SOTER Report 6

APPLICATION OF THE SOTER METHODOLOGY to A SEMI-DETAILED SURVEY (1:100,000) in THE PIRACICABA REGION

(São Paulo State, Brazil)

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Application of the SOTER methodology to a semi-detailed survey (1:100,000) in the Piracicaba region (São Paulo State, Brazil).

ABSTRACT

The methodology for small scale digital map and database compilation -the SOTER methodology- was applied at scale 1:100,000, in a pilot area in the Piracicaba region (São Paulo, Brazil). Existing geological, geomorphological and pedological documents were used to delineate a map of SOTER units whose terrain and soil attributes were stored in a digital database.

A total of 344 polygons were identified. These were grouped into 53 SOTER units. The grouping criteria were soil development, trophic character, texture profile, rootable depth, nature of substratum and surface form.
Some of the original SOTER concepts were slightly modified and some attributes were added to the databases, in order to make the methodology compatible with the local conditions and the semi-detailed scale.

It was concluded that, with a few adjustments, the SOTER methodology is very well applicable to scale 1:100,000.
Important advantages of the SOTER approach in comparison with traditional maps, are that "tailor made" thematic maps can be derived automatically and delivered on request for many different types of potential users, and that the database can be subject to constant updating. The principal problems for routine application of SOTER in Brazil are the need for relatively advanced computer hardware and software systems, especially when high quality graphic output is required, and for professionals who are accustomed to such systems.
For SOTER to become a world standard it is necessary to develop standard ready-to-use SOTER software for both simple and advanced information systems.

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1. INTRODUCTION

The principal objective of the SOTER project is to develop a World SOils and TERrain digital database at a scale of 1:1M (ISSS, 1986a,b; Van Engelen and Pulles, 1991).
A consequence of the cartographic limitations imposed by the small scale of 1:1M is that delineations can only take account of the broad forms of the landscape and of the highest hierarchical levels of lithological and pedological components.

Therefore a special physiographic-lithologic-pedologic approach was developed for SOTER, in such a way that, in spite of the small scale, a large amount of soil and terrain data can be stored and retrieved. The basic mapping unit is the "SOTER unit". Each SOTER unit is composed of one or more terrain components, and each terrain component is composed of one or more soils. The SOTER database stores information on the characteristics of the terrain components and soils and on the frequency of their occurrence and relative position within the SOTER units. However, only the SOTER unit is geo-referenced, and not its composing parts.

The sources for the SOTER database consist primarily of material produced by local (national, regional) survey teams, e.g. soil survey reports, geologic maps, etc. It would be extremely interesting when in the future source material could be delivered in a format that is compatible with the SOTER methodology. This would help to maximize the consistency of the database and facilitate the constant updating of SOTER.

Application of a universal methodology for storing and retrieving soil and terrain information can also be a great help for these survey teams and the users of their results, who will have easy access to a huge amount of information that can be used for correlation and agrotechnology transfer.

National surveys are becoming increasingly detailed (1:250,000 to 1:50,000). It is important to know to which extent the SOTER methodology can be used for such larger scales, and whether major modifications will be necessary to increase the flexibility of the method so that it can easily be adapted to local needs, without loosing the compatibility with the World database.

The objective of this study is to use the SOTER methodology in a pilot area in order to test its applicability at semi-detailed (1:100,000) scale.

Note 1.: In this work the terms SOTER, SOTER manual, SOTER unit and terrain component refer to the 4th Edition of the SOTER manual (Van Engelen and Pulles, 1991), if not stated otherwise.

Note 2.: This paper gives a description of the methodology that the authors found most adequate for the pilot area. It is meant as an example of how the SOTER approach can be used at semi-detailed scale. Not as a supplement to the SOTER manual.

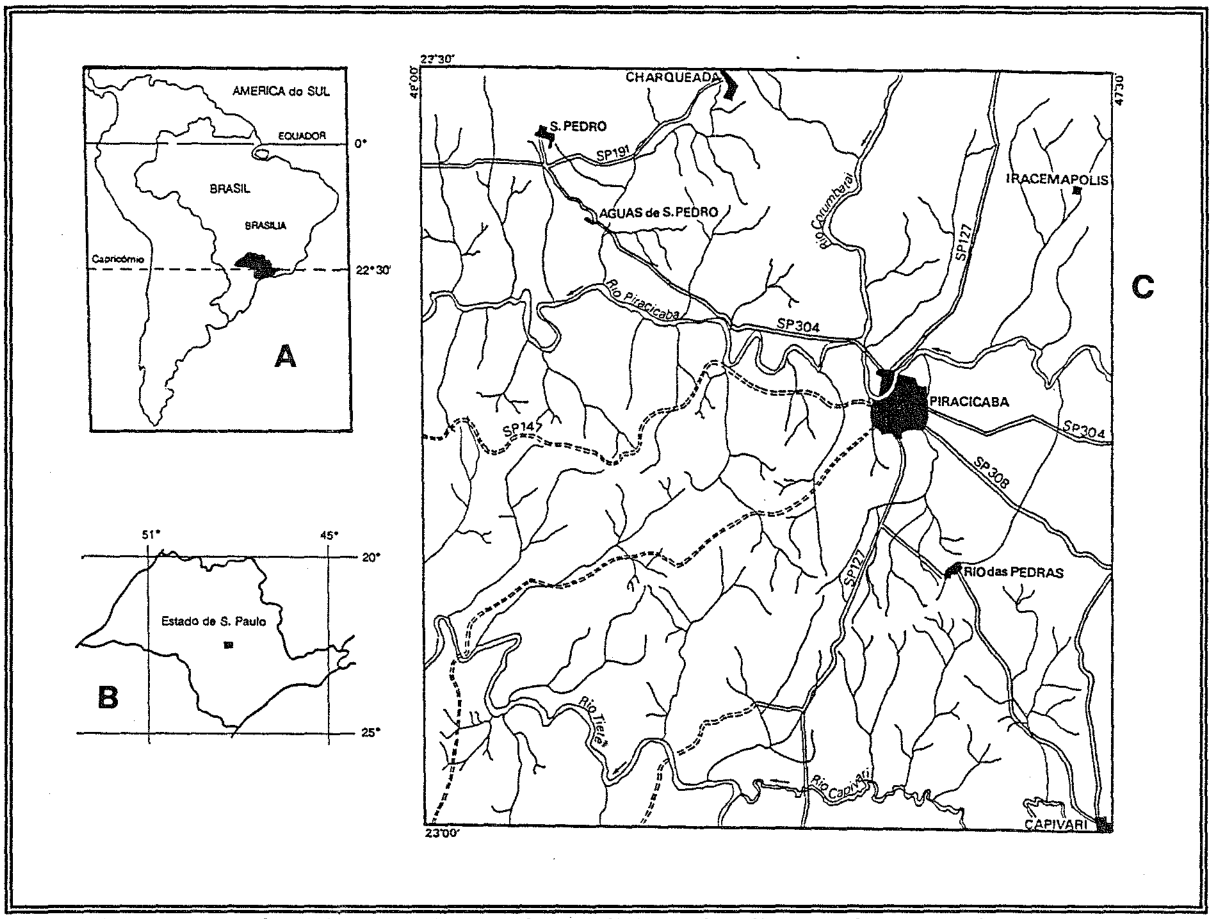

Figure 1. Location of São Paulo State in Brazil (A); The pilot area in São Paulo State (B) and the principal landmarks in the pilot area (C).

