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Alluvial soils in the Swiss Alps : historical, geomorphological and pedogenetic aspects

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à Léo

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Abstract

Floodplains are represented by flat or nearly flat land occasionally or periodically flooded by a stream or adjacent river. They are constituted of particularly rich ecosystems, both in quantity and diversity. Dynamic floodplain is conditioned by the water discharge and the matter fluxes, consisting in a large amount of sediments transferred from the upper catchments to the lower valleys. Both contribute to the floodplain's geomorphological diversity. Erosion, transport and deposition create also an important ecological diversity through a permanent drop in age of the fluvial forms and the vegetation successions.

Braided rivers were in the past one of the most typical landscape of Swiss alpine and pre-alpine valleys, but since the middle of the 19th century, this landscape has progressively disappeared, largely due to the development of flood protection structures and the water exploitation for energetic and food security reasons. These constructions had lead to severe modifications of the river system, notably incision, landscape homogenization, loss of biodiversity or fluvial process changes. Therefore, two general principles appeared: security, which prevailed before 1970 when focalisation was exclusively made on systematic regulations of most alpine river flows, and conservation of natural systems that emerged from about 1970 in the context of respecting the ecological functioning of nature,

the biodiversity and, in particular, the alluvial ecosystems.

Previous studies carried out in different floodplains have already shown these modifications, but only few were carried out in the Swiss alpine arc. Moreover, a global analysis of the exceptional hydrological events combined with a description of the channel morphology changes through time would give precious information on the complexity of the Swiss alluvial valleys functioning. In addition, as floodplain ecosystems are confronted with various ecological, hydrological and socio-cultural constraints limiting the public action, and are in the heart of complex social negotiation, a better understanding of the social representations of nature and risks is needed to assess the complementarities between security and biodiversity.

In this context, an interdisciplinary project (*Flood'Alps* project) has been set up to describe the evolution of the relationships between these two principles between 1850 and 2000 in three alluvial valleys of the Swiss Alps, representing three geographical, geological and cultural regions. The Sarine River, in the Intyamou valley in the canton of Fribourg, was the main study site, while the Rhine River in the canton of Graubünden and the Ticino River in the canton of Ticino were considered of secondary importance. Several research fields were

investigated: hydrology, ecology (mainly soil science) and sociology.

In the present thesis research, we proposed to better understand the landscape modifications through time of the three alpine floodplains. The alluvial soil formation and evolution related to these alterations are still not fully understood and is thus the heart of the present research, which tackles at different scale levels from the general interdisciplinary study on landscape to particular specialized processes of soil development.

In a first approach, we explored the floodplain landscape evolution during the last 150 years at the catchment area scale, and tried to detect the consequences of the numerous human impacts on alluvial zones. Literature evoking the main historical events was also used and the different hydrological data, such as embankment events, were summarized. Furthermore, and only for the main study site, a set of six maps were digitalised and analysed in order to evaluate the different vegetation types and landscape units through time. In the Sarine River, the results showed that the very first embankments have been built since 1885 in order to stabilize the gravel bars and the banks against erosion. From the beginning of the 20th century, a general diking and canalization with one pair of continuous and unsinkable dikes were made to collect the flows in a single uniform channel. The main aim was to protect the existing farming land and forests of the communes and gain some others if possible. The consequences were the narrowing of the potential river divagation and the riverbed incision. Pioneer vegetation was gradually replaced by softwood forests, which were then cleared or substituted by hardwood forests. In the case of the Rhine River, embankments started in 1832 and lasted for 60 years. The valley became progressively colonized by the forests (principally pines) that appeared in natural and artificial manner. The bottom of the valley was transformed in productive lands with the use of tributary sediments diverted in successive settling tanks, which provoke fine particle sedimentation, improve and elevate the soil. In the Ticino River, situated in the principal

road through the Alps from North to South Europe, the landscape was modified early. Embankments probably appear already in the 19th century and the gained lands were used for agriculture, forest exploitation and urbanisation.

At a lower scale level, a better comprehension of the aggradation and soil formation processes in soils, nowadays disconnected from the current flow, as well as a better knowledge of their spatial distribution along the riparian corridor, was studied to understand the global functioning of a floodplain. The vertical succession of the horizons, presenting pedogenic features or consisting of overbank sediments, was described at the functional set and unit levels. In a first approach, soils of the Sarine River were surveyed. Results revealed that the discriminating parameter between the different types of soils was mainly the soil texture of the horizons, reflecting the variety of alluvial deposits. The presence of coarse material suggests a sedimentation process with a high slow velocity, as fine, thin sediment layers describe an active sedimentation, but with a slow flow velocity. A vertical sequence, with several thin horizons at the bottom and a well developed A horizon on the top, can be explained by a sufficiently long floodplain stability to generate pedogenic features, such as soil structure.

These results show also a close linear relationship between the total thickness of the profile and the number of horizons leading to the description of four facies models. These facies models, optionally combined together or not, at the functional unit level, permit to explain the functioning of the entire valley with alternation of stable and unstable phases (meaning regularity with development of soil pedogenic features and irregularity in term of natural floods) at the functional set level of the river environment in space and time. The four facies models were also verified in the two other sites indicating similar modifications in soil formation. Coarse material was found in the depth illustrating a past alluvial activity. Nevertheless, clear distinct particularities have appeared among each study area related to the local and regional properties (e. g. geology, hydrology).

At the lower level of the soil profile, the identification of the present-day state of the soil, as well as the understanding of what was happening in deepness reflecting the history of the study site, was relevant. Thus, a descriptive typology, based on the identification of pedological parameters indicating some evolution of the soil, was made in the Sarine River study site guided by two hypotheses presented in a model containing two axes. A first gradient represents a progression between the “lake” situation (where the influence of chemical processes is higher) and the “river” situation (where physical processes are predominant). The second gradient corresponds to a transition between the natural (e. g. willow forest) and the agricultural environments (e. g. field of maize). Fourteen soil profiles were described and sampled for further physicochemical analysis. Results revealed a diversity of soil types throughout the study area. Weakly developed buried soils (e. g. FLUVIOSOL TYPIQUE polyphasic) were found in active alluvium accumulation zones, when buried soils showing pedogenesis features were described in more stable zones. Moreover, double attributions were applied to some soil profile references reflecting effects of embankments on soil functioning (e. g. FLUVIOSOL TYPIQUE on REDUCTISOL TYPIQUE polyphasic). Anthropogenic impacts on fluvial environment have significantly redesigned the pattern of alluvial soil evolution and may be detected in the soil profile.

Finally, and at the lowest scale level, the research focused on the humiferous episolum, which is considered as a good indicator of short-term and small-scale variations under the influence of vegetation or sedimentation changes. In two pioneer communities (willow and alder forests), soil structure formation was analysed in this upper organo-mineral part by holding account of the nature of the recent

alluvial deposits. This layer, directly in contact with organic matter, affects in turn the colonization by the soil fauna (earthworms and enchytraeids). It has been showed here that the tree population age cannot be used alone as an indicator of the humus form formation and evolution. Biological and physicochemical parameters, especially particle size distribution and earthworm categories, also strongly influence aggregation in the initial phases of soil structure formation in an alluvial context, such as the Sarine River. We conclude that, in various initial conditions, the first steps of soil evolution present particular stages of development, sometimes different from the evolution of older ones.

Conclusively from all results of the thesis, we found that the combination of various scales and techniques allowed the connection between the dynamics of soil structuring processes in described humiferous episolum and the general fluvial mechanisms due to river regulation and management. Human impact has great importance on alluvial zone functioning and damages caused to floodplains are generally irreversible and initial stages could never be found again, unless restoration efforts are taken into account. The results of this multi-scale approach suggest further developments for a better understanding of the floodplain ecosystems. Finally, some perspectives for future research are suggested.

Keywords: Floodplain; Alluvial soil; Human impact; Multi-scale approach; Soil typology; Humiferous episolum; Soil fauna; Soil structuring.

Mots clés: Plaine alluviale; Impact humain; Sol alluvial; Approche multiscalaire; Typologie des sols; Episolum humifère; Faune; Structure.

1. General introduction

This general introduction presents the context of the thesis with an overview on floodplain and alluvial environments. The Flood'Alps project, in which this thesis was integrated, is then exposed. Finally, the main objectives and layout of this thesis are introduced.

1.1. Context of the research

Streams and rivers are among the most fascinating and complex ecosystems on earth (Naiman and Bilby, 1998). They touch all parts of the natural environment and almost all elements of human culture. Acting as integrators and centers of organization within landscape, they provide numerous resources (e. g. fish and clean water). Their roles in our life are various (e. g. transportation, energy, diffusion of wastes, recreation). Moreover, alluvial zones are defined as heterogeneous and complex functioning, and natural riparian zones are some of the most diverse, dynamic and complex areas (Naiman and Decamps, 1997).

Floodplains are recognized as a highly sensitive environment in a complex context related to temporal changes of topography, hydraulic, sedimentology and water quality (Anderson *et al.*, 1996). The floodplain landform assemblage presents thus a potentially complex sedimentological background with three-dimensional flow dynamics leading to

high temporal and spatial variation in flow throughout the domain. In this context, the environmental changes happening in floodplains are detected by soils, reflecting in their profiles the sequence of buried soils and representing a record of alternating processes of alluviation and *in situ* pedogenesis (Alexandrovskiy *et al.*, 2004).

Human activities, such as construction of dams and levees, channelization, or intensive agriculture, have strongly altered most of the large river floodplains in the world. Kang and Stanley (2005) reports that 77% of 139 large river systems in North America, Europe and the former Soviet Union are affected by fragmentation of the river channels by dams. For example, in the United States, only 2% of the rivers run without restraint (Vitousek, 1997). The preservation of these free-flowing rivers is thus very important, because they contain biodiversity that can persist due to organism dispersal effective in both upstream and downstream directions (Nilsson *et al.*, 2005). In fragmented and regulated rivers, such dispersal is strongly limited and these facts need to be taken in consideration for a global planning management.

