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Three-dimensional GIS cartography applied to the study of the spatial variation of soil horizons in a Swiss floodplain

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Abstract

In this study, we propose to establish a framework for the study of the spatial variability of the soils found in the floodplain of the Sarine River and for the visualisation of soil distribution patterns in two- and three-dimensions (2-D, 3-D). This environment is characterised by a large lateral and vertical spatial variability of soils that corresponds to the temporal and spatial variations of the fluvial dynamics of the Sarine. The study was carried out using existing Geographical Information System (GIS) functions combined with applications specific to soil cartography. This particular GIS cartography is based on the notion of the soil horizon instead of that of the soil diagnostic profile. A Global Positioning System (GPS) survey was carried out in order to construct a local Digital Elevation Model (DEM) and to ascertain the spatial coordinates for each of the 181 soil obsevation locations. All data were stored in a GIS database, and both landform modeling and soil cartography was undertaken. GIS, ARC/INFO, and Vertical Mapper for MapInfo were adequate for our linear triangulation interpolation, for contour processing and for the creation of cross-sections as well as the corresponding vertical profiles. These vertical profiles served to illustrate the superposition of soil horizons along any line across the sampled area. A 3-D representation of soil was obtained using the quadratic finite-element method, which is generally employed in geological studies and which we adapted especially for the representation

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of soil horizons. 3-D cartography of this type allows the spatial pattern of a given horizon — including the variation of its thickness, the superimposition of the different soil horizons, the total soil depth, and the number of horizons at any given location — to be followed through space. Our approach, furthermore, facilitates the perception of soil horizons and their juxtarelationships as 3-D objects, and permits the visualisation of the relationships that exist between any given horizon (or sequence of horizons) and the surface topography. In thus enabling the realistic representation and easy visualisation of the spatial distribution and variability of soils in the landscape, our methodological approach provides a powerful instrument for soil scientists, and a useful decision-support tool for ecosystem management.

Keywords: three-dimensional visualisation; soil mapping; GIS; alluvial soil; Switzerland; pedometrics

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1. Introduction

Several authors have already discussed the two main models used in the development of soil cartography: namely, the discrete and the continuous models (Baize, 1986; Aubert and Boulaine, 1989; Lark and Beckett, 1998).

Traditional soil cartography is based on the discrete model of soil spatial variability. This assumes that soil characteristics or type change abruptly at soil boundaries. In general, each map unit represents a pedological characteristic that is a constant or unique type of soil. In the latter case, the unit is defined by a ‘‘representative soil profile’’ (Soil Survey Staff, 1976). The discrete model is not usually realistic because natural boundaries in landscape tend to be gradual rather than abrupt. Nevertheless, at intermediate mapping scales, traditional soil cartography can offer the appropriate solution (Voltz and Webster, 1990; Lagacherie et al., 1995), because soil boundaries can be easily identified by changes in the landscape (break of slope, changes of parental material, vegetation, etc.).

The continuous model provides another way of approaching soil spatial variability. This assumes that soil characteristics vary gradually through space. Among the available techniques that facilitated the use of continuous model, geostatistics is the one which has been seen as most appropriate for use in soil science (Voltz and Webster, 1990; Voltz et al., 1997; De Gruijter et al., 1994; Qian and Klinka, 1995). To address the continuum aspect of soils, FitzPatrick (1986) recommended that soil cartography be based on the notion of horizons rather than on that of soil profiles. Cartography by soil horizon despite being based on the discrete model of spatial variation, facilitates the perception of soil as it appears. This approach has three advantages. First, it considers soil as a three-dimensional (3-D) body. Secondly, it takes the spatial variability of soil horizons into consideration. Thirdly, it allows the superpositional pattern of the soil horizons to be analysed. These advantages have been discussed by several authors (Boulet et al., 1982a,b, 1989; Girard, 1983, 1989; Girard et al, 1989;

King, 1986; Pedro, 1989; Ruellan et al., 1989). Up until now, soil cartography by horizons has mainly been applied to tropical soils or soils whose horizons are clearly differentiated (Bocquier, 1973).

Moreover, Geographical Information System (GIS) technology has greatly facilitated the 3-D visualisation of soil as a continuous surface. Visualisation techniques such as these have been developed recently in the field of geology (Bouzelboudjen and Kimmeier, 1998; Houding, 1994). By contrast in soil science, this kind of representation is in its infancy (Ameskamp, 1997; Benz, 1995; Heijs et al., 1996; Pereira and FitzPatrick, 1998).