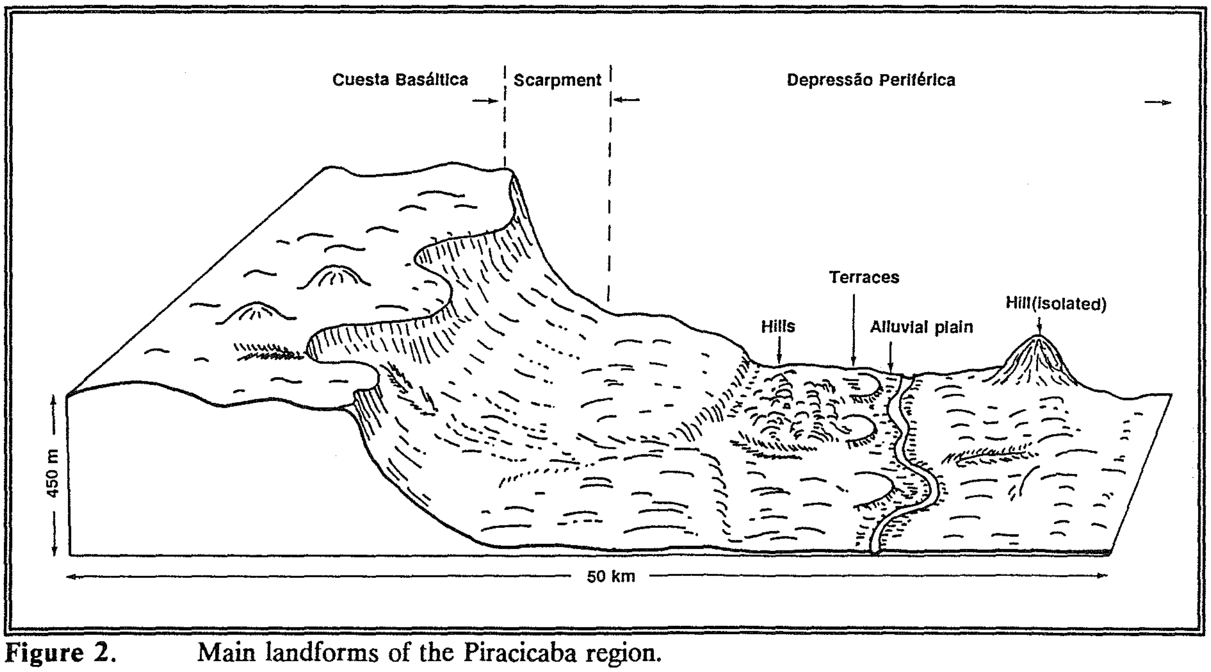

Figure 2. Main landforms of the Piracicaba region.

2. SITUATION

2.1 Location

The study area is the region covered by the Piracicaba sheet, delimited by the geographic coordinates 22°30'-23°00'S and 47°30'- 48°00'W.
It is an area of approximately 2860 km^2, situated in central São Paulo State, Brazil (Figure 1).

2.2 Physiography

The region occurs within two of the five broad physiographic provinces of São Paulo State: The *Depressão Periférica* and the *Cuesta Basáltica* (IGG, 1974). These two provinces are separated by a 400m high scarpment, which is the most prominent geomorphologic feature of the region (Figure 2).

The region of the *Cuesta Basáltica* is a plateau, about 1000m above sea level, which covers an area of several thousands of km^2. It occurs in a relatively small area in the north-western part of the study region. The relief is dominantly undulating to rolling.

The *Depressão Periférica* is a large longitudinal depressional area with a width that varies from 20-100km, that cuts the entire state of São Paulo along 250km. It is bordered by the *Cuesta Basáltica* in the west, and by the *Planalto Atlântico* in the east. (The latter does not occur in the region covered by the Piracicaba sheet).
This area is cut by two important rivers (Tietê and Piracicaba) and by some minor streams, which sculptured the undulating to gently rolling relief, and formed terraces and alluvial plains. The general landscape of the *Depressão Periférica* is completed by some remnant isolated hills and a few areas with strongly dissected relief.

2.3 Geology and Lithology

According to the 1:500,000 geologic map (IPT, 1981) of São Paulo State, the region has a quite complicated geologic pattern. The most common lithologies are sedimentary rocks (sandstones, argilites and siltites), basalts, dolerites and recent alluvial sediments (Figure 3). The *Cuesta Basáltica* consists in the study region of Mesozoic basalts, covered by sandstone of Cenozoic origin. The basalts only appear at the surface in valleys, and at the scarpment, where the sandstone cover was removed.
The *Depressão Periférica* is dominated by Paleozoic sedimentary rocks of fine granulometry. Intrusive rocks (dolerites=diabases) formed on top of these sediments. These are present as areas with a diameter of a few km^2, or as dikes, mostly with an approximate North-South direction. Some dikes cut the entire sheet.
The recent alluvial sediments occur as Pleistocene terraces or as active floodplains of the rivers Piracicaba, Tietê, Corumbataí and Capivari.

There is no consensus about the exact origin of some of the geologic formations. Different denominations are being used by different authors.

2.4 Soils

A semi-detailed soil survey (scale 1:100,000) of the region has recently been published by Oliveira & Prado (1989). In general they found a good correlation of soils with geology and physiography. Ferralsols occur principally at almost flat and gently undulating surface forms: Haplic Ferralsols, with loamy texture at the *Cuesta Basáltica* and Pleistocene terraces; Haplic Ferralsols with clayey

texture on the claystones and shales of the *Depressão Periférica* and very clayey (>60%), Rhodic Ferralsols on the basalts and dolerites.
Areas with undulating relief are dominated by soils with an Argic B horizon: Acrisols and Lixisols in areas with sandstone, shales and argilites; Nitisols in areas with basalt and dolerite. Areas with strongly dissected relief are characterized by the presence of Leptosols.
Gleysols, Cambisols, Planosols and Fluvisols are characteristic for the alluvial plains.
The "Major Soil Groupings" that are most widespread in the region are the Acrisols and Ferralsols.

2.5 Climate

Alfonsi (in press) pointed out that the climate of the pilot area can be classified as Cwa (Köppen), i.e. a subtropical climate with the mean temperature of the warmest month being higher than 22°C and a precipitation of less than 30mm in the driest month (Figure 4a).
The spatial variability of (average) climate parameters is relatively small. The mean annual temperature is between 19.0° and 19.5°C in the highest parts of the region, (the *Cuesta Basaltica* plateau), whereas the average annual temperature of the lowest parts, like the valleys of the rivers Piracicaba, Tietê, Corumbataí and Capivari, is between than 20.5° and 21.0°C (Figure 4b). Rainfall has a similar spatial distribution. Average annual precipitation varies from >1400mm/yr at the plateau, to <1300mm/yr in the valleys (Figure 4c).

The annual moisture deficits, calculated according to the method of Thornthwaite and Mather, is nil at the high plateau and 20mm in the Piracicaba and Tietê valleys (Figure 4d). This difference seems too small to be of interest as a climatic parameter for interpretative studies.
The soil moisture regime and soil temperature regime, as defined by Soil Taxonomy (Soil Survey Staff, 1976) are respectively udic and thermic (Oliveira et. al., 1975).

2.6 Natural vegetation

The natural vegetation types in the area, in terms of SOTER definitions, are "subtropical evergreen seasonal forest" and "evergreen broad-leaved shrubland without grass undergrowth". The latter, locally known as "cerrado", is principally confined to the poor and sandy soils.
In a few small spots a subtropical drought deciduous forest was noted. Its presence is possibly due to a soil-depth-induced dryer soil moisture regime (Sombroek, 1987). All trees in these spots loose their leaves during the dry season, and some xeromorphic plants (cactaea) occur.

2.7 Land use

The principal kind of land use in the region is sugarcane. It is dominating on the clayey dusky red soils, and is also expanding towards the poor sandy soils, which are still mainly used for grazing and forestry. Other relevant kinds of land use are annual crops (black beans, cotton, maize, vegetables) and coffee.
The management level is medium to advanced. Application of lime, artificial fertilizers and pesticides, and the use of agricultural machinery are common practice. Irrigation (sprinkler) is mainly confined to some minor enterprises with cultivation of vegetables.