Considering these heavy man-induced alterations, the European Council decided to protect alluvial forests in Europe. Moreover, it asked its member states to establish an inventory of their alluvial zones with the aim of conservation, pro-

tection and even restoration (Conseil de l'Europe, 1982). Switzerland was the first country to make an inventory of its alluvial zones (Kuhn and Amiet, 1988) and to map their vegetation (Gallandat *et al.*, 1993). Since 1992 the inventory of alluvial zones of national importance has come into effect with 169 reported objects. Almost 80% of known animal species, as well as more than 40% of vascular plants found in Switzerland, were present in these alluvial zones representing only 0.26% of the Swiss territory. In 2002, 97 new objects situated under an altitude of 1800 m were proposed as a 2nd complement to the federal inventory. The total surface of these latest objects represents 29% of the surface of the previous inventory (corresponding to 0.33% of the Swiss territory; Thielen *et al.*, 2002). Nevertheless, all these objects are under heavy pressure from human activities, mostly embankments, tourism and plantations, and the evolution dynamics of these ecosystems has been modified by changes in hydrodynamic regime (Gallandat *et al.*, 1993).

Alluvial zones may be compared to the wildland–urban interface defined by Struglia and Winter (2002) as a unique social and ecological zone. They precise that pressure on these particular areas will continue to increase in magnitude and complexity, as populations grow and get more diverse. As the management of wildland areas close to densely populated urban regions gets more complex, there is increasing recognition that human activities are creating profound environmental impacts. Multiple components - ecological, economic, political, and sociocultural - must be successfully integrated in the management of these particular areas, and this is particularly true in alluvial zones. Indeed, with the increase of flood events (e. g. the dramatic floods occurred in August 2005 in Europe) and pressure made on rivers, human dimension must be taken in consideration in the floodplain management. The challenges of managing alluvial areas are particularly relevant in Switzerland, where rivers are unique from hydraulic, economic and also biological points of view and, in addition, because of their proximity to a large urban population.

Considering these particularities, several studies have been carried out about dynamics of alluvial vegetation in Europe (Deiller *et al.*, 2001; Pautou, 1984; Pautou, 1988; Pautou and Girel, 1994; Malanson, 1993; Schnitzler, 1995; Schnitzler, 1997; Trémolières *et al.*, 1998; Turner *et al.*, 2004;) and in Switzerland (Gallandat *et al.*, 1993; Werffeli *et al.*, 1997; Roulier, 1998; Kohler *et al.*, 2000; Favre, 2004). Studies on the fauna have also been conducted (e. g. Griesser, 1992; Burbrink *et al.*, 1998; Russell *et al.*, 2004; Tockner *et al.*, 2006; Reese and Batzer, 2007). On the other hand, only few researches focused on alluvial soils particularly in Switzerland (Bureau, 1995; Fierz *et al.*, 1995; Guenat *et al.*, 1999; Mendonça Santos, 1999) and even less on social perception of environmental risk in floodplains. An interdisciplinary approach, the *Flood'Alps* project, has therefore been proposed with the general aim of integrating aspects of security, related to the natural system, and the representation of the floodplain landscape.

1.2. The *Flood'Alps* project

1.2.1. Context of the project

In the past, braided rivers were one of the most typical landscapes of the Swiss alpine and pre-alpine valleys, as it was the case in the French Alps (Bravard *et al.*, 1986; Bravard, 1989; Bravard and Peiry, 1993). The dramatic floods, which occurred in the 19th century, caused serious damages and showed the necessity to give up the local and community flood protection systems and to think protection against floods in a more systematic way (Vischer, 1989; Nienhaus, 2002).

The observation of past modifications of the alpine floodplain landscape, the increasing attention devoted to the respect of natural ecosystems, climate change, and the present revolution in agriculture, show that our relations with alpine floodplains are changing. As a general hypothesis, we may summarise the situation as follows, in three periods:

- 1st period, 1850 to about 1970: security and exploitation of resources had priority. The security

principle was a main concern and was opposed to nature conservation. In Switzerland, focus was especially laid on hydraulic security with the development of structures against floods (dikes), alimentary security (extension of agricultural zones) and energetic security (construction of dams). Floodplains were considered as resources needing to be exploited while protecting. The only zones remaining in a natural state were those that could not be exploited for topographical or financial reasons.

- 2nd period, about 1970 to 2000: security was discussed, but still opposed to the natural system. This transition period showed the principle of natural system getting gradually more important: despite a few early trials, the two principles were still opposed. During important floods, the limits of embanking the river in the minor riverbed appeared. Since 1975 floods and inundation events have appeared to increase especially in the Central and Southern Alps (Bader and Kunz, 1998).

- 3rd period, since 2000: security and natural system will be complementary. New ecological or economic constraints lead to break the opposition between the two principles. The maintenance of a natural system must not compromise the security, and inversely the construction of security structures must not affect the natural values of the floodplains, but may help them to be improved. For example: the extension of the floodplain width allows the flood energy to be dissipated on the spot while creating typical biotopes of dynamic floodplains.

Thus, a general hypothesis was emerged tending to establish a change of paradigm currently happening with an opposition paradigm between security and natural system, between 1850 and 2000 approximately. This antagonism conducted to a negative feedback between age-old constructions and biological value of ecosystems. Since 2000, a complementary paradigm between security and the natural system has appeared leading to a positive feedback between age-old constructions and the biological value of the ecosystem.

1.2.2. Methodology

The Flood'Alps project was an interdisciplinary study that tried to understand the evolution of the relationships between these two general principles – security and conservation of biodiversity - between 1850 and 2000 in alluvial valleys of the Swiss Alps, and to provide keys for present and future management decisions. It was part of a National Research Program *PNR48* - Landscapes and habitats of the Alps - supported by the Swiss National Science Foundation (SNF). The Federal Office for the Environment (OFEV) also participated to the funding. Three different disciplines took part in this study:

- *sociology*, whose contribution was indispensable for a general reflection (e. g. in different cultural parts of Switzerland) and inter- or even trans-disciplinarity on the dispositions to take for a management of natural risks,

- contribution of *hydrology* was essential because water management and procedure of protection have been developed and realized through hydrological reactions.

- *ecology* (combining landscape evolution and soil science) was providing a dynamic image of the alluvial landscape of the concerned sites during the two historical periods (1850-1970 and 1970-2000). The ecological studies established the environmental balance of security measures taken and the repercussions of political decisions and social representations. Alluvial soils, reflecting past history and dynamics with phenomenon of sedimentation and erosion, as well as proportion of surfaces of different ecosystems, were used to understand the evolution of our system.

Moreover, research about legislation evolution was carried out in order to understand evolution of law and their organisation depending on the levels of political organisation of Switzerland: local, cantonal, federal. This domain also provided information on the environmental supervision policy and of its success and failure in floodplains.

For the selection of the study sites, the sociological criteria was in first priority, because it appeared essential taking into account the cultural and “so-

cio-psychological” diversity in Switzerland. In order to generalize our results to the Swiss alpine arc, the three cultural regions were taken in consideration and the following sites were chosen (one of them was priority and the others were secondary; fig. 1.1):

Priority site in the North of the Alps: **Sarine River**, between Montbovon and the Lake of Gruyère. This area was chosen because several data sets were already available, mostly on vegetation (vegetation maps according to the federal inventory; Gallandat *et al.*, 1993) and others (Roulier, 1998), as well as on soil science (Bureau, 1995; Weber, 1998; Mendonça Santos, 1999).

Secondary sites in the East-central of the Alps : **Rhine River**, between Thusis and Sargans; and in the South of the Alps: **Ticino-Moesa Rivers**, in the Arbedo area. This site selection was only indicative

and some flexibility was possible for each research discipline.

This project was officially completed in 2005 with the publication of several results particularly in sociology briefly presented below (Nedelcu and Hainard, 2006; Nedelcu *et al.*, in press), as well as in hydrology (Guex *et al.*, 2003) and in ecology and soil science (Augsburger, 2004; Gremaud, 2004; Gremaud *et al.*, 2004; Weber *et al.*, 2004; Dupertuis, 2005; Bullinger-Weber and Gobat, 2006; Bullinger-Weber *et al.*, 2007). A precise research on legislation was made by “*Service conseil Zones alluviales*” (2004) and some elements are presented in the appendix 1. Several aspects related to the application part of the research were treated by the office *Dio-nea SA* in Locarno. The present thesis is an integral part of the soil science and landscape results of the Flood’Alps project.

