alpha^*$, $n^*$, $I^*$, $\theta_r^*$). Each of the transformed model parameter was regressed linearly on the following soil properties: CS (i.e. percentage < 50 mm), OM, D bulk density, $M_{50}$, the qualitative variable topsoil or subsoil and derived properties such as OM$^2$ or ln(OM). This procedure resulted in the following five-vector pedotransfer function on the transformed scale:

$$\phi^* = T^*(\pi) + \varepsilon^*$$

in which $T^*$ is the pedotransfer function, $\pi$ denote the soil properties, $\varepsilon^*$ is the random term representing errors in the estimation and $\phi^*$ denote the transformed model parameters. The five-vector $\varepsilon^*$ was approximately multinormally distributed with mean 0 and covariance matrix $\Sigma$. After back-transformation the relation obtained the form:

$$\phi = T(\pi) + \varepsilon$$

in which $T(\pi)$ is the back-transformation of $T^*(\pi)$ and in which the five-vector $\varepsilon$ is no longer normally distributed, whereas its mean will in general differ from 0.
The uncertainty distribution of the soil physical parameters (\( \Phi \)) were studied with Monte Carlo simulation in the case of known soil properties (\( \pi \)), pedotransfer function (\( T' \)) and covariance matrix \( \Sigma \). Random realizations of error term (\( \varepsilon' \)) in the estimation of the soil physical parameters were drawn as follows. Let the 5-by-5 matrix \( L \) of the parameters \( K' , \alpha' , n' , l' , \theta'_s \) denote the Cholesky decomposition of the covariance matrix \( \Sigma \), which implies that \( LL^T = \Sigma \). Let \( u \) denote a five-vector consisting of independent standard normal random variates. Then \( Lu \) has a multinormal distribution with mean 0 and covariance matrix \( LL^T = \Sigma \). Thus \( Lu \) is a realization of \( \varepsilon' \). Algorithms for Cholesky decomposition are widely available. Adding \( \varepsilon' \) to \( T'(\pi) \) yielded a random realization of \( \Phi' \), which was backtransformed into a random realization of the soil physical parameters \( \Phi \).

The number of realizations of pedotransfer errors \( \varepsilon \) per location was chosen so that the information per model-run about the variance components would be maximal if the pedotransfer to soil variance ratio was equal to 95/5. This approach resulted in 20 realizations of the pedotransfer error \( \varepsilon \) and thus in 20 sets of soil physical parameters in the Van Genuchten equations per location and per layer.

In vertical direction, Table 1 shows the 88 profile descriptions that express the variability of the considered mapping unit in a statistically representative way. In horizontal direction, Table 1 shows the 20 sets of soil physical parameters expressing the uncertainty in the pedotransfer functions used. As a consequence, a total of 1760 model runs were made in a Monte Carlo procedure.

<table>
<thead>
<tr>
<th>Data type</th>
<th>Model input</th>
<th>Model output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water-table depths</td>
<td>Soil properties</td>
<td>Soil hydraulic functions</td>
</tr>
<tr>
<td>( \gamma_1 )</td>
<td>( \pi_1 )</td>
<td>( \phi_{1,1} ) ( \phi_{1,2} ) ... ( \phi_{1,20} )</td>
</tr>
<tr>
<td>( \gamma_2 )</td>
<td>( \pi_2 )</td>
<td>( \phi_{2,1} ) ( \phi_{2,2} ) ... ( \phi_{2,20} )</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>( \gamma_{88} )</td>
<td>( \pi_{88} )</td>
<td>( \phi_{88,1} ) ( \phi_{88,2} ) ... ( \phi_{88,20} )</td>
</tr>
</tbody>
</table>

Mean: \( \mu \)

Var: \( V \)

Total variance \( \Psi = \text{Var}(\pi) = U + V \)
Results

It appeared that uncertainty of pedotransfer functions was an important factor when simulating the functional aspects of soil behaviour 'days with a good workability' and 'days with sufficient aeration'. The combination of variability of basic soil properties and of water-table depths dominated when simulating the functional aspects 'breakthrough characteristics of chloride and of the adsorbing chemicals cadmium and Isoproturon'. With the exception of the simulated functional aspect 'days until 10% chloride breakthrough', the uncertainty in the other simulated functional aspects was largely explained by spatial variability in the evolution of water-table depths. Sampling should therefore mainly aim at adequately describing variability of basic soil properties including water-table depths in case leaching of chemicals is studied, but should also aim at an adequate description of soil hydraulic functions using pedotransfer functions when functional aspects of soil behaviour of a physical nature are studied.

Fig. 1. Relative importance of different sources of variability in explaining the uncertainty in five simulated functional aspects of soil behaviour.
References


The application of pedotransfer functions in predicting groundwater recharge at regional scale

C. Kosmas\(^1\), N. Danalatos\(^2\), E. Ntzanis\(^3\) and N. Yassoglou\(^1\)

\(^1\) Agricultural University of Athens, Laboratory of Soils and Agricultural Chemistry, Iera odos 75, Athens 11855, Greece
\(^2\) University of Thessaly, Department of Agriculture, Volos, Thessaly, Greece
\(^3\) Tobacco Experimental Station of Agrinion, Ministry of Agriculture, Agrinion 30100, Greece

Abstract

Simulations of water transport were conducted for the Acheloos alluvial plain covering an area of 5,075 hectares (scale 1:10,000). The WAVE model, simulating water and solute transport in the soil, was applied using measured and derived hydraulic properties from pedotransfer functions. Continuous pedotransfer functions were used to generate soil moisture retention characteristics curves using standard soil data recorded in routine soil surveys such as particle size distribution, bulk density and soil moisture content at saturation. The WAVE model was applied using the average values of soil properties describing each mapping unit. The model was validated in lysimeters and under field conditions using real climatic data and data derived by the General Circulation Model (GCM) for the study area. The obtained data indicated that pedotransfer functions can be satisfactorily used in predicting groundwater recharge at regional scale using soil physical properties given in soil survey reports.

Introduction

Various simulation models have been developed during the past decade describing water and solute transport in the soil-water-crop-atmosphere system (Barraclough, 1989; Addiscott, 1987; Vanlooost et al., 1994). These models vary widely in their conceptual approach and degree of complexity and preoccupations of their developers. The relationships between soil matric potential and hydraulic conductivity and the soil moisture content at various matric potentials are of particular interest in applying these models. Direct measurement of these properties is difficult, and the spatial variability
increases the number of samples required to adequately describe an area such as an alluvial plain.

Soil hydraulic data of an area is more difficult to obtain than physical data such as particle size distribution, organic matter content, bulk density, etc. Several approaches exist to estimate the water content at certain potential values using routinely collected data in soil survey (Bouma and Van Lanen, 1987, Danalatos et al., 1994, Wosten et al., 1994). Soil survey data are traditionally used for agricultural purposes, as well as such data are increasingly used for environmental and other interpretations. An estimation method that describes the soil water retention relationship based on other soil characteristics is referred to as pedotransfer function (Tietje and Tapkenhinrichs, 1993). Such pedotransfer functions can be derived by relating existing hydraulic data with soil physical properties given in soil survey reports.

The objective of this work is the application of the WAVE model in predicting the ground water recharge under different climatic conditions, using existing pedotransfer functions describing soil moisture retention characteristics and apply them at regional scale using data collected routinely in soil survey reports.

Materials and Methods

The study area

The study area is located in western Greece, comprising part of the Acheloos river plain and has a total extent of about 5,075 ha. The soils in the lower Holocene plain are calcareous, moderately deep to very deep, well drained to very poorly drained, coarse to very fine-textured. They have an organic matter content that varies between 1.4 and 4.3%; however, the majority of them have low values, and a variable CaCO₃ content (0.4-19.1%). The soils are mainly classified as Typic Xerofluvent, Aquic Xerofluvent, and Typic Fluvaquent (Soil Survey Staff, 1975). Soils on the upper Holocene and Pleistocene terraces are acid with a well structured argillic (Bt) horizon, well to moderately drained, medium to fine-textured and they are classified as Typic Haploxeralf or Typic Rhodoxeralf. Most soils are cultivated with corn, vegetables and tobacco, and receive surface irrigation during the dry season. Some of the main characteristics of the soil used for the local validation of the WAVE model (Water and Agrochemicals in the soil, crop and Vadose Environment (Vanchooler et al., 1994) are given in Table 1.

The climate of the area is characterised as Meso-mediterranean with a long dry summer and a relatively mild, wet winter (Bagnoules-Gaussen). The average annual precipitation in the area is relatively high (R=1010 mm), with more than 75% of the rainfall occurring from November to early May. The average air temperature is 17.9°C, with absolutely maximum temperature of 44.8°C occurring during August. Water
Table 1. Characteristics of the soil used for validation of the WAVE model.

<table>
<thead>
<tr>
<th>Horizon</th>
<th>depth (cm)</th>
<th>sand (%)</th>
<th>silt (%)</th>
<th>clay (%)</th>
<th>O.C. (%)</th>
<th>pH</th>
<th>WCR (v/v) *</th>
<th>WCS (v/v)</th>
<th>a</th>
<th>n</th>
<th>lambda</th>
<th>Ksat (cm/h)</th>
<th>BD (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ap</td>
<td>0-45</td>
<td>31.9</td>
<td>42.8</td>
<td>25.3</td>
<td>0.74</td>
<td>6.4</td>
<td>0.053</td>
<td>0.401</td>
<td>0.254</td>
<td>1.206</td>
<td>0.519</td>
<td>80.9</td>
<td>1.42</td>
</tr>
<tr>
<td>BA</td>
<td>45-59</td>
<td>31.7</td>
<td>28.7</td>
<td>29.6</td>
<td>0.57</td>
<td>5.8</td>
<td>0.078</td>
<td>0.328</td>
<td>0.080</td>
<td>1.275</td>
<td>0.571</td>
<td>92.2</td>
<td>1.43</td>
</tr>
<tr>
<td>Bt1</td>
<td>59-84</td>
<td>32.4</td>
<td>35.7</td>
<td>31.9</td>
<td>0.31</td>
<td>4.9</td>
<td>0.065</td>
<td>0.361</td>
<td>0.012</td>
<td>1.812</td>
<td>0.606</td>
<td>88.6</td>
<td>1.48</td>
</tr>
<tr>
<td>Bt2</td>
<td>84-103</td>
<td>35.6</td>
<td>35.6</td>
<td>32.9</td>
<td>0.18</td>
<td>5.6</td>
<td>0.072</td>
<td>0.397</td>
<td>0.018</td>
<td>1.771</td>
<td>0.523</td>
<td>60.6</td>
<td>1.56</td>
</tr>
</tbody>
</table>

*WCR=residual water content, WCS=saturated water content, a, n and lambda=Van Genuchten parameters, Ksat=saturated hydraulic conductivity and BD=bulk density.

deficit occurs during the whole growing period of the summer crops. During the winter time the ground water table is rising close to the soil surface in the poorly drained soils due to low evapotranspiration and the high rains falling during that period.

Collection of data related to hydrodynamic properties of soils

Representative soil mapping units were selected and measurements such as saturated hydraulic conductivity (41 mapping units, 63 horizons), unsaturated hydraulic conductivity (4 mapping units, 8 horizons), and soil moisture retention characteristics (17 mapping units, 65 horizons) were conducted. Additional data such as clay content, bulk density, fluctuations of ground water table, etc., were collected from the existing soil survey of the area (Kosmas, 1996).

The study soils were characterised for particle-size distribution by the pipette method (Gee and Bauder, 1986). Water retention in the range 0 to -33 kPa was measured in undisturbed soil samples and from -100 to -1500 kPa in disturbed soil samples (Klute, 1986). Saturated hydraulic conductivity was measured with double ring infiltrometers. Unsaturated hydraulic conductivity was measured in the upper three soil layers in undisturbed soil columns using a ring infiltrometer, with a diameter of 40 cm. In each infiltrometer, tensiometers were installed at two depths to measure the vertical hydraulic head gradient. A crust of hydraulic cement with different porosity was applied on the soil surface within the ring infiltrometer and the conductivity rates were measured at different heads using a differential manometer device (Boolthink et al., 1991).

The soil moisture retention characteristics were determined using (a) the Van Genuchten closed-form-equations (Van Genuchten, 1980), (b) the water retention data for each 300 cm² undisturbed sample, (c) the measured hydraulic conductivities in the field, (d) the one-step outflow data, and (e) the optimization fitting program (SFIT) described by Kool and Parker (1987). The model of Mualem was used for estimation of the unsaturated hydraulic conductivity. The shape parameter lambda of the Mualem model was estimated from measured values of (a) the saturated hydraulic conductivity, (b) the one-step outflow data and (c) the optimisation fitting program SFIT. The obtained values of lambda were grouped in textural classes according to the soil mapping system used in the study area.
Application of pedotransfer functions

Soil moisture retention characteristics for the different mapping units were additionally estimated using a logarithmic model that incorporates simple soil properties such as total pore space, clay content, and bulk density (Danalatos et al., 1994).

\[
\theta(h) = \theta(0) \cdot \exp[\ln^2(10h) \cdot (-0.0365 + 0.000932 \cdot \text{clay})] \\
\theta(h) = \theta(0) \cdot \exp[\ln^2(10h) \cdot (-0.0175 + 0.000195 \cdot \text{clay})]
\]

where \( \theta(h) \) is the moisture content at pressure \( h \) (v/v), \( \theta(0) \) is the saturation soil moisture content (v/v), \( h \) is the pressure head (kPa). The data required were obtained from the existing soil survey of the area using the average values of each mapping unit. According to the above equations, two major groups of soil horizons could be distinguished, the well-structured (equation 1) and the structureless to weakly structured (equation 2). As an example of the estimation of soil moisture retention curve using the equation (1) is given in Figure 1 showing that the calculated \( \theta(h) \) curve is satisfactorily compared with the measured \( \theta(h) \) values for a silty clay loamy soil.

![Soil moisture characteristic curve calculated with equation (1) and measured values for a silty clay loamy soil.](image)

**Fig. 1.** Soil moisture characteristic curve calculated with equation (1) and measured values for a silty clay loamy soil.

Model validation at local scale

The WAVE model was validated at local scale (a) in a series of five lysimeters having the dimensions of 100 cm in height and 80 cm in diameter, and (b) under field conditions for a period of 7 months. The application of the model in the lysimeters indicated that soil moisture in the whole soil profile can be satisfactorily described after calibration of the model. Bypass flow of water through macropores in well structured soils (as the study soil) or in swelling soils forming cracks during the dry period requires a certain calibration of the model parameters for the accurate prediction of the water fluxes. The maximum model error (ME) for the calibration of the soil moisture content was higher (14.1%) in the upper 10 cm soil layer, while in
the lower soil layers the ME was ranged from 3.1% to 7.6%. The ME for the whole lysimeter was 6.4%.

Figure 2 demonstrates that the predicted actual evaporation rates were satisfactorily described by the WAVE model during the period when the top soil was relatively wet as compared to its measured values in the lysimeters. In the contrast, the actual evaporation was overestimated during the dry period (August through October) when the soil was dried out. This discrepancy should be attributed to the mulching of the surface soil layer.

![Cumulative evap. vs Time](image1.png)

**Fig. 2.** Measured and predicted (WAVE model) actual evaporation rates from a bare soil.

![Soil moisture vs Time](image2.png)

**Fig. 3.** Predicted and measured values of soil moisture at the depth of 5-10 cm at field conditions.

The volumetric soil moisture content was satisfactorily described by the model under field conditions during the whole growing period of tobacco (Fig. 3), corrected for the bypass water measured in the lysimeters, and assessing a certain amount of irrigation water that was intercepted by the plant canopy especially after July when the plants had attained their maximum growth. The peaks in the curve of the simulated data
correspond to irrigation events during which measurements of soil moisture content by the neutron probe was not feasible.

In order to apply the WAVE model to the alluvial plain in which poorly drained soils are also included, the model was validated to a poorly drained soil with relatively shallow ground water table, usually fluctuating between 15 cm and 160 cm from the soil surface. The model was calibrated for a period of four months during the winter and then the model was applied for the following two wet periods 1995 and 1996, from September to April. During the simulation period, no vegetation was considered because the majority of the soils are cultivated with corn and tobacco during the summer period, leaving them almost bare from September to April. The variations in the ground water table are well reproduced during the winter and early spring period when the soils remain bare (Fig. 4). The level of the ground water table was not possible to be predicted during the summer period, when the soils are cultivated with corn or tobacco and intensively irrigated by furrow irrigation due to great spatial, temporal and quantitative variability. During that period high amount of irrigation water is applied, the amount depending on length of the furrows in each field, the time of application, and the frequency of irrigation.

![Graph](image)

Fig. 4. Relation of measured and simulated values of the ground water level in a poorly drained soil.