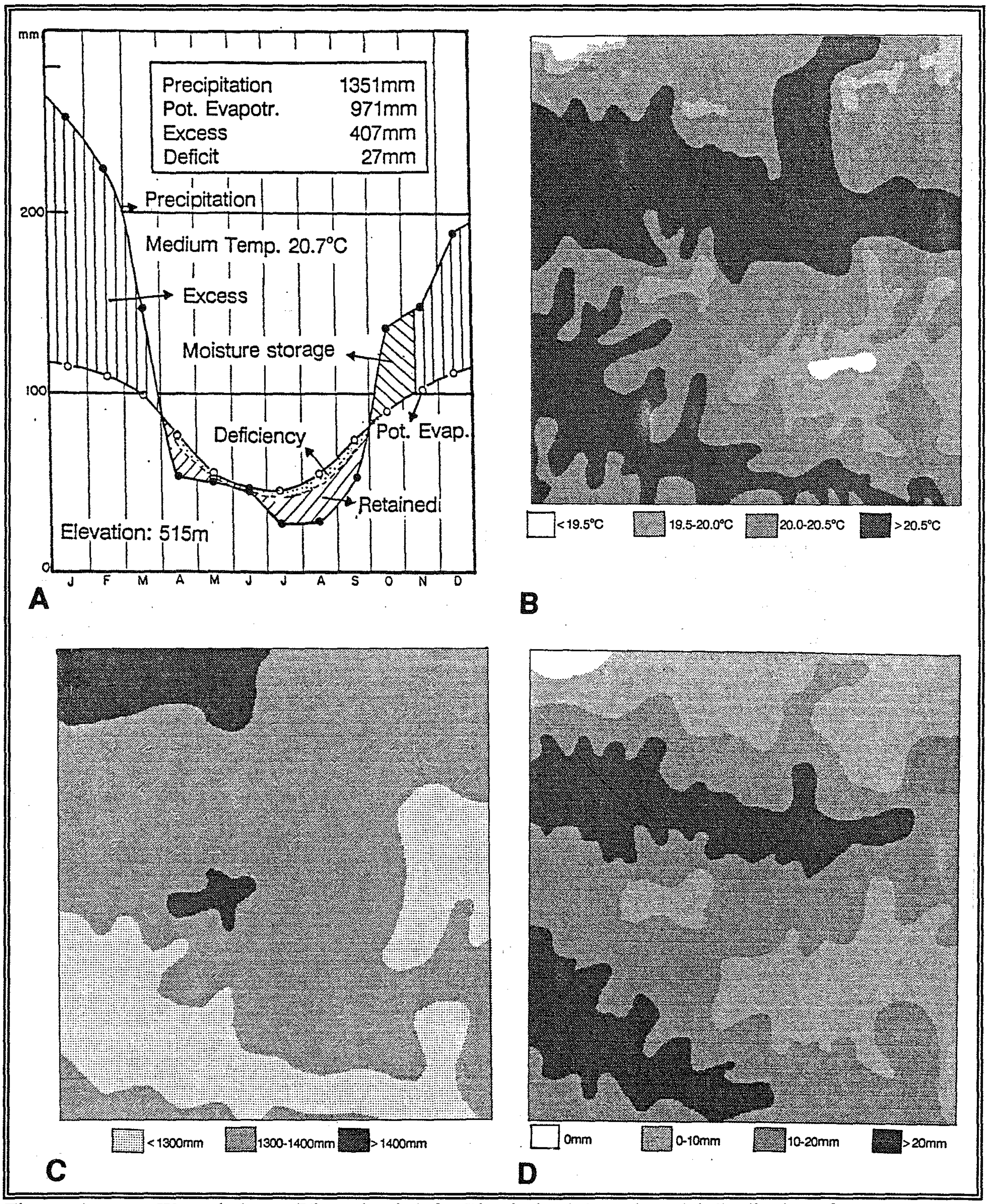

Figure 4. Water balance (Thornthwaite) for Piracicaba (A); and spatial distribution of average annual temperature (B), precipitation (C) and moisture deficit (D). Source: Alfonsi (in press).

3. METHODOLOGY

The SOTER manual gives clear rules on how SOTER units must be described. However, the system is very flexible with respect to the way that polygons can be distinguished and grouped into SOTER units. Each survey team can (within reasonable limits) establish its own criteria. This philosophy combines the advantages of (1) the absence of restrictive classification systems that force surveyors to put unsatisfying labels on mapping units, with (2) the preservation of possibilities of correlations between different surveys, by comparing (combinations of) attributes of SOTER units. The application of more or less detailed differentiating criteria is allowed. This facilitates the adjustment to different scales.

The process that transforms source information into a database of SOTER units, terrain components and soils may appear somewhat complicated for those who are not familiar with the methodology. Therefore section 3.1 gives a brief stepwise explanation of the method applied. Section 3.2 and 3.3 give a more detailed discussion on the method that we applied to differentiate polygons and to group them into SOTER units.

3.1 Methodological strategy

Step 1. Geologic, geomorphologic and pedologic documents were studied in order to find out which physiographic aspects of the landscape were most compatible with the lithologic and pedologic pattern.

Step 2. Maps on geomorphology, erosion surfaces, drainage patterns and topography were used to identify physiographic compartments. The results were drawn on 1:50,000 maps.

Step 3. The obtained physiographic delineations were compared with the 1:50,000 pedological source map[1]. When any of the delineations enclosed more than one soil mapping unit, an appraisal of their similarity was done in order to decide whether or not they should be lumped together in order to avoiding senseless multiplication.

Step 4. The polygons were grouped into legend units: The SOTER units. The following criteria were used for this grouping: Nature of soil development (SOTER manual); trophic character (EMBRAPA, 1981); soil texture along the profile; rootable depth (SOTER manual); nature of the substratum and the kind of surface form (FAO, 1977). The product was a map that represents the basic document for future digitalization.

Step 5. Soil profiles to represent the SOTER units were selected from the database of the Instituto Agronômico de Campinas. For their choice the mean or median values of the most important attributes were taken into consideration (see also 5.4).

3.2 From source maps to polygons

Most maps that are used as sources for the 1:1M SOTER project have a small scale (e.g. 1:500,000 to 1:1M). A delineation (polygon) at such scale corresponds to a considerable portion of an overall landscape, which embodies different landforms and land features, and, obviously also soils. The legend of small scale soil maps is usually defined in broad terms and soil mapping units may enclose different classes at a high level of classification.

Although there is often a remarkable correlation between broad geomorphic patterns and soil distribution, it is obvious that, at such small scales, geomorphic parameters are more manageable

[1]The published 1:0.1M soil map (Oliveira & Prado, 1989) is an exact copy of this base map.

differentiating criteria than soil characteristics, because they normally are prominent, discrete and homogeneous elements of the landscape. This is shown by the schematic representations of SOTER units in the SOTER manual.

When (semi-) detailed maps are produced, major landforms loose their convenience to differentiate between mapping units. For such surveys smaller pieces of the landscape, like Land features (as defined by FAO, 1986) and Surface forms (FAO, 1977) appear to be more appropriate physiographic differentiating criteria. These two elements: Land features and Surface forms were the attributes used in this study to identify physiographic units, here called "Homogeneous physiographic land features" (HLF). The HLF differentiates physiographic units at the level of the terrain component of the SOTER manual.

The basic sources of information used in this study (pedological, geological and relief-geomorphological maps) were available documents, which were not made with the objective to fit the SOTER concept. The geologic maps revealed to be of little use, partly due to the small scale of 1:0.5M (IPT, 1981) or 1:0.25M (Landin, 1982). Even the more detailed geologic maps (Petrobras w/d) only indicate the major geologic formations, and not the different lithologies. However, the soil map of the Piracicaba region (Oliveira & Prado, 1989) also takes account of geology because parent material is one of the diagnostic criteria of the soil classification system in use in Brazil. When the boundaries of HLFs were compared with the soil map the following situations were encountered:

a) The HLF embodies just one simple soil mapping unit.
b) The HLF embodies two simple soil mapping units.
c) The HLF embodies one compound soil mapping unit.
d) The HLF embodies two compound soil mapping units.

To decide whether two or more soil mapping units, embodied by a HLF are sufficiently similar to form one polygon for SOTER depends on (1) the expertise of the person that must take the judgement; (2) the purpose of the project and (3) the accuracy of the algorithm used to obtain thematic maps. In practice it is a quite subjective decision. We considered only those soil characteristics supposed to be important for interpretation with respect to agricultural use: granulometry, the presence of layers with contrasting texture, drainage class, Trophic character (EMBRAPA, 1981), and effective depth.
The possibilities to form polygons and the terrain components and soils within them by overlay of the HLF-map with the soil map are represented in Table 1.

Table 1. Combinations of soil mapping units and HLFs to SOTER units with one or more soils.