In alluvial soils, the sequence of horizons at a given location is the result of sedimentation and in-situ pedogenesis; these two processes overlap but inheritance is predominant (Gerrard, 1992; Mendonça Santos et al., 1997a). This absence of genetic features in soil profiles, combined with the horizontal and vertical variability of textural configuration of alluvial soils cannot be correctly described by the method based on soil diagnostic profiles (Finkl, 1980; Gerrard, 1992). The horizon approach would seem to describe the complexity and variability of these soil profiles better.

Our aim here is to propose a GIS cartographic framework in order to map and study the spatial variability and distribution pattern of soil horizons in a floodplain, and to represent soil as a continuum in 3-D.

The research was carried out using some existing GIS functions along with applications specifically developed for digital soil horizon cartography. The application of the methodology to a floodplain is justified by the fact that floodplain soils possess a high degree of spatial variability (both lateral and vertical) due to the inheritance process, which is extremely difficult to reveal by the classical approach.

2. Material and methods

2.1. Study area

The floodplain is located along the River Sarine near Fribourg in Switzerland (Fig. 1). It is about 750 m above sea level. The area under examination covers approximately 1 ha. A detailed description of the site has already been published (Mendonça Santos et al., 1997a,b).

2.2. Methodology

The research was carried out using existing functions in GIS software (ARC/INFO and Vertical Mapper of Map Info) with specific applications to soil horizon cartography. Fig. 2 illustrates the three principal parts of the

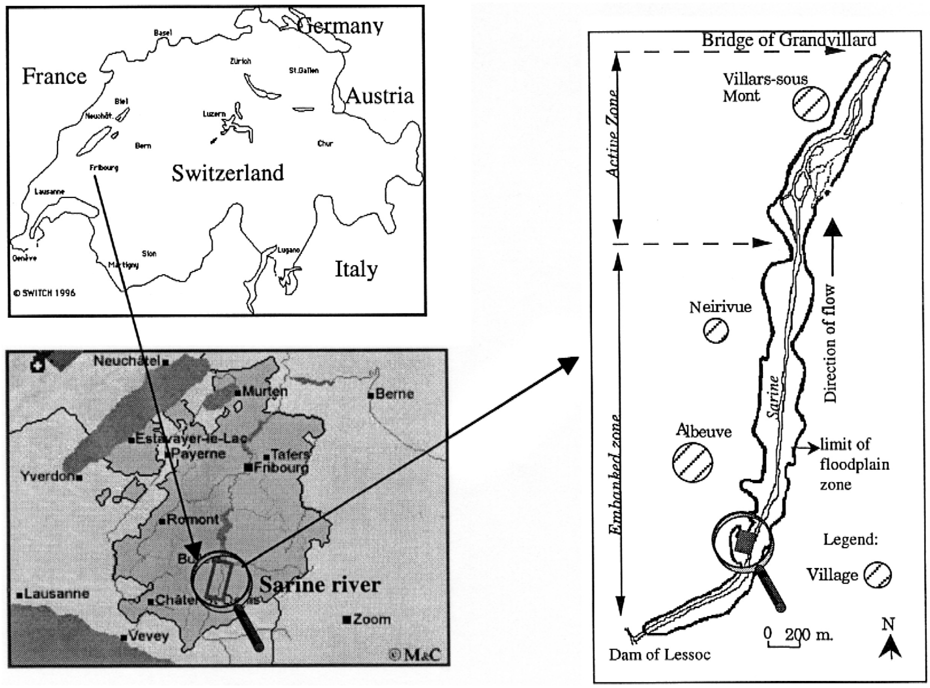

Fig. 1. Location of the study site.

methodology supported by a GIS database: data acquisition, landform modeling, and soil horizon cartography.

2.2.1. Data acquisition

A total of 181 points were surveyed using a pedological (core sampling) drill. The sampling network was a regular grid (5 m in EW direction and 10 m in SN direction). The following properties were recorded for each point: total depth (the bottom limit is the D horizon = strand with calcareous pebbles), number of horizons, thickness and field texture of each horizon.

In addition, the following properties were determined for the topsoil:

- organic matter content, determined by combustion at 600°C;
- presence or absence of coarse material — gravel and pebbles, > 2 mm;
- structure — grade, class, and type — according to the Soil Survey Manual (Soil Survey Staff, 1976); and
- the presence of carbonates, detected in the field by HCl effervescence.