Results and Discussion

Model application at regional scale

After the validation, the WAVE model was applied at a regional scale in part of the Acheloos alluvial plain using the average values of soil texture, bulk density and saturated hydraulic conductivity for each mapping unit given by the soil survey report. The typical soil moisture retention curve for each mapping unit was estimated using the equations (1) or (2). The model was applied to the mapping units under the occurring weather conditions from September to May. As it is expected, water drained in the depth below 1.5 meters decreased with increased clay content of the mapping units (Fig. 5).
The amount of total rainfall occurring in the study area during the above period was 934 mm, while the total amount of water drained from whole area, as it is estimated by the model for each mapping units and referred to the total area, was 328 mm, or 35.1% of the occurring rainfall. The leachate measured in the lysimeters was 351.6 mm, while an amount of 374.2 mm was predicted by the WAVE model for the same period. The obtained data from the lysimeters indicates that the model may satisfactorily predict the recharge of the aquifer in the alluvial plain applied at regional scale using hydraulic data derived from pedotransfer functions.

![Cumulative measured rainfall and simulated drainage in different mapping units of the Acheloos alluvial plain for the period of 9 months. Numbers correspond to textural classes of mapping units for three different depths (111 corresponds to course textures, 434 corresponds to very fine textures).](image)

**Fig. 5.** Cumulative measured rainfall and simulated drainage in different mapping units of the Acheloos alluvial plain for the period of 9 months. Numbers correspond to textural classes of mapping units for three different depths (111 corresponds to course textures, 434 corresponds to very fine textures).

**Climate change and ground water recharge**

The WAVE model was applied for a period of 30 years using climatic data derived by the GCM under normal conditions (1xCO₂) and under conditions of doubling CO₂. The simulation was conducted considering the whole area in one case as free of vegetation and in the other case as cultivated with corn and receiving 280 mm of irrigation water during the growing period. An average reduction of about 10% and an increase of about 50% is predicted for the area by the GCM under conditions of doubling CO₂ for rainfall and evapotranspiration, respectively. As Figure 6 shows, the ground water recharge will be greatly affected under conditions of doubling CO₂. An average reduction of 27% is predicted in the ground water recharge if CO₂ is doubled. As Figure 6 shows, the cumulative drainage of water below 1.5 meters is slightly affected by the crop (average reduction 7.5%). The small difference can be explained by the fact that (1) the corn fields are considered bare during the rain period, and (2) drainage that may occur late in spring is limited by the growing plants.
Fig. 6. Cumulative drainage in the Acheloos alluvial plain corresponding to normal conditions (1CO₂) and conditions of doubling CO₂.

Acknowledgements

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References


Preliminary analysis of soil properties variation for the development of pedotransfer functions

F. Moreno, D. De La Rosa, J.E. Fernandez and L. Andreu

Instituto de Recursos Naturales y Agrobiologia de Sevilla (IRNAS - CSIC)
P.O. Box 1052, 41080 Sevilla, Spain.

Introduction

In southwest Spain many different soil types can be found in a small area (Arrue, 1976; AMA-CSIC, 1985). Thus, soil properties (e.g. soil texture) can vary within a wide range.

For many purposes like land evaluation (De la Rosa, 1996), prediction of soil water balance (Moreno et al., 1988; Andreu et al., 1994), application of simulation models (Andreu et al., 1996), etc., the development of pedotransfer functions must take into account the variability of soil properties. The objective of this presentation is to show the range of variation of soil data, previously obtained by the group of IRNAS, that are being used to derive hydraulic parameters within the EU project (Contract No. CHRX-CT94-0639).

Soil data

Soil data were collected from different works carried out by the IRNAS group in southwest Spain. The selected data correspond to different representative soil profiles of SW Spain. The texture of these soils covers a wide range, from sandy soils to very clayey soils. All the profiles correspond to agricultural soils under both rainfed and irrigated conditions. Some of them are reclaimed salt affected soils. These soils are drained and irrigated, in which the main crops are cotton and sugarbeet. Other soils correspond to olive orchards.
Table 1 shows the range of variation of some soil properties from 11 representative soil profiles. These results show that the clay content of the selected soils varies from 13% to 68%. For this reason the water content at saturation varies also in a wide range (23.2 - 56.5%). Other important fact is that the saturated hydraulic conductivity shows values between 2 and 78 cm/d.

Table 1. Range of variation of some soil properties for the 0-1 m soil layer

<table>
<thead>
<tr>
<th>Soil property</th>
<th>Range of variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay content (&lt;0.002 mm; % w/w)</td>
<td>13.4 - 68.3</td>
</tr>
<tr>
<td>Silt content (0.02-0.002 mm; % w/w)</td>
<td>8.6 - 46.3</td>
</tr>
<tr>
<td>Sand content (2-0.02 mm; % w/w)</td>
<td>76.6 - 0.2</td>
</tr>
<tr>
<td>Organic matter content (% w/w)</td>
<td>0.5 - 1.6</td>
</tr>
<tr>
<td>Bulk density (g/cm$^3$)</td>
<td>1.10 - 1.60</td>
</tr>
<tr>
<td>Particle density (g/cm$^3$)</td>
<td>2.60 - 2.76</td>
</tr>
<tr>
<td>Total porosity (% v/v)</td>
<td>23.5 - 61.0</td>
</tr>
<tr>
<td>Water content at saturation (% v/v)</td>
<td>23.2 - 56.5</td>
</tr>
<tr>
<td>$\theta_{13\text{ mm}}$ (cm$^3$/cm$^3$)</td>
<td>29.7 - 53.1</td>
</tr>
<tr>
<td>$\theta_{15\text{ atm}}$ (cm$^3$/cm$^3$)</td>
<td>9.0 - 35.8</td>
</tr>
<tr>
<td>Saturated hydraulic conductivity (cm/d)</td>
<td>2.6 - 78.0</td>
</tr>
</tbody>
</table>

The relationship between the hydraulic conductivity and the pressure head, K(h), in the range near saturation, is shown in Figure 1. The hydraulic conductivity was determined in the field from measurements carried out with tension disc infiltrometers. The results of Figure 1(a) show the hydraulic conductivity-pressure head relationships for three of the selected soils. Differences between soils are in accordance with their different textures. The seasonal change of K(h) is shown in Figure 1(b) for a sandy loam soil.
Fig. 1. Hydraulic conductivity measured, in the range near saturation, using tension disc infiltrometers: (a) differences between soils, (b) sandy loam soil, seasonal variation into the same soil (Moreno et al., 1995; Angulo-Jaramillo et al., 1997; Moreno et al., 1997)
References


Evaluation of pedotransfer functions using the laboratory database of a soil information system

V. Hennings¹, U. Müller² and O. Tietje³

¹ Federal Institute for Geosciences and Natural Resources, Stilleweg 2, D-30655 Hannover, Germany
² Geological Survey of Lower Saxony, Stilleweg 2, D-30655 Hannover, Germany
³ Chair of Environmental Sciences: Natural and Social Science Interface, Swiss Federal Institute of Technology, Voltastr. 65, ETH-Zentrum VOD, CH-8092 Zürich, Switzerland

Introduction

Several pedotransfer functions for estimating the soil hydraulic properties were published in the eighties. To prevent repetition and identify the most appropriate approach within a target oriented method selection for the method base of a soil information system, existing algorithms must be tested on the basis of measurements of local soils.

The main objectives of this paper are:
- to quantify the validity of pedotransfer functions for estimating the water retention curve and the saturated hydraulic conductivity against a consistent set of measurements,
- to compare existing approaches using a common database, and
- to obtain a ranking according to the accuracy of the predicted values.

The NIBIS database

The database of the Lower Saxony Soil Information System (NIBIS) (Horn et al., 1991) contains field and laboratory data for soils in Lower Saxony, in the northwestern part of Germany. At present chemical data for about 2700 soil profiles and soil-physical data for about 900 soil profiles are ready for processing. The inventory includes measured water retention curves for 1987 horizons; measured values for saturated hydraulic conductivity are available for 1161 horizons.
All measurements are related to undisturbed, horizontally oriented cores with a volume of 250 cm\(^3\). Each water retention curve is defined by four points (pF = 0, 1.8, 2.5, 4.2). The measurement procedure can be described as the standardized pressure membrane technique (Hartge, 1965). The laboratory technique applied used to measure saturated hydraulic conductivity can be described as a special type of the falling-head method (Hartge 1961, 1965). The value given in the NIBIS laboratory database is the geometric mean of seven replicate samples.

Example 1:
**Estimation tables for the new German soil mapping guidelines**

The third edition of the German soil mapping guidelines (AG Bodenkunde, 1982) contains tables for estimating field capacity (pF > 1.8), available water capacity (pF = 1.8 – 4.2), and air capacity (pF < 1.8) as a function of soil texture, bulk density and organic matter content by class-pedotransfer functions. For the new, fourth edition (AG Bodenkunde, 1995) these parameters had to be recalculated using an enlarged database. The new tables are presented by Krahmer et al. (1995).

In general, the results of checking the class-pedotransfer functions in the third edition can be summarized as follows (Hennings and Müller, 1993):

- In the past, the pore volume of humus-free soils has been overestimated, especially for clay loams and silty clays and, in general, for soils of large bulk densities.
- The positive and negative corrections for organic matter content were clearly too small.
- A new classification was proposed as a consequence of the empirical frequency distribution of bulk density values.

These results show that class-pedotransfer functions, applied by many users at soil surveys and engineering offices, have to be checked on the basis of a database of laboratory measurements with state and/or national coverage.

Example 2:
**Evaluation of pedotransfer functions for estimating the water retention curve**

**Selection of pedotransfer functions**

Six pedotransfer functions to estimate the water retention curve were selected for this investigation (Table 1). The first three approaches are “point regression methods“; for predicting the water content at certain matric potentials. The fourth model, from Saxton et al. (1986), describes the retention function with constant, linear or exponential relationships in specified subranges. These retention functions do not have a continuous derivative and are not applicable in simulation models. The last two approaches are “functional parameter regression methods“ for estimating the parameters of any model in order to determine the water retention curve as a
continuous function. Therefore Rawls and Brakensiek (1985) and Vereecken et al. (1989) use the equation of Van Genuchten (1980).

The results for a silty clay are illustrated in Figure 1 as an example. Five pedotransfer functions overestimate water contents at certain suctions, and only the pedotransfer function of Rawls and Brakensiek (1985) predicts lower values.

Table 1. Properties of the selected pedotransfer functions

<table>
<thead>
<tr>
<th>Reference</th>
<th>Input variables</th>
<th>Estimated pF values</th>
<th>Principle</th>
<th>Restrictions</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Renger (1971)</td>
<td>silt (2-63 µm) clay (&lt; 2 µm) bulk density organic matter</td>
<td>0, 1.8, 2.5, 4.2</td>
<td>4 regression equations for every bulk density class, positive and negative corrections according to organic matter content</td>
<td></td>
</tr>
<tr>
<td>(2) Gupta &amp; Larson (1979)</td>
<td>sand (50-2000 µm) silt (2-50 µm) clay (&lt; 2 µm) bulk density organic matter</td>
<td>1.60, 1.85, 2.0, 2.30, 2.52, 2.78, 3.0, 3.30, 3.60, 3.85, 4.0, 4.18</td>
<td>12 regression equations for 12 matric potentials disturbed samples; data base: 43 soils</td>
<td></td>
</tr>
<tr>
<td>(3) Rawls &amp; Brakensiek (1982)</td>
<td>sand (50-2000 µm) silt (2-50 µm) clay (&lt; 2 µm) bulk density organic matter</td>
<td>1.60, 1.85, 2.0, 2.30, 2.52, 2.78, 3.0, 3.30, 3.60, 3.85, 4.0, 4.18</td>
<td>12 regression equations for 12 matric potentials disturbed samples; data base: 43 soils</td>
<td></td>
</tr>
<tr>
<td>(4) Saxton et al. (1986)</td>
<td>sand (50-2000 µm) clay (&lt; 2 µm)</td>
<td>0 - 4.2</td>
<td>3 regression equations for 3 pF intervals organic matter content not taken into account</td>
<td></td>
</tr>
<tr>
<td>(5) Rawls &amp; Brakensiek (1985)</td>
<td>sand (50-2000 µm) clay (&lt; 2 µm) bulk density</td>
<td>continuous function</td>
<td>4 regression equations to estimate 4 parameters of the Van Genuchten equation (m = 1 - 1/n) organic matter content not taken into account</td>
<td></td>
</tr>
<tr>
<td>(6) Vereecken et al. (1989)</td>
<td>sand (50–2000 µm) clay (&lt; 2 µm) bulk density organic carbon</td>
<td>continuous function</td>
<td>4 regression equations to estimate 4 parameters of the Van Genuchten equation (m = 1) data base: 182 samples</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 1. Comparison of six selected pedotransfer functions for a single data set (45% clay, 50% silt, 5% sand)

Quantitative error criteria
A qualitative ranking can be obtained using the mean difference (MD) and the root of the mean squared difference (RMSD) between measured and estimated results.

\[
MD = \frac{1}{b-a} \int_{a}^{b} \left( \theta_p - \theta_m \right) d\log|\psi|
\]

\[
RMSD = \left[ \frac{1}{b-a} \int_{a}^{b} \left( \theta_p - \theta_m \right)^2 d\log|\psi| \right]^{1/2}
\]

\( \psi \) = matric potential (hPa)
\( \theta_p \) = predicted water content (vol.-%)
\( \theta_m \) = measured water content (vol.-%)
MD = mean difference
RMSD = root of the mean squared difference

Both error parameters are calculated for the pF range 0 – 4.2.
Results

Means of both error parameters (Table 2) can be used to derive general conclusions, i.e. for all texture classes or all soils in a region. More detailed results are given by Tietje and Hennings (1993).

Table 2. Mean values of the mean difference (MD) and the root of the mean squared difference (RMSD) for six selected pedotransfer functions (n = 1177)

<table>
<thead>
<tr>
<th>Reference</th>
<th>MD</th>
<th>RMSD</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Renger (1971)</td>
<td>-0.20</td>
<td>3.77</td>
</tr>
<tr>
<td>(2) Gupta &amp; Larson (1979)</td>
<td>4.69</td>
<td>7.12</td>
</tr>
<tr>
<td>(3) Rawls &amp; Brakensiek (1982)</td>
<td>4.32</td>
<td>9.18</td>
</tr>
<tr>
<td>(4) Saxton et al. (1986)</td>
<td>1.89</td>
<td>7.89</td>
</tr>
<tr>
<td>(5) Rawls &amp; Brakensiek (1985)</td>
<td>-7.48</td>
<td>8.00</td>
</tr>
<tr>
<td>(6) Vereecken et al. (1989)</td>
<td>-1.35</td>
<td>3.66</td>
</tr>
</tbody>
</table>

The results can be summarized as follows:

- Of the three methods used to calculate water content for individual matric potentials on the basis of linear regression analysis, the equations of Renger (1971) stand out because they yield the least deviation between estimated and measured values. The algorithm of Vereecken et al. (1989) is the better of the two methods for estimating the parameter values of the Van Genuchten equation.

- Tested on the basis of water retention curves of European soils, "European" pedotransfer functions seem to perform better than "American" pedotransfer functions.

- The methods examined here show no distinction with respect to which type of substrate they are best suited.

Example 3:
Evaluation of pedotransfer functions for estimating saturated hydraulic conductivity

Selection of pedotransfer functions

For this investigation, six pedotransfer functions were again selected (Table 3). There are two kinds of methods for predicting saturated hydraulic conductivity:

The first group of methods estimate the required value by (generally multiple, nonlinear) regression analysis of input variables such as clay, sand, organic matter content and bulk density. These methods include procedures by Cosby et al. (1984), Brakensiek et al. (1984), Saxton et al. (1986) and Vereecken et al. (1990).
The second group of methods try to derive a physicoempirical relationship between the particle-size distribution and conductivity. For this purpose Bloemen (1980) represents the particle-size distribution by the median grain size and a grain-size distribution index and calculates the ks value from these two auxiliary variables. The Campbell (1985) approach is based on the assumption that the particle size distribution is approximately lognormally distributed and can be represented by a geometric mean particle size diameter and a geometric standard deviation. Campbell proposes an empirical equation for estimating ks. For both these approaches the particle size distribution should be as detailed as possible. Knowledge of only three fractions (clay, silt, and sand) may reduce the performance considerably.