Number of soil mapping units in HLF	Type of soil mapping unit	similarity of soil mapping units	Number of SOTER units distinguished	Number of terrain componenents within a SOTER unit	Number of Soils within a SOTER unit
1	simple	-	1	1	1
	compound	-	1	1	≥2
2	simple	I ≃ II	1	1	2
		I ≠ II	2	1	1
	compound	I ≃ II	1	1	≥2
		I ≠ II	2	1	≥2

These configurations offer a more simple picture than the scheme of the SOTER manual, because in this case each polygon has invariably only 1 terrain component, which may contain 1 or more different soils (Figure 5).

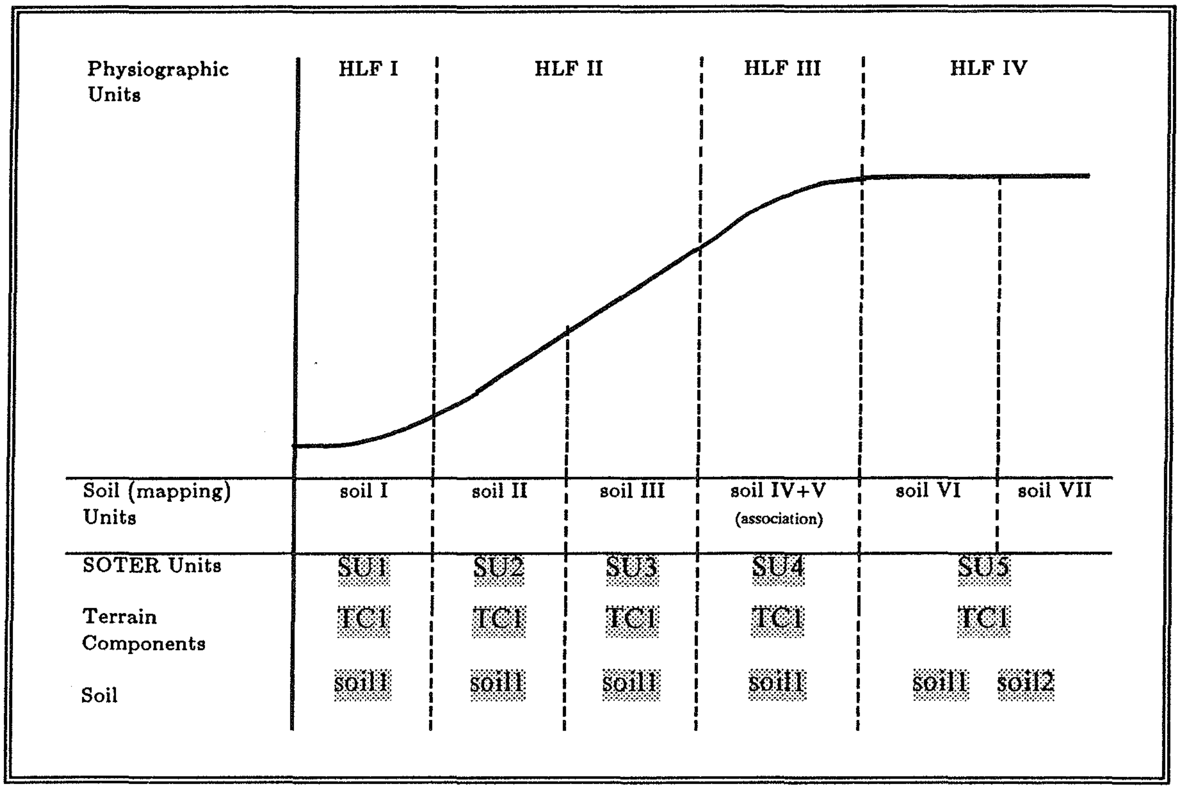

Figure 5. SOTER Units and their relation with physiography and soil in the Piracicaba region.

3.3 From polygons to SOTER units

Each of the polygons formed in the way described in section 3.2 can be represented as a SOTER unit. However, many polygons have similar characteristics. It would be an unnecessarily large job to fill the SOTER database with the attributes of each of them; the files would occupy an excessive space of disk and computer memory and deriving thematic maps would be unnecessarily slow. Therefore it is more convenient to identify SOTER units as collections of polygons with similar characteristics.

In order to make efficient and sensible groupings it is important that the criteria used to group polygons can easily be derived from the source maps and that they correlate with other important characteristics that are not explicitly related in the legend of the source maps. As this is a pilot study, we found it also convenient to fill the SOTER files for each polygon first, after which several criteria were used to group the polygons to SOTER units. Once these criteria are definitely established it will be easier to distinguish the SOTER units first and fill the files afterwards.
The grouping criteria do not necessarily have to be available in the SOTER files. However, the possibility of deriving them is an advantage when correlations between different surveys are to be made, or when different methodologies for legend construction are to be tested. The criteria that we used are also compatible with the soil classification system in use in Brazil (EMBRAPA, 1981), so that future derivation from existing soil maps can be optimized.

The following criteria were used:

1. Nature of soil development
2. Trophic character
3. Soil texture
4. Rootable depth
5. Nature of substratum.

3.3.1 Nature of soil development

For this criterion the codes and definitions used in the SOTER manual were applied. Table 2 lists the dominating soil forming processes that were identified in the region.

Table 2. Dominating soil forming processes in the Piracicaba region

Soil forming Process	SOTER Code	Soil classes (FAO, 1988)
Lixic	LI	Acrisols, Lixisols
Primic	PR	Leptosols, Arenosols
Ferralic	FA	Ferralsols
Gleyic	GL	Gleysols
Cambic	CB	Cambisols
Nitic	NI	Nitisols
Luvic	LU	Luvisols
Chermic	CH	Phaeozems
Podzic	PO	Podzols

3.3.2 Trophic character

The "Trophic character", used in this study combines an indication of the absolute content of basic cations (**Sum of Bases** = exchangeable Ca+Mg+K+Na) with the **Base Saturation** (=100%.S/CEC_{pH7}) and with the **Aluminium Saturation** (=100%.Al^{3+}/ECECsoil).
In this study the Trophic character was used to separate SOTER units, because it is considered of great importance with respect to soil management.
The following "Trophic classes" were distinguished:

Eutrophic: Soils with Base Saturation $\geq$50% and Sum of Bases >1.0 meq/100g throughout the upper 125cm of the soil, or until the substratum whichever is shallower.

Dystrophic: Soils with Base Saturation <50% or Sum of Bases $\leq$ 1.0 meq/100g; and Aluminium Saturation $\leq$50% throughout the upper 125cm or throughout the solum, whichever is shallower.

Allic: Soils with Aluminium Saturation > 50% within 125cm depth.

All data necessary to determine the "Trophic class" are provided in the SOTER database: CEC_{soil}, $ECEC_{soil}$, exchangeable Ca, Mg, K, Na and Al.

3.3.3 Soil texture profile

Three aspects related with soil texture were used to discriminate between SOTER units:

- Textural differentiation within the profile
- Texture class
- Presence of coarse fragments

Textural differentiation within the profile
One of the most important aspects that distinguishes soils of the study region is the occurrence of textural changes along the profile. When such changes are pronounced they form a major limitation for root development and imply the requirement of careful management and erosion control.
The most important criterion to distinguish between classes is the "**textural ratio**", i.e. the ratio of clay content of the horizon with maximum clay content to that of the horizon with minimum clay content.
Four classes for textural differentiation were distinguished:

Isotropic: Soils with a uniform or almost uniform (textural ratio $\leq$ 1.2) texture throughout the profile: Ferralsols, Arenosols, Podsols, Leptosols, some Cambisols.

Anisotropic: Soils with clear textural changes within the profile (textural ratio > 1.2), related with pedogenetic clay migration, without presenting contrasting textural differentiation: Nitisols, Phaeozems, some Acrisols and Lixisols of the study region.

Contrasting: Soils with strongly contrasting particle size classes within the profile (a: textural ratio > 2.0 and b: clay increase > 20% absolute or 100% relative within 7.5cm), but without presenting stratification: Planosols, some Acrisols and Luvisols.

Stratified: Soils of alluvial plains with stratified textural pattern (eq. Fluvic properties): Fluvisols, Gleysols, some Cambisols.