Horizon nomenclature was allocated according to the ‘‘Référentiel Pédologique 1995’’ (A.F.E.S., 1995). In addition, topsoil texture and structure were used for the identification of the different horizons. In order to be able to

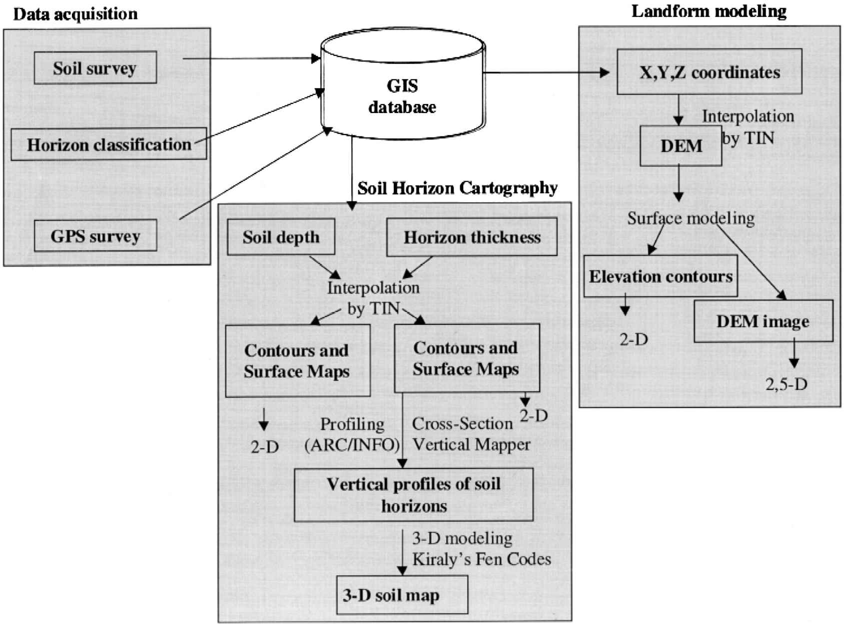

Fig. 2. Diagrammatic representation of the methodology.

construct our soil model, we were obliged to impose an order of horizon position that corresponded to our data set, the assumption being that this order was honoured at unobserved locations.

A Global Positioning System (GPS) survey was carried out to determine the co-ordinates (X, Y, Z) of each soil survey point to a precision of 50 cm in the horizontal plane and 2 cm in the vertical. All data were stored in a GIS database (Info of ARC/INFO). Table 1 shows an example of these data entries.

2.2.2. Landform modeling

The data from the GPS survey were interpolated using a Triangular Irregular Network (TIN) and from this a Digital Elevation Model (DEM) was built. This technique allows for the surface of each triangle to pass exactly through each measured data value. According to Bonham-Carter (1994), this approach is the most appropriate one where data are known to have relatively small margins of error. We believe this was the case for our survey.

2.2.3. Soil cartography

The characteristics of our data set — regular grid, dense sampling, and relatively precise measurements — made the use of the TIN interpolation technique particularly appropriate. The 3-D soil cartography by horizons was established using the following steps. Firstly, the Z (elevation) values of the

Table 1
Database entries for horizon thickness

Site number	Soil id	*X* (m)	*Y* (m)	*Z* surface (msm)	Horizon[*] thickness (cm)											
					Aca	Jp(sl)	M(s)	Jp(ls)	IIJp(sl)	IIM(s)	IIJp(ls)	IIIJp(sl)	IIIM(s)	IVJp(sl)	Jp(l)	IVM(s)
1	T12S0b	571161.9315	151168.5340	747.6490	10	15	40	0	0	20	0	0	0	0	15	0
2	T12S1	571156.2130	151170.3250	747.9025	20	0	30	0	0	0	0	0	0	0	0	0
3	T12S1b	571151.3005	151171.9975	748.1160	10	0	50	0	0	25	0	0	0	0	15	0
4	T12S2	571146.7775	151173.7245	748.1895	17	3	0	0	0	0	0	0	0	0	0	0
5	T12S2b	571142.0255	151175.2765	748.2325	15	0	0	0	0	0	0	0	0	0	0	0
6	T12S3	571136.9065	151176.7745	748.2280	18	20	0	0	0	0	0	0	0	0	0	0
7	T12S3b	571132.5110	151178.0635	748.2470	10	0	15	0	0	0	0	0	0	0	0	0
8	T12S4	571127.7810	151179.7580	748.0235	15	23	0	0	0	0	0	0	0	0	0	0
9	T12S4b	571123.0855	151181.1345	747.8785	10	50	0	0	0	0	0	0	0	0	0	0
…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…
…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…
…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…
181	L0S14	571191.0528	151295.9160	746.6770	6	0	22	0	4	18	0	5	7	0	0	0

[*] Horizon designations, Aca, Jp(sl), etc., follow A.F.E.S. (1995). Référentiel pédologique.

bottom of each horizon were calculated with basis on the surface elevation value, measured by GPS and the horizon thickness. Secondly, these values were interpolated and contour processing was applied to create isolines contouring the soil survey points. Thirdly, maps with both isolines and filled contour areas were generated in 2-D.