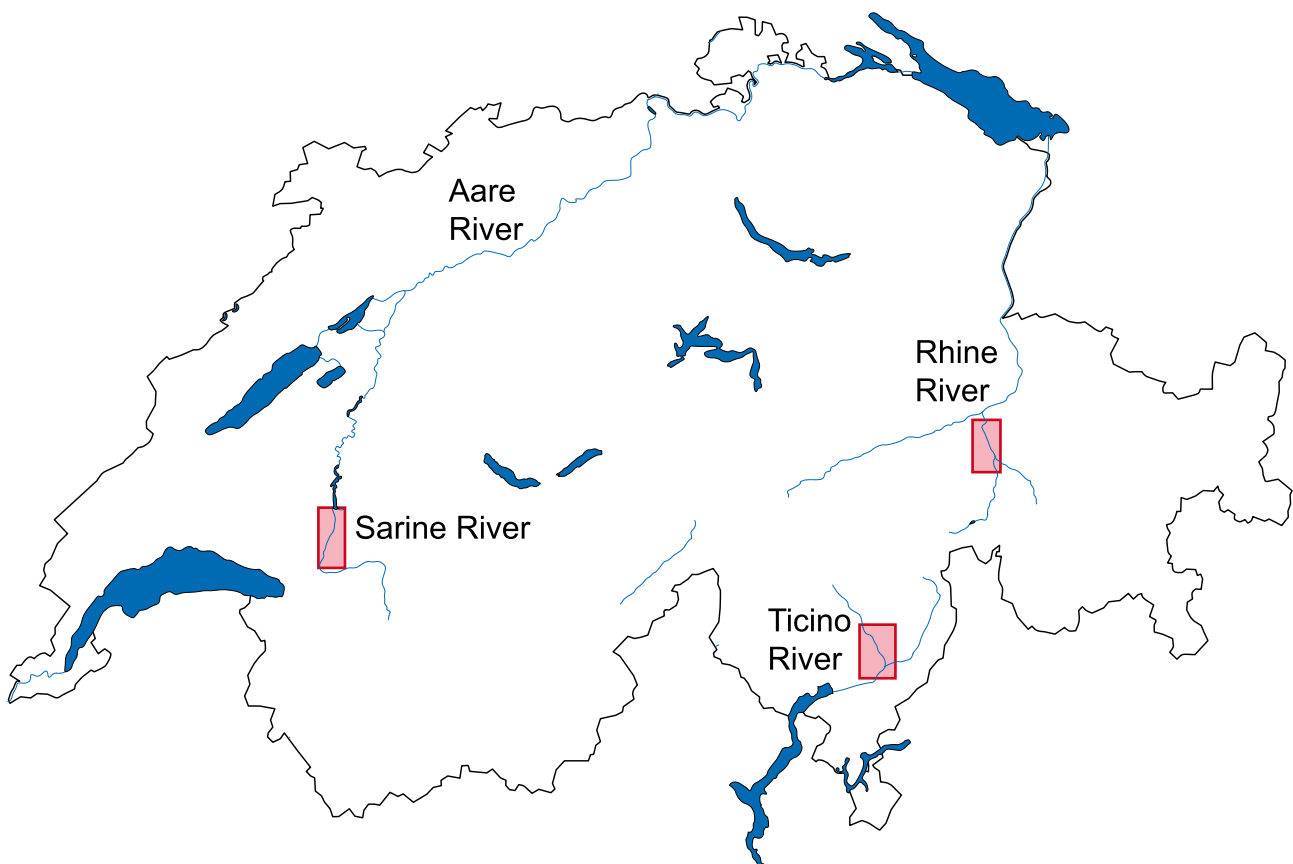


Fig. 1.1. General localisation of the three study areas : Sarine, Rhine and Ticino Rivers.

1.2.3. Sociological perception of risk and security

Some sociological features of the Flood'Alps project are presented here in order to briefly expose the evolution of the social perceptions and the notion of risk, as well as some methodological aspects. The notion of risk induced two elements: hazard and vulnerability (Favier and Granet-Abisset, 2000). Thus, insurance models were developed to manage industrial risk. As a social phenomenon through which social link is expressed, risk became a new manner to reflect the human-nature relationship (Petterti-Watel, 2000; Jodelet, 2001). Technological and scientific progress was at the basis of industrial development of the modern societies. At the end of 19th century, necessity of large embankment projects was socially addressed, not only to protect human lives and goods, but to assure energetic (construction of dams), alimentary (extension of agricultural zones) and sanitary security (disease prevention). Later on, illusion that human can totally control nature had to be faced within emergence of irreversible and/or unexpected damages, leading to new long-term environmental risks (Catton and Dunlap, 1978). With the 1970s and emergence of ecologist movement, it appears that risk may be domesticated, but also that nil risk does not exist (Guilhou and Lagadec, 2002). Urban extension and demographic densification constituted heavy pressures on natural systems implying a split between nature and local populations (Sassen, 2001).

In the framework of the Flood'Alps project, the sociological aspect consisted of a better knowledge of the socio-economic sources of the floodplain transformations. Landscape and social risk representations (Jodelet, 1989) were investigated by a complete analysis of the sociological literature (risk and environment sociology), and by qualitative interviews for a better understanding of the "rationality" of the social and scientific responses to natural and environmental risks. Moreover, scenarios were constructed and proposed to the different actors in order to locate potential attitudes and behaviours towards risk (Nedelcu and Hainard, 2004). Pictures were also presented to the speaker to get some more comments.

Semi-directive interviews were made in the three studied areas with 38 persons, and about 20 of them were decision-makers and professionals. People in direct contact with alluvial zones were preferred (residents, actors – for a professional or leisure reason). Moreover, the cultural background was taken into consideration, principally the language. Data from the three study sites were analyzed simultaneously in order to compare and detect the convergent tendencies. More precise information about the methodology is given in Nedelcu and Hainard (2006). In the context of this thesis, the sociological results are not exposed, but they may be consulted in two recent publications (Nedelcu and Hainard, 2006; Nedelcu *et al.*, in press). The present thesis follows a comparable methodology with the selection of the same study areas and a common aim to generalize the tendencies to these three regions.

1.3. Objectives of the thesis

This research deals with four main topics related to the Flood'Alps project hypotheses, following a gradient of organisation levels in floodplains. In this multi-level scale environment, it appears relevant to have a multi-level scale approach, from general interdisciplinary study on landscape to particular specialized processes of soil structuring (fig. 1.2). Moreover, it has been shown that in order to study the role of soil in ecosystems, it is necessary to study it at different scales from the biogeographical region to the selected microsite (Auger *et al.*, 1992)

Firstly, it appears important to answer the question, how floodplain landscapes have evolved for about 150 years at the catchment area scale and what have been the consequences of the numerous human impacts on alluvial zones?

Secondly, it is essential to understand how soils, reflecting past history and dynamics, have been formed and evolved, and what have been the consequences of human impacts on them? At this floodplain level, the following question is also raised: what are the differences between the three study areas?

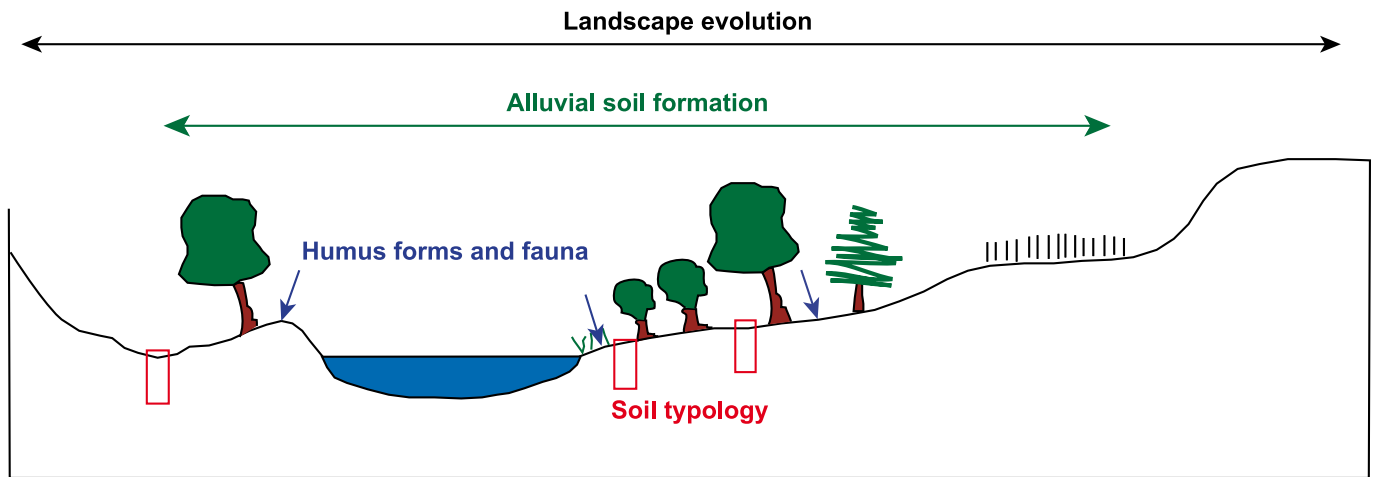


Fig. 1.2. Schema of the multi-level scale environment of alluvial zones and the thesis approach, from general interdisciplinary study on landscape to particular specialized processes of soil structuring.

Following this, it also emerged importantly to identify the present-day state of the soil, at the station level, and to understand what was happening in depth in terms of sedimentologic, as well as pedogenetic processes. A descriptive typology based on the identification of pedological parameters permits to detect the different events happening in the study area.

Finally, as alluvial soils are considered as young soils depending on a complicated genesis (interaction between inheritance and *in situ* evolution) and situated in a heterogeneous environment (i.e. herbaceous vegetation, tree population, alluvium) it appears important to investigate, at the microsite level, the mechanisms influencing alluvial initial soil formation (biologically and chemicophysically) and to answer the question, how does soil formation evolve, particularly at the humus form level, in relation with the different sediment deposition?

1.4. Thesis layout

This thesis manuscript is arranged in six chapters:

Chapter 1 is the current one and introduces the context, objectives and framework of this research.

Chapter 2 reviews the state of the research in the floodplains and alluvial zones, and describes the research sites concerned with their historical and landscape evolution.

Chapters 3 and **4** are the body of the document corresponding to three publications (one is already published - Bullinger and Gobat, 2006 - and the other ones are in preparation). They deal with the comprehension of alluvial soil formation at the level of the main study site – Sarine River – as well as the level of the three study areas (chapter 3), and at a finer scale level with the soil typology of the Sarine River (chapter 4).

Chapter 5 focuses on humus forms in order to understand the very first steps of alluvial soil formation (results have already been published in Bullinger-Weber *et al.*, 2007).

Finally, **chapter 6** synthesizes main contributions, limits and perspectives of this research.