Table 3. Properties of the selected pedotransfer functions

<table>
<thead>
<tr>
<th>Reference</th>
<th>Input variables</th>
<th>Principle</th>
<th>Restrictions</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Cosby et al. (1984)</td>
<td>clay (&lt; 2 µm) sand (50–2000 µm)</td>
<td>1 regression equation</td>
<td>for all textures</td>
</tr>
<tr>
<td>(2) Saxton et al. (1986)</td>
<td>clay (&lt; 2 µm) sand (50–2000 µm)</td>
<td>1 regression equation</td>
<td>for all textures</td>
</tr>
<tr>
<td>(3) Brakensiek et al. (1984)</td>
<td>clay (&lt; 2 µm) sand (50–2000 µm) bulk density</td>
<td>1 regression equation</td>
<td>for all textures</td>
</tr>
<tr>
<td>(4) Vereecken et al. (1990)</td>
<td>clay (&lt; 2 µm) sand (50–2000 µm) bulk density organic matter</td>
<td>1 regression equation</td>
<td>for all textures</td>
</tr>
<tr>
<td>(5) Bloemen (1980)</td>
<td>contents of at least 3 particle size fractions of any classification</td>
<td>calculation from median grain size and grain size distribution index</td>
<td>ks measured with the crust method and a sample volume larger than 6000 cm³</td>
</tr>
<tr>
<td>(6) Campbell (1985)</td>
<td>contents of at least 3 particle size fractions of any classification, bulk density</td>
<td>calculation from geometric mean particle size and geometric standard deviation</td>
<td>estimation depends on the number of particle size fractions</td>
</tr>
</tbody>
</table>

**Quantitative error criteria**

Owing to the lognormal distribution of the saturated hydraulic conductivity, the error of the prediction is quantified using the geometric mean and standard deviation of the error ratio of the predicted \( (ks^p) \) and the measured \( (ks^m) \) conductivity values:

\[
\varepsilon = \frac{ks^p}{ks^m}
\]

The geometric mean error ratio GMER, calculated using \( n \) soil samples, yields the average factor with which the predictions exceed or fall below the measured values and in the best case equals 1.
\[ \text{GMER} = \exp \left( \frac{1}{n} \sum_{i=1}^{n} \ln(\varepsilon_i) \right) \]

The geometric standard deviation of the error ratio GSDER is a measure of the deviation from the mean. The prediction is exact in all cases if and only if the geometric standard deviation of the error ratio is 1.

\[ \text{GSDER} = \exp \left[ \left( \frac{1}{n-1} \sum_{i=1}^{n} (\ln(\varepsilon_i) - \ln(\text{GMER}))^2 \right)^{1/2} \right] \]

Because different pedotransfer functions are based on grain-size fractions with different particle-size limits, the mass proportions in the different fractions were converted by loglinear interpolation to the international scheme based on a limit of 50 \( \mu \text{m} \) between silt and sand. Soil texture classes were calculated according to the USDA or FAO classification system respectively (USDA, 1951; FAO, 1990).

Results

Means of both error parameters (Table 4) can be used to derive general conclusions, i.e. for all texture classes or all soils in a region. More detailed results are given by Tietje & Hennings (1993).

Table 4. Geometric mean error ratio GMER and geometric standard deviation of the error ratio GSDER for six selected pedotransfer functions \( n = 1067 \)

<table>
<thead>
<tr>
<th>Reference</th>
<th>GMER</th>
<th>GSDER</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Cosby et al. (1984)</td>
<td>1.42</td>
<td>7.86</td>
</tr>
<tr>
<td>(2) Saxton et al. (1986)</td>
<td>1.19</td>
<td>7.72</td>
</tr>
<tr>
<td>(3) Brakensiek et al. (1984)</td>
<td>0.17</td>
<td>11.52</td>
</tr>
<tr>
<td>(4) Vereecken et al. (1990)</td>
<td>1.65</td>
<td>12.91</td>
</tr>
<tr>
<td>(5) Bloemen (1980)</td>
<td>0.33</td>
<td>21.64</td>
</tr>
<tr>
<td>(6) Campbell (1985)</td>
<td>0.21</td>
<td>10.28</td>
</tr>
</tbody>
</table>

Table 4 shows the error parameters calculated using the whole data set to evaluate the six selected pedotransfer functions in general. The algorithms of Brakensiek et al. (1984), Campbell (1985) and Bloemen (1980) tend to underestimate the saturated hydraulic conductivity, while the predictions according to Saxton et al. (1986), Cosby et al. (1984) and Vereecken et al. (1990) generally lead to higher values than obtained by laboratory measurements. The geometric mean error ratio GMER calculated with
the Cosby et al. (1984) approach is larger than 1 for most of the texture classes, excluding silt loam and silty clay loam.

Table 4 shows that the geometric standard deviations of the error ratio GSDER of most of the pedotransfer functions differ only slightly. Only the Bloemen (1980) algorithm stands out because it yields the largest difference between estimated and measured values.

![Graph showing geometric standard deviation for error ratio within FAO textural classes for six selected pedotransfer functions.](image)

**Fig. 2.** Geometric standard deviation of the error ratio within FAO textural classes for six selected pedotransfer functions

Additionally subdividing into texture classes Figure 2 shows that all estimation methods perform best for loamy sand. With increasing clay content and possible macropore effects the prediction is deteriorating. The geometric standard deviation of the error ratio reaches maximum values for silty clay and clay soils.

Results can be summarized as follows:

- The prediction of the saturated hydraulic conductivity using a pedotransfer function is inaccurate. The geometric standard deviation of the error ratio is about 4 to 20 and is about the same as the standard deviation of the data.

- Pedotransfer functions based only on grain-size distribution and represented by a simple regression equation (e.g., Cosby et al., 1984) lead to results that are similar to those of more complex models (e.g., Brakensiek et al., 1984). Integration of additional independent variables, such as bulk density and organic matter content, does not significantly reduce the GSDER.
This study applied six pedotransfer functions to soil data from northern Germany. The methods examined here do not reflect any distinction with respect to the location they were developed for.

The variability of the NIBIS data within the textural classes showed good agreement with the variability of the error ratios of the pedotransfer functions. This indicates that the inaccuracy of the ks prediction is due to the inherent variability of the saturated hydraulic conductivity (including measurement error, spatial variability, and sample error).

The pedotransfer function should be chosen on the basis of the textural class for which a ks prediction is to be made.

Conclusions

Pedotransfer functions designed for estimating the water retention curve differ significantly in accuracy, but the application of different algorithms for different texture classes is not recommendable.

Pedotransfer functions designed for estimating saturated hydraulic conductivity differ only slightly in accuracy, but it may be best to use a different algorithm for each texture class.

A similar investigation on pedotransfer functions for estimating the unsaturated hydraulic conductivity curve is planned.

References


Tietje, O. and Hennings, V. 1996. Accuracy of the saturated hydraulic conductivity prediction by pedo-transfer functions compared to the variability within FAO textural classes. – Geoderma, 69, 71–84.


Field trip in ‘Petite Beauce’
The soils of the 'Petite Beauce' area: Contribution to the study of the groundwater recharge

A. Bruand, S. Ould Mohamed, O. Duval and P. Quétin

INRA, Centre de Recherche d’Orléans, Unité de Science du Sol - SESCPE, Avenue de la Pomme de Pin - 45160 Ardon - France

Introduction

In the Beauce region (10 000 km²), the agricultural practices and environmental characteristics have combined to make this area particularly sensitive to pollution from agricultural sources (Thiery and Séguin, 1986; Séguin, 1987; Ould Mohamed, 1995). In this region, water management problems are of both a quantitative and qualitative nature with respect to water utilisation for irrigation and drinkable water, respectively. Groundwater recharge usually occurs from December to April and mainly results from soil drainage (Mégnien and Desprez, 1973; Ould Mohamed, 1995). These studies also showed that water flow is dominantly vertical because of the high permeability of the soil and geological bedrock which is a Miocene lacustrine limestone (Aquitanian).

The main features of the landscape are plateaus or weakly undulating surfaces. The limits of the Beauce region correspond roughly to the outcrop of the Aquitanian limestones of which the thickness is about 200 m in the deepest zone of the sedimentary basin (Fig. 1). The soils formed in silty clay loam and silt loam clay Quaternary formations which cover the Aquitanian limestones. The thickness of the Quaternary formations is usually less than 1.5 m, particularly in the 'Petite Beauce' area.

The site of the quarry 'Les Sapins Douset'

The quarry is located 30 kilometres North-West of Orléans in the 'Petite Beauce' area (Fig. 1). In the latter, the water management problems are particularly important because of (i) the thin soils which explains the necessity to irrigate crops during
summer, (ii) the low amount of available water from the aquifer and a recharge which is closely dependent on the soil drainage, (iii) and the agricultural practices related to an intensive farming with high yield objectives.

Climate

The 'Petite Beauce' has a temperate continental climate with an annual average temperature equal to 10.5°C. The mean annual rainfall and potential evapotranspiration are 630 mm and 767 mm, respectively (1962-1993 period, Penman equation for the potential evapotranspiration).

The cumulative rainfall and potential evapotranspiration from December 1 to April 30 over the 1962-1993 period are 249 mm and 165 mm, respectively. Although the class ranging from 200 to 350 mm represents 66% of the total effective, the cumulative rainfall distribution over the studied period shows a high variability. In contrast, there is low variability in the potential evapotranspiration distribution; the 100-250 mm class represents 100% of the variation.

![Map of the Petite Beauce region](image)

Fig. 1. Location of the site (after Alcaydé et al., 1990)
Geology

Around the quarry, the thickness of the Aquitanian limestones decreases from the North-East to the South-West, the Cretaceous and Eocene formations outcrop 15 kilometres South of the quarry.

In the 'Petite Beauce', non calcareous and sandy to sandy-clay materials are also present locally, underlaying the clayey loam Quaternary materials and lying on Aquitanian limestones (Fig. 2). These non calcareous materials which filled depressions at the top of the Aquitanian limestones are also Miocene formations (Burdigalian fluvial deposits). They varied highly, laterally and vertically, in particle size distribution and clay mineralogy (Chéry et al., 1996).

---

Fig. 2. Description of the vertical succession of layers which were found in boring holes realised in an area where the Burdigalian formations were recognized (after Chéry et al., 1996).

In the quarry, the Aquitanian limestones are about 35 m thick, lying in discontinuity on Eocene limestones a few meters thick and then on clays with flints resulting from the weathering of the Cretaceous chalk. The upper layer of the Aquitanian formations is a powdery limestone of which the upper part was cryoturbated during ice periods of the Quaternary.

Hydrology

There are few brooks or rivers in Beauce because of the high permeability of the geological bedrocks. The only ones which are encountered correspond to outcrops of the groundwater table, i.e. drainage axes of the latter towards peripheral rivers such as the Loire, Loing and Loir rivers. The piezometric surface is very flat and it ranges from 15 m down to 20 m straight under the site of the quarry.
Agriculture

About 86% of the total land surface is cultivated. The main crops have been wheat, barley and maize for the thirty last years (Ailliott and Verbèque, 1995). About 80% of the land surface is equipped for irrigation which is generally used. From 30 to 90 mm and 120 to 180 mm of irrigation water are usually applied to soft wheat and maize, respectively, depending on the climate characteristics of each year. The irrigation of maize usually stops in early September and it is harvested in early October.

Description of the soil

The soil is developed in silty clay loam materials overlying the lacustrine limestone that was cryoturbated in its upper part during the Quaternary (Ould Mohamed and Bruand, 1994). The main pedological evolution is a decarbonation of the shallow horizons and the formation of calcareous crust at the bottom of the silty clay loam materials. This soil was classified as a Typic Eutrochrept (Soil Survey Staff, 1975 and 1994), a Calcaric Cambisol (FAO) or CALCISOL calcareique (AFES, 1995).

The profile shows three superposed units from the surface downward (Fig. 3, Tables 1 & 2):

- a silty clay loam material in which the main pedological evolution is a decarbonation of the upper horizons (horizons Ap and B) and the formation of a calcareous crust (K horizon) at the base. The clay content fine earth decarbonated fraction is close to 30% and the coarse fractions are silt size particles, mainly. The bulk density ranges from 1.22 to 1.38 in the Ap horizon, and from 1.37 to 1.45 in the B1 and B2 horizons (Nicoulaud et al., 1995; Bruand et al., 1996).

Fig. 3. Schematic diagram of the profile showing the three superposed units: the Cambisol with the A, B and K horizons; the cryoturbated unit with the IIC1, IIC2, IIC3 and IIC4; and the fragmented powdery limestone with the M1, M2 and M3 horizons (after Ould Mohamed and Bruand, 1994).
- a calcareous and loamy material resulting from Quaternary cryoturbation. Several
generations of cryoturbation can be easily identified, each one differing from the others
by the nature of the cryoturbated materials (proportion of gravels and stone, carbonate
content of the fine earth fraction, iron oxy-hydroxyde content, ...). The clay content of
the decarbonated material in the IIIC1 horizon is 38 %, indicating that the soil which
was cryoturbated had a higher clay content than the present soil cover. The bulk
density ranges from 1.35 to 1.38 in the IIIC1 horizon.

- and a powdery limestone with a carbonate content ranging from 89 to 98 %. This
limestone shows a fine ovoid structure which is less developed downward. The bulk
density ranges from 1.43 in the upper part of the powdery limestone down to 1.54 at its
bottom.

Spatial variability of the soils in the landscape

The result of the slight pedological evolution is that the soil is variable because of
differences in the thickness of the clayey loam material, which varies from 20 to 120
cm (Duval and Isambert, 1992). The surface area of the different classes of soil
thickness was estimated from the soil survey of the studied area (Bourennane, 1992;
Chéry, 1995).

The soil map of a 4 000 ha area illustrates the spatial distribution of soils all around the
site (Fig. 4).

A recent study, based on a precise digital elevation model showed that the thickness of
the silty clay loamy material was correlated to slope orientation (Fig. 5) (Bourennane et
al., 1996). The silty clay loam material is found in the slopes oriented North-East ; on
the other hand, in the slopes oriented South and South-West, the soil is very thin and
calcareous.

Table 1. Description of the soil profile
(Soil terminology after FAO, 1990 : 'Guidelines for soil profile description')

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ap 0-25 cm</td>
<td>Dark yellowish brown (10YR4/4); moist; cultivated; silty clay loam; no coarse fragments; non calcareous; common organic matter; many fine roots; many earthworm burrows; weak to moderate medium subangular blocky structure; abrupt boundary.</td>
</tr>
<tr>
<td>B1 25-50 cm</td>
<td>Dark brown (7.5YR4/4); moist; silty clay loam; no coarse fragments; non calcareous; few organic matter; many fine roots; strong coarse angular blocky structure; abrupt boundary.</td>
</tr>
<tr>
<td>B2 50-60 cm</td>
<td>Dark brown (7.5YR4/4); moist; silt loam; common calcareous gravels; moderately calcareous; few organic matter; strong coarse angular blocky structure; abrupt boundary.</td>
</tr>
<tr>
<td>K 60-65 cm</td>
<td>Very pale brown (10YR7/3); dry; calcareous silt loam; strongly calcareous; many calcareous pseudomyceliums; cemented; sharp boundary.</td>
</tr>
</tbody>
</table>
Horizon | Description (continued)
--------|--------------------------------------------------
II C1 65-65/120 cm | Reddish brown (5YR5/4) with many yellow mottles (10YR7/6); strongly calcareous; very few organic matter; many calcareous gravels and few calcareous stones; many calcareous pseudomyceliums; irregular abrupt boundary.
II C2 65/120-115/145 cm | Pale yellow (2.5Y8/2); cryoturbated limestone; very few organic matter; abundant calcareous gravels, stones and boulders; many calcareous pseudomyceliums; granular structure; irregular or broken boundary.
II C3 115/145-115/170 cm | Brownish yellow (10YR6/8) with red (2.5YR4/6) and pale yellow (5Y8/3) mottles; cryoturbated limestone; very few organic matter; abundant calcareous gravels, stones and boulders; many calcareous pseudomyceliums; granular structure; irregular or broken abrupt boundary.
II C4 115/170-120/190 cm | Light gray (5Y7/1); cryoturbated limestone; abundant calcareous gravels, stones and boulders; many calcareous pseudomyceliums; granular structure; irregular sharp boundary.
M1 120/190-200cm | Gray (10YR6/1); powdery limestone; no coarse fragments; no pseudomyceliums; gradual boundary.
M2 200-240 cm | Gray (5Y5/1) with few oxyzided strong brown (7.5YR5/8) mottles; powdery limestone; no coarse fragments; massive structure; gradual boundary.
M3 240-260 cm | Light gray (10YR7/1) with many oxyzided mottles; powdery limestone; no coarse fragments; massive structure.
> 260 cm | Bedrock, Aquitanian limestone, slightly weathered.

