GIS AND SPATIO-TEMPORAL MODELLING FOR THE STUDY OF ALLUVIAL SOIL AND VEGETATION EVOLUTION

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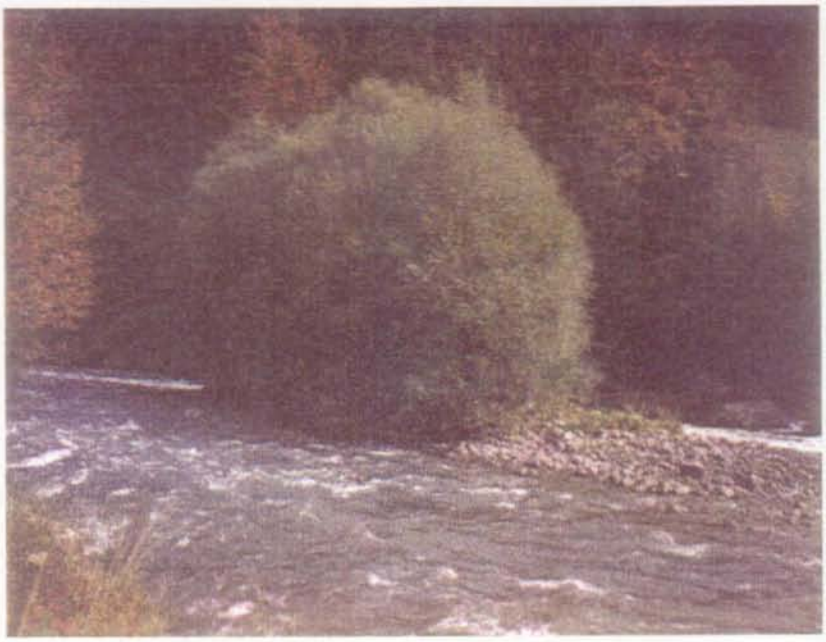

Cette thèse est dédiée à ***Félix Brefin****, pour son amour et patience.*

Time present and time past
Are both perhaps in time future
And time future contained in time past

....

Time past and time future
What might have been and what has been
Point to one end, which is always present

....

And the end and the beginning were always there
Before the beginning and after the end.
And all is always now....

(Eliot 1944, *in* «Burnt Norton» in Four Quartets, p.7)

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Summary

This research was developed in an interdisciplinary context, as collaboration between the Pedology and GIS Institutes of the Rural Engineering Department of the Swiss Federal Institute of Technology (EPFL).

Within the Pedological domain, this work comes within the scope of environmental research aiming at the analysis of the sensitivity of the alluvial ecosystems to natural and anthropic changes. Within the GIS domain, this research comes within the scope of the GIS design methodologies applied to different thematic domains, and on the other hand into the research concerning the integration of time into GIS applications.

The interest of alluvial zones is the fact that these ecosystems have an large complexity and biological diversity, which surpasses, in general, that from other temperate environments because of their rapid dynamic. This dynamic, running in a human scale, permits reliable historical reconstruction. In spite of their ecological interest (e.g. large diversity of species, land-water interface, flood regulator...), these ecosystems are among the most threatened in Europe because of the high degree of man-induced alteration.

Recently, the European alluvial zones have been inventoried with the goal of conservation, protection and restoration. Subsequently, Switzerland has established an inventory of its alluvial zones (0,25% of the territorial area) and mapped the vegetation. Since 1992, a Federal Edict has regulated the protection of the 169 sites considered to be of national importance, and suggests measures of their management. The management suggested in the Federal Edict must be based on rigorous scientific knowledge about such ecosystems. At the present such knowledge is quite fragmented. The speed of transformations, the vegetation change patterns and direction, as well as the most adequate scales to bring out the spatio-temporal changes in this environment is still questions without answers.

Concerning alluvial soils, there is little available data, principally that about alluvial soils developed from the recent sediments. The establishment of a model able to represent in space and time the entities and its changes becomes fundamental for the comprehension and management of such an environment.

This research has pursued a double aim: On the one hand, it is a matter of improving our knowledge about alluvial environment upon human action, and particularly about the formation, evolution, the present-day variability and spatial distribution of soil. On the other hand, the focus is done in the design of a GIS Methodology able to integrate the spatio-temporal information and the particularity of environmental research.

In order to fulfil these objectives, this research relies on an integrated approach that combines synchronic and diachronic approaches into a double research methodology: a pedological methodology and a GIS design methodology that integrates the spatio-temporal information. With such an approach we were able to study the present-day state of soils in relationships to the change sequence lead by fluvial dynamics and/or human interventions. The benefits from such an interdisciplinary research are:

1. To offer to the pedological experts a methodological framework useful for the structuring of the scientific reasoning, for the expression of the causal relationships and for the application modelling. In addition, the basis for a most adequate choice of the GIS technology to the implementation of the application is also given.

2. Such an application allows GIS experts to identify new spatio-temporal structures that should be take in consideration into the modelling process, as well as the identification of other particularities related to the dynamic of alluvial environment. In addition, such an application can also gives new insights for the spatio-temporal GIS specifications.

To help understand of the present-day state of soil, its variability, spatial distribution, evolution and relationships with the vegetation, a pedological research methodology that combines a synchronic approach (the study of the present-day soil state) with a diachronic one (based on the historic reconstruction of the site) were undertaken. For the diachronic approach, the need GIS was identified.

To better outline the morphological variability of soils, a three-dimensional GIS cartography was undertaken. This approach is based in the notion of soil horizon and allowed the representation of soils as a continuum in space and facilitated the study of their lateral and vertical variability, as well as the soil-topography relationships. Such an approach seems to be the most appropriated for studying the spatial variability of soils, and particularly, alluvial soils (due to their complex soil formation process, with inheritance and pedogenesis that intercalate in space and time).

The complexity of the alluvial environment with its dynamic aspects and its interactions in terms of soil formation process led us to use GIS beyond the performances as software. Such as instuitutional context, we needed a GIS design methodology able to take into consideration the complexity of environmental research and to benefit from its expertise The proposition of such an approach has become one of the main points of this work.

The problem structuring, the identifying of the causal links, the decision about the data and processing to be modelled, as well as the modelling of the application itself, were largely facilitated by the use of the proposed GIS design methodology. Moreover, GIS has also played an undeniable role in the site history reconstruction, and particularly in the change detection and analysis. In spite of the uncertainties expressed by the unexpected transitions, the employed method, the analysis of change based on data discrete in time, has permitted the identification of changes in a time span of 62 years with an average time step of 12 years. Changes were quantified, qualified and their directions and patterns identified.

This research has provided the means to answer the principal questions addressed in the literature about spatio-temporal modelling: “what, where, when”. In the present study, the thematic (changes in land cover), the spatial (the location of changes) and the temporal component (when changes have happen) were answered. As an extension of the triad model, the explanation of the how (information about the landscape structure – fragmentation and change quality) were also addressed. Based on the site history, hypotheses were drawn about the why of changes and the site evolution.

This research could bring useful data and knowledge for the management and the protection of alluvial zones, as suggested in the Federal Edict. More precisely, this work has showed that the anthropic impacts (e.g. embanking, river rectification,...), as well as flooding, has played an important role in the formation and evolution of the soil and the vegetation of the Sarine River’s floodplain. As a result, this floodplain has become dryer (stabilisation of the main channel and the riverbanks, river deepening...). At the time, the floodplain of the Sarine River is dominated by the forest categories, with an indeterminate status (in detriment to the pioneer and intermediate categories). The vegetation is less diverse and loses its alluvial character quickly.

Résumé

Cette recherche s'est déroulée dans un cadre interdisciplinaire, sous forme d'une collaboration au sein du Département de Génie Rural de l'Ecole Polytechnique Fédérale de Lausanne, entre les chaires de Pédologie et celle des SIRS (Systèmes d'Information à Référence Spatiale).

Dans le domaine de la Pédologie, ce travail s'inscrit dans l'axe de recherche ayant pour but l'analyse de la sensibilité des écosystèmes alluviaux aux changements naturels et anthropiques et plus particulièrement, la dynamique des sols alluviaux. En ce qui concerne les SIRS, cette recherche s'inscrit dans l'axe ayant pour but la méthodologie de développement concerté des SIRS pour différentes thématiques, et d'autre part, dans l'axe s'intéressant à l'intégration du temps dans les applications SIRS.

L'intérêt des zones alluviales réside dans le fait que ces écosystèmes possèdent une grande complexité et une importante diversité biologique qui dépasse généralement celle d'autres milieux tempérés, du fait de leur dynamique rapide. Cette dynamique, qui se déroule à une échelle humaine, permet des reconstitutions historiques fiables. Malgré leur grand intérêt écologique (haute diversité spécifique, interface terre-eau, régulateur des crues...), ces écosystèmes sont menacés de disparition en Europe, en raison de leur fort degré d'anthropisation.

Dans un but de conservation et protection, voire restauration, les sites alluviaux ont été recensés en Europe. Par la suite, la Suisse a été le premier pays à établir un inventaire de ses zones alluviales (0,25% de la surface du territoire) et à en réaliser la cartographie de la végétation. Enfin, depuis 1992, une Ordonnance fédérale réglemente la protection de 169 sites classés d'importance nationale et prévoit des mesures pour leur gestion.

La gestion prévue dans ce cadre législatif doit reposer sur des bases scientifiques fiables, qui sont à l'heure actuelle fragmentaires. La connaissance de la vitesse des transformations et des «patterns» de changement de la végétation, ainsi que de l'échelle spatio-temporelle la plus adéquate pour mettre en évidence les changements de ce milieu, sont encore mal connues. Les données sur ces sols peu nombreuses, surtout dans les cas des sols alluviaux développés sur des alluvions récentes. L'établissement d'un modèle capable de représenter dans l'espace et dans le temps, les entités et les changements d'état de ces milieux devient fondamental pour leur compréhension et leur gestion.

Cette recherche a ainsi poursuit un double objectif. Il s'agit d'une part d'améliorer la connaissance des milieux alluviaux sous impact humain et plus particulièrement sur la mise en place, l'évolution, la variabilité et la répartition spatiale des sols alluviaux. D'autre part, il s'agit de développer une méthodologie de conception des SIRS qui puisse intégrer l'information spatio-temporelle et les particularités de la recherche environnementale.

Pour atteindre ces objectifs, cette recherche a bénéficié d'une démarche intégrée, combinant une approche synchronique et une approche diachronique au sein d'une double démarche de recherche: une méthodologie d'investigation pédologique et une méthodologie de conception d'un SIRS spatio-temporel. Avec une telle démarche, nous avons pu replacer l'état actuel des sols dans la séquence des changements induite par la dynamique fluviatile et/ou les interventions humaines, afin d'expliquer leur mise en place, leur variabilité et leur répartition spatiale. Les apports de cette interdisciplinarité sont:

1) un cadre structurel utile aux pédologues pour aider la prospection scientifique, ainsi que pour identifier et exprimer les relations causales entre les événements et déboucher sur la modélisation conceptuelle des données et des traitements. De plus, ce cadre méthodologique offre les bases pour le choix des technologies S.I.R.S les plus pertinentes pour l'implantation du modèle;

2) un tel cadre applicatif permet aux experts en SIRS d'identifier de nouvelles structures et processus spatio-temporels qui doivent être pris en compte lors de la modélisation, d'autres particularités liées à la dynamique des écosystèmes alluviaux, et de préciser finalement certains éléments de cahier des charges pour les SIRS spatio-temporels.

La méthodologie pédologique a été basée à la fois sur une approche synchronique pour étudier l'état actuel des sols, et sur une approche diachronique pour effectuer l'historique du site. Pour cette dernière approche, le besoin d'utiliser les SIRS a été identifié. Pour mieux mettre en évidence la variabilité morphologique des sols, une approche cartographique par horizons et sa représentation en trois dimensions à l'aide des SIRS a été proposée. Cette approche paraît la mieux adaptée à l'étude des sols alluviaux, dont les processus de formation sont complexes (héritage et pédogenèse *in situ* s'intercalent dans l'espace et dans le temps).

Les complexités du milieu alluvial, avec son aspect dynamique et ses interactions en termes de processus de formation des sols, nous a orienté vers une utilisation des SIRS au-delà de ses performances en tant que logiciel. A l'image des démarches de conception des SIRS dans le contexte institutionnel, ce que nous avions besoin c'était une démarche de conception des SIRS capable de prendre en compte les complexités de la recherche environnementale et, de s'alimenter de son expertise, pour mieux comprendre les relations de cause et d'effet entre les activités humaines et l'environnement. La proposition d'une telle démarche est ainsi devenue un des points forts de notre travail.

La structuration du problème, l'identification des liens causals, et celle des données et des traitements ont été grandement facilitées par l'utilisation de la démarche SIRS. Cette démarche a aussi été indispensable pour la reconstitution historique du site et pour l'analyse des changements. Malgré l'incertitude traduite par des transitions non attendues, la méthode utilisée a permis l'identification des changements au cours d'une période de 62 ans, avec un intervalle de temps moyen de 12 ans. Ces changements ont pu être quantifiés et qualifiés. De plus, le «pattern» et la direction de ces changements ont pu aussi être décelés.

Cette recherche a aussi permis de répondre aux principales questions touchant la modélisation de données spatio-temporelles: «*what*, *where*, *when*» (quels changements, où et quand se sont-ils passés). De plus, nous avons réussi à mettre en évidence comment (*how*) ces changements se sont-ils passés (information sur la structure du paysage – fragmentation et qualité des changements). Enfin, en s'appuyant sur l'historique du site, nous avons pu émettre des hypothèses sur le pourquoi (*why*) de ces changements et de l'évolution de ce site.

Cette recherche a ainsi pu fournir des données et des connaissances utiles à la gestion et à la protection des zones alluviales, ainsi que prévu dans le cadre de l'Ordonnance. Plus particulièrement, par ce travail nous avons pu montrer que l'action anthropique (endiguements, correction du lit...) ainsi que les crues ont joué un rôle important sur la mise en place et l'évolution des sols et de la végétation. La zone alluviale de la Sarine s'est asséchée (stabilisation du canal principal et des rives, enfoncement du lit...). Elle est à présent, dominée par la végétation à bois dur, à caractère indéterminé, et cela au détriment de la végétation pionnière et intermédiaire. La couverture végétale est moins diversifiée et perd son caractère alluvial rapidement.

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General Introduction

I.1 The research framework

Alluvial zones[1] have a heterogeneous and complex functioning (Naiman and Décamps, 1990). The heterogeneity of alluvial zones is linked to a rapid dynamic and to the coexistence of allogenic (erosion, transportation and sedimentation) and autogenic (linked to ecological successions) processes, that produces a large biological diversity, which is generally superior to that of other environments in the Temperate Zone. The interest of alluvial ecosystems can be summarised as follows (Imboden, 1976; Yon, 1984; Pautou, 1984; Naïman and Decamps, 1997):

- A high specific diversity that constitutes an exceptional genetic inheritance. For example, the alluvial zones in Switzerland that represents only 0,25% of the territory accommodate more than 1200 vegetal species, which corresponds to 40% of the 3000 reported in Switzerland;
- Alluvial zones exert a capital role on watercourses because they act as a land-water interface. In addition to their function as flood regulators, they have a role of organic matter supplier to the aquatic environment, as well as a ground water purifier and as a pool of mineral elements;
- Moreover, alluvial ecosystems have an intrinsic inestimable value as an example of a natural environment, where the vegetation was formed at the end of the Tertiary. Finally, such an ecosystem also has an aesthetic value. Economic numbers cannot express these values.

Despite their ecological importance, these ecosystems are among the most threatened in Europe because of their high degree of man-induced alteration. To ensure the safeguard of these areas, the European Council (Conseil de L'Europe, 1982) asked its member states to make an inventory of their alluvial zones, with the goal of conservation, protection and even restoration.

Following this request, Switzerland was the first country to establish an inventory of its alluvial zones (Kuhn and Amiet, 1988) and to map them (Gallandat *et al.*, 1993). Since 1992 a Federal Edict has regulated the protection of the alluvial sites considered to be of national importance (Conseil Fédéral Suisse, 1992). The Edict's aim is "the conservation, and the development of the native fauna and the flora, as well as the essential ecological elements to their existence and conservation and, as far as it could be judicious and feasible, the re-establishment of the natural dynamic of water regime and carriage". This Edict also makes provisions for constraint measures to be employed in case of attacks to the entirety of such ecosystems.

1 Alluvial zones are defined as places alongside the torrents, the rivers and the lakes, that are periodically or episodically flooded. In such an environment, the plants roots are temporally reached by strongly fluctuating ground water (Kuhn and Amiet, 1988).

These assessments put in evidence that nearly all of the 169 reported important alluvial sites are under heavy pressure from human activities. According to Gallandat *et al.*, (1993), the most frequently observed attacks on the entirety of the sites are essentially embankments (59% of the sites), followed by tourism (43%), plantations (39%), waterway rectification (38%) and miscellaneous deposits (15-25%). Furthermore, changes in the hydrodynamic regime following hydraulic improvements (embankments and waterway rectification) have modified the evolution dynamics of these ecosystems and lead to changes in soil and vegetation (Gallandat *et al.*, 1993).

For the moment, if the dynamic of the alluvial vegetation has been studied at the European level (Pautou, 1983; Bravard *et al.*, 1986; Pautou and Girel, 1994; Yon and Tendron, 1981; Malanson, 1993) and at the Swiss level (Gallandat *et al.*, 1993; Roulier, 1997), only few works are focused on alluvial soils.

In fact, there are few studies concerning the evolution of young soils. The existing works (Bornand, 1978; Gerrard, 1987; Gury, 1990; Miedema, 1992) treat essentially alluvial soils that have been submitted to a long time *pedogenesis*, essentially upon Quaternary terraces. Nevertheless, only a few studies concern the formation and evolution of young soils from the sediment's colonisation (Nanson and Beach, 1977; Bureau *et al.*, 1994; Bureau, 1995) and their evolution after human impacts (Mendonça Santos, 1995; Bureau *et al.*, 1995).

The management suggested in the Federal Edict must be based on rigorous scientific knowledge about such ecosystems. In the research context, the comprehension of the evolution of such ecosystem requires a global approach, which identifies entities and processes in space and time.

The current state and the historic evolution of vegetation and soil, the direction and patterns of changes, as well as the most adequate scale to bring out the spatio-temporal changes in this environment are still questions without answers. The establishment of a model capable of representing entities and phenomena in both space and time is thus a priority of research. Consequently, the use of a GIS that includes the temporal dimension seems to be an indispensable step towards the structuring and representation of the problem, as well as it will allow for the analysis of the dynamic components of such an ecosystem.

Nevertheless, current capabilities of GIS are not completely suited to a descriptive and historical representation, and management of spatial data evolution. This inability to consider the time dimension within current GIS models has been outlined by several authors (Langran, 1992; Peuquet, 1994). Particularly, the integration of time within non-spatial models is still considered a complex objective. Current approaches do not allow reproduction of all temporal situations nor explicit understanding of the nature and type of changes that occur (Beller, 1991).

Moreover, the successful development of GIS within environmental sciences requires the identification of spatio-temporal models that offer support for understanding natural or man-induced phenomena (Openshaw, 1994; Yuan, 1994; Peuquet and Duan, 1995; Claramunt and Thériault, 1995; Claramunt and Thériault, 1996). For instance, the monitoring of environmental changes requires a temporal information system that can support spatial and temporal queries and analysis. Additionally, such a temporal GIS may supply relevant spatio-temporal data to specialised modelling and simulation studies. A temporal GIS provides, through analysis of temporal data, a step forward in studying causal relations between processes and the interpretation of change patterns, because causal links are implicit in the principle of temporality. Change pattern can be, in fact, a consequence of causal relationships between successive states of events (Allen *et al.*, 1995).

The management of natural resources involves the understanding of environmental processes, related cause-and-effect interrelationships and change patterns over time. In this way, the spatio-temporal domain is considered one of the most important research directions of the GIS scientific community (NCGIA 94-9, 1994). Research proposals deal largely with formalising spatio-temporal models on the basis of discrete or matrix spatial structures (Langran, 1992; Peuquet and Duan, 1995). Current models are based on extensions of cartographic representations of space models (Langran, 1992; Workboys, 1994) or on a paradigm that distinguishes between the thematic, the spatial and the temporal dimensions of real-world systems (what, where, when) (Peuquet, 1994).

Recent progress in the representation of time within GISs offer different solutions to scientific and planning studies oriented toward the incremental representation of dynamic entities in space (Cheylan and Lardon, 1993; Workboys, 1994; Peuquet and Duan, 1995; Claramunt and Theriault, 1995, Hornsby and Egenhofer, 1997). Nevertheless, problems remain concerning the implementation of dynamic entities into commercial software.

I.2 The research aim

This research has both a fundamental and an applied nature, and pursues a double aim as well:

- On the one hand, it is a matter of improving our knowledge about alluvial ecosystems and particularly about the formation, evolution, and present-day variability and spatial distribution of alluvial soils, as well as their relationships to land cover changes through time;
- On the other hand, the focus is done in the design of a GIS methodology that should be able to integrate the time dimension and other particularities of the environmental research, such as causal links and spatio-temporal processes.

This research relies on an integrated approach that combines a pedological methodology with the structuring and modelling of spatio-temporal data and processes within a GIS methodology. This kind of research is a first step towards acquiring fundamental knowledge of alluvial ecosystem evolution and a model for the integration of spatial-temporal environmental information towards ecosystem management perspective (within the scope of the Federal Edict).

I.3 The application context and the methodological approach

Our applied study focuses on the evolution of alluvial soils and vegetation in the embanked floodplain of Sarine River (Fribourg State) in Switzerland. This type of ecosystem is interesting from the application point of view because of its relatively rapid dynamics (on the order of several hundred years), which enables the realisation of a reliable historical reconstruction. More generally, this study involves the analysis and representation of spatio-temporal phenomena, in order to provide a better understanding of the evolution of alluvial soils and vegetation.

The scheme illustrated by the Figure I.1 summarises the application context of this research and the methodological approaches undertaken. The present-day state of this site expresses the fluvial dynamics through time. After the beginning of this century, anthropic action (embankments, waterway rectification...) has joined fluvial dynamics and modified this environment. Change repercussion has affected the vegetation and the soil evolution in different ways.

The complexities of this environment became apparent after the first field surveys: an important variability of alluvial soils under simplified vegetation was detected. Moreover, it was impossible to explain this variability and their spatial distribution as well as the evolution degree of these soils. Several questions have emerged: How to explain the large variability of soils in space? What scales to adopt in this study? What is the relationship between soil and vegetation?

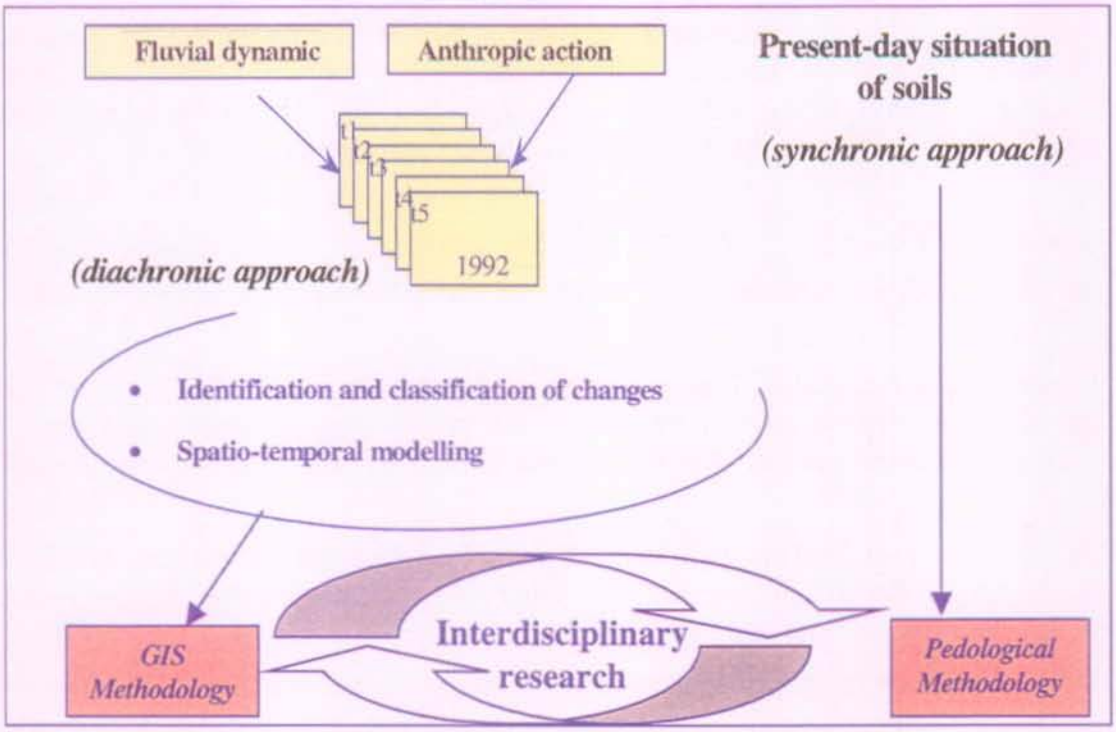

Figure I.1 – The scheme of the application context and the methodological approach

These questions have driven our attention to the need of combining synchronic and diachronic approaches. With the synchronic approach the study of the present-day situation of vegetation and soil (morphologic criterion of soil evolution) was done into the Pedological methodology, while the diachronic approach will enable us to identify landscape changes through time, by using GIS technology. The aim of such an integrated approach being to study the present-day situation of soils in relationship with the sequence of natural and/or man-induced changes.

The complex context of this site (fluvial dynamic and anthropic action influencing the present-day situation), with its dynamic aspect, its relations and interactions, has lead us to use GIS in a larger sense than a software for the spatial representation. In fact such a context requires a GIS methodology that should be able to integrate the particularities of the environmental research and get information from its expertise, in order to better understanding the cause and effect relationships between the human activities and the environment. The proposition of such a GIS design methodology applied to environmental research approach has become the second aim in this work.

Once the application was well established (following the Pedological Methodology), the design of the GIS Methodology was undertaken. Such a methodology constituted a basis for the scientific reasoning ("thinking tool") and problem structuring in a rigorous and holistic way.

By following such an integrated approach, the causal links between events were identified and formalised in a cyclic way. The expression of causal links constituted a cognitive support for the modelling of the static and dynamic properties of the system. This has also permitted the identification of the most adequate scales to study the problem, as well as facilitated the identification of attributes and relations between data for the modelling of the problem. Furthermore, it will facilitate communication between experts from different domains.

In this work, different scales of space and time were considered. Land cover changes study for example, was performed in a regional scale (the study site) whereas soil study was performed in a local and detailed scale. Concerning the temporal scale, land cover changes were studied in time span of 62 years with an average time step of 12 years, according to the alluvial vegetation characteristics.

For the representation of environmental changes, our objective was to identify and quantify changes, as well as to identify the pattern and direction of changes and the spatio-temporal processes underlying changes. Such a study constitutes a thematic reference for the comprehension and explanation of alluvial ecosystem evolution and gives new insights for the modelling of spatio-temporal phenomena.

Finally, this work has the challenge of combining methods and expertise of two different disciplines of knowledge, which was not always an easy task: different expectations from each side, terminology specific from each discipline, and above all, the remarkable differences at the methodological approach level and what it signify for each discipline. This is principally an experimental approach for the Pedology and a non-experimental one, close to that of social sciences, for the GIS. Despite such limitations, the integration of the Pedological and GIS methodologies has permitted a better understanding of the problem and gave the means for its modelling and analysis.

I.4 The thesis' layout

This thesis was written in the scientific paper format, each chapter being a complete and individual part, composed by an abstract, a brief introduction to the subject, the results and conclusion, and the corresponding bibliographic references. Moreover, their eventual relations with other chapters were also indicated in the end of their conclusion. Some chapters are published in or submitted to international scientific journals (cf. footnote indications) and for this reason, some redundancy (e.g. the site description could be found several times) or sometimes discontinuity (e.g. chapter 6 is the logic sequel of chapter 2) can be found. The thesis is organised in three principal parts, each one containing several chapters: Part I: Methodological approach, for Pedology and GIS; Part II: Pedological results, and Part III, Spatio-temporal Modelling. In this part, a GIS design methodology is proposed in order to integrated complexities of environmental research. Furthermore it is applied to the pedological application and several results of the integration GIS-Pedology are also presented.

Figure I.2 illustrates the layout of this thesis. After the General Introduction, the first part (Part I) will present the Material and Methods of Pedological and GIS domains. Pedological Methodology (Chapter 1) reports the choice of the study site, its general characteristics and historic evolution. Furthermore, a specific methodological approach to study soil is developed, in order to understand its present-day state, spatial distribution and evolution. Chapter 2 addresses a brief state of art of GIS use and expresses the need of a GIS design methodology for support environmental research.

In Part II, results concerning soils are presented and discussed. These chapters (3, 4 and 5) correspond to the first aim of this thesis, which is focused on improving our knowledge about the formation, evolution and present-day variability, and spatial distribution of soil and vegetation. More specifically, Chapter 3 gives the present-day condition of soil of the whole site, as determined by a general soil survey. In this chapter, soils are grouped by clustering analysis and analysed using PCO (Principal Co-ordinates analysis). The principal morphological types of FLUVIOSOLS found in our study site are described and analysed with regards to the site history and their distribution in space. Chapter 4 evaluates the impact of embanking on the soil and vegetation evolution in the embanked stretch. Chapter 5 gives information about the spatial distribution of soils based upon the notion of soil horizons, in two-and three-dimensions, for a sub-site of the embanked stretch. From a GIS point of view the development of these chapters correspond to the data acquisition process, while for the pedological perspective, these chapters bring the basis for the knowledge of alluvial soils, its characteristics, variability and spatial distribution into the scope of the studied site.

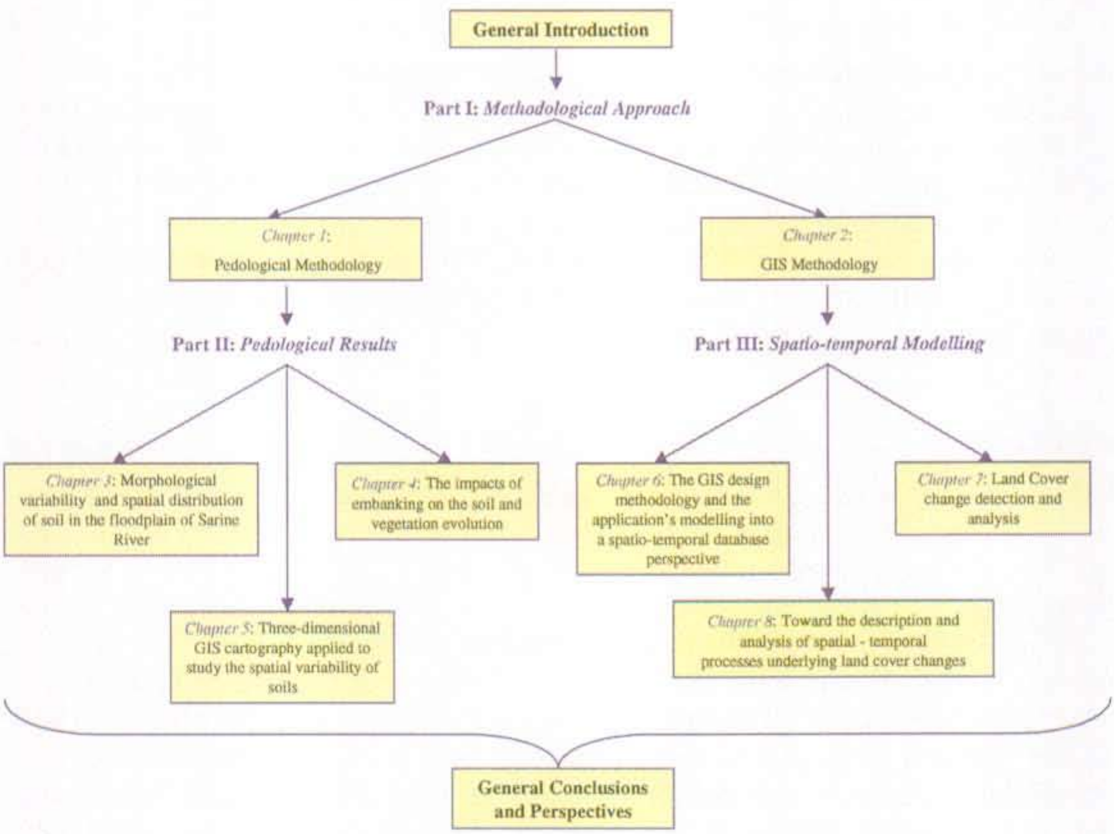

Figure I.2 –The thesis's layout

Results concerning GIS in a specific or general way are presented in Part III. In Chapter 6, a GIS design methodology able to integrate the complexities of environmental research was proposed, with regards to the needs expressed in Chapter 2. Then, the application is modelled following the phases stated in the GIS methodology, towards a spatio-temporal GIS perspective. Furthermore, the interactions between the GIS and the pedological methodologies are briefly evaluated and a GIS specifications are addressed. Chapters 7 and 8 can be viewed as the result of the integration proposed in the GIS methodology. The results of these chapters interest both, Pedology and GIS disciplines. More precisely, in Chapter 7 Land Cover changes are identified, quantified and analysed through time. Furthermore, change quality, direction and pattern of change are determined, in order to answer the triad framework: what, where, when (Peuquet, 1994) and its extensions: how and why (Claramunt and Thériault, 1996). In Chapter 8 the identification of spatio-temporal processes subjacent to changes and their formalisation are undertaken. Such processes were related to the site history in order to help in the explanation of how and why changes occur. Finally, conclusions are drawn and the implications for future research are outlined.

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Part I: Methodological Approach

Chapter One

Pedological Methodology

Abstract

In this chapter, the general characteristics of the study site were stated and a Pedological methodology was developed. This methodology was based on a diachronic approach (historic reconstitution of the study site) and on a synchronic approach (present-day state of soil and vegetation). The aim of this methodology was to focus on the understanding of the present-day state of soils, its morphological variability and spatial distribution. First of all, a general soil survey was undertaken in order to characterise soils. Furthermore, a multivariable statistic technique was undertaken to calculate similarities between the soils. A soil typology was proposed and discussed with regards to the degree of soil evolution. A soil profile representative of the principal typological groups of soils was described and analysed. Finally, two other soil surveys were undertaken, with the goal of: a) to study the impact of embanking on the soil-vegetation relationships; and b) to produces a three-dimensional cartography of soil by horizons, which illustrates the variability and spatial distribution of FLUVIOSOLS in the Sarine River's floodplain.

1.1 Introduction

Soil is defined as "the space-time continuum forming the upper part of the earth's crust" (FitzPatrick, 1986). Mineral and organic materials, in solid, liquid or gaseous forms together form soils. Dokuchaev, a pioneer Russian pedologist established in the 19th century that soils develop as a result of the interaction of five factors: parent material, organisms, topography, vegetation and time. The first four are environmental factors, which interacts through time to create a number of specific processes leading to horizon[2] differentiation and soil formation. The combinations of these factors give several soil types. Many taxonomic classifications were developed in several countries, in order to organise and structure soil knowledge and accommodate local soil variability. Nevertheless, independently of the chosen classification, soils must be studied within a framework of three data types (A.F.E.S., 1995):

- those referring to their constitution (texture, chemical and mineralogical composition...);
- those concerning their structural organisation (variability, spatial distribution...);
- those associated with their dynamics, behaviour, and development.

In the context of our study, the "Référentiel Pédologique" (A.F.E.S., 1995) was chosen as the soil reference system and following this reference, the soil type of our study site is FLUVIOSOLS (or alluvial soils). Alluvial soils are generally associated with river floodplains, but because the complexity of their formation processes, a satisfactory definition is not easily found (Gerrard, 1992). The "Référentiel Pédologique" (A.F.E.S., 1995) distinguishes the FLUVIOSOLS from other weakly developed soils for three main reasons, that can be summarised as follows:

2 Soil Horizon is defined as a layer of soil or soil material approximately parallel to the land surface and differing from adjacent genetically related layers in physical, chemical, and biological properties or characteristics (America, 1997).

- they are always found in a low position in the landscape;
- they are developed from recent material, river *alluvium* that has been transported and deposited by water. The quality of the river *alluvium* depends of the diversity of soil and geological materials upstream;
- they are characterised by the presence of a permanent or periodic groundwater with marked fluctuations and they are flooded during the wet seasons.

Furthermore, new deposition of alluvium is possible during heavy floods and buried horizons may occur in this kind of soil. Finally, these soils have a little or no *pedogenesis*. In fact, alluvial soils exhibit characteristics of both, sediment transport and deposition, and soil formation that overlap in space and time. Sediment stratification is common in such an environment and influences the development of pedogenic properties (Gerrard, 1987).

Due to the complex nature of the FLUVIOSOLS formation processes, inheritance and *in situ* formation processes, these soils could be very heterogeneous and hard to classify (Finkl, 1980; A.F.E.S., 1995; Gerrard, 1987). Moreover, only few studies focus on these soils (Nanson and Beach, 1977; Bureau, 1995).

This chapter presents the study site, its general characteristics and historic evolution, as well as the developing of a Pedological Methodology for distinguishing the present-day state of the soils, its morphological variability and spatial distribution. It was based on a diachronic approach (historic reconstitution of the study site) and on a synchronic approach (present-day state of soil and vegetation), in order to approach the complexity of the alluvial environment.

1.2 Choice and characterisation of the study site

The site "Les Auges de Neirivue" was chosen due to the characteristics of its human altered alluvial site, where the alluvial character of the vegetation is changing (Gallandat *et al.*, 1993). Furthermore, the availability of data and the easy access make this site a particularly good one for our research. Finally, the fact that this site presents an embanked zone and an active one within the same regional conditions could be important for drawing comparisons.

1.2.1 Geographic location

The study site "Les Auges de Neirivue" called object number 66 by Kuhn and Amiet (1988) is located in the State of Fribourg, between the dam of Lessoc and the bridge of Grandvillard (Figure 1.1), in the medium course of the Sarine River and its floodplain. It is about 750m above sea level and the surface delimited by Kuhn and Amiet (1988) is about 78 ha. Nevertheless, a surface of 96 ha was considered for the change detection analyses (Chapter 7).

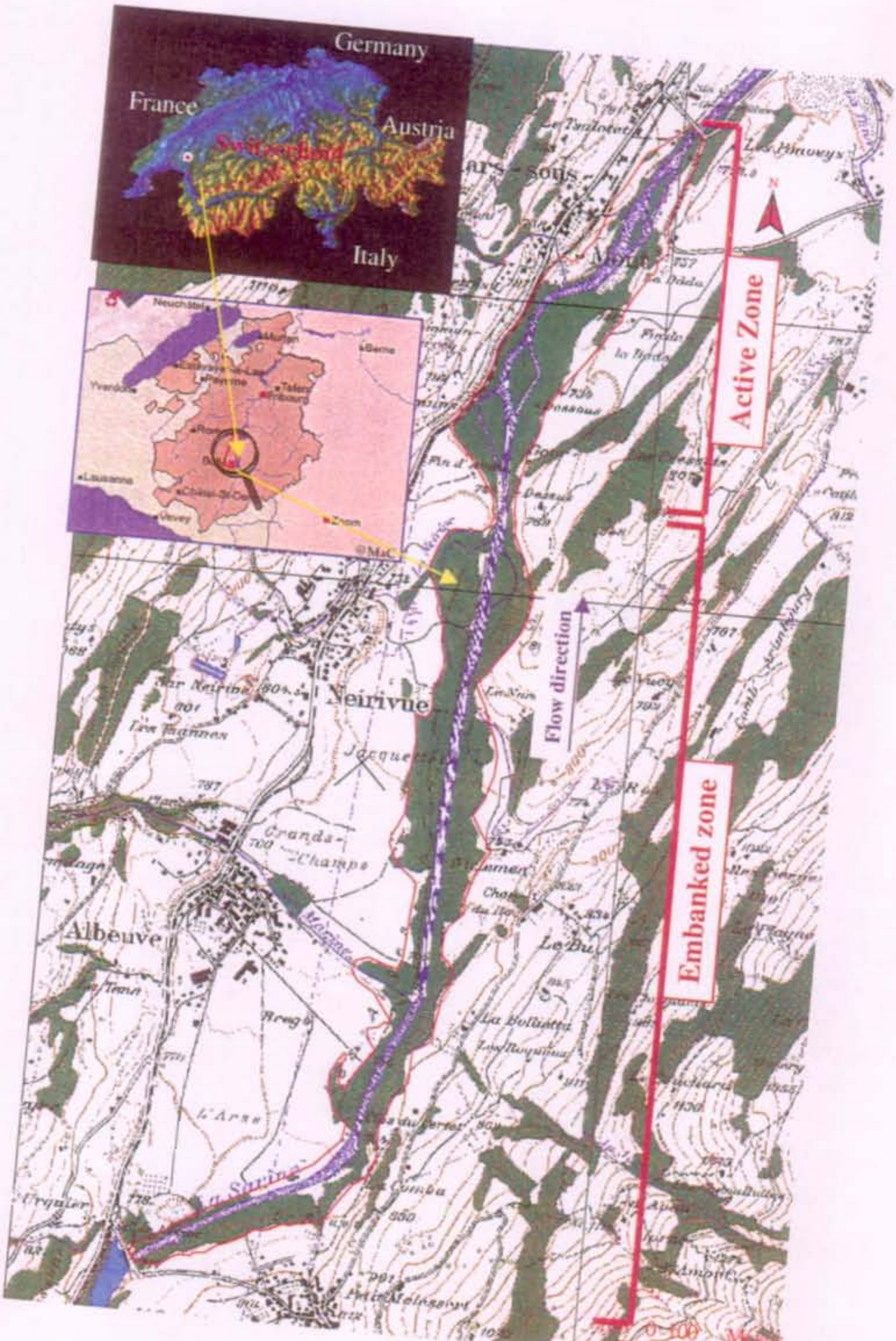

Figure 1.1 – The study site location (The base map is a property of the Office Fédéral de Topographie, Suisse, CP25/100).

1.2.2 Climate

According to the meteorological data from the Broc station (located near the study site), the climate is prealpine with an average annual precipitation of 1200 mm (maximum of 392mm and minimum of 228 mm) and an average annual temperature of 7,1 °C (with a minimum of -2,1 °C at January and a maximum of 16,5 °C at July) (Fallot, 1991).

1.2.3 Geology

The source of the Sarine River is located at the Sanetch glacier, a region constituted by calcareous and marl rocks. Following its course, the Sarine River crosses a region constituted of a conglomerate of sandstone and schist, with some layers of fine calcareous (Gétaz, 1977). As a consequence, the alluvial gravel (D layer) of the study site is constituted essentially of calcareous pebbles.

1.2.4 Geomorphology

The study site is characterised by a succession of alluvial basins separated by rocky constrictions. The bed of the Sarine River is composed of coarse calcareous pebbles ranging from 10 to 30 cm of diameter. The average slope is 0,64‰ (Gétaz, 1977).

1.2.5 Vegetation

The Figure 1.2 (modified from Gallandat *et al.*, 1993), shows the principal types of vegetation of the study site (this vegetation map was digitised and integrated into our database, which script is shown in Appendix 1.1. As could be observed, the embanked zone is dominated by vegetation type number 6 (other alluvial forest with an indeterminate status) in the left side of the river and vegetation type 7 (non-alluvial forest) in the right side. The active zone still shows vegetation that is typically alluvial. Concerning the vegetation type number 6, the "indeterminate status" is expressed by a mixture of some typically alluvial species and some species of the regional climax (Gallandat *et al.*, 1993). For more details concerning the sub-unites that compose each vegetation type, as well as the flora composition of each unity see Gallandat *et al.*, (1993). The legend of Figure 1.2 summarises the other vegetation types that could be found in the study site.

1.2.6 Hydrology

From its source, the Sarine River follows a 78,9 Km course, draining a watershed of 639 Km^2 (measured at Broc, after the confluence of the Trême). The Sarine River is the principal river for the Fribourg State (Gétaz, 1977; Noël and Fasel, 1985). Its annual average flow rate was 23,7 m^3/s (average of 60 years), with a maximum flow rate of 43,8 m^3/s in Mai and a minimum flow rate of 12,4 m^3/s in January. The highest peak flow (480 m^3/s) was observed in September of 1940. According to the classification of Arrigon, (1976) the flow speed is quick (50 to 70 cm/s). After the construction of the dam of Lessoc, the flow speed was modified in a range from 3-5 m^3/s (endowment flow) to 41 m^3/s (maximal restitution flow). The historic profiles of the Sarine River could be see in Bureau, (1995).

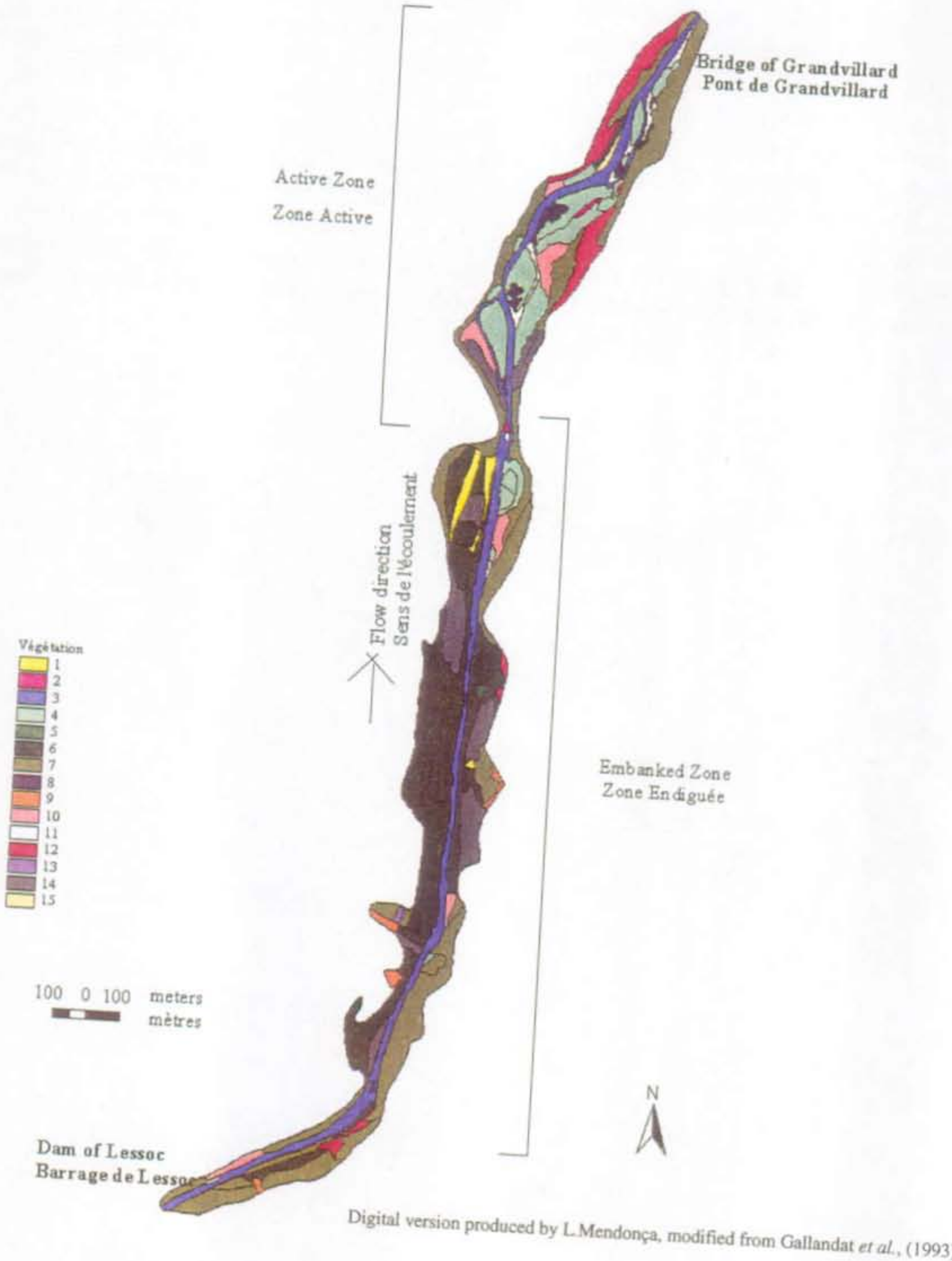

Figure 1.2 – Simplified Vegetation Map. Legend: 1) Other herbaceous communities; 2) fen land; 3) water; 4) Alder (*Alnus incana*) forests; 5) Ash (*Fraxinus excelsior*) forests on coarse deposits; 6) other alluvial forests with an indeterminate status; 7) non alluvial forests; 8) Willow (*Salix sp*) shrubs typical of high altitude; 9) rich grassland; 10) riparian forests; 11) bared deposits; 12) constructions; 13) cutting or planting in alluvial zone; 14) cutting or planting in non alluvial zone; 15) pioneer herbaceous vegetation typical of high altitude.

1.2.7 Historic evolution

According to Gétaz, (1977), the Sarine River is fast-flowing, even torrential, which for long time has caused worry for the local population, because of its extraordinary floods that have destroyed roads, habitations and agricultural fields. The importance of the damages was so important that the Fribourg State instituted in 1852 a law regulating the drying of the swamps, the rivers rectifying and the construction of embankments. Nevertheless, the systematic works concerning the hydraulic installations were started only in 1885 with the financial support of the Swiss Confederation. With regards to the embanking and the river rectifying works in the floodplain of Sarine River, even if they were presented to the Federal Council, in the Culman rapport of 1865, these works were systematically constructed only between 1910 and 1920. Figure 1.3 shows an extract of the Embanking map. The Swiss Confederation, the Fribourg State and the local communities all finally supported them at that time.

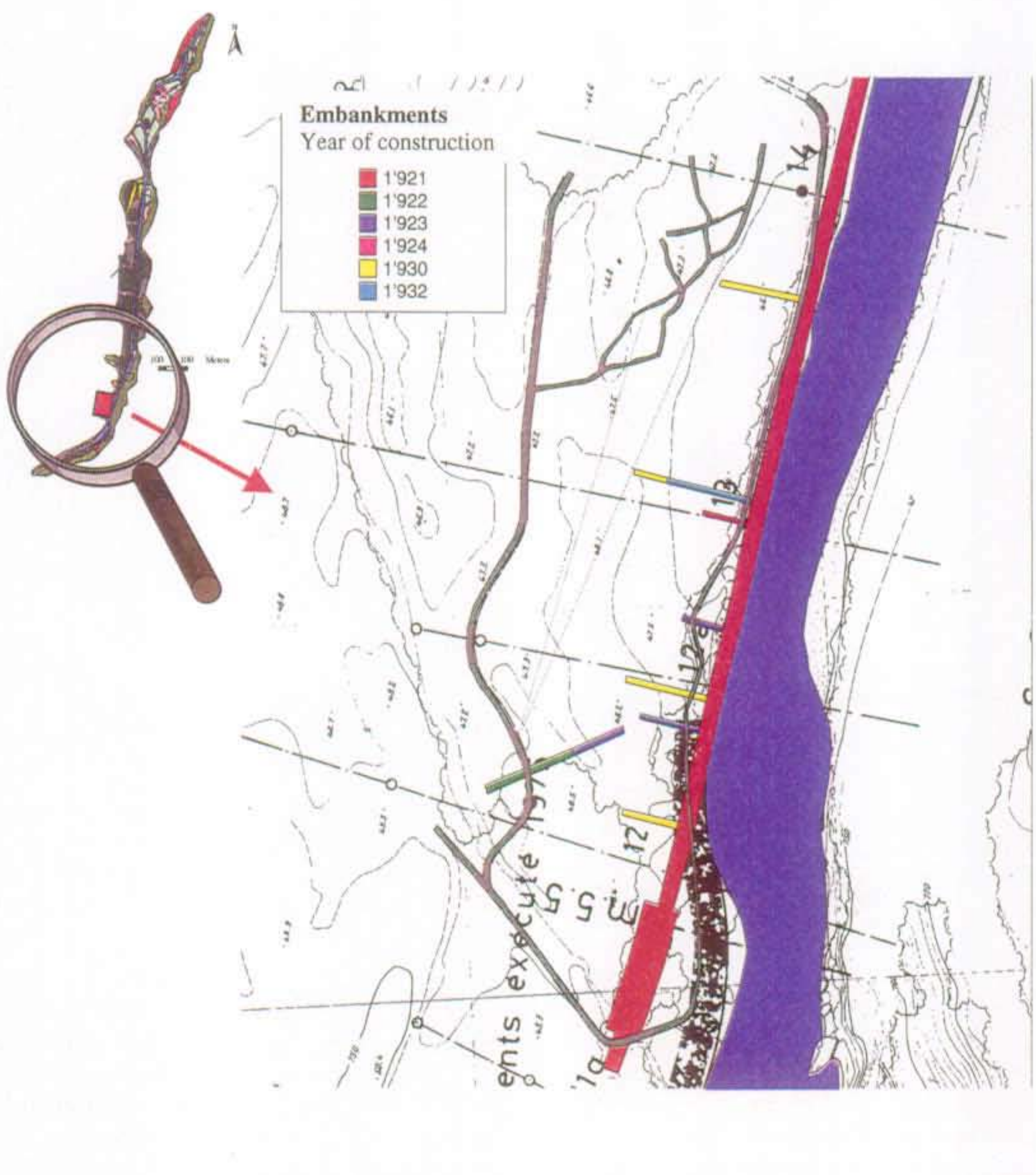

Figure 1.3 – Extract of the Embanking Plan of the Sarine River's floodplain (digitized by A. Jotterand)

The dikes were made up of metallic nets filled with stones and placed crosswise and in the lengthwise in the river. These constructions have gradually permitted the modification of the river geography, which has finally lost its braided character and has become straight and rectilinear. However, violent floods (July and September of 1968, 1970 and other) (Bureau, 1995) time and again drastically shattered these works. They were redone many times (Gétaz, 1977) and presently they are not yet finished and their cost is augmenting. Furthermore, hydroelectric installations (the dams of Rossinière and Lessoc) have been constructed upstream. These works were done with the aim of controlling the flows of water and material. For this reason, the riverbed has lowered by many meters and its course has been rectified, becoming a riverbed of 30 to 45m of width (Gétaz, 1977, Bureau *et al.*, 1994). Consequently, the eroding strength of the river course has augmented and this has caused a deficit of carriage. With less material to transport, the watercourse has more energy and could dig out and remove the materials of their own bed. It is the situation at the moment.

1.3 The methodological approach

To understand the present-day state of the soil, its variability, spatial distribution and evolution in the floodplain of Sarine River, a pedological research methodology based on the historic reconstruction of the site (diachronic approach) and on the present-day soil state (synchronic approach) was undertaken. Concerning the diachronic approach, change in space and time will be considered and compared with other historic data, like embanking plans, in order to better understand the formation, evolution and present-day situation of soil.

1.3.1 Diachronic approach

This approach considers the present-day situation of the study site with regards to their history. Following this approach, the present spatial distribution of soils, their variability and degree of evolution will be explained by the historic change in space and time. The following documents were used directly or indirectly to study changes in the floodplain of the Sarine River:

A set of black and white aerial photographs for the years 1930, 1943, 1955, 1969, 1980 and 1992. From aerial photographs land cover maps were derived for each corresponding year by photo-interpretation. A first methodological publication comparing the traditional approach (photo-interpretation and hand-made maps) and the computer-aided photo-interpretation and GIS integration approach was realised at the beginner of this study (Mendonça Santos *et al.*, 1997b) and is presented in Appendix 1.2.

Based on land cover maps, spatio-temporal change analysis was performed for each pair of dates. Land cover spatio-temporal change analysis was performed with a Geographic information System (GIS) producing *cross-classification maps* (transition or change maps) that show changes from one class to another, and *cross-tabulation matrix* (that show the transitions among all the classes in % of area). Afterwards, some patterns indices as well as change indices were calculated. These procedures as well as the corresponding results and interpretations are presented in Chapter 7.

1.3.2 Synchronic approach

Using this approach, detectable differences in the present-day soils are studied by the identification of pedological parameters, which could indicate some evolution of the soil (morphological and physico-chemical parameters) and placed with regards to the site history. The functional aspect (as treated by Bureau, 1995) is out of the aim of this thesis.

1.3.2.1 Choice of the morphological parameters to describe soils

As previously defined, FLUVIOSOLS are young soils, developed from recent material that has been transported and deposited by water (A.F.E.S., 1995), therefore, with little *pedogenesis*. In this study site, they seem to be very heterogeneous in particle-size distribution and morphological characteristics. In order to ascertain and characterise the soil processes formation and evolution, some pedological criteria were proposed. The parameters described (Appendix 1.3) concern the surface horizon, the horizon just after the surface horizon or the *solum* as a whole and have two different natures:

- criteria relative to the soil inheritance process (*alluvium* deposition in this case): depth, texture, CaO_3 content and quantity of textural horizon.
- criteria related to the *in situ* soil evolution process: organic matter (O.M.) content, thickness and structure characteristics of the surface horizon.

Nevertheless, due to the fact that *pedogenesis* and inheritance coexists in these soils, the nature of certain criteria (or parameters) is not always clear (for instance, CaO_3 content and texture).

1.3.2.2 Soil Survey Approach

To understand the variability and the spatial distribution of soils, different levels of investigation were undertaken: a general survey to characterise soil for the whole site; a survey on the embanked stretch to study the impact of embanking on the soil and vegetation evolution and a survey at a small sub-site of the embanked stretch, to construct a three-dimensional cartographic modelling. The particularities of each soil survey will be presented later. In a general way, soil sampling was done by a core sampling drill (for the soil structure evaluation, a shovel was employed) in a systematic way (every 5 meters) along transversal transects, perpendicular to the river channel.