2. Floodplain landscape evolution in Sarine, Rhine and Ticino Rivers

2.1. Introduction

The study of historical channel changes is an important part of understanding fluvial systems (Winterbottom, 2000). By appreciating the past, we can evaluate the impact of human development on river form and character and understand actual channel dynamics. The numerous historical studies of European rivers show similar changes (e. g. Petts *et al.*, 1989; Marston *et al.*, 1995; Lorenz *et al.*, 1997; Spaliviero, 2003; Ward *et al.*, 2002). Mountain and piedmont area streams were distinguished by their intense hydrodynamic activity. This process was aggravated by slope destabilisation due to agricultural and grazing activities. Between 14th and 19th century rivers were characterised by high rates of erosion and aggradation leading to the development of braided channels and were in a state of disequilibrium (Bravard *et al.*, 1997). During these centuries floods did not spread out regularly, and it has been notified that the European Alps suffered of a recrudescence of floods during the 19th century.

In Switzerland before the 18th century no systematic water level measures were made except on particular sites like bridges or bank walls (OFEG, 2003). The 18th century marked a turning in the way of looking at water. The discharge rates were then measured and the look at natural environments evolved. Indeed, with the development of scientific knowledge, the societies gradually tried to control nature. Social

representations related to water progressively changed and guided the water management. The increase of floods during the 19th century, causing inundations and formation of marshy zones and with it the apparition of malaria, coincided with the increase of the Swiss population. The need of protection, in order to defend lands and goods, became a priority at the scale of the entire territory. Thus, since the 19th and 20th century, the trend of instability was reversed in many river systems due to human intervention, like canalization, flow regulation and gravel extraction. Channel narrowing and incision were the main results of these impacts and lead to an increased isolation of rivers from their floodplains (Winterbottom, 2000).

Swiss alpine rivers were not excluded from these processes and were also canalized and submitted to perturbation, such as hydro-engineering. Indeed, the water of numerous small tributaries in the Swiss Alps has been used for hydropower generation, by abstracting water and re-directing it into other sub-catchments (Brunke, 2002). Tributaries were thus affected and showed a significant reduction of the discharge regime. The notion of security had then priority and these works were based on the principles of prevention that reinforced the feeling that nature can be controlled. Anthropogenic pressures on floodplains became aggressive for nature and provoked a

drastic reduction in their natural functions, as well as a decrease in their surfaces.

With the awareness that humans have extensively altered river systems, a better knowledge of floodplain and alluvial zone landscape evolution is quite relevant. Riparian landscapes examine the ecological systems of streamside and floodplain areas for the perspective of landscape ecology (Malanson, 1993). Landscape ecology is based on the hypothesis that interactions among biotic and abiotic components of the landscape are spatially mediated. This definition includes the notions of flows of energy, material or species, as well as interactions between these components. Such concept implies an approach to the study of the environment that emphasizes complex spatial relations and was not possible in the current research because of time and cost limits. Thus, only a very simple approach taking in consideration historical facts and events leading to modifications in the river system, and evolution of the risk notion, were questioned at the level of the study section areas.

2.1.1. Floodplains

Floodplain areas are ecotones forming a transition between aquatic and terrestrial environments. They are characterized by complex ecological systems and are dynamic spatial mosaics, more or less connected with the active channel of the river. These lateral connections are essential for the functioning and integrity of a floodplain (Thoms, 2003). The various landscape patches induce a hierarchical system that can be considered at different levels. Thoms (2003) also reported that many floodplain management strategies often fail to provide scientific knowledge at the appropriate scale.

The fluvial hydrosystem is defined as a *eco-complex* and may be viewed as a nested hierarchy of subsystems with different levels controlled by different rates and types of processes (Petts and Amoros, 1996). Five distinct levels are then described: the *drainage basin*; the *functional sectors*, delimited by changes in valley width and gradient due to different flow, water-quality and sediment regimes draining subbasins of different geological,

climatic and biogeographical character; the *functional sets*, defined as sections of typical ecological units; the *functional units*, characterized by a typical plant and animal community; and the *mesohabitats*, subdivisions of functional unit.

2.1.2. Alluvial zones

As a floodplain, whatever its current occupation, includes the whole valley floor setting up by processes of fluvial sedimentation and erosion, the alluvial zone represents the part of the floodplain always under influence of the stream, more or less directly (fig. 2.1). Steiger *et al.* (2005) use the term “riparian zone”, which can be considered as a synonym to alluvial zone, and define it for stream ecosystems in a functional view. They focus on the linkages between terrestrial and aquatic ecosystems in the context of fluvial landforms and the hydrogeomorphic processes that form them. In French the term “*zone riveraine*” is used for a larger zone including not only stream and river banks, but also lakeshores, and is associated with all types of watercourses including swamps, wetlands, tributaries, side channels and intermittently wetted areas.

In unmanaged systems, the riparian zone represents highly dynamic areas within the fluvial landscape, but these zones are often coveted by numerous conflicting activities (e. g. agriculture, tourism, urbanization...) leading to significant modifications of riparian zone structure and functioning by riverine societies. However, Naiman and Décamps (1997) precise that the spatial extent of the riparian zone is difficult to delineate precisely because of the heterogeneity of the different patterns related to variable conditions of the fluvial processes. Moreover, this delimitation is especially complex in terms of biological functioning with longitudinal and lateral connectivity and organism movements.

The following paragraphs present thus the geographical context in which floodplains and alluvial zones are studied in the case of this research, as well as the landscape evolution of the chosen sites.

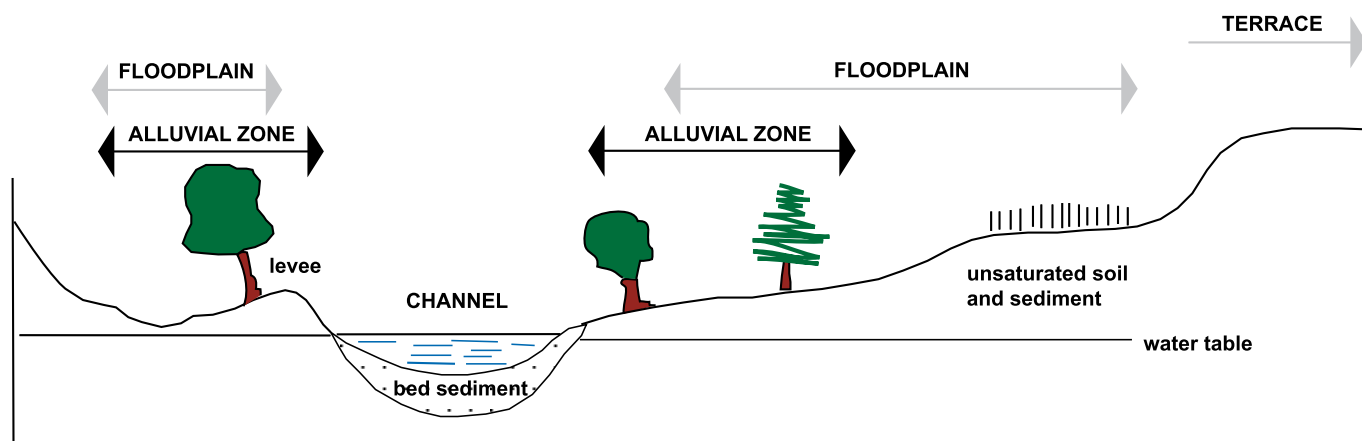


Fig. 2.1. Schematic diagram of the lateral floodplain system (modified from Steiger *et al.*, 2005).

2.2. The Sarine River site

This paragraph presents the main study site (Sarine River), by its general characteristics, hydrological parameters, as well as historical and landscape evolution. A brief description of the two other sites (Rhine and Ticino Rivers; see 2.3.1 and 2.3.2) is also included in the following paragraphs. These three sites were selected principally for the sociological research of the Flood'Alps project in the three principal cultural regions of Switzerland to study their diversity and similarity (see 1.2). Thus, the same sites were used for the soil survey with two in the North part of the Swiss Alps and one in the South part.

2.2.1. General description

The main studied site is located along the Sarine River in the Intyamou valley between Lessoc (770 m asl) and the Gruyère Lake near Broc (670 m asl; in the canton of Fribourg; fig. 2.2 and 2.3). It is situated in the North Western of the Swiss Alps and is a tributary of the Aare River, which flows into the Rhine River. It follows from its source to the confluence with the Aare River a 78.9 km course (Mendonça Santos, 1999), and crosses different cantons (Bern, Vaud, Fribourg).

This area was chosen because two types of character are present: a human altered alluvial site, where the alluvial character of the vegetation is changing, and an active zone, where processes of

erosion and sedimentation still take place in spite of various human impacts occurring upstream (e. g. presence of dams). This active zone (called sometimes also “natural zone” in the text) may be defined as a system of restoration of the balance of alluvial processes integrating anthropogenic aspects of the catchment area. In these particular sectors, sedimentation and erosion processes are sufficiently active to ensure the permanence of an active alluvial system.

Furthermore, the availability of data and the easy access make this site particularly interesting for our research. Several studies have already been undertaken on this river, in particular on vegetation (Gallandat *et al.*, 1993; Roulier, 1998; Gremaud, 2004; Dupertuis, 2005) and on soil (Bureau, 1995; Fierz *et al.*, 1997; Weber, 1998; Mendonça Santos, 1999; Kayumba, 2000; Augsburg, 2004; Bullinger-Weber and Gobat, 2006; Bullinger-Weber *et al.*, 2007; Morier, 2006).

The source of the Sarine River is located at the Sanetsch glacier, a calcareous and marl rock region (Wildhorn nappe). But it crosses a region constituted of a conglomerate of sandstone and schist with some layers of fine limestone in the Prealps domain (Gétaz, 1977). The alluvial gravel of the study area is thus constituted essentially of calcareous pebbles (Mendonça Santos, 1999).