The information needed to group polygons according to these classes is provided in the SOTER database: texture data of various layers and the presence or absence of Fluvic properties.

Texture class
The classes provided in the SOTER manual for classifying texture groups of unconsolidated materials (SOTER manual, section 23), and not the more detailed texture classes of soil layers (SOTER manual section 94), were used to discriminate SOTER units, because the former are better correlated with the texture classes of the soil classification system in use in Brazil. Nevertheless, the classes can be easily derived from texture (class) data provided in the layer file (SOTER manual section 85-94):

Y	Very clayey	> 60% clay
C	Clayey	Sandy clay, silty clay and clay, up to 60% clay
L	Loamy	Loam, sandy clay loam, clay loam, silt, silt loam and silty clay loam
S	Sandy	Loamy sand, sandy loam
X	Extremely sandy	Sand

Classes with soils of Anisotropic or Strongly contrasting texture are designated by two classes. E.g.: S/C: Soils with sandy texture in the upper horizon(s) and clayey texture in the subsurface horizon (i.e. the horizon with highest clay content within 125cm).

Presence of coarse fragments
Three classes for coarse fragments in the surface horizon were distinguished:

0 None

1 < 25% gravel or stones by weight

2 > 25% gravel or stones by weight

Note that the class boundaries are not defined in terms of % by volume, as indicated by the SOTER manual (section 83). The determination of coarse fragments by weight is routinely executed at the Pedology department of the Instituto Agronômico de Campinas.

3.3.4 Rootable depth

The concept of rootable depth that we used to distinguish SOTER units is the same as given by the SOTER manual (section 38): "Depth in cm to which root growth is not restricted by any physical or chemical characteristics, such as an impenetrable or toxic layer. Strongly fractured rocks, e.g. shales may be considered as rootable."

We considered chemically inert layers as not rootable. Chemically inert layers occur e.g. in the B-horizon of Geric Ferralsols. Root growth is restricted in such layers because of the virtual absence of exchangeable bases, even if they don't present toxic levels of aluminium.

Five classes for maximum rootable depth were distinguished: 0-25cm, 25-50cm, 50-100cm 100-200cm and >200cm.

3.3.5 Nature of the substratum.

The "Nature of the substratum" was only taken into account as a discriminant factor for distinguishing SOTER units with shallow soils (<100cm). For such soils the nature of the substratum can have important relations with respect to land qualities like water and oxygen availability, erodibility, possibilities for mechanization and nutrient availability,

For the classification of "the nature of the substratum" the conventions used in the section on lithology of the SOTER manual (section 22 and Appendix 1) were applied. Soils with stone beds were put in a separate class. The latter is provided in section 53 of the SOTER manual. The following classes were identified in the study region:

IB2 + IB3 Basalt + dolerite

SC2 Sandstones

SC3 Siltstone, claystone

SC4 Shale

S Stone bed

As some of these groups were considered too broad, the Geologic formation to which the substratum belongs was considered as an additional discriminating criterion for SC2 and SC3:

SC2-1 Sandstones of the Botucatu and Piramboia formations

SC2-2 Sandstones of the Itaqueri Formation.

SC3-1 Sedimentary rocks of the Itararé formation (Tubarão Group)

SC3-2 Sedimentary rocks of the Tatui, Irati, and Corumbatai formations (Passa Dois Group).

3.3.6 Surface form

The surface form was included as a criterion to differentiate SOTER units, because it is considered of fundamental importance for the assessment of erodibility and trafficability.
The following classes, adopted from the Soil Survey manual (Soil Survey Staff, 1951), were distinguished:

Indication	General slope class
Level	<2%
Gently Undulating	3-5%
Undulating	5-8%
Rolling	8-16%
Hilly	16-30%
Steeply dissected	30-50%

The landform can easily be derived from the terrain component data (section 18 of the SOTER manual).

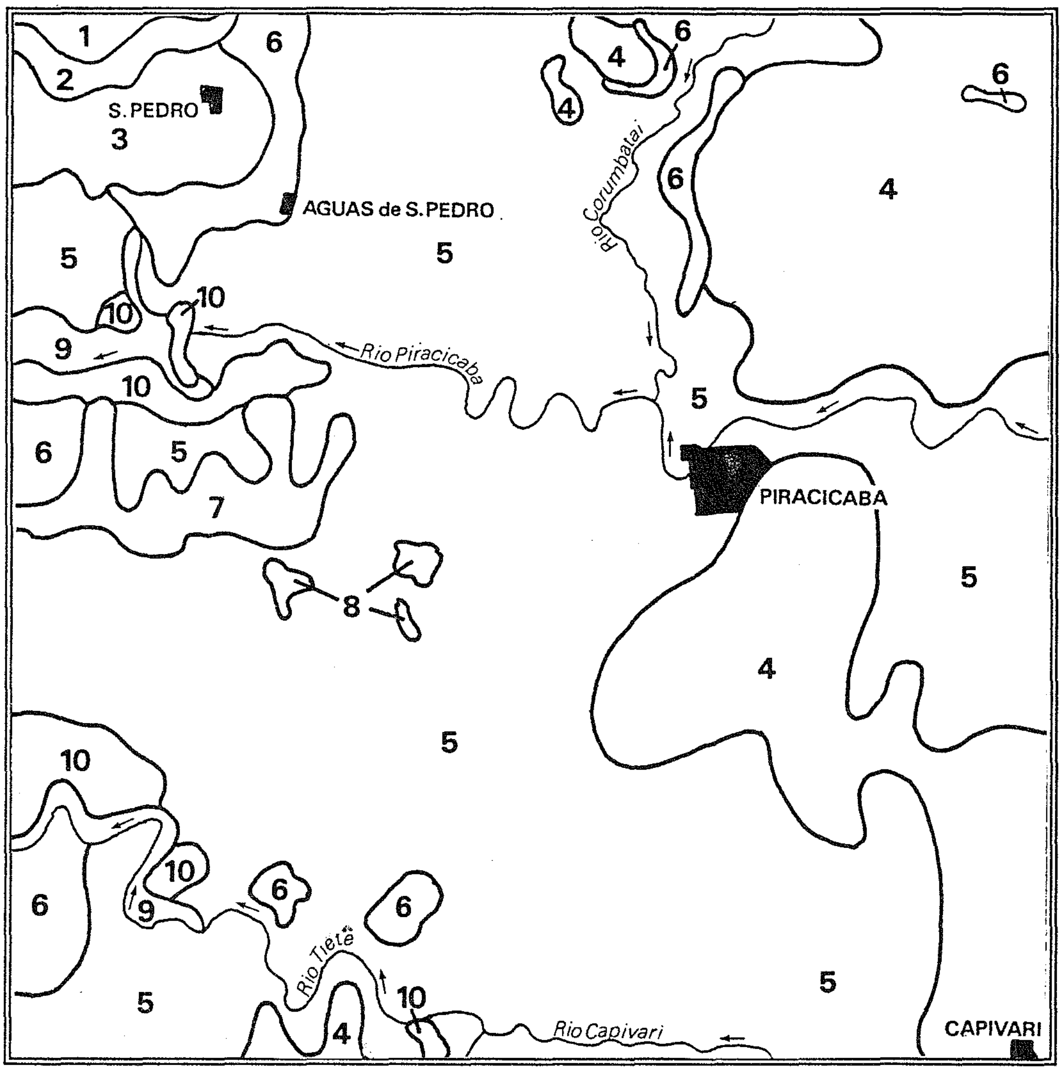

Figure 6. Principal physiographic compartments in the study area, according to form and intensity of the relief.

1. Cuesta Backslope
2. Cuesta Scarpment
3. Piedmont slope
4. Weakly dissected upland
5. Moderately dissected upland
6. Strongly dissected upland
7. Summits
8. Isolated hills
9. Alluvial Plains
10. Terraces

4. RESULTS

4.1 The Physiographic units

Four "regional landforms" (SOTER manual, item 3) were identified: (1) Plateau, (2) Hills, (3) Plains and (4) Mountains (Figure 2).
These four regional landforms were divided into 10 "physiographic compartments". Table 3 summarizes the main characteristics of each of these compartments with respect to their landform, lithology, pedology, and land use. The areas of major occurrence are shown in Figure 6.