The choice of surveying soil by transversal transects was based in complexity of FLUVIOSOLS formation (overlapping of inheritance and in situ evolution processes), previously discussed. The choice of transects location was done based on the historic documents. They correspond to places where the river channel has changed through time or, in contrast, has remained stable. With this approach, we hope to intersect the two conditions of the soil formation process, as well as differences in the local topography and geomorphologic conditions.

The co-ordinates of each soil survey point were determined by a GPS (Global Positioning System. Data concerning all aspects of the soil survey was captured in an Excel table format and included in our database. More precision about each soil survey are given as follows:

- The first survey, a general soil survey concerning the whole site, was done in order to ascertain the pedological variability of the studied floodplain. A population of 277 soils was studied. Distinctions should be done between the soils that are the most developed and stable, the youngest soils (frequently changed by sediments deposition) and the intermediate soils. The results concerning this exploratory data are presented and discussed in Chapter 3. Figure 1.4 illustrates the transects location of the general soil survey (in red), 4 transects in the embanked stretch and 8 transects in the active stretch.

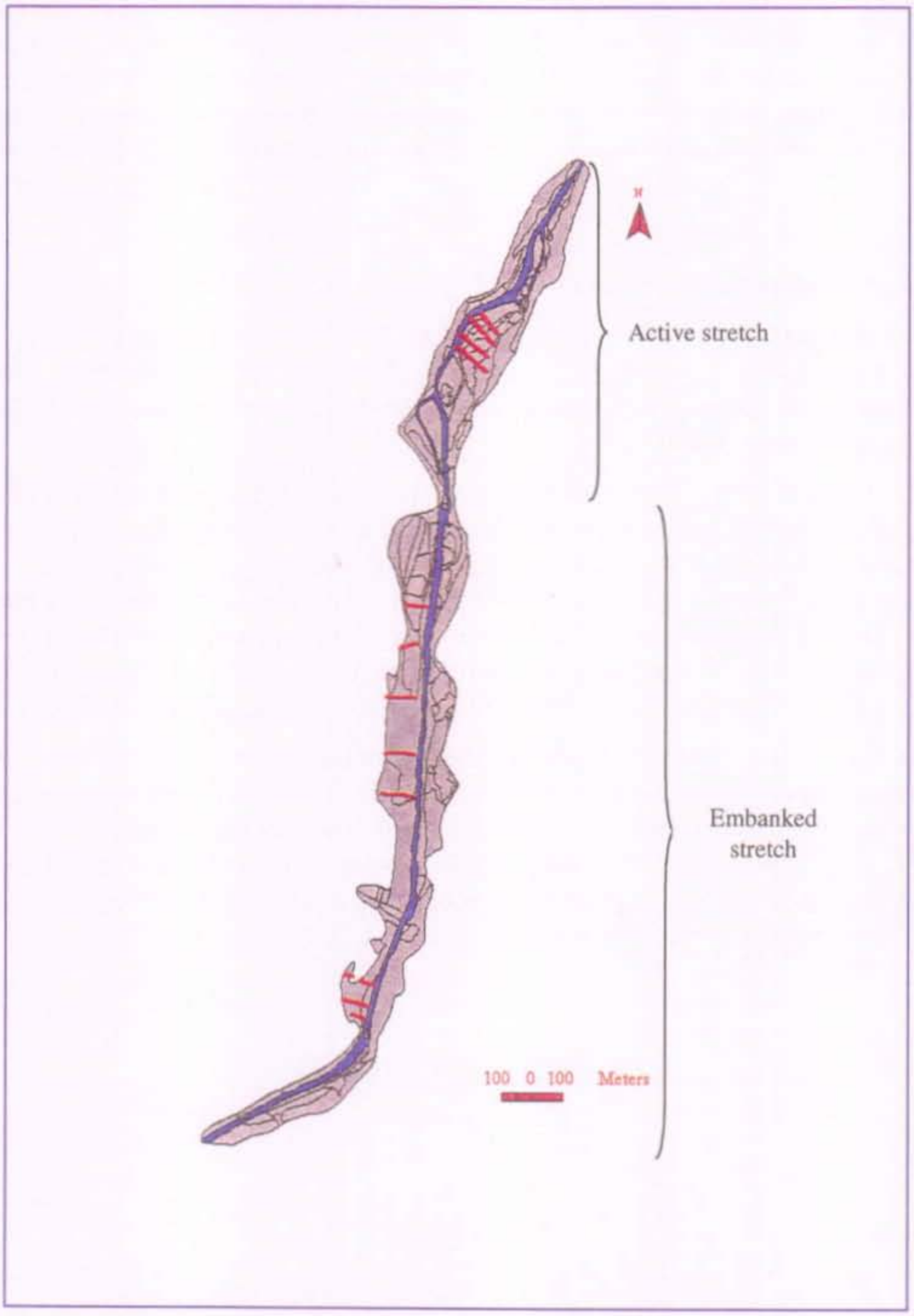

Figure 1.4 – The transects location of the general soil survey (in red; the Sarine river, in blue).

- In addition to the eight transects of the embanked stretch, other soil points were surveyed away from transects, but in the embanked zone (population = 303 soils), in order to study the impact of the embanking and the interrelationship between the two, soil and vegetation. The results have been the basis of a scientific publication (Mendonça Santos *et al.*, 1997a) that will be presented in details in Chapter 4.
- Finally, a small sub-site of the embanked stretch was more finely surveyed in a regular grid of 5m in EW direction and 10 m in SN direction (population = 181 soils). The aim of this detailed survey was the implementation of the three-dimensional soil cartography of these soils, based on their horizons. This approach seems to be the most adequate for representing the variability and spatial distribution of soils in such environment. The results, methodology and discussion of such an approach have been made the object of a scientific communication (Mendonça Santos *et al.*, submitted) and will be presented in Chapter 5.

1.3.2.3 Variability and spatial distribution of soils

Due to the complex nature of alluvial soils and the difficulty to describe and classify them, (described by many parameters of different nature at the same time) multivariable statistics analyses are strongly recommended (Legendre and Legendre, 1984a; Legendre and Legendre, 1984b; Webster and Oliver, 1990).

To perform the multivariable analyses and particularly to calculate similarity between soils, the Progiciel – R software (Legendre and Vaudor, 1991) was employed. First of all, soil data (from the general survey and from the embanked stretch, separately) were coded in order to generate the input file for these analyses (Appendix 1.4). Afterwards, the similarity between soils was calculated by the Gower's coefficient, an association symmetric coefficient (Gower, 1971). This coefficient was chosen because it permits the combination of quantitative, semi-quantitative, binary and even qualitative data (soil descriptors or parameters, in this case).

Moreover, the use of this coefficient permits the attribution of different weights for the parameters that are assumed to have a more important contribution to the studied phenomena. The output file is a similarity matrix that could be transformed into a distance matrix. From this matrix, the two following multivariable analyses were done: a) the clustering analysis (hierarchical grouping) and, b) the principal co-ordinates analysis (ordination). Figure 1.5 summarises all the steps for performing the multivariate analyses.

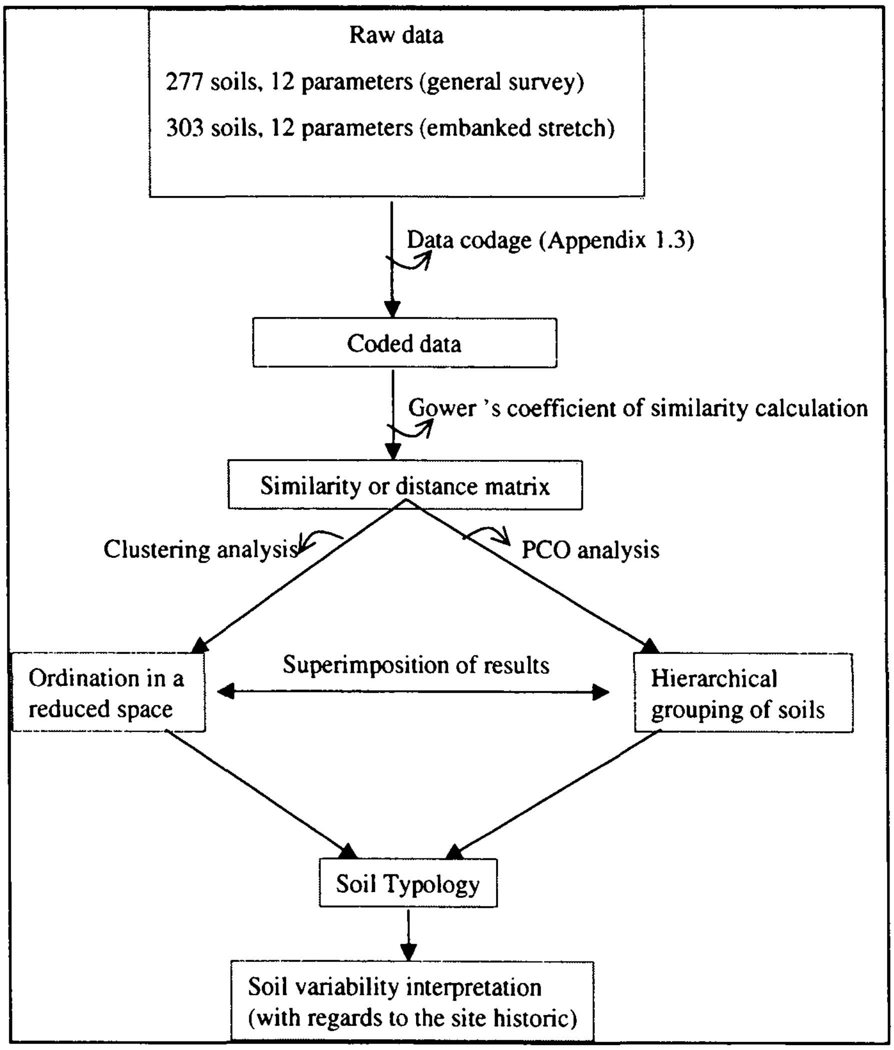

Figure 1.5 – The scheme of the multivariate analysis used to ascertain soil variability at whole site and embanked stretch surveys.

a) Soil clustering (grouping)

By clustering multidimensional analysis (Legendre and Legendre, 1984b) the soil population was hierarchically partitioned, with regards to the twelve soil parameters described in the Appendix 1.2, according to their similarity. The intermediate linkage clustering algorithm (Sneath, 1966) was chosen and the proportion used was of 0,5 (50%); it signifyies that to belong to a group, a soil must be at least 50% similar to the other soils in this group. A contingency table (Legendre and Legendre, 1984a; Legendre and Legendre, 1984b) defines the characteristics of each group. The fusion level between groups is defined by a distance (D) that express their similarity: the smaller the distance, the bigger the similarity. The output file is a dendrogram whith some complementary statistical measures (Pearson's **r**, Gower's distance and entropy). With these measures the pertinence between the clustering produced and the original similarity matrix can be evaluated (Legendre and Vaudor, 1991) and the fusion level was used to decide where to cut the dendrogram. According to Legendre and Legendre, (1984b), the choice of the clustering method is dependent on the kind of grouping that would be more desirable to represent the studied reality and their structure. The choice of a hierarchical clustering technique, for example, implies that groups will be mutually exclusive. One of the advantages of this technique is that it imposes a data structure; in the other words, even if data belongs to a continuum, inside a given group the objets (soils) are sufficiently similar with regards to the studied parameters.

b) Principal Co-ordinates Analysis (PCO)

To better illustrate the similarity between the soil groups, a PCO (Gower, 1966) was done. This technique produces an ordination in a reduced space, for instance, a multidimensional metric frame based on the similarity or the distance matrix. The advantage of PCO on the Principal Component Analysis (PCA) is that not only quantitative data could be analysed, but also binary data (scored 0 or 1) or even qualitative data.

Several outputs are possible: 1) a file containing the eigenvalues and the % of the variance expressed by each value; 2) three graphics of the objets (axis I-II, I-III, and II-III) among which only the first (axes I-II) was considered; 3) a file containing the co-ordinates for each object according to the other principal axes required by the program that could be used for further analyses; 4) a Shepard's diagram that permits the comparison between the distances inside the original similarity matrix (the X-axis) and the distances inside the reduced space (the Y-axis) in 2 or more dimensions.

Furthermore, in order to present these results in a graphical way, the result from the clustering analysis was superimposed to that from the ordination (PCO), as suggested by Sneath and Sokal, (1973) and Legendre and Legendre, (1984b).

c) Soil typology

Finally, a soil typology is undertaken in order to characterise soil groups (separated by the clustering analysis) and discussed with regards to the site history and geomorphological position.

d) Soil profiles representatives of the principal groups of soils

To better understand the vertical organisation of the principal soil groups, representative soil profiles were chosen, described and analysed. The choice of the profiles was based on the dominant morphological characteristics of each group of soil and also some typical geomorphological position where a given group of soils could be found. The parameters used to describe the soil profiles are shown in Appendix 1.5. To complete the details of the soil field description, samples by soil horizon (about 1 Kg) were taken for the physico-chemical analyses: pH, organic carbon (C_{org}), nitrogen (N_{total}), calcium carbonate ($CaCO_3$), soil texture, cations exchange capacity (CEC). In addition, for each surface horizon, five soil samples were taken to determine the bulk density.

e) The physico-chemical soil analyses

The soil samples were air-dried and sieved at 2,0 mm. From what remainders small samples were taken for the physico-chemical analyses (after passage in a statistical Minemet separator).

The soil samples for the C_{total} analysis were burnt at 1000°C in O_2 presence in a *Wösthoffa Bochum Casumat.* The CO_2 liberated was measured by conductimetric method. For the $C_{mineral}$ analysis, H_3PO_4 (phosphoric acid) was added to the soil samples and the CO_2 liberated was also measured by the conductimetric method. $C_{organic}$ was then calculated by difference ($C_{organic} = C_{total} - C_{mineral}$). $CaCO_3$ content was obtained by multiplying the $C_{mineral}$ by 8,33 (100/12).

For the soil texture (particle size) determination, the soil samples were treated with H_2O_2 in order to destroy the organic matter. The particles were dispersed by a sodium pyrophosphate ($Na_4P_2O_7.10H_2O$) solution (40g/l). The particles with a size of 200-50 µm were water-sieved and the smallest particles (<50µm) were separated by sedimentation process (according to Stokes's law). Results are expressed in % of the mineral material. The soil texture classification was based on the textural triangle of the Swiss Society of Pedology (SSP).

The pH_{H_2O} (ratio ½,5) was determined by potentiometry. The pH_{KCl} was not determined because all soils were calcareous.

Furthermore, the sub-samples destined to the N_{total}, analyses were previously finely ground. The sub-samples on N_{total} determination were mineralised by Kjeldahl method and analysed by colorimetry at 660 nm.

The sum (S) of the exchangeable cations (Ca^{2+}, Mg^{2+}, Na^+ and K^+) with the exchangeable acidity (A) constitute together the soil capacity of exchange (T) that was determined at the PH_{soil} by saturation with a $BaCl_2$ solution and analysed by ICP (Inductively Coupled Plasma Atomic Emission Spechtrometry). As the soil pH was always higher than 6,5 the exchangeable acidity (A) was not determined. In this particular case, S=T.

The soil sample for the bulk density determination (only for the surface horizons) was taken in a cylinder of 100 cm^3 previously weighted. Afterwards, it was dried at 105°C and weighted. The result (in g/cm^3) corresponds to the average of five repetitions. More details concerning the soil analyses methods employed in this study can be found in Baize, (1988).

1.4 Conclusion

By following this pedological methodology, the study site will be characterised and the variability and spatial distribution of soils in the floodplain of Sarine River will be studied at different levels of perception: the whole site characterisation, the impact of embanking on the soil and vegetation evolution in the embanked stretch, and the three-dimensional cartographic modelling of soil variability and spatial distribution). Furthermore, the results will be confronted to the site historic, in order to understand the evolution of such an ecosystem upon the anthropic impacts. These results are presented in Part II: *Pedological Results*, in chapters 3, 4 and 5, respectively.

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Chapter Two

GIS methodology

Abstract

GIS technology has opened new perspectives in the environmental research and management field. In this chapter, the use of GIS technology by environmental scientists is discussed, firstly in the sense of a computer toolbox and then, in the larger sense, as a support to environmental research. In this way, the need for developing a GIS design methodological is addressed, because that develop to institutional GIS are not adequate. Such a methodological framework should able to integrate the particular characteristics of environmental research (wide variety of data, entities that change in space and time, events that are causally linked...) and help with structuring real-world phenomena and deciding about the GIS technology the most adequate to implement environmental application.

2.1. Introduction

The need for a better understanding of the effects of human activities on the environment at local, regional and even global scales has become essential to support environmental research, planning and management. This implies the analysis of a large and complex set of data, in different scales and ranging from the past to the present-day. This new scope of environmental research has created the need of a challenge between science and technology and particularly, GIS (Geographical Information Systems).

GIS has emerged during the 1980s and has changed the way of managing spatial data. *Geographical* implies that data are located spatially (geographic co-ordinates), *information* implies that data in a GIS are organised to yield useful knowledge, and the word *system* implies that GIS is built from several interrelated and linked components with different functions (database management, image processing, general statistics, desktop mapping, drawing...) (Bonham-Carter, 1994). There are several definitions for GIS: toolbox, database and organisation-based points of view. Among the many tool-based definitions of GIS, that given by (Burrough, 1986) seems quite representative: "*a powerful set of tools for collecting, storing, retrieving at will, transforming and displaying spatial data from the real world for a particular set of purposes*".

Different fields of knowledge have used and taken advantage of GIS capabilities for resource management, land-use planning, transportation, decision-making, and so on (Burrough, 1986; Bonham-Carter, 1994; Joerin, 1998). Within the same context, several works in the soil science field have used GIS capabilities with different purposes (Girard *et al.*, 1989; Delcros, 1993; Robbez-Masson, 1994; Lathrop *et al.*, 1995; Legros, 1996).

Nevertheless, the research in the GIS field has also evolved and presently, several works within the organisational context focus on GIS as a more global concept that includes "*hardware, software, data, people, organisations and institutional arrangements for collecting, storing, analysing, and disseminating information about areas of the earth*" (Dueker and Kjerne, 1989).

In this chapter, the need of using GIS technology in the context of environmental research will be discussed and justified, as well as its different definitions and the extent to which it is needed for our study.

2.2. GIS as a computer toolbox

In the context of this thesis, the need of using GIS technology arose as we were trying to apply the diachronic approach proposed in the Pedological methodology. Following this approach, the present-day state of soil, as well as their variability and spatial distribution should be studied with regards to the site history. The advantages of using GIS technology upon the traditional approach (photo-interpretation and hand-made maps) were commented on an introductory paper (Appendix 1.2) (Mendonça Santos *et al.*, 1997b). In the context of this paper, GIS is employed and put in perspective of its toolbox-based definition. Furthermore, other parts of this thesis were realised using GIS technology (e.g. soil cartography). Figure 2.1 illustrates the first interest of this research in using GIS technology and its different capabilities.

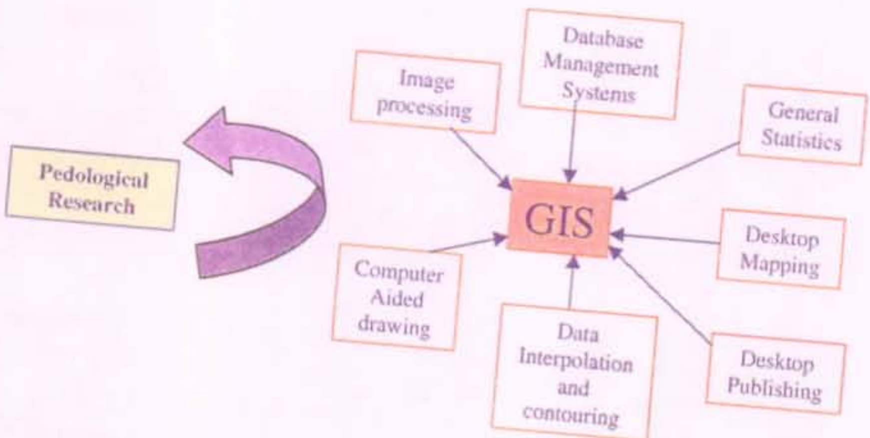

Figure 2.1 –GIS and its components, as first employed in the Pedological research

2.3. – GIS as a management support system

In this sense, GIS has a larger extent, including hardware, software, data, people, organisations and institutional arrangements (Figure 2.2). As emphasised by Chrisman, (1997), this definition differentiates between the data in the system, and the information that results from the system. In this way GIS have a larger context that includes institutions and cultures, because its includes also people. Institutional (or organisational) GIS plays a role in the development of a given activity through all the life cycle of a GIS (Pantazis and Donnay, 1996) and specially, in the management and administration of data, as well as in the decision-making process.

In order to consider all components of such an extended GIS context, the design of a sound GIS methodology is necessary, in order to enhance the efficiency of the problem modelling, based on a well-structured transformation of data into manageable information (Golay and

Nyerges, 1994; Golay, 1995). Some GIS design methodologies have been proposed (Yao, 1985; Collongues *et al.*, 1989; Pantazis and Donnay, 1996).

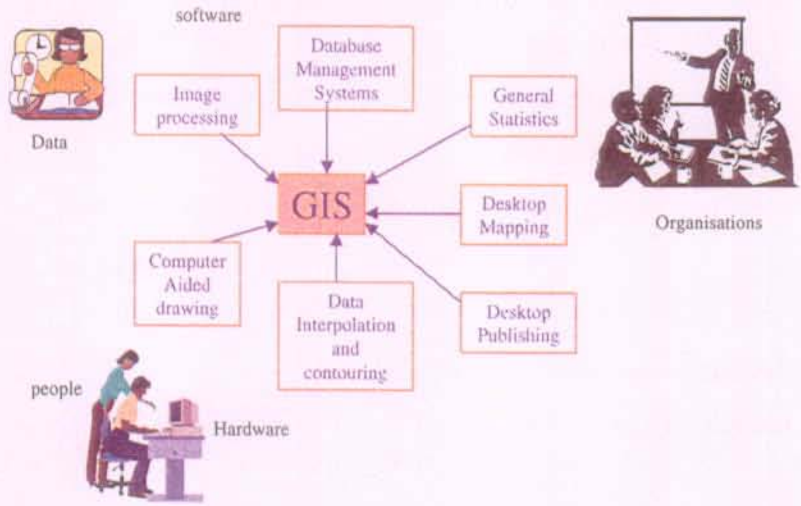

Figure 2.2 - GIS and its components, as a management support system

2.4. – GIS as an environmental research support

In the research context, more than accumulating and analysing data within the light of the new technologies, the challenge is the comprehension and the explanation of real-world phenomena and above all, the structuring of the knowledge about them. Nevertheless, the GIS design methodologies super-cited are not directly adequate to environmental research, nor institutional GIS itself. These methodologies were developed with regards to the specificity of institutional GIS and not to environmental problems and less yet in the context of research. One exception is the work of Gayte *et al.*, (1997). However, more than a GIS design methodology applied to the environmental context, they propose a formalism to model environmental data at a logical computational level without discussing the impact of the methodology for environmental studies.

The complex nature of our environmental application, with its dynamic aspect and many interactions between their components, has determined the research of a new methodological approach. Such a methodology must consider the problem in a holistic and flexible way, allowing the support of the scientific reasoning, with feedback or modifications, as well as the expertise of several disciplines. This approach can be related to the systemic one, employed by Prélaz-Droux, (1995) and De Sède and Thériault, (1996). Finally, in what manner are environmental data different from other data?

2.4.1 *Environmental data– characteristics*

The interest in developing a GIS design methodology in the context of environmental research is justified by the complex characteristics of environmental data, as well as their causal interrelationships and dynamic aspect. The modelling of environmental applications must consider the following points:

- Data sets are large and heterogeneous: non spatial data (text, alpha-numeric), spatial (points, lines, polygons...), temporal (instant, duration, sequence...) or complexes (images, graphics...);
- Data in different scales and variable accuracy must be integrated (different scales to study different components of a same system, data accuracy adequation...)
- Information is located in space (spatial dimension) and time (temporal dimension);
- Dynamic spatio-temporal processes (they evolve in space and time);
- Different nature of data processing (spatial analysis, statistics, cartography);

2.4.2 The need of integrating time component into GIS

In order to access the complexity of environmental systems and the multi-faceted nature of environmental problems, GIS must integrate the time component in order to describe and explain real-world entities.

Geographical entities evolve in space and time. The modelling of such a system requires a GIS, which can support both spatial and temporal queries and analysis. Nevertheless, present capabilities of conventional GIS are not completely suited to a description, and historical representation and management of spatial data evolution.

This inability to consider the time dimension within current GIS models has been outlined by several authors (Langran, 1992;Peuquet, 1994; Peuquet and Wentz, 1994). Integration of time within atemporal spatial models is still considered a complex objective. Current approaches do not allow the reproduction of local temporal situations, nor an explicit understanding of the nature and type of changes that could occur (Beller, 1991).

However, the successful development of GIS within environmental sciences requires the identification of spatio-temporal models that offer support for understanding natural or man-induced phenomena (Openshaw, 1994; Yuan, 1994; Peuquet and Duan, 1995; Claramunt and Theriault, 1995 and 1996). According to Al-Taha and Barrera, (1990), the interest of the temporal information could be summarised as follows:

- Observation or inference of the rules that cause changes;
- Planning based on information about the past;
- Prediction of future behaviour;
- Present-day data analysis based on previous observations and elucidation of the causal relationships.

In addition, a temporal GIS provides, through the analysis of temporal data, a step forward in studying causal relations between processes and the interpretation of change patterns. Actually, causal links are implicit in the principle of temporality because the management of temporal entities involve the analysis of change patterns that should be a consequence of causal relationships between successive states of events (Allen, 1996). As observed by Beller, (1991), "*adding a temporal dimension to a data set provides tools to investigate causality*".

In fact, assuming that state 2 is a function of state 1, we assume a causal relationship between objets.

2.4.3 The need of modelling causal links between events

Only a few works have addressed the problem of modelling causality within GIS (Beller, 1991; Whigham, 1993; Edwards *et al.*, 1993; Allen *et al.*, 1995). Beller, (1991) has proposed to model causality in an indirect way by the modelling of events as objects spatially and temporally referenced in the database. In this way, causal links can be inferred from the analysis of objects.

Nevertheless, only the analysis of causal links inferred from objets is not sufficient. In the context of environmental research, the expression of causal links has an important role to play in helping to elucidate relationships between events and in the mastering of the complexities. However, as stressed by Allen *et al.*, (1995) not all events are necessarily causally related to other events. In fact, it is the role of the environmental experts to identify causal links according to their relevance to the application (especially in the research context, the design is an intrinsic and continuous process of reflection and choices). GIS experts participate in helping to better express and model the causal links considered important to elucidate the problem.

Following the stated requirements of environmental research, the design of a GIS methodology applied to environmental research (Figure 2.3) must integrate: (1) data sets that are complex and varied; (2) the dynamic aspect of the real-world entities (entities evolve in space and time); and (3) causal relationships between events. In this way, such a methodology can be helpful to structure the problem and facilitates the cognitive process of constructing hypotheses about data behaviour. In addition, it can also be helpful to facilitate communication between experts from different scientific domains.

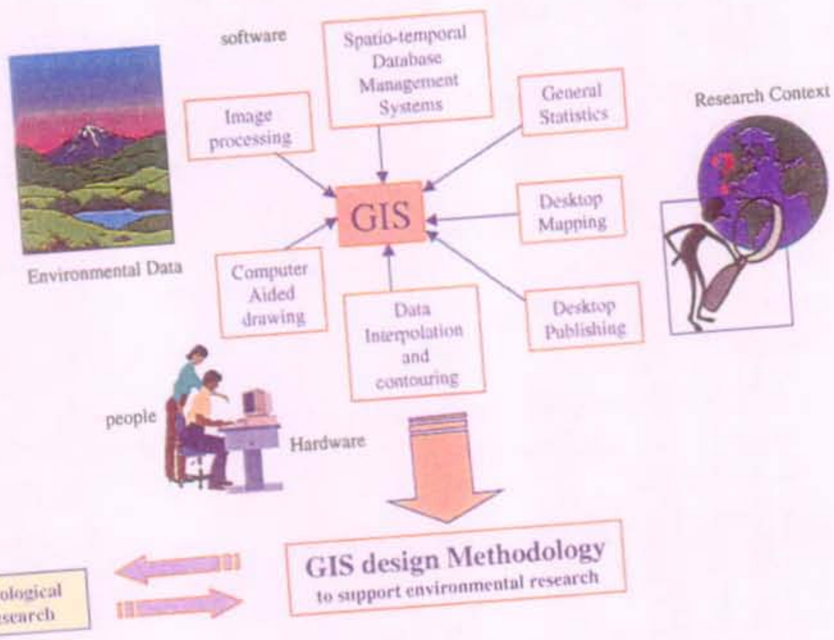

Figure 2.3 - GIS and its components as an environmental research support

In order to address the needs expressed in the above paragraphs, a particular GIS design methodology was developed and applied to our environmental study. Furthermore, its consequences on the pedological methodology (and vice-versa) were briefly evaluated (Chapter 6).

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Part II: Pedological Results

Chapter Three

Morphological variability and spatial distribution of soil in the floodplain of the Sarine River

Abstract

In order to ascertain the general characteristics of soils, to understand their spatial distribution and variability in the floodplain of Sarine River, an exploratory soil survey was done in the whole site. The results concerning a population of different 277 soils are presented in this chapter. Furthermore, a soil typology is undertaken and some soil profiles are described in detail, in order to illustrates the different soil types. Despite these soils seem to be relatively close together (fusion level close and several intermediate groups), they present an important variability in terms of morphological characteristics and spatial organisation. Furthermore, the site history and the local geomorphology were used to explain differences in the evolutionary stage of soils. In fact, inheritance and pedogenesis are present in the formation of such soils. However, inheritance seems to be the dominant process.

3.1 Introduction

The soil formation processes govern spatial variability of soils, as previously discussed (Chapter 1). The study of the *pedogenesis* has been largely used to understand the variability and spatial distribution of soils (Buol *et al.*, 1973; FitzPatrick, 1986; Duchaufour, 1991). However, in the study of alluvial soils (FLUVIOSOLS), the river dynamic, the quality of the alluvium material, as well as the local geomorphologic characteristics must be taken in consideration, in addition to the *pedogenesis* itself (alluvial soils have a little or no *pedogenesis*), in order to set up their variability.

Following the Pedological methodology stated in Chapter 1, this chapter presents the results, discussion, illustrations and conclusions about the soil variability and spatial distribution, from the landscape perception level (soil characterisation from the general soil survey).

3.2 Variability and spatial distribution of soils – results

3.2.1 Clustering analysis

With the clustering technique, the most similar objets are grouped on together. According to the characteristics of the algorithm employed (the choice is dependent on the aim) the soil population have particular hierarchical partition that is mutually exclusive. Objets that have an intermediate position were forced to belong to a group, in order to obtain a general model of the reality. Finally, an optimum classification must be sought, but it will always be a local optimum classification rather than a global one (it concerns only the particular set of individuals). And as stated by Webster and Oliver, (1990), "even if it is the best possible, there is no ready means of knowing that it is".

By clustering multidimensional analysis, the soil population of the general survey (277 soils) representing the whole site was hierarchically partitioned according to the twelve descriptors (soil parameters, Appendix 1.2) discussed in Chapter 1. The clustering algorithm separates eight groups (1, 2, 3...8) according to their degree of similarity. A simplified dendrogram that illustrates these groups and their degree of fusion is shown in Figure 3.1. This clustering analysis has reproduced 71,5 % of the variance of the original matrix of similarity. The similarity between the groups is traduced by the degree of fusion, which is expressed in distance (D). Smaller the distance bigger the similarity. Group 1, for example, is very different from the other (D=0.49). The groups 3 and 4 are closer to each other (D=0.33) than to group 2 (D=0.36).

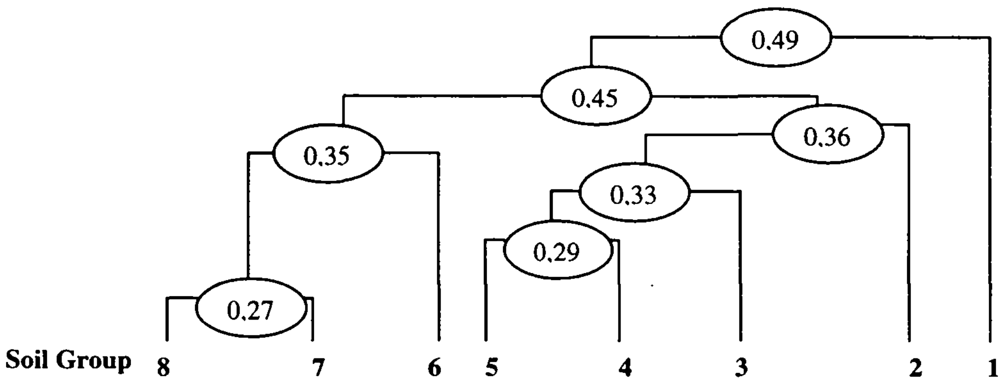

Figure 3.1 - Soil clustering dendrogram for the whole site. The value indicated inside the circle corresponds to the degree of fusion (degree of similarity) expressed in distance (D).

3.2.3 Principal Co-ordinates Analysis (PCO) - results

To better visualise the similarities between these groups of soils a PCO was performed. The result of this technique was superimposed on that from the clustering analysis. (Figure 3.2). The two primary axes explain 33,4% of the total variance. In fact, the PCO guards the relationships of distance between individuals (the soils). As discriminated by the clustering analysis, the PCO shows the group 1 completely separated from the other. This kind of projection shows also that some groups (2 and 3) do not form a homogeneous spatial cluster.

The Shepard's diagram (Appendix 3.1) with three axes shows the cloud points near the diagonal but it is not very narrow. This configuration indicates that despite the possibility to represent the original distances in three axes, they would be better represented in five axes (Appendix 3.2).

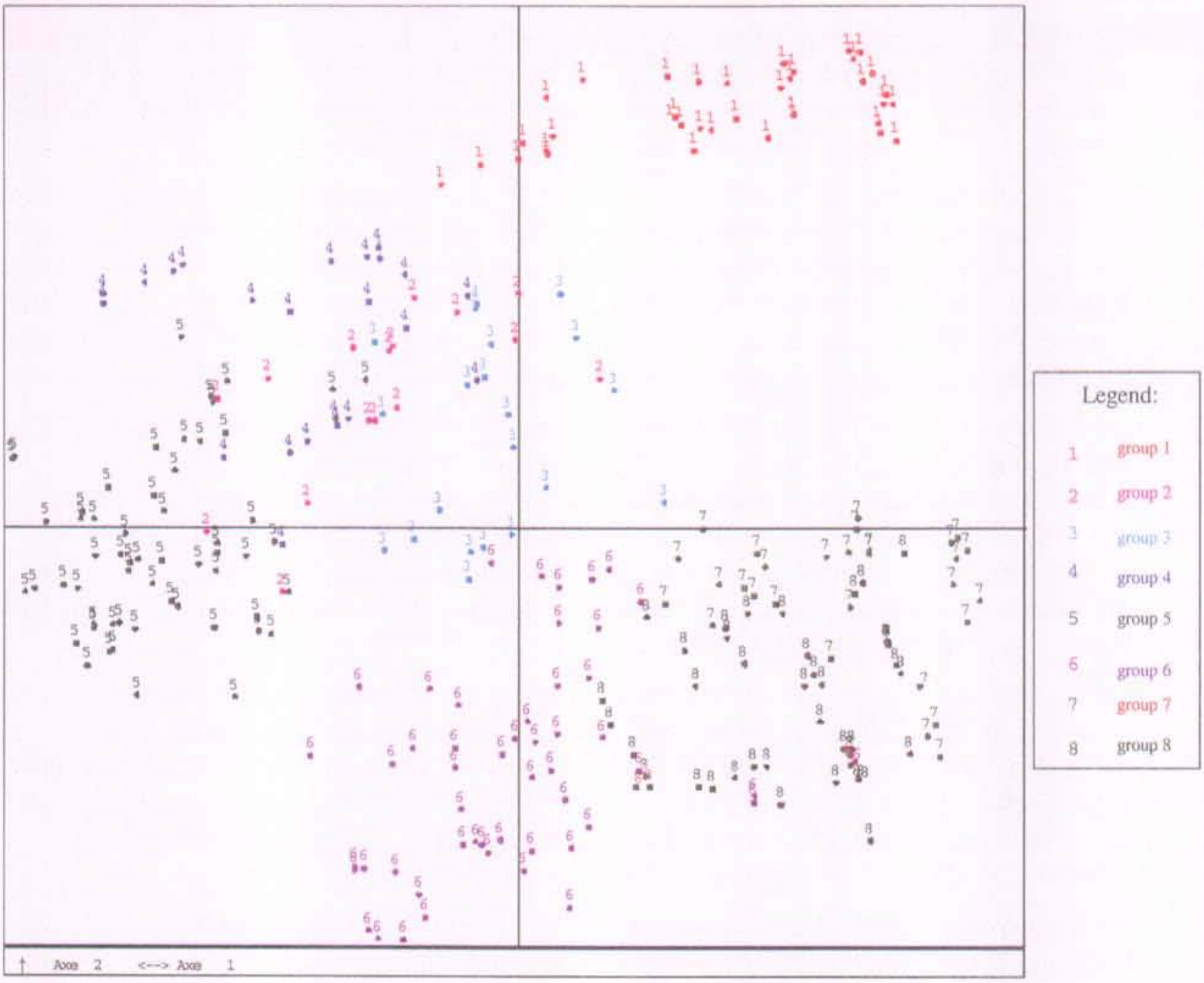

Figure 3.2 – Graphical representation of the PCO result, superimposed on that from the clustering analysis of soils. The numbers correspond the soil groups and the points indicates the location of each soil inside the two axes.

3.2.4 Soil typology

The pedological characteristics of each group of soils, as well as the their frequency in % (F) are shown in Table 1.

Soils from ***group 1*** (14% of the population) have a variable deepness[3] and between 1 and 2 horizons (75% of the observations). Only these soils have the surface horizon with a single grain platy structure, or no structure (100% of the observations). This horizon rests directly on the gravel deposits (pebbles) (52% of the observations) or on sandy horizon (26%). Moreover, these soils have the lowest M.O. content (75% of the observations have only 2,5 to 8% of M.O.) and a rather coarse texture (26% sand and 50% sand/loamy).

The soils from ***group 2*** (5% of the population) have between 2 and 3 horizons (75% of the observations) or between 3 and 5 horizons (the remaining 25%). The soils from this group are deep (25% of the observations were between 92 and 100 cm; and 50% were between 29 and

3 Deepness is used in this thesis in relation to the soil itself and begins in the terrain surface and ends at the gravel deposits (layer D).

92 cm). The surface horizon of these soils is rather thin[4] (between 3 and 16 cm for 75% of the observations) or a maximum of the 16 to 25 cm (for the remaining 25%). The texture is loam/sandy (64%) or sometimes, loamy (15%). The structure[5] of the surface horizon is sub-angular blocky (for 100% of the observations), very fine (50%) to fine (29%), weakly developed (71%) and the distinction is not very clear (86%).

The principal characteristic of soils from ***group 3*** (7,5% of the population) is that they have only one horizon (100% of the observations). These soils are relatively few deep, with a maximum of 35 cm (but 75% of the observations have only between 5 and 15 cm). They have a high M.O. content (75% have between 5 and 15% M.O. and 25% has up to 19%). The texture of the surface horizon is rather loamy or loam/sandy (for 86% of the observations). The structure is moderate, fine sub-angular blocky for 100% of the observations.

Soils from ***group 4*** and ***5*** (28,5% of the population) are moderately deep to deep with a varied number of horizons, from 1 to 7. The texture of the surface horizon is loamy or loam/sandy; the structure is sub-angular blocky, fine to medium and clear (sometimes very clear). The principal differences between these two groups is that group 4 is richest in M.O. and their structure is more developed (strong) and very clear (for the 100% of the observations). In contrast, the group 5 has at least 2 horizons (but could have up to 7) and the surface horizon never rests on the gravel deposits.

Soils from ***group 6*** (18% of the observations) are quite deep (75% of the observations is between 35 and 99 cm), and often up to 7 horizons (minimum 2). They have a thin surface horizon (between 3 and 10 cm for 75% of the observations) which rests on a loam/sandy horizon (72%) or on a sand/loamy horizon (24%) and never directly on the gravel deposits. These soils have a loamy (76%) or loam/sandy texture (24%) and the structure is crumb (for all observations), thin to very thin, moderate to strong and moderately clear.

Soils from ***group 7*** (11% of the population) can be between 2 and 60 cm depth and have 1 to 3 horizons. They are very similar to soils from ***group 8*** with regards to the surface horizon, which is thin (in both groups 75% of the population are between 2 and 10 cm thick). The texture of the surface horizon ranges from loam/sandy to loamy. These soils are the most organic of the studied population, where the group 7 is richer than group 8. The structure is crumb for both groups (100% of the observations) and very thin. The degree of development and the facility to distinguish the structure is nevertheless different (it is moderately developed and clear for the group 8 and weakly developed and not very clear for the group 7). However, the soils from ***group 8*** (16% of the population) are among the less deep (with a maximum of 38 cm) and yet often with one horizon (only 10% of the population have 2 horizons).

3.2.5 Soil profiles representative of the soil groups.

In order to illustrate the soil morphological variability, soil profiles are chosen representing some of the principal soil types found in the floodplain of the Sarine River. The choice of the soil profiles was done according to the dominant characteristics of each soil group represented. Afterwards, they were described and analysed in detail. They are presented in Appendix 3.3, according to the following plan:

4 Thickness is used specifically related to soil horizons.

5 The soil structure is defined by four parameters: type, class, degree of development and clearness.

- the profile location characteristics (local vegetation, geomorphology...)
- the morphological description of each soil horizon;
- the physico-chemical results of the analyses for each horizon;
- the schematic design of the soil profile and the corresponding photograph.

The profiles described in Appendix 3.3 can be related to the diagnostic *sola* illustrated in the "*Référentiel Pédologique 1995*" (A.F.E.S., 1995). Furthermore, the use of adjectives (qualifiers) to complete the description of a Reference horizon is recommended. Those related to the soils described in our study are briefly defined here, in order to facilitate the understanding of the soil description:

- *typical* – describes a *solum*, which meets the definition and the main concept of a Reference horizon, in this case, FLUVIOSOLS.
- *calcareous* – describes a carbonate-rich horizon or *solum* in which CaCO3 is the only one present or is largely dominant ($CaCO_3/MgCO_3$ molar ratio > 8). Overall effervescence with cold acid.
- *humiferous* – describes a horizon or a *solum* which has an organic carbon content higher than the norm, but not a holorganic horizon or *solum* (*solum* in which the fine earth is entirely organic).
- *brunified* – describes a *solum* (other than a BRUNISOL, for example, a PELOSOL, an ORGANOSOL, a FLUVIOSOL) that shows the features of brunification, notably the presence of a true, well-aerated S horizon.

polycyclical or polygenetic – describes a *solum* in which current *pedogenesis* is superposed upon the effects of an earlier different kind of *pedogenesis*, which produced certain morphological or mineralogical characteristics. In this study this qualifier indicates the presence of buried horizons resulting of the successive

Table 3.1 – Pedological characteristics of the soil sub-groups. The texture abbreviations are: lo=loam; sa=sand; cl=clay; lo/sa=loam/sandy; sa/lo=sand/loamy; lo/cl=loam /cleyey; D=layer D (strand with calcareous pebbles)

Soil groups	1-Depth (cm)	2-Number of horizons	3-Thickness of the surface horizon (cm)	4-M.O. content (%)	5-Texture*	6 -Reaction to HCl	7-Structure type	8 - Structure class	9 - Structure development	10 - Structure clearness	11 - Pebbles in the surface horizon	12 - Second horizon texture
group 1 **F=14%** **38 soils**	82-100 (10%) 46-82 (15%) 10-46 (50%) 2-10 (25%)	3-5 (10%) 2-3 (15%) 1-2 (75%)	16-28 (25%) 5-16 (65%) 2-5 (10%)	12-15 (10%) 8-12 (15%) 2.5-8 (75%)	sa/lo (50%) sa (26%) lo/sa (19%) lo (5%)	strong (97%) moderate (3%)	single grain coarse platy (100%)	thin (18-42%) medium (5%) very thin (77%)	-----------------	------------	not (58%) yes (42%)	D (52%) lo/cl (3%) lo/sa (5%) sa (24%) sa/lo (16%)
group 2 **F=5%** **14 soils**	92-110 (25%) 29-92 (50%) 20-29 (25%)	3-5 (25%) 2-3 (75%)	16-25 (25%) 3-16 (75%)	11.5- 12.5(10%) 10-11.5 (15%) 6-10 (75%)	lo/sa (64%) lo (15%) sa/lo (10%) lo/cl (5%)	strong (79%) moderate (21%)	sub- angular blocky (100%)	thin (29%) coarse (7%) medium (14%) very thin (50%)	weak (71%) moderate (29%)	clear (14%) not very clear (86%)	not (71%) yes (29%)	cl (7%) lo/cl (7%) lo/sa (7%) sa (7%) sa/lo (72%)
group 3 **F=7,5%** **21 soils**	20-35 (10%) 15-20 (15%) 5-15 (75%)	1 (100%)	20-35 (10%) 15-20 (15%) 5-15 (75%)	15-19 (25%) 5-15 (75%)	lo (43%) lo/sa (43%) sa/lo (10%) lo/cl (5%)	strong (81%) moderate (19%)	sub- angular blocky (100%)	thin (71%) medium (5%) very thin (24%)	strong (14%) weak (19%) moderate (67%)	clear (57%) not very clear (43%)	not (48%) yes (52%)	D (100%)
group 4 **F=8%** **23 soils**	84-110 (10%) 38-84 (15%) 18-38 (50%) 8-18 (25%)	4-5(10%) 2-4 (15%) 1-2 (75%)	20-25 (25%) 10-20 (25%) 3-10 (50%)	18-20 (10%) 13-18 (15%) 7-13 (75%)	lo/sa (61%) lo (30%) lo/cl (9%)	strong (91%) moderate (4,5%) weak (4,5%)	sub- angular blocky (100%)	thin (44%) medium (52%) very thin (4%)	strong (100%)	Very clear (100%)	not (61%) yes (39%)	D (30%) lo/cl (22%) lo/sa (4%) sa/lo (44%)
group 5 **F=20,5%** **57 soils**	72-100 (25%) 40-72 (50%) 18-40 (25%)	5-7 (10%) 4-5 (15%) 2-4 (75%)	20-25 (10%) 12-20 (15%) 3-12 (75%)	11-18 (25%) 7-11 (65%) 1-7 (10%)	lo (86%) lo/sa (12%) lo/cl (2%)	strong (91%) moderate (9%)	sub- angular blocky (100%)	thin (77%) medium (18%) very thin (5%)	strong (47%) weak (7%) moderate (46%)	clear (72%) not very clear (10.5) very clear (17.5%)	not (82.5%) yes (17.5%)	lo/cl (5%) lo/sa (81%) sa/lo (14%)
group 6 **F=18%** **50 soils**	66-99 (25%) 35-66 (50%) 10-35 (25%)	5-7 (10%) 4-5 (15%) 2-4 (75%)	20-25 (10%) 10-20 (15%) 3-10 (75%)	11.5-18 (25%) 4.5-11.5 (75%)	lo (76%) lo/sa (24%)	strong (70%) moderate (30%)	crumb (100%)	thin (40%) medium (18%9 very thin (42%)	strong (30%) weak (18%) moderate (52%)	clear (58%) not very clear (36%) very clear (6%)	not (82%) yes (18%)	lo (2%) lo/sa (72%) sa (2%) sa/lo (24%)
group 7 **F=11%** **30 soils**	49-60 (10%) 23-49 (15%) 7-23 (50%) 2-7 (25%)	2-3 (25%) 1-2 (75%)	15-22 (10%) 10-15 (15%) 2-10 (75%)	22-49 (10%) 15-22 (15%) 6-15 (75%)	lo/sa (53%) sa/lo (27%) lo (20%)	strong (73%) moderate (20%) weak (7%)	crumb (100%)	thin (3.5%) medium (3.5%) very thin (93%)	weak (90%) moderate (10%)	not very clear (100%)	not (47%) yes (53%)	D (60%) sa (30%) sa/lo (10%)
group 8 **F=16%** **44 soils**	10-38 (25%) 3-10 (75%)	2 (10%) 1-2 (90%)	16-20 (10%) 10-16 (15%) 2-10 (75%)	21-27 (10%) 17-21 (15%) 9-17 (50%) 4-9 (25%)	lo (64%) lo/sa (34%) sa/lo (2%)	strong (77%) moderate (11,5%) weak (11,5%)	crumb (100%)	thin (23%) very thin (77%)	strong (23%) moderate (77%)	clear (84%) not very clear (9%) very clear (7%)	not (39%) yes (61%)	D (89%) sa (7%) sa/lo (4%)

The following FLUVIOSOLS were found in the studied floodplain. They are illustrated in Appendix 3.3 and represent some of the soil groups identified in this study.

- typical calcareous FLUVIOSOLS: Aca/D (A horizon of juxtaposition) (e.g. profile I – representative of the group 1);
- typical calcareous FLUVIOSOLS: Aca/D, with an A horizon bio-macro-structured) (e.g. profile II – representative of the group 3);
- calcareous FLUVIOSOLS "in process of brunification": Aca/Scah/D (e.g. profile III – representative of the group 5);
- typical calcareous FLUVIOSOLS: Aca/Jp/D (e.g. profile IV –group 6);
- typical calcareous FLUVIOSOLS: Aca, Jp, C/ D (e.g. profile V – group 6);
- polygenetic (or polycyclical) calcareous FLUVIOSOLS: Aca, Jp/M/II Jp/II M/II Aca/IIIM/IIIAca/D (e.g. profile VI – group 6);
- calcareous FLUVIOSOLS "in process of brunification": Aca/Scah/C, D (e.g. profile VII – group 6);
- typical calcareous humiferous FLUVIOSOLS: Acah/C, D (e.g. profile VIII – group 7);
- typical calcareous humiferous FLUVIOSOLS: Aca/D (e.g. profile IX – group 8);
- typical calcareous humiferous FLUVIOSOLS: Aca/D (e.g. profile X– group 8);

As observed, there are several soils that have the same diagnostic *solum*, like typical calcareous FLUVIOSOLS, but they can be morphologically different (e.g. different horizons sequences or different physico-chemical characteristics) (the schematic design as well as the photographs and the physico-chemical results presented in Appendix 3.3 shows these differences).

There is no corresponding diagnostic *solum* to the polycyclical (or polygenetic) one, but the presence of buried horizons as well as the qualifier that describes the superimposition of the different kind of *pedogenesis* are admitted for the FLUVIOSOLS.

In the context of this study the nomination FLUVIOSOLS calcareous "in process of brunification" was preferred to FLUVIOSOLS brunifiés (or brunified) in order to emphasise that the pedogenetic process is not yet clearly expressed. Even if these soils have already a horizon with all the characteristics of an S horizon (see definition later) the $CaCO_3$ is still present (thus it makes an **Sca horizon**). However, these kind of soils could be related to the diagnostic *solum* "FLUVIOSOLS brunifiés" because the **Sca** horizon has the same characteristics of the **S** horizon (imperfect attribution). More information concerning Reference horizons description as well as diagnostic *sola*, can be found in the "*Référentiel Pédologique 1995*" (A.F.E.S., 1995). Nevertheless, in this work some modifications concerning the horizon nomenclature were made with regards to the results of the physico-chemical analyses:

- None of the surface horizon was denominated **Js**. In reality, their organic carbon contents were always higher than 1%, consequently these horizons belongs to the **A** horizon category (1 to 8% of organic carbon). Furthermore, their well-developed crumb granular or sub-angular blocky structure suggests a biological origin. Furthermore, due to the presence of $CaCO_3$, they were nominated **Aca**, which signifies an **A** calcareous (**A** horizon giving overall effervescence with HCl).

- Deep horizons that have a texture finer than that of the layer **M**, with a structure less developed than that of the **S** horizon was nominated **Jp**. In this way, all **Jp** horizons, described in this work, have always a loam/sandy or sand/loamy texture and a weak to moderate structure.
- The layers of alluvium sand were nominated **M** rather than **C**, in order to underline that they were not altered *in situ*. These layers constitute a primary rock (friable moving rock) in themselves that have been fragmented before their transport. In the study site they belong to the sub-type **Msi** (siliceous rocks).These layers are always related to a discontinuity (physical and mechanical) of the *solum*.
- The mineral horizons that have suffered some geochemistry *in situ* alteration and whose structure is yet very close to that of the original material were nominated **C**, despite their absence in the FLUVIOSOLS diagnostic *sola* presented in the "Référentiel pédologique 1995" (A.F.E.S., 1995).
- The layers **D** have the same meaning as described in the "Référentiel pédologique 1995" (A.F.E.S., 1995). They are hard, but fragmented materials that have been displaced or moved. The unconsolidated material is dominated by coarse fragments (in our case, calcareous alluvial gravel = **Dca** layer).

3.3 Variability and spatial distribution of soils – discussion

The statistical methods employed (clustering and PCO analyses) are complementary to the exploration of the relationships among individuals spread in multidimensional space (soils, in this case) and will be discussed together. Nevertheless, some care in the interpretation should be taken, because these methods are descriptive, rather than quantitative.

In this way, the results show a morphological variability of soil in the studied floodplain, as illustrated by the soil partition in eight groups. ***Group 1*** is very different from the other groups. Soils from this group are the only for which the surface horizon is structureless (single grain platy), which reflets their mineral nature. The organic matter present is mainly inherited, in the form of faecal pellets, which are only juxtaposed with the mineral particles and not bounded to them. These soils are the most recent of this floodplain (their youth is due to the recent *alluvium* deposition by flooding). Soils from this group are found in the active stretch, close to the river.

Otherwise, soils from all other groups present a surface horizon with a mixed organic and mineral material (bio-macro-structured **A** horizon). The *in situ* evolution is better expressed in soils from group 6 and 8.

Soils from ***group 6*** are medium to deep soils, with several horizons. Some soils from this group have an **Sca** horizon and other, polygenetic horizons (even buried horizons could be found). Their **A** horizon presents a fine texture (majority loamy) and the structure is well-developed granular, thin or very thin. These soils are found just behind embankments or far way from the river.

Group 8 is also constituted of the well-developed alluvial soils, however the evolution process for these two groups is somewhat different. Soils from ***group 8*** are thin (maximum 38 cm), constituted of only one horizon (90% of the population). They have a fine texture (loamy to loam/sandy) and a well-developed organic structure (a crumb structure). These soils are also very rich in M.O. and were found in the highest topographic positions (e.g. an old island of the embanked stretch) that has been protected from flood through time (and consequently from sedimentation) and colonised by vegetation before the embanking process. Furthermore, this group also includes soils that have the same characteristics but that were found in the old lateral river branches.

Group 7 is very similar to ***group 8***, but their surface horizon (they could have more than one horizon) is less developed (90% is weakly developed). They have a variable depth (2 to 60 cm) and were found in upland zones covered by Picea *sp*.

The other groups are intermediate groups. This behaviour could be observed in the PCO graphic (Figure 3.2), that shows a net separation of the population into two clusters: the ***group 1*** and the other groups. Furthermore, the cluster formed by the other group shows a partition into two other clusters, diagonally separated. Above this imaginary diagonal (beginning at the origin) the groups 2, 3, 4 and 5 and below, the groups 6, 7 and 8.

Even if the studied soils seem to be relatively close together (fusion level close and several intermediate groups), they present an important morphological variability: they pass from soils with a **Jp** horizon (the youngest soils) to soils with an **Sca** horizon (that expresses the highest evolutionary degree within the confines of our study). Furthermore, the morphology of the **A** horizon is also varied: from an **A** horizon structureless for group 1, to soils with a crumb structure, for group 8 (the crumb structure expresses the influence of the organic matter in the horizon development). Concerning the soil texture (particle size classification) determined in the laboratory, the results are summarised in the textural triangle (Figure 3.3), according to the classification of the Swiss Society of Pedology (SSP). The described soil profiles show the evolution that ranges from a coarse texture (sandy) for the young soils to a finest texture (loam/sandy and even loamy) to more developed soils.

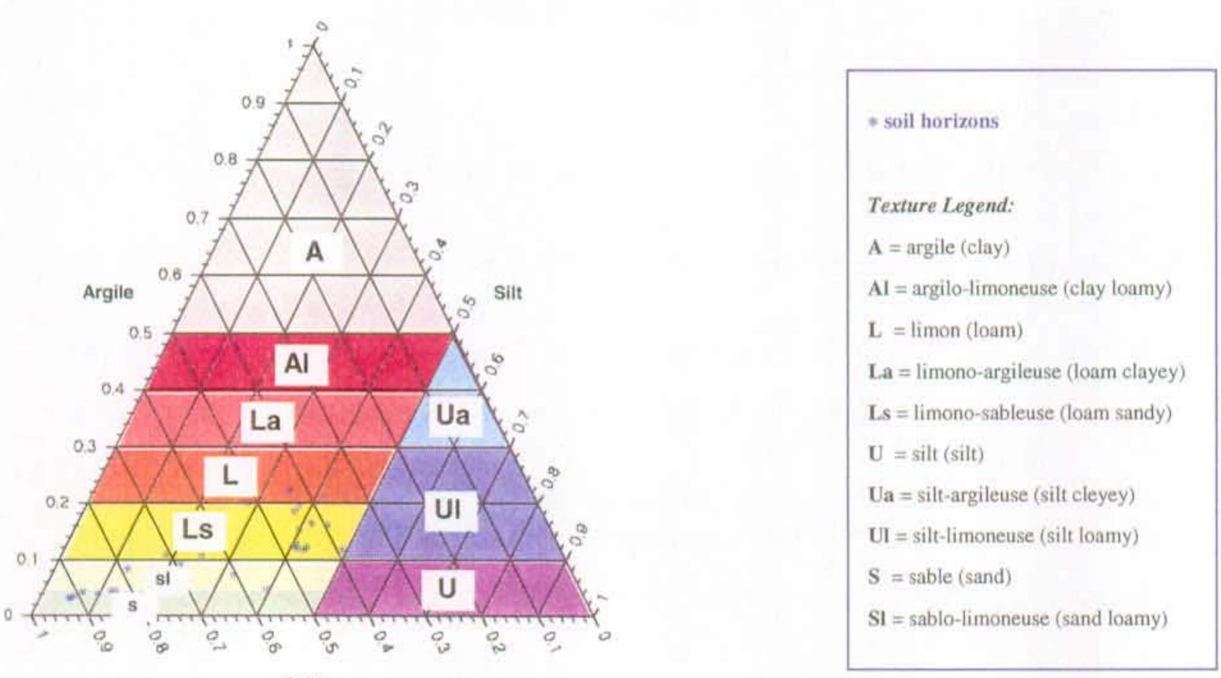

Figure 3.3 – Soil texture classes according to the SSP classification, in %.