Table 2. Analytical data of the soil profile

<table>
<thead>
<tr>
<th>Horizon</th>
<th>depth /cm</th>
<th>coarse fragments</th>
<th>carbonate</th>
<th>particle size distribution (mm)</th>
<th>fine earth fraction /%</th>
<th>particle size distribution (mm)</th>
<th>fine earth decarbonated fraction /%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ap</td>
<td>0-25</td>
<td>0.0</td>
<td>0.0</td>
<td>30.4 29.7 37.5 1.6</td>
<td>0.8</td>
<td>30.4 29.7 37.5 1.6</td>
<td>0.8</td>
</tr>
<tr>
<td>B1</td>
<td>- 50</td>
<td>0.0</td>
<td>0.6</td>
<td>30.9 29.3 37.7 1.2</td>
<td>0.9</td>
<td>29.2 32.4 35.7 1.9</td>
<td>0.8</td>
</tr>
<tr>
<td>B2</td>
<td>- 60</td>
<td>9.5</td>
<td>21.4</td>
<td>25.4 36.1 30.5 3.4</td>
<td>4.6</td>
<td>29.1 32.0 36.4 1.6</td>
<td>0.7</td>
</tr>
<tr>
<td>K</td>
<td>- 65</td>
<td>66.7</td>
<td></td>
<td>26.6 39.3 32.2 1.5</td>
<td>0.3</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>II C1</td>
<td>- 65/120</td>
<td>55.0</td>
<td>58.6</td>
<td>26.4 28.1 15.5 13.8</td>
<td>16.2</td>
<td>38.0 23.1 30.0 5.1</td>
<td>4.0</td>
</tr>
<tr>
<td>II C2</td>
<td>- 115/145</td>
<td>60.0</td>
<td>90.0</td>
<td>22.0 32.1 6.1 7.3</td>
<td>32.5</td>
<td>68.4 11.2 17.3 2.0</td>
<td>1.0</td>
</tr>
<tr>
<td>II C3</td>
<td>- 115/170</td>
<td>48.0</td>
<td>82.0</td>
<td>30.7 31.6 5.1 6.5</td>
<td>26.1</td>
<td>97.0 0.0 2.4 0.5</td>
<td>0.0</td>
</tr>
<tr>
<td>II C4</td>
<td>- 120/190</td>
<td>64.0</td>
<td>96.7</td>
<td>19.3 32.0 7.8 7.8</td>
<td>33.1</td>
<td>81.0 0.0 10.8 2.7</td>
<td>5.4</td>
</tr>
<tr>
<td>M1</td>
<td>- 200</td>
<td>0.0</td>
<td>97.5</td>
<td>23.4 54.7 13.1 5.5</td>
<td>3.3</td>
<td>71.0 0.0 16.1 3.2</td>
<td>0.0</td>
</tr>
<tr>
<td>M2</td>
<td>- 240</td>
<td>0.0</td>
<td>93.2</td>
<td>33.2 44.4 12.8 5.9</td>
<td>3.7</td>
<td>81.7 8.5 7.3 1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>M3</td>
<td>- 260</td>
<td>0.0</td>
<td>88.5</td>
<td>36.4 45.9 11.1 4.5</td>
<td>2.1</td>
<td>91.8 4.5 2.2 0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>Horizon</td>
<td>depth /cm</td>
<td>pH</td>
<td>H₂O</td>
<td>C org /%</td>
<td>exchangeable cations /cmol kg⁻¹</td>
<td>CEC</td>
<td>Fe Deb /g kg⁻¹</td>
</tr>
<tr>
<td>---------</td>
<td>-----------</td>
<td>----</td>
<td>-----</td>
<td>---------</td>
<td>-----------------</td>
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<td>---------------</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Ca⁺⁺</td>
<td>Mg⁺⁺</td>
<td>Na⁺</td>
</tr>
<tr>
<td>Ap</td>
<td>0-25</td>
<td>8.0</td>
<td>1.37</td>
<td>25.7</td>
<td>0.7</td>
<td>0.1</td>
<td>0.7</td>
</tr>
<tr>
<td>B1</td>
<td>-50</td>
<td>8.1</td>
<td>0.92</td>
<td>26.7</td>
<td>0.7</td>
<td>0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>B2</td>
<td>-60</td>
<td>8.2</td>
<td>0.70</td>
<td>51.6</td>
<td>0.7</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>K</td>
<td>-65</td>
<td>8.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>II C1</td>
<td>-65/120</td>
<td>8.5</td>
<td>0.30</td>
<td>50.2</td>
<td>0.4</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>II C2</td>
<td>-115/145</td>
<td>8.5</td>
<td>0.28</td>
<td>43.9</td>
<td>0.3</td>
<td>0.2</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>II C3</td>
<td>-115/170</td>
<td>8.0</td>
<td>0.24</td>
<td>49.5</td>
<td>0.5</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>II C4</td>
<td>-120/190</td>
<td>8.5</td>
<td>0.28</td>
<td>40.7</td>
<td>0.2</td>
<td>0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>M1</td>
<td>-200</td>
<td>8.8</td>
<td>0.25</td>
<td>42.0</td>
<td>0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>M2</td>
<td>-240</td>
<td>8.3</td>
<td>0.20</td>
<td>42.7</td>
<td>0.3</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>M3</td>
<td>-260</td>
<td>8.0</td>
<td>0.18</td>
<td>45.3</td>
<td>0.3</td>
<td>0.2</td>
<td>0.1</td>
</tr>
</tbody>
</table>

**Hydraulic properties of the soil**

The water retention curves ($\psi_M(\Theta)$) and the unsaturated hydraulic conductivity curves ($k(\Theta)$) were established from field measurements at different sites and from laboratory determinations (Ould Mohamed et al., 1997a).

In the field, measurements were performed during three successive winter-spring periods (from December 1 to May 31): in 1991-92, 1992-93 and 1993-94 at a site which was close to the quarry (Ould Mohamed, 1995; Ould Mohamed et al., 1997b). Unsaturated hydraulic conductivity, $k(\Theta)$, was measured using the internal drainage method (Vachaud et al., 1978).

In the laboratory, the water retention curves ($\psi_M(\Theta)$) and the unsaturated hydraulic conductivity curves ($k(\Theta)$) were established using the evaporation method (Wind, 1968; Tamari et al., 1993). Samples were collected in four sites in the 4000 ha area where the soil distribution was studied. Saturated hydraulic conductivity ($k_{sat}$) was measured using the constant head method, based on Darcy's law.

The $\psi_M(\Theta)$ and $k(\Theta)$ curves were described using the analytical functions proposed by van Genuchten (1980) and Mualem (1976). The results showed little variability in the hydraulic properties at the different depths in the studied soils (Table 3). This is consistent with the small variability in soil texture and porosity with depth at each site and the low variability between the soils at the different sites within the studied area.
Fig. 4. Soil map, area of Villamblain (Beauce)
Fig. 5. Relative frequency of presence of the silty clay loam materials versus slope orientation aspect (after Bourennane et al., 1996).

Table 3. Soil hydraulic parameters of the studied soil used in numerical simulation according the van Genuchten (1980) and Mualem (1976) functions

<table>
<thead>
<tr>
<th>Locations</th>
<th>Depth (m)</th>
<th>Sample size</th>
<th>n</th>
<th>α (m⁻¹)</th>
<th>θ_s (m³ m⁻³)</th>
<th>θ_r (m³ m⁻³)</th>
<th>K_s (10⁻⁶ m s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ap</td>
<td>0.25</td>
<td>190</td>
<td>1.18</td>
<td>1.26</td>
<td>0.418</td>
<td>0.140</td>
<td>2.35</td>
</tr>
<tr>
<td>B1</td>
<td>0.35</td>
<td>190</td>
<td>1.25</td>
<td>1.16</td>
<td>0.420</td>
<td>0.174</td>
<td>3.05</td>
</tr>
<tr>
<td>Site A</td>
<td>B1</td>
<td>0.45</td>
<td>190</td>
<td>1.27</td>
<td>0.409</td>
<td>0.160</td>
<td>3.05</td>
</tr>
<tr>
<td></td>
<td>B1</td>
<td>0.55</td>
<td>190</td>
<td>1.31</td>
<td>0.415</td>
<td>0.162</td>
<td>3.25</td>
</tr>
<tr>
<td></td>
<td>B2</td>
<td>0.65</td>
<td>190</td>
<td>1.26</td>
<td>0.409</td>
<td>0.166</td>
<td>3.25</td>
</tr>
<tr>
<td>Ap</td>
<td>0.25</td>
<td>50</td>
<td>1.36</td>
<td>1.09</td>
<td>0.415</td>
<td>0.172</td>
<td>5.2</td>
</tr>
<tr>
<td>Site B</td>
<td>B1</td>
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<td>50</td>
<td>1.26</td>
<td>0.426</td>
<td>0.184</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td>B2</td>
<td>0.65</td>
<td>50</td>
<td>1.22</td>
<td>0.418</td>
<td>0.168</td>
<td>6.5</td>
</tr>
<tr>
<td>Ap</td>
<td>0.25</td>
<td>50</td>
<td>1.24</td>
<td>0.92</td>
<td>0.404</td>
<td>0.187</td>
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</tr>
<tr>
<td>Site C</td>
<td>B1</td>
<td>0.45</td>
<td>50</td>
<td>1.22</td>
<td>0.410</td>
<td>0.190</td>
<td>6.2</td>
</tr>
<tr>
<td></td>
<td>B2</td>
<td>0.65</td>
<td>50</td>
<td>1.17</td>
<td>0.420</td>
<td>0.197</td>
<td>5.5</td>
</tr>
<tr>
<td>Site D</td>
<td>Ap</td>
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<td>1000</td>
<td>1.18</td>
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<td>0.17</td>
<td>0.1</td>
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<tr>
<td></td>
<td>B1</td>
<td>0.45</td>
<td>1000</td>
<td>1.17</td>
<td>0.417</td>
<td>0.16</td>
<td>0.5</td>
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<tr>
<td>Total sites</td>
<td>Total depths</td>
<td>3250</td>
<td>1.20</td>
<td>1.02</td>
<td>0.415</td>
<td>0.180</td>
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</tr>
</tbody>
</table>

*Generated by evaporation method (Wind, 1968)*
Estimating long-term drainage

The simulation of long-term soil drainage was carried out on 3500 ha by taking into account the variation in soil thickness, initial water content and climate characteristics over a 32-year period.

The model used was based on a numerical solution of the Richards' equation, using a finite element method. Assigning small spatial variability to hydraulic properties, the role of both soil thickness and initial water content on flow prediction was analysed. Five initial water contents were defined with regard to the field capacity: 100, 90, 80, 70 and 55% of field capacity, and four main represented soil thickness were studied: 30, 60, 100 and 150 cm. The $\psi_m(\Theta)$ and $k(\Theta)$ curves were recalculated with the whole data set.

![Histograms of drainage classes](image)

Fig. 6. Frequency histograms for the different classes of drainage which were calculated using a one-dimensional finite element model based on a numerical resolution of the Richards' equation. Variation induced by soil thickness change for each initial water content conditions (100% of field capacity: a, 55% of field capacity: b) (after Ould Mohamed et al., 1997b)
Results showed that the initial water content was an important factor in the drainage predictions (Fig. 6) (Ould Mohamed et al., 1996b). However, for both the high initial water content (i.e. close to the field capacity), when the difference between rainfall and potential evaporation is low, and for a low initial water content (55 and 70% of field capacity) whatever the climate characteristics, the soil thickness has more influence on water drainage estimation.

A spatial extrapolation of the model was carried out by combining the calculated drainage (which corresponded to the different types of soil thickness and initial water contents in the study area) and the spatial distribution of crops and classes of soil thickness (Fig. 7) (Ould Mohamed et al., 1996b). The simulated water drainage was compared with groundwater recharge measurements which carried out nearby the experimental site. Results showed a close relationship between the simulated drainage and groundwater recharge over the studied period, indicating that the model could be applied to other areas of the Beauce region with appropriate parameters.

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Fig. 7. Variation in time of the groundwater recharge calculated from piezometrical measurements (WR), and simulated drainage (D) (after Ould Mohamed et al., 1997)
References


The experimental site of Villamblain:
An example of an action programme to reduce the nitrogeous diffused pollution of the Beauce calcareous aquifer

N. Schnebelen¹, E. Ledoux¹, A. Bruand², R. Darthout², G. Creuzot³, B. Verbèque⁴ and P. Courtemanche²

¹ CIG, Ecole des Mines de Paris (ENSMP), 35 rue St Honoré, 77300 Fontainebleau, France.
² Unité de Science du Sol - SESCPF, Avenue de la Pomme de Pin, INRA, 45160 Ardon, France.
³ SEMA, DIREN Centre, Cité Coligny, 131 Faubourg Bannier, 45042 Orléans Cedex 01, France.
⁴ Chambre d'Agirculture du Loiret, 13 Avenue des Droits de l'Homme, 45921 Orléans Cedex 09, France.

Introduction

As most of the agricultural regions, the "Petite Beauce" area must cope with both economic imperatives and of the same time with quantitative and qualitative management problems of water resources. In the qualitative field, a regular increase of the nitrate concentration has been observed for several decades in the main drinking water resource: the Beauce calcareous aquifer. At the present time, many drinking water wells in "Petite Beauce" area exceed the 50 mg/l limit. Others aquifers are concerned as well. In the light of this established fact, a "Nitrate regional programme" has been conducted for several years by the Regional Chamber of Agriculture. Today it also includes programmes in connection with pollution by pesticides.

Within the framework of the regional programme, a field experiment has been carried out for five years on the site of Villamblain. The aim of this field experiment is:
- to apply, on the site of Villamblain, the code of good agricultural practices recommended at national level by the CORPEN (national organisation committee for reducing water pollution by nitrate coming from agricultural activities) and to measure
(i) its practicability, (ii) its impact on the yields and farms economy, (iii) and its
efficiency in reducing the nitrogenous diffused pollution of the Beauce calcareous aquifer straight down the site;
- to contribute to the realisation of a model enabling the control of the Beauce calcareous aquifer, in order to solve the qualitative and quantitative water management questions.

Presentation of the experimental site

Location, methods and equipment

Located between Orléans and Châteaudun, the selected site has an area of 700 ha, of which 670 ha are agricultural land. The Agricultural Chamber of the Loiret has been managing the nitrogenous fertilisation and the long intercropping period (between

![Geological cross section](image-url)

*Fig. 1. Geological cross section*
cereal harvest in summer and the next culture plantation in spring) inside the site since 1991, according to the CORPEN recommendations (CORPEN, 1993). Outside the site, the farmers have carried out their usual agricultural practices.

The experimental devices, which enable the study of both the water flow and solute transport from the soil surface toward the aquifer, include opened and closed lysimeters, columns with porous ceramic cups, single and multiple piezometers.

**Geological and hydrogeological characteristics**

The site of Villamblain is located in the West part of the Beauce calcareous aquifer formation. In a large sense, this formation includes the whole lacustrian facies, with calcareous dominance, which where formed from the Lutetian to Aquitanian (Miocene) in the South-West of the Paris basin (Fig. 1) (Desprez and Mégnien, 1975).

Straight down the site, the tertiary lake sediments is about sixty metres thick. It is lying on a substratum made up of an eocene detritic formation (clays with flints) in discontinuity on the cretaceous substratum. The lacustrian facies are wrinkled by synclinal and anticlinal axes whose main direction is South-East - North-West (Armorican direction).

![Fig. 2. Piezometric map of the study area (values in metre)](image)

The experimental site is located in the free part of the Beauce calcareous aquifer, more precisely in the sub-catchment area of the Mauve of Detourbe, an affluent of the Loire river. In the region of Villamblain, the general flow is going toward the South-West direction (Fig. 2). Locally, the surface of the aquifer is influenced by underground
drainage axes (karstic system) which roughly correspond to dry valleys on the surface. The main hydraulic gradient is very low: 0.06 %. For a transmissivity ranging from $5 \times 10^{-2}$ to $10^{-1} \text{ m}^2/\text{s}$ and a 10 \% porosity, the estimated velocities range from 160 to 320 m/year (Jordana, 1992; Schnebelen, 1995).

The piezometric level has been measured in the vicinity of the site to the South at Poiseaux (Epiéds-en-Beauce) since 1974 (Fig. 3). The main factors of the variation are winter rainfalls and irrigation, the latter being highly developed over the last decade.

![Graph](image)

**Fig. 3.** Variation of the groundwater table over the last 22 years (1974-1996)

**Results from the field experiments**

**Evolution of the agricultural practices inside the site**

In comparison with the usual agricultural practices, the farmers have significantly reduced the total nitrogenous amounts which are supplied to the crops (10 \% to 15 \% less by year). This evolution of the practices is particularly true for maize, with a 60 kg/N/ha/year reduction of fertilisation without any decrease in the yield (Verbèque and Revalier, 1993 and 1994).

During the long winter interculture, catch crops are planted in late August to reduce nitrate flow towards the aquifer for the winter-spring which is the recharge period.
Since the beginning of the experiment, the catch crops have represented about 40% of the land (against 0% in 1991). In consequence, uncovered soils have been about 12% since 1992 (against 50% in 1991).

**Effects of the modified agricultural practices on the nitrate concentration of water in the soil**

Inside the site, the agricultural practices have been modified in two ways:
- the amount of nitrate which is supplied by fertilisation to each crop is calculated by taking into account both the amount of nitrate remaining in the soil in early spring and the estimated yield of the crop;
- in late August, catch crops are grown after wheat or barley harvest to reduce nitrate concentration in the soil for the autumn and thus, at the beginning of the groundwater recharge period.