Based on the corresponding grids of the 2-D maps and using the ‘Profiling’ procedure in ARC/INFO, or alternatively using the ‘Cross-section’ procedure in Vertical Mapper (MapInfo) software, cross-sections could be generated along any line traversing the sample area.

Finally, a 3-D volume model was carried out in order to represent soil as a continuum in the landscape. This was achieved using a quadratic finite element method, the Kiraly’s Fen Code (Király, 1985) adapted to soil modeling. The 2-D surface network is vertically replicated at each soil horizon to obtain a 3-D finite element network. It means that each sample point is really represented by a vertical edge of the 3-D network.

In the finite-element method, the unknown function is approximated over a subset of the entire global domain by using interpolation functions. In the present paper, only linear interpolation functions are employed. The entire model domain must be discretised into 1-D, 2-D, or 3-D elements. The program allows for the use of either triangles or rectangles for 2-D elements and either tetrahedra, triangular prisms, or cubes for 3-D elements. These elements may undergo further deformation. The number of element shapes allows for considerable flexibility in designing for example, a 3-D network for analysing water and transport in highly heterogeneous porous media (Eisenlohr et al., 1997a,b). In this paper, the post-processing routine allows the possibility of creating a series of cross-sectional planes or 3-D block diagrams.

3. Results and discussion

Fig. 3 illustrates the different steps for building a DEM: the soil survey points and the TIN network mesh (Fig. 3a); contours, the isolines of contour elevation (Fig. 3b); and a block diagram of the DEM in so-called 2.5-D (Fig. 3c). The DEM constructed in this way allows the visualisation of local differences in topography that would not be possible with an ordinary DEM (1:25 000). On our site, three areas are distinguished. The highest area, which corresponds to an old island and its extension that is easily visible in the middle of the site. Secondly, the intermediate zone situated on the left side of the site. Thirdly, the lowest area, a depression on the right side of the site (close to the river, which is not shown here).

Fig. 4 shows the spatial pattern of soil depth. The thinnest profiles are to be found in the highest areas, while the thickest ones are in the depression.