The length of the study section is 12 km with an average slope of 6.4‰. The catchment area covers 639 km² with an average altitude of 1520 m asl.

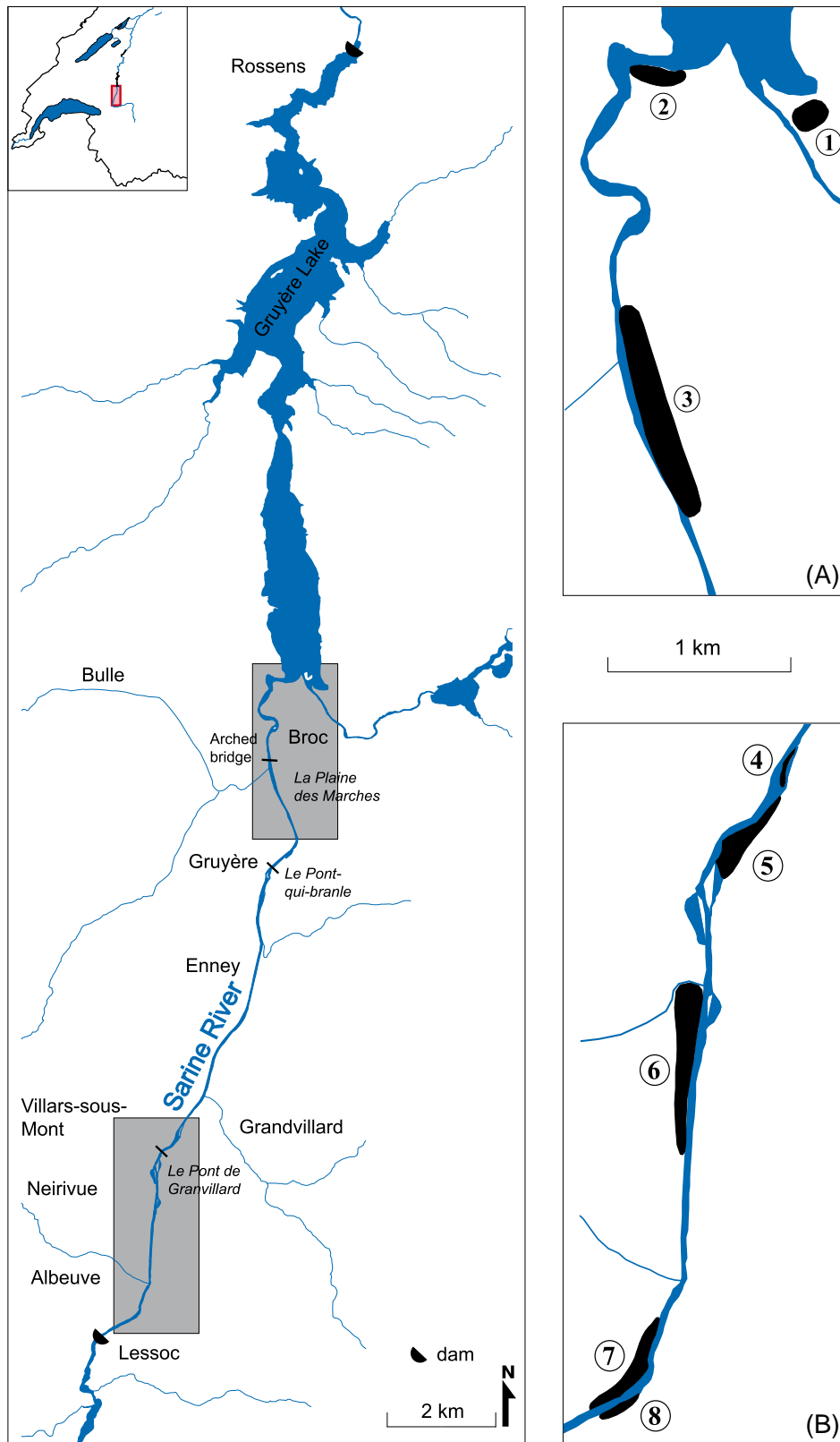


Fig. 2.2. Localisation of the two major study areas of the Sarine River: A) downstream area of Broc (sites 1 to 3); and B) upstream area between Lessoc and Grandvillard (sites 4 to 8).



Fig. 2.3. View of the upstream part of the Sarine River site from Villars-sous-Mont.

The hydrological regime is an intermediate nival regime. From 1923 to 2006, the mean annual discharge in the measuring site of Broc was 23.6 m³/s (fig. 2.4) with a maximum flow rate in May and a minimum in January. The climate is prealpine with a measured annual precipitation mean of 406 mm between 1970 and 2003 (maximum of 52 mm in summer and minimum of 23 mm in winter; fig. 2.5) and an average annual temperature of 7.1°C (minimum of -2.1°C in January and maximum of 16.5°C in July; Bureau, 1995).

For the landscape study, an entire section between Lessoc dam and the bridge “Le Pont-qui-Branle” was selected (fig. 2.2). For the soil survey research presented in chapter 3, two different sections were chosen inside whose eight distinct zones were surveyed (see detailed descriptions in 3.3.1). Inside these two sections, different spots were selected for the soil typology (14 soil profiles, see fig. 4.2 in

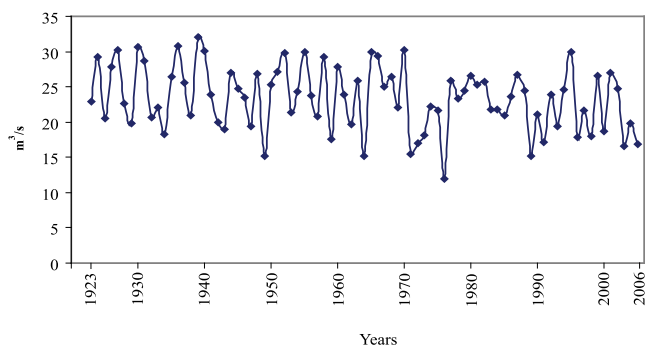


Fig. 2.4. Annual mean flow in m³/s from 1923 to 2006 at the measuring site of Broc (Château d'en bas; source: Hydrological data, OFEG).

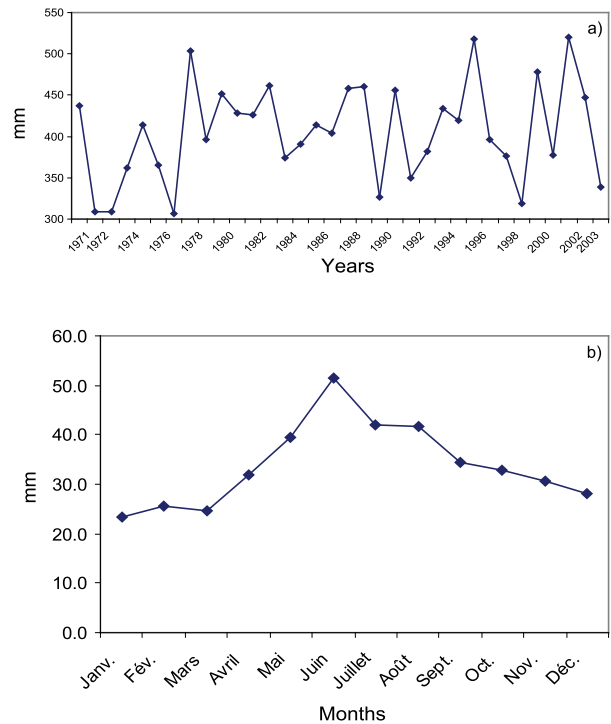


Fig. 2.5. Annual (a) and monthly precipitation mean (b) in mm (source: WSL, site of Broc, Château d'en bas. Data produced by Martine Rebetez).

4.2.1). Finally, soil structuring research presented in chapter 5 was carried out in the area of Grandvillard (sites 4 and 5 in fig. 2.2; see 5.2.1).

2.2.2. Geomorphology

All the study zones are situated on the low terraces only a few meters above river level (from 50 cm to 2 m) and in a distance of few meters to about 100 m from the main river channel. The total thickness above basal gravel varies slightly throughout the study area, but these variations should not affect the results. The geomorphology of the study section is characterized by a succession of alluvial basins separated by rocky constrictions (Mendonça Santos *et al.*, 1997), but some geomorphological particularities are observed.

Precise information is given for the studied zones that were chosen for the soil survey (see 3.3.1). For example, before the construction of the Rosens dam and the formation of the Gruyère Lake in 1948, the sites 1 and 2 (see (A) in fig. 2.2) were formed of gravel bars colonized by pioneer annual herb communities or willow shrubs covering the

entire base bed of that part of the valley. Nowadays, and despite an artificial origin due to the dam, this area is characterized by a dynamic system of slow velocity river and lake environments with slow sedimentation.

Before the embankments started after 1960, site 3 named “*La Plaine des Marches*” was still regularly inundated and during floods the zone appeared like a small “lake” (called “Lake of Broc” by the local population; fig. 2.6). This section is nowadays constituted of flat fields laid on a gravel substrate (fig. 2.7). About the upstream area, the site 4 (see (B) in fig. 2.2) is situated on gravel bars colonized by willow shrubs for about 20 years. Differences in micro-geomorphology are visible inside this site: natural levees and channel fills. The site 5 is also located in an active environment, but the colonization by tree population has started for 20 to 100 years. Micro-geomorphological conditions are

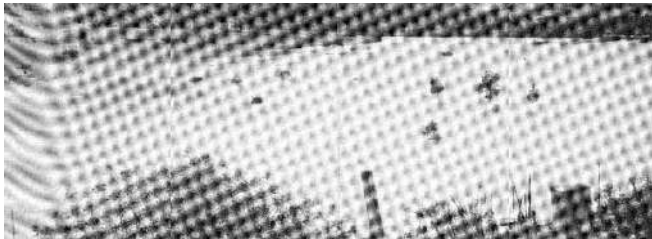


Fig. 2.6. “*La Plaine des Marches*” inundated after a flood (around 1940). Until 1960, Sarine River overflowed regularly forming the “Lake of Broc” (source: Bugnard, 1987).