Furthermore, their spatial organisation is also very differentiated: from 1 horizon resting directly on the layer D, e.g. group 3 (100% of the population) and 8 (89%), in contrast, have many horizons, group 6 (polygenetic soils). With regards to the deepness, soils can varies from 0,2m till more than 1m. Between these extremes, soils with intermediate characteristics were found. In addition, the spatial pattern of changes is complex (it will be better illustrated in Chapter 5 by a three-dimensional representation of soil horizons).

The morphological and physico-chemical data confirms the variability of the FLUVIOSOLS of the Sarine River's floodplain, already suggested by the clustering results. However, as confirmed by the reaction to the HCl (predominantly between moderate and strong), the floodplain of the Sarine River is a calcareous environment (geologically dominated by calcareous and marl rocks). Upon this condition, the *pedogenesis* is limited. The inheritance process seems to be dominant and responsible for the soil variability as well as their spatial distribution.

3.4 Conclusions

The results of the general survey undertaken with the aim to study the variability and spatial distribution of soils, shows that there is an important morphological variability of FLUVIOSOLS in the Sarine River's floodplain. Furthermore, both inheritance and *in situ* evolution are present and overlap in space and time, but the inheritance process is dominant and seems to be the principal responsible for the soil variability and spatial distribution.

The *in situ* evolution for such soils seems to be better expressed by the quality of the **A** horizon (except for soil with an Sca horizon). In fact, the humus seems to better integrate evolutionary changes.

This work shows the interest of analyse alluvial soils with regards to the historic data, in order to understand the complexity of such environment (overlapping of soil formation processes, and consequent soil variability and spatial distribution).

3.5 References

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Chapter Four

Impacts of embanking on the soil-vegetation relationships in a floodplain ecosystem of a prealpine river[6]

Abstract

Most of the Swiss floodplains of national importance are embanked. Our aim is to understand the impacts of recent embankments (built about the beginning of the present century) on the soil and vegetation along a prealpine river. Embanking is responsible for selective retention of material (here calcareous alluvium). The variation in the quality and quantity of the alluvium is the main factor determining soil diversity. The morphological and the physico-chemical properties of the soil are linked to original geomorphologic position (island, old channel, distance from the embankment, etc). The large variation in the soil is associated with a small diversity among the plant communities: from a phytosociological point of view, most of them no longer have the status of a floodplain community. Their isolation from the alluvial dynamics changes the conditions and speed of evolution of both the soil and the vegetation. This study shows the different kinetics of vegetation and soil following human impact.

4.1 Introduction

Alluvial ecosystems are complex and biologically diverse (Imboden, 1976; Carbiener, 1983; Pautou, 1984; Gallandat, Gobat & Roulier, 1993). Today, in Europe, these ecosystems are threatened (Yon & Tendron, 1981; Yon, 1984; Wenger, Zinke & Gutzweiler, 1990; Schnitzler & Carbiener, 1993) because they have been disturbed by human impact.

The European Council (Conseil de l'Europe, 1982) has recommended that an inventory of alluvial zones be made in order to prevent them from vanishing, and in 1988 an inventory of European floodplain zones was started (Kuhn & Amiet, 1988). Switzerland was a pioneer in this field: a floodplain survey was done, and it was followed by legal protection of floodplains (Conseil Fédéral Suisse, 1992). Most of the Swiss floodplains surveyed have been affected by man in one or more ways; in particular there have been embankments (59%), tourism (43%), plantations (39%), straightening of rivers (38%) and diverse kinds of deposition (15-25%) (Gallandat *et al.*, 1993).

Man has had similar impacts on other floodplains in Europe, for example on the Rhine (Carbiener, 1983; Schnitzler, 1988), the Rhône (Bravard, Amoros & Pautou, 1986; Girel & Doche, 1983; Pautou, 1983 and 1988; Pautou & Wuillot, 1989), and the Danube (Haubenberger & Weidinger, 1990).

Our aim in this study is to identify the effects of embanking on the fluvial dynamics and soil evolution in order to understand the present spatial distribution of soils and to compare the evolution of the soil with that of the vegetation. We combine a historical approach with an analysis of the present-day scene.

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6 This work was published in Global Ecology and Biogeography Letters (1997):6, 339-348, with the following co-authors: C. Guenat, F. Bureau, C. Thevoz and J.-C. Védy (the revue format is kept, then redundancies are normal). ©1997 Blackwell Science Ltd.

4.2 Presentation of the study site

4.2.1 Present state

The study site (*Les Auges de Neirivue*, near Fribourg in Switzerland) and its characteristics were presented in Chapter 1. This chapter concerns the embanked stretch, specifically (Figure 4.1). The river here is strongly confined between embankments, whereas lower in its course it has an alluvial zone (used for the comparison in the last section).

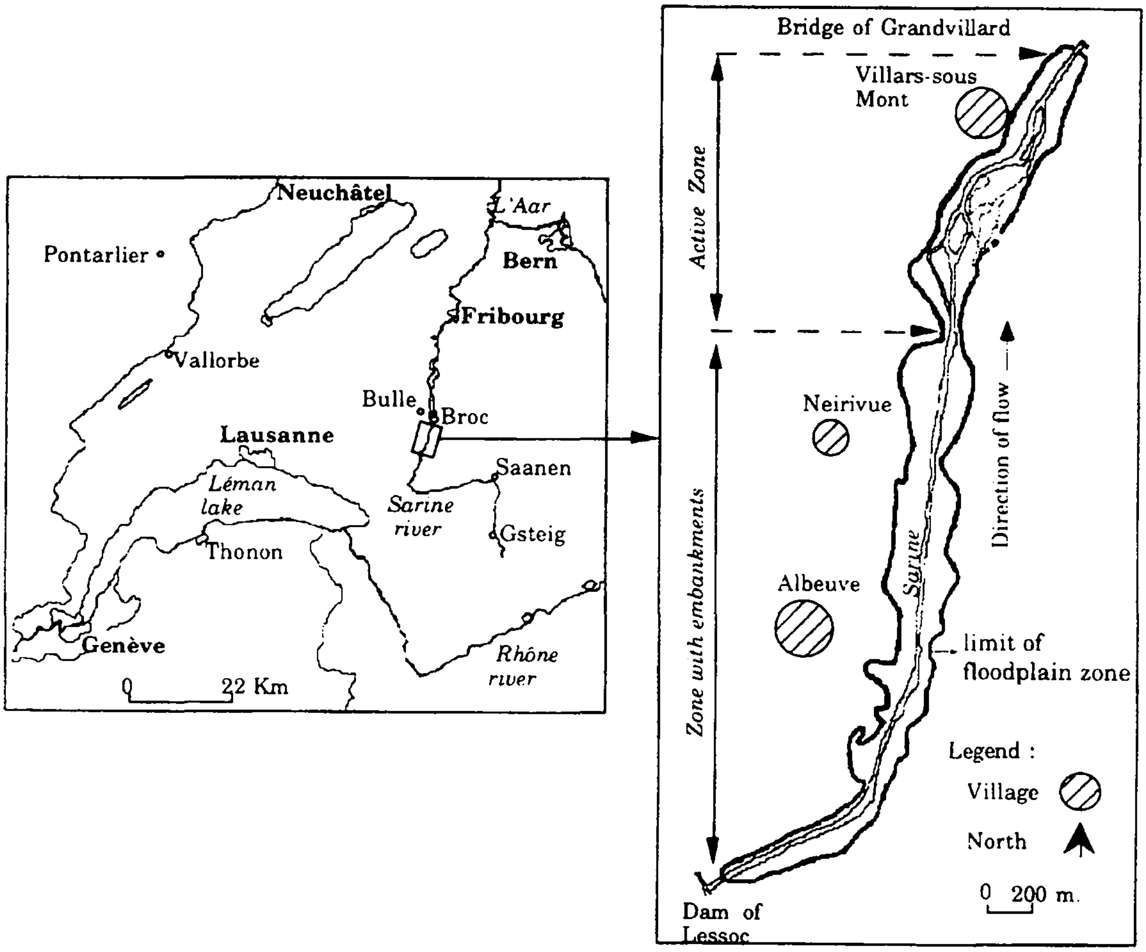

Figure 4.1 – The study site location

The climate is prealpine (Fallot, 1991) with an average annual rainfall of 1200 mm and with wet summers and relatively dry winters. The average annual temperature is 7.1°C; July is the warmest month, and January is the coldest.

The hydrological regime of the Sarine is intermediate nival, with a maximum flow in spring and a minimum in January. The average annual flow calculated between 1923 and 1992 is 23.7 m^3/s (maximum peak flow: 460 m^3/s). The geomorphology of the site is characterised by a succession of alluvial basins separated by rocky constrictions (Gétaz, 1977). The average slope is 0.64 ‰. The alluvial deposits are rough and calcareous.

4.2.2 Historical evolution in the embanked stretch

This stretch of the river has been controlled by construction of various hydraulic installations, in particular dams and embankments. The high embankments made about 1920 had been constructed in two steps: first transverse embankments and second longitudinal ones. By constraining the main channel these installations increased the capacity of the river to erode and caused incision of the riverbed by 1 to 3 m in 60 years. This phenomenon is accentuated by a shortage of sediments following the stabilisation of tributaries and the installation of hydroelectric power plants in the upper Sarine (Bureau *et al.*, 1994). The dam, completed in 1973, is responsible for daily variations of the flow ranging from 3 to 41 m^3/s. On particular occasions the surplus water can be released by sluices and then generate floods. As a result of this, the hydrodynamic regime of the Sarine river has changed (Gétaz, 1977).

An example of the historical evolution is shown in Fig. 4.2. The channel has become straighter and simpler with the time, after embanking. Changes in land cover have also occurred, particularly an increase in the vegetated area. The consequence of modifying the hydrological regime is the isolation of the vegetation from the alluvial dynamics.

4.3 Methods of investigation

We studied the whole of the embanked stretch in order to understand the soil diversity, and then examined specific sites to explain the soil evolution. Together, we hoped to understand the geomorphological evolution and the present state of the ecosystem.

The historical development can be interpreted from a map (1918) showing ancient embanking and black-and-white aerial photographs of the stretch (1930 and 1955). These show differences in land cover and geomorphological situations. The last version (1995) of the *Soil reference system*, proposed by the French association for the soil study (A.F.E.S.), was used to describe the soil profiles. The properties used will be discussed in the next section.

The present spatial distribution of soils in the embanked stretch of the river has been elucidated by surveying and mapping the present-day situation. The soil survey was based on observations at 303 points at which the following properties were recorded: depth, number of horizons, thickness of each horizon, HCl effervescence, organic matter content, and percentage of coarse material.

Afterwards, observation points were grouped hierarchically following the computation of similarities between them (Gower, 1971). We used intermediate linkage clustering for the grouping (connexity 0.5) (Sneath, 1966). The characteristics of each group are defined by a contingency table (Legendre & Legendre, 1984 a-b). The group fusion level is defined by a distance (D).

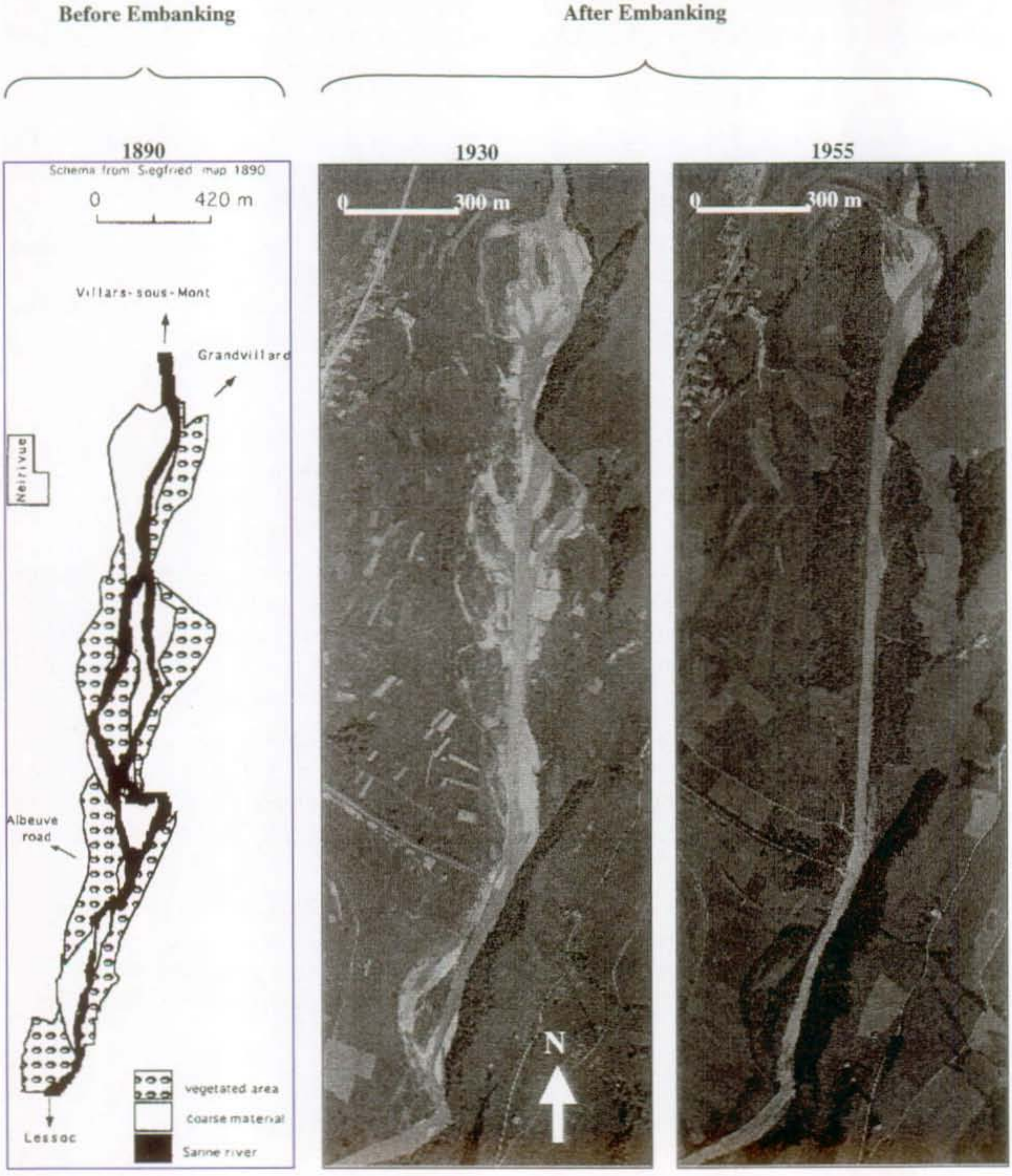

Figure 4.2 - Changes in land cover and channel evolution with the time.

4.4 Results and Discussion

4.4.1 Soil diversity in the embanked stretch

The clustering separates four groups of soil (Fig. 4.3). The characteristics of each group are shown in Table 4.1.

Table 4.1 - Characteristics of the soil groups

Parameters	**Group I** (39% of samples)	**Group II** (16% of samples)	**Group III** (35% of samples)	**Group IV** (10% of samples)
Depth	Thin: Mean = 26 cm ± 19 cm 75% ≤ 30 cm 50% between 10 and 30 cm	Thin : Mean = 19 cm ± 8 cm 75% ≤ 21 cm 50% between 10 and 21 cm	Deep: Mean = 55 cm ± 19 cm 75% ≤ 65 cm 50% between 40 and 65 cm	Very deep: Mean = 99 cm ± 24 cm 75% ≤ 120 cm 50% between 90 and 120 cm
Number of horizons	1 (59%) 2 (32%)	2 (94%)	2 (34%) 3 (64%)	3 (17%) 4 (38%) 5 (24%)
$CaCO_3$ (1)	Mean = 35% ± 8% 75% ≤ 39% 50% between 32 and 39%	Mean = 33% ± 5% 75% ≤ 36% 50% between 29 and 36%	Mean = 36% ± 8% 75% ≤ 39% 50% between 31 and 39%	Mean = 38% ± 7% 75% ≤ 43% 50% between 33 and 43%
Organic matter (2)	Mean = 11% ± 3.5% 75% ≤ 12% 65% between 8 and 12%	Mean = 13% ± 3% 75% ≤ 14% 65% between 11 and 16%	Mean = 11% ± 3.5% 75% ≤ 12% 65% between 7 and 12%	Mean = 10% ± 4% 75% ≤ 11% 65% between 7 and 11%
Presence of coarse elements	100%	---	---	---

(1) Calcimeter of Bernard

(2) Rate of ashes; combustion by 600°C

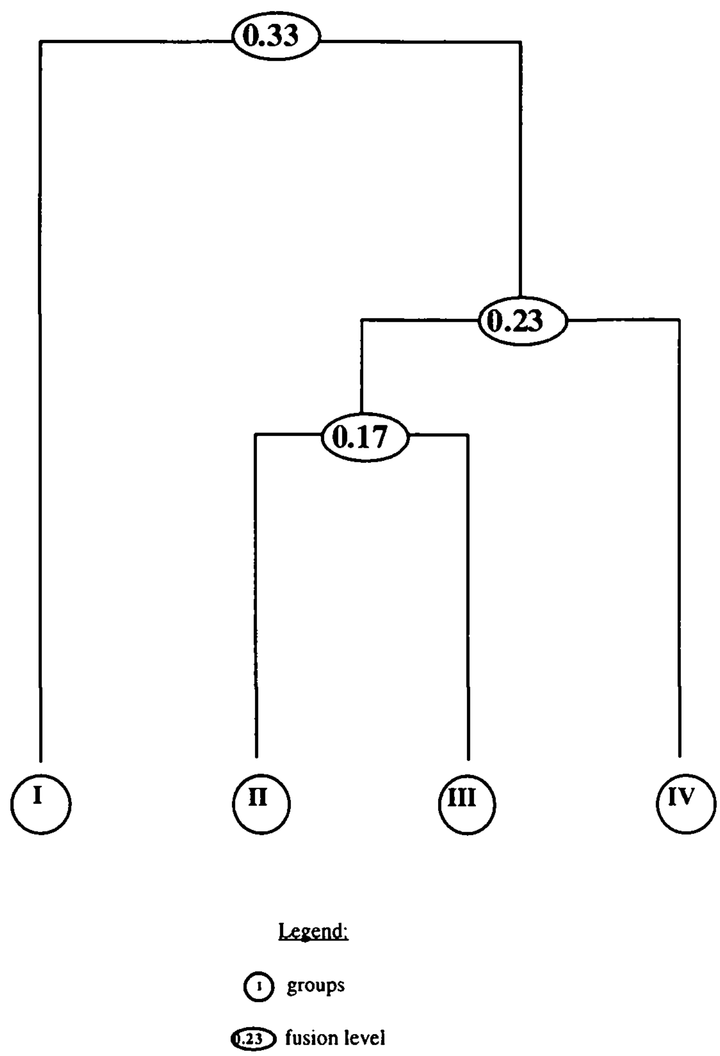

Figure 4.3 - Simplified dendrogram for 303 soil profiles

The first group (I in Fig. 4.3) and the largest consists of thin soil with only one horizon and is clearly distinct from the other. It is the only group in which the soil contains coarse material. Groups 2 and 3 are not so distinct from each other. Group 4, with few sites (10% of samples), consists of very deep and polygenetic soil in several superposed layers of sediments (up to 8).

All the soil contains abundant $CaCO_3$ (mean = 35-38% ± 5-8%), and the organic matter contents are similar for the groups I, III and IV. The exception is the group II, which contains somewhat more. All four groups are similar, which suggests that soil formation is essentially due to sedimentation rather than *in situ* evolution. Sedimentation can be expressed by the soil thickness, the presence of coarse elements, and the number of horizons (which are mainly sedimentary) in the conventional sense. There is no relation between thickness and loss of carbonates (the $CaCO_3$ content is similar throughout). In other words, *in situ* pedogenesis has been weak.

4.4.2 The origin of the current soil diversity

Fig. 4.4 shows four old geomorphological situations along the river as reported on the map of 1918. An example of a soil profile on each is shown in Fig. 4.5. Data on the general, physical and chemical characteristics for each profile are given in Table 4.2. The soil is a calcareous FLUVIOSOL, which corresponds to Entisol, suborder Fluvents, in the Soil Taxonomy (Soil Survey Staff, 1992).

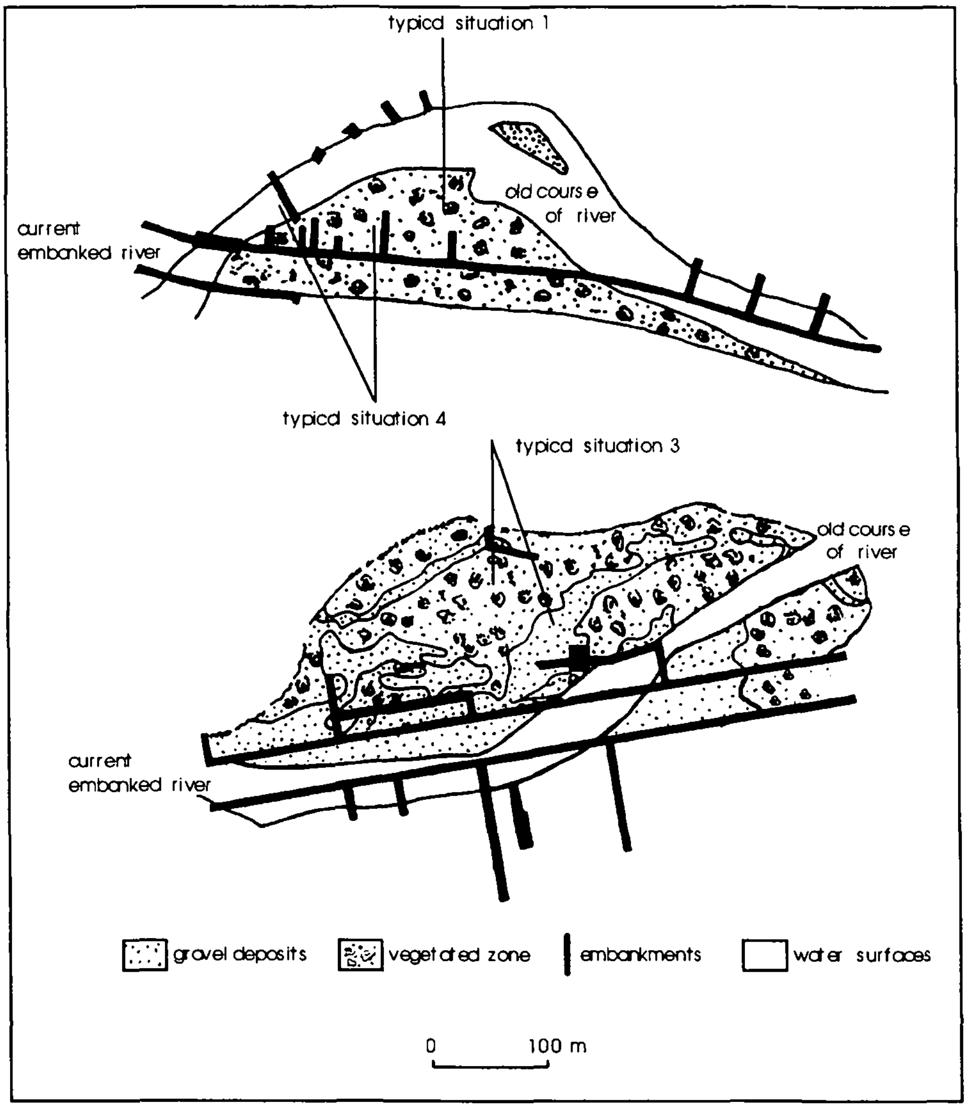

Figure 4.4 - Schema of old geomorphological situation along the river

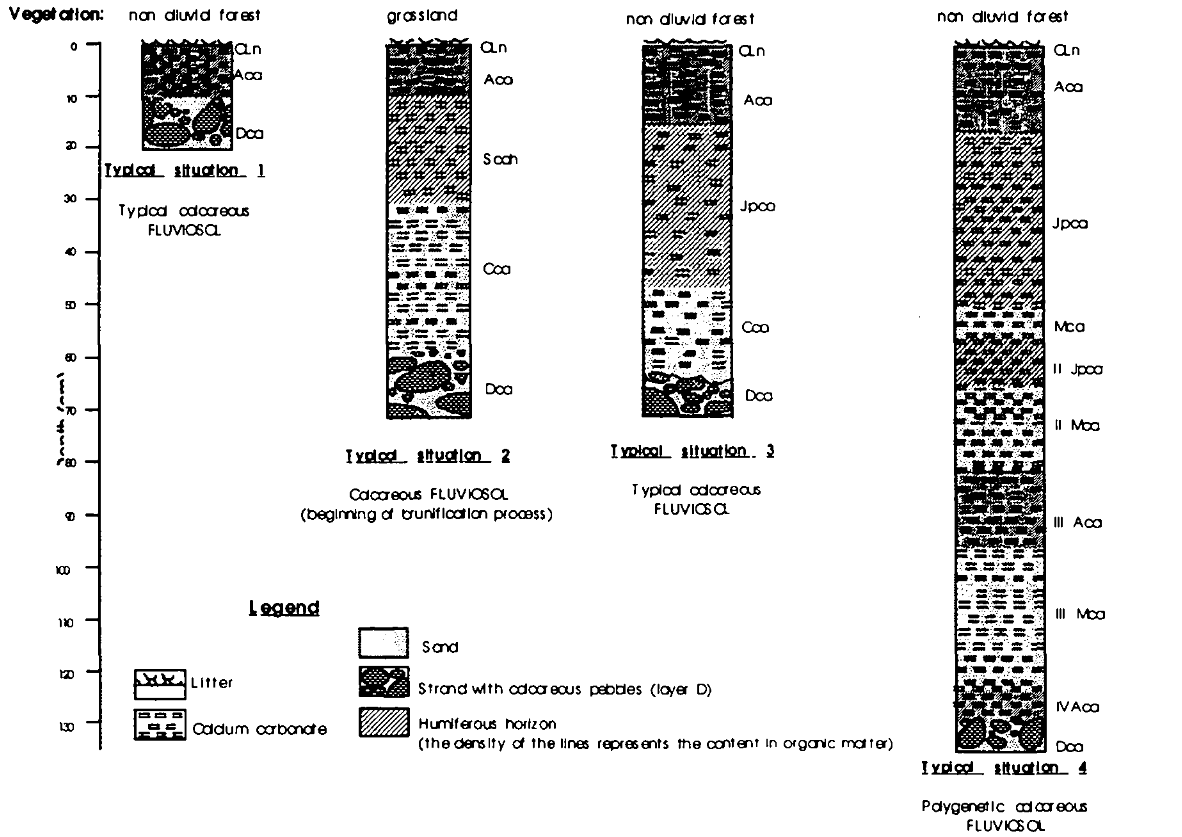

Figure 4.5 - Soil profiles of geomorphological typical situations

Four situations have been identified:

- *situation 1*: the soil is in the highest topographic position, for example an old island (Fig.4.4.). It has been protected from sedimentation since 1918 or perhaps earlier. At that time, it was already colonised by vegetation. It is thin (around 10 cm), contains much organic matter (8%), has a well developed organic structure, a low bulk density (0.49 g/cm^3) (Table 4.2 and Fig. 4.4 and 4.5) and is biologically very active (humus type mull - Duchaufour, 1991). Today the soil is covered by an alluvial floodplain forest with an indeterminate status (in this case, essentially *Picea abies* forest).

- *situation 2*: this is far from the river (around 150 m) where fine sediments were deposited in slack water. This soil is moderately deep and contains the most clay (22%). It is beginning to turn brown (horizon Scah, with a well pedologic developed structure - Table 4.2 and Fig.4.5) and has been under by grass for at least 100 years.

- *situation 3*: here were braided sediments deposited by the river as it changed course. The typical calcareous FLUVIOSOL is found here. The soil has an intermediate depth and morphological characteristics (Table 4.2 and Fig. 4.4 and 4.5) and is today covered by an alluvial floodplain forest with an indeterminate status.

- *situation 4*: this soil is developed just behind the embankments (less than 30 m) or in a old embanked branch of river (Fig.4.4). This calcareous polygenetic FLUVIOSOL is the deepest (more than 80 cm) with many layers (up to 8) caused by episodic deposition of alluvium (Table 4.2 and Fig. 5.5).

Table 4.2 – General physical and chemical characteristics for the four soil profiles as shown in Fig. 4.5, locations as in Fig. 4.4.

Profil Number	Distance river (m)	Depth (cm)	Horizon	Thickness (cm)	Color(1) (moist)	pH (2) water	Corg(3) (%)	N tot(4) (%)	CaCO3(5) (%)	Exchangeable cations (meq/100g) (6)				Bulk density (g/cm3) (7)	Particle size distribution (%) (9)		
										Ca	Mg	K	Na		Sand	Silt	Clay
1	20.0	10.0	Aca	0-10	7,5 YR 2/2	7.8	8.2	0.4	37.7	34.1	0.9	0.2	0.1	0.49	70.6	17.9	11.5
2	80.8	60.0	Aca	0-10	7,5 YR 3/2	7.7	5.4	0.3	31.7	29.4	1.1	0.5	0.2	0.94	37.5	40.7	21.8
			Scah	10-30	7,5 YR 2/2	8.0	2.3	0.1	35.4	17.0	0.5	0.2	0.1		39.5	44.0	16.5
			C	30-60	10 YR 4/2	8.2	1.5	0.1	35.9	12.6	0.1	0.4	0.1		47.5	39.6	12.9
3	100.1	65.0	Aca	0-15	7,5 YR 3/1	7.9	3.6	0.2	38.0	24.3	0.6	0.1	0.1	0.81	55.8	38.7	5.5
			Jp	15-45	7,5 YR 3/4	8.1	1.0	0.1	48.7	11.8	0.3	0.1	0.1		69.0	21.2	9.8
			C	45-65	7,5 YR 4/4	8.5	0.0	0	60.5	5.2	0.2	0.0	0.1		90.6	5.3	4.1
4	61.2	130.0	Aca	0-15	7,5 YR 2/2	8.1	3.6	0.3	31.5	24.9	0.7	0.2	0.1	0.94	39.0	48.7	12.3
			Jp	15-50	10 YR 3/4	8.1	1.6	0.1	36.2	14.7	0.4	0.1	0.2		46.7	39.9	13.4
			M	50-55	7,5 YR 4/4	8.6	0.4	0	51.9	5.3	0.2	0.0	0.1		91.3	4.9	3.8
			II Jp	55-65	10 YR 4/3	8.3	0.8	0	39.2	8.4	0.3	0.1	0.1		60.3	31.8	7.9
			II M	65-80	10 YR 4/6	8.5	0.5	0	57.6	9.0	0.2	0.0	0.1		91.7	4.6	3.7
			III Aca	80-95	7,5 YR 2/2	7.8	2.5	0.1	33.9	18.9	0.9	0.1	0.1		46.7	40.9	12.4
			III M	95-124	7,5 YR 4/4	8.5	0.2	0	52.7	5.6	0.3	0.0	0.2		88.5	6.6	4.9
			IV Aca	124-130	7,5 YR 1.7/1	7.9	3.0	0.2	39.1	19.5	0.9	0.1	0.2		45.8	41.9	12.3

(1) Munsell color charts
(2) pH water (ratio 1/2.5)
(3) C org. = organic carbon (combustion and titration of the CO2 released with a Carmograph Wösthoff 8-ADG)
(4) N tot = total nitrogen content (minaralization type Kjeldahl, colorimetric titration Technicon
(5) CaCO3 = carbonates (reaction with H3PO4 and titration of the CO2 released with a Carmograph Wösthoff 8-ADG)
(6) Exchangeable bases (Cation Exchange Capacity at soil pH, exchange with KCl and NH4Cl)
(7) Bulk density (cylindre of 100 cm3)
(8) Particle size analysis: particle size < 2mm
(9) Structure (grade, class and type) - Soil Survey Manual(1951)
* **particular structure in organic sheets, arranged around a horizontal plane**

This particular ecosystem owes its character to geomorphic processes rather than *in situ* pedogenetic ones. The weak pedogenesis could be related to an initially large amount of carbonate in the alluvium and a short time for evolution.

4.4.3 Comparison between the embanked zone and the active zone

The map of vegetation (1:10'000) made by Gallandat *et al.* (1993) shows the following:

1) an active stretch which contains a large variety of forest communities typical of an alluvial ecosystem: (a) mixtures of willow (*Salix elaeagnos*) and alder (*Alnus incana*); (b) alder and ash (*Fraxinus excelsior*); (c) alluvial floodplain forest with an indeterminate status and; d) non alluvial forest, composed of beech, sycomore and spruce forest (*Fagus silvatica*, *Acer pseudoplatanus*, *Picea abies*).

According to Bureau *et al.* (1995), the soil of the active zone shows a pedological diversity which is related to different states of vegetation. Raw calcareous FLUVIOSOL and calcareous FLUVIOSOL are colonised by willow communities, alder communities are associated with the calcareous polygenetic FLUVIOSOL, and alder-ash communities have grown up on calcareous FLUVIOSOL. The soil under the beech forest is calcareous FLUVIOSOL that is just beginning to turn brown. The brunification process is related not to the alluvial dynamics (it is far from the river now and above flood level). Soil and vegetation can be arranged along chrono-toposequences.

2) an embanked stretch characterised by a fairly uniform plant community (forest of alluvial floodplain with an indeterminate status and grassland). Generally the forest here no longer has the status of an alluvial community. Our results show that the soil is morphologically diverse, but the pedogenesis is discreet and, except under grass, is weaker than the one of non-alluvial forest in the active zone.

4.4 Conclusion

By combining historical records with an examination of the present-day soil and vegetation we have been able to show that the alluvial zone has changed during a short time (less than 100 years) after embanking till now. In this stretch of the river valley, the effects of embankments have been enhanced by the action of the hydroelectric installations of the upper Sarine in 1970.

The change of the hydrodynamic Sarine's regime by embanking (Gétaz, 1977) associated with the original geomorphologic situation (Fig.4.4) seem to be responsible for the changes of the vegetation evolution and soil formation, evolution and present spatial distribution.

In general, our results show that embanking has affected the soil in two ways: 1) a local effect on the sedimentation (trapping sediments behind the noninundated embankments). This process would produce the thick soil (situation 4) and; 2) an effect on the whole stretch by protecting it from the alluvial dynamics and by creating new pedological conditions (absence of erosion).

According to our results of soil profiles analysis, the inheritance of new material has dominated pedological *in situ* development. This pattern can be explained by the abundance of calcium carbonate in the alluvium, which delay the pedological evolution. Thus, the soil is little differentiated (essentially calcareous FLUVIOSOL and some FLUVIOSOL beginning to turn brown).

The aerial photographs show that the vegetation has closed up quickly after embanking (about 30 years - Fig.4.2). This agrees with Gallandat *et al.* (1993), who observed a loss of vegetation diversity and even of its alluvial status. Nevertheless, we have found under this uniform vegetation a large morphological diversity of FLUVIOSOL.

In other words, the evolution of the vegetation along the embanked stretch has become disconnected from that of the soil. However, even if the changes are evident, the functioning of this ecosystem need further research.

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Chapter Five

Three-dimensional GIS cartography applied to study the spatial variability of soils in a Swiss floodplain[7]

Abstract

We propose a framework to study and represent in 2- and 3- dimensions (2-D, 3-D) the spatial variability and distribution pattern of soils in the Sarine River's floodplain. This environment is characterised by a high lateral and vertical spatial variability of soils corresponding to temporal and spatial variation of fluvial dynamic. This study was carried out by using the functions of existing GISs (geographical information system) with specific applications to soil cartography. This GIS cartography is based on the notion of soil horizon instead of soil diagnostic profile. A GPS (Global Positioning System) survey was carried out in order to construct a local DEM (Digital Elevation Model) and ascertain the co-ordinates for each of the 181 soil points. All data were stored in a GIS database, and both landform modelling and soil cartography was undertaken. Both GIS, ARC/INFO and Vertical Mapper for MapInfo were adequate to undertake triangulation interpolation, to run contour processing and to create cross-sections as well as the corresponding vertical profiles, in order to illustrate the superposition of soil horizons along any line across the sampled area. A three-dimensional representation of soil was obtained by quadratic finite element method, generally used in geological studies and adapted to the representation of soil horizons. This 3-D cartography allows one to follow through space the spatial pattern of a given horizon, the variation of its thickness, the superimposition of the different soil horizons, the total soil depth, and the number of horizons at any given point. Furthermore, this approach facilitates the perception of soil as a continuum in space and permits the visualisation of the possible relationships between one horizon and/or the soil and the topography, for example. By enabling a realistic representation and easy visualisation of the spatial distribution and variability of soils in the landscape, this methodological approach is a powerful tool for soil scientists, and could provide a useful decision-support tool for ecosystem management.

5.1 Introduction

Several authors have discussed the two main models used in the development of soil cartography, i.e., the discrete and the continuous models (Baize, 1986; Aubert and Boulaine, 1989, Legros, 1996; Lark and Beckett, 1998). Traditional soil cartography is based on the discrete model of soil spatial variability. This model assumes that soil characteristics or type change abruptly at soil boundaries. In general, each map unit represents a pedological characteristic that is constant or a unique type of soil. In the latter case, the unit is defined by a "representative soil profile" (Soil Survey Staff, 1976). Webster and Oliver (1990) consider the discrete model as inflexible "because classification into soil series or stratigraphic units, for example, tends to be a once-for-all exercise. Once the classes are defined and their boundaries mapped, little can be conveyed about their variation in composition from place to place".

7 Paper presented at the Symposium 17 of the XVI World Congress of Soil Science (Montpellier, France) and submitted to GEODERMA – special issue about "Advances in soil survey using modem tools", with the following co-authors: Mahmoud Bouzelboudjen (Neuchâtel University), Claire Guenat (EPFL-IATE/Pédologie) and François Golay (EPFL-IGEO-SIRS).

In general, the discrete model is not realistic because natural boundaries in landscape tend to be gradual rather than abrupt (except in some cases, like geological discontinuity, change of incline, etc). Nevertheless, in some cases (very sharp changes in soil properties and at intermediate mapping scales), traditional soil cartography can be more appropriate (Votz and Webster, 1990; Lagacherie *et al.*, 1995).

Another way to approach soil spatial variability is the continuous model. This model assumes that the soil characteristics vary gradually over space. To address the continuum aspect of soils, FitzPatrick (1986) recommended to base soil cartography on the notion of horizons instead of soil profiles.

This method combines three advantages: (1) it considers soil as a three-dimensional continuum, (2) its takes into consideration the spatial variability of soil in the landscape, and (3) the superposition pattern of the soil horizons can be analysed. These advantages of the cartography by horizons have already been discussed by several authors (Boulet *et al.*, 1982 ab; Boulet *et al.*, 1989; Girard, 1983; Girard, 1989; Girard et al, 1989; King, 1986; Pedro, 1989; Ruellan *et al.*, 1989). Lahmar *et al.* (1989) has used soil formula (possible or real sequences of horizons) instead of soil profile to draw soil maps. Soil cartography by horizons has been applied more often to tropical soils or soils whose horizons are clearly differentiated (Bocquier, 1973).

In the past, the lack of tools to deal with the continuous model has led soil scientists to adopt the discrete model to classify and map soils (Burrough, 1986; Bouma and Bregt, 1989). However, Burrough (1993) has outlined the technical progresses (geostatistical, digital database, GIS, fuzzy logic, chaos theory...) made during the last twenty years (e.g., to record, analyse, and use information about spatial soil variability) that have rendered the used of continuous model possible.

Among these techniques, and because of its advantages, geostatistics is more and more used in soil science (Voltz and Webster, 1990; Gruyter *et al.*, 1994; Qian and Klinka, 1995; Voltz *et al.*, 1997; Burrough and McDonnell, 1998). Furthermore, the use of GIS technology is greatly facilitating the 3-D visualisation of soil as a continuum.

These visualisation techniques have been recently developed in the field of geology (Bouzelboudjen and Kimmeier, 1998; Houding, 1994). By contrast, in soil science this kind of representation is still in its infancy (Ameskamp, 1997; Benz, 1995; Heijs *et al.*, 1996; Pereira and FitzPatrick, 1998).

As previously discussed in Chapter 1, the *pedogenesis* of alluvial soils is particularly influenced by the composition of the sediments that varies with erosion and deposition processes (fluvial dynamic). Horizons in these soils are mainly differentiated by their texture, therefore the notion of a "soil-diagnostic profile" does not apply to floodplain soils. In addition, the thickness of the horizons provides information on the characteristics of the sedimentation processes.

In such soils the sequence of horizons at a given location is the result of sedimentation and *in situ pedogenesis*, and these two processes overlap (Gerrard, 1992; Mendonça Santos *et al.*, 1997a). Consequently, the method based on soil diagnostic profile is not appropriate to classify and map floodplain soils (Finkl, 1980; Gerrard, 1992), and the approach by horizons (continuous model) seems to be more adequate to describe the complexity and variability of these soils.

This study was carried out by using the functions of existing GIS with specific applications to soil cartography. This chapter focuses on the methodological aspects of the study. The cartography was based on the notion of soil horizon instead of soil diagnostic profile. The application of the methodology to a floodplain is justified by the fact that floodplain soils have a high spatial variability (lateral and vertical) due to the influence of the variation of fluvial dynamic in space and time.

5.2.Material and methods

5.2.1 Study area

The study site has already been described and illustrated in Chapter 1. However, the sub-site object of this particular three-dimensional cartography, as well as the soil sampling plan is illustrated in Figure 5.1.

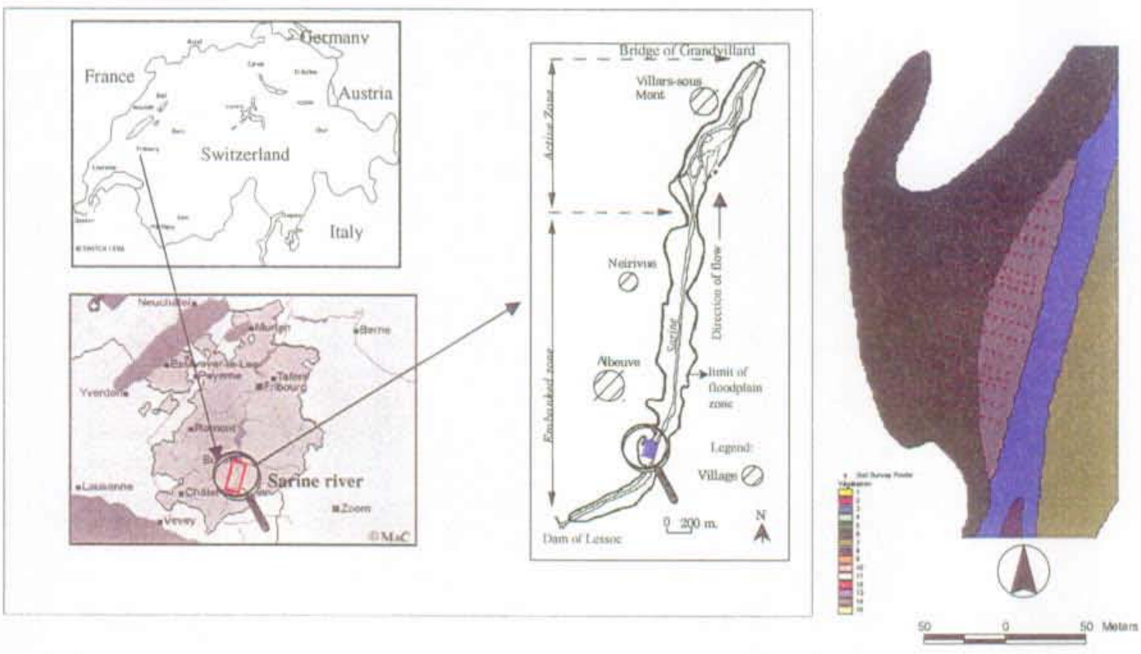

Figure 5.1 – The study site location (in red), the location of the sub-site object of this chapter (in blue) and the soil sampling plan.

5.2.2 Methodology

This study was carried out by using the functions of existing GIS (ARC/INFO, Arc View and Vertical Mapper of Map Info) with specific applications to soil horizon cartography. Figure 5.2 illustrates the three principal parts of the methodology that are supported by a GIS database: data acquisition, landform modelling and soil horizon cartography.

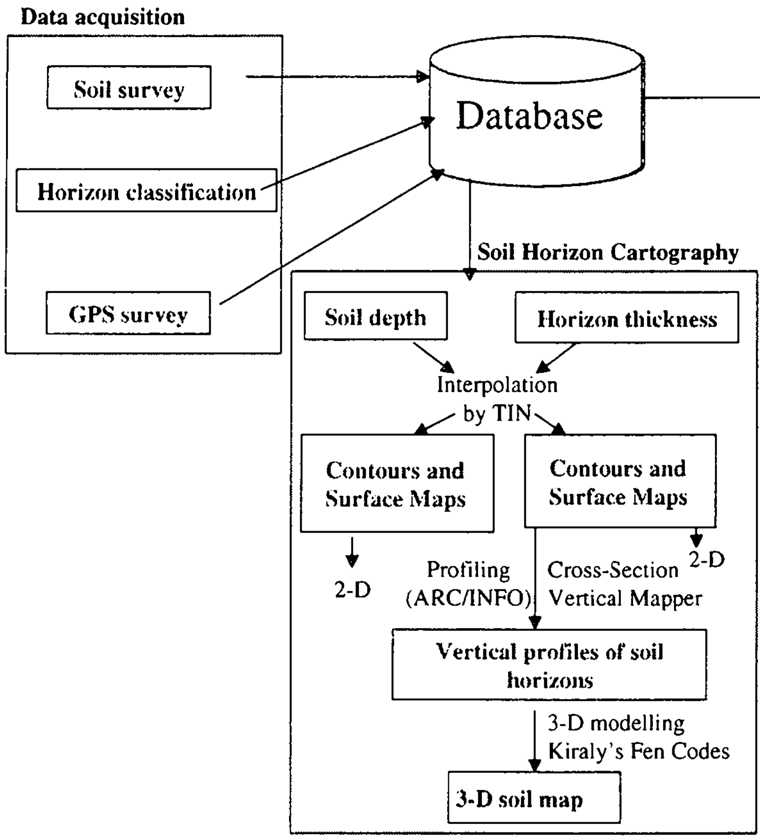

Figure 5.2 - Scheme of the methodological approach

5.2.2.1 Data acquisition

The soil population (181 soils) was surveyed using a pedological (core sampling) drill. The sampling network was a regular grid (5 meters in EW direction and 10 meters 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 texture (field texture) of each horizon.

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

- presence or absence of coarse material (gravel and pebble);
- organic matter content (determined by combustion at 600°C);
- structure (grade, class, and type) according to the Soil Survey Manuel (Soil Survey Staff, 1951), and
- the presence of carbonates (detected in field by HCl effervescence).

Horizon classification was carried out according to the "Référentiel Pédologique 1995" (A.F.E.S., 1995). In addition, soil texture and the structure of the topsoil were taken into consideration to classify the different horizons. To enable modelling, we had to decide, according to the data set, an order for horizon appearance (sediment deposition).

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

5.2.2.2 Landform modelling

The data of the GPS survey were interpolated using a TIN (Triangulation Interpolation Network) and a DEM (Digital Elevation Model) was built. With this technique, the surface of each triangle passes exactly through each known data value. According to Bonham-Carter (1994) it is desirable in cases where data are known to have relatively small errors, such as in our case, where X, Y, Z co-ordinates were determined in a accurate surveying.

5.2.2.3 Soil cartography

Due to its characteristics (regular grid, dense sampling, and precise measures) our data set could have been interpolated by different techniques (TIN, kriging, Inverse Distance Weighting...). In this work, only the results obtained with the TIN technique were presented.

The three-dimensional soil cartography by horizons was performed in a GIS environment by the following steps. First, the Z (elevation) values of the bottom of each horizon were calculated (based on the surface elevation value, measured by GPS and the soil depth). Then, these values were interpolated and contour processing was used to create isolines contouring the soil survey points. Maps with both isolines and filled contour areas were generated in 2-dimensions.

Based on the corresponding grids of the two-dimensional maps, vertical profiles (cross-sections) could be drawn along any line across the sampled area, using the Profiling procedure in ARC/INFO or Cross-section in Vertical Mapper (Map Info) softwares.

Finally, a three-dimensional volume model was created in order to represent soil as a continuum in the landscape. It was done using a quadratic finite element method (Kiraly's Fen Codes)(Király, 1985) adapted to soil modelling. This 3-D volume is based on a network of triangular elements (with 6 nodes) and rectangular elements (with 8 nodes) which goes through all the points measured.

5.3. Results

Figure 5.3 illustrates the different steps for building a DEM: the soil survey points and the TIN network mesh (a); the isolines of contour elevation (b); the DEM (c) in 2,5 D. The constructed DEM allows the visualisation of local differences in topography, not possible in the official DEM (1:25.000). In the studied sub-site, three regions are illustrated: the highest, that corresponds to an old island and its prolongation, that could be easily viewed in the middle of the site; a medium zone on the left side and a depression on the right side, which is close to the river, and not shown here.

Figure 5.4 shows the spatial pattern of the soil depth for the studied sub-site. As can be observed, the thinnest soils are found in the highest topography and the deepest soils, in the depression area, close to the river channel. In fact, the spatial distribution of the deepest soils follows the island and its prolongation.

Table 5.1 – Database entries for horizons thickness

					Horizons thickness (cm)											
Number	**Soil_id**	**X(m)**	**Y(m)**	**Zsurface (msm)**	**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

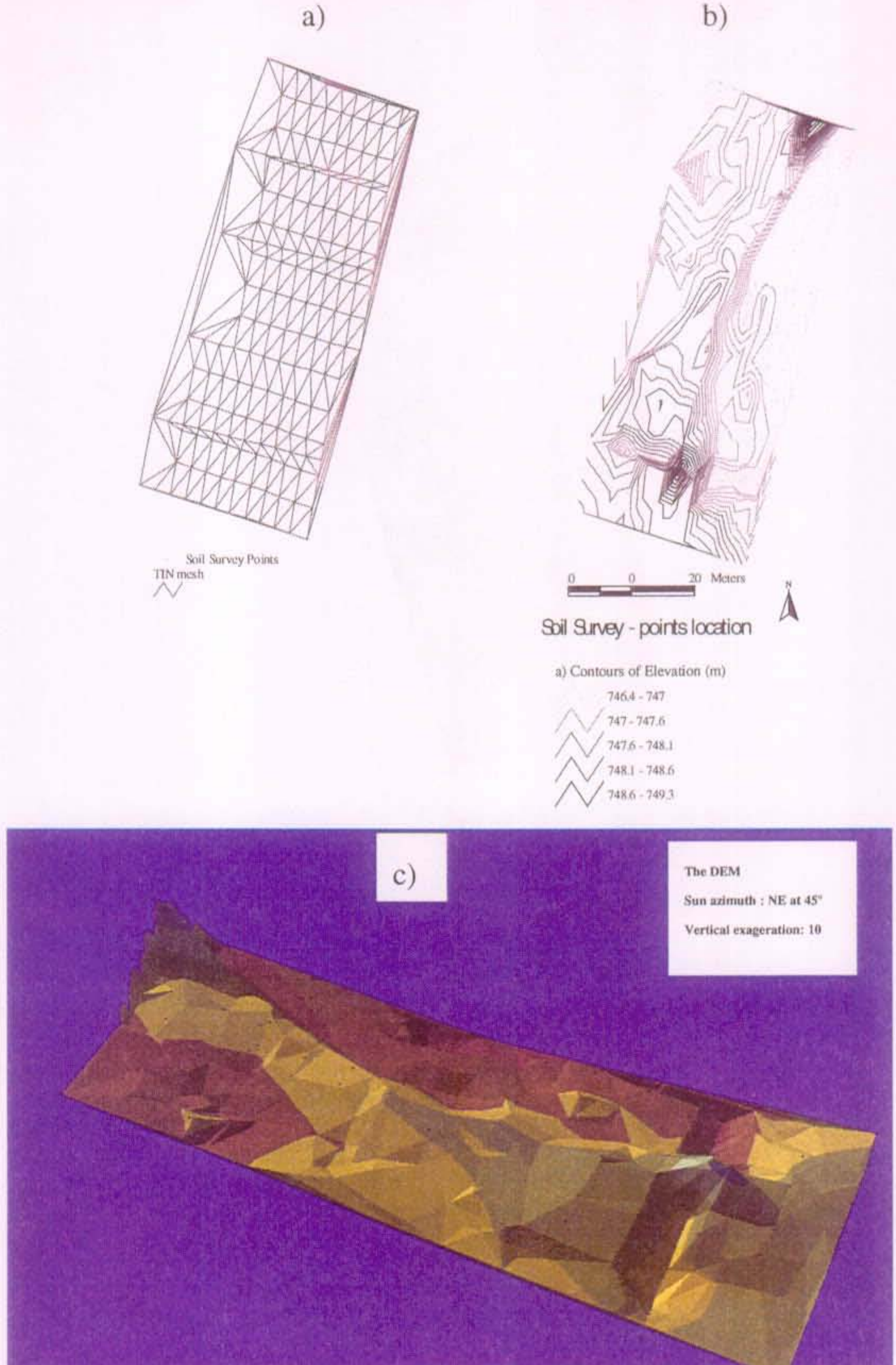

Figure 5.3 - The Digital Elevation Model of the study site; a) The triangulated network (TIN) that honours each soil survey point; b) The elevation contours of the site; c) The DEM (2.5-D); bright = the top, dark = depression.

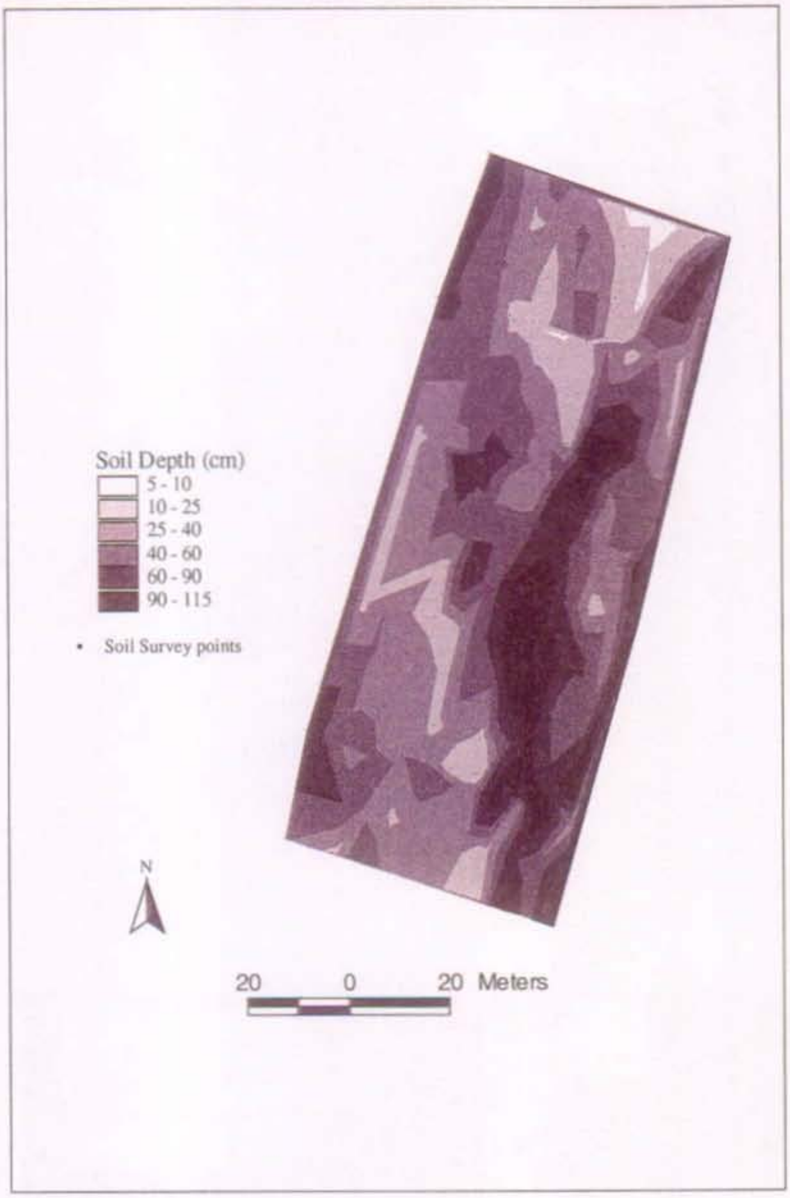

Figure 5.4 – Spatial pattern of the soil depth

Horizon thickness was mapped in 2-D for each of the twelve horizons. The maps of Figure 5.5 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 variation of their thickness;
- control the presence/absence of a given horizon at any particular point. For example, the first map concerns the A horizon which is present everywhere, while the last one concerns the M horizon (a sandy horizon), which is present only at some points. The white values in the two last maps signify the absence of the referred horizon;
- compare the spatial pattern of distribution of the different horizons;

Furthermore, these maps can also be draped on the surface plot of the DEM in order to study the relationship between horizon and topography. Nevertheless, the 2-dimensional representation is not capable of integrating all of the soil horizons simultaneously. This is consequently, insufficient for the purposes of pedogenetic studies, though they do constitute an indispensable step towards for the 3-D representation.