The overlay of the "physiographic compartments map" with the "slope gradient map" resulted in the map of HLFs, which, in combination with the pedologic base map resulted in the final delineations, consisting of 344 polygons.
Application of the grouping criteria discussed in section 3.3, resulted in the identification of 53 SOTER units.

4.2 Characteristics of SOTER units

Table 4 shows the relation between the identified SOTER units and the edaphic and physiographic criteria that were used for their identification.

4.2.1 Nature of soil development

The study region has a large diversity with respect to the "nature of soil development". Nine different dominant pedogenetic processes were identified (n° of SOTER units are given between brackets): Primic (15), Lixic (16), Ferralic (12), Luvic (2), Nitic (2), Chernic (1), Podzic (1), Gleyic (1) and Cambic (3).
Predominating in the region are the "Lixic" (illuviation of low activity clay) and the "Primic" (absence of advanced soil forming processes) natures of soil development, which cover respectively 45% and 21% of the surface of the study area.
Another important "nature of soil development" is the "Ferralic", represented by 58 polygons, that cover 15% of the area.
SOTER units with Cambic, Luvic, Chernic and Podzic nature of soil development are represented by small polygons, that together cover less than 1% of the study area.

4.2.2 Trophic character

143 polygons, belonging to 23 SOTER units have "Eutrophic" soils. As most of these polygons are small, they cover only 23% of the total surface area.
The "Allic" character was identified for 120 polygons (35%), grouped into 20 SOTER units. These SOTER units cover 60% of the surface area in the study region.

4.2.3 Soil texture profile

Most soils of the study region have an "Isotropic" textural pattern along the profile: 169 polygons, grouped into 30 SOTER units. This textural pattern occurrs among all five texture classes (see section 3.3.3), but most commonly for the clayey texture class.
The soils with strongly contrasting texture classes within the profile are also of major importance in the region. This textural pattern was identified for 69 polygons that were grouped into 13 different SOTER units. Together they cover 41% of the total surface area of the region. These soils are of special importance with respect to soil conservation, because of their susceptibility to erosion.
The "Stratified" textural pattern was identified in only 2 SOTER units, that cover less than 1% of the study region.

Table 3. Main characteristics of physiographic compartments.

Regional Landform	Physiographic Compartment	Relief dominant slope	Elevation (m)	Lithology		Soils		Land use	
				Dominant	Second.	Dominant	Secondary	Dominant	Secondary
Plateau (T)	Cuesta Backslope	Undulating to rolling 7-30%	860-960	Sandstone (SC2-2)		Ferralsols (loamy)	Leptosols	Grazing (HI1)	Sugarcane (AP1) Forest (FP)
Mountains (M)	Cuesta Scarpment	Very Steep >50%	680-860	Basalt (IB2)	Sandstone (SC2-1)	Leptosols		Natural forest (IA2)	
Hills (H)	Strongly dissected upland	Str. rolling 15-20%	500-680	Sandstones (SC2-1)	Argillites, shales (SC3-2 + SC4)	Leptosols	Lixisols Acrisols (shallow phase)	Ranching (HE3)	Natural forest (IA2)
	Isolated hills	Undulating 3-5% (Summits) Very steep >40% (base)	740-790 540-560	Dolerite (IB3)	Argillites, shales (SC3-2 +SC4)	Ferralsols (clayey) Leptosols	Phaeozems	Natural forest (IA2)	Coffee (AT3)
Plain (P)	Piedmont slope	Undulating 3-5%	550-680	Sandstone (SC2-1)	Dolerite (IB3)	Arenosols	Ferralsols (loamy)	Woodland (FN) Grazing (HI1)	Sugarcane (AP1)
	Weakly dissected upland	Undulating 3-5%	560-780	Dolerite (IB3)	Argillites, shales (SC3-2 +SC4)	Ferralsols ((very) clayey)	Nitisols Acrisols	Sugarcane (AP1)	Annual crops (AA4)
	Moderately dissected upland	Gently rolling 8-10%	480-620	Sandstone (SC2-1)	Argillites (SC3-1 +SC3-2)	Acrisols	Lixisols Alisols Leptosols	Sugarcane (AP1)	Annual crops (AA4)
	Summits	Undulating 3-5%	520-600	Sandstone (SC2-1)	Conglomerate (SC1)	Arenosols	Ferralsols (loamy)	Grazing (HI1) Woodland (FN)	Sugarcane (AP1)
	Alluvial Plain	Level <2%	450-470	Fluvial sed. (UF)		Gleysols	Cambisols Planosols Fluvisols	Grazing (HI)	Sugarcane (AP1)
	Terraces	Level to Undulating <5%	480-530	Sandstone (SC2-1)	Fluvial sed. (UF)	Ferralsols (loamy)	Arenosols Acrisols	Sugarcane (AP1)	Annual crops (AA4)

The presence of stones and gravel was observed in 17 polygons (3 SOTER units), that cover only 0.8% of the study region.

4.2.4 Rootable depth

The study region is dominated by soils that do not impose severe restrictions with respect to root growth: 82% of the surface (225 polygons) present a rootable depth >100cm. The surface area with severe limitations with respect to root growth (rootable depth <50cm) is restricted to 18% of the area (119 polygons).

4.2.5 Surface form

The vast majority of the polygons (92%), corresponding with 97% of the surface area have general slopes < 16%. 47% (161) of the polygons (32% of the area) have general slopes < 5%. This illustrates that the major part of the Piracicaba region presents a suitable relief for mechanized agriculture.

Table 4. Characteristics of the SOTER Units.

Soil development	Trophic character	Texture pattern within profile	Texture class + (stoniness)	Rootable depth class (cm)	Substratum	Slope class	SOTER unit	Number of Polygons
Primic (PR)	Eutric	Isotropic	Sandy	25-50	SC2-1	8-16%	1	3
						16-30%	2	5
			Loamy	25-50	SC3-1	8-16%	3	11
						16-30%	4	3
				25-50	SC3-2	8-16%	5	20
						16-30%	6	4
			Clayey	25-50	IB2	8-16%	7	3
						16-30%	8	4
						>30%	9	8
			Clayey (2)	25-50	O	2-5%	10	4
						8-16%	11	10
	Distric	Isotropic	Clayey	25-50	SC2-2	16-30%	12	4
	Allic	Isotropic	Extremely sandy	>200	-	<2%	13	5
						2-5%	14	17
						8-16%	15	1
Lixic (LI)	Eutric	Anisotropic	Clayey/Very Clayey	100-200	-	2-5%	16	13
						5-8%	17	5
						8-16%	18	14
		Contrasting	Loamy/Clayey	>200	-	5-8%	19	1
			Loamy/Clayey (1)	50-100	-	8-16%	20	1
	Distric	Anisotropic	Sandy/Loamy	100-200	-	<2%	21	2
						2-5%	22	14
						5-8%	23	2
						16-30%	24	1
		Contrasting	Loamy/Clayey	100-200	-	5-30%	25	23
						8-16%	26	2

	Allic	Contrasting	Extremely sandy/ Loamy	100-200	-	8-16%	27	12
				>200	-	<2%	28	1
						2-5%	29	5
						5-8%	30	8
						8-16%	31	3
Ferralic (FA)	Eutric	Isotropic	Very clayey	>200	-	5-8%	32	1
	Distric	Isotropic	Very clayey	>200	-	2-5%	33	6
						8-16%	34	4
	Allic	Isotropic	Very clayey	>200	-	<2%	35	2
						2-5%	36	18
						8-16%	37	1
			Very clayey (1)	100-200	-	8-16%	38	2
			Clayey	>200	-	<2%	39	2
			Loamy	>200	-	<2%	40	3
						2-5%	41	9
						5-8%	42	2
			Sandy	>200	-	2-5%	43	8
Luvic (LU)	Eutric	Contrasting	Loamy/Clayey	50-100	-	2-5%	44	8
						5-8%	45	6
Nitic (NI)	Eutric	Contrasting	Clayey/Very clayey	>200	-	5-8%	46	3
						8-16%	47	12
Chernic (CH)	Eutric	Anisotropic	Loamy/Clayey	100-200	-	2-5%	48	3
Podzic (PO)	Eutric	Anisotropic	Extremely sandy	50-100	-	5-8%	49	1
Gleyic (GL)	Distric	Stratified	n.r.	25-50	-	<2%	50	23
Cambic (CB)	Allic	Isotropic	Loamy	100-200	-	<2%	51	3
						2-5%	52	5
		Stratified	n.r.	100-200	-	<2%	53	13

5. MODIFICATIONS OF SOTER DATABASE FOR USE IN THE PIRACICABA REGION

In order to adjust the SOTER methodology to the available information and to scale of 1:100,000 some concepts were applied differently than indicated by the SOTER manual. It was also considered important to add some information used by Brazilian soil scientists to SOTER's layer attributes, in order to facilitate interpretation.