Fig. 2.7. View of the actual “*La Plaine des Marches*” (with the Gruyère castle behind plane on the right).

also contained inside the site: natural levees, active or abandoned channel fills. Site 6 is situated under a mature forest, but with different morphological characteristics such as abandoned channel fills and natural levees. Sites 7 and 8 are now closed to the main river channel and do not show any particular features.

2.2.3. Vegetation

The different types of vegetation are shown on the vegetation map according to the federal inventory for the site “*Les Auges de Neirivue*” (appendix 2; object n° 66 of the inventory of alluvial zones of national importance; Gallandat *et al.*, 1993). The embanked zone (lower part of the map at the level of Albeuve and Neirivue) is dominated by vegetation called “other alluvial forest with indeterminate status” (unit 16.1) on the left side of the river (mostly spruce, ash, planted poplar), as the right side is composed of “non-alluvial forest” (unit 16.2). The active zone (upper part of the map at the level of Grandvillard) consists of a mosaic of draped willow forests (*Salicetum elaeagno-daphnoidis*, unit 6.1; eutrophic variation, unit 6.3; and brushes of draped willow and thermophilous species, unit 6.4) with white alder forests (unit 8), some patterns of eutrophic variation (unit 8.4), and patterns of other alluvial forests with indeterminate status (unit 16.1) or non-alluvial forests (unit 16.2).

For the site “*Les Auges d’Estavannens*” (appendix 3; object n° 65 of the inventory of alluvial zones of national importance; Gallandat *et al.*, 1993), the upstream part is mostly covered by unit 16.1 (other alluvial forest with indeterminate status) and the downstream section by a mixing of planting in alluvial zone (unit 18.1), clearing in alluvial zone (unit 18.3), other forests (units 16 and 16.1), as well as small patterns of alder forest and riverine forests (units 10 and 12).

A third object of the federal inventory “*Broc*” (appendix 4; object n° 64 of the 2nd complement of the inventory of alluvial zones of national importance; Thielen *et al.*, 2002) is included in our study section and located on the shore of the Gruyère lake. On the right bank of the Sarine River, its vegeta-

tion is described as white willow riparian forests (*Salicetum albo-fragilis*, unit 7.1) with bushes of different willows (*Salix viminalis*, *S. triandra* and *S. purpurea*; *Salicetum triandro-viminalis*, unit 7.2) and wide areas of *Phalaris arundinacea* (low marsh, unit 5 Par; Gremaud, 2004). On the right bank of the Jogne River, vegetation consists of a mosaic of white willow forests (unit 7.1), bushes of willows (unit 7.2), low marsh with *Phalaris arundinacea* alone (unit 5 Par), and mixing with nitrophilous annual vegetation (*Bidentetea tripartitae*, unit 4.3/5). The deposition of fine sediments (clay and silt) during the first years after the creation of the Gruyère lake permitted the white willows to colonize a small surface in 1958 and in 1960. The second white willow cohort has installed only from the beginning of the 1980', when a change in water level regulation occurred (Gremaud, 2004). The surface of the willow riparian forest has then increased rapidly to about 40 hectares in 2000 and became one of the widest white willow forests in Switzerland at that altitude.

2.2.4. History, landscape evolution: data collection and analysis

In this study, only some precise historical events were taken in consideration and analyzed. The aim of our study was not a complete review of the Intyamou valley history. Information about the historical evolution of the Sarine River was principally based on literature (Gétaz, 1977; Bugnard, 1987; Cochard *et al.*, 1988; Märki, 1993), as well as on a map of the canton of Fribourg drawn by Alexander Striensky between 1844 and 1851. Different hydrological data were also presented, as well as a summary of the embankment events (Guex, 2004). The plans of the embankments achieved in the study site between 1917 and 1974 were digitized by Dupertuis (2005).

The data concerning the landscape was principally based on the results of a Master diploma (Dupertuis, 2005). A set of six aerial photos taken in 1930, 1943, 1955, 1969, 1980 and 1998, were used to study the spatio-temporal modifications of landscape between the dam of Lessoc and the bridge "Le Pont-qui-Branle" (fig. 2.2). These aerial

views were digitized and treated in Geographical Information Systems (GIS) software (ArcView GIS 3.3 and ArcInfo 9, ESRI).

The surfaces of the different vegetation types were mapped and calculated in order to obtain information on the evolution of the Sarine surroundings. A 500 m wide strip covering the whole flooded area of the river was defined. Inside this perimeter, different types of vegetation and landscape units detectable on the aerial views were mapped as described in fig. 2.8. The protocol used for the cartography of alluvial zones of national importance was adapted to the data (Thielen *et al.*, 2003). The detailed method is given in Dupertuis (2005).

Cartography units	Code
Agricultural area	0
Water	1
Sediments	2
Tributaries and their floodplain	3
Grass	4
Softwood	6
Plantations and wood cuts	7
Hardwood	8
Non-alluvial forest	10
Gravel pits	11
Buildings (houses, etc.)	12
Military zone	13
Sporting installations	14
Other disturbances	15
Camping	16

Fig. 2.8. Different vegetation types and landscape units detectable on the aerial views (from Dupertuis, 2005). Softwood unit represents forests whose tree wood is characterized by a relatively low hardness (e. g. willow, alder, poplar), when hardwood unit defines species whose wood presents a relatively high hardness (e. g. elm, ash, beech).

2.2.5. Historical evolution

Since the 18th century, the landscape of the Intyamou valley was modified by clearings in order to gain lands for pastures, meadows and fields. At that time, the Sarine River was a real braided river consisting of a number of channels separated by mobile gravel islands. The first idea of embanking the Sarine River appeared in 1825 and the initial plans were drawn in 1842. Between 1844 and 1851, the earliest topographic map of the canton of Fri-

bourg was made at the 1:25'000 scale by Alexandre Strienski showing for the Intyamou valley a typical alluvial dynamic with five parallel channels (appendix 5).

As the extraordinary floods of the Sarine River had for a long time destroyed roads, habitations and agricultural fields, the canton of Fribourg instituted in 1852 the cantonal law regulating the swamp drying, river correction 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, after the institution of the federal law of water policy in 1877. The first project about the general embanking of the Sarine River arose in 1897, called “General embankment of the Sarine river from the cantonal limit of Vaud to the cantonal limit of Bern” (original name: “*Endiguement de la Sarine de la limite cantonale vaudoise à celle bernoise*”), and consisted of two plans divided in several sections (Guex, 2004).

The very first embankments were built between upstream of Enney and the bridge of Estavannens in order to stabilize the gravel bars and the banks against erosion (appendix 6). These transverse dikes or break water heads (“*éperons*”) were constituted of pebbles fixed together (“*gabions*”) and were from 30 to 40 meters spaced out. The second ones were built between the bridge of Estavannens and the bridge “*Le Pont-qui-Branle*”, and corresponded to 500 m of longitudinal dikes on the right banks of the Sarine River (Guex, 2004). Then, a mixing of longitudinal dikes and break water heads was constructed between “*La Plaine des Marches*” and the arched bridge of Broc (see fig. 2.9). Finally, new dikes were also created just upstream the confluence with the Jogne River. These engineering works were not the product of a common effort between the different villages, but the result of private effort to protect one’s land against flooding erosion without any collaboration (Dupertuis, 2005).

The planned embankments began during the World War I and were conducting up to 1938. In practice, these works were started between 1910 and 1920. In 1916 authorities adopted the first systema-



Fig. 2.9. Arched bridge of Broc (anonymous lithographic between 1750 and 1870; source: Bugnard, 1987).

tic general plan for the Sarine River with the aim of preserving the riverside fields against floods and bank erosion. This decision was the consequence of the catastrophic flood of 1913, which necessitated immediately huge works to strengthen the Sarine riverbanks. A general diking and canalization with one pair of continuous and unsinkable dikes were made to collect the flows in a single uniform channel. The main aim was to protect the existing farming land and forests of the communes and gain some others if possible. The consequences were the narrowing of the potential river divagation and the riverbed incision. In 1938, almost the whole stretch between the bridge of Lessoc (nowadays Lessoc dam) and the Grandvillard bridge was embanked (appendix 6; Dupertuis, 2005).

After the 1944 flood, a further embankment project was led to reconstruct the damaged structures and to build new ones. These works were made between 1944 and 1954. Violent floods (July and September 1968, and 1970, in particular) caused other damages and shattered again drastically these works, and almost the whole lengths of embankments had to be rebuilt between 1968 and 1974. As a result, in 1974, the 70% (about 13 km) of the riverbanks were embanked. The dyking of the Sarine River was originally planned to be achieved in 20 years. However, the frequent floods and the

increased building costs delayed the developments in the Gruyère valley (Gétaz, 1977).

So, during almost 40 years, the Sarine River was progressively straightened and disconnecting from their floodplain (fig. 2.10). The creation of a serie of dams in the upstream part of the watershed (dams of Rossinière and Lessoc) led to important sediment retention and caused the total disappearance of a very dynamic floodplain. These corrections played more the role of domestication of water than defence against floods, and appeared to be the paradigm of security for floodplains in most of the country. *The stake was more to dominate rivers than really isolate them*, but the consequences of these buildings were traduced by a modification of traditional practices in the way of a distance between rivers and local populations. The split appeared at different levels and was first visual and esthetical, then social, and finally ecological (Nedelcu and Hainard, 2006).