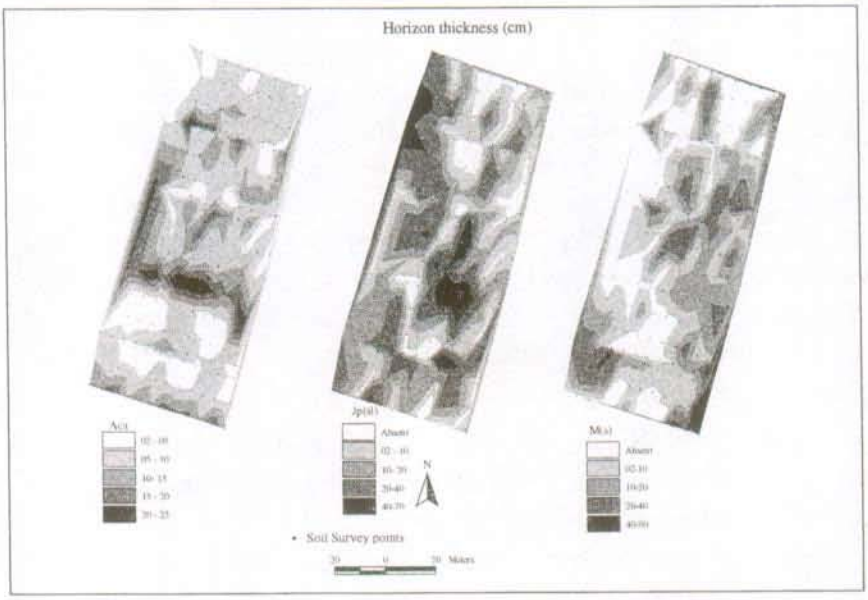

Figure 5.5 - Maps of horizon thickness for the first three horizons

Some results obtained with the 3-D approach are illustrated by Figure 5.6. In the upper-left corner the DEM shows the location of three cross-sections (two transversals and one alongside the river). The vertical profiles of soil horizons (or cross-section) can be visualised in this figure. The legend in the right side of the vertical profiles indicates the horizon classification, according to the "*Referentiel Pédologique* 1995" (A.F.E.S.).

As can be observed, the cross-section L1, which is located close to the river channel, passes from an elevation of 748m, crosses all the depression area (with the minimum of 746m) and ends at the old island (the highest point in the site, more than 749m). Even if the elevation difference is small, locally it is a very important factor to the sedimentation process. As can be observed, in the lowest points, the quantity of horizons is bigger than in other points. The corollary is that in the highest point (the old island, at the end of the transect), the soil have only one horizon. The same tendency is verified in the other cross-sections, that shows also the intermediate soil in terms of quantity of horizons.

The three-dimensional representation (Figure 5.7) shows the soil as a volume in space and conserves the advantages of the vertical profile (or cross-section) representation. It represents the same facts into a volume viewing and shows that several cuts could be done, following a given perspective, according to the wanted goal.

5.4. Discussion

For pedological studies and particularly those concerning alluvial soils, such a GIS-cartography that allows the representation of soil as a continuum model in three-dimensions is a very important advance. Such an approach allows visualisation and facilitates the interpretation of the relationships between horizons (lateral and vertical), as well as that with the topography. Despite the focus given in the methodological approach itself, the analysis of the results shows that in the studied floodplain, soils with few horizons or even with only one horizon are found in the highest positions and that with several horizons superimposed are found in the zones of depression. This pattern illustrates clearly the influence of the river dynamic upon soils, and particularly on that close to the river, in the lowest topography. These are soil essentially formed by the alluvial deposition, with several horizons and a coarse texture (according to soil survey results – chapter 3). In contrast, the soils from the highest position, and in particular those with one horizon, are organic soil, with a well-developed structure and a thin texture. In fact, these soils were for a long time protected from floods, due to their high position in the studied site.

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

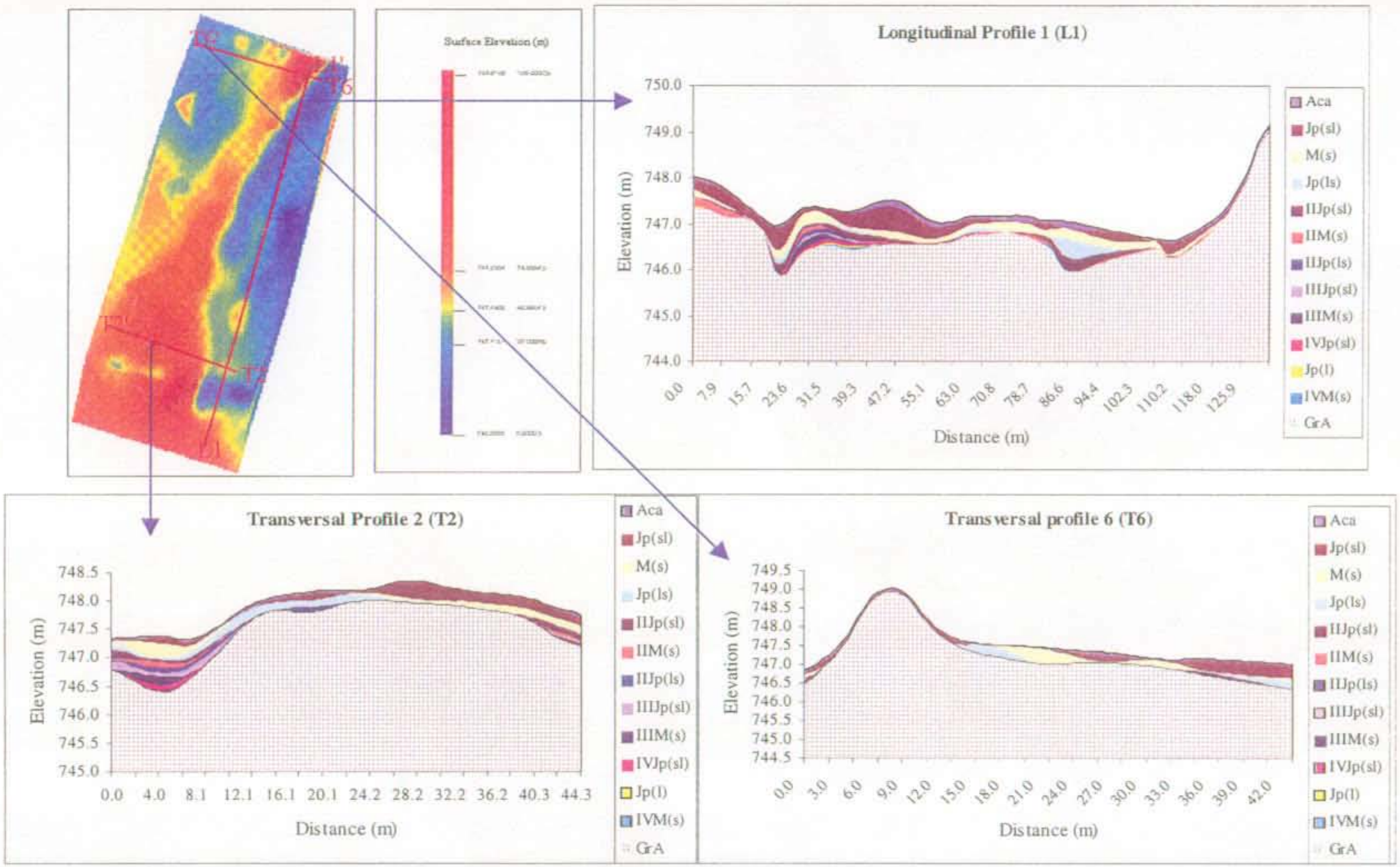

Figure 5.6 - DEM image with cross-sections location and the corresponding vertical profiles of soil horizons

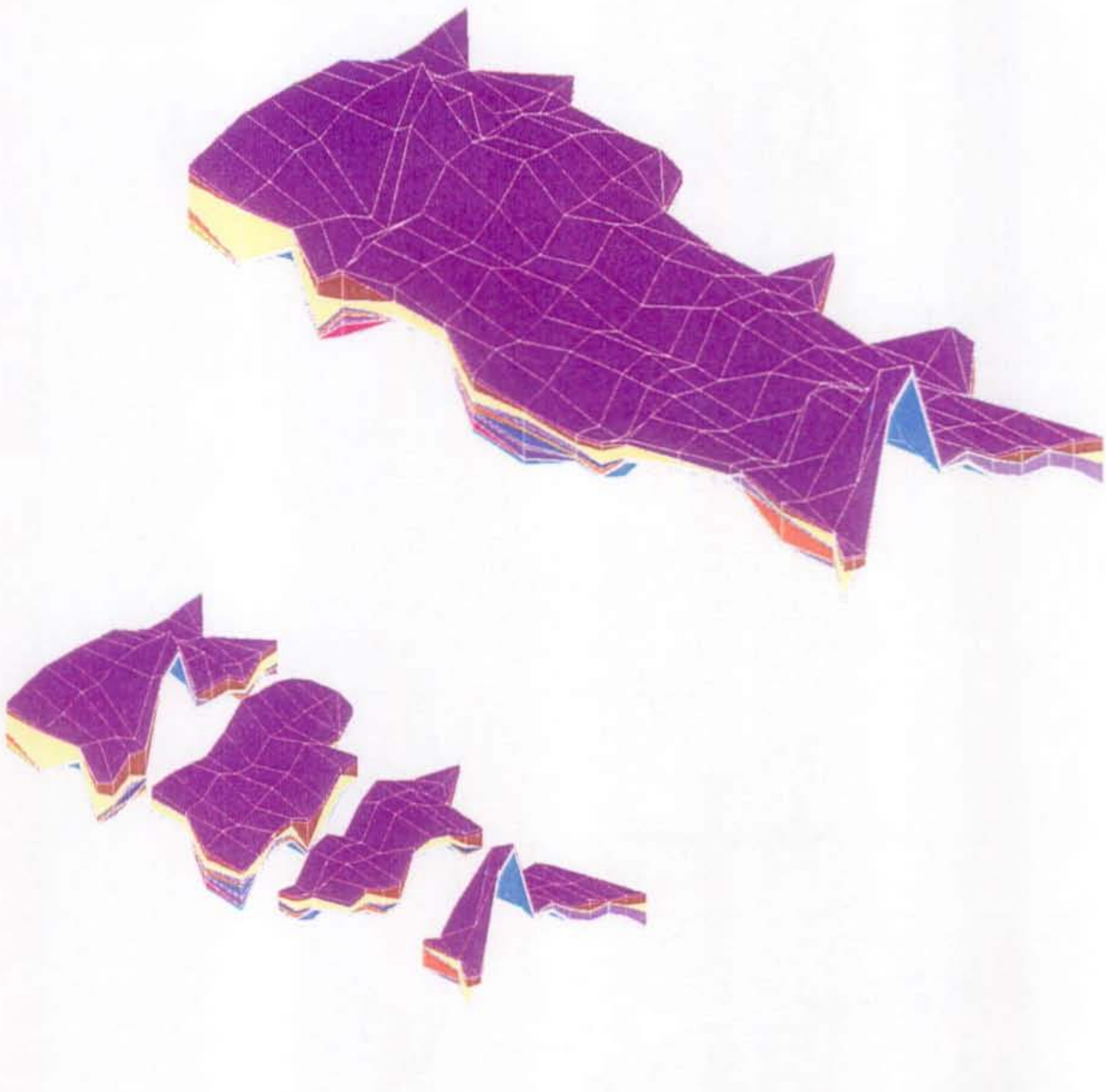

Figure 5.7 - Three-dimensional soil volume model (sun azimuth: N at 60°, tilt: 30°, vertical exaggeration: 10). The vertical nods of the network correspond to the soil survey points. a) the whole site; b) three transversal cuts.

5.5 Conclusions, limits and future improvements

Concerning the methodological approach undertaken, the three-dimensional GIS cartography has some relevant advantages beyond that of traditional cartography. It permits a more realistic representation of soil, because it is based on a continuous model of the reality. Furthermore, it facilitates visualisation of the spatial distribution and variability of soil in the landscape. In addition, this three-dimensional GIS cartography offers a flexible approach, particularly considering 1) the non-requirement of any previous classification; 2) the choice of the soil parameters to be mapped; 3) the number and location of cross-sections to be done.

This work demonstrates the undeniable utility of GIS technology for soil scientists, in facilitating data set management, spatialisation, analyse, visualisation and mapping in a interactive way.

With regards to the study of the variability and spatial distribution of soils, such an approach seems to be the most adequate to study the present-day situation of soils, and explain their formation and evolution processes, principally for alluvial soils, which formation is the resulting of inheritance and in situ pedogenesis processes overlapping in space and time. In this way, it has facilitated the visualisation and understanding of the lateral and vertical soil variability: thickness variation of a given horizon, the total soil depth, as well as the number of horizons and its superimposition. The representation of soil horizon superimposition enables the perception of soil as a continuum in space, instead of discrete soil units. Finally, this approach allows us to visualise clearly the relationships between the topography and either one horizon or the complete soil ensemble. In order to explain such a relationship, as well as the formation and spatial distribution of soil, the site history should be considered.

Future improvements must focus on the use of geostatistical techniques in order to quantify the spatial variability of these soils (with error estimation). Furthermore, since the sedimentation process can also influence the spatial distribution of vegetation in such environment, the relationships between soil and vegetation at a local scale should give interesting insights for the comprehension of the change dynamic in embanked floodplains. Finally, this GIS-assisted cartography can be associated with thematic maps in order to provide a useful decision-support tool for the management of such ecosystem.

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Part III: GIS and Spatio-Temporal Modelling

Chapter Six

The GIS[8] design Methodology and the application[9] modelling within a spatio-temporal database perspective

Abstract

A GIS design methodology developed with regards to the environmental research context was undertaken based on the existent propositions applied to institutional GIS design. The complex nature of our environmental application - the study of the evolution of an alluvial ecosystem after the human intervention -, as well as the need in the research context to understand and explain how and why things happen, have driven our attention to undertake a GIS methodological approach that could help in the structuring of scientific reasoning and that integrates the dynamic aspect of real-world entities. In this chapter, the different phases for constructing such a framework were presented. Afterwards, the proposed framework is used to help in structuring and modeling our application. By using the proposed framework, the problem is described and analysed with regards to the relationships between the different components. Afterwards, it is expressed in terms of a causal links network, in order to help the understanding of the problem and evaluate the requirements in data and processing for the development of the database conceptual model. Furthermore, the spatio-temporal data and processing model is expressed in a rigorous way, by using a formal language. Such a cyclic approach permits a continuous enrichment of the initial application and the re-generation of hypotheses, in order to describe how things happen or would have happened in space and time and how entities are related within the spatio-temporal framework. Consequently, in the research context, the accent of such a GIS methodology is rather on the two first phases, Description or Analysis and Design phases, that give the cognitive basis to model and represent the system, than on the subsequent ones, the implementation and maintenance phases. Finally, the general relevance of such a methodology for environmental research, as well as the interactions between the two methodological approaches, Pedological and GIS methodologies are discussed. A GIS specification is proposed in order to project the requirements of such a context to which GIS technology should answer within the perspective of the model's implementation.

6.1 Introduction

The need to describe geographical data by spatial, temporal and attribute components has been discussed and several conceptual frameworks have been proposed (Langran, 1992; Frank *et al.*, 1992; Cheylan and Lardon, 1993; Workboys, 1994; Peuquet, 1994). Recent progress in the representation of time within GIS offer different solutions to increment the representation of dynamic entities in space (Peuquet and Duan, 1995; Peuquet and Qian, 1996; Claramunt and Thériault, 1995; Claramunt and Thériault, 1996; Hornsby and Egenhofer, 1997). Several database modelling frameworks have been proposed to structure

8 In the context of this thesis, GIS has a large sense that goes beyond the notion of a software toolbox. It is defined rather as a system that includes hardware, software, data, people, organisations and institutional arrangements for collecting, storing, analysing, and disseminating information about areas of the earth (Dueker and Kjeme, 1989). In French, it corresponds to SIRS (Systèmes d'Information à Référence Spatiale), also used as a synonymous of SIG (Systèmes d'Information Géographiques) and SIT (Systèmes d'Information du Territoire).

9 In the context of this thesis, the application is the study of the evolution of the soil and vegetation of the Sarine River's floodplain after human impacts

data and relationships between data (Caron and Bédard, 1993; Story and Worboys, 1995; Hadzilacos and Tryfona, 1997; Parent *et al.*, 1997).

Nevertheless, current GIS softwares do not really integrate the time dimension. The lack of temporal component in current GIS means that GIS analysis of past events and future trends is difficult or even impossible to do. Furthermore, temporal GISs need to incorporate the dynamic aspect of natural phenomena, in order to identify changes and processes underlying changes.

Our application concerns the evolution of alluvial soils and vegetation in a human altered zone. More generally, this study involves the analysis and representation of spatio-temporal phenomena in a structured way, in order to facilitate and support scientific prospecting. As well, this research context provides a set of general database modelling characteristics that could help enhance the reflection about the representation of spatio-temporal models.

In order to address these needs, a particular GIS design methodology was undertaken and presented in the first part of this chapter. The second part of this chapter deals with the modelling of our application in following the proposed GIS methodology. Moreover, the interactions between the Pedological and the GIS methodologies will also be discussed. Finally, the perspectives and limits in terms of a future implementation of the resulting conceptual database model is discussed (GIS specifications).

6.2 The GIS design Methodology

The GIS design methodology proposed here was developed with regards to other examples of the literature (Collongues *et al.*, 1989; Pantazis and Donnay, 1996; Gayte *et al.*, 1997; Adam and Gangopadhyay, 1997) but adapted to the needs and specificity of our application (the modelling of environmental changes into a research context).

Pantazis and Donnay, (1996) comment the advantages of using a methodology to designing GIS. In the particular context of research, in addition to these advantages, the challenge is to use such a methodology as a mean thread to support scientific reasoning and research structuring.

In this way, such a methodological approach has to consider the problem in a holistic and flexible way and should help in the application's structuring and in the hypothesis's construction. Moreover, it should allow feedback or modifications, as well as the expertise of several disciplines, in order to consider the complex nature of environmental applications. This could be related to the systemic approach employed by Prélaz-Droux, (1995) and De Sède and Thériault, (1996).

Even if the design of a GIS methodology does not include all the phases of the life cycle of a GIS (birth, design, technical realisation or implantation, maintenance and death), the proposed approach considers all them: (1) description or analysis, (2) design, (3) implementation and (4) maintenance (Figure 2.1). However, the focus is given in the two first phases that are directly related to the cognitive process and independent of any technology. They can give new insights for the modelling of environmental problems, as well as the means to realise a better choice in terms of GIS technology to the subsequent phases (surrounded by a dotted line), that are steps of the life cycle of GIS, but external to the design process (thus, out of this thesis' aim).

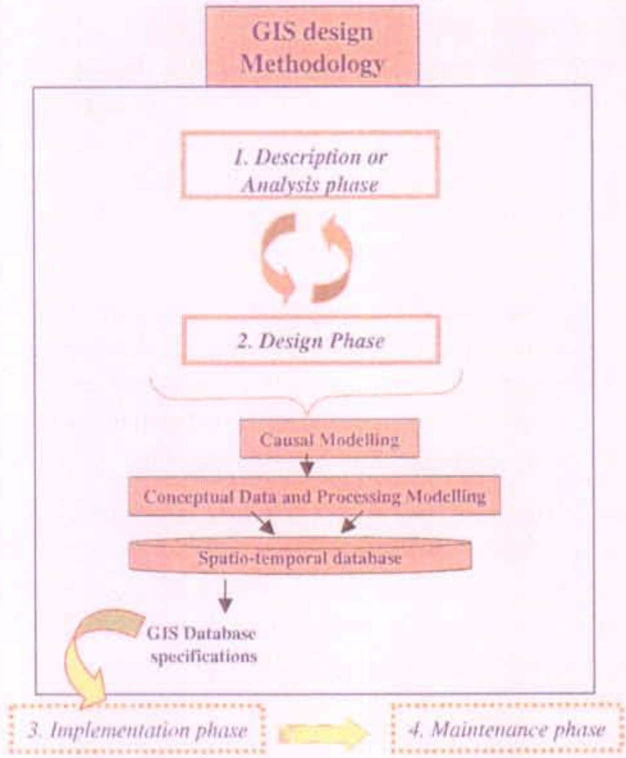


Figure 6.1 – The GIS design Methodology's phases.

1. ***Description or Analysis phase*** – In this phase, the aim, context and limits, as well as the application requirements is defined: what the system should do, the activities to be supported, and the information required and so on. Furthermore, an analysis of the dynamic aspects of the application is undertaken based on the historical and current data, for example. This phase is directly dependent of the expertise of environmental research.

2. ***Design phase*** – This phase has a strong cognitive component. The problem as a whole must be approached and the causal relationships that are important with regards to the application aims must be identified and expressed. In this phase, the questions "what, where, when, how and why" must drive the attention, in order to express more clearly the studied problem, even if these questions can not be answered here.

   The expression of causal links should constitute a powerful cognitive support for the conceptual modelling of the static and dynamic properties of the system. It must give a perception about the granularity[10] of the problem, its complexity and specificity, as well as help to decide about what scales should be adequated to study the problem and what attributes and relations are required to the data and processing modelling.

10 The order of magnitude or level of generalisation at which phenomena exist or are perceived in space and time (Laurini and Thompson, 1992).

With the evolution of the knowledge in the application domain, the expression of the causal links can be enriched in a cyclic way.

Finally, the problem must be expressed in a rigorous and formal way, data and processing must be structured, relationships established following a defined formalism. It should be considered in light of the conceptual model of data and processing. This step will permit the mastering of the problem and help to improve the communication between the experts of the different disciplines involved. Furthermore, it should also support cyclic reasoning in order to include new relationships and new data if necessary to support the drawn hypotheses.

Such a cyclic approach should permit a continuous enrichment of the initial application and the re-generation of expert hypotheses, in order to describe how things happen or would have happened in space and time and how entities are related. This phase must be independent of any technology. Nevertheless, some information from other phases could be taken to complete the reasoning and construct hypothesis.

3. ***Implementation phase*** - (logical and physical database models) – In this phase, the computational solution is chosen and the conceptual model is translated into a database structure (the logical model), according to the DBMS (Data Base Management System) platform selected for implementation (relational, network, hierarchical, object-oriented). At the physical level, the internal details of the file organisation and data access are designed (according to the DBMS chosen). A technical evaluation of the system (performances and limits) is recommended.
4. ***Maintenance phase*** –This phase is related to the using and updating of the information, in order to support new researches developments, as well as the management and planning.

6.3 – The application modelling

This part of Chapter 6 concerns the modelling of our application - the study of the evolution of an alluvial ecosystem after the human intervention -, following the proposed GIS design methodology. As previously discussed, it will concerns more specifically phases 1 and 2.

The complete methodological approach with the fulfilment of all its phases is however, interesting in the context of the development of administrative and legal databases that are oriented to environmental management and planning studies, but do not constitute a aim in the present context. Moreover, the impact of using such an approach in the research context will also be commented on, as well as some perspectives concerning a future implementation (GIS specifications).

The layout of this part (the application's modelling), as well as the interactions between the two methodologies (Pedological and GIS) are illustrated by Figure 6.2 and will be fulfilled in the following paragraphs. As can be observed, the first phase of the GIS methodology is based on the information from the Pedological one (dotted rectangle) and constructed in an interactive way, in order to keep all particularities or complexities of the pedological research. After the design and the modelling of the application, a brief evaluation of the consequences of the GIS methodology on the Pedological one and vice-versa is done.

6.3.1 The Descriptive phase

6.3.1.1 The application definition, context and aim

The research description, study context and aim, the choice of the study site and its general characterisation were described in more detail in previous chapters, General Introduction and Pedological Methodology, and will not be treated here, in order to avoid redundancy. The data requirement, acquisition and processing were determined by the needs stated in the Pedological Methodology (Chapter 1). Following this methodology, the present-day state of soil were determined and studied with regards to the site history.

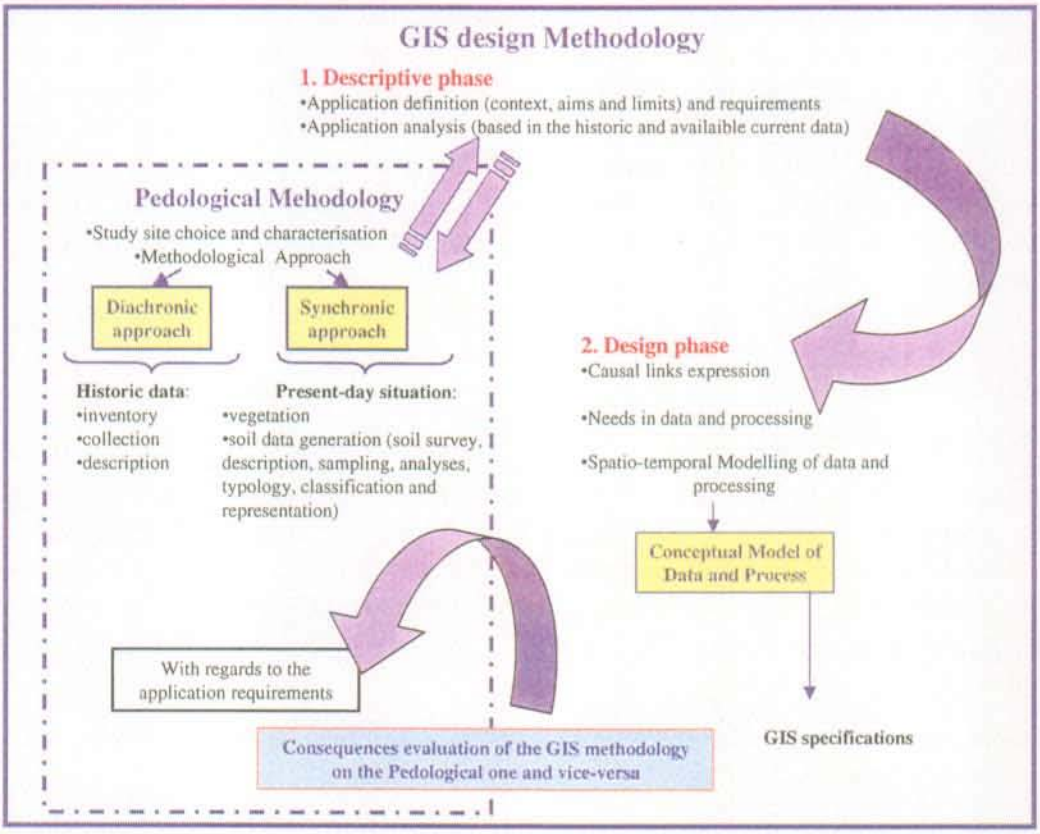


Figure 6.2 - The application's modelling schema (and the interactions between the two methodological approaches)

6.3.1.2 The application analysis

The application concerns the alluvial ecosystems and particularly the evolution of alluvial soils and vegetation following embanking process in the Sarine River's floodplain. This type of ecosystem is of interest because of its relatively rapid dynamics (on the order of several hundred years), which enables the realisation of a reliable historical reconstruction. The ecological importance and characterisation of such ecosystems has been previously discussed, as well as the legal basis established for their protection.

As commented in the General Introduction, nearly all of the 169 important alluvial sites in Switzerland are under heavy pressure from human activities. According to Gallandat *et al.*, 1993, the principal attacks on the entirety of the Sarine River floodplain are essentially embankments (59%) and waterway rectification (38%). Following the historic documents (embanking plans, aerial photographs), the historic evolution of the Sarine River's floodplain has changed through time, with visible changes in the channel geometry and vegetation pattern (these changes will be treated in Chapter 7 and 8). As a result of the human intervention, the current dynamics of the vegetation no longer corresponds to those of a natural alluvial system (Gallandat *et al.*, 1993). Concerning soils, it seems that a gap exists between the evolution of the vegetation and that of the soils, but few studies in this domain have been undertaken.

From this analysis, the important idea to be retained is that the application has a complex nature, with cause-effect interactions between components and an evolution pathway that was modified by human actions. As stressed by Openshaw, (1994), the identification of environmental patterns in space and time is a complex, deductive task that requires observations, expertise and the development of spatio-temporal analysis methods. Furthermore, the causal relationships involved must be explicitly represented, in order to clarify and help the understanding of the problem, even if their modelling is still conceptual (Allen *et al.*, 1995).

6.3.2 The Design phase

6.3.2.1 The expression of causal links

The expression of these causal links will be presented in a schematic way, following the semantic proposed by Allen *et al.*, (1995). Causal modelling is situated at the highest level of the perception of environmental phenomena. The focus will be done in the expression of causality that is often implicit, with the aim of better understanding the problem, constructing the work's queries and acquiring the basis for the conceptual modelling of data and processing.

Some elements used in our model are briefly defined, according to Allen, (1996), who also included a philosophical discussion about causality and events:

- *Objects* and their *states*. An object is something that could be identified, described and localised in space or time, although it need not be localised in this conceptual level. State refers to the attribute values of each object, as well as to each object's geometry and also to its possible existence.
- *Events* are considered to be changes of state in objects (changes in existence, geometry and attribute values). They are the central element of causal model and can be decomposed into sub-events, which may or may not be causally linked. Furthermore, events can be described in different levels of generalisation.
- *Conditions* may come from any other entity (other conditions, any pre-existing state, or any previous event occurrence). Allen *et al.*, (1995) have expressed conditions as Boolean statements (*if rate flow = x, then y*), but in this descriptive phase, this is not absolutely necessary. In fact, the important issue here is that condition has a restrictive role in the causal analysis.
- And the *relations* that describes how the events are linked (Produces, Is part of).

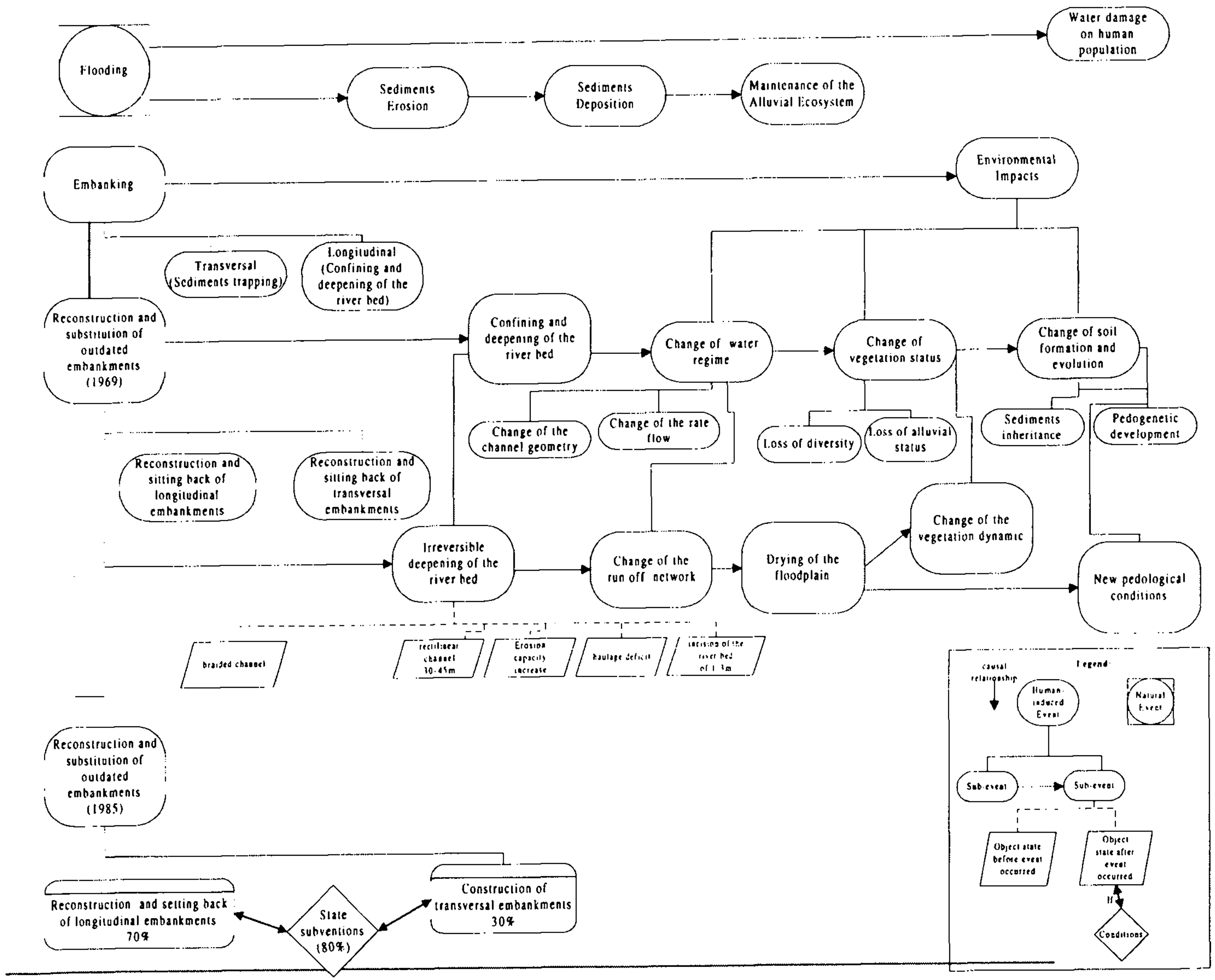
In this approach the "Agent" component of the Allen's model (Allen, 1996), which incorporates the notion of intentionality and have a reason to act, is not represented because it is considered here as an external component to the system. Therefore, the model begins with the events that could be natural or human-induced. Based on these elements, the causal links involved in the embanking process of the Sarine River's floodplain, which could be important, are illustrated in Figure 6.3. The framework was constructed with Visio Professional software.

As can be observed, the embanking process seems to be responsible for the principal changes that have arisen in the Sarine River's floodplain. As previously discussed, the embanking process was undertaken with the aim to avoid flood damages on the local population.

Nevertheless, with embanking works the maintenance of the alluvial ecosystem has been altered and the whole floodplain has changed through time. The first consequence of the embanking process was the confining of the riverbed by sediment trapping and the passage from a braided to a rectilinear channel. As a result, the riverbed has become deeper and hence, the water regime has changed. These events have caused the drying of the floodplain that, in turn, have caused changes in vegetation and soil.

The study of the causal relationships and their illustration in an expressive way constitutes a help to elucidate data, attributes and relations required to the data and processing modelling. Besides, from such a cognitive exercise, several questions related changes and processes could emerge. Finally, some components of the conceptual scheme could be introduced into the data model, according to their importance to the understanding of the problem.

Figure 6.3 – Schema of the causal model of the Sarine River's floodplain embanking



6.3.2.2 Data and processing requirement specification

Following the problem's expression (Fig.6.3), the reality to model consists of natural and anthropic events that intercalate in space and time. With regards to the established aim (to understand the evolution of the floodplain after embanking), the GIS model must include spatial and temporal information and their interrelationships in a structured way, in order to be useful for such an application.

As suggested by Golay, (1992), such a model must integrate data and processing, in order to take into account the complex links between data and their behaviour. In other words, changes must be identified, analysed and the change pattern determined. Concerning soils, to understand how changes caused by human impacts have affected their present spatial distribution, variability and degree of evolution an expert soil appraisal was also necessary (see Chapter 1 - Pedological Methodology). The association of these historic and present-day data will allow the soil expert to generate hypotheses concerning the vegetation and soil evolution in this floodplain.

In order to represent the application semantics, a relevant data collection of soil, vegetation, hydraulic and historical data that build the backbone of the spatio-temporal GIS model is considered. The principal data sources are characterised as follows:

- A set of aerial photographs for the years 1930, 1943, 1955, 1969, 1980 and 1992 which is continuous in space, discrete in time (represented by a yearly temporal interval) and represent a temporal series.
- Land Cover maps, derived from aerial photographs for each corresponding year, which are continuous in space and discrete in time.
- A vegetation map established in 1988 (scale 1:10,000) that is discrete in both space and time.
- River flow rate data
- Flood data (dates, duration, flow rate). Continuous data in space and discrete in time.
- Embanking maps realised along the century, which are discrete in both space and time.
- Soil data derived from field soil survey (points and profiles) and laboratory analysis are discrete in both space and time.

6.3.2.3 The spatio-temporal conceptual model of our application

Our conceptual database model was constructed with the CASE (Computer-Assisted Software Engineering) tool called Perceptory, chosen based on the comparison proposed by Pouliot *et al.*, (1997). Perceptory is a visual modelling tool, developed by Bédard, (1999), that integrates a Spatial, a Temporal and a Multimedia Plug-in for Visual Languages (PVL), specially developed to high-level conceptual object class models of spatio-temporal databases with multimedia capabilities. Perceptory constitutes a template for VISIO software (Visio Corporation, 1977) that makes use of its flexibility and other advantages. The formalism used in Perceptory is UML (Unified Modelling Language), a new standard object-oriented language developed by Booch *et al.*, (1994) and Booch *et al.*, (1999) to specify, visualise, construct and document different applications.

For a better comprehension of the database model principles, the principal modelling elements of Perceptory are briefly described in the following paragraphs:

Class: a set of objects, persons, concepts or events from the real world. Generalisations are contained in the class and the particularities are contained in the objects. The objects are constructed from the class by instantiation. Three parts compose the class: the name, the attributes and the operations. Into the first part, the name of the class, as well as its spatial and temporal reference, its geometric evolution and multimedia presentation is used to describe the class identity. The second part concerns the state of a class (its attributes), that could have spatial, temporal and multimedia references. An attribute could be composed (a + signal is put after the name of the attribute and precision are given in the dictionary) and derived [11](in this case, a / is put before the name of the attribute and the derivation roles are described into the dictionary). The last part of a class concerns its behaviour (the operations that are performed on the data).

Package: is a schema sub-set. It contains different components, e.g. classes, relations and attributes.

Generalisation: concerns a classification relationship between a more general (super-class) and a more specific element (sub-class). A super-class could have several sub-classes and a sub-class could belong to several super-classes (a multiple generalisation). The super-class of a generalisation could be an abstract class (not directly instantiated). In this case the class name is indicated in *italics*. Finally, several constraints could be applied to a generalisation.

Association: represents the structural relationships between the object classes. It is represented by a verb, in an active or passive form, written in italic in the middle of the line representing the association. A target symbol indicates the pathway one should follow. A class-association could be created if a given association has attributes or operations. An association is accompanied by two cardinalities that indicate the minimum and maximum number of objects of a class that could be linked to an object of another class. Constraints could be applied to an association. In addition to the normal association type, two more types are possible: the aggregation and the composition. An *aggregation* represents an asymmetric association in which one of the extremities has a predominant role. It could be multiple and is represented by a white diamond close to the aggregate. A composition represents an association in which one of the extremities encompasses the other. The *composition*, in contrast to the aggregation, implies a constraint on the multiplicity value of the aggregate: only 0 or 1 values can be taken. A black diamond closer to the composite represents the composition association.

The graphical components of Perceptory are attached to a powerful data dictionary, where all textual information is recorded. The pop-up menu that gives access to the dictionary, as well as other important components is illustrated in Appendix 6.1. For the class component, for example, the principal fields of the dictionary concerns its semantic, spatial, and temporal definition, as well as its spatial evolution, media, attributes and operations.

Concerning the spatial definition of objects, Perceptory has kept only the basic and intuitive geometric features: point, line and polygon. These features are represented by graphical notation called pictograms, as follows:

point (0-dimensional shape)
line (1-dimensional shape)
polygon (2-dimensional shape)

11 The geometry of an object can also be derived from other. In this case, the pictogram (the graphic symbol) is shown in italic.

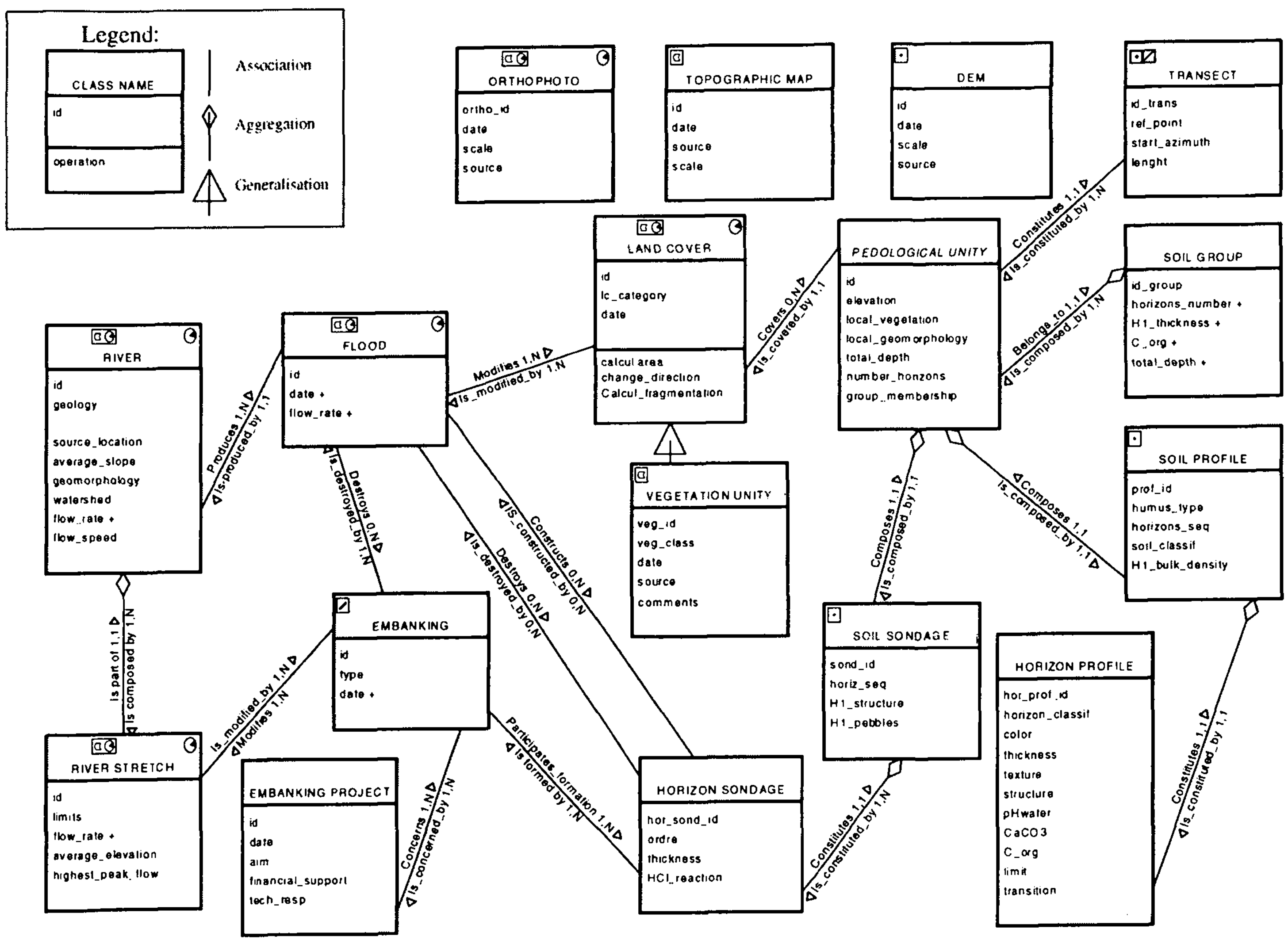
They are directly available in the pop-up menu (or in the dictionary) and can be applied to an object class, an attribute or a relationship. All textual descriptions concerning the spatial (and even the temporal) geometry and their evolution must be written into the dictionary. All combinations between these features are possible and other features as (*) for any possible shape or (!) for complicated shapes can also be employed. Furthermore, other possibilities are available to express a particular geometry (e.g. an aggregation of shapes, an alternate shape, complex or multiple shapes) (Bédard, 1999). In these cases, more precision must be given in the dictionary.

Concerning the temporal reference, the basic pictograms of Modul-R (Caron, 1991; Bédard *et al.*, 1996) were kept in Perceptory (Figure 6.5). These permit the description of the class existence, as well as the spatial evolution (in combination with the geometric shapes). The three principal features are summarised as follows:

Time-punctual existence
Time-interval existence
Complex time existence

Details and explanations, as well as complexities and exceptional situations are recorded into the dictionary (they could be treated later, at implementation). The graphical representation of our application database model (the evolution of the Sarine River's floodplain after embanking) is shown in Figure 6.4.

Figure 6.4 – The spatio-temporal conceptual object class model of the Sarine River's floodplain



The conceptual database model was not an end in itself. In the context of this interdisciplinary research, its construction was constrained by two principles: the first was to support scientific reasoning: this gave meaning to structure, to master and better describe the problem, to infer or identify relationships, to decide about the necessary processing to be undertaken (expressed by the operations at the class level) and to document the application. The second was to support and facilitate communication between the pedological and GIS experts.

Moreover, such a modelling framework supports cyclic analysis in order to include new classes or relationships. It permits a continuous enrichment of the initial application in data and processing. To illustrate this synergetic aspect of such a framework, let us consider the following example: From experience, soil experts know that soil is a result of several natural agents (e.g. parent material, relief, climate, vegetation and organisms) that interact through time to create soil. They also know that river dynamics (Flood and its erosion/deposition processes) have an influence upon the alluvial soil formation. Thus, they can already establish a preliminary causal link among these classes (Soil Horizon and Flood). However, in the present condition of embanked floodplain (as expressed in the causal study), the anthropic factor has played an important role in the studied floodplain. Thus, such experts will integrate a causal association between these two classes (Soil Horizon and Embanking). Some more insights could also be derived after the Pedological methodology development and new relationships with other classes within the database schema can be inferred. Eventually new data acquisition or processing (e.g. floods characteristics, soil data spatialisation...) would be necessary, in order to support environmental hypotheses.

In synthesis, such a functional approach can lead to collaboration between scientific experts of different domains. Environmental experts contribute to the identification of spatio-temporal trends and causal links. GIS experts provide an interesting insight into the deduction and corroboration of these patterns by the application of a structured framework in order to describe, express, analyse and model spatio-temporal data.

Concerning the chosen CASE tool, it was easy to learn and allowed the construction of a clean and expressive conceptual database model that has the advantage of integrating data and processing within the same framework and into the same formalism. It also allows the development of a model that is closer to our perception of the studied problem. Furthermore, Perceptory is a freeware standard-oriented UML (and ISO TC211-compatible.

Perceptory keeps this richness at the dictionary level and permits the construction of a scheme that is simple but easily understood. In the context interdisciplinary research this can be considered as another advantage, in order to facilitate the communication between experts from different domains (of course it should fulfil the application semantic requirements). Furthermore, a rich documentation of the application could be taken as an output. This will facilitate the implementation phase (stated in GIS design Methodology, but out of this thesis's aim).

A weakness in the present version of Perceptory concerns the expression of spatial constraints, like topological relationships (e.g. inclusion, intersect). Presently, they are only written in the dictionary. According to Bédard (personal communication), a module that fully supports such integrity constraints will probably be available in the near future. Moreover, the new version of Perceptory (in test) contains a report generator that integrates the ISO TC211 standard.

Despite these advantages, Perceptory) is not yet very stable and does not cover all phases of the development of a GIS (it does not have a code generator that can be mapped towards a logical model, for example).

6.4 –Interactions between the GIS and the Pedological methodologies – an evaluation

The GIS design methodology proposed in this chapter provides a methodological support for environmental experts that may improve the data and processing structure for their application context. The emphasis is placed on the Description (or Analysis) and Design phases. The development of a well-focused causal relationship model favours an efficient exploration of possible causal links that give some insights about environmental data and their dynamic behaviours. The definition of the object class within the conceptual model helps to express the problem in a rigorous way that integrates data and processing functions within a same model and language. Such a framework, as previously discussed, supports scientific reasoning (allows a better structuring of the problem, a cyclic hypothesis's generation possibility) and facilitates communication between environmental and GIS experts. On the other hand, GIS specialists could have some useful insights about the complexity of environmental applications and about primitives to improve spatio-temporal model. Such an interactive modelling favours users' feedback and brings the resulting model closer to the represented real-world system. Finally, such a modelling process allows GIS experts to propose adequate solutions at both the data and processing level and a successful implementation of the conceptual model.

6.5 – GIS specifications

As shown in this chapter, the proposed GIS methodology supports scientific reasoning acting as a "thinking tool"and allows the identification of causal links between events and its expression. Moreover, it keeps a strong interaction with the application domain and facilitates the communication between experts from different background. Furthermore, it facilitates the modelling of the application and establishes the basis for the implantation of the system (towards logical and physical models), that would be important for other applications, like management and planning. As shown in the schema of Figure 6.7, the application includes the static and dynamic properties of environmental data. The implementation of the conceptual database leads towards a logical model that can support the representation, query, and analysis of spatio-temporal data and processes. A successful temporal GIS must support the modelling of natural phenomena by integrating their location, states, events, and processes. Following such a temporal GIS model we must be able to answer some spatio-temporal queries of our application, which have emerged during the causal study and the modelling process. They can be summarised as follows:

- Did the river channel change between 1930 and 1992?
- How did this change happen in space?
- Where and when changes have occurred in the land cover?
- How did the land cover change occur (change proportion and quality of change)
- What is the change pattern?
- What processes are behind the changes?

- How much time will be necessary to complete the loss of the alluvial character of this floodplain?
- What scenarios should be possible?

These spatio-temporal queries express the needs in terms of database capabilities, which are in particular, necessary for a better representation of spatio-temporal entities in space and time, as well as the relationships between them. Furthermore, in answering such questions, an environmental expert will be able to quantify and qualify changes, as well as identify change patterns. This will constitute the basis for explaining what processes are subjacent to changes, in order to know why changes occur. The establishment of such a GIS model represents and integrates the complexity of such an application in space and time. This is a fundamental step to the comprehension and management of the environment.

As discussed before, the conceptual model must be independent of any technical solution. The use of an object-oriented (OO) formalism like UML does not imply any constraint for the logical model: it could be any logical model, but the chosen database solution must keep a high level of the semantic richness expressed in the conceptual model. The implantation of such a model will certainly bring up other questions and challenges that need to be raised in conjunction by environmental and GIS scientists.

An example of an application designed with an OO formalism (POLLEN) and implemented upon a relational SGBD (called 4D) and GIS (Map-Info, for instance) is given by Gayte *et al.*, (1997). They discuss the necessary adaptations and limitations required for the implementation of each component of the conceptual model, particularly towards a relational architecture. Within relational databases, resulting data of the conceptual model are mapped to tables, where relationships between entities are defined using appropriated links between the tables. The preservation of data integrity and respect for the normal forms are essential.

On the other hand, the implementation of an OO logical architecture implies some different mechanisms: firstly, the database design is a fundamental part of the overall application design process; secondly, the technical solution can be considered as closer to the human-view (modelling) of the real world.

In other words, the OO database architecture allows the modelling of the three principal components of a data model:

- the static properties such as objects, attributes and relationships;
- the integrity rules over objects and operations;
- the dynamic properties such as operations or rules defining new database states based on applied state changes.

The most important aspect of OO method is that it links together data and the operations that are performed on data (to analyse their behaviour), in order to be closer to real-world objects. Object-oriented design methods are now mature enough to be applied within a design process, they seem particularly adequate to model our application, in order to take in consideration the dynamic evolution expressed by the causal model and the conceptual model (Figure 6.3 and 6.4).

Nevertheless, there are only few GIS commercial products that are object-oriented (e.g. Apic, SmallWorld) and they seem to be still in a maturation state, not including functionality to model spatio-temporal evolution, but rather offering a object-oriented user-developing interface.

The next step seems to be to promote the dialog between environmental experts and developers, in order to construct a more adequate product, able to model dynamic entities in space and time. Furthermore, such a product must include a friendly interface for user-optimisation (without the need of writing a particular code). Nevertheless, the "panacea software" does not exist, because each application has its own characteristics and particularities to be modelled. The challenge here, is not the research or developing of new, ready-to-use GIS software, but rather to be able to decide about what GIS tools can be complementary and adequate to answer the questions identified in the application causal modelling and addresses in the data and processing modelling. Finally, by using such a methodological framework, one can better address the perspectives of how such tools must evolve to integrate the complexities of environmental research.

6.6 Conclusion

Current research and management projects are often based on the application of scientific and practical behaviours and experimental surveys. The integration of GIS resources to support such tasks has been widely developed during the past years. However, in most cases GIS is still used as a tool to apply a limited set of analytical functions to existing data sets describing the environment.

The need to undertake a GIS design methodology applied to the environmental research was discussed in chapter 2. The framework proposed is only a flexible approach for an environmental research purpose. It was based on the literature about GIS design done within an institutional context and, here, adapted to the requirements of environmental research. Other phases could be added within the function of the research context and specificity (like a feasibility study or as an opportunity one). In our specific case, they were not necessary, the aim of the GIS design methodology being rather to support the scientific reasoning process and help to structure the problem, and master the complexities of environmental applications.

Environmental research is an important area for the application of spatio-temporal models, since it provides a complete set of modelling primitives that include the thematic, spatial and temporal domains. The flexible approach proposed is helpful for identifying a more flexible process of identifying and assessing possible causal relations among different phenomena. It relies on the on-going analysis of the database conceptual model that is described by the UML formalism, enriched by spatial and temporal structures.

From a database point of view, such a method allows the integration of the environmental data and part of the scientific expertise in terms of objects, relationships, changes and process definitions (operations).

From an application point of view, this approach allows the definition of an integrated and global system representation as well as the definition of a GIS model for use in a scientific context. Such a system allows the corroboration of spatio-temporal processes and the detection of change patterns. The proposed framework includes a cyclic design process that permits the continuous generation of environmental hypotheses and their integration within the spatio-temporal database model, as well as new data and analysis.

This proactive approach has been applied to the study of alluvial soil ecosystem, and it could be used for the study of other environmental studies dealing with in the representation of dynamic systems within GIS. However, further work is needed to enhance the quality of feedback loops between the thematic expertise of environmental scientists and the computer-supported exploration of such a database model (implantation phase) with a further inclusion of causal relations and data accuracy.

A better understanding of space-time phenomena relevant to environmental studies (by change detection and analysis, process identification) is necessary to apply adequate data analysis processes. This requires a structured study of change patterns and later, the definition of taxonomies of spatio-temporal processes at a high conceptual level as proposed by J.-P. Cheylan (personal communication). Such an objective will be developed within Chapter 7 and 8. In these chapters, the operations expressed in the conceptual model as well as change detection and analysis and processes identification will be realised by using GIS technology, but without complete database implementation, as this is not completely the objective of our study.

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Chapter Seven

Spatio-temporal land cover changes in the Sarine River's floodplain as determined from aerial photographs and GIS

Abstract

This chapter describes land cover spatio-temporal changes and patterns of changes in the floodplain of the Sarine River in Switzerland. The study and description of land cover changes is based on a set of aerial photographs from which photointerpretation was done. Spatio-temporal analyses were performed using a Geographic information System (GIS), in order to detect, describe and evaluate land cover changes its pattern of change. The use of GIS and its spatial analysis functions has permitted the generation of land cover maps, transition maps (cross-classification maps) that show changes between land cover classes by time step (pairwise comparison) and cross-tabulation matrix (that show the transitions among all the classes in % of area). These classes represent the main categories of land cover homogeneous region of the study area. In addition, change sequences are analysed in order to identify change direction and pattern of change. Therefore, some landscape pattern indices were calculated (frequency of each category, diversity and dominance indices and number of patches, mean patch size and size variability of patches for each category), as well as change indices (turnover time). The main analysis results show that this floodplain has become dryer (stabilisation of the main channel and the riverbanks), dominated by the forest categories and less diverse with time. The turnover time for each land cover category through time confirms these results. Human impacts (embankments, dams...) and flood events seem to have to played an important role in the evolution of this site and its present-day condition. Despite the uncertainties expressed by the unexpected transitions, the method used has permitted the integration of the spatial and temporal properties and patterns of the studied floodplain. The GIS component of this project allowed the quantification and visualisation of change in space and time.

7.1 Introduction

Several authors (Forman and Godron, 1986; Dunn et al., 1991) have stated that the spatial configuration of landscape elements can be attributed to a combination of environmental correlates and human forces that operate at different spatial and temporal scales. The combination of natural and modified elements creates complex patterns of change (Di Castri and Hadley, 1988; Dunn et al., 1991). The understanding of changing patterns is important for landscape conservation and planning. In this way, Geographic Information Systems (GIS) have become an unavoidable tool to perform quantitative and qualitative analysis of changes, in addition to its known capabilities for the collecting, storing, retrieving, transforming and displaying spatial data (Burrough, 1986; Burrough and McDonnell, 1998). The management of natural resources involves integration and interpretation of various forms of data in spatial and temporal scales. Particularly, the potential of a conventional GIS can be greatly expanded by adding the temporal dimension.

The need to consider temporal dimension in GIS has been emphasised by several authors (Langran and Chrisman, 1988; Beller, 1991; Langran, 1992; Peuquet, 1994; Peuquet and Wentz, 1994; Peuquet and Qian, 1996; Claramunt and Thériault, 1995). They agree that current approaches of GIS are not suitable to reproduce all temporal situations, or explicit understanding of the nature and type of changes. For the study and monitoring of environmental changes, for example, an information system that can support both, spatial and temporal queries, analysis and modelling are required.

A model for the time-based analysis of spatio-temporal data in a GIS, the triad model, was proposed by Peuquet, (1994) and Peuquet and Qian, (1996). This framework expresses the multidimensional complexity of spatio-temporal data by considering the information according to three independent representations (feature-based, location-based and time-based) that can be respectively addressed by the following questions: what, where and when.