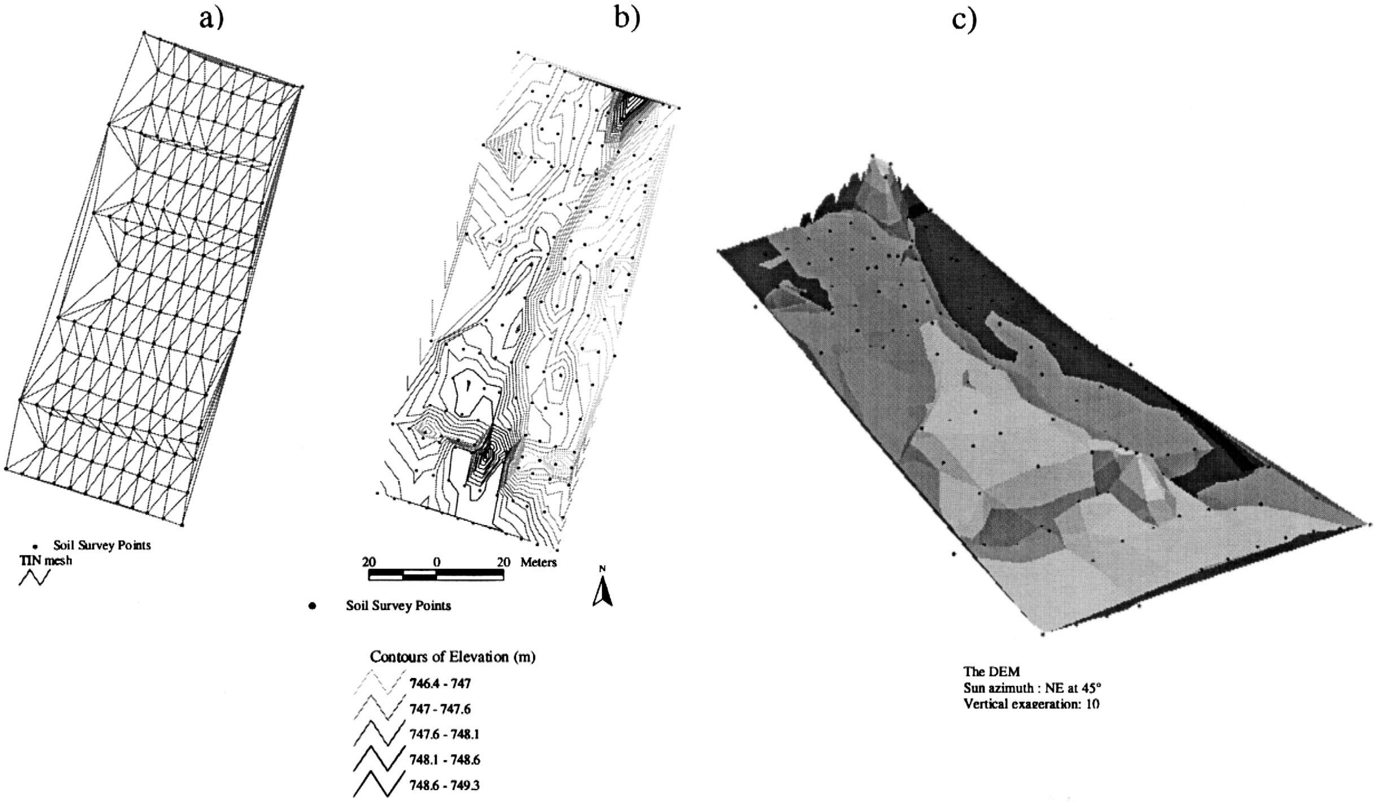

Fig. 3. DEM of the study site. (a) The triangulated network (TIN) that honours each soil survey point; (b) the elevation contours of the site; (c) the block diagram of the DEM (2.5-D); bright = the top, dark = depression.

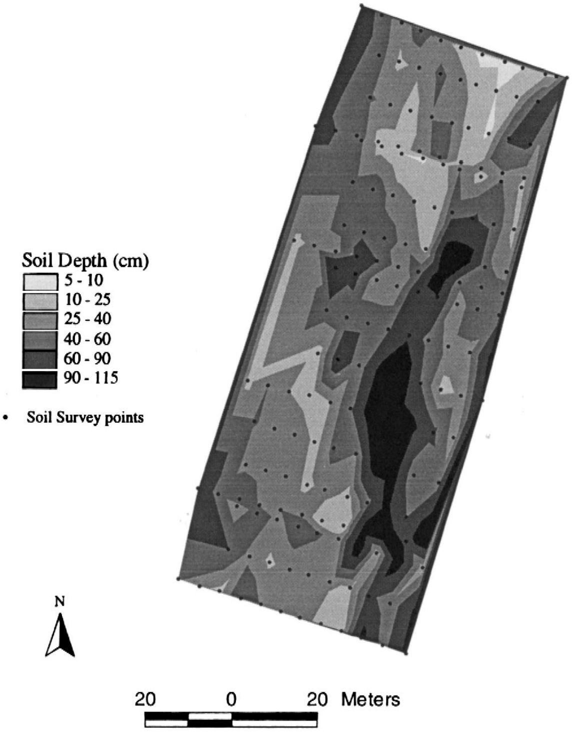

Fig. 4. Map of total soil depth.

Horizon thickness was mapped in 2-D for each of the 12 horizons. The maps of Fig. 5 illustrates the thickness variation of the first three horizons, Aca, Jp(sl), and M(s). These maps enable us to:

- visualise the spatial distribution pattern of each horizon and the variation of their thickness;
- observe the presence or absence of a given horizon at any particular point;
- compare the spatial distribution patterns of the various horizons.

For example, the left-most map shows the A horizon (Aca) which is present everywhere, while the right-most one depicts the M horizon (a sandy horizon), which is present only at some points. The white zones in the middle and right maps signify the complete absence of the horizon in question.

These maps can also be draped on the surface plot of the DEM in order to study the relationships between horizons and surface topography. Nevertheless, the 2-D representation is not capable of integrating all of the soil horizons simultaneously, a necessary requirement for pedogenetic studies. It does constitute an indispensable step towards the necessary 3-D representation, however.