Fig. 2.10. View of a straightened stretch of the Sarine River from the Lessoc dam.

2.2.6. Landscape modifications

From a regional development point of view, the study area has evolved a lot since the middle of the 19th century. Due to population growth, the effective agricultural area has increased rapidly, mainly the meadows. This increase was possible because of the development of the uncultivated areas, the embankment improvements, the drying of marshy zones, or clearances (synthesis in appendix 7). After deduction of the uncultivated, built and aquatic surfaces, the study area is composed nowadays of forests (about half of the surface), meadows (a quarter of the surface) and pastures. So, the “SAU” (“Surface Agricole Utile”, effective agricultural surface) has doubled in two centuries (Bugnard, 1987).

The increase of the population also provoked an increasing demand of timber and firewood. During the 19th century, the deforestation appeared first in the upper mountains and caused catastrophic floods. The transport of trunks down the slopes caused such disruption to the soil that aggravation of erosion and mud flows were observed. Moreover, floating, consisting of leaving the cut trunks to the current, which guided them along its course, appeared. This practice did not cause particular flooding, but seemed to increase erosion in steep sections (OFEG, 2003). Floating was used on the Sarine River at the end of the 19th century (fig. 2.11) and permitted to transport, at the beginning of spring, the trees cut during the winter. The damages caused to the banks, as well as to the railroad and the road development, explained the progressive restrictions to this transport method, and the last permitted floating on the Sarine River happened in 1914.

The aim of the flood protection structures was principally the preservation of the agricultural surfaces against floods and erosion. The main impact of these constructions, which have occurred since the end of the 19th century (synthesis is given in fig. 2.12), was the disappearance of multiple channels replaced by one single channel and the progressive colonization of gravel surfaces by vegetation. The changes observed in the floodplain landscape



Fig. 2.11. Floating on the Sarine River at the end of 19th century (source: Cochard *et al.*, 1988).

between 1851 and 1998, based on the study of seven maps (Striensky map and six aerial views), may be described as follows (appendixes 5 to 8; Dupertuis, 2005):

In 1851, the Sarine River had a typical braided system with multiple channels and islets formed by gravels and sediments (appendix 5).

In 1930, the embankments were recent and appeared on the aerial view. Alluvial vegetation was still present and composed almost only of softwood forests and gravel bars. However, since 1851, important surfaces of alluvial forest have been cleared on the border of the floodplain and were replaced by fields (e. g. on the right bank at the level of Grandvillard and on the left bank between Villars-sous-Mont and Enney; appendix 8).

In 1943, alluvial vegetation still covered the main part of the floodplain, but softwood forests have progressively replaced the herbaceous vegetation. For example, a former oxbow at the level of Albeuve, isolated from the river by the embankments, had been covered with vegetation (fig. 2.13). Some additional surfaces of forest had been cleared near Estavannens on the right bank and on the level of Enney on the left bank (appendix 7). Moreover, a little military house had appeared on the right bank close to Grandvillard (appendix 9).

On the view of 1955, a part of the floodplain forest on the right side in Estavannens had been cleared and the military zone of Grandvillard had expanded. The embankments, visible in 1943, were covered with vegetation. In “*Les Auges de Neirivue*”, remained active after the important floods of 1944 and 1950, alluvial forests were eroded and the main channel changed its pattern and flowed

Year	Chronological events
1880-1890	First projects of a systematic embankments
1913	Flood that caused riverbeds destruction
1916-1954	General embankments
1944 and 1956	Floods that implied reconstruction works
1968	Catastrophic flood that caused dikes destruction (7 km) and reconstruction
1973	Construction of Lessoc dam

Fig. 2.12. Main constructions occurring since the end of the 19th century (source: Guex, 2004).



Fig. 2.13. View of the former oxbow near Albeuve and replaced nowadays by meadows.

around an island barely covered with riparian vegetation (appendix 10).

In 1969, the hardwood forests covered the same surface as the softwood forests, while sediments and herbaceous areas had greatly decreased and were limited to the areas closer to the water channel. Constructed surfaces appeared and replaced the agricultural lands. In “*Les Auges de Neirivue*”, the first poplar plantations became visible and took the place of a small part of alluvial forest. The damages caused by the major flood of 1968, on the opposite bank of the camping of Enney for example, were visible. The average incision had reached values as high as 2.15 m in “*Les Auges de Neirivue*” and 2.61 m in “*Les Auges d’Estavannens*” with a maximal incision of 5.3 m at the level of Enney since 1916 (Weber *et al.*, 2004). A camping had appeared on the Enney territory at the edge of the floodplain forest (appendix 11).

On the view of 1980, the hardwood forests covered the major part of the floodplain, sediments and herbaceous vegetation had almost disappeared. In the region of Grandvillard, the surface of gravel pits and the military zone on the right bank had increased, but in the active part of “*Les Auges de Neirivue*”, an island had appeared partly covered with softwood vegetation (fig. 2.14, on the left). The construction of the dam of Lessoc (fig. 2.15) had been achieved since 1973 and implied changes in the pattern of the river (appendix 12).

On the 1998 photo (considered as current state), the river still run in the 30 m wide rectilinear



Fig. 2.14. View of the active part of “*Les Auges de Neirivue*” near Grandvillard.



Fig. 2.15. View of the Lessoc dam.

channel defined by the embankments. Within the active part of “*Les Auges de Neirivue*”, the island was covered only by softwood vegetation and had not really changed since 1980. Residential areas had increased, replacing farming land. Four football pitches were also established: one on the right bank, close to “*Les Auges de Neirivue*”, two on the territory of Grandvillard beside the military zone and one on the territory of Enney. The gravel pit beside the military zone was also much extended (appendix 13).

After 1998, only field or bibliographic considerations can be given. An important flood in January 2004 with a flow discharge peak at 380 m³/s (fig. 2.16) happened, and coarse sediments and woody debris (fig. 2.17) were deposited particularly on the

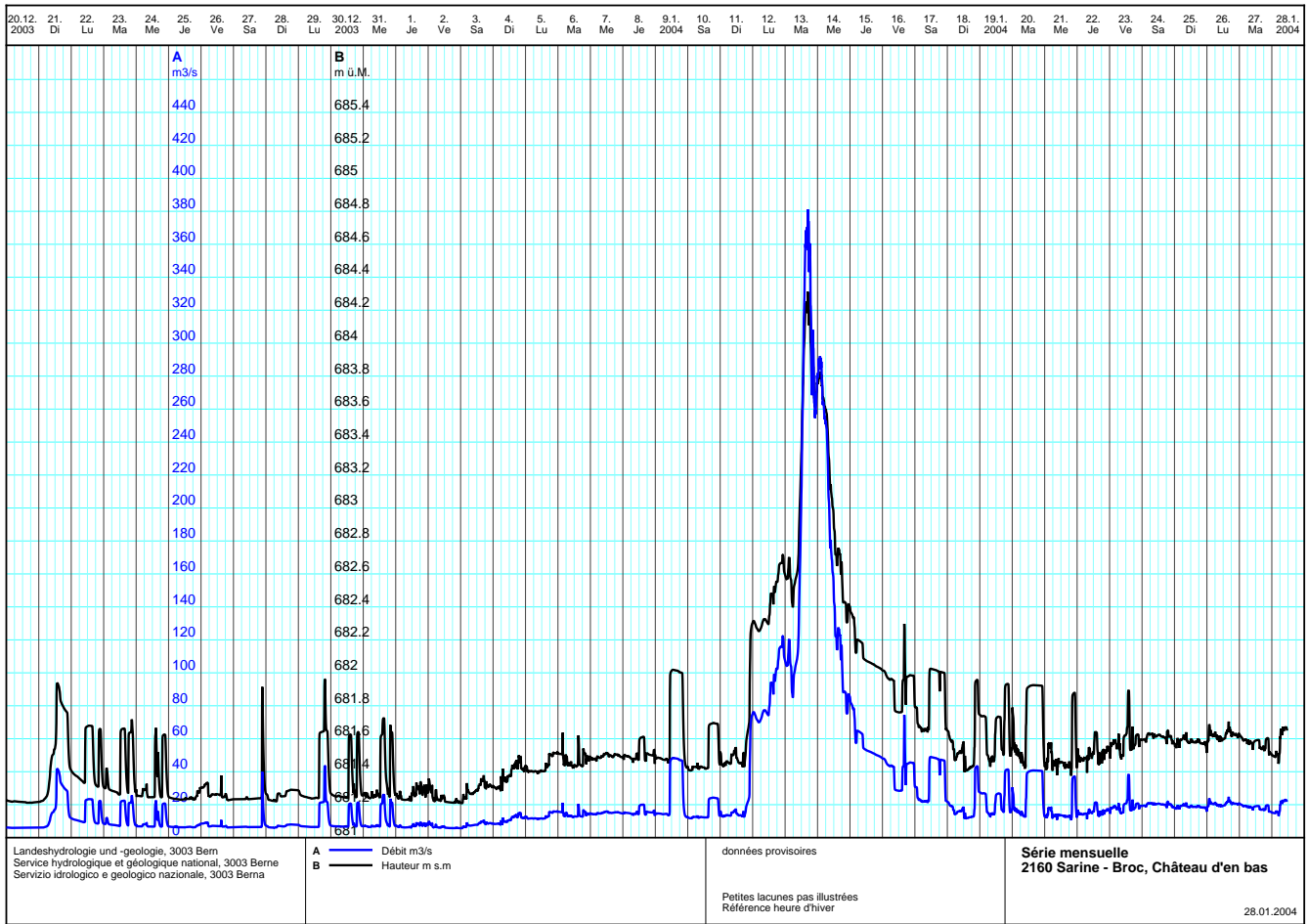


Fig. 2.16. Flow in m³/s at the measuring site of Broc from December 20th 2003 to January 28th 2004 (Château d'en bas; source: OFEV, <http://www.hydrodaten.admin.ch/f/index.htm?lang=fr>).

island in the active part of “*Les Auges de Neirivue*”. These thick deposits were coarse (18 cm of coarse sand; see soil profile 9 in 4.3.2) that demonstrated



Fig. 2.17. Woody debris deposited during the flood of January 2004 (photo J.-M. Gobat).

a violent inundation (fig. 2.18). No damages were observed. Moreover, another violent flood took place on 22nd August 2005 particularly intense in Fribourg city downstream the Rossens dam. This phenomenon was also observed in Europe and hit mainly Romania, Switzerland, Austria and Germany, as well as several other countries in Central and Eastern Europe during August 2005. The Swiss capital of Bern was also heavily hit after the Aare burst its banks. The town of Brienz saw 400 residents evacuated. The village of Lauterbrunnen in the Bernese Alps was completely cut off. Six people died in Switzerland when only material damages were observed in the Sarine region. The total damage costs have reached more than 3 billions francs in Switzerland.