With this approach, events can be detected, measured and spatio-temporal analysis could be performed concerning the changes. In addition, one more component must be included in such a framework in order to give indication about *how* events take place (Claramunt and Thériault, 1996). Another question that should at least be addressed is *why* events occur. In answering these questions and associating them to the site history, the understanding of the phenomena could be approached, as well as the possible process responsible by changes. According to Allen *et al.*, (1995), causal links are implicit in the principle of temporality because change should be a consequence of causal relationships between successive states of events[12]. Despite the evident interest of these two last questions for the study of environmental change, their implementation in the present-day GIS database is not yet a reality.

Temporal changes in landscape, their consequences and the methods used to their detection were summarised by Dunn *et al.*, (1991). Concerning data, three principal categories are reported by this author: aerial photography, digital remote sensing and published data and census. In spite of the drawbacks reported by Lindgren, 1985) and Jensen, (1986) their works have demonstrated that photointerpretation provides the most accurate classification (90% or higher) of temporal landscape changes. The limits reported by these authors can be summarised as follow: the first aerial photographs date from the mid- to late 1930s; dates on which aerial photographs were taken are not always the key-data for the studied event; problems with the quality of some photographs; problems and distortion between different years; and finally, detection of change using aerial photographs is time-consuming and cumbersome.

Concerning the other data sources, remote sensing technology has become very important to monitoring and quantifying landscape changes with better temporal resolution than traditional aerial photography. Nevertheless, the present-day spatial resolution of satellite images is too large for many ecological applications or local scale studies (79 x 79m for Landsat MSS; 30 x 30m for Landsat TM; 10x 10m for SPOT panchromatic). Published census data could be an interesting way to set up the initial condition of a given study and to use in conjunction with the two other. Nevertheless, it is more reliable over large areas (Ilbery and Evans, 1989).

The aim of this chapter is to detect, identify and analyse land cover changes and change patterns in the human altered floodplain of the Sarine River in a time span of 62 years. During the development of this work, the three questions proposed in the Peuquet's triad model - what, where, when - will be kept in mind as well as the how question, proposed by (Claramunt and Thériault, 1996). The why question will also be considered while trying to explain the evolution of the studied floodplain.

12 An event denotes some change in some location(s) or some object(s). Attributes of an event can include the new state of a set of objects, the new state of a set of locations for that moment, or both (Peuquet, 1994).

Furthermore, this study will set up the basis for the analysis of the relationships between land cover change dynamics and the present-day soil states, to be treated later.

7.2 Study Area

7.2.1 Present state

We studied a site at *Les Auges de Neirivue*, near Fribourg in Switzerland. It is approximately 750 m above sea level and covers 96 ha. It is a part of the floodplain of the Sarine River, a tributary of the Aare. The river has a strongly embanked stretch and lower in its course it has an active alluvial zone. The climate is pre-alpine (Fallot, 1991) with an average annual rainfall of 1200 mm, wet summers and relatively dry winters. The average annual temperature is 7.1 °C; July is the warmest month, and January is the coldest. The hydrological regime of the Sarine is intermediate nival, with a maximum flow in spring and a minimum in January. The average annual flow calculated between 1923 and 1992 is 23.7 m^3/s (maximum peak flow: 460 m^3/s). The geomorphology of the site is characterised by a succession of alluvial basins separated by rocky constrictions (Gétaz, 1977). The average slope is 0.64 ‰. For more details, see Chapter 1.

7.2.2 Historical evolution of the study site

This river has been controlled by construction of various hydraulic installations, in particular dams and embankments. The high embankments, built about 1920 were constructed at two different times in two ways: first transverse embankments, followed by longitudinal ones. By constraining the main channel these installations increased the capacity of the river to erode and caused incision in the riverbed of 1 to 3m within 60 years. This phenomenon was accentuated by a shortage of sediments following the stabilisation of tributaries and the installation of hydroelectric power plants in the upper Sarine (Gétaz, 1977). The dam, completed in 1973, is responsible for daily variations of the flow ranging from 3 to 41 m^3/s. On particular occasions the surplus water can be released by sluices, generating floods. As a result, the hydrodynamic regime of the Sarine River has changed (for more details, see Chapter 1).

7.3 Material and Methods

7.3.1 Spatio-temporal landscape characterisation

A set of black and white aerial photographs from the Swiss Federal Office of Topography taken in July or August of 1930, 1943, 1955, 1969, 1980, and 1992 was used to study the spatio-temporal land cover changes in the floodplain of the Sarine River (Figure 7.1A and B). The average granularity (temporal resolution) was 12 years and the 1930 aerial photography was considered as the starting point to set up the initial condition, even though a state before embankments would be more suitable.

Firstly, these aerial photographs were transformed into orthogonal digital photographs (*orthophotos*). A spatial resolution of 4m could be obtained. Land cover categories were identified by photo-interpretation, based on the principles stated in Campbell, 1987). The result of the photo-interpretation process was then mapped by on-screen digitising into a vector format, using Idrisi software, a GIS raster environment (Eastman and Mc Kendry, 1991; Eastman, 1997). After the vectors were translated into a raster format (it is a requirement of Idrisi software to perform change analysis). Then, land cover maps were produced for different periods of study, with land cover categories corresponding in a more general scale, to those described by Gallandat *et al.*, (1993) for the Swiss floodplains. Visual field observation was done to check the pertinence of the categories as determined for the map of 1992.

To characterise landscape composition and configuration, some landscape pattern indices (information theoretical indices) for each date were calculated: Total area (A), Proportion of each land cover class (P), Diversity (H), Dominance (D), Number of Patches (NP), Mean Patch Size (MPS) and patch size variability (patch size standard deviation and coefficient of variation).

The proportion of each legend category for example, gives information on the composition of the mosaic considered (Hulshoff, 1995). In other words, changes in this index in time (for a considered interval of time) indicate the increase or decrease in area of a legend category. P gives no information on the spatial location of change (it could nevertheless, be viewed in the maps). The diversity index indicates the degree to which a given number of landscape elements are represented on a map in equal proportions (O'Neill et al., 1988; Turner and Ruscher, 1988; Kienast, 1993). The higher the value of H, the more diverse the landscape. Diversity (H) was calculated by:

$$H = -\sum_{k=1}^{m} \left(P_k\right) \ln \left(P_k\right), \text{where:}$$

m = number of land cover categories

$\left(P_k\right)$ = relative area of each land cover category

The Maximum Diversity was calculated by:

$$H_{max} = \ln(m)$$

The *Maximum Diversity* is reached when all land cover categories are represented in equal proportions. The Dominance index (D) measures the extent to which one or a few category types dominate the landscape (O'Neill et al., 1988). It does not indicate which legend category dominates (for this purposes, the proportion of each land cover category was calculated before). Dominance was calculated by:

$$D = \left(\frac{H_{max} - H}{H_{max}} \right)$$

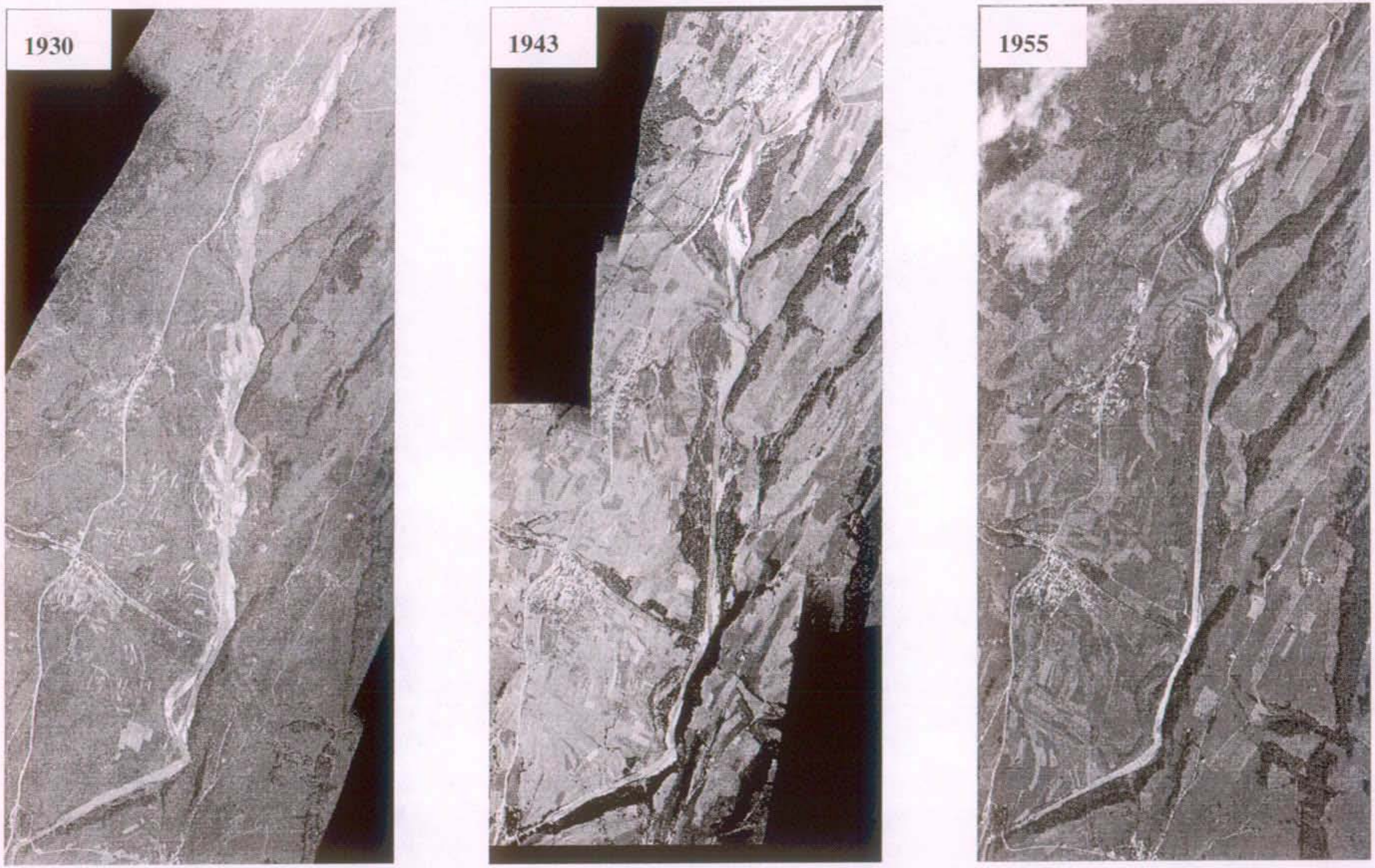

Figure 7.1A - The set of aerial photographs (1930, 1943 and 1955) used to study the historic evolution of the Sarine River floodplain

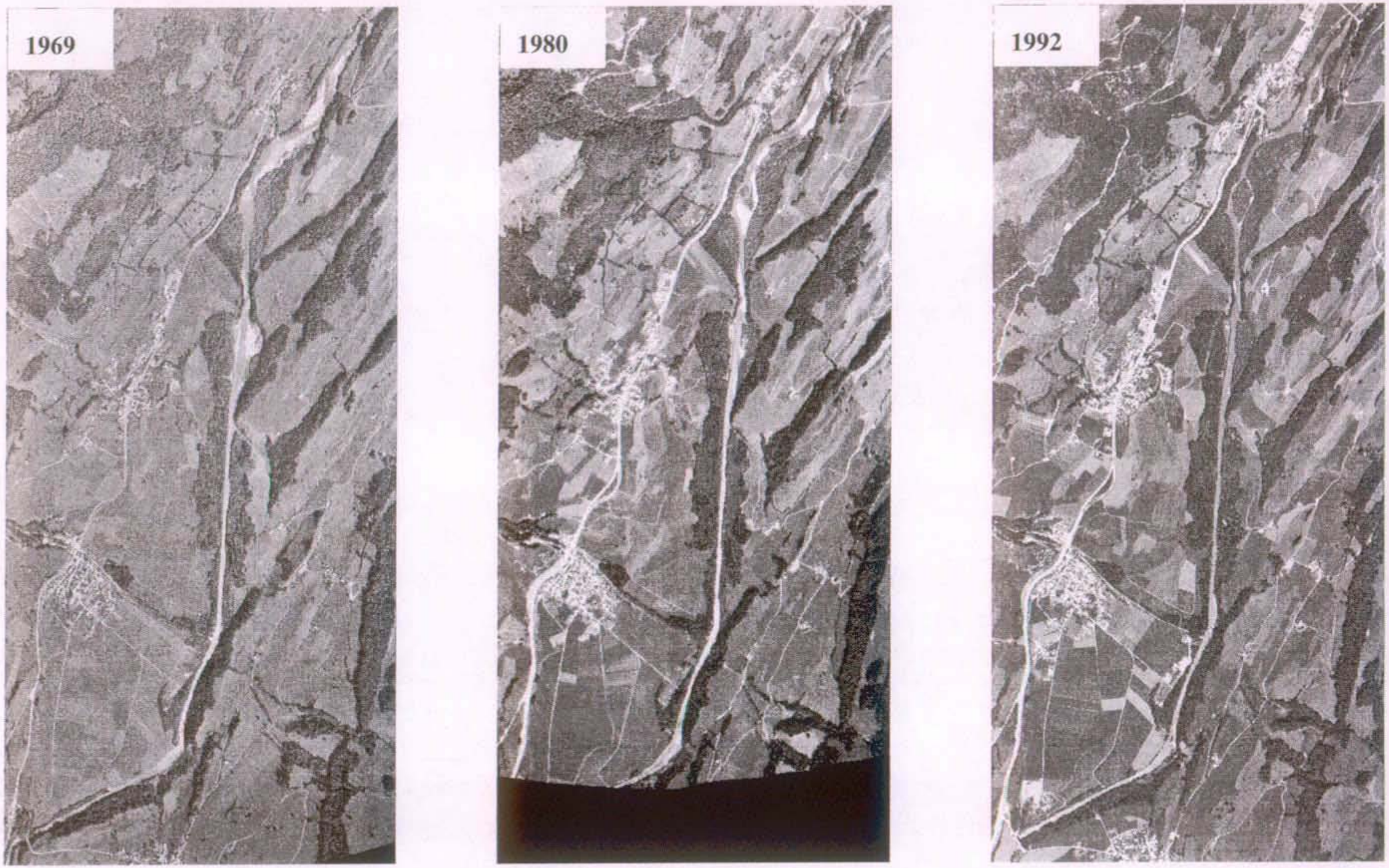

Figure 7.1B - The set of aerial photographs (1969, 1980 and 1992) used to study the historic evolution of the Sarine River floodplain

By this formulae, Dominance is normalised to range from 0 to 1, as used by Kienast, (1993). Low values indicate that the landscape considered has many legend categories (for instance, land cover types), represented in approximately equal proportion and conversely, high values indicate that the landscape is dominated by one or only a few legend categories.

Number of patches (NP) and mean patch size (MPS) are direct information on the landscape configuration and its fragmentation even though they are not spatially explicit measures (Mcgarigal and Marks, 1995). They were considered by legend category and so, MSP is a function of the number of patches of a given legend category and total category area. MPS is given in hectares and was calculated by:

$$MPS = \frac{A}{N}\left(\frac{1}{10.000}\right) \text{ where:}$$

A = Total Area (m2)

NP = Number of Patches

MSP represents an average condition and could be best interpreted in conjunction with total category area, number of patches and patch size variability. For instance, variation in patch size was captured by two indices: Patch Size Standard Deviation (PSSD) and Patch Size Coefficient of Variation (PSCV). Both give information about the landscape heterogeneity, not captured by mean patch size, for example. PSSD is a measure of absolute variation and is a function of the mean patch size and the difference in size among patches. This is in fact, the root mean squared error (deviation from the mean) in patch size. This expresses the population standard deviation (Mcgarigal and Marks, 1995). It was calculated by:

$$PSSD = \sqrt{\frac{\sum_{i=1}^{m}\sum_{j=1}^{n}\left[a_{ij}\left(\frac{A}{NP}\right)\right]^2}{NP}}\left(\frac{1}{10.000}\right)$$

The other index, patch size coefficient of variation, measures the relative variability about the mean (variability as a percentage of the mean), not absolute variability. This is the population coefficient of variation, not the sample coefficient of variation (Mcgarigal and Marks, 1995). It was calculated by:

$$PSCV = \frac{PSSD}{MPS}(100)$$

A greater variability in patch size measure indicates less uniformity in pattern, and may reflect differences in underlying processes affecting landscape. Nevertheless, both measures (PSSD and PSCV) assume a normal distribution about the mean. In a real landscape, the distribution of patch size may be highly irregular and in these cases, the inspection of the actual distribution itself would be more informative (Mcgarigal and Marks, 1995).

7.3.2 Land Cover change detection and change pattern identification

Based on land cover maps, change detection was established using a qualitative change analysis technique (Cross-classification/Cross-tabulation), applied to each pair of land cover images (pairwise comparison).

With this technique we have performed two operations: Firstly, an image cross-classification that can be described as a multiple overlay showing all combinations of the logical AND operation. The result is a new image that shows spatially the locations of all combinations of the categories in the original images (as land cover categories have changed or not through time). A legend is automatically produced showing these combinations. Secondly, an image cross-tabulation in which the categories of one image are compared with those of a second image and tabulation is kept of the number of cells in each combination. As a result of this operation, we obtain a table (cross-tabulation matrix), as well as a measure of the correlation between the two images (the Kappa Index of Agreement, KIA). The KIA measure ranges from 0.0 (no correlation) to 1.0 (perfect correlation) and could be applied only if the two images have the same number of categories (Rosenfield and FitzPatrick-Lins, 1986). The cross-tabulation matrix shows the frequency of change between all land cover categories (the frequencies with which classes have remained the same - along the diagonal, or have changed - off-diagonal frequencies).

Nonetheless, unexpected transitions could occur as a result of some uncertainty produced by at least four factors: land cover type recognition, digitising, quality of aerial photographs and the overlay technique (Delcros, 1993). For this reason, all transitions were analysed and described with regards to their nature and viability in the study site, according to the work's hypotheses that follow:

- First of all, the dynamic of alluvial ecosystems is not always linear but rather cyclic (as a consequence of the river dynamic). Thus, change direction could be progressive (from a herbaceous vegetation towards a forest) or regressive (flood can destroys an alluvial vegetation and some time later, pioneer vegetation will colonise the same place).
- Second, according to Gallandat *et al.*, (1993), plant successions in the natural alluvial ecosystems pass from a pioneer state to a shrub state to tree state, according to a typical evolution pattern identified in this kind of flood plain by the environmental experts: *pioneer vegetation ⇒ willow ⇒ alder ⇒ ash (with rectrogradation).*

This succession will be considered as the basis hypothesis, with two modifications:

a) Considering that land cover categories identified by photo-interpretation are on a more general scale (impossibility to recognise plant species), the following sequence is assumed as a progressive dynamic: *water* ⇒ pebbles ⇒ herbaceous/shrub ⇒ open forest.

b) Moreover, as the study site has been changed by human impacts, the two last categories (non-alluvial forest and grassland) that do not participate in the alluvial process will also be considered in the change dynamics. Furthermore, it is admitted, as explained before, that categories could retrograde.

Based in these two hypotheses and the uncertainties mentioned previously, unexpected transitions were then eliminated (in substituting their values by zero). The cross-tabulation matrices as well as the cross-classification maps are then simplified by the elimination of the unexpected transitions and only the reliable transitions are considered for the change pattern analysis. Based in the viable transitions, change direction and pattern of change for each time step is illustrated. Furthermore, the turnover time for each land cover category by time step was calculated with basis in the area changing from one category to another (Bakker et al., 1994). This index gives some information about change pattern through time and was calculated by:

$$\text{Turnover time} = \left(\frac{A_v}{\delta A_v}\right) \cdot t, \text{ where:}$$

A_v = initial area of a land cover category

δA_v = total area changing into another land cover category

t = time span

7.4 Results

7.4.1 Spatio-temporal landscape characterisation

By photo-interpretation, seven categories of land cover were determined. They are defined as follow:

1. Water: the river channel and its branches with or not submerged vegetation;
2. Pebbles: bared deposits of coarse material (pebbles, gravels, sands, silts, clays), with maximum 1% of vegetation that could be temporally covered by water;
3. Herbaceous/Shrub: includes pioneer herbaceous vegetation and bush (predominantly Willow - *Salix* sp) as well as some sparse young Alder (*Alnus incana*);
4. Open forest: mixed alluvial forest with an indeterminate status. This category is mostly composed of alluvial species as Alder (Alnus incana), Ash (*Fraxinus excelsior*), Beech (Fagus silvatica) and some non-alluvial species such as Spruce (*Picea excelsa*) and Maple (*Acer pseudoplatanus*) in minority;
5. Non-alluvial forest: composed essentially of a dense Spruce forest (*Picea excelsa*) and generally located at the edges of the floodplain;
6. Grassland: rich grassland located out of the edges of the floodplain (outside the alluvial dynamics). They are mowed each year;
7. Construction (isolated rural warehouse in the edge of the site limits; not considered in the analyses).

As can be observed in the land cover maps (Figures 7.22 and 7.3), the floodplain of the Sarine River has drastically changed over time. In 1930 (ten years after the first embankments) the river channel is still braided. With time, the channel has become straighter and simpler.

Changes in land cover have also occurred, particularly an increase in the forested area (categories 4 and 5), while categories 1, 2 and 3 (water, pebbles and herbaceous/shrub) have decreased. The area values (ha) and proportions of each legend category (%) shown in Table 7.1 confirm these observations. It can also observed that between 1930 and 1943 change has been more drastic (the area of water category for example, has decreased of the 50%, passing from 23.6 to 11.6 % of the total surface). In the same time span, 51.4 % of the total area has been occupied by forest (categories 4 and 5 together), against 36.2 % in 1930.

Figure 7.4 illustrates the evolution of the land cover categories over time in % of the total area (96 ha). In a graphic way it confirms the opposite evolution between water and open forest (category 4) 23 years after the beginning of embankments.

As can be observed, the area occupied by category 5 (non-alluvial forest) has also increased, but in a less drastic way until 1943. Figure 7.5 gives additional information about the landscape composition. With time, the diminution of categories 1 and 3 (and 2, after 1955) goes with an increase in the forested area (categories 4 and 5). In fact these two categories dominate the floodplain vegetation. Furthermore, category 5 has even dominated the landscape in the last time step, in contrast to the category 2, which is disappearing.

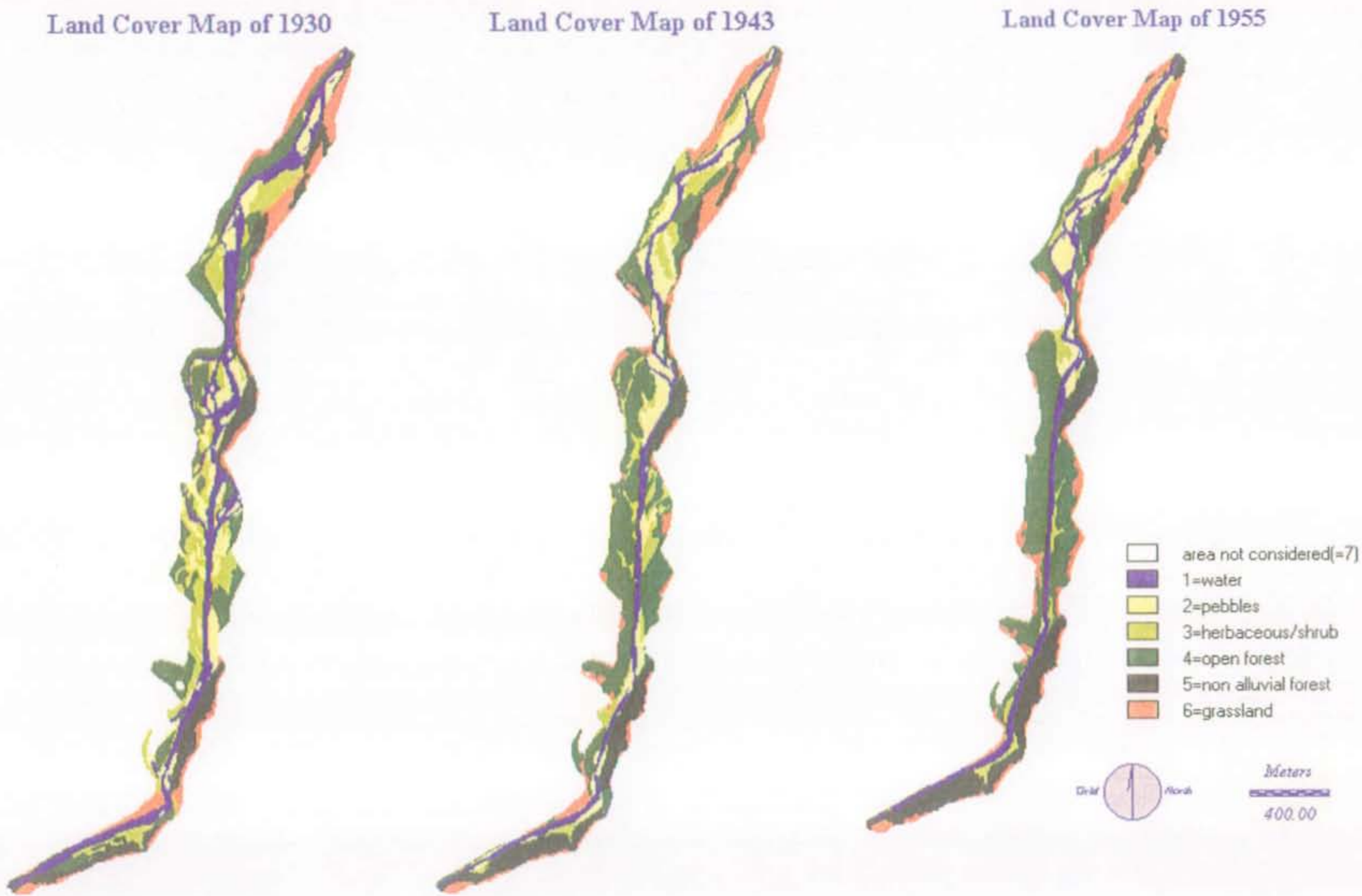

Figure 7.2 – Land Cover Maps of 1930, 1943 and 1955

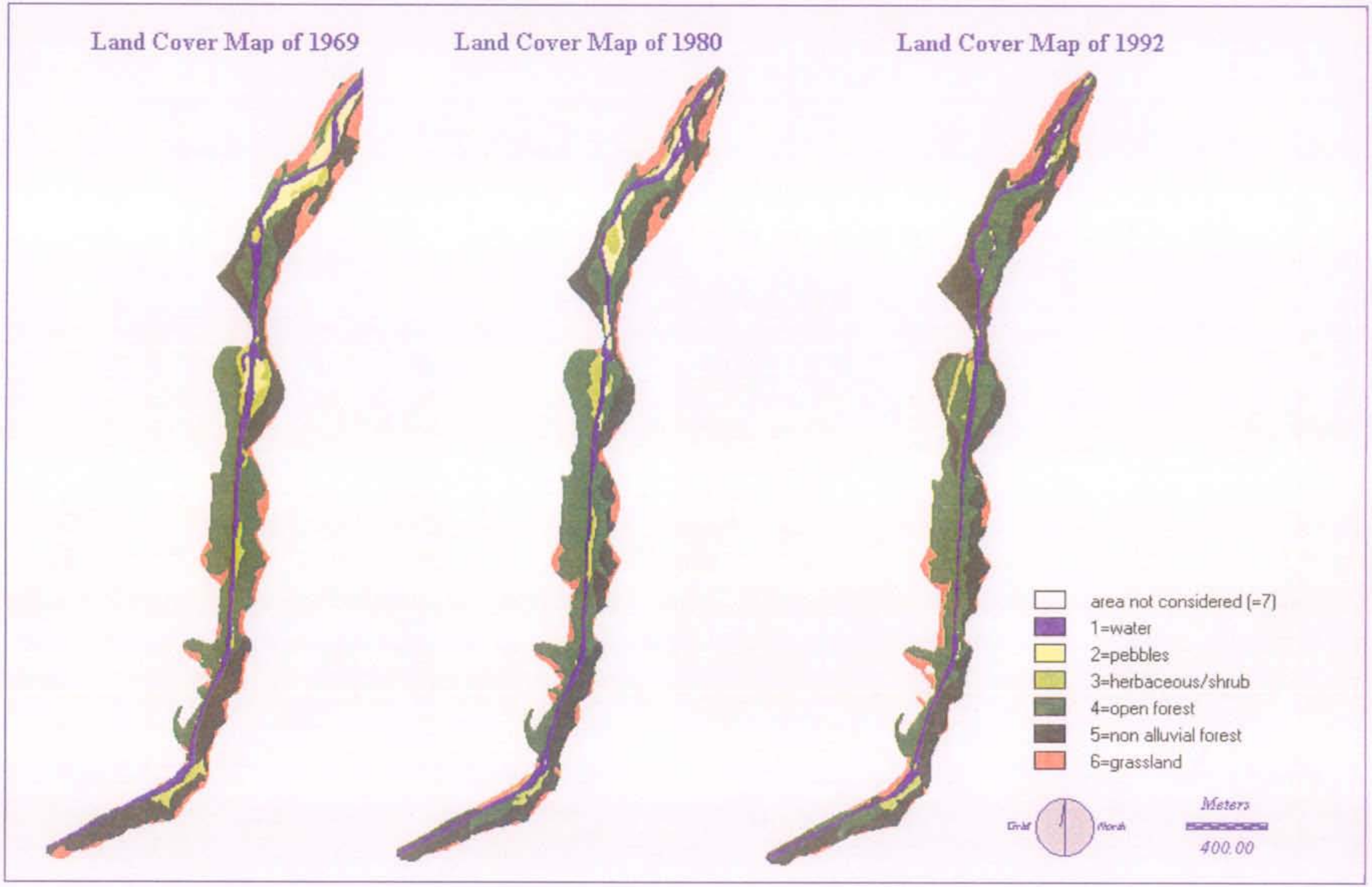

Figure 7.3 – Land Cover Maps of 1969, 1980 and 1992

Table 7.1 - Land Cover categories area distribution (ha and %) over time

Year	water		pebbles		herb/shrubs		open forest		non all.forest		grassland	
	ha	%	ha	%	ha	%	ha	%	ha	%	ha	%
1930	22.7	23.6	11.9	12.4	15.3	16.0	21.0	21.9	13.7	14.3	11.4	11.9
1943	11.1	11.6	13.1	13.6	9.4	9.8	33.7	35.1	15.6	16.3	13.1	13.6
1955	14.6	15.2	8.9	9.2	4.7	4.9	31.9	33.2	20.8	21.7	15.1	15.8
1969	13.6	14.2	4.8	5.0	5.0	5.2	32.6	34.0	27.5	28.7	12.4	12.9
1980	12.3	12.8	3.2	3.4	4.4	4.5	34.2	35.7	31.3	32.6	10.6	11.1
1992	12.1	12.6	0.3	0.3	2.5	2.6	34.4	35.8	36.4	37.9	10.4	10.9

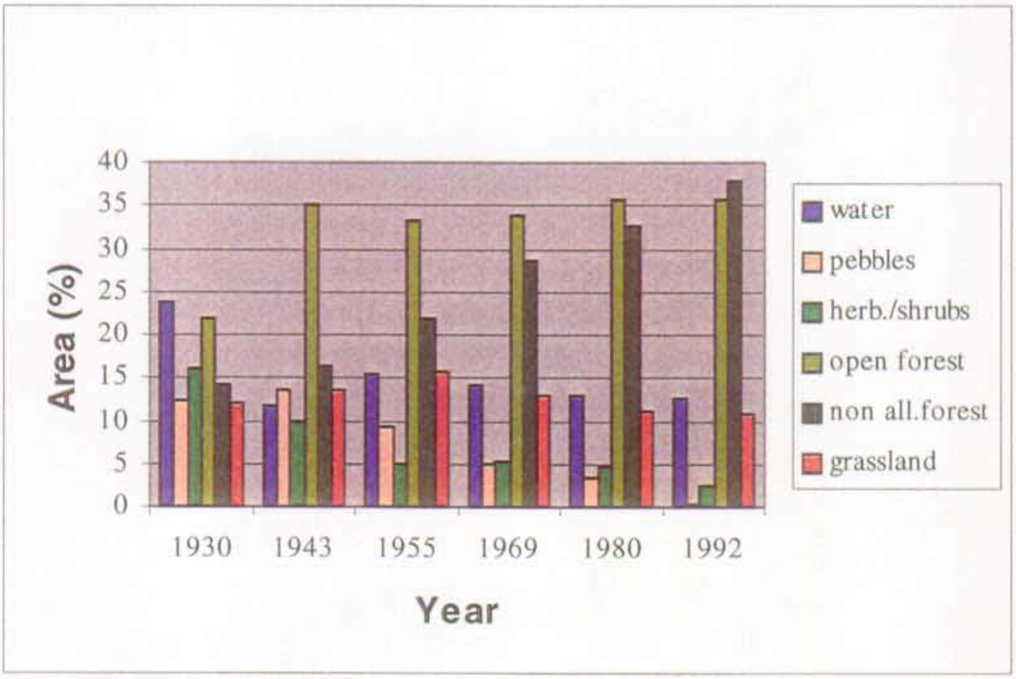

Figure 7.4 - Land cover evolution through time

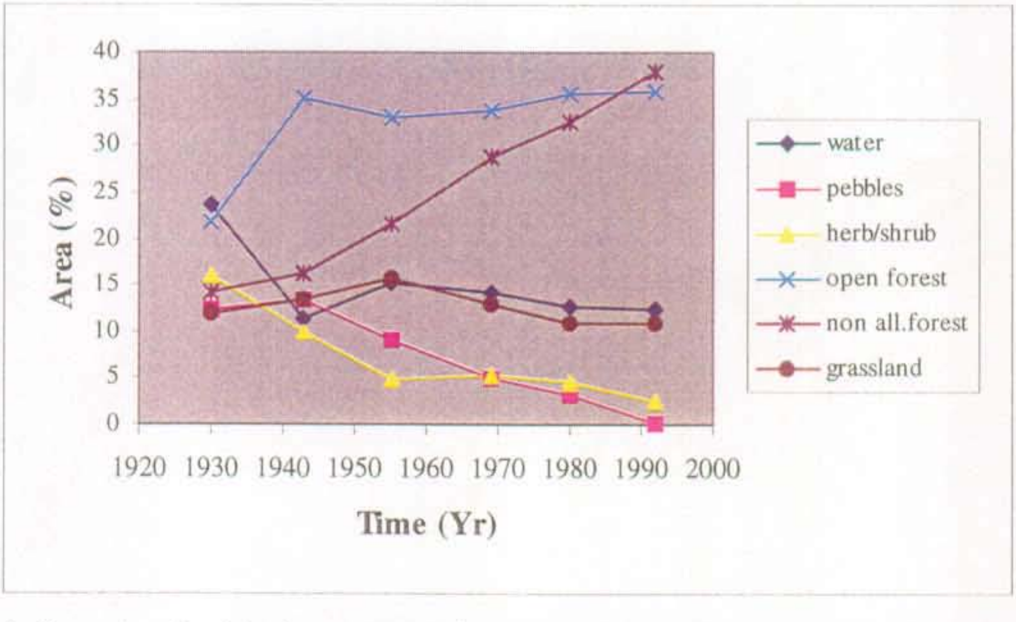

Figure 7.5 - Proportion of each land cover category by year

Concerning landscape configuration, Table 7.2 summarises the results of some landscape pattern indices over time. The Maximum Diversity (H_{max}) is constant because the number of land cover categories is the same for all time steps. This will permit a better comparison of the index Diversity (D). The floodplain of the Sarine River has become less diverse with time (from 1,7 to 1,3). This is confirmed by the values of the Dominance index, which seems to be more sensitive in this case. In 1930 land cover categories are distributed in a more equitable proportion (Dominance index is close to zero). This index has increased of a factor of 12 in 62 years (from 0,020 to 0,246).

Table 7.2 - Landscape pattern indices trhough time

Year	Diversity (H)	Max. Diversity (Hmax)	Dominance (D)
1930	1.756	1.792	0.020
1943	1.684	1.792	0.060
1955	1.642	1.792	0.083
1969	1.571	1.792	0.123
1980	1.494	1.792	0.166
1992	1.350	1.792	0.246

Table 7.3 completes the information about the landscape configuration and more specifically about landscape fragmentation. In general, for the three first categories (1, 2 and 3), the number of patches (NP) has decreased after 1955 and even after 1943 for the category 3. Furthermore, the decrease in NP for category 3 goes with an increase in the mean size patch (MSP) for the period between 1969 and 1980. In 1992, the increase of the NP (18) associated with the very small MPS (0,13) indicates a high fragmentation level for category 3. The smallest patches compose category 2 (like category 3). Except for category 2, the NP has augmented in the last year of observation (1992). Concerning category 5, the number of patches has been more stable through time, but the mean size patch (MSP) has become greater after 1955. Category 4 has an intermediate behaviour: NP has decreased after 1943, and especially in 1955. Afterwards, NP is increasing. As discussed in the next point, category 6 (grassland) will not be considered in the alluvial dynamic. For this reason, the result of its fragmentation is not presented here. Finally, the variation in patch size expressed by PSSD and PSCV that give information about the landscape heterogeneity are remarkably high. As explained before (Material and Methods section), a greater variability in patch size measures indicates less uniformity in pattern. Nevertheless, due to the great irregularity in the distribution of patch size (a few very large patches and several very small patches), and considering that both measures assume a normal distribution about the mean, the values are rather interpreted as a tendency.

7.4.2 Land Cover change detection and change pattern identification

Figure 7.6 (cross-classification map between 1930 and 1943) shows an example of output map resulting from the pairwise comparison technique. These maps relate all transitions between land cover categories and shows spatially the locations of these combinations (*what* and *were* land cover categories have changed through time). These maps show also the stability process (no change). The legend enumerates these combinations. The left-hand categories refer to the map listed on the left in the title (1930 in this case) and those on the right refer to the image listed on the right in the title (1943). To simplify the legend description, land cover categories defined are represented by their numbers (1, 2, 3, 4, 5 and 6). In this way, a given transition with a legend (2:3) signifies that the corresponding location in the map was pebbles category (2) in 1930 and has changed to herbaceous/shrub category (3) in 1943. If a given transition has the same values (e.g. 2:2) this signify that no change has occurred for such a category in the time span considered or, in other words, that category 2 has remained category 2 and so on.

Table 7.3 - Patch index by land cover category through time (NP=Number of Patches; MPS=Mean Size Patch, in ha; PSSD= Patch Size Standard Deviation and PSCV= Patch Size Coefficient of Variation, in %)

Year	**water(1)**				**pebbles(2)**				**herb/shrubs(3)**				**open forest(4)**				**non all.forest(5)**			
	NP	MPS	PSSD	PSCV	NP	MPS	PSSD	PSCV	NP	MPS	PSSD	PSCV	NP	MPS	PSSD	PSCV	NP	MPS	PSSD	PSCV
1930	6	3.77	8.30	220.35	59	0.20	0.27	133.59	52	0.29	0.59	201.08	22	0.96	1.62	168.42	10	1.36	1.33	97.52
1943	5	2.20	2.96	134.77	35	0.37	0.51	137.99	43	0.22	0.27	122.64	20	1.68	3.70	219.47	9	1.72	1.92	111.68
1955	6	2.42	5.38	222.22	31	0.28	0.55	194.01	22	0.21	0.28	132.73	9	3.54	4.93	139.37	12	1.74	3.35	192.25
1969	1	13.48	0.00	0.00	12	0.40	0.57	141.80	12	0.41	0.34	83.00	11	2.95	5.19	175.93	10	2.74	3.82	139.60
1980	2	6.02	1.72	28.49	16	0.20	0.24	118.77	10	0.43	0.42	98.64	12	2.84	5.36	188.67	11	2.81	4.19	149.09
1992	5	2.36	4.64	196.14	8	0.04	0.04	95.70	18	0.13	0.22	166.79	18	1.89	3.99	211.49	14	2.58	3.76	145.76

The corresponding cross-tabulation matrices obtained for each pair of dates is presented in Table 7.4. In these primitives cross-tabulation matrices, changes of frequencies between all land cover categories are listed (the frequencies in which classes have remained the same - along the diagonal, or have changed - off-diagonal frequencies). The overall KIA that measures the correlation between each pair of images is reported.

Based on the categories of land cover defined (and excepting the category 7, not considered in the analysis), 30 transitions are theoretically possible (Figure 7.7). Nonetheless, according to the work's hypotheses stated before, not all transitions related in the primitive cross-tabulation matrices were as expected. In particular, the following transitions were considered as unexpected in this study:

- From water, pebble and herbaceous/shrubs to non-alluvial forest (transitions 1:5, 2:5 and 3:5). It seems incompatible with the category 5 description itself and within the time span considered.
- From water, pebble and herbaceous/shrubs to grassland (transitions 1:6, 2:6 and 3:6). The principal reason to consider these unexpected transitions, is their spatial location. In the present case, this comes always from the edges of the studied site and the categories 1, 2 and 3 are found near the river course.
- As related in the category definition, grassland is mowed each year thus it is impossible to retrograde from grassland to open forest and less to non-alluvial forest. Therefore, transitions 6:4 and 6:5 are unexpected.

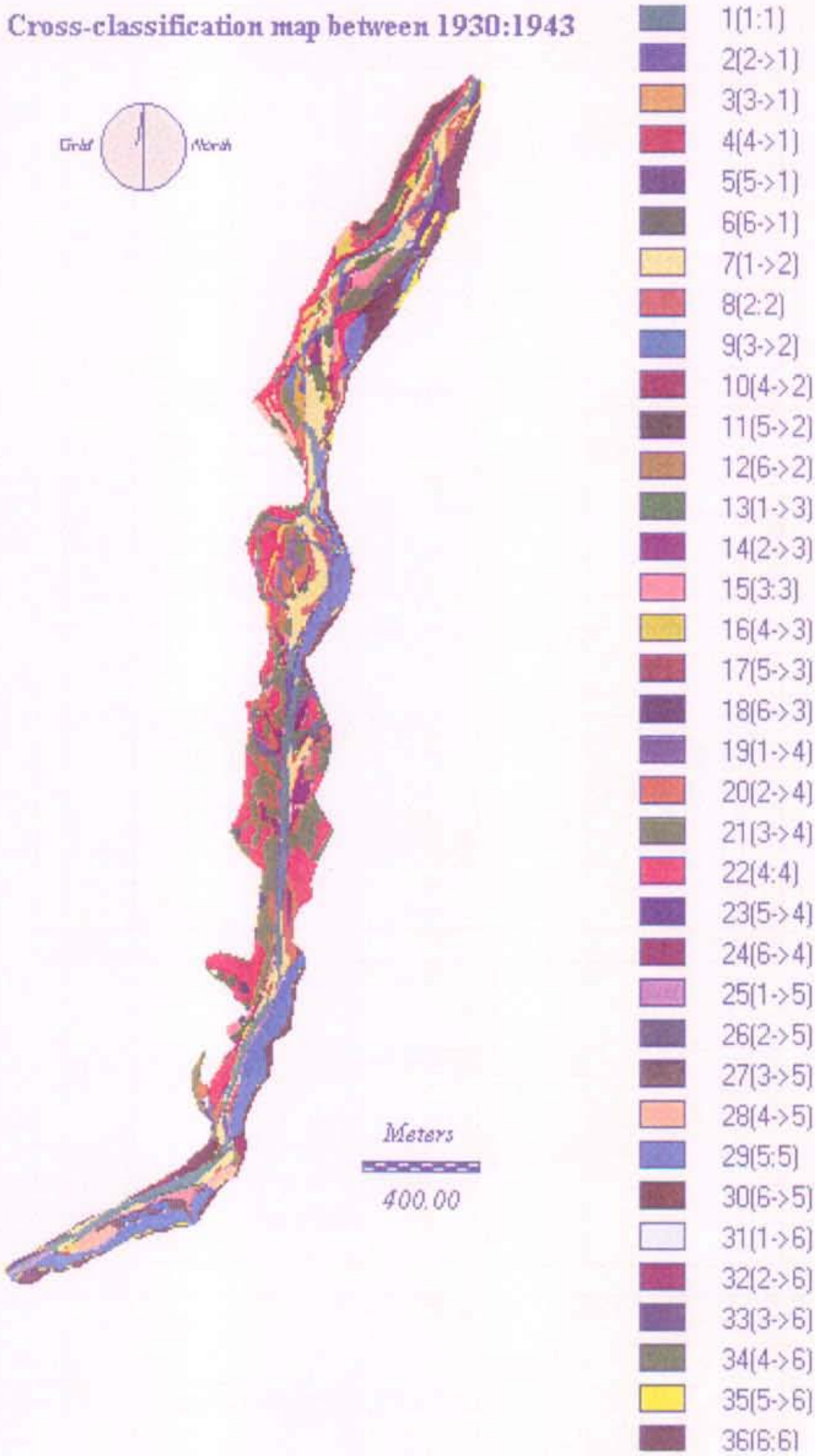

Figure 7.6 – Spatial location of all theoretical transitions between land cover categories (->) and stable areas (:)

Table 7.4 Cross-tabulation matrices (% of the total area = 96 ha) for each time step

	Land Cover Classes	1943						
		water	pebbles	herb/shrub	open forest	non all.forest	grassland	total
	water	8.2	8.2	3.1	3.4	0.7	0.1	23.6
	pebbles	2.0	3.5	2.7	4.1	0.1	0.0	12.4
	herb/shrub	0.7	0.8	2.2	10.5	1.1	0.7	16.0
1930	open forest	0.3	1.0	1.5	14.2	1.8	3.0	21.9
	non all.forest	0.2	0.1	0.1	1.7	11.1	1.0	14.3
	grassland	0.1	0.0	0.2	1.2	1.5	8.8	11.9
	total	11.6	13.6	9.8	35.1	16.3	13.6	100.0

Overal Kappa between the two images: 0.7105

	Land Cover Classes	1955						
		water	pebbles	shrub	all.forest	non all.forest	grassland	total
	water	5.5	2.1	1.0	1.2	1.8	0.0	11.6
	pebbles	4.2	4.8	1.0	1.9	1.5	0.2	13.6
	shrub	2.1	0.9	0.7	5.0	0.5	0.6	9.8
1943	all.forest	2.7	1.4	1.7	23.1	2.7	3.6	35.2
	non all.forest	0.0	0.0	0.1	1.0	14.0	1.2	16.3
	grassland	0.7	0.0	0.3	0.9	1.4	10.3	13.5
	total	15.2	9.2	4.9	33.1	21.8	15.8	100.0

Overal Kappa between the two images: 0.7657

	Land Cover Classes	1969						
		water	pebbles	shrub	all.forest	non all.forest	grassland	total
	water	9.1	1.7	1.2	1.7	1.6	0.0	15.2
	pebbles	2.8	2.9	1.1	1.8	0.7	0.0	9.2
	shrub	0.7	0.4	1.8	1.0	1.0	0.0	4.9
1955	all.forest	1.1	0.1	0.7	27.0	3.7	0.5	33.2
	non all.forest	0.3	0.0	0.4	0.1	20.0	0.9	21.7
	grassland	0.2	0.0	0.0	2.3	1.7	11.5	15.8
	total	14.2	5.0	5.2	34.0	28.7	12.9	100.0

Overal Kappa between the two images: 0.8412

	Land Cover Classes	1980						
		water	pebbles	herb/shrub	open forest	non all.forest	grassland	total
	water	7.2	1.4	1.1	3.2	0.9	0.4	14.2
	pebbles	1.1	1.0	0.6	1.8	0.4	0.0	5.1
	herb/shrub	0.8	0.2	1.5	1.9	0.7	0.1	5.2
1969	open forest	0.9	0.5	1.1	25.6	4.8	1.1	34.1
	non all.forest	2.6	0.2	0.2	2.3	22.8	0.7	28.8
	grassland	0.0	0.0	0.0	0.7	2.7	9.2	12.7
	total	12.7	3.4	4.5	35.6	32.4	11.5	100.0

Overal Kappa between the two images: 0.8142

	Land Cover Classes	1992						
		water	pebbles	herb/shrub	open forest	non all.forest	grassland	total
	water	9.4	0.2	0.3	1.6	1.3	0.1	12.8
	pebbles	1.5	0.1	0.2	1.2	0.4	0.0	3.4
	herb/shrub	0.4	0.0	0.9	2.6	0.4	0.2	4.5
1980	open forest	0.6	0.1	0.7	26.1	7.2	0.9	35.7
	non all.forest	0.6	0.0	0.5	4.3	25.7	1.5	32.6
	grassland	0.0	0.0	0.0	0.1	2.8	8.2	11.1
	total	12.6	0.3	2.6	35.8	37.9	10.9	100.0

Overal Kappa between the two images: 0.8265

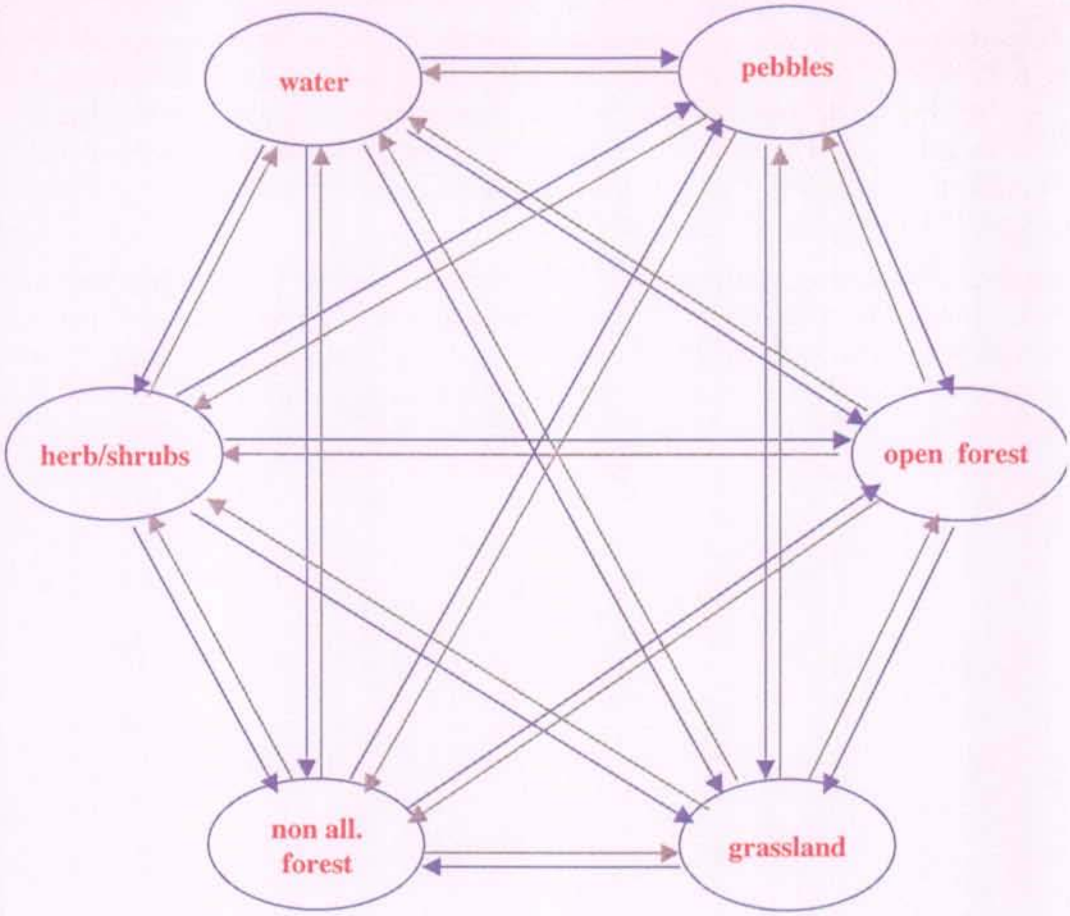

Figure 7.7 - All theoretically possible transitions between the land cover categories

In eliminating the unexpected transitions from Figure 7.7, change direction and pattern of change for each time step are illustrated by Figure 7.8. For the time step 1930/1943, the dynamic is rather progressive, but the biggest changing area concerns the transition herb/shrub to open forest (3:4) and water to pebbles (1:2). For the time step 1943/1955, the dynamic for categories 1, 2 and 3 is rather regressive (it signifies the rejuvenation of the system). However, the transition herb/shrub to open forest is still important (but less than before).

In a general way, a progressive dynamic dominates the time step 1955/1969, but in a different way: changes occur mainly from category 4 to 5. A located regressive dynamic could also be observed concerning the transition pebbles to water. For the time step 1969/1980, the progressive dynamic is always dominant, but the area changing from open forest to non-alluvial forest is yet more important. The same tendency was verified for the time step 1980/1992 and with a strong augmentation of the area changing from open forest to non-alluvial forest.

Figures 7.9 and 7.10 illustrate these viable transitions in space and time (*where* and *when* changes occur) and give information about the quality of changes (e.g. pebbles that pass to herbaceous/shrub category...). Table 7.5 summarises in a quantitative way, the differences between the successive time steps concerning the area changing as well as the stable areas for all viable transitions. Considering land cover categories confounded all together, the area of stable zones has increased through time, passing from 46,3 ha in the time step 1930/1943 to 67,6 ha in 1980/1992 period. The stable zones are composed mainly by categories 4 and 5 especially after 1955. The turnover time by land cover category calculated with basis in Table 5 is shown in Table 7.6. The non-alluvial forest category (5) is the most stable. Pebbles and herbaceous/shrub categories (2 and 3) have the same turnover time average values. These categories are the less stable.

Water category has a turnover time that is 50% (average) highest than the turnover time for categories 2 and 3. The time step 1955/1969 shows a drastic increase of the turnover time for all categories (excepted category 2, that has also increased, but not drastically). Afterwards, the turnover time has decrease for all categories in the time step 1969/1980.

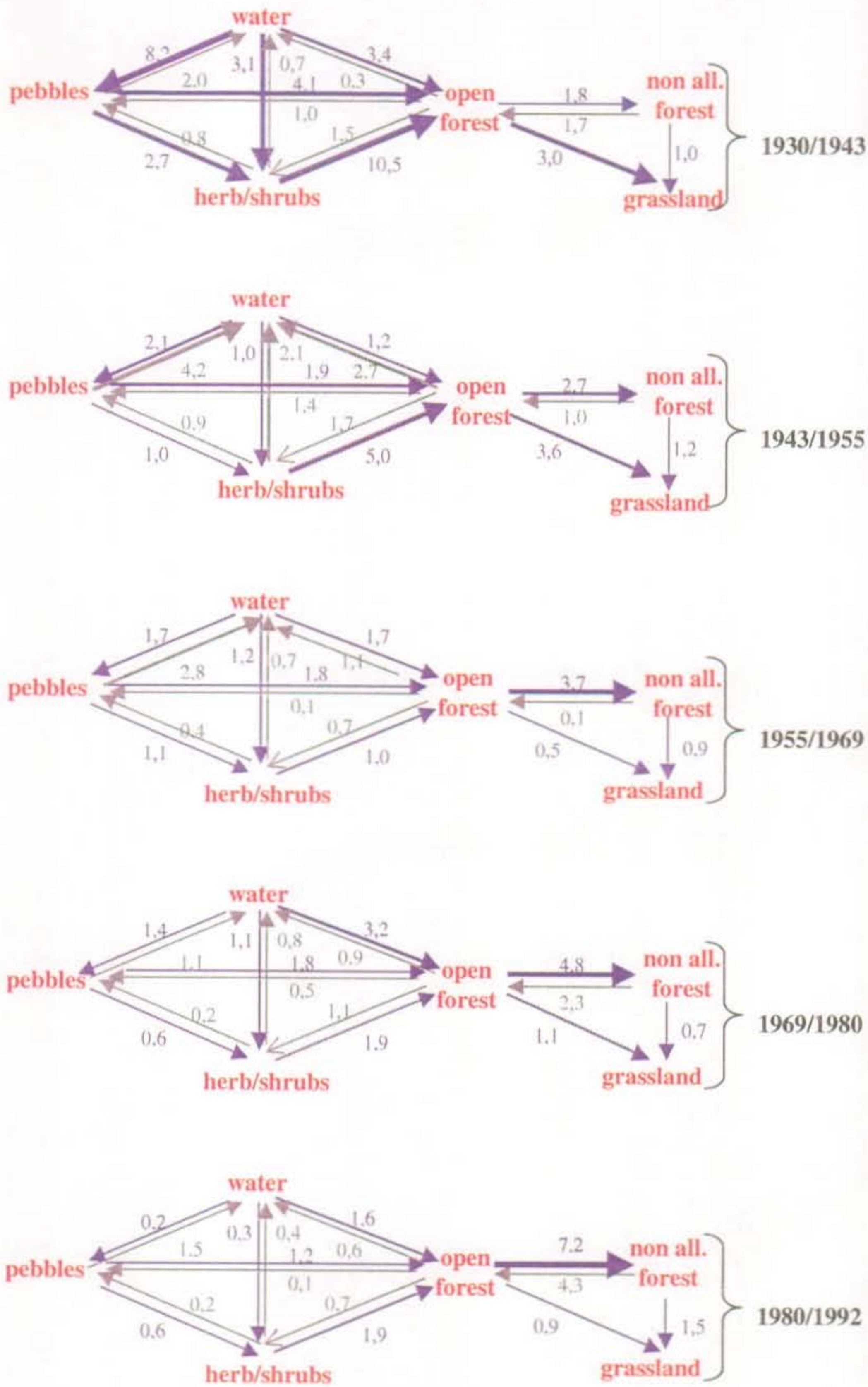

Figure 7.8 - The viable transitions of land cover categories (by time step), with the proportion of area changing between categories (%), change direction and pattern of change. The blue arrows indicates a progressive dynamic while the grey arrows, a regressive one. The thick arrows indicates a biggest proportion of change.