Most of the modifications applied have major relevance for the Brazilian situation, or for application at (semi-) detailed surveys. Some of the modifications can also be considered for adoption by the SOTER manual in future revisions.

5.1 Length of slope, position in terrain, slope gradient

One of the objectives of SOTER is to facilitate the retrieval of thematic maps from the information available in the terrain-, terrain component- and soil- files.

The length of slope (SOTER manual item 19) and the position of the soil within the terrain component (SOTER manual item 37) are interrelated attributes and are considered to be indispensable for the assessment of e.g. rate and risk of water erosion.

At 1:1M scale SOTER units commonly cover large elements of a landscape and enclose e.g. a collection of hills. This does not happen at (semi-)detailed scale. Then a polygon embodies at most a hill side, or even just a segment of a hill side (section 3.2, Figure 7). In such cases, variables like the position of the soil and length of slope within a terrain component become irrelevant, or, at least, unsuitable. For example the assessment of erosion hazards can not be accurate when only segments of slopes and the position of the soils within those segments are taken into account.

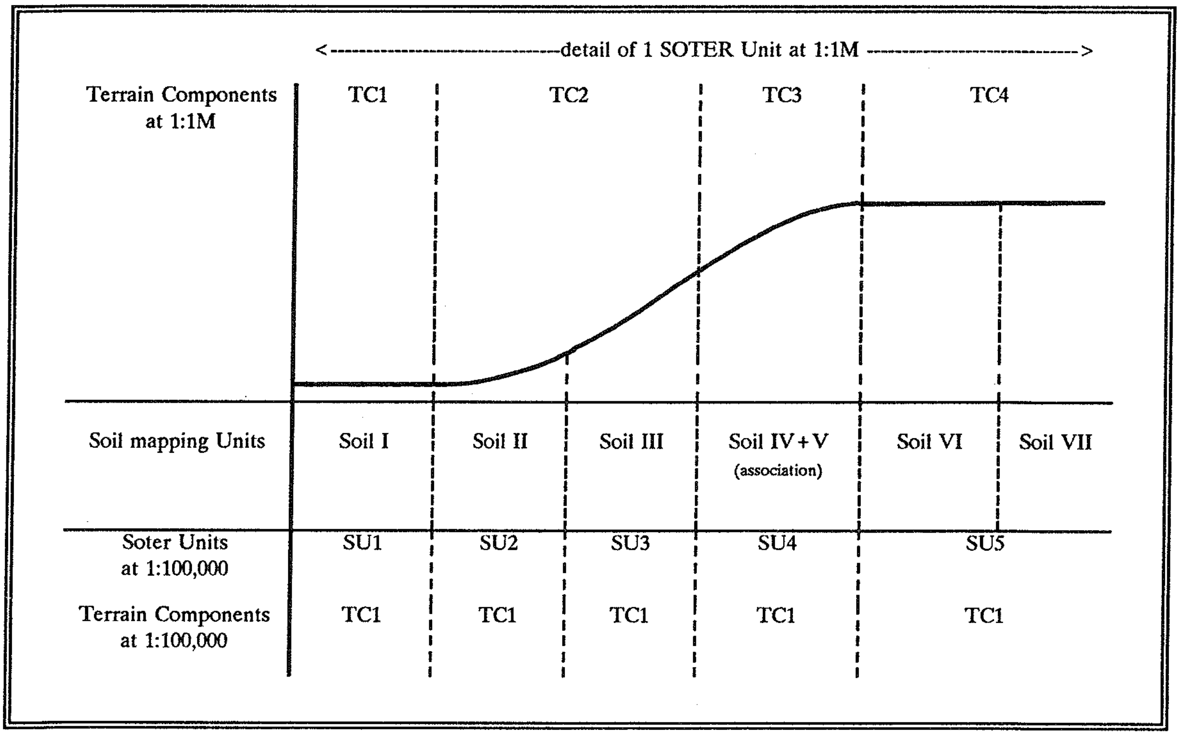

Figure 7. SOTER units and terrain components at 2 different scales.

An additional advantage of considering the overall hillside is obtained when (semi-)detailed maps are assembled to global maps. This involves the lumping together of SOTER units. In the case that slope length and position are related to the SOTER unit these data will have to be adapted. If overall hillsides are considered the data can remain unchanged.

5.2 Parent material

In tropical regions it is very common to find superficial unconsolidated mantles as soil parent material. These covers are often generated from pre-weathered and reworked polygenetic materials. The parent material does not originate from one unique source and very often the exact origin is not clear.
This situation is also common in the Piracicaba region (Chapter 2; Coutard et al., 1978a,b)
The SOTER procedures manual does not provide a suitable code for such situations.

In this study a new group "Polygenetic Unconsolidated materials" was introduced. It applies to the major class "Unconsolidated materials" for "general lithology" and "parent material" (SOTER manual, items 10 and 22). The code for this group is "UR" (Unconsolidated Reworked).

5.3 Incidence of erosion

The main purpose of the SOTER project is to store soil and terrain data from which information can be extracted in the form of thematic maps.
While erosion hazards risk can be assessed with the data provided by SOTER, information on the actual state of soil degradation cannot be abtained without additional sources.
Some soil maps (Almeida et al, 1981,1982; Oliveira & Prado, 1989) indicate the occurrence of the main gullied areas. In this study the information on the extension, type and severity of erosion was accommodated in the SOTER terrain component file using the same codes as recommended in the GLASOD manual (ISRIC, 1988).
If such information is considered too volatile, it may also be stored in a separated file, like the file for description of land use and vegetation, which can be updated more frequently.

5.4 Representative profile & soil variability

The principal sampling tool that was used during the soil survey of the Piracicaba region was the auger. No time and money was available to dig profile pits systematically. Some of the soils that occur in the region were already thoroughly known from neighbouring regions, and others had a very small extension. In such cases no pit was dug at all. This method of fieldwork is justified, because the soils in the region (mostly strongly weathered ones) have little variation with respect to structure and porosity.
As a consequence some soils could not be represented by a "representative profile". Therefore data on augered samples were used as a source for the profile file.

On the other hand the spatial variability of chemical characteristics in strongly weathered soils can be considerable, even at short (<100m) distances within the same physiographic unit (e.g. Oliveira, 1973; Reichardt et al., 1986). To use data of just one site to qualify the potentials and limitations of a soil can also be of little relevance. The knowledge of soil variability within mapping units can be important for land resource managers who want to assess the reliability of their appraisal. Therefore it is common practice in São Paulo State to present statistics for each mapping unit in the soil survey report. (e.g. Oliveira et al., 1979; Oliveira & Prado, 1987; Sakai & Lepsch, 1987).
Although soil variability within small areas was obvious, the profile differentiation of soils within the same mapping unit was usually similar. Therefore, in this survey the "average soil" (attribute) is not an artificial "monster" as might be the case for small scale maps with many complex mapping units that may not be averaged.
In the present work some statistics (normalised mean, median) were also used to decide whether Soil mapping units should be lumped together in the same SOTER unit.

Considering the above it was decided to use together with the profile file another file to store data on statistics (e.g. (normalised) mean, median, variance). This file will use the same list of attributes already provided in the SOTER manual, but adding some codes to inform about the kind of statistics employed together with a number to show the size of the analyzed population. This part is not yet implemented, because of the lack of application software.