Two lysimetric devices were built inside the experimental site, and two others outside the site (Fig. 4). These devices enabled the collecting of water at 1.5 m depth and measuring the nitrate concentration for the winter-spring period, under modified and non modified agricultural practices. The mean nitrate concentration which was measured on the whole water flow for each winter-spring period is much lower in the experimental site (from 40 to 50 mg/l against 70 to 200 mg/l in the lysimeters located outside the site) (Bruand et al., 1993; Dartout et al., 1994 and 1995).

![Lysimetric device with the closed (1) and opened (2) lysimeters](image)

Fig. 4. Lysimetric device with the closed (1) and opened (2) lysimeters

The effect of catch crops on the winter-spring recharge, i.e. the amount of the water infiltration at 1.5 m depth, has been quantified since the beginning of the experiment. Results showed a significant decrease in the water infiltration under catch crops although they are crushed in late November or early December.
Impact of the modified agricultural practices on the groundwater quality straight under the site of Villamblain

In space, the measured nitrate concentration increases not only from upstream to downstream, but also from the bottom to the top of the aquifer (chemical stratification). The horizontal gradient is supposed to result from mixing between groundwater and infiltration water with a higher nitrate concentration than at the bottom of the groundwater. The vertical gradient in nitrate concentration could also be related to the existence of interstratified semi-permeable layers within the lacustrine limestones.

In time, the nitrate concentration would result from the combinaison of (Fig. 5):
- a regional contribution related to the global horizontal flow of the aquifer. The annual increase of this regional pollution was about 2 mg/l upstream the site and 3 to 4 mg/l downstream (up to 1994).
- a local less stable contribution, related to the straight down site infiltration of water throughout the unsaturated zone of the site. The high amplitudes of this contribution correspond to rapid vertical circulation; the low amplitudes would depend on differences in the succession of the crops on the site.

Since 1994, the nitrate concentration has been inclined to become stable or even to decrease in some piezometers inside the site. This would be related to the modified agricultural practices.

The concentration of pesticides has also been measured in the groundwater for two years. About sixty different molecules were researched (concentration higher than 0.01 to 0.05 µg/l according to the molecules), but only atrazine, simazine and their respective metabolites exhibited significant concentrations (> 0.1 µg/l) in the aquifer. As for the nitrate, the lowest concentrations are measured at the upstream and in the deepest boreholes.

Model development

A mathematic model is being used on an area of 10800 ha including the experimental site in order (i) to take into account the different processes which control the flow of contaminants from the soil to the aquifer throughout the whole unsaturated zone and (ii) to quantify the impact of the modified agricultural practices on the underground water quality.

The model is developed jointly by ENSMP and INRA and it is adapted to the study case of Villamblain. A first simulation of the nitrate migration towards the aquifer was performed in 1995, using the "Coupled Model" and the model "NEWSAM" of the "Ecole des Mines de Paris" (Ledoux, 1980; Ledoux and Tillie, 1987).
Fig. 5a. Evolution of the nitrate concentration in the piezometers located upstream the site of Villamblain

Fig. 5b. Evolution of the nitrate concentration in the piezometers located downstream the site of Villamblain
The first results (Schnebelen, 1995) showed that a 50% decrease in the nitrate concentration in the unsaturated zone can lead to a 20% decrease in the nitrate concentration in the saturated zone downstream the site. The improvement is perceptible, but limited in space because of the size of the site which is only 700 ha of the area of 10800 ha where the model was applied.

For the further simulation, our aim is to include (i) the spatial and temporal variability of the agricultural systems, in relation to the soil distribution on the site, (ii) and the geological, hydrogeological and geochemical heterogeneity of the Beauce calcareous aquifer above the site. This should give a better representation of the nitrate concentrations evolution in the aquifer.

References


Section 2:

The HYPRES database
A description of the HYPRES database

(HYdraulic PROperties of European Soils)

Allan Lilly

Macaulay Land Use Research Institute, Craigiebuckler, Aberdeen, AB15 8QH Scotland

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Introduction

Simulation models are increasingly being used in land use planning and in the investigation and prediction of a wide range of complex environmental processes. Many of these models are concerned with water and solute movement in the vadose zone and require water retention and unsaturated hydraulic conductivity data. However, these properties are often difficult and time consuming to measure and there is renewed interest in the establishment of pedotransfer functions in order to estimate them from more easily measured soil properties.

In order to facilitate the development of these pedotransfer functions, the EU have funded a project (Using existing soil data to derive hydraulic parameters for simulation modelling in environmental studies and in land use planning ~ CHRX-CT94-0639) in which a number of European Institutions are collaborating to develop a database of measured soil hydraulic properties from which a range of pedotransfer functions can be derived. In the first instance, class pedotransfer functions will be developed based on the five soil texture classes (plus organic soils) currently used to describe the soil units depicted on the 1:1 000 000 Soil Map of the European Communities. Later, multiple regression of the soil hydraulic properties against individual particle size classes will be used to derive continuous pedotransfer functions and novel techniques such as Neural Networks may also be employed. The database has the acronym HYPRES which stands for HYdraulic PROPERTIES of European Soils and is described in more detail below.

Description of the database

It is anticipated that HYPRES will have a much wider application beyond that currently envisaged and so it is important that it has a good relational structure that is not restrictive and which allows the data to be easily extracted using a variety of attributes or by a combination of attributes. Therefore, the database has been developed within an Oracle Relational Database Management System which is flexible and can be designed to accommodate the diversity of the data that are being collected and manipulated.

The HYPRES database comprises seven separate tables (Appendix 2) which are linked by geo-reference (Oracle field gridref) and, where appropriate, by the horizon notation (horizon). The attributes stored in each table closely resemble those stored in UNSODA, a public domain database of soil hydraulic properties (Leijn, Alves, van Genuchten and Williams, 1994). The data stored in UNSODA were the result of deliberations by the delegates at an International workshop on Indirect methods for estimating the hydraulic properties of unsaturated soils. who felt that these were the most important soil attributes for improving existing parametric and physico-empirical models and for deriving new pedotransfer functions (van Genuchten, Leijn and Lund, 1992). However, the UNSODA database had certain limitations that made it unsuitable for the storage and manipulation of the European data hence the creation of the database within a proprietary database system such as Oracle.
Table BASICDATA

This table stores the relevant profile and environmental data, contact names and addresses and textual descriptions of the methods of analyses. While it is unlikely that every field will be filled, there are some key fields which must have data to allow links with the data stored in allied tables, these are gridref and horizon. A proposed European wide geo-referencing system can be applied retrospectively provided each sample location has been given a local geo-reference and that the particular system used is known.

Description of the fields

gridref:

It is important that each profile or sample location is properly geo-referenced to allow manipulation of the data within Geographic Information Systems (GIS). The system of geo-referencing will be based on the GISCO standard which discretises Europe into 100 x 100 kilometre grid cells. This system gives a resolution to within 1 m allowing this field also to function as the unique identifier. An alternative method of using latitude and longitude would give a variable resolution depending on the sample location and even if quoted to seconds, would only allow a resolution of around 35 m in Scotland.

name:

The name field will be used primarily as a method of cross referencing with any existing profile descriptions which will be held in other databases and provides a shorthand method of referring to individual sample locations. Normally the names will be from the locality where the soil was sampled, for example, a research station or farm.

FAO_soil:

To allow linkages with the digitised 1: 1 000 000 Soil Map of the European Communities (1985), it is proposed that each soil sampled will be classified according to the FAO published soil classification system to subgroup level. The soil taxonomic unit should be quoted and not the soil map unit. A conversion to the revised FAO/UNESCO soil map legend (1994) can be employed at a later date.

country:

This field will contain the CORINE code for each country, for example:

<table>
<thead>
<tr>
<th>Country</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greece</td>
<td>30</td>
</tr>
<tr>
<td>France</td>
<td>33</td>
</tr>
<tr>
<td>Slovakia</td>
<td>42</td>
</tr>
<tr>
<td>Germany</td>
<td>49</td>
</tr>
<tr>
<td>Scotland</td>
<td>441</td>
</tr>
<tr>
<td>Netherlands</td>
<td>31</td>
</tr>
<tr>
<td>Spain</td>
<td>34</td>
</tr>
<tr>
<td>Denmark</td>
<td>45</td>
</tr>
<tr>
<td>Portugal</td>
<td>351</td>
</tr>
<tr>
<td>Northern Ireland</td>
<td>442</td>
</tr>
</tbody>
</table>
localnir:
The geo-reference of the sample location in the standard method used in each country and to a resolution of 1 m (if possible). This geo-reference can then be converted to the GISCO system while still retaining a link with profile descriptions held in other national databases. In some cases, only approximate geo-references were given, for example, to within 50 metres.

localmsg:
The soil type in the taxonomy of each country or region (where possible). Again this preserves a link with any existing soil profile database.

Localseries:
The name of the soil series (where possible or appropriate) in the naming convention as used in each individual country. This should be a taxonomic unit and not a soil map unit.

top_depth_gw:
The average maximum height attained by a ground watertable, for example, if the watertable regularly rises to within 40 cm of the soil surface then 40 will appear in this field. If not applicable, that is, there is no groundwater table then NA was recorded. If a groundwater table was present (or likely to be present) but the depth was not determined, ND was recorded.

bot_depth_gw:
The average minimum level of the ground watertable below the soil surface, for example, if it retreats to 130 cm below the soil surface in summer then 130 should appear. If not applicable, that is, there is no groundwater table then NA was recorded. If a groundwater table was present but the depth was not determined then ND was recorded.

sitedescr:
This is a field for free text to describe the sample location and any other relevant information, for example, in terms of land use, geography, weather prior to sampling.

sampledate:
The date that the soil was sampled, not when the laboratory determination was done. This distinction is important particularly where the hydraulic properties are known to vary significantly with seasonal changes. This field will be blank if the sample date is not known.

annrain:
This field can be used to give an indication of the long term climatic conditions pertaining to the site. The average annual rainfall is given in mm. This field retains
compatibility with UNSODA and allows an assessment of the climatic conditions of
the site. Where no data are available then ND was recorded.

*ave_jan_temp:*

The long term average January temperature in degrees Celsius. This field retains
compatibility with UNSODA and allows an assessment of the climatic conditions of
the site. If this attribute has not been determined then ND was recorded.

*ave_jul_temp:*

The long term average July temperature in degrees Celsius. This field retains
compatibility with UNSODA and allows an assessment of the climatic conditions of
the site. If this attribute has not been determined then ND was recorded.

*contact_name:*

The name of the person contributing the data and who has some knowledge of the data.

*contact_address:*

The address and affiliation of the data contributor.

*email:*

Email address for rapid contact.

*publisher:*

Any relevant references where the data or methodologies have been published. It may
have been necessary to abbreviate the list. If there is no information for this attribute,
then ND was recorded.

*comments1:*

Free text to describe what analyses were done on the samples (for example, laboratory
water release, field saturated hydraulic conductivity), reasons for sampling the soils,
the nature of the site and any related soil profile descriptions or soil chemical data.

*comments2:*

Space for additional free text.

*keywords:*

This field may be used to select data from the database according to the methodologies
used. This inevitably means some standardisation of terminology to describe the
various techniques.

*numbber_hor:*

This field provides a rapid assessment of the number of related samples in a profile
and will help in the manipulation of the data. This should only be the number of soil horizons in each profile for which data are held within the database.

**rating:**
In order to keep some compatibility with UNSODA, contributors gave a subjective rating to the quality of their data using the numbers 1-10. Where they did not wish to do this, -9 was entered.

**rated_by:**
Name of the person rating the data, this will normally be the owner of the data. If the data were not given a rating, then NA was entered.

<table>
<thead>
<tr>
<th>Table SOIL_PROPS</th>
</tr>
</thead>
</table>

This table of soil properties holds both descriptor data and data likely to be used in deriving pedotransfer functions. In general the data held in this table are primary data although there are some derived data, an example being, the Mualem-van Genuchten parameters. The attribute which links this table with the previous one is the gridref. The horizon designation is used to link it to subsequent tables which hold the soil hydraulic data. Again these fields are largely compatible with UNSODA.

**Description of the fields**

**gridref:**
This will be the same as the geo-reference given in the BASICDATA table and functions as the unique identifier for all tables. Based on a GISCO standard, this system will give a resolution to within 1 m.

**horizon:**
The horizon designation is used in conjunction with gridref to uniquely identify each sample and should follow the FAO system published in *Guidelines for soil description, 3rd Ed* (FAO, 1990). Spacing of the horizon notation is important to allow quick and accurate selection from the database. The first space is normally reserved for a numeral which identifies lithological discontinuities within the profile however, in cases where a horizon has been buried, for example, by alluvial or colluvial deposits, a 'b' is placed in this character space. Under the FAO system of horizon notation, this suffix is normally placed at the end of the sequence, however, as it is important to recognise a horizon as being buried, it is proposed that it is placed in the first character space to make it more prominent.

The next two character spaces accommodate the Master horizon designation, while the fourth and fifth spaces are for subhorizon designation. The sixth space is for the numeric designation of vertical subdivisions. Where the sampling of a soil horizon at one location (that is, within one profile) has been replicated, the horizon notation
should contain a suffix in the last character space in the field for example _A_p_a and _A_p_b (where _ represents a space) so that horizons can be indicated thus:-

```
  A  p  a
  A  p  b
  B  C  g  x  l  a
  A  h
```

**top_depth:**
The upper sample depth where possible and not the upper depth of the horizon although this field often contains only the depth to the horizon.

**bot_depth:**
The lower sample depth where possible and not the lower depth of the horizon although this field often contains only the depth to the bottom of the horizon.

**structure1:**
This field has a brief description of the primary soil structure of a soil horizon using the FAO definitions and ped size classes wherever possible (FAO, 1990) for example, 'Moderate medium subangular blocky'. Appendix 1 shows the FAO size classes. If another system has been used that could not be converted, then this is indicated in the comments. If the primary soil structure has not been recorded then the notation ND is used.

**structure2:**
This field should describe any secondary structure in the horizon in the same manner as above. If the secondary soil structure has not been recorded, or is not present, then the notation ND is used.

**USclay:**
The percentage of the <2000 mm fraction that is in the FAO/USDA size range of clay particles, that is <2 mm. Where this size fraction has not been directly determined, the data of the proportion of each size fraction will be stored in table RWP/PSD and the proportion of the particles in this size range will be determined from an estimation procedure.
USsilt:
The percentage of the <2000 mm fraction that is in the FAO/USDA size range of silt particles, that is 2-50 mm. Where this size fraction has not been directly determined, the data of the proportion of each size fraction will be stored in table RAWPSD and the proportion of the particles in this size range will be estimated.

USsand:
The percentage of the <2000 mm fraction that is in the FAO/USDA size range of sand particles ie 50-2000 mm. Where this size fraction has not been directly determined, the data of the proportion of each size fraction will be stored in table RAWPSD and the proportion of the particles in this size range will be estimated.

ksat:
The measured saturated hydraulic conductivity of the horizon in cm day$^{-1}$. The method to determine this property is given in the keywords field and a brief description given in the comments field. A value of -9 indicates that this attribute has not been determined. This attribute is different from the mg$_{\text{ks}}$ which is derived from a curve fitting procedure during the parameterisation of the K/h relationship.

satwat:
This field contains data on the measured saturated water content expressed as a proportion of the total sample volume or as a proportion of the fine earth fraction (ie <2000 mm) and this is indicated in the comments field. The method of determination should be given briefly in the comments and keywords fields if appropriate and if different from the method used to determine the soil water retention curve. The value -9 is entered where this attribute has not been determined. This attribute is different from the mg$_{\text{sat}}$ which is derived from a curve fitting procedure during the parameterisation of the θ/h relationship.

bulk_den:
Simply the soil dry bulk density expressed in g cm$^{-3}$. The method can be described in the comments field. A value of -9 is entered where this attribute has not been determined.

particle_den:
The measured density of the soil particles in g cm$^{-3}$. A value of -9 is entered where this attribute has not been determined.

porosity:
The measured total porosity. This attribute has been retained to remain compatible with UNSODA, and is often equal to the saturated water content. This value can be expressed as a proportion of the total soil volume or as a proportion of the <2000 mm fraction and this is indicated in the comments field. A value of -9 is entered where this attribute has not been determined.
**org_mat:**

In order to keep compatibility with UNSODA, the organic matter content should be given, not the Organic Carbon content. The value should be expressed as a percentage of the <2000 mm soil fraction. A value of -9 is entered where this attribute has not been determined.