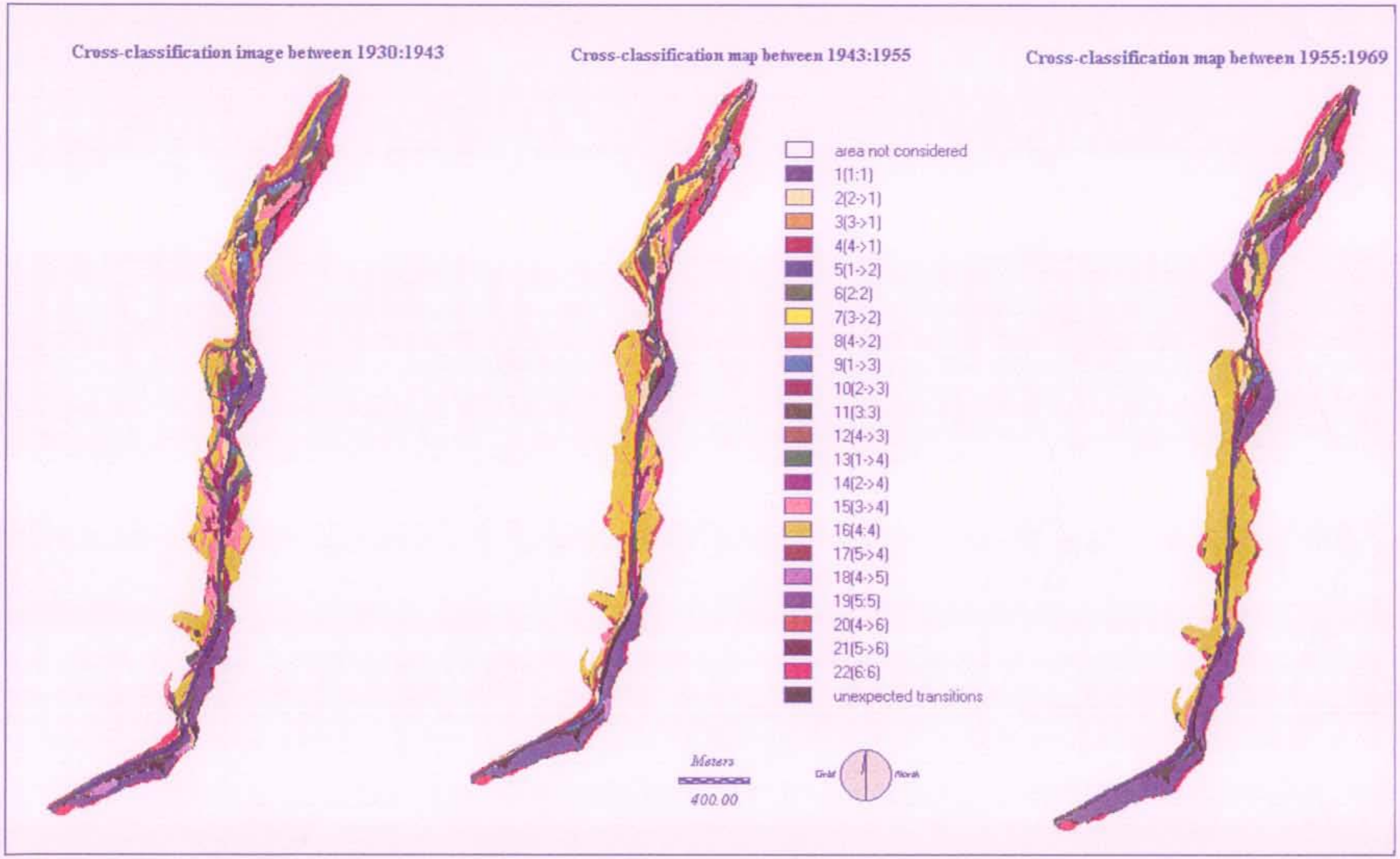

Figure 7.9 – Cross-classification maps showing spatially the viable transitions for the time steps 1930-1943, 1943-1955 and 1955-1969

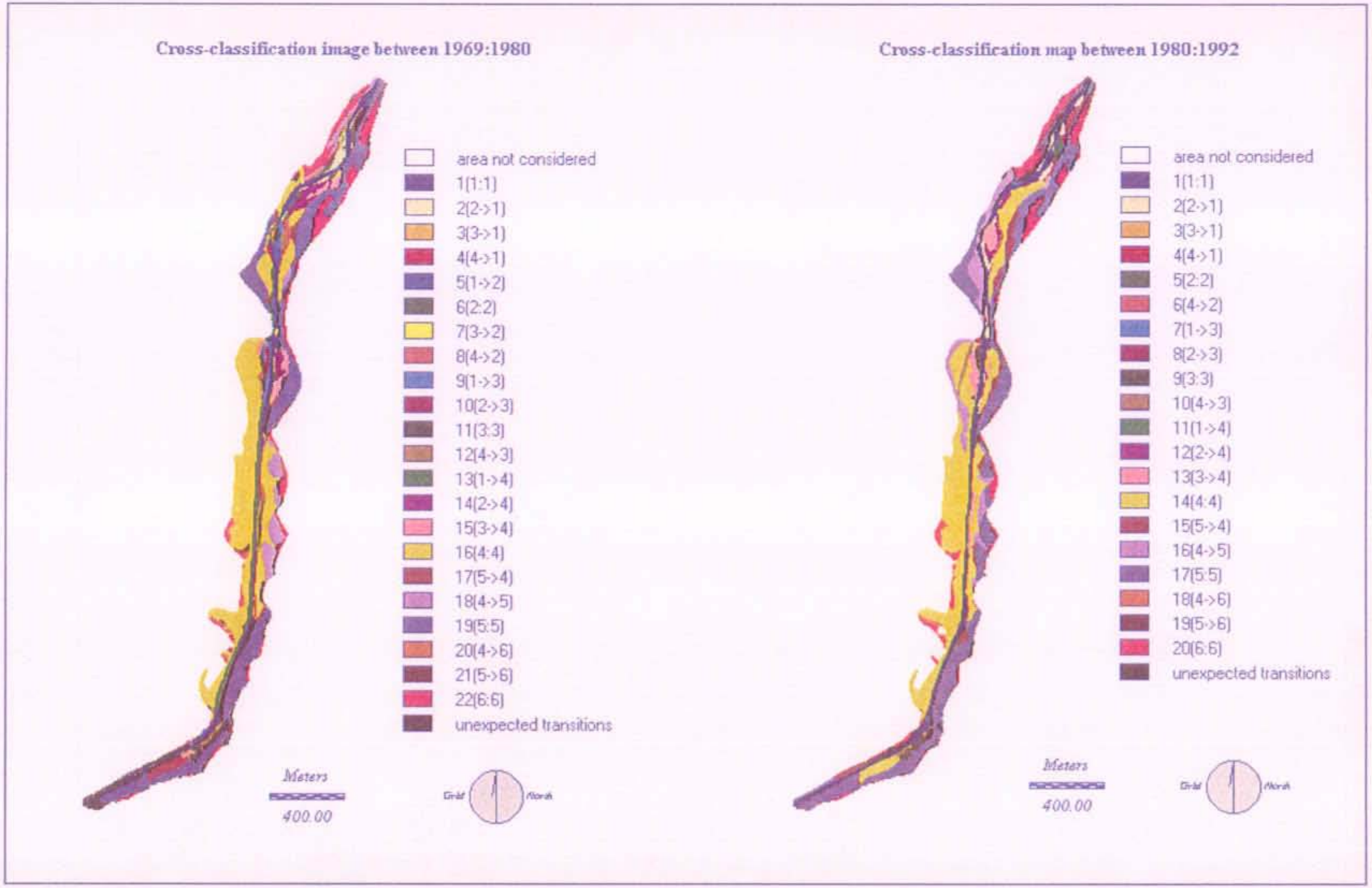

Figure 7.10 – Cross-classification maps showing spatially the viable transitions for the time steps 1969-1980 and 1980-1992

Table 7.5 - Summary of area changing from one land cover category to another (ha)

Transition (from--->to)	1930/1943	1943/1955	1955/1969	1969/1980	1980/1992
1:1	7.9	5.2	8.8	6.9	9.0
1:2	7.9	2.0	1.6	1.3	0.2
1:3	2.9	0.9	1.1	1.1	0.3
1:4	3.2	1.2	1.6	3.0	1.5
Total area of category 1	22.0	9.4	13.1	12.4	10.9
Stable area	7.9	5.2	8.8	6.9	9.0
Changing area	14.1	4.1	4.3	5.4	1.9
2:1	1.9	4.1	2.7	1.0	1.5
2:2	3.4	4.6	2.8	1.0	0.1
2:3	2.6	1.0	1.1	0.6	0.2
2:4	3.9	1.8	1.7	1.8	1.1
Total area of category 2	11.8	11.5	8.2	4.4	2.9
Stable area	3.4	4.6	2.8	1.0	0.1
Changing area	8.4	6.9	5.5	3.4	2.8
3:1	0.7	2.0	0.6	0.8	0.3
3:2	0.7	0.9	0.4	0.2	0.0
3:3	2.1	0.7	1.7	1.4	0.9
3:4	10.0	4.8	1.0	1.9	2.5
Total area of category 3	13.6	8.4	3.7	4.3	3.8
Stable area	2.1	0.7	1.7	1.4	0.9
Changing area	11.4	7.7	2.0	2.9	2.9
4:1	0.3	2.6	1.0	0.9	0.6
4:2	1.0	1.3	0.1	0.5	0.1
4:3	1.5	1.7	0.7	1.1	0.7
4:4	13.7	22.1	26.0	24.6	25.1
4:5	1.7	2.6	3.5	4.6	7.0
4:6	2.9	3.5	0.5	1.0	0.8
Total area of category 4	21.0	33.8	31.9	32.7	34.2
Stable area	13.7	22.1	26.0	24.6	25.1
Changing area	7.3	11.7	5.9	8.1	9.1
5:4	1.7	1.0	0.1	2.2	4.1
5:5	10.7	13.5	19.2	21.9	24.6
5:6	1.0	1.1	0.8	0.6	1.5
Total area of category 5	13.3	15.5	20.2	24.7	30.2
Stable area	10.7	13.5	19.2	21.9	24.6
Changing area	2.6	2.1	1.0	2.9	5.6
6:6	8.5	9.8	11.0	8.8	7.9
Total area of category 6	8.5	9.8	11.0	8.8	7.9
Stable area	8.5	9.8	11.0	8.8	7.9
Changing area	0.0	0.0	0.0	0.0	0.0
Total stable area	46.3	55.9	69.5	64.6	67.6
Total changing area	43.8	32.5	18.7	22.7	22.3

Table 7.6 - Turnover time (year)

		Land Cover categories				
time step	**time span (t)**	**water**	**pebbles**	**herb/shrubs**	**open forest**	**non all.forest**
1930/1943	13	20.2	18.2	15.4	37.2	65.9
1943/1955	12	27.3	20.1	13.1	34.7	89.7
1955/1969	14	42.5	21.0	26.0	75.5	296.6
1969/1980	11	25.1	14.2	16.4	44.4	95.4
1980/1992	12	69.0	12.4	15.8	45.0	65.0
Average		36.8	17.2	17.3	47.4	122.5

7.5 Discussion

This study shows that land cover evolution of the Sarine River's floodplain could be reconstructed from 1930 up to the present day (1992). Only seven land cover types could be distinguished, which allowed us to focus on only major changes. Even with a relatively coarse approach, land cover recognition was not always easy to perform. Visual control in field surveys has confirmed our classification, but some categories were hard to separate because they are not very clear even in the field (e.g. category 4).

The first results indicate that the river channel was still braided in 1930 (Fig. 7.1, 7. 2 and 7.3) and the land cover categories (Fig. 7.5) were equitably represented. This floodplain has become dry and largely dominated by the forest categories (4 and 5) and the pioneer and the intermediate stages tend to disappear. This evolution could be due to an alluvial dynamic, which is less and less active.

Nevertheless, the increases in area for the different categories do not follow the same pattern. For example, the area occupied by category 5 until 1943 has augmented, but in a less drastic way than for category 4. This is an expected result because category 5 is a non-alluvial forest in a final stage and 23 years are not sufficient for the augmentation of this category. In fact, to reach this category, a combination of time, distance of the river channel and topography are required. In the other words, this category of vegetation is found in marginal areas of the alluvial floodplain.

This first part of the results could be viewed as the answer to the three questions addressed by the Peuquet's framework, that relates the state of an object in a given location and at a given time. Change detection (and location of change) is important, because not only it does influence the possible future states, but also it is a reflection of past states.

The analysis of the landscape configuration (or fragmentation) gave more information about changes, but more importantly about *how* changes occur (Table 7.3). In the other words, *how* the patches of each land cover category has changed in number and size through time. As observed, there is a clear rupture after 1955. This difference is expressed by the decrease in number of patches (for categories 2 and 3) and also by the increase in the mean patch size (for categories 5 and also 4). It confirms the visual interpretation of Figures 7.2 and 7.3.

Furthermore, for category 3, the decrease of the number of patches goes with the increase of the mean size patch after 1955. These patterns express a different dynamic of the land cover categories. Finally, the year 1992 seems to be somewhat atypical. The augmentation of the number of patches for category 1 is surprising and hard to explain. For this category, the patches are in fact, the riverbed and its functional branches. In the beginning, with a braided system several river branches were present, but this has changed after 1955. An augmentation in 1992 could be due to some fragmentation in the active part of the alluvial floodplain (in the northern sector of the site) after floods.

Nevertheless, what is important to consider is that the surface of category 1 has drastically decreased (50%). Concerning the augmentation of the number of patches for categories 3 and 4 (for the same year), it goes with a decrease in the mean size patch for both categories. One plausible explanation for this is the cutting/plantation or other anthropic phenomena verified in the field and by the shape of some patches in the land cover maps.

The cross-classification/cross-tabulation technique is a relevant GIS function that allowed the spatial location of change (*where* changes occur), as well as informed about the quality of change through time (e.g. a given X, Y location has changed from category 3 to category 4 in the time step T) (or *how* and *when* changes in a given location (*where*) has occurred). Furthermore, it has permitted change quantification based on values of the cross-tabulation matrices. These matrices have also facilitated the analysis of all possible transitions.

Most of the calculated transitions were as expected. The few that were not can be explained by one or a combination of the four factors previously mentioned. The fact that land cover maps were performed by digitising must be taken in consideration. Even taking care to work in zoom windows (pixel scale), digitising always introduces some uncertainties that will affect the area calculation (for each category and as a whole), as well as originate small polygons and consequently, unexpected transitions.

An example of unexpected transition due to the quality of aerial photographs, is water to grassland. These two categories are clearly different in the photographs and spatially distant from each other. This unexpected transition can therefore not be due to inaccuracies in type recognition, or digitising, but rather caused by inaccuracies in the maps. The overall KIA between each pair of images could confirm this. As can be observed, this measure of agreement is small for the first images comparison (1930/1943 and 1943/1955) and is probably due to the bad quality of the first aerial photographs. Concerning drawbacks due to overlay technique itself, small polygons could be produced and then, unexpected transitions.

In our case, unexpected transitions range from 6-9% of the total area for the time steps considered. Considering that our aim was to study change detection and patterns of change rather than change quantification in itself, this accuracy is considered to be Bakker et al., 1994) have considered less than 5% of error as a high accuracy). To be more accurate, the analysis of change direction and pattern of change, as well as the calculation of the turnover time, were done after the elimination of unexpected transitions.

The analysis of the changing area has shown that in a general way, the first three categories have decreased their areas with time, contrary to categories 4 and 5. Category 6 was considered as marginal to the alluvial process. Considering that no return to other categories was permitted, the area occupied tends to be stable with time. The small variation in area (from 7,9 to 11,0 ha) could be explained by either, lack of temporal/spatial resolution or data management.

Although the transition 3 to 4 occurs under natural circumstances as a result of endogenic alluvial processes, its rate was greatly increased by the floodplain drying and the consequent isolation of the main channel. The analysis of change dynamics between land cover categories is an important way to characterise change direction and the pattern of changes through time. Furthermore, it could help the understanding of processes subjacent to changes. These results have shown that the area changing has decreased with time, principally for the three first categories.

The present-day pattern of change of the Sarine River's floodplain is portrayed by the augmentation of the forested area in detriment of the categories 1, 2 and 3. It is the adaptation of the ecosystem to the new conditions resulting from human impacts (hydrological regime's change and the consequent isolation of the vegetation from the alluvial dynamics). This data agree with the observations made by Gallandat *et al.*, (1993) concerning the vegetation. They observed that current dynamics of Swiss floodplain vegetation no longer corresponds to those of a natural alluvial system. As a result of the human intervention, this evolution pattern has been modified: pioneer and intermediate states tend to disappear, the forested area had increased and the alluvial forest becomes less diverse due to the presence of non-alluvial species.

According to the indices calculated, this floodplain were more diverse in 1930 (ten years after the first embankments) and is becoming less diverse with time. Changes were traduced by the drying out of the floodplain, the geometry of the main channel (moistly rectilinear rather than braided) and flood limitations.

The turnover time has confirmed the stability of category 5 (non-alluvial forest). This category is in fact, essentially composed of *Picea sp*, that do not participate actively in the alluvial process. In contrast, the pebbles and the herbaceous/shrub categories are the less stable. The increase in the turnover time for all categories in the time step 1955/1969, as well as the decrease in the time step 1969/1980, could be explained by the flood phenomena that has been very important between 1955 and 1968 (Bureau, 1995).

In the present-day situation, water and non-alluvial categories are the more stable, followed by open forest category. These results are explained by the history of the Sarine River's floodplain. With the drying of the floodplain after embankments and dam construction the main channel has became stable as well as the riverbanks. The variation that could yet be possible is expressed by the turnover time of categories 2 and 3. As can be observed in the cross-classification maps, these transitions are found principally in the northern sector, still considered an active floodplain (Bureau et al., 1994). These two categories assure the alluvial character of this site. The turnover time for grassland category was not calculated because as grassland is mown each year, no transition from this category to another is admitted in this study.

7.6 Conclusion and Perspectives

GIS has facilitated the change detection and analyses performed in this study. Despite the uncertainties expressed by the unexpected transitions, the method used has permitted the integration of spatial and temporal aspects. Changes could be identified, located in space and time, quantified and qualified. Furthermore, change pattern could also be determined.

In this work, we were able to answer the principal queries addressed in the theoretical framework of Peuquet, (1994): *what* (changes in land cover), *where* (the spatial location of changes), *when* (the evolution through time). Furthermore, the question addressed by Claramunt and Theriault, (1996) could also be answered: *how* change occurs (information about landscape fragmentation and the qualitative information about changes). To answer the *why* question (explanation), only a detailed study relying on the identified changes and the present-day state of the vegetation and soils would be adequate to explain all the components of change. Nevertheless, the site historic and the expert knowledge were used to explain the *why* for these changes.

With regards to the landscape pattern, rate and direction of change, the human impacts (embankments, dams...) and flood events seem to play an important role on the evolution of this site and its present-day situation. The floodplain of the Sarine River has become dryer (stabilisation of the main channel and the riverbanks), dominated by the forest categories (in detriment to the categories 1, 2 and 3) and less diverse with time. The turnover time for each land cover category through time confirms these results: stabilisation of water and forest categories.

However, the analysis and description of environmental phenomena is a function of the considered temporal granularity, the spatial scale and the application aims. Thus a spatio-temporal model is conceived to run at its own spatial and temporal scale. Land cover changes were identified by using an average temporal granularity of twelve years between snapshots. Continuous record (or nearly continuous) seems to be the ideal condition for detecting changes and identifying processes underlying changes (Chrisman, 1998).

Nevertheless, the chosen granularity used in our study is relevant in the context and magnitude of changes of the floodplain vegetation (Salo, 1990). The chosen spatial resolution, 4m, for the identification of land cover categories and the related changes, was also determined with respect to the environmental and physical properties of our region of interest. However, as each process is devised to run at its own scale, the observation of land cover changes at a more precise scale, in both space and time, may have lead to some different results. Nevertheless, our results confirm the general tendency of the vegetation evolution observed for such a floodplain ecosystem in Swiss and European scales.

Furthermore, the cross-classification maps that illustrate the location of changes give information about the quality of changes as well, and shows that in a future work a change study must be performed separately for the two stretches (embanked and active). Further work must also focus on the relationships between land cover change dynamics and the present-day soil evolution.

From a methodological point of view, a more flexible classifying technique, for example fuzzy logic, should be better suitable to the delimitation of land cover categories because environmental changes are rather continuous than discrete in space. In addition, a more rigorous quality control could be also important, in order to avoid or limit error propagation. Finally, this work set up the basis for the following Chapter 8 that will project our results in the perspective of methodological advances in spatial representation and analysis of processes underlying changes within temporal GIS.

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Chapter Eight

Towards the description and analysis of spatial - temporal processes underlying land cover changes

Abstract

*From the modelling of environmental changes identified and quantified in the previous chapter, a description of the spatial and temporal properties of the different components of our environmental study is proposed in this chapter. The spatial and temporal dimensions in geographical and environmental modelling are fundamental aspects previously discussed in this thesis. As previously stated, the development of temporal GIS has recently appeared as an important conceptual and methodological issue within the GIS research community. Particularly, the integration of the thematic (**what**), spatial (**where**) and temporal (**when**) dimensions is essential within temporal GIS. This chapter develops an analysis of the spatio-temporal properties of our environmental study in order to identify the spatial and temporal nature of land cover changes from a more formal point of view. The spatio-temporal processes that represent the mechanisms of environmental changes (**how**) illustrate the dynamic component of our application. In addition, the development of scientific explanations that attempt to understand and explain the nature of these changes (**why**) is also included in this analysis. The spatio-temporal component of our application is further developed with respect to spatio-temporal process taxonomies identified by recent GIS research. A categorisation of environmental changes in the context of land cover changes is proposed, as well as how this categorisation supports a qualitative description of the environmental changes identified in the previous chapter. Finally, changes are analysed with regards to the context of temporal reasoning methods that make a distinction between prediction, planning, explanation and exploration studies.*

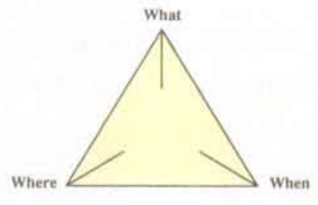
8.1 Introduction

The development of GIS and its application to environmental studies imply the extension of the classic static component of GIS toward a more dynamic representation of environmental phenomena (Langran and Chrisman, 1988; Langran, 1992; Al-Taha and Barrera, 1990; Kelmelis, 1998). In landmark research, Peuquet, (1994) introduced the Triad framework for the analysis of spatio-temporal phenomena within temporal GIS.

Designing an efficient GIS to study geographical phenomena is considered as a holistic approach that needs to be reflected by the modelling level. Peuquet's triad framework integrates the spatial, thematic and temporal dimensions. It supports the description of facts in 4 dimensions (x,y,z,t).

The application of the triad framework implies the introduction of some important spatio-temporal concepts, particularly facts and events. Facts enable observation of changes. A fact has a given truth-value during a period of time (i.e., a fact corresponds to the object and state properties identified during our design study - Chapter 6).

An event has been previously defined as the change of state of an object (i.e., change in existence, geometry or thematic value of an object). Facts and events are represented within the temporal, the spatial and the thematic dimensions. The following figure illustrates the principles of the triad framework.



Description

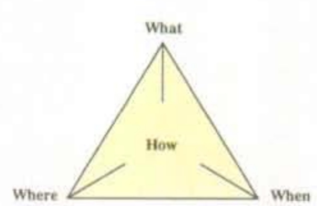
Figure 8.1 - Peuquet's triad framework

In fact, the triad framework reflects the development of our geographical database at the description level. The dimensions used within the Peuquet's framework are useful for the description of spatial and temporal properties. However, the analysis of environmental phenomena also implies the description of spatio-temporal processes.

A spatio-temporal process can be defined as an action that modifies one to many spatial entities. The representation of spatio-temporal processes combines the description of real-world entities (e.g., homogeneous land cover areas in the context of our study), and the mechanisms involved in spatial change.

Spatio-temporal processes allow the explicit integration of the time dimension components. They have been integrated as a component of geographical studies by early work in temporal geography (Clark, 1959; Hägerstrand, 1977). If some spatio-temporal processes can be derived from the analysis of a geographical database designed using the triad model, an explicit representation of the properties of these processes is still required in order to describe the temporal networks that connect the spatial objects which are affected by these processes.

This need has led to an extension of the triad framework and an integration of the ***how*** component at the experimentation level (Claramunt and Thériault, (1995 and 1996). The following figure illustrates the first principle extension of the triad framework. Within such a framework, the semantics of these spatio-temporal processes can be described.



Experimentation

Figure 8.2 - First extension of the triad framework

In the context of our study, spatio-temporal processes are derived through the observation of spatial and/or thematic changes. The description of spatio-temporal processes expresses the mechanisms of geographical changes. However, scientific studies go further in terms of the comprehension and explanation of the observed phenomena. This is addressed by a combination of the descriptive and dynamic components of our system and the generation of hypotheses that attempt to explain the nature of these changes, i.e., the ***why*** component. This leads to consideration of ***why*** as an explicit second extension of the triad framework as illustrated by the following figure:

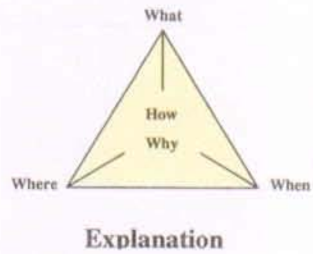


Figure 8.3 - Second extension of the triad framework

The extension of the triad approach provides a methodological framework that can be used for the description of the spatial, thematic and temporal dimensions of our environmental study. The three successive levels of the extended-triad framework can be characterised as the description, experimentation and explanation levels (Claramunt *et al.*, 1998). The following sub-sections will successively describe these different levels.

8.2 Description level

The description level provides a support to describe the spatial and temporal properties of our application. Within GIS, continuous and discrete representations are both used for the description of environmental phenomena. They have complementary properties that are well known and used by the GIS community.

The principles used within our spatio-temporal analysis is to consider and cross-compare successive temporal snapshots (T1, T2...T6) of our study site, in order to identify and analyse changes (C1, C2....C5) between each pair of dates and processes (P) underlying changes (Figure 8.4).

This approach provides a discrete approximation of changes within the time dimension. Local changes between two time steps are not considered, nor interpolated. However, this approximation is sufficient enough for the objectives of our application in terms of the magnitude and patterns of changes in floodplain environment (Salo, 1990). As discussed by Chrisman, (1998), the key to such a study is not the transition themselves, but the intention to record processes underlying changes.

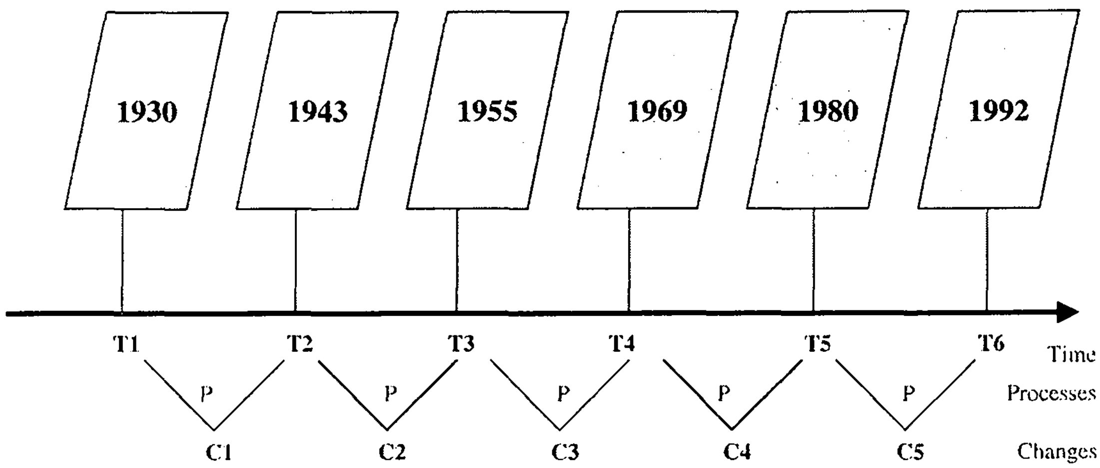


Figure 8. 4 – Principles of spatio-temporal analysis between successive temporal snapshots

8.3 Experimentation level

The description of environmental spatio-temporal processes is a complex task that reflects the wide range of changes that happen in real-world systems. Different taxonomies can be used depending on the objectives of the application domain.

Scientific studies generally use a set of observed processes using the expertise of the application domain to describe them. On the other hand, formal representations of space attempt to identify a set of primitive spatio-temporal processes that can be used with temporal GIS applications in order to reproduce these phenomena. The former can be characterised as a deductive analysis of spatio-temporal phenomena, the later as an inductive one (Goodchild *et al.*, 1996; Thériault and Claramunt, 1999).

Spatio-temporal models have to distinguish trend and fluctuation processes in light of change analysis (Bornkamm, 1988). A trend represents an average change (thematic and/or spatial properties) over a significant time interval leading from one stage[13] to another one, i.e., between two successive land-cover categories within the scope of our application. A fluctuation is a rapid change in relation to the application granularity (i.e., the temporal interval unit of observation). A fluctuation is a short time change that reflects the influence of local events. It is reversible (Miles *et al.*, 1988) and oscillates around the trend.

In the present context, only trend changes were considered, since they represent a significant evolution within the studied floodplain. Moreover, studying spatio-temporal processes implies to distinguish between local and global dynamics (Miles *et al.*, 1988). Global

13 Stages in this case, have the same sense as given by Knapp (1974), where typical plant communities follow each other in time at the same site.

dynamics represents landscape[14] changes (e.g. appearance of a new land cover class), in contrast to local changes (e.g. mutation of a land cover category towards a different one).

In the context of this thesis, the local changes are related to a homogeneous area of space for a considered instant of time and with respect to a land cover category.

With regards to the change management into temporal GIS, such a distinction (landscape and local levels) is a need already discussed in the literature (Cheylan and Lardon, 1993; Frank *et al.*, 1992) because environmental phenomena can be differently perceived according to the scale of observation. Indeed, different algorithms will be required for their implementation. Moreover, this categorisation was derived from the observation of changes identified between successive temporal snapshots, in Chapter7 (a bottom-up, deductive analysis).

Different models of spatio-temporal processes have been proposed by the GIS research community (Cheylan and Lardon, 1993; Claramunt and Theriault, 1995; Hornsby and Egenhofer, 1997; Frank *et al.*, 1992). They generally make distinction between the changes that concern the life, the motion (varying and changing), and the genealogical changes (Cheylan, 1999) or functional dynamism (Claramunt and Thériault, 1995).

Life changes correspond to appearance and disappearance phenomena. Motion changes are classified as contraction, expansion, rotation, displacement, re-allocation (including split and merges processes).

Genealogical changes have been recently studied using the notion of identity (Hornsby and Egenhofer, 1997). Operations make a distinction between changes that preserve or do not preserve the identity of a geographical object. Functional processes describe geographical relationships that are constrained in both space and time, e.g., succession, permutation, diffusion, production and reproduction, (Claramunt and Thériault, 1995 and 1996).

A classification of the processes underlying land cover changes detected in Chapter 7, are proposed here, according to current taxonomies for the description of spatio-temporal processes within GIS. Such a classification could provide some useful insights in terms of the representation of these processes within GIS and for an analysis of the spatial properties of land cover changes within the context of our study.

Difference between changes identified at a landscape level (Figure 8.5) and changes at a local level (Figure 8.6) was done. The former analyses the conjunction of object changes within a specific area (e.g., fragmentation) while the later focuses on individual object changes (e.g. expansion).

At either landscape or local levels, motion processes are thus excluded by nature. Moreover, the concept of identity defined in Hornsby and Egenhofer (1997) is not appropriated in the context of homogeneous areas, as those do not have an identity but rather describe a region of space with some common characteristics.

At the landscape level, processes like Fragmentation, Perforation, Diversification and Simplification were identified (Figure 8.5). These processes lead to both spatial and thematic changes. They are defined as follows:

14 Forman and Forman and Godron, (1986) define landscape as a "heterogeneous land area composed of a cluster of interacting ecosystems that is repeated in similar form throughout". Several definitions are possible, in function of the situation being considered. In the context of this thesis, landscape is the interactive mosaic of land cover patches, relevant to the change study.

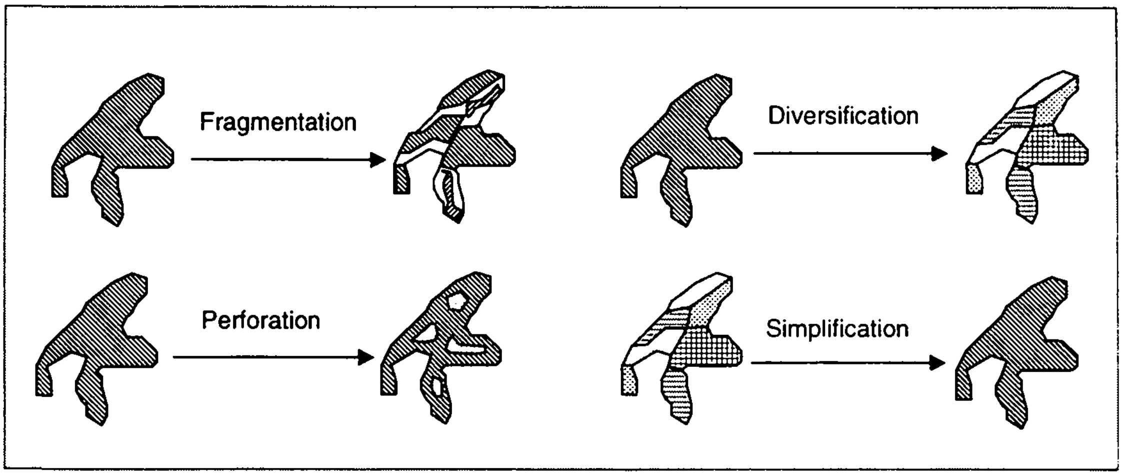


Figure 8.5 – Land cover changes at the landscape level

- *Fragmentation*: is a well known process in landscape ecology that corresponds to the breaking of an object[15] into several parts that are often widely and unevenly separated (Forman, 1995). For example, from the results of the number of patches identified in the previous chapter, the floodplain of the Sarine River was more fragmented in 1930 than it was in either 1955 or 1992.
- *Perforation*: is the process of making "holes" in an object (Forman, 1995). Dispersed "islands" of herbaceous/shrub vegetation in an open forest area could illustrate an example of perforation in the context of our application.
- *Diversification*: expresses the variability in landscape composition (Turner, 1990b). For example, the studied floodplain was more diversified in 1930 than in 1992 (diversity index has passed from 1,7 to 1,3).
- *Simplification*: expresses the dominance of one category upon the *other* (it is the contrary of diversification). According to our results (previous chapter), in 1930 land cover categories were distributed in a more equitable proportion (dominance index was close to zero). This index has increased with time, passing from 0,020 to 0,246 (a factor of 12 in 62 years). For instance, the non-alluvial forest category dominated the floodplain in the time span of our study.

These processes represent spatial patterns that involve changes within a considered region of space, the study site, for example aggregation of individual local changes toward landscape changes.

Finally we observe that some classes may even disappear, e.g., classes 2 and 3 according to our previous results, are disappearing. Such a process is called an attrition process by Forman and Godron, (1986). We can remark that within our case study no new classes are appearing.

15 An object represents an instance of a real world phenomenon, i.e., the instance of a land cover category within our application.

At the local level, several processes were identified and described as follows. They can produce both spatial and thematic changes of a given homogeneous area (Figure 8.6). Constraints could be linked to processes (e.g. an expansion is always accompanied by a neighbourhood contraction, and conversely).

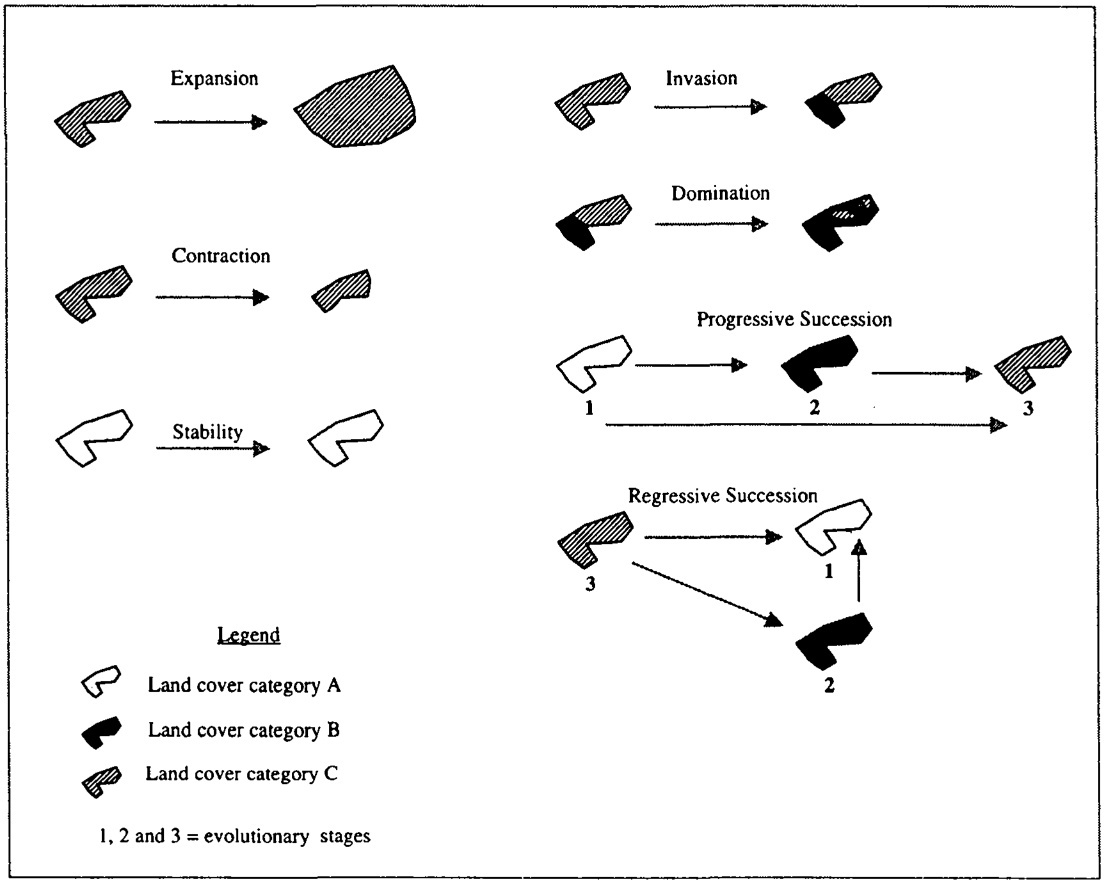


Figure 8.6 -Land cover changes at local level (spatial and thematic evolutions)

- *Expansion*: expresses an increase of the area of an object. Expansion is the typical process underlying changes in the river channel after a flooding.
- *Contraction*: is the reverse process of the expansion. In our application, the river channel suffered a contraction by the embanking action and its consequences through time.
- *Stability*: represents the absence of change in area (spatial change) and in theme (thematic evolution) of a given object. This can be modelled in both, local and landscape levels. In the present context, the non-alluvial forest category has been stable in several parts of the study site, principally after 1955.
- *Invasion*: An object of a different category takes place into an existing one, throughout the succession process. However, not every invasion results in a consequent spreading

(or even domination). Typically, this could be illustrated by pioneer vegetation (herbaceous/shrub category) that invades pebbles category sometimes after floods.

- *Domination*: one object is dominated by another (or several) object (s) of a different category. In the context of this study, thenon-alluvial forest category has dominated the other, especially after the drying of the floodplain by the embanking effects.
- *Succession*: is the process that expresses a hierarchy in changes. In the alluvial context, vegetation follows a typical succession pattern, passing from a pioneer stage to a final forested stage (with possible rectrogradation phenomena due to flood impacts, this is called regressive succession in this thesis). The anthropic impact through time has changed the alluvial dynamic and have repercussion on the vegetation succession: the intermediate stages tend to be jumped, in both directions, progressive and regressive succession. In the other words, succession can also be discontinuous.

8.4 Explanation level

The explanation level is based on deduction/induction analyses. The observation of environmental changes at complementary abstraction levels associated to the site history provides the comprehension of the evolution of the land cover categories in space and time. This enables the generation of hypotheses in order to explain environmental changes and pattern of changes that occurred during the studied time interval.

In the context of this research and at the landscape level, stability process, for example, could be explained by two events: absence of floods[16] and embankment (or both). Regressive succession is associated with flood events. Progressive succession in this context expresses a balanced alluvial dynamic, where the vegetation evolution follows a topo-chrono-sequence from a pioneer to a final stage (*pioneer vegetation ⇒ willow ⇒ alder ⇒ ash).* Such a succession was verified in the northern section of the studied site by Bureau, (1995). The dominance process verified for the non-alluvial forest category expresses in this context the anthropic action and,in particular, embanking.

As previously discussed, this ecosystem has become dryer, and more and more stable through time. It has permitted the expansion and the dominance of forest categories to the detriment of the pioneer and intermediate vegetation. At the landscape level, the floodplain of Sarine River has become less fragmented, less diversified and dominated by the forest categories (simplification), in response to to the anthropic impacts through time.

8.5 Discussion

Scientific studies oriented toward the observation of environmental changes should be developed at temporal and spatial scales that reflect the processes involved in the present application domain. Identification and description of spatio-temporal processes are important to formalise knowledge about changes. In the scope of this chapter, these processes were identified and described. Furthermore, when associated to the site history, such an exercise can help to clarify the *why* question concerning the studied environment.

16 In this context, only floods of an important magnitude, capable of produce erosion/deposition and submersion phenomena are considered.

Such an analysis reflects the explanation orientation of the present study. Exploration, explanation, prediction and planning (Figure 8.7) are fundamental temporal analysis perspectives (Peuquet, 1994).

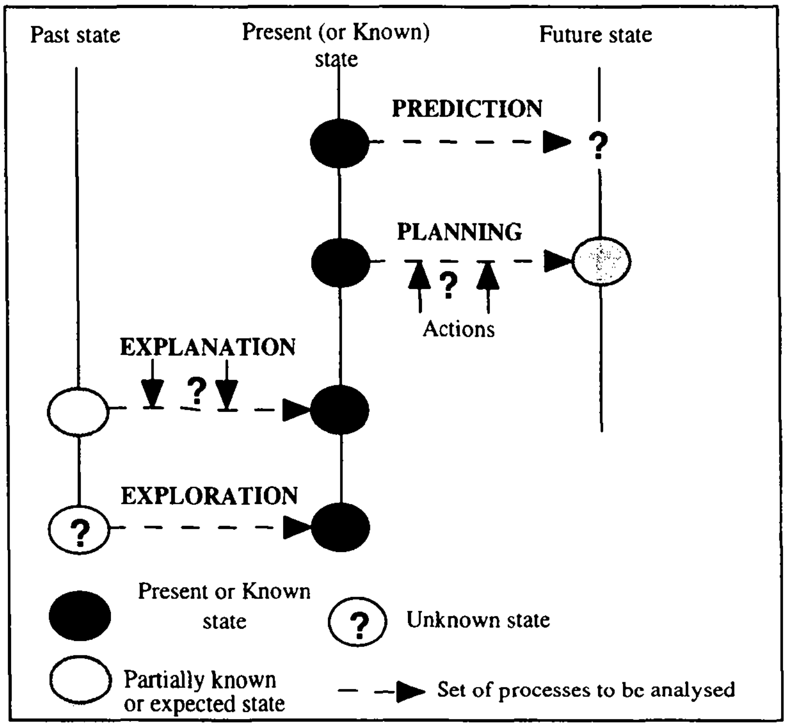


Figure 8.7 –The scope of temporal analysis

The respective characteristics of each kind of environmental studies is defined as follows:

- Exploration attempts to identify and understand a past state of a known system from a known state of this system.
- Explanation tries to identify and understand the evolution of a system, which has lead to a known state of this system.
- Prediction estimates future states of a system from a known state and a relative knowledge of the way this system evolves (without external influences).
- Planning searches for a sequence of actions and events which can lead to a desired state of a system from a known state of this system (the planner can influence the system by actions).

All of these perspectives are concerned with the discovery of relationships between the different components of dynamic systems: states, events, processes and actions. The change analysis of the present environmental application corresponds to an explanation study of the underlying spatio-temporal processes, according to this classification.

Any tentative oriented to the definition of future changes may be categorised as a prediction analysis and either planning if we propose some actions that may influence future environmental states.

The above figure illustrates the scope of our explanation study and gives some perspectives about the potential application of temporal analysis, particularly with respect to prediction and planning studies that could be considered as a future improvement of the research objectives and results developed during this thesis.

8.6 Conclusions

The triad approach provides a relevant basis to develop spatio-temporal database, because it considers the thematic (*what*), geographical (*where*) and the temporal (*when*) domains in the same structure.

However, it needs to be completed by a description of the dynamic aspects of environmental changes in order to study the spatio-temporal processes that underlie environmental changes (*how*). Furthermore, combining the identification and description of spatio-temporal processes with historical environmental data provides a step forward for the explanation of changes (*why*).

The integration of these spatio-temporal modelling principles supports a qualitative description of land cover changes and processes. Our study makes a distinction between changes at the landscape and local levels. It allowed a formal description of land cover changes processes identified with regards to our application.

Such a spatio-temporal framework extends current approaches in the modelling of spatio-temporal processes by the integration of the complexity of environmental changes and the specific properties of environmental processes. This provides a step forward in the integration of these modelling concepts to the complexity of environmental changes.

Such an analysis can be used for identifying spatio-temporal primitives that should be integrated into the database model and implementation. Nevertheless, to approach these processes and explain their why, a methodological framework including the analysis and expression of causal links, was helpful to clarify the causal relationships between events and answer the particular needs of environmental studies oriented toward the analysis of changes.

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General Conclusions and Perspectives

This research had the challenging objective of combining methods and expertise from two disciplines: GIS and Pedology. The results of this thesis benefit from this interdisciplinary approach, in particular, from the combination of the pedological methodology, which was based on synchronic and diachronic, and a sound GIS design methodology which promotes the identification and expression of causal links between events, acting as a "thinking tool", and which gives the possibility to perform change analyses in space and time.

In a general way, this work has contributed to the advance of the knowledge of environmental ecosystems by the study of the present-day situation of the vegetation and soil, as well as the characterisation, variability and spatial distribution of soil in the floodplain of Sarine River. Moreover, a three-dimensional approach, based upon the notion of horizon was proposed to represent soil variability (lateral and vertical). Concerning GIS, this work has emphasised the need of developing a GIS design methodology able to integrate the complexities of environmental research.

The principal conclusions of this research are summarised in the next paragraphs. They concern the Pedology, the GIS research or more often, the integration GIS/Pedology. The general benefit of such an interdisciplinary research and the limits and perspectives of this thesis are further given.

This work emphasised the importance of combining synchronic and diachronic approaches to integrate different scales necessary for the understanding of current vegetation and soil variability and spatial distribution in the alluvial floodplain. More specifically, the use of multivariable analysis to characterise the soil population and the three-dimensional GIS cartography proposed seems to be the most appropriate approach to study soil in such a complex environment.

From the **soil** surveys it has emerged that there is a large morphological variability of FLUVIOSOLS in the Sarine River's floodplain (eight groups were discriminated by clustering analysis). Despite their large diversity, the FLUVIOSOLS of the studied floodplain are not very different in their physico-chemical characteristics (pH, $CaCO_3$ content), but rather from their morphological characteristics. Soils range from very young calcareous FLUVIOSOLS recently deposited and still close to the alluvium material, without any structure to that with a well-developed structure and an Sca horizon, that is "in process of brunification". The number of horizons can also be quite variable, from soils with only one horizon to that with twelve.

The combination of pedological analysis and historical data have demonstrated that inheritance and *in situ* evolution processes overlapping in space and time are responsible for the formation of the these alluvial soils. However, inheritance seems to be the dominant process. The weak *pedogenesis* could be related to an initially large amount of carbonate in the alluvium material and a short time of evolution. This could also explain the weak physico-chemical distinction between them. The original geomorphologic position plays an important role in the present-day spatial distribution of soils and their morphological variability (in addition to inheritance and *in situ pedogenesis*).

In such an environment, the three-dimensional GIS-cartography proved to be very adequate for studying the present-day variability and spatial distribution of these soils. This approach has allowed the continuous representation of soil horizons in space (instead of soil units separated by boundaries). Among the many advantages of such an approach, it outlined the vertical and horizontal variability of soil horizons and integrated horizon thickness. Furthermore, the analysis of the horizons superimposition and the number of horizons combined to the site's history and the local geomorphologic conditions, topography, distance from the river course, allowed and facilitated the explanation of the formation and spatial patterns of distribution of these soils.

Human impacts (embanking, dam construction...) have caused changes in the evolution of the studied floodplain. The geometry of the river channel has changed with time. It has passed from a braided to a rectilinear system. With time, the river channel was confined and has become deeper. As a consequence, the water regime has changed, causing modifications in vegetation and soil evolution. Concerning soil, the effect of embanking was observed in two levels. At a general level, embanking had an effect on the whole floodplain, by protecting it from alluvial dynamics and by creating new pedological conditions. At a local level, embanking has favoured the sedimentation process just behind non-inundated embankments. Concerning the vegetation, embanking has influenced the vegetation evolution (vegetation filled up quickly, within 30 years after embanking). The floodplain of the Sarine River has become dryer, dominated by the forest categories (in detriment to the pioneer and intermediate states), and less diverse with time. The maps resulting from the cross-classification technique show the location of change and give some qualitative information about the changes as well. A gap between the evolution of vegetation and soil was observed.

The study of change, resulting from the **integration GIS/Pedology,** was performed using pre-existing GIS technology, without complete database implementation (out of this thesis's objectives) with the aim of identifying, quantifying and qualifying spatio-temporal land cover changes that were perceived, from 1930 up to the present-day. Moreover, change directions and patterns, as well as processes underlying change, were identified and formalised. The identification of change patterns in space and time and processes underlying changes lead to a better understanding and explanation of the evolution of the floodplain of the Sarine River and give insights and primitives for the future implementation of the database model.

The pattern of evolution of the Sarine River's floodplain is not an isolated case. The rapid dynamic of changing, the embanking impacts, and the consequences upon the vegetation and soil can be found in other floodplains of other rivers in Europe, under the same environmental conditions, e.g. middle course river with fast-flowing and calcareous geology.

Nevertheless, as each process is devised to run at its own scale, the observation of land cover changes at a more precise scale, in both space and time, may have lead to some different results. The use of data mining technology could help discovering new trends in an automatic way. However, our results confirm the general trend of the vegetation evolution observed for such a floodplain ecosystem at Swiss and European scales.

The results of this thesis have confirmed the complexity of the alluvial environment, linked to the very rapid dynamics perceived most quickly in the vegetation, but also in the soil. The impact of embanking on the evolution of soil and vegetation in the Sarine River's floodplain has been demonstrated. Nevertheless, within this present-day uniform vegetation, a large morphological diversity of FLUVIOSOLS is found. It confirms the gap existing between vegetation evolution and that of soil in this human-altered alluvial environment.

Concerning the contribution to the **GIS research**, this work has emphasised the need of developing a GIS design methodology that has facilitated the analysis and the structuring of the environmental study by the identification and expression of the causal relationships and the analysis of the spatio-temporal changes. Furthermore, such an approach allows cyclic reasoning and keeps a strong interaction with the environmental expertise. Finally, it facilitated the identification of data and processing requirements, which are necessary to the modelling process and gives the basis to choose the most adequate GIS technologies for the implementation of the database model. More specifically, the integration of GIS resources to support environmental research has allowed the points described in the following paragraphs.

The identifying or inferring of causal relationships between events and its modelling, e.g. embanking has caused changes in soil and vegetation evolution. The identifying of these facts helps to decide which analyses to perform and leads to the establishment of an explicit relationship between them into the database model. From the analysis of the problem has emerged the need of a GIS including the temporal component and the ability to manage the dynamic aspect of environmental applications has become clear.

Following these requirements, the development of a framework that includes spatial and temporal information as well as data processing in a flexible way was undertaken. The choice of a formalism that integrates environmental data and processing within the same model is important for the construction of a model close to the reality.

Finally, such a GIS approach allows one to answer the principal queries: *what* (changes in land cover), *where* (the spatial location of changes), *when* (change evolution through time) and its extensions, *how* changes happened (information about landscape fragmentation and the quality of changes) and *why* or the hypotheses to explain changes with regards to the site history (changes related to vegetation hydrology and geomorphology). From this study of change through time, the principal spatio-temporal process related to environmental application were identified and described (stability, expansion, invasion, dominance, succession...). The representation and management of change and patterns of change, as well as the process underlying changes are not integrated into current GIS. In this work, the focus was done on the identification of change and spatio-temporal processes specific to environmental applications into a perspective of methodological advances in spatial representation and analysis within GIS, in order to successfully fulfil the scientific objectives of environmental research.

The analysis of the consequences of this work on the pedological and GIS researches can be summarised as follows:

- Concerning the environmental study, this research has rather contributed to the advance of the knowledge of alluvial ecosystems and particularly the soil characterisation and the evolution of the floodplain, as well, in addition to the methodological contribution to study such a complex environment. Furthermore, this work gives several elements that must be taken in consideration with regards to the management and protection stated in the federal Edict about the Alluvial Ecosystems in Switzerland and Europe.

- Concerning GIS, the complex nature of the application - the study of the evolution of soil and vegetation in a human-altered floodplain - has emphasised the need for a GIS design methodology to support scientific reasoning in environmental science, acting as a "thinking tool". The contribution of such a methodological approach is helpful for environmental experts by functioning as a main thread to improve the application's structuring, helping the identification of causal links and its formalism. Moreover, this methodology has permitted the modelling of the dynamic properties of the application. This context allowed GIS experts to have new insights, such as the identification of spatio-temporal processes underlying changes, which should help to improve current taxonomies proposed within temporal GIS. Therefore, the two methodological approaches undertaken in this work help to facilitate the accomplishment of such an interdisciplinary research and its established aims.

- Finally, this thesis has shown the advantages of using such an interdisciplinary framework that allowed advances in the knowledge of the formation, spatial distribution and evolution of alluvial soil and vegetation, as well as in the modelling of the problem into temporal GIS. Furthermore, such a methodological approach gives the basis for the choice of the most adequate GIS technology to be employed into a structural and holistic approach.

Nevertheless, this research is only a first step, a modest example towards a more collaborative research that includes multidisciplinary fields of knowledge. **Further researches** in both Pedological and GIS domains are necessary and should be focused on the following points:

From a methodological point of view, a new research issue could be the use of a more flexible classifying technique, like a fuzzy set, to delimit land cover categories, because environmental changes are rather continuous than discrete in space. For the same reason such a technique should also be employed to define the limits between soil horizons. Error propagation study could also be important for such a study.

In inspite of the good soil sampling used in the 3-D cartographic approach, that allows a realistic interpolation of data with any technique, geostatistical techniques like kriging should be used in order to estimate errors from soil data interpolation. The results from the application of the three-dimensional cartography should be related to a local vegetation survey, at the same sub-site and in a more detailed scale, in order to improve the evolution model of embanked alluvial sites.

Change study must be performed separately for the two stretches (embanked and active), in order to perform and compare the relationships between land cover change dynamics and the present-day soil state. Furthermore, the functioning of the soil in the embanked stretch should also be undertaken and compared to that established by Bureau (1995) in the active stretch.

Concerning GIS, the proposed design methodology, should be generalised to other environmental studies, in order to test its appropriateness. This could also help in identifying specific processes and primitives that will improve the quality of the spatio-temporal model.

Environmental change, causal links and change processes should be integrated into spatio-temporal data models, in order to represent evolving natural phenomena. Furthermore, the implementation of the spatio-temporal conceptual model into an object-oriented database model can be particularly suitable to better represent the dynamic aspect verified in the evolutionary process of the Sarine River's floodplain. A technical evaluation of such an implementation will also lead to new insights for both GIS and environmental experts.

Another attempt will be to promote the challenge for environmental experts and database developers, in order to design GIS software, which is better adapted with integrated database functions that include spatio-temporal queries and analysis and the principle of interoperability between CASE and GIS tools. It should be able to record, retrieve and analyse dynamic entities (that change in space and time), identify data patterns and processes, and support data predicting.

Appendices

Computer Script to the Vegetation Map et soil survey points[1]

(ARC/INFO and ArcView Softwares)

Carte de la végétation actuelle et emplacement des sondages pédologiques du site alluvial La Sarine (Haute-Gruyère)

I - INTRODUCTION

Les écosystèmes alluviaux européens, menacés de disparition, sont caractérisés par une grande complexité et diversité biologique dépassant généralement celles des autres milieux des régions tempérées. Par ailleurs, leur intérêt économique fait que leur degré d'anthropisation est élevé. Il en résulte une destruction des milieux humides et leur remplacement progressif par des écosystèmes terrestres moins diversifiés.

Pour garantir la sauvegarde de ces milieux, un premier pas a été franchi en 1982 par le Conseil de l'Europe, qui a demandé à ses états-membres de recenser leurs zones alluviales, dans un but de conservation et de protection, voire même de restauration (Conseil de L'Europe 1982). Suite à cette requête, la Suisse a été le premier pays à établir un inventaire de ses zones alluviales (0,25% de la surface du territoire) (Kuhn and Amiet 1988) et à en cartographier la végétation. Enfin, depuis 1992, une Ordonnance fédérale réglemente la protection des 169 sites considérés d'importance nationale (Conseil Fédéral Suisse 1992)

En Suisse, l'atteinte la plus fréquente observée sur l'ensemble des sites est l'endiguement (59% des sites) (Gallandat, Gobat et al. 1993). Cette atteinte modifie la dynamique fluviale et entraîne des changements au niveau du sol et de la végétation (Bureau 1995), (Mendonça Santos, Guenat et al. 1997). Parmi d'autres modifications, (Gallandat, Gobat et al. 1993) ont constater la perte de corrélation entre l'évolution des sols et celle de la végétation.