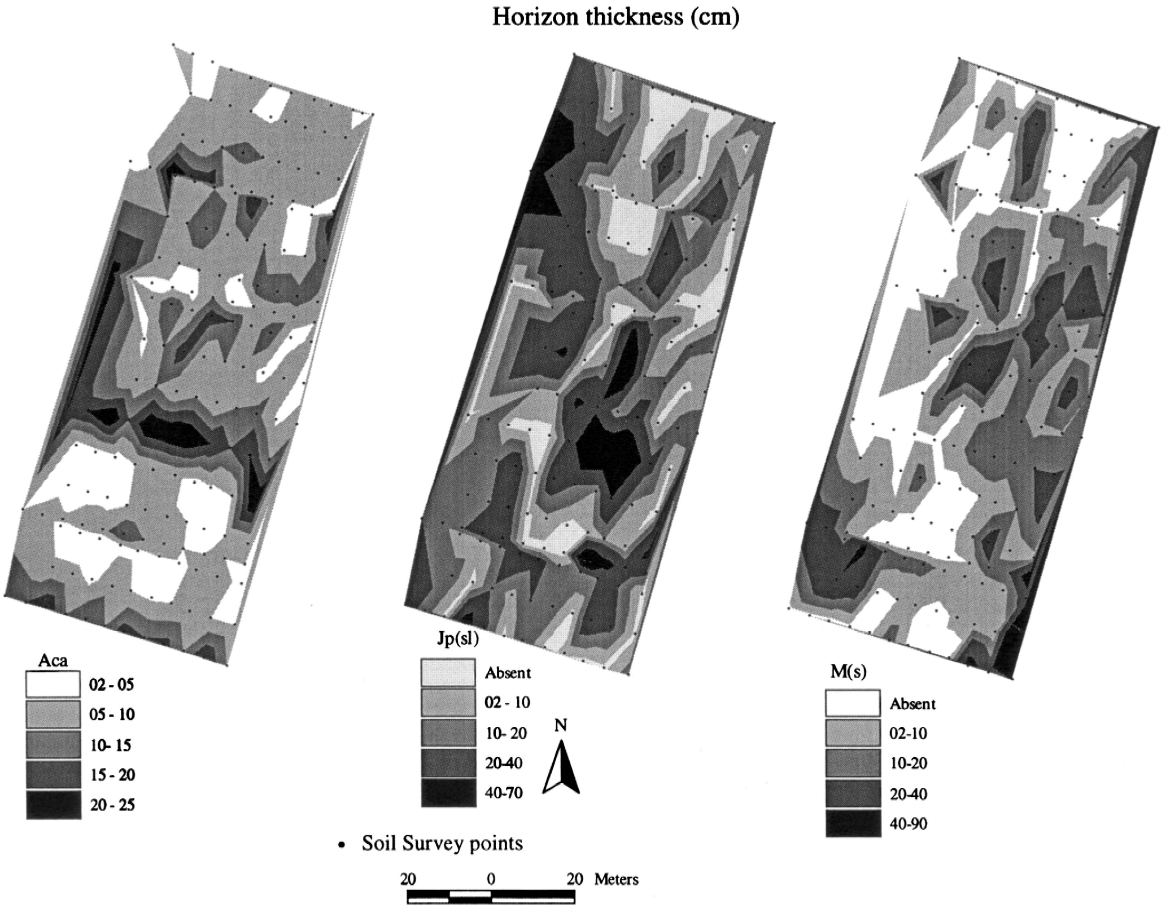

Fig. 5. Maps of horizon thickness for the first three horizons.

Some results obtained with the 3-D approach are illustrated in Fig. 6. In the upper left-hand corner of the figure, the DEM shows the location of three cross-sections (two perpendicular to the river and one alongside it). The rest of the figure is comprised of the three cross-sections in question. The legend on the right side of the cross-sections indicates the horizon classification. All the soils are ‘‘calcareous FLUVIOSOLS typiques’’, according to the ‘‘Référentiel Pédologique 1995’’ (A.F.E.S., 1995).

Cross-section L1, which is located close to the river channel, starts from an elevation of 748 m, crosses the depression (with a minimum of 746 m) and ends at the old island (the highest point in the site, at more than 749 m). Although the surface elevation difference (relief) is small, it constitutes an important factor in the sedimentation process. There are more horizons at the lowest positions than elsewhere. On the old island, at the end of the transect, for example, the soil contains only one horizon. A similar tendency is corroborated in the other cross-sections. This pattern illustrates clearly the influence of river dynamics upon these soil profiles. Soil profiles with several horizons are essentially formed by alluvial deposition in old branches or close to the river channel in bottom areas. By contrast, the thinnest soils from the highest position have been protected from floods. The presence of a given horizon and its thickness provides information about sedimentation processes due to the same flood event. The spatial configuration of one horizon can be explained by relating it to the presence of under-horizon(s), without any reference to the present-day topography. Thus, the sedimentation processes are easier to reconstruct. For example, the central part of the longitudinal profile (L1) demonstrates the past existence of two distinct geomorphological sectors, which are characterised by different sedimentary sequences of horizons. These sectors were subsequently interconnected by fluvial dynamics (presence of the same horizons) and the past topographical variation has been attenuated. This cartographic approach is useful for identifying the two processes that result in alluvial soils: sedimentation and in-situ pedogenesis. As soil units are very difficult to define and to delimit — because all soil profiles belong to the same class (calcareous FLUVIOSOLS) and because they mainly differ in number and thickness of horizon and vary within a short distance — a more classical approach would have been inappropriate.