**mvg_sat:**

This field holds the data either from the parameterisation of the measured soil moisture retention curve and hydraulic conductivity/pressure head relationship or the parameters as determined using inverse and multi-step outflow methods. The methodology will be recorded in the *keywords* field. The Mualem-van Genuchten (mvg) parameter of saturated water content is a curve fitting parameter and is generally not equal to either total porosity or to the saturated water and so it merely defines the starting point of the fitted curve (van Genuchten, Leij and Yates, 1991). The parameterisation procedure will be applied consistently over the whole dataset, but, by retaining the actual measured data within the database, there are opportunities in the future to either use different parameterisation schemes or to apply any improved mvg parameterisation.

**mvg_resid:**

This field holds the data either from the parameterisation of the measured soil moisture retention curve and hydraulic conductivity/pressure head relationship or the parameters as determined using inverse and multi-step outflow methods. The methodology being recorded in the *keywords* field. The Mualem-van Genuchten (mvg) parameter of residual water content is a curve fitting parameter and may not represent the true residual water content of the soil (van Genuchten et al., 1991). It defines the end point of the fitted curve.

**mvg_alpha:**

The mvg parameter, alpha, is an empirical constant which defines the shape of the fitted curve.

**mvg_n:**

The mvg parameter, n, is an empirical constant which defines the shape of the fitted curve.

**mvg_m:**

The mvg parameter, m, is an empirical constant which defines the shape of the fitted curve.

**mvg_l:**

The mvg parameter l is a pore-connectivity parameter of relevance only to the description of the hydraulic conductivity/pressure head relationship.
mvg_ks:
The mvg parameter Ks is the hydraulic conductivity at saturation. Due to possible large
increase in conductivity with small changes in pressure head near to saturation, this
parameter is best seen as a fitting parameter and not necessarily equal to the measured
saturated hydraulic conductivity (ksat).

comments:
Comments on any aspects of attribute measurement in this table, for example, saturated
water content or conductivity, methods for determining particle size or organic matter
contents and, in particular, an indication of which soil volume the porosity values are
related to and the derivation of the mvg parameters.

keywords:
The keywords which describe the methods used. These will be standardised throughout
in order to facilitate data manipulation.

| Table RAWPSD |

This table holds the particle size data where a system other than the FAO/USDA
classification of particle size class has been used. Although only two fields are shown,
size and percent, the table holds as many multiple pairings as necessary. The data are
used in an interpolation procedure to provide approximations to the FAO/USDA
classes which are then stored in the appropriate fields in the SOIL_PROPS table. In
most instances there will be no need to access this table.

Description of the fields

gridref:
As previously described. It is vital that the geo-reference and horizon designations are
exactly as those given in the SOIL_PROPS table in order to keep all the data from one
horizon intact.

horizon:
As previously described.

size:
The particle size class. In order to allow this field to be entirely numeric it is proposed
that the first particle size indicated will be read as 'less than'. The second, will be taken
to be the range between the first and second and so on. For example, in the table where
the particle size ranges follow the British Standard Texture Classes we have:
<table>
<thead>
<tr>
<th>psize</th>
<th>pcnt</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>12</td>
</tr>
<tr>
<td>60</td>
<td>40</td>
</tr>
<tr>
<td>2000</td>
<td>48</td>
</tr>
</tbody>
</table>

This will mean that there is 12 percent clay (<2 μm), 40 percent 'silt' (2-60 μm) and 48 percent 'sand' (60-2000 μm).

**pcnt:**
The proportion of particles in the size range specified expressed as a percentage of the total mass of the soil fraction which is less than 2000 μm in size.

**Table WAT RET**

This table holds data on the θ/h relationship generally where there are only a few field or laboratory determinations or where a 'fixed point' procedure has been used, for example, by desorption on tension tables. The remaining data are held in the table RAWRET and are often data derived by the evaporation method. Keeping these datasets separate will facilitate analysis of the data although this table can be subsequently used to hold estimated values derived from a parameterisation of the soil moisture retention curves.

It is envisaged that users will most often access this table for soil moisture retention data (either measured or derived), therefore, the descriptions of the methods used will also be stored here. Where no fixed point data are available, the description of the methods is currently stored in the table BASICDATA in preference to storing this information in the table of raw data (RAWRET).

**Description of the fields**

**gridref:**
As previously described. The geo-reference and horizon designations should exactly match those in the previous tables in order to keep all the data from one determination intact.

**horizon:**
As previously described.

**flag:**
Indicates whether the data are derived from laboratory (l) or field (f) measurements.

**head1 - head25:**
The value of the pressure head in cm of water expressed as a positive number although pressure head is in fact negative.
theta1 - theta25:
The soil moisture content at a stated pressure head expressed as a proportion of the volume of the soil. Indication as to whether the soil volume expressed as total volume including stones (for example, from field measurements) or the volume of the fine earth fraction only, that is, the volume of the soil minus the volume of stones will be made in the comments field.

comments:
Comments on, and description of, the methods used to derive the θ/h relationship. In particular indicate whether the data are derived from field or laboratory measurements and whether the values relate to total soil volume or the fine earth fraction.

keywords:
The keywords describing the methods used. These will be standardised in order to facilitate data manipulation.

| Table RAWRET |
This table primarily holds all the data from the θ/h relationship as derived from the evaporation method. The geo-reference and horizon designations consistent with previous tables in order to keep all the data from one determination intact. This table holds as many q/h determinations as were made for each sample. A description of the method will be found in the table BASICDATA.

Description of the fields

gridref:
As previously described. The geo-reference and horizon designations should exactly match those in the previous tables in order to keep all the data from one determination intact.

horizon:
As previously described.

flag:
Indicates whether laboratory (l) or field measurement (f).

head:
The value of the pressure head in cm of water expressed as a positive number, although this attribute is in fact, negative.
theta:
The soil moisture content at a stated pressure head expressed as a proportion of the volume of soil. Indicate if the soil volume is total volume including stones (for example, from field measurements) or the volume of the fine earth fraction only i.e. the volume of the soil minus the volume of stones.

| Table KUNSAT |

This table is similar to table WAT_RET except that it holds a subset of the unsaturated hydraulic conductivity data. There is an allied table for holding the raw data (RAWUNSAT).

The moisture contents will be quoted as a proportion of the total soil volume or as a proportion of the fine earth fraction where appropriate and this is indicated in the comments field.

Description of the fields

gridref:
As previously described. The geo-reference and horizon designations should exactly match those in the previous tables in order to keep all the data from one determination intact.

horizon:
As previously described.

flag:
Indicates whether laboratory (l) or field measurement (f).

ind_var:
This indicator variable indicates whether the unsaturated conductivity measurements are relative to moisture content (theta) or pressure head (head), both expressed as positive numbers.

var1 - var25:
The value for either the pressure head or the moisture content. The pressure head should be in cm of water and the moisture content is expressed either as a proportion of the total soil volume or as a proportion of the fine earth (<2000 μm) fraction.

cond1 - cond25:
The unsaturated hydraulic conductivity at each of the indicator variable values in cm day⁻¹.
comments:
Comments on the methods used to determine the unsaturated hydraulic conductivities, in particular, an indication of whether the values relate to field or laboratory measurements and whether they are relative to pressure head or moisture content.

keywords:
Keywords to describe the techniques used to determine the unsaturated hydraulic conductivities. These will be standardised in order to facilitate data manipulation.

**Table RAWUNSAT**

This table will primarily hold all the data on the unsaturated hydraulic conductivity derived by the evaporation method and will be able to hold as many pairs of K/h determinations as were made for each sample.

**Description of the fields**

**gridref:**
As previously described. The geo-reference and horizon designations should exactly match those in the previous tables in order to keep all the data from one determination intact.

**horizon:**
As previously described.

**flag:**
An indication as to whether the data are from measurements made in the field (f) or laboratory (l).

**ind_var:**
An indication as to whether the unsaturated hydraulic conductivity is related to pressure head (head) in cm of water, expressed as a positive number or moisture content (theta).

**var:**
The value of the related variable in cm of water if against pressure head or the moisture content expressed as a proportion of the soil volume.

**cond:**
The unsaturated conductivity expressed in cm day^{-1}. 
Acknowledgements

The financial support of the Scottish Office Agriculture, Environment and Fisheries Department during the preparation of this document is gratefully acknowledged.

References


### Appendix 1. FAO Soil structure classes (FAO, 1990)

<table>
<thead>
<tr>
<th>Class</th>
<th>Platy</th>
<th>Prismatic</th>
<th>Blocky</th>
<th>Granular</th>
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<tr>
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<td>&lt; 1 mm</td>
<td>&lt; 10 mm</td>
<td>&lt; 5 mm</td>
<td>&lt; 1 mm</td>
</tr>
<tr>
<td>Fine</td>
<td>1 - 2 mm</td>
<td>10 - 20 mm</td>
<td>5 - 10 mm</td>
<td>1 - 2 mm</td>
</tr>
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<td>Medium</td>
<td>2 - 5 mm</td>
<td>20 - 50 mm</td>
<td>10 - 20 mm</td>
<td>2 - 5 mm</td>
</tr>
<tr>
<td>Coarse</td>
<td>5 - 10 mm</td>
<td>50 - 100 mm</td>
<td>20 - 50 mm</td>
<td>5 - 10 mm</td>
</tr>
<tr>
<td>Very Coarse</td>
<td>&gt; 10 mm</td>
<td>&gt; 100 mm</td>
<td>&gt; 50 mm</td>
<td>&gt; 10 mm</td>
</tr>
</tbody>
</table>

The grade of the structure can also be added, these are: Very weak, Weak, Moderate, Strong and Very strong.
### Appendix 2. Database Structure

Oracle tables for the European soil hydraulic properties database. Each column represents a separate table linked by geo-reference and horizon.

<table>
<thead>
<tr>
<th>BASIC_DATA</th>
<th>SOIL_PROPS</th>
<th>RAWPSD</th>
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<th>RAWRET</th>
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<th>RAWUNSAT</th>
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</table>
Oracle table BASICDATA for European soil hydraulic properties database

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<th>FIELD NAME</th>
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<th>SIZE</th>
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<tbody>
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<td>date when the sample was taken</td>
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<td>FAO soil classification in full</td>
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Oracle table SOIL_PROPS for European soil hydraulic properties database

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<th>COMMENTS/DESCRIPTION</th>
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<td>grid ref to 1m resolution using GISCO tiling system</td>
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<tr>
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<td>horizon designation (following the FAO)</td>
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<td>NUMBER</td>
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<td>upper sample depth</td>
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<tr>
<td>bot_depth</td>
<td>NUMBER</td>
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<td>lower sample depth</td>
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<td>percentage of silt as defined by USDA (2-50 µm)</td>
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<td>USsand</td>
<td>NUMBER</td>
<td></td>
<td>percentage of sand as defined by USDA (50-2000 µm)</td>
</tr>
<tr>
<td>ksat</td>
<td>NUMBER</td>
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<td>measured saturated hydraulic conductivity (cm day⁻¹)</td>
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<td>satwat</td>
<td>NUMBER</td>
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<td>measured saturated water content</td>
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<td>mvg_resid</td>
<td>NUMBER</td>
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Oracle table RAWPSD for European soil hydraulic properties database

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<td>horizon designation (as per FAO)</td>
</tr>
<tr>
<td>psize</td>
<td>NUMBER</td>
<td></td>
<td>size range of particles if other than USDA (express in microns)</td>
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<tr>
<td>pcnt</td>
<td>NUMBER</td>
<td></td>
<td>proportion of particles within the specified size range</td>
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<tr>
<td>seqno</td>
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</tbody>
</table>
Oracle table WAT_RET for European soil hydraulic properties database

<table>
<thead>
<tr>
<th>FIELD NAME</th>
<th>TYPE</th>
<th>SIZE</th>
<th>COMMENTS/DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>grid ref</td>
<td>CHAR</td>
<td>16</td>
<td>grid ref to 1m resolution using GISCO tiling system</td>
</tr>
<tr>
<td>horizon</td>
<td>CHAR</td>
<td>7</td>
<td>horizon designation (as per FAO)</td>
</tr>
<tr>
<td>flag</td>
<td>CHAR</td>
<td>1</td>
<td>indicate whether the data are field or laboratory measurements</td>
</tr>
<tr>
<td>head1</td>
<td>NUMBER</td>
<td></td>
<td>value of the first determination (cm)</td>
</tr>
<tr>
<td>head2</td>
<td>NUMBER</td>
<td></td>
<td>value of the second determination (cm)</td>
</tr>
<tr>
<td>head3</td>
<td>NUMBER</td>
<td></td>
<td>value of the third determination (cm)</td>
</tr>
<tr>
<td>...head25</td>
<td>NUMBER</td>
<td></td>
<td>to a maximum of 25 determinations</td>
</tr>
<tr>
<td>theta1</td>
<td>NUMBER</td>
<td></td>
<td>moisture retained at the first head</td>
</tr>
<tr>
<td>theta2</td>
<td>NUMBER</td>
<td></td>
<td>moisture retained at the second head</td>
</tr>
<tr>
<td>theta3</td>
<td>NUMBER</td>
<td></td>
<td>moisture retained at the second head</td>
</tr>
<tr>
<td>...theta25</td>
<td>NUMBER</td>
<td></td>
<td>to a maximum of 25 determinations</td>
</tr>
<tr>
<td>comments</td>
<td>VARCHAR2</td>
<td>255</td>
<td>comments on the methods used to determine the moisture content/ pressure head relationship</td>
</tr>
<tr>
<td>keywords</td>
<td>VARCHAR2</td>
<td>120</td>
<td>keywords used to describe the techniques used to determine water retention.</td>
</tr>
</tbody>
</table>

Oracle table RAWRET for European soil hydraulic properties database

<table>
<thead>
<tr>
<th>FIELD NAME</th>
<th>TYPE</th>
<th>SIZE</th>
<th>COMMENTS/DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>grid ref</td>
<td>CHAR</td>
<td>16</td>
<td>grid ref to 1m resolution using GISCO tiling system</td>
</tr>
<tr>
<td>horizon</td>
<td>CHAR</td>
<td>7</td>
<td>horizon designation (as per FAO)</td>
</tr>
<tr>
<td>flag</td>
<td>CHAR</td>
<td>1</td>
<td>indicate whether the data are field or laboratory measurements</td>
</tr>
<tr>
<td>head</td>
<td>NUMBER</td>
<td></td>
<td>value of the pressure head applied (cm)</td>
</tr>
<tr>
<td>theta</td>
<td>NUMBER</td>
<td></td>
<td>moisture retained at the applied head</td>
</tr>
</tbody>
</table>
Oracle table KUNSAT for European soil hydraulic properties database.

<table>
<thead>
<tr>
<th>FIELD NAME</th>
<th>TYPE</th>
<th>SIZE</th>
<th>COMMENTS/DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>grid ref</td>
<td>CHAR</td>
<td>16</td>
<td>grid ref to 1m resolution using GISCO tiling system</td>
</tr>
<tr>
<td>horizon</td>
<td>CHAR</td>
<td>7</td>
<td>horizon designation (as per FAO)</td>
</tr>
<tr>
<td>flag</td>
<td>CHAR</td>
<td>1</td>
<td>indicate whether the data are from field or laboratory measurements</td>
</tr>
<tr>
<td>ind_var</td>
<td>CHAR</td>
<td>5</td>
<td>indicate whether the conductivity is related to pressure head (cm) or to moisture content (theta)</td>
</tr>
<tr>
<td>var1</td>
<td>NUMBER</td>
<td></td>
<td>value of the first determination (head or theta)</td>
</tr>
<tr>
<td>var2</td>
<td>NUMBER</td>
<td></td>
<td>value of the second determination (head or theta)</td>
</tr>
<tr>
<td>var3</td>
<td>NUMBER</td>
<td></td>
<td>value of the third determination (head or theta)</td>
</tr>
<tr>
<td>...var25</td>
<td>NUMBER</td>
<td></td>
<td>to a maximum of 25 determinations</td>
</tr>
<tr>
<td>cond1</td>
<td>NUMBER</td>
<td></td>
<td>hydraulic conductivity at the first indicator value (cm day(^{-1}))</td>
</tr>
<tr>
<td>cond2</td>
<td>NUMBER</td>
<td></td>
<td>hydraulic conductivity at the second indicator value (cm day(^{-1}))</td>
</tr>
<tr>
<td>cond3</td>
<td>NUMBER</td>
<td></td>
<td>hydraulic conductivity at the third indicator value (cm day(^{-1}))</td>
</tr>
<tr>
<td>...cond25</td>
<td>NUMBER</td>
<td></td>
<td>to a maximum of 25 determinations</td>
</tr>
<tr>
<td>comments</td>
<td>VARCHAR</td>
<td>255</td>
<td>comments on the methods used to determine ksat including</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td>whether the values were determined in the lab or field and</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>whether theta or pressure head has been used</td>
</tr>
<tr>
<td>keywords</td>
<td>VARCHAR</td>
<td>120</td>
<td>keywords to describe the techniques used to determine unsaturated hydraulic conductivity.</td>
</tr>
</tbody>
</table>

Oracle table RAWUNSAT for European soil hydraulic properties database.