Ce projet constitue une première partie de la préparation des donné spatiales pour la thèse de doctorat de l'auteur, dont un objectifs est de mettre en évidence la répartition spatiale des différents types morphologiques de Fluviosols et de vérifier leur rapport avec la végétation actuelle et avec l'historique du site.

II - PRESENTATION DU SITE

2.1 - Les données générales

L'étude porte sur le site d'importance nationale n° 66 - Les Auges de Neirivue - à l'aval du barrage de Lessoc, dans les Préalpes fribourgeoises, à une altitude d'environ 750 m. Le site étudié a une surface de 78 hectares. D'après les données météorologiques de la station de Broc, située à proximité du site, le climat est préalpin, avec des précipitations annuelles

[1] Projet GIS développé sur ARC/INFO 7.0 (station de travail SUN) et Arc View3.0 (sur PC), dans le cadre du Cours SIG organisé par l'Institut de Géologie et le Centre d'Hydrogéologie de l'Université de Neuchâtel, du 27-31 Janvier 1997, dans le cadre du Cours SIG et Base de Données sous la direction du Dr. Mahmoud Bouzelboudjen.

moyennes de 1200 mm; la température annuelle moyenne est de 7,1 °C, avec un minimum de 2,7 °C en janvier et un maximum de 16,5 °C en juillet (Fallot 1991) Le bassin versant est essentiellement constitué de roches à dominante calcaire, ainsi que de marnes et de flysch (Getaz 1977).

2.2 - Les données historiques

Le cours de la Sarine a été systématiquement endigué entre 1910 et 1920 pour garantir la protection des zones riveraines contre les inondations lors des crues. Ces travaux ont consisté en la construction de gabions métalliques, dans le sens transversal puis longitudinal de la rivière, accompagnée de la rectification du cours (lit de 30 à 45 m de largeur et pente longitudinale moyenne variant entre 5 et 7‰) (Getaz 1977) Ces aménagements ont augmenté la capacité érosive de la rivière et provoqué l'enfoncement du lit (Getaz 1977); (Bureau, Guenat et al. 1994)et (Bureau 1995). De plus, deux ouvrages hydroélectriques ont été construits en amont du site (barrages de Rossinière et de Lessoc) et fonctionnent respectivement depuis 1972 et 1973.

Suite à ces aménagements, le régime de la Sarine s'est modifié: à l'origine le débit annuel moyen était de 23,7 m^3/s (moyenne de 60 ans), avec un maximum de 43,8 m^3/s en mai et un minimum de 12,4 m^3/s en janvier (Getaz 1977); le plus fort débit de pointe (480 m^3/s) a été enregistré en septembre 1940. Actuellement les variations journalières de débit sont induites par le barrage (3-5 m^3/s pour le débit de dotation et 41 m^3/s de débit maximal restitué).

III - MATERIEL ET METHODES

4.1 - Les données disponibles

Les documents à disposition sont les suivants : carte de la végétation actuelle (échelle 1:10'000) (Gallandat, Gobat et al. 1993) et 277 sondages pédologiques géoréférencées et décrites par l'auteur en fonction de 12 paramètres pédologiques de description.

4.2 - Le traitement des données

1) <u>Les étapes nécessaires pour le développement du travail (résumé)</u>

a) Concernant la carte de végétation

Dessiner sur une feuille calque, les polygones relatifs aux différentes classes de végétation ;

"Scanner" cette carte des polygones de végétation

Ouvrir cette image "scannée"dans Arc/Info et apporter toutes les corrections nécessaires ;

Construire la topologie (dans Arc/Info, module BUILD/CLEAN)

Imprimer les informations concernant les labels des polygones

Créer un fichier Excel contenant les labels donnés par Arc/Info et la légende correspondante

Joindre les tables Arc/Info et Excel

Exporter vers Arc/View (fichier e00)

Réaliser un "layout" et retravailler la légende

Concernant les points de sondage pédologique

Transformer le fichier excel des données pédologiques en fichier .txt, avec trois colonnes: n° du point de sondage, x, y (en métres).

Envoyer ce fichier .txt par e-mail (attach file) directement sur la station de travail

Dans Arc/Info, utiliser la commande GENERATE pour créer un nouveau cover avec les points de sondage (regarder le bouquin/cours Neuchâtel pour le détails de la commande...)

Exporter tous les données vers Arc/View 3.0

2) <u>La description de chacune des étapes (en détailles)</u>

a) Pour la carte de la végétation:

1. Préparation du support calque

1. Compilation de la carte de végétation (polygones) au 1:10.000 sur calque, en additionner 4 points de contrôle (+) dont les coordonnées géographiques sont connues.

Matériel utilisée : Calque Multitrace 90 micros T3TD et Rotring 0.2 mm)

2. Elaboration d'une légende de la végétation (sur papier) pour servir de référence à la légende Arc/Info

2. "Scanner" de la carte de végétation

Matériel utilisée : Logiciel PowerScan sur Macintosh

Scanner A0 du Service de Gaz de la Ville de Neuchâtel

Résolution : 200 dpi (Il vaut mieux faire du 300 dpi, surtout quand on a des petits polygons)

Sortie : Fichier .PICT (**Sarineveg.PICT**)

3. Conversion .PICT en .TIFF(image) et exportation vers la station de travail

3.a - Conversion du fichier .PICT en fichier .TIFF (format compatible avec Arc/Info)

Matériel utilisé : Logiciel GraphConverter sur Macintosh et support d'enregistrement Syquest.

1. Ouvrir le fichier .PICT et le convertir en .TIFF non compressé et format IBM (**SarinevegGC-IBM.TIFF**)

2. Enregistrer sur Syquest (ou autre bande magnétique)

3.b - Envoi du fichier .TIFF du Macintosh vers la station de travail (UNIX) contenant Arc/Info

Matériel utilisé : Logiciel de Communication Fetch sur Macintosh.

1. Remplir la fenêtre de communication avec les informations suivantes : l'adresse de destination (login) le nom de l'utilisateur possédant une compte (user) et son mot de passe (password).

2. Choisir le format **binaire** et **données bruts** (Raw Data). Envoyer.

4. Conversion dans ARC/INFO du fichier image (.TIFF) en fichier "raster" (GRID)

Arc: IMAGEGRID **sarinevegGC-IBM.TIFF veggrig**

5. Conversion du fichier raster (GRID) en fichier vector (du type ligne ou arc)

Arc: GRIDLINE **veggrid vegcover**

6. Rotation, elimination des TIC's du Scanner, addition des nouveaux tic's et attribution des coordonnées réelles aux nouveaux tic's

6a. Rotation de l'image (si nécessaire, pour corriger une éventuelle mal position lors du passage au scanner)

1. Entrer dans Arctools (**ARC**: ARCTOOLS)

2. Choisir le mode EDIT TOOLS.

3. Sous le menu FILE choisir COVERAGE OPEN.

4. Sélectionner **vegcover** et choisir l'option ARC.

5. Vérifier si l'image est bien placée, soit si les 4 croix du dessin (+) correspondent:

a) Si oui, passer au point **6b**.

b) Si ce n'est pas le cas, faire la rotation de l'image (dans mon travail une rotation de 0.3° s'est avérée nécessaire!)

6. Clicker sur le bouton EDIT ENV. et régler les paramètres dans la fenêtre ARC ENVIRONMENT PROPERTIES:

VERTEX DISTANCE = 0

NODE SNAP = OFF

ARC SNAP = 0

APPLY

7. Sélectionner toute l'image à l'aide du **select all** du Pan Zoom

8. Ouvrir la fenêtre COMMANDS du menu Arctools

9. Dans la fenêtre commands taper: ROTATE «angle en degrés» (en positif pour tourner l'image dans le

sens inverse des aiguilles d'une montre)

10. Placer le curseur à l'endroit de l'angle de rotation (à choisir selon le cas...)

11. Vérifier si le résultat obtenu est satisfaisant; si non, continuer le processus)

12. Sauver l'image sous ***vegrot***

6.b - Elimination des tic's du Scanner

1. Dans le menu EDIT choisir CHANGE EDIT FEATURE

2. Sélectionner TIC

3. Dans le menu DISPLAY choisir l'option DRAW ENVIRONMENT GENERAL

4. Sélectionner l'option IDS sur la ligne TIC

5. Apply

6. Ouvrir la fenêtre PAN ZOOM dans le menu DISPLAY pour avoir une boîte à outil (zoom, sélection...)

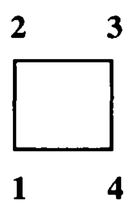
7. Supprimer les 4 tic's crées par le Scanner en les sélectionnant puis en utilisant le bouton DEL de la fenêtre TIC.

6c - Addition des nouveaux tic's

1. Faire des "zoom's" successives sur les zones contenant les tic's de référence terrain (+).

2. Créer un nouveau tic sur chacun des tic's terrain (+) en utilisant la touche ADD, en les plaçant précisement sur la croix du dessin.

Attention!!!! Prendre note de l'ordre des tic's!!!



3. Sauver les changements avec le nom de ***vegtic***.

6d. Changement des coordonnées des nouveaux tics

1. Sortir d'ARCTOOLS

2. Dans ARC: GENERATE ***vegreal***

3. **GENERATE:** COPYTICS ***vegtic***

4. **GENERATE:** QUIT

5. **ARC:**TABLES

6. **ENTER COMMAND**: SELECT ***vegreal.TIC***

7. **ENTER COMMAND**: LIST liste des tics affiché en coordonnées scanner

8. **ENTER COMMAND**: UPDATE

9. **ENTER RECORD NUMBER**: 1

10. **EDIT ?** : XTIC = 570300

11. **EDIT ?** : YTIC = 150500

EDIT ? : return

12. **ENTER RECORD NUMBER** : etc pour tics 2 3 4 avec *2*: 570300, 154700
3: 572200, 154700
4: 572200, 150500

13. **ENTER COMMAND**: LIST liste des tics en coordonnées réelles (vérifier !!!....)

ENTER COMMAND: QUIT

14. **ARC: TRANSFORM** ***vegtic vegreal***

Noter les erreurs due à la transformation.

15. Dans Arctools, ouvrir l'image **vegreal** pour vérifier si tout est correct. Si oui, supprimer les croix du dessin en utilisant le bouton DEL de la fenêtre Arc & Node.

16. Sortir d'ARCTOOLS

ENTER USER NAME: QUIT

7. Création d'un cadre pour le coverage (SI NECESSAIRE!!! - exemple pris du travail de Steeve)

Créer un fichier ASCII lignes ou polygones dans un éditeur de texte:

1. **$:** EDIT *CADRE*

2. Entrer les coordonnées

ex.: lignes ex.: polygones

1
480000,114000
497500,114000
END
2
497500,114000
497500,138000
END
3
497500,138000
480000,138000
END
4
480000,138000
480000,114000
END
END

1, 480000,114000
497500,114000
497500,138000
480000,138000
480000,114000
END
END

3. Rentrer dans ArcInfo
ARC: GENERATE *FRAMECO*
GENERATE: INPUT *CADRE*
GENERATE: LINES « ou » POLYGONS
GENERATE: QUIT

4: Construire la topologie des lignes ou polygons du cadre
ARC: BUILD *FRAMECO LINES « OU »* POLYGONS

8. Superposition du cadre avec le coverage

1. **ARC:** ARCTOOLS
2. Choisir le mode EDIT TOOLS.
3. Afficher *LITHO* en choisissant l'option ARC.
4. Dans la fenêtre EDIT ARCS & NODES presser sur le bouton EDIT ENV.

5. Régler les paramètres dans la fenêtre ARC ENVIRONMENT PROPERTIES:

VERTEX DISTANCE = 0

NODE SNAP = OFF

ARC SNAP = 0

APPLY

6. Dans la fenêtre EDIT ARCS & NODES choisir la commande GET FROM COVER et sélectionner le coverage *FRAMECO*

7. Sauver l'ensemble sous *LITHOTOT* en utilisant SAVE AS dans le menu FILE

<u>9. Correction des erreurs dans ArcTools</u>

1. **ARC:** ARCTOOLS

2. Choisir le mode EDIT TOOLS.

3. Afficher ***vegreal*** en choisissant l'option Arc & Nodes

4. Pour travailler précisément ouvrir la fenêtre PAN ZOOM dans le menu DISPLAY

5. Sous le menu DISPLAY choisir DRAW ENVIRONMENT: GENERAL

6. Sous NODE choisir DANGLE dans la fenêtre DRAWING OPTION puis l'option SYMBOLS en sélectionnant une des propositions présentées.

7. Si on a créer un cadre: creer des noeuds à l'intersection entre le cadre et les vecteurs le coupant en sélectionnant le cadre et

en utilisant le bouton INTERSECT

8. Corriger tous les "dangles" en utilisant les outils de la fenêtre EDIT ARC & NODES et faire le tour de l'image en détails pour vérifier si le scanner n'a pas créé des petits polygones supplémentaires.

9. Sous le menu FILE sauver le coverage sous le nom ***vegcorr***.

10. Quitter ArcTools

11. Construire la topologie du coverage avec la commande:

ARC: BUILD ***vegcorr*** POLYGONS

ARC: CREATE LABELS ***vegcorr***

12. Pour vérifier les corrections:

ARC: DESCRIBE ***vegcorr***

Vérifier que le nombre de dangling node =0 et qu'il n'y aie qu'un seul polygone avec le label 0.

Obs.: BUILD n'a pas été la bonne procédure (dans mon cas!) pour la construction de la topologie. Le programme a détecté plusieurs intersections et donné le message suivant: "*Use CLEAN instead of BUILD or rather the fuzzi tolerance if using CLEAN*". J'ai donc utilisé la procédure CLEAN et l'image a été sauvé avec le nom de **vegcorr2**

10. Etapes pour la préparation d'un fichier d'impression du coverage *vegcorr2* sur plotter avec la limite des polygones et leurs labels

10a - Création d'une colonne de labels (Zonemars) en format ASCII

1. **ARC:** LIST *vegcorr2.PAT*
2. **ARC:** ADDITEM ***vegcorr2.PAT vegcorr2.PAT*** **ZONEMARS** 4 8 B
3. **ARC:**TABLES
4. **ENTER COMMAND:** SELECT *vegcorr2.PAT*
5. **ENTER COMMAND**: CALCULATE ZONE = ***vegcorr2***.-ID
6. **ENTER COMMAND:** QUIT
7. Sauvegarder la colonne des labels dans un fichier Ascii

10b - Création d'un fichier ASCII (.dat) avec le label des polygons)

1. Entrer dans ARCPLOT
2. **ARCPLOT:** &WATCH *veg.DAT*
3. **ARCPLOT**: LIST ***vegcorr2*** POLY # ZONEMARS
4. **ARCPLOT:** &WATCH &OFF

10c - Création d'un fichier .aml dans un editeur de texte pour définir les paramètres du texte d'impression pour les labels des polygons

1. Ecrire les lignes suivantes:

mapextent vegcorr2

textsize 4pt (cette taille a été décidée en fonction de l'échelle du document)

labeltext vegcorr2 zonemars (nom de la colonne où se trouve les labels)

&return

2. Enregistrer avec l'extension **.aml**

10d - Création d'une vue dans Arctools

1. Entrer dans Arctools

2. Choisir le mode **MAP TOOLS**
3. Sous le menu **VIEW** choisir **NEW**
4. Dans la fenêtre **ADD NEW THEME** cliquer sur **COVERAGE** et **POLY**
5. Remplir la fenêtre **POLY Theme Properties**:

    Identifier: *vegcorr2*

    Data Source: *vegcorr2*
6. Presser le bouton **Coverage**
7. Cocher la case **Atribute** et y choisir l'option **ZONEMARS**
8. Changer la valeur de l'option **Polygon outline** = 1 (pour avoir les polygones tracés en noir)
9. Contrôler que l'option « Draw Shaded polygon » ne soie pas cochée
10. Presser le bouton **Text**
11. Choisir l'option **ZONEMARS** dans la colonne **Atribute**
12. Cocher la case **Execute macro** et sur la ligne de commande écrire le nom du fichier **.aml**
13. Presser le bouton **Draw Scale** et inscrire l'échelle de la carte
14. Vérifier la présentation générale avec le bouton **Preview**
15. Si cela convient clicker sur le bouton **Ok**
16. Dans la fenêtre **Theme Manager**, passer le fichier **vegcorr2** de **Theme** à **Draw List**.
17. Vérifier l'échelle de la carte (1:10000)
18. Sauver la vue sous ***vegcorr2_VIEW***

10e - Création du layout de la carte dans MAP TOOLS

1. Sous le menu **MAP** choisir **NEW**
2. Dans la fenêtre **Layout Properties** cliquer sur le bouton **Custom**
3. Choisir la taille et l'orientation du papier.
4. Clicker sur **OK**

5. Dans la fenêtre **Add New Object** sélectionner l'option **View.**
6. Dans la nouvelle fenêtre, remplir les champs:

Identifier: *vegcorr2_VIEW*

View File: *vegcorr2_VIEW*

7. Vérifier l'échelle, si besoin la changer (1:10000)
8. Choisir la taille du cadre ou le supprimer en mettant toutes les valeurs à 0
9. Vérifier l'allure de carte, en clickant sur le bouton **Preview.**

10. Clicker sur **OK**

11. Dans le menu **MAP** sauver le Layout avec la commande **Save As** sous ***vegcorr2_LYT***

10f - Création d'un fichier d'impression (plusieurs options au choix, selon le hardware disponible)

Sur le plotter A0 de Neuchâtel:

1. Sous le menu **MAP** choisir **Create Graphics File**

2. Choisir *vegcorr2_LYT,* avec l'option **.GRA** et clicker sur **OK** (création automatique de *vegcorr2_LYT.GRA)*

3. création d'un fichier HPGL/INBD (traceur DCAL):

ARC: HPGL *LITHOCOR_LYT.GRA* # # # # 7585 A 0 FILL

sur la SUN du GR-EPFL:

1. Sous le menu **MAP** choisir **Create Graphics File**

2. Choisir le fichier *vegcorr2_LYT*

3. Choisir l'option **eps** (Encapsuled Post Script)

4. Clicker sur **Ok**

5. Aller dans Print Tools

6. Préciser le nom du fichier et choisir le plotter A0 qui s'appelle: dgrhpa0

7. Clicker sur **OK**

11. Attribution des attributs des polygons

11a - Attribution des attributs en face de chaque label dans le fichier ASCII veg.DAT

1. Envoyer le fichier veg.DAT sur un PC ou MAC contenant le logiciel Excel

2. Dans excel, ouvrir ce fichier en choisissant l'espace comme séparateur.

3. Alligner les valeurs à gauche (afin d'éviter la création d'une colonne supplémentaire.

Supprimer les entête des deux colonnes.

4. Rentrer les attributs en face de chaque label en utilisant la carte imprimée et la carte de référence avec la légende correspondante (Carte de végétation - Gallandat *et al.*, 1993)

5. Sauver le résultat comme ***SNATURE.DAT*** dans un fichier Ascii utilisant l'espace comme séparateur.

11b. Importation des attributs dans la Table vegcorr2.PAT

1. Lancer un compilateur fortran

Si besoin modifier le contenu du programme *SCAML* en fonction du nom du coverage ou des colonnes

2. Taper les commandes suivantes pour lancer le program *SCAML* (Annexe A):

a) for scaml

b) link slcaml

c) run slcaml

3. Créer un fichier *SNATURELOU.AML (Annexe 1)*

4. Depuis Arc créer une colonne supplémentaire appelée NAT avec la commande:

ARC: ADDITEM *vegcorr2.vegcorr2.PAT* NAT 4 8 B

5. Lancer *SNATURE.AML* depuis **ARCPLOT** avec la commande:

ARCPLOT: &snature

6. Vérifier le contenu du fichier *vegcorr2.PAT*

7. Lister et imprimer vegcorr2.pat comme table de référence

ARC: LIST *LITHOCOR.PAT*

12. Création des fichiers d'exportation

Pour obtenir un fichier d'exportation .e00 utiliser la commande:

ARC: EXPORT COVER ***vegcorr2 veg4c.e00***

13. Importation des «covers» dans ArcView 3.0 (sous windows 95)

1. Créer, un dossier spécifique pour le projet Arc View

2. Faire passer le fichier *veg4c.e00* de la station au PC,en format binaire, via le réseau.

3. Depuis windows 95, lancer le programme **Import71** fournit avec **ArcView 3.0**

4. Dans la fenêtre ouvrir, sélectionner le chemin d'accès au fichier *veg4c.e00*

Dans le champ Output Data Source spécifier le dossier crée pour le projet Arc View

Cliquer OK dans les deux fenêtres successives.

<u>14. Organisation du projet dans ArcView</u>

14a. création du projet ArcView

1. Lancer **ArcView 3.0**

2. Sauver le projet dans le menu **File,** avec l'option **Save Project as** sous: C:\My Documents\ dataARCVIEW***sarineriver.APR***

3. Ouvrir une nouvelle vue en cliquant sur l'icône **View** puis sur le bouton **New**

4. Dans le menu **View** choisir l'option **Properties**.

5. Changer le nom de la vue dans le champ **Name**: *veg (postérieurement le nom de la view a été changé pour «**La Sarine**»*

6. Dans le menu **View** sélectionnez **Add Theme**

7. Se positionner dans le répertoire: C:\My Documents\ dataARCVIEW

8. Sous **Data Source Types** choisir l'option **Feature Data Source**

9. Charger le dossier **VEG4c (ainsi, le theme sur la végétation est crée!)**

10. Avec le theme VEG4c selectionné, aller dans le menu **Theme**, choisir **properties** et changer le nom pour: **Végétation**.

11. Sauver le projet.

14b. Création automatique de la table d'attributs

1. Activer le thème **végétation** et l'afficher en cochant la case

2. Cliquer sur le menu **Theme** et sélectionner **Table**

3. Création automatique de la table *Attributes of veg4c*

5. Sauver le projet

14c. Jonction de deux tables

1. Création d'un fichier ASCII (.txt) deux colonnes : NAT et une autre (LABEL) contenant la légende correspondante à chaque classe de végétation de la colonne NAT

2. Sauver sous...**veglabel.txt**

3. Dans Arc View, sélectionner l'icône **Tables** et la table *Attributes of veg4c* et l'ouvrir.

4. Sélectionner la table *veglabel.txt* et l'ouvrir.

5. Sélectionner l'option **Tile** dans le menu **Windows**.

6. Activer la table *veglabel.txt* et sélectionner le champ **NAT**.

7. Activer la table *Attributes of veg4c* et sélectionner le champ **NAT**

8. Joindre les deux tables en utilisant l'option **Join** du menu **Table**.

9. Sauver le projet.

b) Pour l'emplacement des sondages pédologiques :

15a. Création d'une nouvelle table et theme à partir d'un fichier ASCII (.txt)

Création d'un fichier texte avec les données des sondages pédologiques

1. Créer un fichier texte (*.txt) (Tab Delimited) avec toutes les informations sur chaque point de sondage, et bien sure, avec les coordonnées X, Y, pour pouvoir les afficher sur la carte de végétation.

2. Sauver ce fichier sous: *sond.TXT*

15b. Création d'une nouvelle table à partir du fichier texte

Ouvrir le projet ***sarinerive*.APR**

Cliquer sur l'icône **Tables** puis sur le bouton **Add**.

Sélectionner le répertoire ou se trouve le fichier *sond.TXT*

Cliquer deux fois sur ce fichier

La table a été crée.

15c. Création d'un nouveau thème: «*Points de sondages pédologiques*» dans la view La Sarine

1. A l'aide de l'option **Add Event Theme** du menu **View**, sélectionner la table **sond.txt** dans la liste de tables, et vérifier que: Xfield = X; Yfield=Y

2. Valider avec **OK**.

Les deux themes font parties maintenant de la vue La Sarine.

15d. Modification de la légende des themes:

1. Cliquer deux fois sur la légende choisie. Une fenêtre de dialogue apparaît. Changer tous les paramètres nécessaires, selon le thème en question.

2. Valider avec **Apply**.

16. Impression du projet

1. Cliquer sur l'icône **Layouts** puis sur le bouton **New**.

2. Sélectionner l'option **Use Template** dans le menu **Layout**, puis cliquer deux fois sur **Portrait**.

3. Afficher le layout en pleine page en cliquant sur le bouton du milieu en haut à droite de la fenêtre.

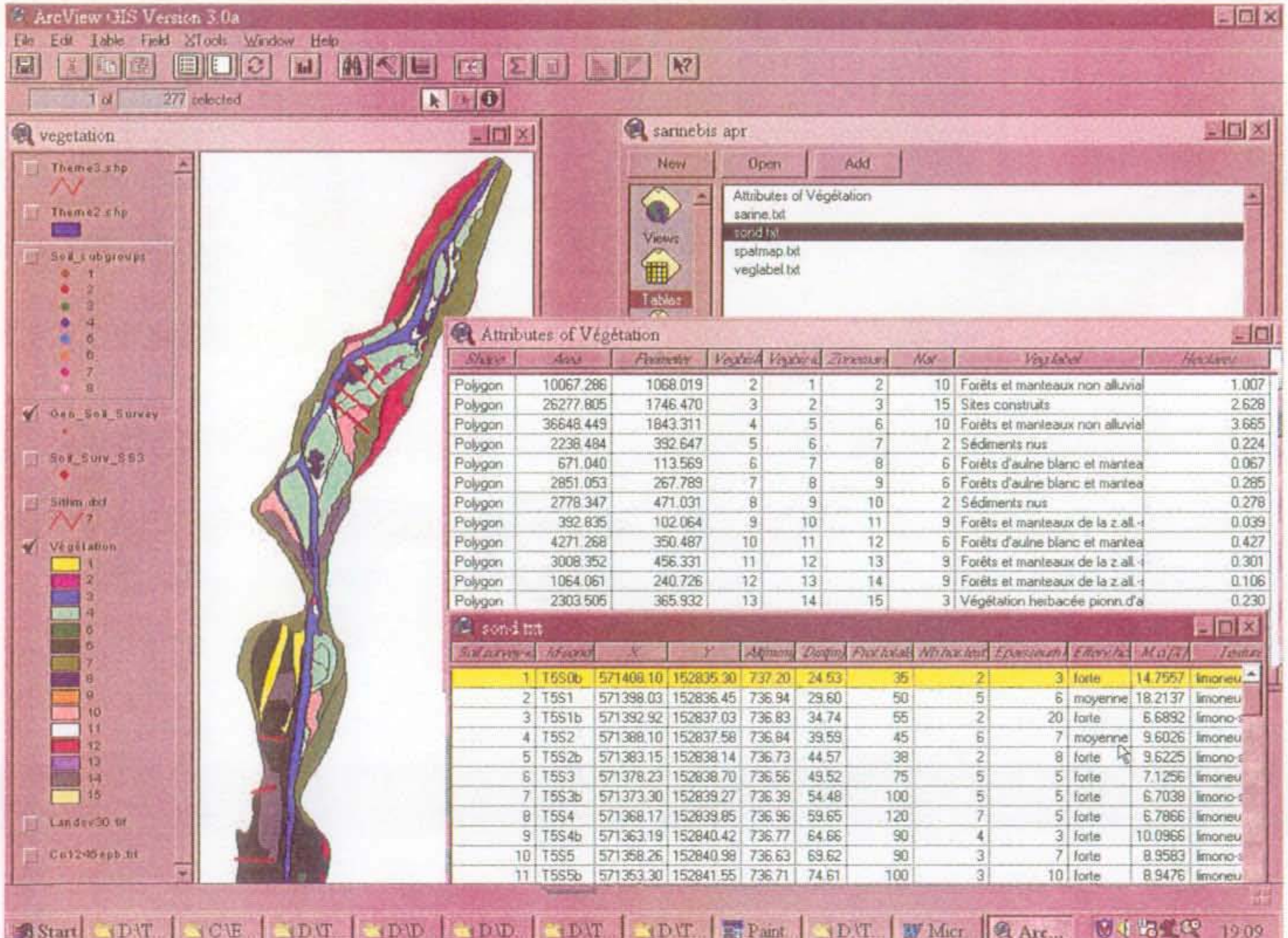
4. La vue, ainsi que la légende, la barre d'échelle, le symbole Nord et la zone réservée au titre sont automatiquement importées

5. Changer tout que s'avère nécessaire et faire la mise en page. (Pour modifier les attributs des éléments textes, sélectionner l'objet et activer la palette de symboles à l'aide du menu **Window** option **Show Symbol Window**...)

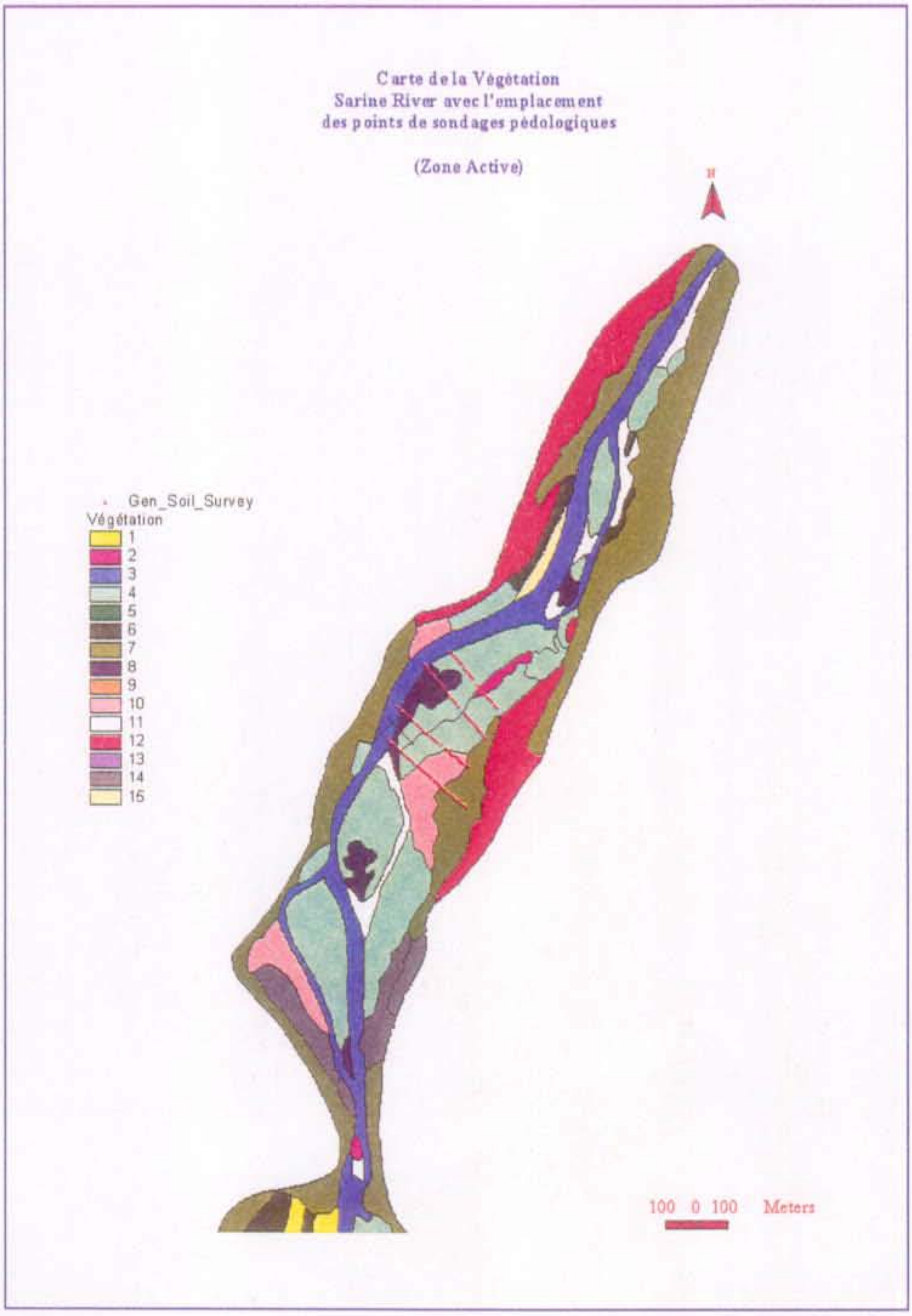
6. Sauver le projet.

7. Imprimer le projet en sélectionnant l'option **Print** dans le menu **File** (Annexe 2)

Extrait de la base de données sur la végétation et sur les sols dans Arc View



Extrait de la Carte de végétation de la Sarine (Zone Active) avec l'emplacement des transects (lignes rouge)



Legend: Simplified Vegetation Map. Legend: 1) Other herbaceous communities; 2) fen land; 3) water; 4) Alder (*Alnus incana*) forests; 5) Ash (*Fraxinus excelsior*) forests on coarse deposits; 6) other alluvial forests with an indeterminate status; 7) non alluvial forests; 8) Willow (*Salix sp*) shrubs typical of high altitude; 9) rich grassland; 10) riparian forests; 11) bared deposits; 12) constructions; 13) cutting or planting in alluvial zone; 14) cutting or planting in non alluvial zone; 15) pioneer herbaceous vegetation typical of high altitude.

Extrait de la Carte de végétation de la Sarine (Zone Endiguée) avec l'emplacement des transects (lignes rouge)

Remerciements:

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Modifications d'une zone alluviale suite à l'endiguement - approche méthodologique[2]

M.L. MENDONÇA SANTOS*, C. GUENAT°, C. THEVOZ+, F. BUREAU°

Abstract

We compare two methodological approaches with the aim to understand the effects of embankments on soil and vegetation spatial distribution along an alpine river. Modifications will be explained by comparing present conditions (soil, vegetation, and geomorphological position) with different situations in the past. Two complementary approaches are being used: first, traditional photo-interpretation allows us to describe variations along the alluvial plain. Second, a GIS enables us to make maps showing the changes in the land use (qualitatively and quantitatively) in time. These maps are useful to identify the current typical situations and to explain the present spatial distribution of soil and vegetation.

I - INTRODUCTION

Les écosystèmes alluviaux européens, menacés de disparition, sont caractérisés par une grande complexité et diversité biologique dépassant généralement celles des autres milieux des régions tempérées. Par ailleurs, leur intérêt économique fait que leur degré d'anthropisation est élevé. Il en résulte une destruction des milieux humides et leur remplacement progressif par des écosystèmes terrestres moins diversifiés.

Pour garantir la sauvegarde de ces milieux, un premier pas a été franchi en 1982 par le Conseil de l'Europe, qui a demandé à ses états-membres de recenser leurs zones alluviales, dans un but de conservation et de protection, voire même de restauration (Conseil de l'Europe, 1982). Suite à cette requête, la Suisse a été le premier pays à établir un inventaire de ses zones alluviales (0,25% de la surface du territoire) (Kuhn et Amiet, 1988) et à en cartographier la végétation. Enfin, depuis 1992, une Ordonnance fédérale réglemente la protection de 184 sites considérés d'importance nationale (Conseil fédéral suisse, 1992).

En Suisse, l'atteinte la plus fréquente observée sur l'ensemble des sites d'importance nationale est l'endiguement (59% des sites) (Gallandat *et al.* (1993). Cette atteinte modifie la dynamique fluviale et entraîne des changements au niveau du sol et de la végétation (Bureau *et al.*, 1995). L'objet de cet article est la confrontation de deux approches méthodologiques permettant d'expliciter la répartition spatiale actuelle des sols et de la végétation dans une zone alluviale endiguée. La première approche fait appel à la photo-interprétation traditionnelle, la seconde à un Système d'Information Géoréférencé (S.I.G.).

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2.2 - Les aménagements hydrauliques

Le cours de la Sarine a été systématiquement endigué entre 1910 et 1920 pour garantir la protection des zones riveraines contre les inondations lors des crues. Ces travaux ont consisté en la construction de gabions métalliques, dans le sens transversal puis longitudinal de la rivière, accompagnée de la rectification du cours (lit de 30 à 45 m de largeur et pente longitudinale moyenne variant entre 5 et 7‰) (Gétaz, 1977). Ces aménagements ont augmenté la capacité érosive de la rivière et provoqué l'enfoncement du lit (Gétaz, 1977; Bureau *et al.*, 1994 et 1995). De plus, deux ouvrages hydroélectriques ont été construits en amont du site (barrages de Rossinière et de Lessoc) et fonctionnent respectivement depuis 1972 et 1973.

Suite à ces aménagements, le régime de la Sarine s'est modifié: à l'origine le débit annuel moyen était de 23,7 m^3/s (moyenne de 60 ans), avec un maximum de 43.8 m^3/s en mai et un minimum de 12,4 m^3/s en janvier (Gétaz, 1977); le plus fort débit de pointe (480 m^3/s) a été enregistré en septembre 1940. Actuellement les variations journalières de débit sont induites par le barrage (3-5 m^3/s pour le débit de dotation et 41 m^3/s de débit maximal restitué).

III - DÉMARCHE MÉTHODOLOGIQUE

La répartition spatiale actuelle du sol et de la végétation est explicitée à l'aide d'une reconstitution historique du paysage. Cette approche diachronique est primordiale pour mieux cerner l'évolution des zones alluviales, écosystèmes à dynamique rapide et souvent anthropisés (Girel, 1991; 1993; 1994; Piquet, 1993; Pautou, 1988).

Dans le cadre de ce travail, deux méthodes de reconstitution historique ont été employées (Fig. 2): la première traditionnelle, est basée sur photo-interprétation manuelle et la seconde fait appel à un Système d'Information Géoréférencé (S.I.G.). Dans les deux cas, deux étapes successives sont essentielles: 1) établissement de cartes d'occupation du sol pour plusieurs dates clés, 2) identification et caractérisation des situations types indiquant des zones stables ou avec des changements importants au niveau hydrologique essentiellement ; ces deux étapes permettent d'expliciter la répartition spatiale actuelle des sols et de la végétation, par extrapolation ou la spatialisation. Nous confronterons ces deux méthodes et dégagerons leurs avantages et inconvénients respectifs.

II - PRÉSENTATION DU SITE

2.1 - Les données générales

L'étude porte sur le site d'importance nationale n° 66 - Les Auges de Neirivue - à l'aval du barrage de Lessoc, dans les Préalpes fribourgeoises, à une altitude d'environ 750 m. Le site étudié se restreint à la zone endiguée (Fig.1). D'après les données météorologiques de la station de Broc, située à proximité du site, le climat est préalpin, avec des précipitations annuelles moyennes de 1200 mm; la température annuelle moyenne est de 7,1 °C, avec un minimum de 2,7 °C en janvier et un maximum de 16,5 °C en juillet (Fallot, 1991). Le bassin versant est essentiellement constitué de roches à dominante calcaire, ainsi que de marnes et de flysch (Gétaz, 1977).

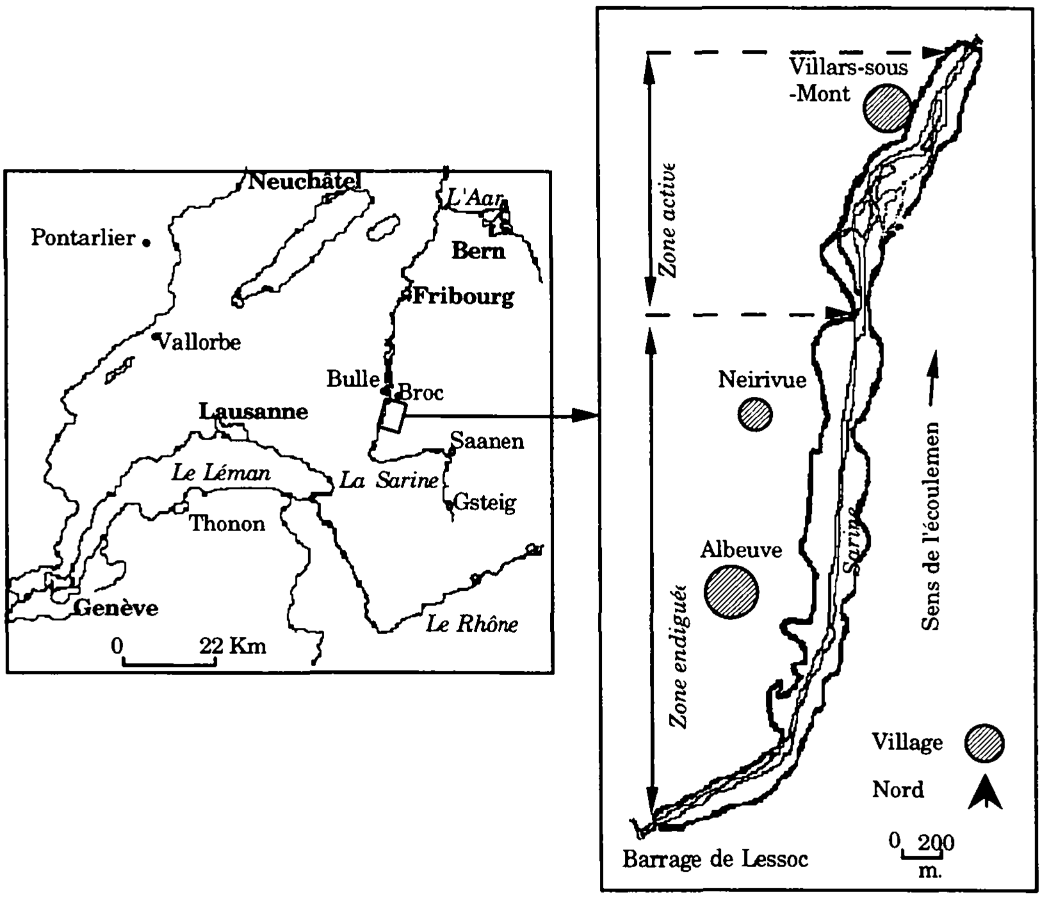

Fig. 1 - Localisation du site d'étude.

Selon la carte de Gallandat et al. (1993), l'unité de végétation dominante porte le n° 16: "autres forêts, manteaux et groupements arbustifs". Cette unité inclut toutes les formations arborescentes ou arbustives qui n'ont pas pu être identifiées lors de la cartographie de la végétation. Dans le cas présent, il s'agit essentiellement de forêts dominées par des espèces non typiquement alluviales comme le hêtre et l'épicéa.

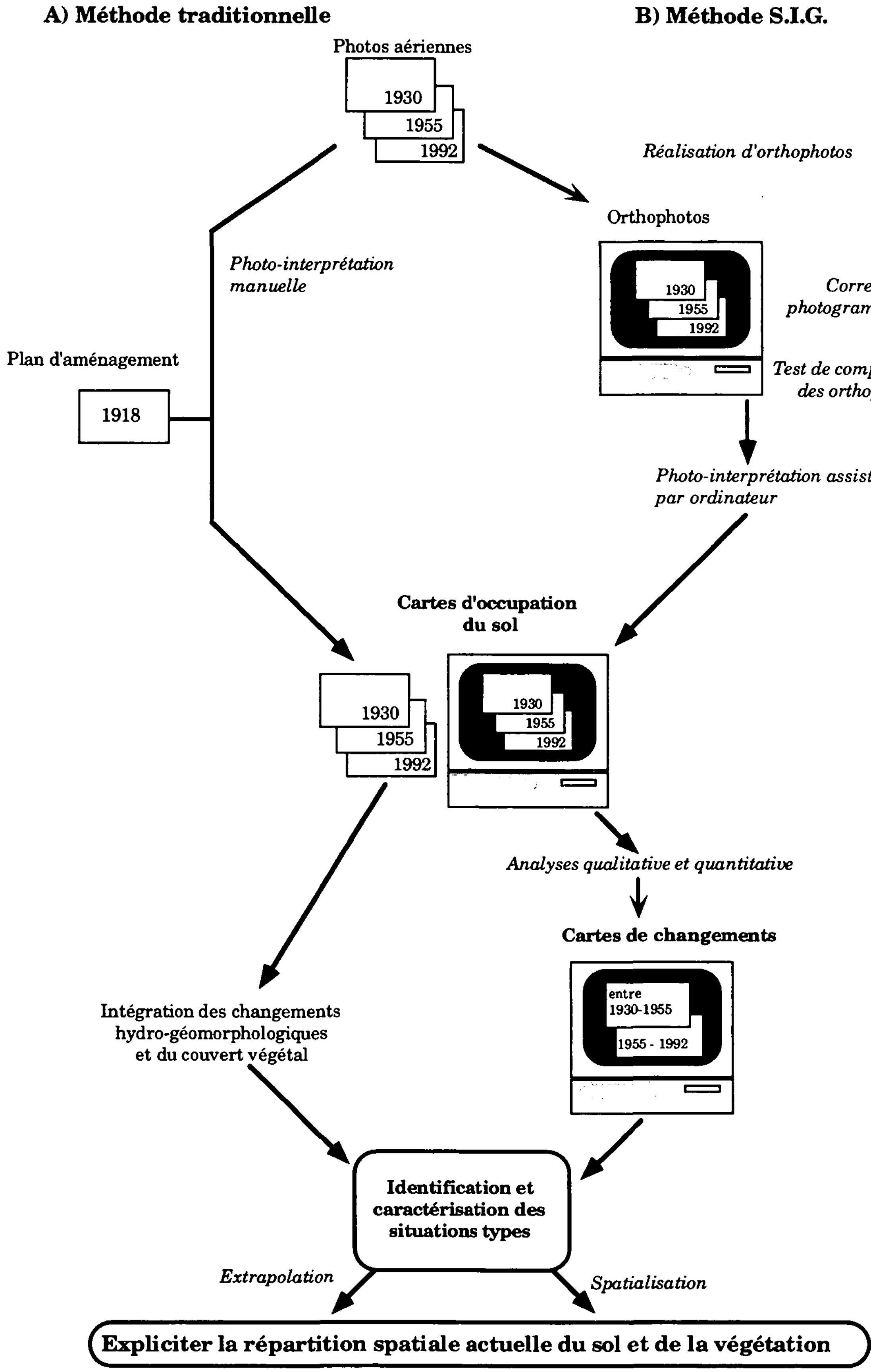
A) Méthode traditionnelle
B) Méthode S.I.G.
Photos aériennes
1930
1955
1992
Réalisation d'orthophotos
Orthophotos
1930
1955
1992
Photo-interprétation manuelle
Correction photogrammétrique
Test de comparabilité des orthophotos
Plan d'aménagement
1918
Photo-interprétation assistée par ordinateur
Cartes d'occupation du sol
1930
1955
1992
1930
1955
1992
Analyses qualitative et quantitative
Cartes de changements
entre 1930-1955
1955 - 1992
Intégration des changements hydro-géomorphologiques et du couvert végétal
Identification et caractérisation des situations types
Extrapolation
Spatialisation
Expliciter la répartition spatiale actuelle du sol et de la végétation

Fig. 2 - Schéma de la démarche méthodologique

IV - MÉTHODES

4.1 - Acquisition des données

Les documents à disposition sont les suivants: plan des aménagements de 1918 (échelle 1:2'000), photos aériennes noir et blanc de 1930, 1955 et 1992, carte de la végétation actuelle (échelle 1:10'000) (Gallandat et al., 1993). Ces documents sont complémentaires mais leur précision n'est pas la même du fait de leur échelle. Les données concernant les sols sont issues de la caractérisation de 8 fosses pédologiques.

4.2 - Traitement des données

1) Méthode traditionnelle

Le mode d'occupation du sol est cartographié par photo-interprétation manuelle et analyse visuelle de cartes et plan d'aménagement pour quelques dates clés: 1918: date de l' endiguement, 1930 et 1955: états consécutifs à l'endiguement, 1992: état actuel. Les changements du mode d'occupation sont déduits de la comparaison visuelle de cette série de cartes et plan. Ensuite, des situations types qui représentent différents cas d'évolution historique ont été identifiées. Ces situations types sont le reflet des modifications au cours du temps des conditions stationnelles (géomorphologique, topographique, hydrologique, pédologique, nature du couvert végétal).

2) Méthode S.I.G.

L'emploi d'un S.I.G. nécessite, au préalable, la numérisation des données. Dans le cas présent, les photos aériennes ont été transformées en orthophotos sur une station INTERGRAPH, avec une précision de quatre mètres. Une régression linéaire permet de vérifier si les orthophotos sont statistiquement comparables. A ce niveau, certaines distorsions photogrammétriques peuvent être corrigées.

Pour la reconstitution historique, ces orthophotos ont été interprétées et analysées avec un système de traitement d'image (Eastman, 1992). Pour chaque date on obtient des cartes d'occupation du sol par la voie de la digitalisation des vecteurs et leur transformation ultérieure en image *raster*. A partir de ces cartes, deux techniques d'analyses de changements dans l'espace et le temps, de nature complémentaire, peuvent être réalisées: l'analyse quantitative et l'analyse qualitative. Ces analyses permettent de: 1) mettre en évidence les changements du milieu entre deux dates, 2) séparer, à l'aide de tests statistiques les changements significatifs de ceux dus à la variation normale, 3) connaître la dynamique et la qualité des changements dans le temps et l'espace.

L'analyse quantitative fait appel à la technique de soustraction d'images ou *image differencing*. L'image résultante a été ensuite traitée à l'aide de tests statistiques basés sur la déviation standard, afin d'établir les vrais changements du milieu.

L'analyse qualitative (classification croisée ou *crossclassification*) aboutit à l'établissement de cartes de changement. Cette technique compare toutes les classes présentes dans les deux images, permettant ainsi, de visualiser sur l'image résultante les changements survenus dans chaque classe d'occupation du sol entre les deux dates d'observation. En ce qui concerne spécifiquement ces analyses spatio-temporelles, les S.I.G. sont largement utilisés pour la détection des changements quantitatifs et qualitatifs (Girard & Girard, 1989; Mendonça Santos et Brown, 1992; Mendonça Santos, 1995; Rock *et al.*, 1986; Waring *et al.*, 1986). Cependant, cette technique d'analyse n'est pas encore bien développée (Singh, 1989) et présente des limites (Eastman & McKendry, 1991). Ses limites rencontrées dans le cadre de ce travail, seront évoquées ultérieurement.

V - RÉSULTATS ET DISCUSSION

5.1 - Méthode traditionnelle

La figure 3 illustre les cartes d'occupation des sols pour quelques dates. Par photo-interprétation, 4 classes ont été identifiées (eau, sédiments nus, sédiments colonisés par une végétation peu dense, végétation dense). La délimitation des unités est uniquement visuelle et dépend de l'appréciation subjective du photo-interprétateur.

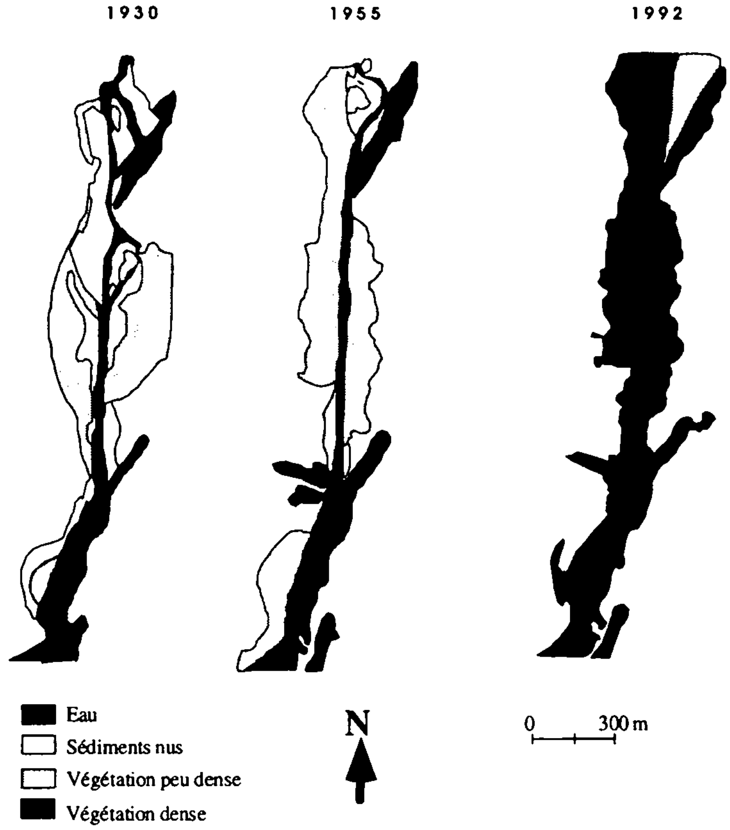

Fig. 3 - Cartes d'occupation du sol pour 1930, 1955 et 1992. Légende: 1=eau; 2=sédiments nus; 3=végétation peu dense; 4=végétation dense.

La synthèse cognitive de ces cartes permet d'identifier 4 situations types (Tab.1). En a), nous avons indiqué la situation géomorphologique à trois époques différentes, en b), le mode d'occupation du sol. Pour 1992, suit encore une indication sur le type de sol, dont la nomenclature fait appel au Référentiel Pédologique (A.F.E.S., 1992).

Tab. 1 - Description des situations types.

Situations types	1918 ou 1930	1955	1992
1	a)Zone probablement exhaussée, rive droite b)Boisé	a)Ilot b)Boisé	a)Zone exhaussée, sur la rive gauche (3 mètres au-dessus de la plaine) b)Boisé (unité 16) Fluviosol calcaire humifère peu profond (env.10 cm)
2	a)Zone d'inondation du lit majeur b)Prairie	a)Zone éloignée de la rive (de 80 à 200 mètres) b)Prairie	a)Zone éloignée de la rive (de 80 à 200 mètres) b)Prairie (unité 20) Fluviosol calcaire à tendance brunifiée (22% d'argiles)
3	a)Zone située derrière des gabions (< 50 mètres) b)Boisé	a)Zone située derrière des gabions (< 50 mètres) b)Boisé	a)Zone située derrière des gabions (< 50 mètres) b)Boisé (unité 16) Fluviosol calcaire polyphasé profond (> 80 cm)
4	a)Zone de tressage fonctionnelle b)Mosaïque de sédiments nus et colonisés	a)Rive endiguée b)Boisé	a)Rive endiguée b)Boisé (unité 16) Mosaïque de Fluviosols calcaires de profondeurs différentes (de 25 à 80 cm)

L'interprétation des données historiques fait ressortir deux grands types de situations. Les deux premiers cas traduisent une évolution en milieu stable; en effet, ces zones sont soustraites à la dynamique fluviatile, l'une de par sa position topographique plus élevée (**1**), l'autre par son éloignement par rapport à la rive (**2**). Par contre, les deux derniers cas montrent des changements liés à une situation d'instabilité: la situation **3** résulte de la modification de la sédimentation suite à l'endiguement (piégeage sélectif d'alluvions), alors que la situation **4** exprime l'effet de divagations du cours antérieures à l'endiguement (sédiments entrecroisés).

5.2 - Méthode S.I.G.

Lors de l'établissement des cartes d'occupation du sol, assistées par ordinateur, cinq classes ont été identifiées: eau, sédiment nu, sédiment colonisé, végétation peu dense, végétation dense. Leur délimitation spatiale est précise (à niveau du pixel - résolution de 4 m), en raison de la précision initiale des orthophotos.

L'image résultante de l'analyse qualitative (classification croisée) des caıtes d'occupation du sol, permet de visualiser les changements d'une classe d'occupation du sol à l'autre dans le temps (Fig. 4). Cette image contient, à gauche, la légende des classes d'occupation du sol et, à droite, une légende numérique qui se lit de la manière suivante: l'égalité ou l'inégalité des chiffres signifie respectivement l'absence ou la présence de changement de classe entre les deux dates mentionnées dans le titre. Par exemple, le code 2:1 signifie la présence de sédiments nus en 1955 et d'eau en 1992.

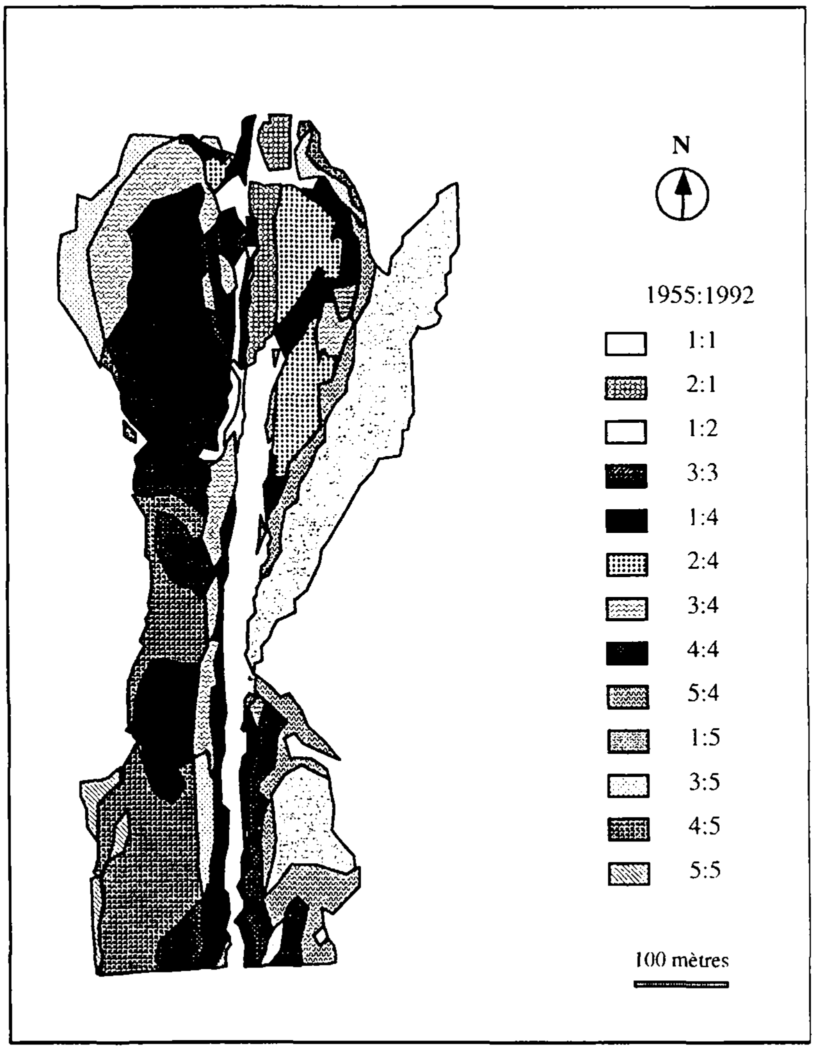

Figure 4 – Carte des changements (classification croisée) entre 1955 et 1992. Légende: 1:eau; 2:sédiments nus; 3:sédiments colonisés; 4:végétation peu dense; 5:végétation dense.