The 3-D representation (Fig. 7) shows the soil as a volume in space and conserves the advantages of a cross-sectional representation. It contains the same information but it presents them in a volumetric view and allows several cuts, following different perspectives, to be made simultaneously. This provides a greatly increased clarity and simplicity of view, thus constituting a valuable perceptive and didactic tool for the visualisation of soil variation.

For pedological studies, and particularly those concerning alluvial soils, GIS-cartography such as this — allowing the representation of soil by horizon, in 3-D — constitutes a useful improvement over current approaches. It is a

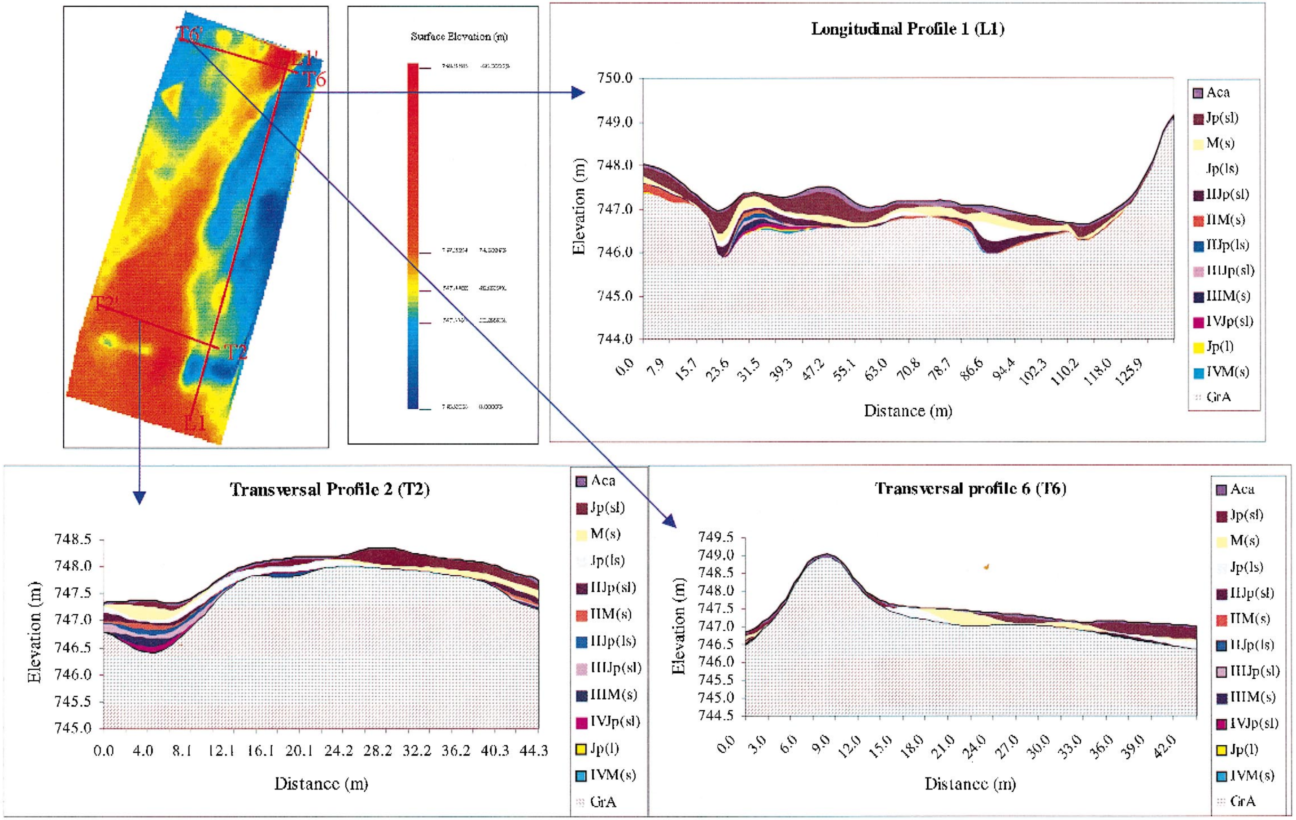

Fig. 6. DEM image showing the location of cross-sections and the corresponding vertical profiles of soil horizons.