<table>
<thead>
<tr>
<th>FIELD NAME</th>
<th>TYPE</th>
<th>SIZE</th>
<th>COMMENTS/DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>grid ref</td>
<td>CHAR</td>
<td>16</td>
<td>grid ref to 1m resolution using GISCO tiling system</td>
</tr>
<tr>
<td>horizon</td>
<td>CHAR</td>
<td>7</td>
<td>horizon designation (as per FAO)</td>
</tr>
<tr>
<td>flag</td>
<td>CHAR</td>
<td>1</td>
<td>indicate whether the data are from field or laboratory measurements</td>
</tr>
<tr>
<td>ind_var</td>
<td>CHAR</td>
<td>5</td>
<td>indicate whether the conductivity is related to pressure head (cm) or to moisture content (theta)</td>
</tr>
<tr>
<td>var</td>
<td>NUMBER</td>
<td></td>
<td>value of the determination (in units of pressure head or theta)</td>
</tr>
<tr>
<td>cond</td>
<td>NUMBER</td>
<td></td>
<td>hydraulic conductivity at the indicator value (cm day(^{-1}))</td>
</tr>
</tbody>
</table>
Section 3:
Workshop report
Report of the second annual workshop of the EU funded project

"Using existing soil data to derive hydraulic parameters for simulation modelling in environmental studies and in land use planning"
INRA Orléans, October 1996

Allan Lilly

Macaulay Land Use Research Institute, Craigiebuckler, Aberdeen, AB15 8QH Scotland

This report is divided into two broad topic areas. The first is a progress report on the work done in year 2 (1996) of the EU funded project 'using existing soil data to derive hydraulic parameters for simulation modelling in environmental studies and in land use planning' while the second attempts to summarise the discussions held both prior to and during the individual presentations made at the workshop held in Orléans in October 1996.

1. Progress report

The following is a summary of the progress report presented by Allan Lilly at the second annual workshop of the EU funded project. Firstly, there is a brief overview of the project aims followed by an outline of the existing database structure, a progress report on data entry and, finally, proposed revisions to the database structure.

Project aims and use of the data

The stated aims of the project are to collect existing soil hydraulic data from a number of institutions within Europe and to derive class and continuous pedotransfer functions from these data. It is also likely that the data will be used in simulation modelling at regional, national and international scales and may well have more applications than are currently envisaged. The ability to link the data to existing European soils datasets is also an important consideration. Therefore, it is vitally important that the database is flexible and has a good relational structure that allows the data to be easily extracted using a variety of fields. Therefore, it was decided to develop the database structure within the Oracle Relational Database Management System.
Format of the database

The Oracle system gives the flexibility needed and can be designed to suit the diverse nature of the data that are being collected and new fields or even new tables can be easily added. The relational structure is not restrictive, allowing numerous complex selection queries to be made on the data, an important consideration in a database with such diversity in the attributes stored and in its potential uses. Data can be loaded automatically and the whole database can be updated with a few simple commands, features which are necessary when dealing with a large database. Another benefit of Oracle is that it readily links to the ARC Geographic Information System (GIS) software which is the format that the 1:1 000 000 soil map of Europe is held.

The database is divided into seven separate tables (Figure 1) which are linked by geo-reference (Oracle field gridref) and, where appropriate, by the horizon notation (horizon). The BASICDATA table contains the 'descriptor' data, that is, information on the soil type, where the profile was located and a description of the site and other environmental conditions. The key field is gridref, which is used both as a unique identifier and to ensure that the soil data stored in subsequent tables can be related to the environmental data. This field will also provide a link between the database and a GIS. This also allows the data to be grouped by other geo-physical factors such as bioclimatic zone without the need to collect and store these additional data.

Although the geo-reference data will initially comprise co-ordinates in a variety of different systems reflecting those in use throughout Europe, each geo-reference will be converted to a common system, once all the data are in the database. This system, known as GISCO, divides Europe into a number of 100 km grid cells within which six figure x and y co-ordinates can be used to locate each profile to within 1 metre. While this resolution may be too fine for a database which covers much of Europe, it does allow a unique identifier to be added to each profile. Other international systems such as latitude and longitude gave a poor resolution that may not have allowed adequate distinction between locations in close proximity. Also the resolution varied depending on location within Europe.

Where the BASICDATA table is linked to all others by the geo-reference, the subsequent tables are linked by both geo-reference and horizon notation as each soil profile is likely to contain more than one sampled horizon. The horizon symbols follow the FAO system and are spaced according to a set of rules in order to make the selection of data easier and allow greater refinement in the selection process. As the horizon field is a key identifying attribute which links tables, there must also be a unique combination of gridref and horizon symbol for each sample in the database; rules are in place to ensure that this occurs.
Fig. 1. Oracle tables for the European soil hydraulic properties database. Each column represents a separate table linked by geo-reference and horizon.

<table>
<thead>
<tr>
<th>BASICDATA</th>
<th>SOIL_PROPS</th>
<th>RAWPSD</th>
<th>WAT_RET</th>
<th>RAWRET</th>
<th>KUNSAT</th>
<th>RAWUNSAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>gridref</td>
<td>gridref</td>
<td>gridref</td>
<td>gridref</td>
<td>gridref</td>
<td>gridref</td>
<td>gridref</td>
</tr>
<tr>
<td>name</td>
<td>horizon</td>
<td>horizon</td>
<td>horizon</td>
<td>horizon</td>
<td>horizon</td>
<td>horizon</td>
</tr>
<tr>
<td>FAO_soil</td>
<td>top_depth</td>
<td>psize</td>
<td>flag</td>
<td>flag</td>
<td>flag</td>
<td>flag</td>
</tr>
<tr>
<td>country</td>
<td>bot_depth</td>
<td>pcent</td>
<td>head1</td>
<td>head1</td>
<td>ind_var</td>
<td>ind_var</td>
</tr>
<tr>
<td>localngr</td>
<td>structure1</td>
<td>head2</td>
<td>theta</td>
<td>var1</td>
<td>var</td>
<td>var</td>
</tr>
<tr>
<td>localmssg</td>
<td>structure2</td>
<td>...head25</td>
<td>var2</td>
<td>cond</td>
<td></td>
<td></td>
</tr>
<tr>
<td>localseries</td>
<td>USclay</td>
<td>theta1</td>
<td>...var25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>top_depth_gw</td>
<td>USsilt</td>
<td>theta2</td>
<td>cond1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>bot_depth_gw</td>
<td>USsand</td>
<td>..theta25</td>
<td>cond2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>sitesdescr</td>
<td>ksat</td>
<td>comments</td>
<td>...cond25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>sampledate</td>
<td>satwat</td>
<td>keywords</td>
<td>comments</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>annrain</td>
<td>bulk_den</td>
<td></td>
<td>keywords</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ave_jan_temp</td>
<td>particle_den</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ave_jul_temp</td>
<td>porosity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>contact_name</td>
<td>org_mat</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>contact_address</td>
<td>mvg_sat</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>email</td>
<td>mvg_resid</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>publicn</td>
<td>mvg_alpha</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>comments1</td>
<td>mvg_n</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>comments2</td>
<td>mvg_m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>keywords</td>
<td>mvg_1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>number_hor</td>
<td>mvg KS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>rating</td>
<td>comments</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>rated_by</td>
<td>keywords</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The table SOIL_PROPS stores much of the data likely to be used in deriving the pedotransfer functions such as particle size class and organic matter contents while the tables WAT_RET and KUNSAT contain moisture retention and unsaturated hydraulic conductivity data primarily where these attributes have been derived for a limited number of fixed points.

The function of the remaining tables is to store 'raw' data (for example, the output from the evaporation method to determine soil moisture retention or unsaturated hydraulic conductivity) prior to any parameterisation procedure or any transformation (for example of particle sizes where any other system apart from the FAO/USDA system has been used). These table are often very large, containing numerous pairs of data. In this state the data are not readily usable. The K/h and θ/h data, in particular, often need to undergo some parameterisation procedure prior to the development of the pedotransfer functions. However, the storage of the 'raw' data is important as it is possible that new and improved parameterisation methods will become available which can then be applied to the raw data to generate new parameters, thus keeping the database as up to date as possible.

**Progress in data entry**

Throughout year 2, data have been processed by staff at the Macaulay Land Use Research Institute (where the Project Researcher is based) for inclusion in the main database. Currently this database comprises approximately 820 soil profiles with soil hydraulic data from around 2800 soil samples and represents contributions from about half the partners in the Network. This includes data from:

- ZALF and BGR (Germany),
- University of Athens and the Aristotle University of Thessaloniki (Greece),
- The Winand Staring Centre (The Netherlands),
- The Macaulay Land Use Research Institute (Scotland),
- Department of Agriculture for Northern Ireland,
- Institut National de la Recherche Agronomique (France),
- Consejo Superior de Investigaciones Científicas (Spain)
- and Estação Agronómica Nacional (Portugal).

Recently, further data have been received from:

- Technical University Berlin,
- Wageningen Agricultural University (Netherlands),
- University of Naples: Federico II (Italy),
- ILWM Katholieke Universiteit Leuven (Belgium),
- Institut National de la Recherche Agronomique (France),
- Soil Fertility Research Institute (Slovakia)
- and the Swedish University of Agricultural Sciences.
This amounts to about a further 750 soil samples which will be added to the database by the end of 1996. The total number of samples either in the database or about to be added amounts to approximately 3550 and includes data from three Institutions which are not officially part of the Network.

**Proposed revisions to the database structure**

During discussions at the first annual workshop of this group held in Hannover, there was concern from some partners that there was no provision within the database for the inclusion of data where experimental procedures used to determine the soil hydraulic properties by an evaporation method yielded an output of Mualem-van Genuchten parameter values rather than paired values of pressure head against retained moisture or conductivity. Over the past year a number of options to handle these data were considered. The first was to use the parameters to determine the moisture content and conductivities at a number of pre-selected tensions and to store these values. However, there was no guarantee that the tensions selected would be those required by subsequent users and gave no significant advantage. Other approaches were to create either a new table specifically to hold these Mualem-van Genuchten parameters from both this *Inverse method* and from subsequent parameterisations of the other datasets or to modify existing tables.

Ultimately, it was decided to alter the existing table, SOIL PROPS, by adding seven fields to accommodate the full range of the Mualem-van Genuchten parameters derived from both methods (Figure 2). Metadata in the *comments* field will flag which method was used to derive these parameters as those parameters derived by the *inverse method* cannot be recalculated in the event of improved parameterisation techniques becoming available.

There was also a request that the geological origins of the soil parent material be explicitly included in the database. However, although it is suggested that this attribute be recorded in the comments field of the BASICDATA table, this information is often lacking and, therefore, it cannot be recorded consistently as a separate field. There is little doubt that geological parent material (or mineralogy), as well as other properties (for example, soil structure) are important in developing pedotransfer functions and some thought should be given to using whatever data we have as a means of stratifying the data prior to deriving the transfer functions.
Fig. 2. Oracle table SOIL_PROPS for European soil hydraulic properties database.

<table>
<thead>
<tr>
<th>FIELD_NAME</th>
<th>TYPE</th>
<th>SIZE</th>
<th>COMMENTS/DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>gridref</td>
<td>CHAR</td>
<td>16</td>
<td>grid ref to 1m resolution using GIUSCO tiling system</td>
</tr>
<tr>
<td>horizon</td>
<td>CHAR</td>
<td>7</td>
<td>horizon designation (following the FAO)</td>
</tr>
<tr>
<td>top_depth</td>
<td>NUMBER</td>
<td></td>
<td>upper sample depth</td>
</tr>
<tr>
<td>bot_depth</td>
<td>NUMBER</td>
<td></td>
<td>lower sample depth</td>
</tr>
<tr>
<td>structure1</td>
<td>VARCHAR2</td>
<td>45</td>
<td>primary soil structure (as per FAO)</td>
</tr>
<tr>
<td>structure2</td>
<td>VARCHAR2</td>
<td>45</td>
<td>secondary soil structure (as per FAO)</td>
</tr>
<tr>
<td>USclay</td>
<td>NUMBER</td>
<td></td>
<td>percentage of clay as defined by USDA</td>
</tr>
<tr>
<td>USsilt</td>
<td>NUMBER</td>
<td></td>
<td>percentage of silt as defined by USDA (2-50 μm)</td>
</tr>
<tr>
<td>USsand</td>
<td>NUMBER</td>
<td></td>
<td>percentage of sand as defined by USDA (50-2000 μm)</td>
</tr>
<tr>
<td>ksat</td>
<td>NUMBER</td>
<td></td>
<td>measured saturated hydraulic conductivity (cm day⁻¹)</td>
</tr>
<tr>
<td>satwat</td>
<td>NUMBER</td>
<td></td>
<td>measured saturated water content</td>
</tr>
<tr>
<td>bulk_den</td>
<td>NUMBER</td>
<td></td>
<td>dry bulk density (g cm⁻³)</td>
</tr>
<tr>
<td>particle_den</td>
<td>NUMBER</td>
<td></td>
<td>particle density (g cm⁻³)</td>
</tr>
<tr>
<td>porosity</td>
<td>NUMBER</td>
<td></td>
<td>total soil porosity</td>
</tr>
<tr>
<td>org_mat</td>
<td>NUMBER</td>
<td></td>
<td>organic matter content (not Organic Carbon)</td>
</tr>
<tr>
<td>mvg_sat</td>
<td>NUMBER</td>
<td></td>
<td>The Mualem-van Genuchten (MVG) parameter of saturated water content</td>
</tr>
<tr>
<td>mvg_resid</td>
<td>NUMBER</td>
<td></td>
<td>The MVG parameter of residual water content</td>
</tr>
<tr>
<td>mvg_alpha</td>
<td>NUMBER</td>
<td></td>
<td>The MVG parameter alpha</td>
</tr>
<tr>
<td>mvg_n</td>
<td>NUMBER</td>
<td></td>
<td>The MVG parameter n</td>
</tr>
<tr>
<td>mvg_m</td>
<td>NUMBER</td>
<td></td>
<td>The MVG parameter m</td>
</tr>
<tr>
<td>mvg_l</td>
<td>NUMBER</td>
<td></td>
<td>The MVG parameter l</td>
</tr>
<tr>
<td>mvg_ks</td>
<td>NUMBER</td>
<td></td>
<td>The MVG parameter Ks</td>
</tr>
<tr>
<td>comments</td>
<td>VARCHAR2</td>
<td>255</td>
<td>comments on methodologies to derive the above values, and their relevance</td>
</tr>
<tr>
<td>keywords</td>
<td>VARCHAR2</td>
<td>255</td>
<td>keywords to describe measurement techniques</td>
</tr>
</tbody>
</table>
Finally, at the first annual workshop it was suggested that we create a list of references on the development and use of pedotransfer functions. Such a reference list has been compiled and is included elsewhere in this publication.

2. Summary of discussions

During Friday 11th October there were a number of presentations made on the use of pedotransfer functions and some subsequent discussion. This section attempts to summarise these discussions under four main headings.

Parameterisation of the K/h and θ/h relationships

There was some debate as to the usefulness of the Mualem-van Genuchten parameterisations of the K/h and θ/h relationships, in particular it is difficult to achieve a good parameterisation in soils with a bimodal pore size distribution. Some also felt that this procedure had too many parameters and that they were autocorrelated. It was also reported that the non-linearity of the equations has led to the prediction of parameters with negative values and although transformation is an option to reduce the occurrence of this, it can introduce bias. However, it is possible to quantify any error introduced during the parameterisation process which can then be accounted for in any subsequent application. Alternative approaches, at least for the derivation of class pedotransfer functions, included scaling procedures, however, scaling may be inappropriate where there are insufficient data over the full range of the K/h and θ/h relationships.

Stratification

There was a great deal of discussion throughout the workshop on the merits of stratification prior to the derivation of pedotransfer functions. Currently, and to meet the EU requirements of the project, it is intended that the data be stratified according to the five soil texture classes as represented on the 1: 1 000 000 soil map of Europe and whether a topsoil or a subsoil. With the addition of organic soils, this results in 11 strata. However, a great deal of evidence was presented that indicates that the transfer functions could be refined if other methods of stratification were applied. Of particular concern was the effect of lithology (or the geological origin of the parent material) on the accuracy of the predictions. Soil structure was also cited as a possible stratum. Topsoil structures in particular are affected greatly by cultivation and land use, resulting in large variability in soil hydraulic properties within texture classes. Although subsoils will be less affected by anthropogenic factors, the samples have come from a wide range of climatic zones and it is likely that soils within the same texture class will have different structural development. There was also the suggestion that the data be stratified by the measurement methods and that separate pedotransfer functions should be developed for macropore and micropore flow, particularly in those soils with a bimodal pore size
distribution. While each of these points are valid and warrant further investigation, we are still under obligation to meet the requirements of the commissioned work, which is to derive pedotransfer functions for texture classes.