Cette méthode permet d'intégrer deux notions, une spatiale et une temporelle. Au niveau spatial on peut délimiter et quantifier avec précision les surfaces affectées par les changements. Au niveau temporel, les entités spatiales peuvent être suivies au cours du temps. Par ailleurs, il est, à ce stade, également possible d'identifier et localiser précisément des situations types. Dans le cas présent, nous n'avons pas exploité cette possibilité.

5.3 – Intérêt des deux méthodes:

Les deux méthodes de reconstitution historique permettent toutes deux d'établir des cartes d'occupation du sol. Cependant la qualité de ces cartes n'est pas la même. Le recours à un S.I.G. facilite la reconstitution historique (Burrough, 1986) et permet d'obtenir des cartes de meilleure qualité et plus précises: le nombre d'unités identifiables est plus important, la séparation entre les unités moins subjective et la délimitation spatiale des unités est plus précise.

De plus, l'outil S.I.G. offre d'autres possibilités pour exploiter ces cartes d'occupation du sol. Il permet notamment d'identifier les vrais changements de ceux aléatoires et de produire des cartes synthétiques de changements du mode d'occupation du sol. L'emploi d'un S.I.G. impose des contraintes qui peuvent être limitantes: par exemple, pour ce type d'analyse, toutes les images doivent posséder les mêmes paramètres: nombre de colonnes et de lignes ainsi que position géographique et résolution spatiale. En outre, la qualité des données de base joue un rôle essentiel.

VI - CONCLUSIONS ET PERSPECTIVES

Les deux approches, méthode traditionnelle et Système d'Information Géoréférencé, sont, dans l'état actuel de notre recherche, complémentaires. En effet, l'utilisation d'un S.I.G. se limite dans le cas présent à l'établissement de cartes de changement du mode d'occupation du sol. Cette méthode permet également de gérer, rapidement et de manière fiable, une importante quantité de données.

Cette méthode peut être un appui pour expliciter les situations type: ce système géoréférencé permet de localiser avec précision les points sur divers types de documents. Les situations types ponctuelles peuvent être extrapolées avec plus de fiabilité, grâce à la carte des changements. De plus, l'analyse quantitative permet de séparer les vrais changements du mode d'occupation du sol de ceux dus à des variations normales dans le paysage; l'approche classique n'est par contre qu'une simple comparaison visuelle de deux documents et n'offre aucune garantie statistique. Dans l'état actuel de nos recherches, le S.I.G. n'est qu'un préambule à l'interprétation des situations types mais il offre des perspectives intéressantes. Par exemple, l'emploi d'un S.I.G. facilite le stockage des données spatiales sous forme digitale, à l'origine d'une base de données spatio-temporelle. Ces données, facilement accessibles peuvent être transformées, analysées et manipulées de manière interactive. Par ailleurs, cela permet le développement des modèles prévisionnels d'évolution en vue de la gestion et le monitoring des écosystèmes alluviaux.

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Pedological Parameters of description used in the soil surveys

(Feuille de description des sondages pédologiques)

Fiche de description n° Auteur: Date:
Transect n° Pt de repair n° (pt0)
Sondage n° Distance / Sarine (m):
Végétation: Arbres

Arbustes

Herbacée

Profondeur totale du sondage (cm) :
Nombre total d'horizons texturaux rencontrés :

Surface → profondeur

A/ A remplir pour tous les horizons rencontrés (utilisation de la tarière)

			H 1	H 2	H 3	H 4	H 5	H6
1	Epaisseur	en cm						
2	Effervescence à HCl	Nulle						
		Faible (oreille)						
		Moyenne (bulle)						
		Forte (mousse)						
3	Matière organiq	Absente						
		Peu humifère						
		Humifère						
		Très humifère						
4	Texture de la terre fine	Sableuse						
		Sablo-limoneuse						
		Limono-sableuse						
		Limoneuse						
		Limono-argileuse						
		Argileuse						

B/ A compléter seulement pour l'horizon de surface H 1 (utilisation de la pelle)

5	Type de structu de la terre fine	Grumeleuse	
		Polyèdrique angulaire	
		Polyèdrique subangulaire	
		Particulaire	
		Autre (préciser)	
6	Classe de struct (=taille des agrégats)	Très fine (<5mm)	
		Fine (5 à 10 mm)	
		Moyenne (10 à 20 mm)	
		Grossière (20 à 50 mm)	
		Très grossière (>50mm)	
7	Degré de développement de la structure	Faiblement développée	
		Moyennement dvpée	
		Bien dvpée	
8	Netteté de la structure	peu nette	
		nette	
		trés nette	
9	Eléments grossi	Pourcentage	
		Taille en cm	

Remarques éventuelles:
(oxydo-réduction, nappe,...)

Soil data coding to the clustering analysis

(Feuille de codage des données pédologiques pour le groupement)

		Fiche de codage				
12 descripteurs						
				Codage		
Quantitatif	**1**	Profondeur totale du sondage (cm) :		les cm		
Quantitatif	**2**	Nombre total d'horizons texturaux rencontrés		le nbre	(0,1,2,3 ou 4)	
		Descripteurs de l'horizon de surface				
Quantitatif	**3**	Epaisseur	en cm	les cm		
Semi-quant.	**4**	Effervescence	Nulle	0		
		à HCl	Faible (oreille)	1		
			Moyenne (bulle)	2		
			Forte (mousse)	3		
Quantitatif	**5**	Matière organique	la quantité	en %		
Qualitatif	**6**	Texture	sableuse	1		
		de la terre fine	sablo/limon.	2		
			limono/sabl.	3		
			limoneuse	4		
			limono/arg.	5		
			argileuse	6		
Qualitatif	**7**	Type de structure	particulaire	1		
		de la terre fine	subang.	2		
			grumeleuse	3		
			autre (préciser)	4		
Semi-quant.	**8**	Classe de structure	Très fine (<5mm)	1		
		(=taille des	Fine (5 à 10 mm)	2		
		agrégats)	Moyenne (10 à 20 mm)	3		
			Grossière (20 à 50 mm)	4		
			Très grossière (>50mm)	5		
Semi-quant.	**9**	Degré de	si particulaire	0		
(localisat°}		développement	Faiblement développée	1		
		de la structure	Moyennement dvpée	2		
			Bien dvpée	3		
Semi-quant.	**10**	Netteté de la	si particulaire	0		
		structure	peu nette	1		
			nette	2		
			trés nette	3		
Binaire	**11**	Eléments grossiers	non	0		
			oui	1		
		Descripteurs de l'horizon sous-jacent				
	12	Texture	Grève all.	0		
Qualitatif			sableuse	1		
			sablo/limon.	2		
			limono/sabl.	3		
			limoneuse	4		
			limono/arg.	5		
			argileuse	6		

An extract of the data coding – the input to the clustering analysis

Fiche-mémoire pour la matrice de base a etre utilisé avec SIMIL (clustering analysis)

	1	2	3	4	5	6	7	8	9	10	11	12
	Descripteurs de l'horizon de surface (H1)											
N° Sondage	Prof.totale (cm)	N° d'hor. texturaux	épaisseur (cm)	Effervesc. HCl	M.O.(%) (perte au feu)	Texture	Structure type	Structure classe	Structure degré dév.	Structure netteté	Elem. grossiers	Texture horiz. sous-jacent
1	35	2	3	3	14.7557	4	3	1	2	2	1	1
2	50	5	6	2	18.2137	4	2	2	1	1	1	3
...	55	2	20	3	6.6892	3	3	2	2	1	1	2
277	45	6	7	2	9.6026	4	2	3	2	2	1	3

Pedological Parameters used to describe Soil Profiles

(Feuille de description des Profiles Pédologiques)

Profile n°: **Transect n°:** **Descripteur:** **Date:**

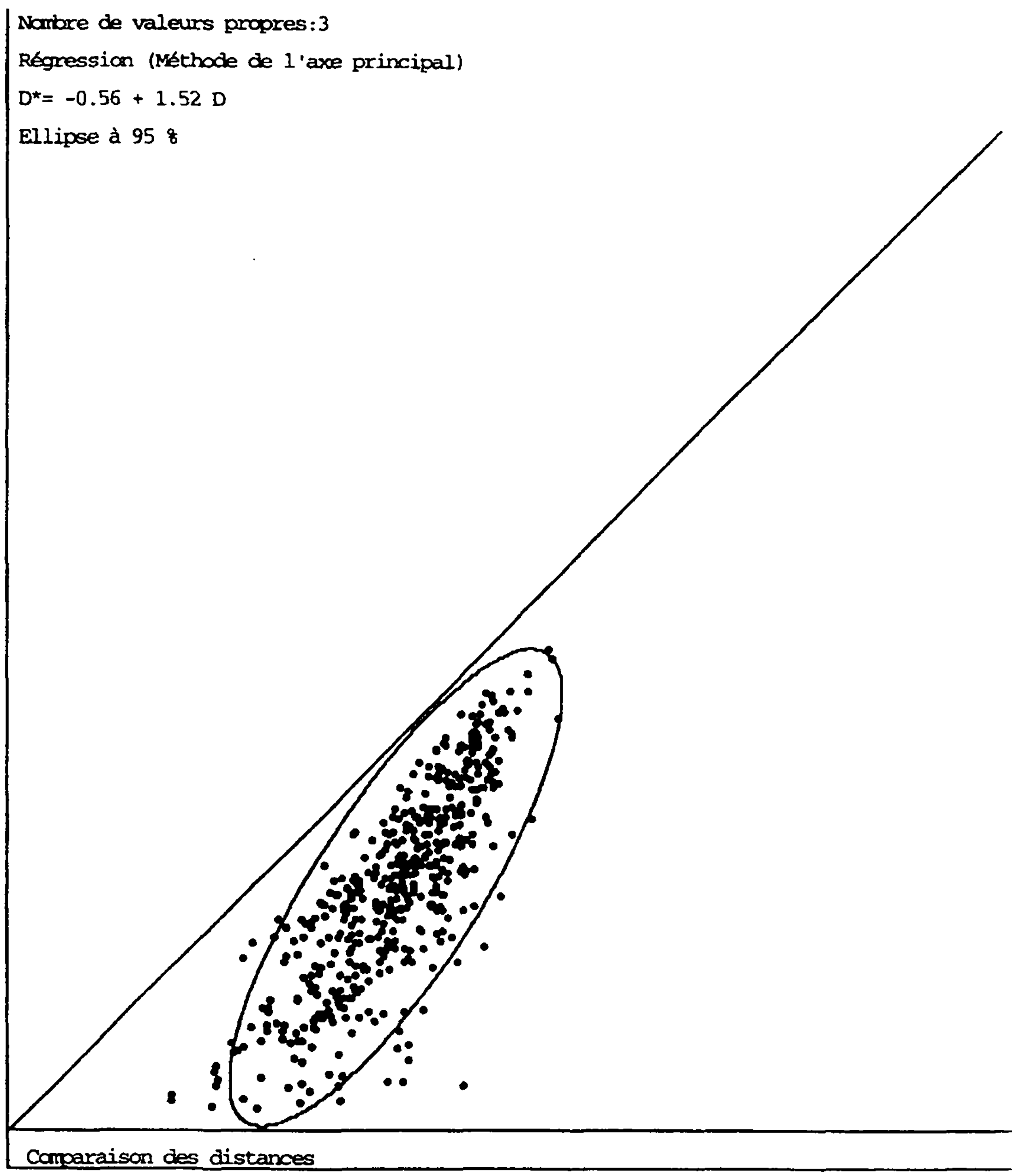
Localisation: Site: Les Auges de Neirivue
Commune:
Coordonnées
Terrain:
Emplacement du profil:
Substrat géologique:
Végétation locale:

Description:

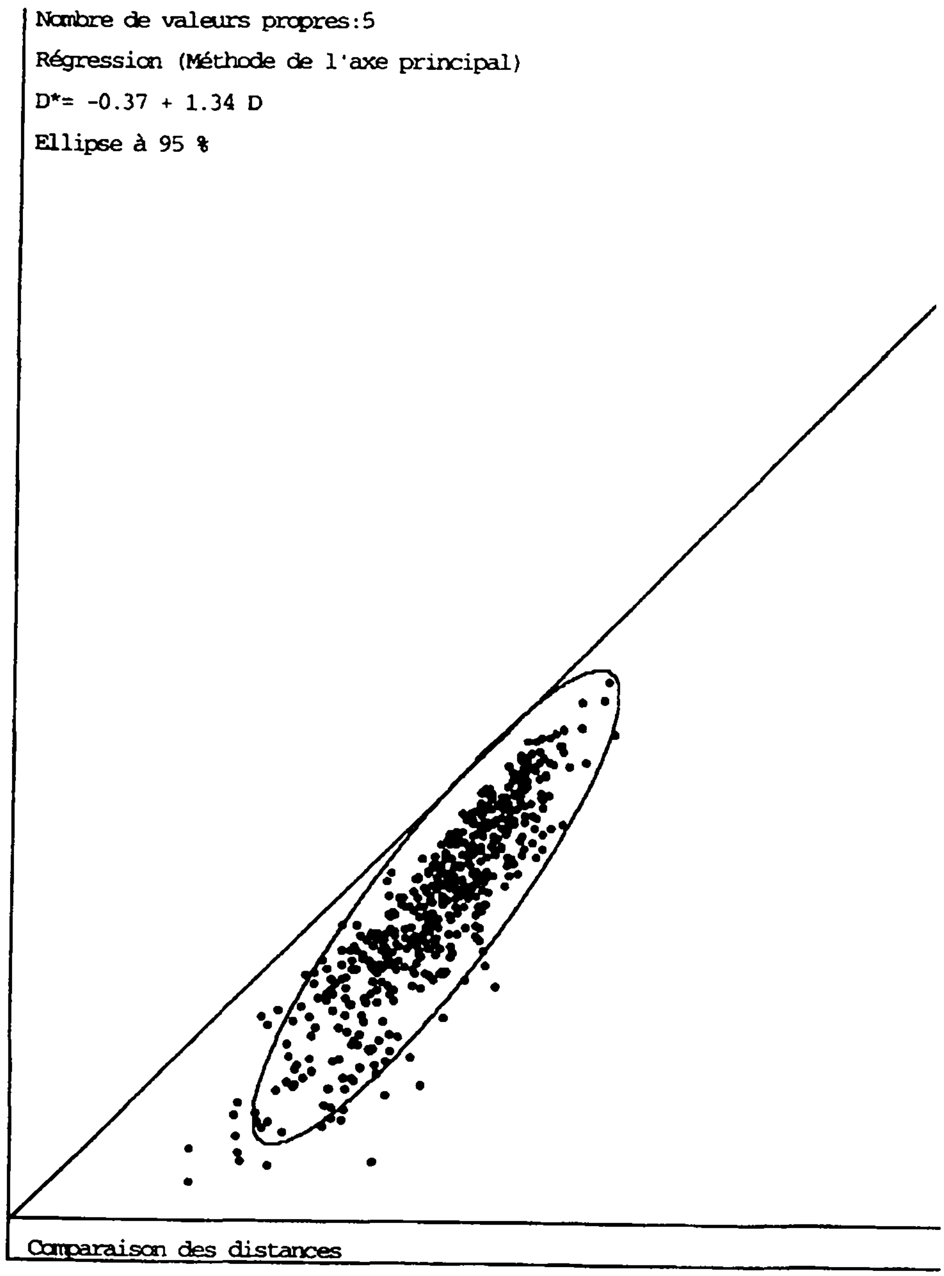
Prof. (cm)	Type d'horizon	Couleur	Texture	HCl	M.O. (%)	Structure				Transition de l'horizon		
						Type	Classe	Dévélop.	Netteté	Type	Limite	Netteté

Remarques:
Elém. Grossiers: % Autres:
Tâches d'hydromorphisme: Profondeur:
Présence de vers-de-terre:Présence de racines:

Shepard's diagram with three axes



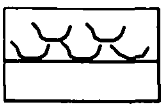
Shepard's diagram with five axes



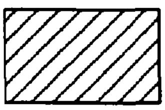
Appendix 3.3

Soil Profiles description and illustration (Description et illustration des profils de sol)

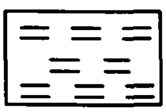
Legend:



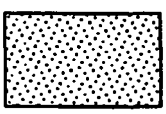
Litter (Litière)



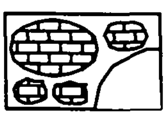
Humiferous horizon (Horizon humifère)



Calcium carbonate(carbonate)



Sand (Sable)



Strand with calcareous pebbles, layer D (Grève alluviale carbonaté, couche D)

Soil profile I (Group 1)

typical calcareous FLUVIOSOL: Jsca ou Aca/D

Données stationnelles

Localisation: Commune de Grandvillard (Fr.), lieu-dit de "Gour-dessous" (carte 1/25 000 n° 1245).
Coordonnées: 571'595/153'915; altitude: 728.70 m.
Végétation: Unité 8Se/6, forêt d'aulne blanc (strate arborescente dominée par Salix elaeagnos)/fourré et manteau de saule d'altitude.
Substrat géol: alluvions récentes carbonatées.
Terrain: relativement plat avec des micro-dépressions
Emplacement: au niveau de la terrasse II, à quelques mètres du profil 2, proche d'une dépression ressemblant à un bras de crue; 40 m du cours principal; exhaussement: 1,2 m environ.
Signes de crues: saules et aulnes penchés vers le bras de crue.
Décrit par: Fabrice Bureau:

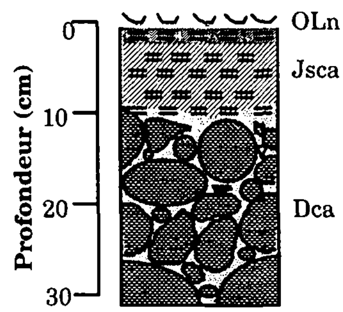
Description Pédologique:

Litière: feuilles de l'année (saule drapé et aulne blanc)
Humus: eumull carbonaté: OLn
0-10 cm :horizon morphologiquement décrit comme **Jsca** (mais considéré comme **Aca** après la détermination du teneur en Corg > 1%), moins de 5% d'éléments grossiers; structure particulaire dominante, mais présence de quelques agrégats localement; racines nombreuses dans les premiers cm; transition nette, limite ondulée.
10-30 cm : **D** (grève alluviale); couleur dominante gris-brun; 70% de graviers et cailloux; terre fine à structure particulaire; pas de racine.

Analyses physico-chimiques

Horizon	Prof. (cm)	Da g/cm^3	pH eau	Corg (%)	N (%)	C/N	$CaCO_3$ (%)	Granulométrie (%) SG	SF	LG	LF	A	Texture (Geppa)
Aca (Js_{ca})	0-10	1.1	7.7	1.9	0.15	13	48	67.3	11.4	2.6	9.7	8.9	S
D	10-30	–	8.3	0.4	0.02	22	59	70.8	12.7	4.1	7.2	5.1	SS

Horizon	Couleur	Cations échangeables (meq/100g)						Tamm (‰)		M-J (‰)		T/M.J	
		K	Ca	Mg	Na	S	S/T	Fe	Al	Fe	Al	Fe	Al
Aca (Js_{ca})	10 YR 3/4	0.23	10.7	0.17	0.13	11.3	100	0.94	0.13	4.13	0.21	0.23	0.59
D	–	0.04	4.8	0.17	0.14	5.2	100	0.69	0.29	3.55	0.16	0.20	1.85



Profile I (Soil Survey Gdv 1) – **Group 1**

Typical calcareous FLUVIOSOL

Soil profile II (Group 3)

typical calcareous FLUVIOSOL: Aca/D

Données stationnelles
Localisation:Commune de Grandvillard (Fr.), lieu-dit de "Gour-dessous" (carte 1/25 000 n° 1245).
Coordonnées: 571'590/153'910; altitude : 728.70 m.
Végétation: unité 8Se/6, forêt d'aulne blanc avec une strate arborescente dominée par *Salix elaeagnos*/fourré et manteau de saule d'altitude.
Substrat géol:alluvions récentes carbonatées.
Terrain: relativement plat avec des micro-dépressions;
Emplacement: au niveau de la terrasse II, à quelques mètre du profil 1, proche d'une dépression ressemblant à un bras de crue; 45 m du cours principal; exhaussement : 1,2 m environ
Signes de crues: saules et aulnes blancs penchés vers le bras de crue.
Décrit par: Fabrice Bureau

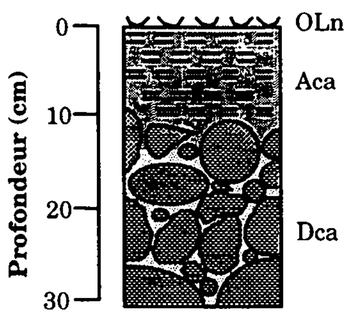
Description Pédologique:

Litière : feuilles de l'année (saule drapé et aulne blancs)
Humus: eumull carbonaté (Oln).
0-10 cm: horizon **Aca** (A1), eumull carbonaté; pas d'éléments grossiers; structure grumeleuse, trés nette, agrégats de 0,5 cm; nombreuses racines, transition trés nette, limite irrégulière (descentes entre les cailloux de la grève).
10-30: cm:couche **D**; couleur à dominante gris-brun; 70% de cailloux et de graviers; terre fine à structure particulaire; pas de racines.

Analyses physico-chimiques

Horizon	**Prof.** (cm)	**Da** g/cm^3	**pH** eau	**C$_{org}$** (%)	**N** (%)	**C/N**	**CaCO$_3$** (%)	**Granulométrie** (%) SG	SF	LG	LF	A	**Texture** (Geppa)
A$_{ca}$	0-10	0.8	7.4	2.6	0.37	7	37	31.9	19.7	9.2	18.7	20.5	Sal
D$_{ca}$	10-30		8.3	0.5	0.02	24	62	77.6	8.5	3.1	6.3	4.6	SS

Horizon	**Couleur**	**Cations échangeables** (meq/100g)						**Tamm** (°/oo)		**M-J** (°/oo)		**T/M.J**	
		K	**Ca**	**Mg**	**Na**	**S**	**S/T**	**Fe**	**Al**	**Fe**	**Al**	**Fe**	**Al**
A$_{ca}$	10 YR 3/2	0.22	22.36	0.51	0.12	23.20	100	2.00	0.27	5.65	0.30	0.35	0.92
D$_{ca}$		0.04	5.29	0.16	0.19	5.68	100	0.68	0.10	2.55	0.12	0.27	0.78



Profile II (Soil Survey Gdv 1) – **Group 3**

Typical calcareous FLUVIOSOL

Soil profile III (Group 5)

calcareous FLUVIOSOL "in process of brunification" : Aca/Scah/D

Données stationnelles:

Commune d'Albeuve (FR).
Coordonnées (m) : 571162.22/151322.50; altitude 748.20 (m):
Végétation: Unité 16.2 - Frêne + végétation arbustive
Terrain: rive guache de la Sarine, à 20.64 m du profil 2 sur l'îlot
Emplacement du profil: distante de 44 m du cours principal de la Sarine
Substrat géologique: alluvions à dominante calcaire

Données Pédologiques:

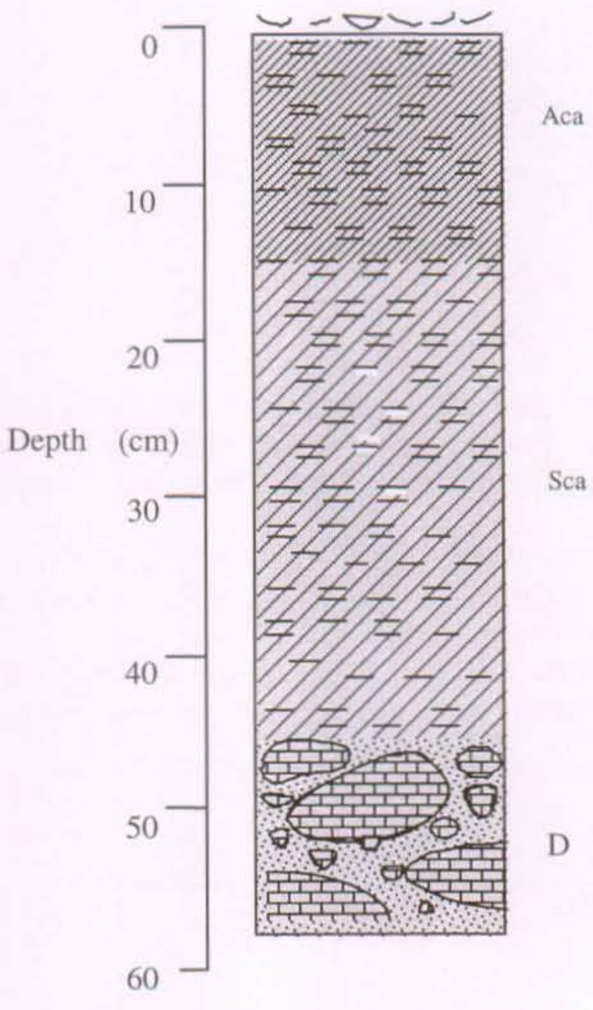
Litière: feuilles de l'année
Humus: eumull carbonaté: OLn
0-15 cm: horizon **Aca**; couleur 7,5YR 4/4; moyenne effervescence à HCl; humifère; texture: limon-sableux; 0% d'élements grossiers; structure polyédrique subangulaire, bien développée, nette, agrégats de5-10 mm; beaucoup de racines fines à moyennes; transition graduelle, limite ondulée.
15-45 cm: horizon **Scah**; couleur 10YR 4/2; moyenne effervescence à HCl; peu humifère; texture limono-sableux; structure polyédrique subangulaire, bien développée, nette; beaucoup de racines fines à grosses; transition diffuse, limite régulière.
45-... cm: **D** (grève alluviale); couleur 10YR 4/3; forte effervescence à HCl; matière organique absente; texture: limono-sableux; structure particulière minérale sableuse. Cailloux de 5-20cm.

Analyses physico-chimiques

Horiz.	Epais. cm	pH eau	C_{org} %	N %	C/N	$CaCO_3$ %	Granulométrie %				
							SG	SF	LG	LF	A
Aca	15	7.8	4.6	0.3	15.9	30.0	11.3	32.6	14.5	22.4	19.1
Scah	30	7.9	2.3	0.1	16.2	33.6	12.1	32.9	15.0	24.2	15.7
D	5	8.1	0.3	0.1	14.9	35.9	8.4	36.5	19.6	22.8	12.7

Horiz.	Cations échangeables (méq/100g)					Da
	Ca	Mg	K	Na	S	g/cm^3
Aca	34.2	0.9	0.2	0.1	35.4	1.04
Scah	20.4	0.5	0.1	0.1	21.1	
D	14.6	0.4	0.1	0.1	15.2	

Remarques: beaucoup de vers-de-terre



Profile III (Soil Survey T10S4) **- Group 5**

Calcareous FLUVIOSOL "in process of brunification"

Soil Profile IV (Group 6)

typical calcareous FLUVIOSOL : Aca/Jp/D

Données stationnelles:
Commune de Neirivue (FR).
Coordonnées (m) : 571332./152070; altitude (m): 741.36
Végétation: Unité 16.1 - Noisettier, chevrefeuille, frêne
Terrain: rive guache de la Sarine, à 1 m du chemin
Emplacement du profil: distante de 30.12m du cours principal de la Sarine
Substrat géologique: alluvions à dominante calcaire

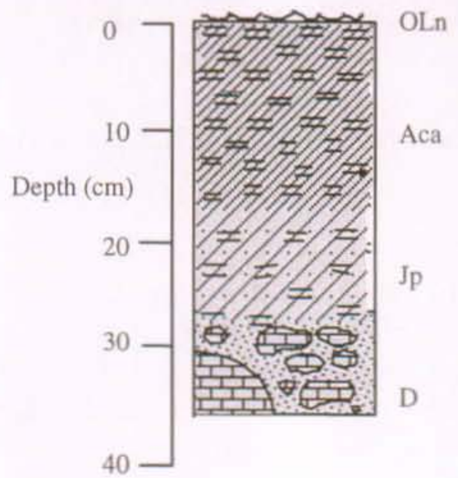
Données Pédologiques:
Litière: feuilles de l'année
Humus: eumull carbonaté: OLn
0-18 cm: horizon **Aca** ; couleur 7,5YR 3/1; moyenne effervescence à HCl; humifère; texture: limono-sableuse; 5% d'élements grossiers; structure polyédrique subangulaire, moyennement développée, nette, agrégats de10-20 mm; beaucoup de racines fines à moyennes; transition graduelle, limite regulière.
18-28 cm: horizon **Jp**; couleur 7,5YR 4/4; moyenne effervescence à HCl; peu humifère; texture limono-sableuse; structure polyédrique subangulaire, moyennement développée, peu nette; beaucoup de racines fines à moyennes; transition abrupte, limite irrégulière.
28 cm ...: horizon **D;** grève alluvial, non prélevée.

Analyses physico-chimiques

Horiz.	Epais.	pH	C_{org}	N	C/N	$CaCO_3$	Granulométrie %				
	cm	eau	%	%		%	SG	SF	LG	LF	A
Aca	18	7.8	3.6	0.2	14.9	32.3	12.3	30.4	14.2	22.9	20.3
Jp	10	7.9	2.1	0.1	15.0	36.2	14.0	28.2	15.9	25.0	16.9

Horiz.	Cations échangeables (méq/100g)					Da
	Ca	Mg	K	Na	S	g/cm^3
Aca	21.9	0.7	0.3	0.1	23.0	0.84
Jp	15.9	0.5	0.2	0.1	16.7	

Remarques: présence de vers-de-terre et crustaces.



Profile IV (Soil Survey T9S2) - **Group 6**

Typical calcareous
FLUVIOSOL

Soil profile V (Group 6)

typical calcareous Fluviosol: Aca, Jp, C/D

Données stationnelles:
Commune de Neirivue (FR).
Coordonnées (m) : 571262.22/152073.59; altitude (m): 741.21
Végétation: Unité 16.1 - frêne, noisetier
Terrain: rive guache de la Sarine, à 5 m d'un chemin
Emplacement du profil: distante de 100.12m du cours principal de la Sarine
Substrat géologique: alluvions à dominante calcaire

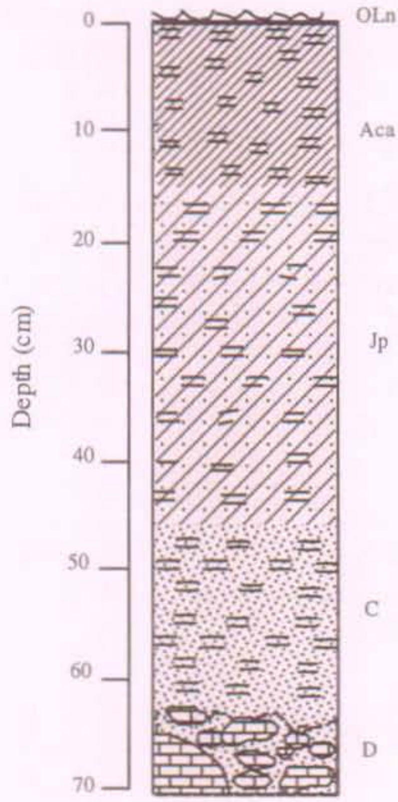
Données Pédologiques:
Litière: feuilles de l'année + aiguilles d'épiceas
Humus: eumull carbonaté: OLn
0-15 cm: horizon **Aca**; couleur 7,5YR 3/1; moyenne effervescence à HCl; humifère; texture: sablo-limoneux; 0% d'élements grossiers; structure polyédrique subangulaire, faiblement développée, peu nette, agrégats de5-10 mm; beaucoup de racines fines à grosses; transition diffuse, limite regulière.
15-45 cm: horizon **Jp**; couleur 7,5YR 3/4; forte effervescence à HCl; peu humifère; texture sablo-limoneux; structure polyédrique subangulaire, faiblement développée, peu nette; beaucoup de racines fines à grosses; transition diffuse, limite régulière.
45-65 cm: horizon **C**; couleur 7,5 YR 4/4; forte effervescence à HCl; matière organique absente; texture: sableux; structure particulière minérale sableuse; transition abrupte, limite ondulée.
65 cm ...: horizon **D;** grève alluvial, non prélevée.

Analyses physico-chimiques

Horiz.	Epais. cm	pH eau	C_{org} %	N %	C/N	$CaCO_3$ %	Granulométrie %				
							SG	SF	LG	LF	A
Aca	15	7.9	3.6	0.2	15.8	38.0	27.6	28.2	9.9	28.8	5.5
Jp	30	8.1	1.0	0.1	11.6	48.7	43.6	25.4	7.9	13.3	9.8
C	20	8.5	0.0	0.0	0.0	60.5	75.2	15.5	2.1	3.2	4.1

Horiz.	Cations échangeables (méq/100g)					Da
	Ca	Mg	K	Na	S	g/cm^3
Aca	24.3	0.6	0.1	0.1	25.3	0.81
Jp	11.8	0.3	0.1	0.1	12.3	
C	5.2	0.2	0.0	0.1	5.6	

Remarques:



Profile V (soil surveyT9S9) **- Group 6**

Typical calcareous FLUVIOSOL

Soil profile VI (group 6)

polygenetic calcareous FLUVIOSOL: Aca, Jp/M/IIJp/IIM/IIAca/IIIM/IIIAca/D

Données stationnelles:

Commune de Neirivue (FR).
Coordonnées (m) : 571333.92/152679.24; altitude (m): 737.36
Végétation: Unité 18.1 - chevrefeuilles, frênes, jeunes épiceas et peupliers plantés
Terrain: ancienne terrasse alluviale, rive guache de la Sarine......
Emplacement du profil: distante de 61,23 m du cours principal de la Sarine
Substrat géologique: alluvions à dominante calcaire

Données Pédologiques:

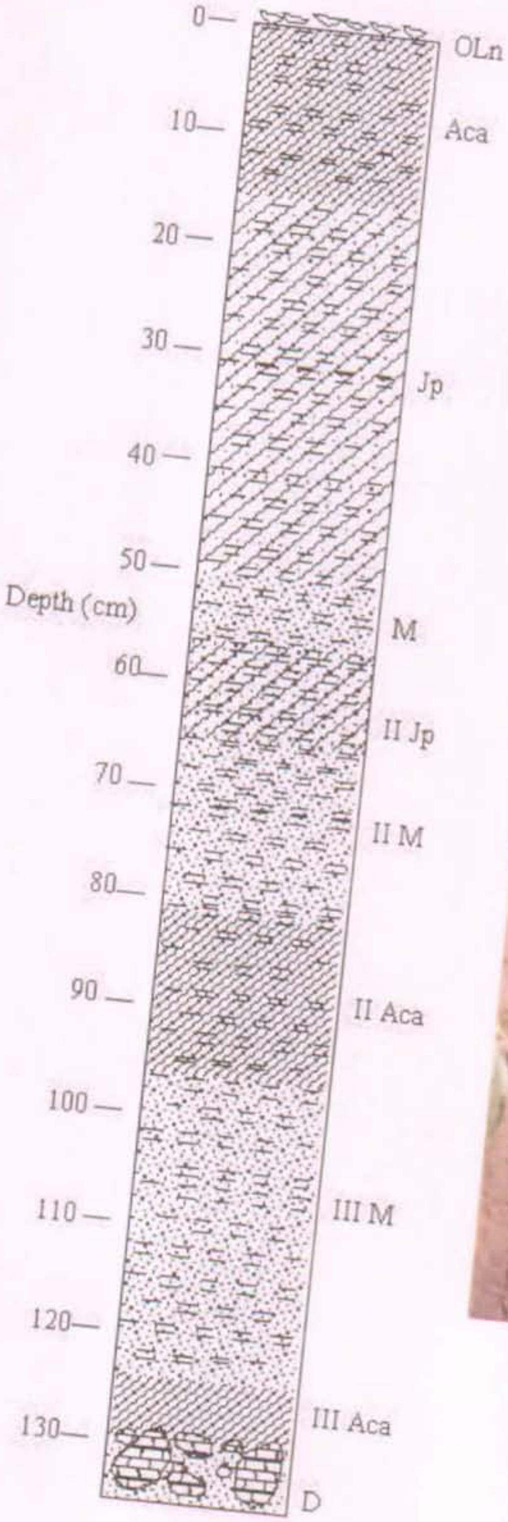
Litière: feuilles de l'année: dominance de feuilles de peuplier
Humus: horizon **OLn**; eumull carbonaté.
0-15 cm: horizon **Aca** ; couleur 7,5 YR 2/2; moyenne effervescence à HCl; humifère; texture: limono-sableux; 0% d'élements grossiers; structure grumeleuse à polyédrique subanguleuse, bien développée, nette, agrégats de 5-10 mm; forte concentration de racines fines à moyennes; transition peu nette, limite régulière.
15-50 cm: horizon **Jp**; couleur 10 YR 3/4; forte effervescence à HCl; peu humifère; texture: limono-sableux; 0% d'élements grossiers; structure polyédrique subanguleuse, moyennement développée, nette, agrégats de 10-20 mm; forte concentration des racines fines à grosses; transition abrupte, limite ondulée;
50-55 cm: couche **M**; couleur 7,5 YR 4/4; forte effervescence à HCl; absence de matière organique; texture sableuse; structure particulière minerale graveleuse, nette; présence de grosses racines; transition abrupte, limite ondulée.
55-65 cm: horizon **II Jp**; couleur 10 YR/4/3; forte effervescence à HCl; peu humifère; texture: sablo-limoneux; structure particulière mineral sableuse, nette; absence de racines; transition abrupte, limite regulière.
65-80 cm: couche **II M**; couleur 10 YR 4/6; forte effervescence à HCl; absence de matière organique; texture: sableuse; structure particulière minerale graveleuse, nette; absence de racines; transition abrupte, limite regulière.
80-95 cm: horizon **II Aca**; couleur 7,5 YR 2/2; moyenne effervescence à HCl; humifère; 0% d'élemets grossiers; structure particulière pudreuse, faiblement développée, peu nette; absence de racines; transition abrupte, limite regulière.
95-124 cm: couche **III M**; couleur 7,5 YR 4/4; forte effervescence à HCl; non humifère; texture: sableuse; structure particulière minérale graveleuse,nette; absence de racines; transition abrupte, limite régulière.
124-130 cm: horizon **III Aca**; couleur (réduite: noir et blanc); moyenne effervescence à HCl; humifère; texture: limono-sableuse; 0% d'élements grossiers; structure particulière organique feuilletée, bien développée, nette; absence de racines; transition abrupte, limite régulière.
130 cm...: horizon **D**; grève alluvial; horizon non prélevé.

Analyses physico-chimiques

Horizon	Epais. cm	pH eau	Corg %	N %	C/N	$CaCO_3$ %	Granulométrie % SG	SF	LG	LF	A
Aca	15	8.1	3.6	0.3	13.7	31.5	6.5	32.5	17.6	31.1	12.3
Jp	35	8.11	1.56	0.1	15.3	36.2	11.9	34.8	18.6	21.3	13.4
M	5	8.6	0.4	0.0	12.0	51.9	81.7	9.6	1.5	3.4	3.8
II Jp	10	8.3	0.8	0.0	16.6	39.2	16.2	44.1	17.9	13.9	7.9
II M	15	8.5	0.5	0.0	13.0	57.6	88.4	3.3	1.9	2.7	3.7
II Aca	15	7.8	2.5	0.1	21.2	33.9	4.8	41.9	16.6	24.3	12.4
III M	29	8.5	0.2	0.0	8.0	52.7	69.9	18.6	2.4	4.2	4.9
III Aca	6	7.9	3.0	0.2	18.7	39.1	4.6	41.2	17.5	24.4	12.3

Horiz.	Cations échangeables (méq/100g) Ca	Mg	K	Na	S	Da g/cm^3
Aca	24.9	0.7	0.2	0.1	26.0	0.94
Jp	14.7	0.4	0.1	0.2	15.4	
M	5.3	0.2	0.0	0.1	5.7	
II Jp	8.4	0.3	0.1	0.1	9.0	
II M	9.0	0.2	0.0	0.1	9.4	
II Aca	18.9	0.9	0.1	0.1	20.0	
III M	5.6	0.3	0.0	0.2	6.1	
III Aca	19.5	0.9	0.1	0.2	20.6	

Remarques: - taches d'hydromorphisme à partir de 55 cm (H4), jusqu'à 124 cm (H7) L'horizon H5 est constitué de sable grossier très oxydé.
- présence de vers-de-terre et racines.



Profile VI (soil survey T6S5) - **Group 6**

Polycyclical or Polygenetic calcareous FLUVIOSOL

Soil profile VII (Group 6)

calcareous FLUVIOSOL "in process of brunification": Aca/Scah, C/D

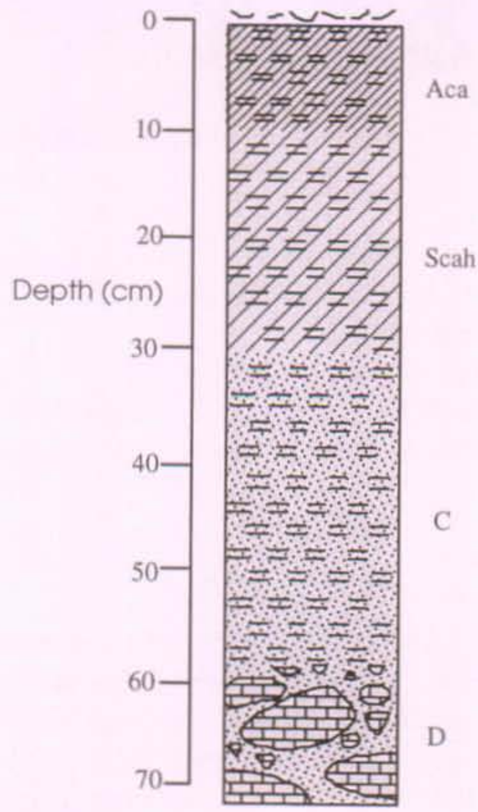
Données stationnelles:
Commune de Neirivue (FR).
Coordonnées (m) : 571309.43/152673.50; altitude (m): 735.50
Végétation: Unité 18.1 - prairie graisse
Terrain: rive guache de la Sarine, sur ancienne prairie
Emplacement du profil: distante de 80.77m du cours principal de la Sarine
Substrat géologique: alluvions à dominante calcaire

Données Pédologiques:
Litière: pas de litière
Humus:
0-10cm: horizon **Aca**; couleur 7,5YR 3/2; moyenne effervescence à HCl; humifère; texture: limoneuse; 5% d'élements grossiers; structure polyédrique subangulaire, bien développée, nette, agrégats de20-50 mm; beaucoup de racines fines; transition distincte, limite regulière.
10-30 cm: horizon **Scah**; couleur 7,5YR 2/2; forte effervescence à HCl; peu humifère; texture limono-sableuse; 5% d'élements grossiers; structure polyédrique subangulaire, bien développée, très nette, agrégats de 20-50 mm; beaucoup de racines fines; transition abrupte, limite régulière.
30-60 cm: horizon **C**; couleur 10YR 4/2; forte effervescence à HCl; matière organique absente; texture: limono-sableuse; structure polyédrique subangulaire, faiblement développée, nette; présence de quelques racines; transition abrupte, limite régulière.
60 cm ...: horizon **D; grève alluvial, non prélevée.**

Analyses physico-chimiques

Horiz.	Epais.	pH	Corg	N	C/N	$CaCO_3$	Granulométrie %				
	cm	eau	%	%		%	SG	SF	LG	LF	A
Aca	10	7.7	5.4	0.3	15.5	31.7	10.8	26.7	16.9	23.9	21.8
Scah	20	8.0	2.3	0.1	16.8	35.4	7.1	32.4	18.3	25.7	16.5
C	30	8.2	1.5	0.1	16.2	35.9	8.0	39.5	16.9	22.8	12.9

Horiz.	Cations échangeables (méq/100g)					Da
	Ca	Mg	K	Na	S	g/cm^3
Aca	29.4	1.1	0.5	0.2	31.1	0.94
Scah	17.0	0.5	0.2	0.1	17.9	
C	12.6	0.1	0.4	0.1	13.2	



Profile VII (soil survey T6S7) **- Group 6**

Calcareous FLUVIOSOL "in process of brunification"

Remarques: présence de quelques vers-de-terre.

Soil profile VIII (Group 7)

FLUVIOSOL typique calcaire: Aca/C,D

Données stationnelles:

Commune de Neirivue (FR).
Coordonnées (m) : 571354.73/152685.73; altitude (m): 737.37
Végétation: Unité 16.1 - végétation herbacée
Terrain: rive guache de la Sarine, sur ancien bras lateral
Emplacement du profil: distante de 34.12m du cours principal de la Sarine
Substrat géologique: alluvions à dominante calcaire

Données Pédologiques:

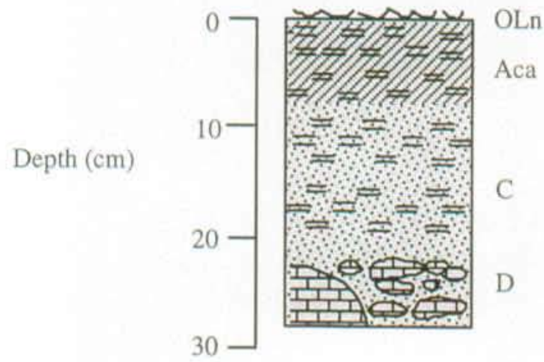
Litière:
Humus: eumull carbomnaté: OLn
0-7 cm: horizon **Aca**; couleur 7,5YR 2/2; forte effervescence à HCl; très humifère; texture: limon-sableux; 60% d'élements grossiers; structure grumeleuse, moyennement développée, peu nette, agrégats de1-2 mm; beaucoup de racines moyennes; transition abrupte, limite regulière.
7-26 cm: horizon **C**; couleur 10YR 4/3; forte effervescence à HCl; absence de matière organique; texture sablo-limoneuse; structure particulière minérale graveleuse; présence de quelques racines; transition diffuse, limite irrégulière.
26 cm...: horizon **D**; grève alluviale typique, non prélevée.

Analyses physico-chimiques

Horiz.	Epais. cm	pH eau	Corg %	N %	C/N	$CaCO_3$ %	Granulométrie %				
							SG	SF	LG	LF	A
Aca	7	7.7	5.5	0.4	14.9	39.8	50.8	13.6	7.1	17.4	11.1
C	19	8.0	0.2	0.1	13.0	52.7	70.9	12.0	4.2	7.8	5.1

Horiz.	Cations échangeables (méq/100g)					Da g/cm^3
	Ca	Mg	K	Na	S	
Aca	27.6	1.3	0.3	0.1	29.4	0.83
C	9.0	0.5	0.1	0.1	9.6	

Remarques:beaucoup de vers-de-terre



Profile VIII - (soil survey T6S2a) - Group 7

Typical calcareous
FLUVIOSOL

Soil profile IX (Group 8)

typical calcareous FLUVIOSOL: Aca/D

Données stationnelles:

Commune d'Albeuve (FR).
Coordonnées (m) : 571181.16/151314.32; altitude (m): 750.32
Végétation: Unité 16.2 - gros épiceas + arbustes + beaucoup d'herbacées (mousses et graminée)
Topographie: rive guache de la Sarine, sur un ancien îlot de topographie plus élevée
Emplacement du profil: distante de 19.97 m du cours principal de la Sarine
Substrat géologique: alluvions à dominante calcaire

Données Pédologiques:

Litière:

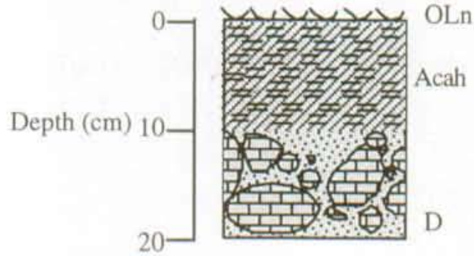
Humus: eumull carbonaté: OLn
0-10 cm: horizon **Aca** ; couleur 7,5YR 2/2; moyenne effervescence à HCl; très humifère; texture: limono-sableux; 20% d'élements grossiers; structure grumeleuse, bien développée, nette, agrégats plus petits que 1 mm; beaucoup de racines fines ; transition abrupte, limite ondulée.
10cm...: horizon **(D)**; grève alluvial typique, avec de cailloux de 10-20 cm; non prélevée.

Analyses physico-chimiques

Horiz.	Epais. cm	pH eau	C_{org} %	N %	C/N	$CaCO_3$ %	Granulométrie %				
							SG	SF	LG	LF	A
H1	10	7.8	5.5	0.4	15.4	37.7	53.3	17.1	5.2	12.7	11.5

Horiz.	Cations échangeables (méq/100g)					Da
	Ca	Mg	K	Na	S	g/cm^3
H1	34.1	0.9	0.2	0.1	35.3	0.49

Remarques: beaucoup de vers-de-terre.



Profile IX (soil survey T10S2) **- Group 8**

Typical calcareous FLUVIOSOLS

Soil profile X (Group 8)

FLUVIOSOL typique calcaire humifère: Aca/D

Données stationnelles:

Commune d'Albeuve (FR).
Coordonnées (m) : 571175.64/151316.70; altitude (m): 748.16
Végétation: Unité 16.2 - végétation arbustive + vég.herbacée dense + beaucoup de mousse. A côté, nous trouvons des gros épiceas
Terrain: rive gauche de la Sarine, à 6 m de l'îlot
Emplacement du profil: distante de 29,38 m du cours principal de la Sarine
Substrat géologique: alluvions à dominante calcaire

Données Pédologiques:

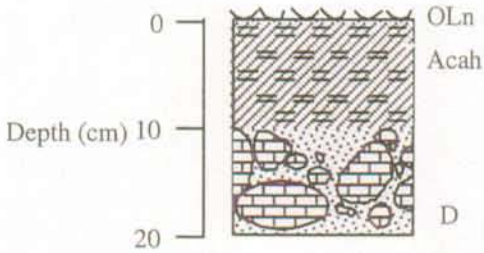
Litière: feuilles de l'année + beaucoup de mousse
Humus: eumull carbonaté: OLn
0-10 cm: horizon **Aca** ; couleur 7,5YR 2/2; faible effervescence à HCl; très humifère; texture: limoneux; 0% d'élements grossiers; structure grumeleuse, bien développée, nette, agrégats plus petits que 1 mm; beaucoup de racines fines ; transition abrupte, limite régulière.
10cm...: horizon **(D)**; grève alluvial typique, avec de cailloux de 5-20 cm; non prélevée.

Analyses physico-chimiques

Horiz.	Epais. cm	pH eau	C_{org} %	N %	C/N	$CaCO_3$ %	Granulométrie %				
							SG	SF	LG	LF	A
Aca	10	7.7	8.2	0.45	18.3	24.5	30.7	12.3	9.2	25.0	22.9

Horiz.	Cations échangeables (méq/100g)					Da
	Ca	Mg	K	Na	S	g/cm^3
Aca	48.5	1.3	0.3	0.1	50.2	0.49

Remarques: beaucoup de vers-de-terre



Profil X (soil survey T10S2b) **- Group 8**

Typical calcareous
FLUVIOSOL

Curriculum vitae

MENDONCA SANTOSBREFIN, Maria de Lourdes
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Formation professionnelle post-grade

Master en Sciences de l'environnement, spécialisation protection des sols
Ecole Polytechnique Fédérale de Lausanne
Lausanne -Vaud, Suisse
Mémoire de recherche soutenu: **«L'impact des endiguements sur la dynamique d'évolution des sols alluviaux - L'apport d'un S.I.G. pour l'étude des changements du paysage»**

M.Sc. en Science des sols
Université Fédérale Rurale de Rio de Janeiro
Rio de Janeiro-RJ, Brésil
Thèse soutenue: **«L'étude des mécanismes de tolérance à l'Aluminium toxique et leur variabilité génotypique en plantes de riz (*Oryza sativa* L.)»**

Formation professionnelle

Diplôme d'Ingénieur Agronome
de l'Université de l'Etat du Maranhão (UEMA)
São Luis-MA - Brésil

Expérience professionnelle

CHERCHEUR EN SCIENCE DES SOLS ET GIS (EMBRAPA/CNPS - Entreprise Brésilienne de Recherche - Centre National de Recherche en Sols) ;

«SCHOLAR VISITING» au Woods Hole Research center (W.H.R.C.) pour un programme de collaboration technique entre les gouvernements brésilien et américain dans le domaine de la Télédétection et Systèmes d'information Géographique (S.I.G.) appliqués à l'étude des impacts environnementaux en Amazonie brésilienne;

ENSEIGNANTE à l'Université de l'Etat du Maranhão (UEMA) en Science des Sols et Physiologie Végétale;

ING. AGRONOME, VULGARISATEUR AGRICOLE à l'Entreprise d'Assistance Technique et de vulgarisation agricole (EMATER-MA, Brésil) ;

INGENIEURE ASSISTANTE à Delta Assessoria et Contabil Ltda (São Luís-MA, Brésil)

Connaissances Linguistiques

Portugais (langue maternelle); Français (couramment, parlé et écrit) Anglais (advanced); Espagnol (notions)

Publications

M.L. Mendonça Santos; M. Bouzelboudjen; C. Guenat and F. Golay (1998). ***The use of a GIS-assited cartography to study the spatial distribution and variability of soil in a floodplain ecosystem*** (Actes du 16ème Congrès Mondial de Science du Sol à Montpellier/France, du 20-26 August 1998). Article soumis à la revue GEODERMA.

M.L. Mendonça Santos; C. Guenat; F. Bureau; J.-C. Védy. (1997). ***Impacts of embanking on the soil-vegetation relationships in a floodplain ecosystem of a pre-alpine riv*****er**. Global Ecology and Biogeography Letters, 6, 339-348.

M.L. Mendonça Santos; C. Guenat; Corine Thévoz; F. Bureau (1997). ***Modifications d'une zone alluviale suite à l'endiguement - approche métodologique***. Géomorphologie, 4, 365-374.

M. L. Mendonça Santos; R.O.P. Rossiello; M.S. Fernandes; E. Zonta. (1996). ***Alcalinization as a mechanism of Al - rhizotoxicity escape in rice*** - Proceedings of IV International Symposium on Plant-Soil interactions at low pH (Braszil).

Participation en Congrès, Symposiums et Colloques

Event: Séminaire EPFL-Cassini (France) - Formalismes, Modèles et Applications Spatio-temporelles - Lausanne, 13 et 14/11/96
Travail présenté: **" Intégration du temps dans un SIRS pour la modélisation spatio-temporelle de l'évolution des sols alluviaux"**

Event: VIe Journées de l'écologie du paysage organisée par le CEMAGREF - Aussois - France, du 09 au 11/10/96
Thème: Biodiversité et paysage.
Travail présenté: **Changements du paysage et diversité des sols en milieu alluvial**

Event: Symposium - European Floodplain forest ecosystems: structure, functioning, conservation - Leicester - England, du 22 au 24/03/95
Travail présenté: **«Effect of embanking on the alluvial soil»**

Event: Colloque - Crues, versants et lits fluviaux - processus naturels et impacts des activités humaines - Paris - France, du 22 au 26/03/95
Travail présenté: **«Modification de la dynamique fluviatile suite a l'endiguement: conséquences sur la zone riveraine - exemple d'un site d'importance nationale suisse»**

Event: VII Symposium Brésilien de Télédétection - Institute de Recherche Spatiale (INPE/Brésil) - Curitiba-PR - Brésil, du 10 au 14/05/93
Travaux présentés: a) **«Intérprétation d'images de satellite et de photos aériennes appliquée au monitoring de l'occupation du sol pour deux communautés de Rio Capim-Paragominas-Pará (Amazonie brésilienne)»**
b) **«Utilisation d'images de satellite pour l'établissement d'une carte d'occupation du sol et pour l'éducation environnementale d'agriculteurs du Rio Capim - Paragominas - Pará»**

Event: XXIII Congrès Brésilien des Sciences du Sol - Soc. Brés. Sci. Sol/Université Fédérale de Porto Alegre - Porto Alegre-RS - Brésil, du 21au 27/07/91
Travail présenté: **«Réorganisation de l'occupation du sol de la région «canavieira» de Campos-RJ»**

Event: III Congrès Brésilien de Physiologie Végétale et Symposium de la Biotechnologie des Plantes - Soc. Brés. de Physiologie Végétale/Université de Viçosa - Viçosa-MG - Brésil, du 24 au 28/02/91
Travaux présentés: a) **«Evaluation de 50 génotypes de riz (*Oryza sativa* L.) de l'Etat du Maranhão par la tolérance à l'aluminium en solution nutritive»;**
b) **«Caractérisation des mécanismes de la tolérance à l'aluminium toxique en riz (*Oryza sativa* L.), cultivé en solution nutritive»;**
c) **«Variation de pH comme mécanisme de l'exclusion d'aluminium en trois génotypes du riz (*Oryza sativa* L.), cultivé en solution nutritive»**

Event: XXII Congrès Brésilien des Sciences du Sol - EMBRAPA - Recife-PE - Brésil, du 23 au 31/07/89
Travail présenté: **«Tolérance des génotypes de riz (*Oryza sativa* L.) à l'aluminium toxique»**

Event: XVIII Réunion Brésilienne sur la fertilité du sol - Soc. Brés. de Sciences du Sol - Guarapari-Es - Brésil, du 23 au 28/10/88
Travail présenté: «Toxicité de l'aluminium dans deux variétés de riz (*Oriza sativa* L.)»