5.5 Depth of soil layers

The SOTER manual is not clear with respect to the type of soil layers that can be described:

(1) Item 55 suggests that a "layer" is the same as a "master horizon" (as defined by FAO, 1977). If this were so, then it is obscure why the manual uses these 2 different terms.
Limiting the possibilities of layer description to master horizons implies that variations within such horizons cannot be indicated. Such variations can be important. For example: a compacted Ah horizon below an Ap; a Bg horizon below a Bw; a thick Bws horizon below a Bt (all with completely different physical and chemical properties).

(2) It is not clear whether the "sequence number for the master horizon" requested refers to the sequence of the layer in the profile, or whether there is any relation with the sequence H,O,A,E,B,C,R of master horizons used by FAO (1977).

(3) The manual recommends to limit the number of layers to 4. It is not mentioned whether gaps are allowed. If gaps are allowed, then not only the depth of the lower boundary, but also of the upper boundary should be provided.

Considering the above the following modifications were introduced for the Piracicaba region:
(1) The layer number consists of two digits; the first of which indicates the master horizon and the second the subhorizon.
(2) Both upper and lower boundary of each horizon are provided, so that gaps between horizons are allowed, when differences between subhorizons are considered of little relevance.

5.6 Microgranular structure

Most (Geric) Ferralsols present a typical structure, often described as "massive porous" or "coffee powder" with large porosity and a very friable consistence. This typical structure is the result of cementation of clay particles by sesquioxides, forming silt and sand sized grains, that are in fact structure elements. The terms "massive" or "single grain" and "structureless" provided by the SOTER manual to identify the form (item 60) and grade (item 62) of the structure are not relevant for these soils.
Therefore the manual was adapted by inclusion of the term "strong microgranular".
The term "structureless" was avoided, because in our opinion all soils present structure.

5.7 E horizon

Some of the Acrisols, Luvisols and Planosols of the Piracicaba region present a clear E horizon, that does not meet all requirements of an "Albic horizon".
Such E horizons are considered important for the assessment of both soil genesis and management possibilities. They are used as diagnostic criterion in some soil classification systems, including the Brazilian (EMBRAPA, 1981).
Therefore we included the E horizon among the diagnostic horizons.

5.8 Fe_2O_3 extractable by H_2SO_4

There is consensus among Brazilian Soil Scientists that crops grown on clayey Rhodic, dystrophic or geric Ferralsols, which originate from basalts and dolerite present a better stand and yield more

than crops on similar soils that originate from shales. This is supposed to be related principally with the higher amount of micronutrients in the soils that originate from basic rocks (Valadares, 1975; Valadares & Catani, 1975; Bataglia et al., 1975; Furlani et al., 1977). This is considered important for soil management. As there is a clear correlation between parent material and Fe_2O_3, and because direct assessment of micronutrients is difficult and expensive, the Brazilian system of soil classification (Camargo et al., 1987) uses the value of "total" Fe_2O_3 (Fe_2O_3 extracted by H_2SO_4 1:1) as a diagnostic criterion to divide Latosols (corresponds roughly with Ferralsols) at the second level of generalisation. Another important aspect of Fe_2O_3 is that it contributes to a stable microstructure, which is responsible for a high infiltration capacity and good workability, even of very clayey soils.
In the present study total Fe_2O_3 was added to the layer data.

5.9 Resin extractable P

Comparison of several P-extraction methods for different crops grown on different soils in Brazil indicated the resin extraction method as the one that is best correlated with crop P uptake and productivity (Van Raij et al., 1986). The method is used as standard routine in São Paulo state, and is being adopted in many other brazilian laboratories.
Therefore P data, determined with the resin extraction method, were added to the layer file.

5.10 Easily weatherable minerals in the fine sand fraction

Information on the content of easily weatherable minerals in the fine sand fraction is useful to assess potential natural nutrient availability, especially for forestry and low input agriculture. The diagnostic property "weatherable minerals" provided by the SOTER Manual (item 100), copied from FAO/Unesco (1988), is very vague because it does not define the quantity of weatherable minerals that must be present. Therefore the item "weatherable minerals in the 50-200μm fraction" was added to the layer file.

5.11 Land use at site of reference pedon

The SOTER manual (Part II) has a separate file for the description of land use and vegetation, because these are considered dynamic land characteristics which need constant updating and because third parties are also working on global databases for the subject.
According to the SOTER manual land use is described at the SOTER unit level.
The land use at the site of the reference pedon is not necessarily the same as the dominating land use of the SOTER unit (it is even possible to refer to profiles situated in other SOTER units); and the land use in the "land use file" will, after updating, be different from the land use at the time of description of the profile.
Changing land use can cause important changes of e.g. organic matter levels and base status to considerable depths (e.g. Lepsch et al. in prep.). Deriving relations for interactions between land use and soil characteristics can be one of the applications of the SOTER database. Therefore the land use or vegetation at the site of the reference pedon at the time of description was added to the profile data.

6 DISCUSSION

This study showed clearly that the SOTER methodology can very well be applied to a scale of 1:100,000. Most of our modifications are additions to the manual, that were considered important because of the local peculiarities of the study region, the possibilities to give more detailed information at an increased scale and because it was found important to maintain the system compatible with the soil classification system in use in Brazil (sections 5.4, 5.7, 5.8, 5.9). These modifications were introduced without violating the principles of the SOTER methodology. Other modifications were made because we had problems to interpret the SOTER manual (sections 5.1, 5.5, 5.10), so that the definitions were sharpened. We believe that the other modifications (5.2, 5.3, 5.6, 5.11) deserve attention to decide on their inclusion in a future revision of the SOTER manual.

Some difficulties were encountered with the application of the SOTER unit as a basic mapping unit. Especially in the initial stages of the project, when a former edition of the SOTER manual was used (ISRIC, 1990). The 4th edition is much more flexible with respect to the mapping criteria. This flexibility is one of the main strengths of the method, because survey teams have much liberty to adapt it to their local needs. On the other hand their exists a certain danger that, if this liberty is too large, this results in difficulties to compare different areas, and to assemble small scale maps from (semi-)detailed maps. Therefore it is important that more guidelines be given with respect to the differentiating criteria. These criteria must not be given in quantitative terms, and may eventually be scale dependent.

Feasability of the SOTER methodology at different scales is not the only condition for SOTER to become a world standard. At least two other conditions must be met: (1) The method must meet the local needs in a way at least as good as traditional methods or other alternatives and (2) The extra effort must be as little as possible.

The first item hardly needs discussion. The method allows a much more efficient manipulation of information than any traditional soil or terrain map can ever do. Once the data are put in the digital data base and linked with a geographical information system, tailor made maps (including traditional soil maps) can be delivered on request to a large variety of planners and decision makers. With respect to item 2, quite a lot of extra effort was put in this project because we were not familiar with the system and because we used existing maps as basic documents. Application of the method in one or two additional pilot areas will probably be enough to establish clear criteria for differentiating SOTER units in the State of São Paulo. Then the method can be applied directly in the field, possibly with about the same effort as put today in traditional soil surveys.

Unfortunately there are also drawbacks for routine application of the method in Brazil. Relatively advanced software and hardware are necessary, especially when good quality maps are to be produced. Cheap and (semi-)public domain packages can be applied (Cochrane and Macedo, 1990), but they lack "user friendliness" and flexibility and graphic output is of low quality. Also, staff with experience in computer systems is hard to encounter. These problems will probably also form a major obstacle for the routine application of SOTER in other developing countries. Part of them could be overcome if SOTER would be delivered as a standard software package, preferably for implementation on more and less advanced systems. Additional advantages of such a package will be the increased facility for the development of application software (e.g. for land evaluation, erosion hazard prediction etc.) and for assembling (semi-) detailed regional maps to generalized national or global maps.

7. CONCLUSIONS

- The SOTER concept, which was designed to produce small scale maps, can be employed with almost the same structure to produce semi-detailed maps.

- With increasing scale major landforms loose their importance as diagnostic parameters to identify SOTER units. Small pieces of the landscape, like land features or land elements, together with surface form become more appropriate diagnostic characteristics to identify physiographic units. These physiographic units showed good correlation with soil mapping units. Consequently soil maps, together with surface form pattern were the main basic data sets used to identify SOTER units.

- For a general application of the SOTER methodology it is necessary that some criteria become more explicit. User friendly standard SOTER software need to be designed in order to increase the accessibility of the method.

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