**Development of the pedotransfer functions**

One of the main aims of the workshop was to exchange ideas on how pedotransfer functions were developed for use at the national or regional scale and to assess their applicability to the European data. Presentations were made where regression analysis had been used, where a rule-based approach had been taken and where neural networks had been employed. Each represents a valid technique but, keeping in mind our commitment to the EU, the use of novel approaches may be beyond the scope of this project. As an aside to the main project, subsamples of the data could be made available to various groups within the network who can develop pedotransfer function independently using different stratifications. The results could be compared with those developed from the main database to assess the importance of factors other than soil texture at the European scale.

**European Soil Bureau**

The issue of management and maintenance of the database beyond the end of the project was raised. While there was a great deal of support expressed for the retention of the database beyond year three at the first workshop held in Hannover, it was also clear that there had to be some safeguards and restrictions on the use of data, for example, by the strict enforcement of a licence agreement. However, there were no suggestions as to how this could be achieved without placing an additional administrative and financial burden on the resources of the individual institution holding the database or forcing that institution into a long-term commitment.

One possible way to ensure continued access to the database is to entrust the management, maintenance and distribution of the data to the European Soil Bureau. This would involve partners in the Network becoming a working group within the Bureau and effectively passing the legal arrangements for the distribution of data, and the licensing of its use, to them. This would be in accordance with the agreement made at the Hannover workshop to follow the guidelines and recommendations of the Soils and GIS working group which meets to formulate policy on data protection within the EU. It is important to note that while this would also allow us access to other EU wide datasets which are under the control of associated working groups, they would also gain access to ours.

Some positive aspects to becoming recognised as a working group within the Bureau are the possibility of updating the database, gaining additional contributions from countries in the former Eastern Block (and so making the database fully 'European'). There is also
the possibility that we could gain more insight into the needs of the various Directorates and so have the ability to prepare new, more focused and better targeted, research proposals. Throughout the workshop it was clear that the Network partners were in favour of becoming a working group within the European Soil Bureau as they perceive clear advantages in placing our work within a wider European context. This will be pursued over the coming year.

Finally, there was a suggestion that our database would provide an excellent opportunity to investigate the nature of the hydraulic conductivity vs pressure head relationship close to saturation with respect to the bimodal distribution of soil pores.
Annexes:

Bibliography
Workshop programme
List of participants
A bibliography of topics relevant to Pedotransfer

Collated by Henk Wösten and Allan Lilly


Tietje, O. and Hennings, V. 1996. Accuracy of the saturated hydraulic conductivity prediction by pedo-transfer functions compared to the variability within FAO textural classes. *Geoderma*, 69, 71-84.


Programme

Thursday 10 October 1996

13.30 - 14.00  Welcome by INRA and by H. Wösten
Introduction by P. Stengel and M. Jamagne

14.00 - 16.00
- The European soil bureau
  L. Montanarella
- European soil information: present status and future perspectives
  D. King
- A pedotransfer rules database to interpret the soils geographical
database of Europe for environmental purposes
  J. Daroussin, D. King
- Development of soil data sets for global environmental modelling
  N.H. Batjes

16.00 - 16.30
  Break

16.30 - 18.15
- Predicting soil properties over a region using sample information
  from a mapped reference area
  M. Voltz, P. Lagacherie, X. Louchart
- The Wind method: A standard laboratory method adopted by
  the French INRA laboratories
  P. Bertuzzi, M. Voltz

  Computer demonstration by J. Daroussin, with the collaboration of
  C. Le Bas, A. Couturier, J. Gaillard, G. Yart

20.30
  Dinner

Friday 11 October 1996

9.00 - 10.30
- Progress report and update:
  collection of data, data transfer
- Future developments:
  research in year 3, possibilities for continuation
  of the network after year 3
  by A. Lilly and H. Wösten
- Seasonal variation of the hydraulic conductivity
  F. Moreno
10.30 - 11.00  Coffee break

11.00 - 12.30  - PTFs and bulk density, stratification of the soils
   J. Hollis
   - Development of a neural network model to predict soil water retention
   E. Koekkoek, H. Boolink
   - Regionalization of soil property functions in a highly variable soilscape
   E. Priesack, W. Sinowski
   - Pedotransfer functions to estimate soil matrix hydraulic properties
   N. Jarvis

12.30  Aperitif and lunch

14.00 - 16.00  - Use of pedotransfer functions and geostatistics to quantify the spatial variability of soil water retention characteristic
   N. Romano
   - Significance of the soil fabric on the water retention properties: Example of clayey soils and consequences on PTFs
   A. Bruand, P. Quétin, O. Duval, H. Gaillard, L. Raison
   - Interest of class pedotransfer functions and soil distribution models for water quality improvement: the case of nitrate in Armorican catchments
   P. Curmi, C. Walter, C. Gascuel-Odoux, P. Durand
   - Effect of the soil structure on soil hydraulic properties: Field and laboratory studies
   J.F. Sillon, O. Marloie, G. Richard

16.00 - 16.30  Break

16.30 - 17.00  - Effects of uncertainty in major input variables on simulated functional soil behaviour

17.00  Conclusion by H. Wösten

Saturday 12 October 1996

9.00 - 17.30  Excursion to the soils of the Beauce area
   Visit to the Chambord castle in the Loire valley
List of Participants

BELGIUM

Lode HUBRECHTS
ILWM Katholieke Universiteit Leuven
Vital Decosterstraat 102
B-3000 LEUVEN
Tel.: 32-16-32-97-27
Fax: 32-16-32-97-60
email: lode.hubrechts@agr.kuleuven.ac.be

DENMARK

Svend ELSNAB OLESEN
Danish Institute of Plant and Soil Science
Dept. of Land Use
Research Centre Foulum
P.O. Box 23
DK-8830 TJELE
Tel.: 45-8999-1707
Fax: 45-8999-1819
email: seo@afa.sp.dk

Mogens GREVE
Danish Institute of Plant and Soil Science
Institute of Plant and Soil Science
Department of Land Use
Research Centre Foulum
P.O. Box 23
DK-8830 TJELE
Tel.: 45-8999-1734
Fax: 45-8999-1819
email: MHG@afa.sp.dk

ENGLAND

Bob JONES
Soil Survey and Land Research Centre
Silsoe Campus
BEDS MK 45 4 DT
Tel.: 441-12525-860428
Fax: 44-1525-863253
email: r.jones@cranfield.ac.uk

John HOLLIS
Soil Survey and Land Research Centre
Cranfield University, Silsoe
Bedfordshire MK45 4Dt
Tel.: 44-1525-863253
Fax: 44-1525-863250
email: j.hollis@silsoe.cranfield.ac.uk

FRANCE

Gilles BASTET
INRA - Science du Sol
Avenue de la Pomme de Pin
45160 ARDON
Tel.: 33-2-38-41-78-45
Fax: 33-2-38-41-78-69

Patrick BERTUZZI
INRA - Science du Sol
Domaine de Saint Paul
Site Agroparc
84914 AVIGNON CEDEX 9
FRANCE
Tel.: 33-4-90-31-61-37
Fax: 33-4-90-31-62-44
email: bertuzzi@avignon.inra.fr

Ary BRUAND
INRA - Science du Sol
Avenue de la Pomme de Pin
45160 ARDON
Tel.: 33-2-38-41-78-50
Fax: 33-2-38-41-78-69
email: bruand@orleans.inra.fr

Yves COQUET
INRA - INA PG
78850 THIVERVAL-GRIGNON
FRANCE
Tel.: 33-1-30-81-54-04
Fax: 33-1-30-81-53-96
email: coquet@grignon.inra.fr
Pierre CURMI
INRA - Science du sol
65 rue de Saint Brieuc
35042 RENNES CEDEX
Tel. : 33-2-99-28-52-25
Fax : 33-2-99-28-54-30
email : curmi@roazhon.inra.fr

Joël DAROUSSIN
INRA - Science du Sol
Avenue de la Pomme de Pin
45160 ARDON
Tel. : 33-2-38-41-78-42
Fax : 33-2-38-41-78-69
email: daroussin@orleans.inra.fr

Odile DUVAL
INRA - Science du Sol
Avenue de la Pomme de Pin
45160 ARDON
Tel. : 33-2-38-41-78-44
Fax : 33-2-38-41-78-69
email : duval@orleans.inra.fr

Marcel JAMAGNE
INRA - Science du Sol
Avenue de la Pomme de Pin
45160 ARDON
Tel. : 33-2-38-41-78-47
Fax : 33-2-38-41-78-69
email : jamagne@orleans.inra.fr

Dominique KING
INRA - Science du Sol
Avenue de la Pomme de Pin
45160 ARDON
Tel. : 33-2-38-41-78-48
Fax : 33-2-38-41-78-69
email : king@orleans.inra.fr

Christine LE BAS
INRA - Science du Sol
Avenue de la Pomme de Pin
45160 ARDON
Tel. : 33-2-38-41-48-03
Fax : 33-2-38-41-78-69
email : le_bas@orleans.inra.fr

Philippe QUETIN
INRA - Science du Sol
Avenue de la Pomme de Pin
45160 ARDON
Tel. : 33-2-38-41-48-01
Fax : 33-2-38-41-78-69
email : quetin@orleans.inra.fr

Guy RICHARD
INRA - Agronomie
Rue Fernand Christ
02007 LAON - FRANCE
Tel. : 33-3-23-23-64-70
Fax : 33-3-23-79-36-15
email : richard@orleans.inra.fr

Nathalie SCHNEBELEN
Ecole des Mines
35 rue Saint Honoré
77305 FONTAINEBLEAU

Pierre STENGEL
INRA - Science du Sol
Domaine de Saint Paul
Site Agroparc
84914 AVIGNON CEDEX 9
Tel. : 33-4-90-31-62-54
Fax : 33-4-90-31-62-32
email : leitgold@avignon.inra.fr

Pierre VACHIER
INRA - INA PG
78850 THIVERVAL-GRIGNON
Tel : 33-1-30-81-54-03
Fax : 33-1-30-81-54-25
email : vachier@grignon.inra.fr

Marc VOLTZ
INRA - Science du Sol
2 place Viala
34060 MONTPELLIER CEDEX 1
Tel. : 33-4-67-61-23-40
Fax : 33-4-67-63-26-14
email : voltz@ensam.inra.fr
GERMANY

Volker HENNINGS
Bundesanstalt für Geowissenschaften
Alfred-Bentz-Haus
Postfach 51 01 53
30631 HANNOVER
Tel.: 49-511-643-2840
Fax: 49-511-643-2304
email: b233henni@rzvax.hannover.bgr.de

Martin KUHN
Institut für Geographie und Geoökologie
TU Braunschweig
Langer Kamp 19c
38106 BRAUNSCHWEIG
Tel.: 49-531-391-5918
Fax: 49-531-391-8170

Udo MULLER
Niedersächsisches Landesamt für Bodenforschung
Alfred-Bentz-Haus
Postfach 51 01 53
30631 HANNOVER
Tel.: 49-511-643-2586
Fax: 49-511-643-2304

Lothar MULLER
ZALF
Eberswalder Strasse 84
15374 MUNCHENBERG
Tel.: 49-33432-82233
Fax: 49-33432-82212
email: lmuller@zalf.de

Rudolf PLAGGE
TU-Berlin
Institute of Ecology
Dept. of Soil Science
Salzufer 11-12
10587 BERLIN
Tel.: 49-30-31-47-35-29
Fax: 49-30-31-47-35-48

Eckart PRIESACK
GSF Institut für Bodenökologie
PF 1129
85758 OBERSCHLEISSHEIM
Tel.: 49-89-3187-3354
Fax: 49-89-3187-3376
e-mail: priesack@gsf.de

Uwe SCHINDLER
Zentrum für Agrarlandschafts und Landnutzungsforschung (ZALF) e. V.
Institut für Bodenlandschaftsforschung
Eberswalder Str. 84
15374 MUNCHENBERG
Tel.: 49-33-432-82353
Fax: 49-33-432-82212
email: uschindler@zalf.de

Walter SINOWSKI
GSF-PUC
Postfach 1129
D-85758 OBERSCHLEISSHEIM
Tel.: 49-89-3187-4571
Fax: 49-89-3187-3369
e-mail: sinowski@gsf.de

GREECE

Constantinos KOSMAS
Agricultural University of Athens
Lab. of Soils and Agric. Chemistry
Iera Odos 75
ATHENS 118S
Tel.: 30-1-529-4097
Fax: 31-1-529-4097
email: lso2kok@auadec.aau.ariadne-t.gr

Kyriakos P. PANAYIOTOPOULOS
Soil Science Laboratory
Aristotle University of Thessaloniki
54006
Tel.: 3031-998725
Fax: 3031-998728
e-mail: panayiotopoulos@olymp.cc.auth.gr

HUNGARY

Attila NEMES
Res. Inst. of Soil Science and Agric. Chem.
Herman Otto’u. 15
H 1022 BUDAPEST
Tel.: 361-1-564-644
Fax: 361-1-558-839
e-mail: nemes@fa.gau.hu [attila@sc.dlo.nl]
ITALY

Andrea AJMAR
Space Applications Institute
Joint Research Centre
21020 ISPRA (VA)
Tel. : 39-332-785341
Fax : 39-332-789074
email : andrea.ajmar@jrc.it

Luca MONTANARELLA
Space Applications Institute
Joint Research Centre
21020 ISPRA (VA)
Tel. : 39-332-785349
Fax : 39-332-789074
email : luca.montanarella@jrc.it

Nunzio ROMANO
Institute of Agricultural Hydraulics
Univ. of Naples "Federico II"
Via Universita 100
80055 PORTICI
NAPOLI
Tel. : 39-81-7755341-7755344
Fax : 39-81-7755311-7755344
email : unias@ccrhpa2.cria.it

THE NETHERLANDS

Niels BATJES
International Soil Reference and
Information Centre (ISRIC)
PO box 353
6700 AJ WAGENINGEN
Tel. : 31-3174-71732
Fax : 31-3174-71700
email : batjes@isric.nl

Harry BOOLTINK
Wageningen Agricultural University
Dept. of Soil Science and Geology
P.O. Box 37
6700 AA WAGENINGEN
Tel. : 31-317-482422
Fax : 31-317-482419
email: harry.booltink@bodlan.beng.wau.nl

Peter FINKE
SC-DLO Winanc Staring Centre
Maryleeweg 11/22
Po Box 125
6700 AC WAGENINGEN
Tel. : 31-317-474258
Fax : 31-317-424818
email : p.a.finke@sc.agro.nl

Esther KOEKKOEK
Wageningen Agricultural University
Dept. of Soil Science and Geology
P.O. Box 37
6700 AA WAGENINGEN
Tel. : 31-13-4676985
Fax : 31-317-482419
email : esther.koekkoek@student.beng.wau.nl

Henk WOSTEN
DLO-Winand Staring Centre
P.O. Box 125
6700 AC WAGENINGEN
Tel. : 31-317-474287
Fax : 31-317-424812
email : j.h.m.wosten@sc.dlo.nl

NORWAY

Per Atle OLSEN
Norwegian Agricultural University
Department of Soil and Water Sciences
P.O. Box 5035 AAS
N-1432
Tel. : 47-64-94-82-12
Fax : 47-64-94-82-11
email : per_atle.olsen@ijvf.nlh.no

PORTUGAL

Maria da Conceição GONCALVES
Estação Agronómica Nacional
Quinta do Marquês
2780 OEIRAS
Tel. : 351-1-4416855/6
Fax : 351-1-4416011
SCOTLAND

Gordon HUDSON
Macaulay Land Use Research Institute
Craigebeuckler
Aberdeen AB15 8QH
Tel. : 44-1224-318611
Fax : 44-1224-311556
email : g.hudson@mluri.sari.ac.uk

Allan LILLY
Macaulay Land Use Research Institute
Craigebeuckler
Aberdeen AB15 8QH
Tel. : 44-1224-318611
Fax : 44-1224-311556
email : a.lilly@mluri.sari.ac.uk

SLOVAKIA

Beata HOUSKOVA
Soil Fertility Research Institute
Garabinova 10
827 13 BRATISLAVA - SLOVAKIE
Tel. : 42-7-257-215
Fax : 42-7-257-087

SPAIN

Félix MORENO
CSIC/IRNAS
Reina Mercedes Campus
P.O. Box 1052E
41080 SEVILLA
Tel. : 34-5-4624711
Fax : 34-5-4624002
email : fmoreno@irnase.csic.es

SWEDEN

Nick JARVIS
Swedish University of Agricultural Sciences
Department of Soil Sciences
P.O. Box 7014
S-750 07 UPPSALA
Tel. : 46-18-672465
Fax : 46-18-672795
email : nicholas.jarvis@mv.slu.se