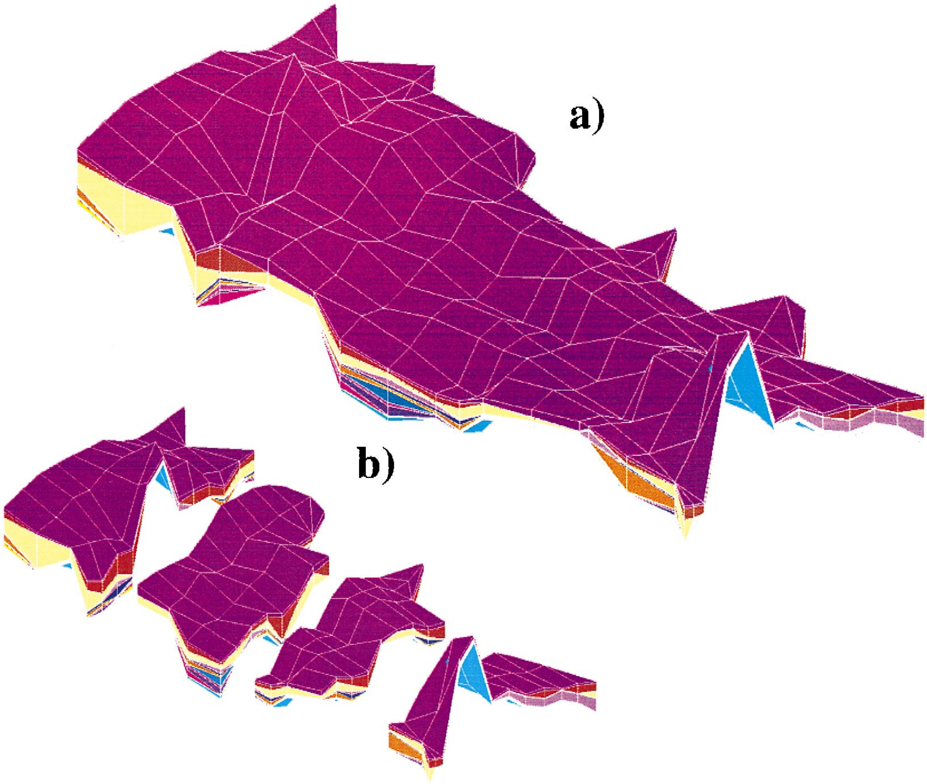

Fig. 7. 3-D soil volume model (sun azimuth: N at 60°, tilt: 30°, vertical exaggeration: 10×). The vertical nodes of the network correspond to the soil survey points. (a) The whole site; (b) three transverse cuts.

useful tool to show how the soil distribution patterns in our study are clearly due to the influence of fluvial dynamics.

This approach has permitted us to observe that the sequence and thickness of the horizons varies over short distances (±50 cm), thus elaborating different patterns of change. This could be explained as a consequence of the overlapping of the different factors that influence the sedimentation process, e.g. topography/geomorphology, distance to the river channel, and so on.

4. Conclusions, limitations and future improvements

3-D GIS cartography based on soil horizons offers a number of advantages over more traditional cartographic techniques. The only necessary classification is related to horizon definition. In addition to this, however, the use of a GIS permits a more flexible approach, particularly when considering the type and number of horizons to be mapped and the choice of cross-sections to be generated. Furthermore, our cartographic approach allows the calculation of horizon volumes. Such calculations could be helpful to pedogenetic explanations (intensity of flood originating a given alluvial deposit), soil properties (water or pollutant storage capacity) or to plan landscape management (sediment extraction for example). Our 3-D GIS representation permits an easier visualisation of the spatial distribution and variability of soil. The methodology is particularly appropriate to the mapping of high spatial variability soils. Our research has demonstrated the undeniable utility of GIS technology for soil scientists, for the facilitation of data-set management, for spatialisation, analysis, visualisation, and mapping in an interactive way. The current model assumes a fixed sequence of horizons, the implications of this assumption needs to be investigated further. Future improvements will also focus on the use of geostatistical techniques in order to quantify the spatial variability of these soils, and uncertainties associated with interpolation. Finally, our GIS-assisted cartography associated with thematic maps could provide a useful decision-support tool for the management of ecosystems.

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