Parallel with ecosystem and landscape evolution, the industrialization occurring since the end of the 19th century causes social modifications among



Fig. 2.18. Coarse sediments deposited during the flood of January 2004.

others in nature and risk perception. The fatalistic attitude gives up to anthropocentric vision of nature and the notion of risk appears with two prevailing elements: hazard and vulnerability (Weber *et al.*, 2004). The risk management falls on technicians and a prevention model is developed, based on the idea, that the nature could be controlled by the scientific and technological progress (Nedelcu and Hainard, 2006). New laws are enacted at both federal and cantonal level and allow huge river training works, socially addressed. They are undertaken not only to protect human lives and goods, but also to assure energetic and alimentary security.

Thus, between 1850 and about 1970, focalisation was exclusively made on security. At the end of this phase, new environmental concerns appeared with the emergence of irreversible and/or unexpected damages, leading to new long-term environmental risks.

2.3. The Rhine and Ticino River sites

2.3.1. The Rhine River

The second site is situated in the East-central Alps area along the Upper Rhine River between Thusis (670 m asl) and Bonaduz (600 m asl) in the Domleschg valley in the Canton of Graubünden (fig. 2.19 and 2.20). The entire length of the Rhine River from its source to its confluence with the North Sea is about 1320 km. It is one of the longest and most important rivers in Europe, crossing nine countries (Pinter *et al.*, 2006).

It was principally selected because it presents two important similarities with the Sarine River: an embanked (fig. 2.21) and an active part (fig. 2.22). Once again, this denomination of active part means that, in spite of various human impacts, sedimentation and erosion processes still occur. Moreover, a sociological study was also conducted in the canton of Graubünden. On the other hand, the main differences between the two studied areas are the geological context and the flow discharge. Several studies about geology, flora or fauna have already been undertaken on this river (Speck, 1976; Ackermann *et al.*, 2000; Klötzli *et al.*, 2005).

From an historical point of view, the term “*Domleschg*” was first used for the localisation of the terraces on the east side of the valley (Ackermann *et al.*, 2000). Nowadays and after many landscape modifications due to the corrections, this term is also applied to the whole valley from the confluence of *Hinterrhein* and *Albula* Rivers (in Sils i.D.) to the beginning of the active zone just after *Rothenbrunnen*.

The Rhine River source is located in the canton of Graubünden, where its two main initial tributaries are called *Vorderrhein* (anterior Rhine) and *Hinterrhein* (posterior Rhine or Upper Rhine; Klötzli *et al.*, 2005). The *Vorderrhein* springs from Lake Tuma near the Oberalp Pass in the Gotthard Massif and passes the Ruinaulta. The *Hinterrhein* starts from the *Paradies* glacier near the *Rheinquellhorn* at the southern border of Switzerland near the

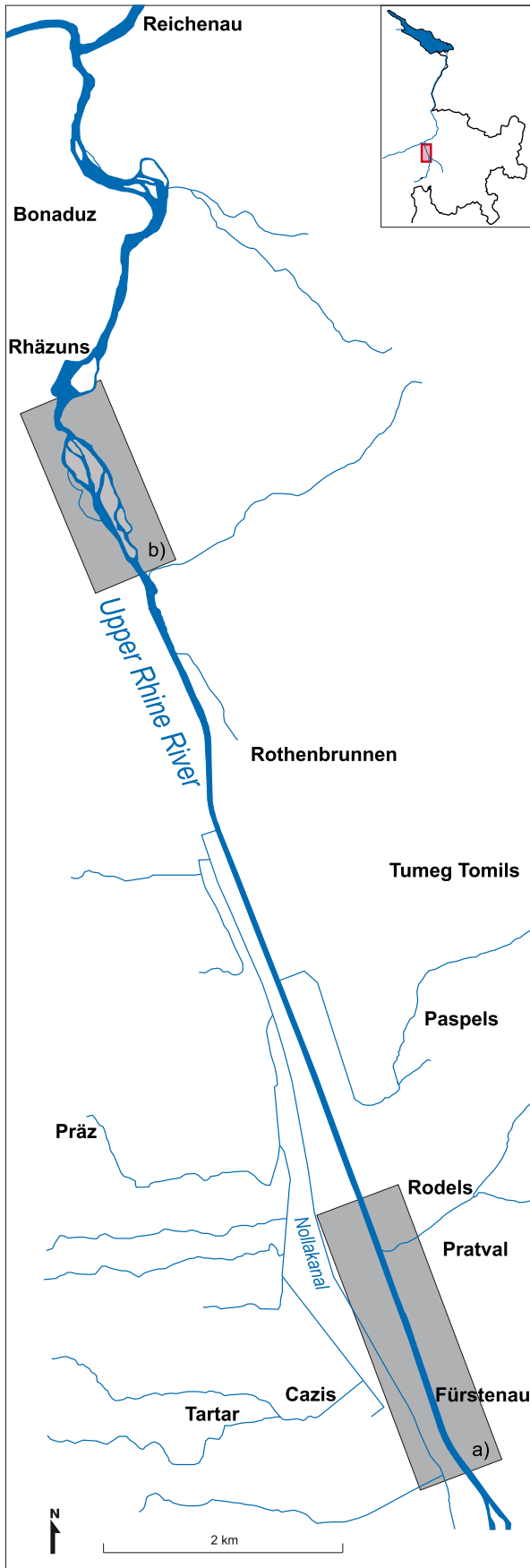


Fig. 2.19. The Rhine River area with its two major study zones: a) upstream area in the embanked part; b) downstream area in the active part.



Fig. 2.20. View of the Domleschg valley at the level of Cazis.



Fig. 2.21. View downstream of the embanked part at the level of Fürstenau.



Fig. 2.22. View of the active part at the level of Rhäzuns.

San Bernardino Pass. Both tributaries meet near Reichenau still in the Canton of Graubünden.

The study section is located along the *Hinterrhein* River, whose main tributaries are the Ragn da Ferrera and Albula Rivers, as well as the Nolla River. This section is 9 km long and consists of two different morphological parts (fig. 2.19): an embanked stretch in the south, defined by fields and forests having an indeterminate status (non alluvial forest), and an active stretch in the north with a large variety of forest communities including mixtures of willow (*Salix elaeagnos*).

From 1974 to 2005, the mean annual discharge in the measuring site of Fürstenau was 40.1 m³/s (fig. 2.23) with a maximum flow rate in June and a minimum in December. The climate is considered as subcontinental with relatively low precipitation (800-1000 mm; Speck, 1976) and an average annual temperature of 7.1°C (minimum of -2.1°C in winter and maximum of 16.2°C in summer from 1961 to 1990; Atlas of Switzerland, 2004).

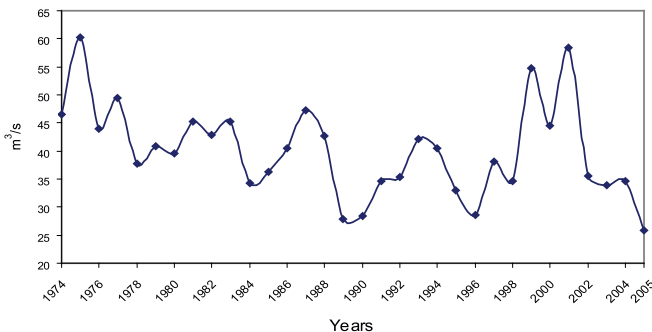


Fig. 2.23. Annual mean flow in m³/s from 1974 to 2005 at the measuring site of Fürstenau (source: Hydrological data, OFEG).

The area is located in the Alpine flysch landscape consisted of Bündner schist nappes with calcareous Bündner schist rocks on the eastern side of the valley and common flysch rocks on the western side. Some lateral moraines are also found and the bottom of the valley is composed of alluvial deposits (calcareous phyllite) from the Quaternary (Atlas of Switzerland, 2004).

Concerning the vegetation of the active zone, the vegetation map (appendix 14) shows the different

types of vegetation according to the federal inventory (Gallandat *et al.*, 1993) for the site “*Rhäsünser Rheinauen*” (object n° 27b of the inventory of alluvial zones of national importance). It consists of a mosaic of draped willow forests (*Salicetum elaeagno-daphnoidis*, unit 6.1; and *Salici-Myricarietum*, unit 6.2) and white alder forests (unit 8) with some patterns of altitude white alder forests (*Calamagrostio-Alnetum incanae*, unit 8.2). A pine forest (unit 15.2), as well as other alluvial forests with indeterminate status (unit 16.Pe), is also present. Another alluvial zones of national importance (object n° 27a of the federal inventory) is located downstream the study zone and consists also of a mosaic of draped willow forests (unit 6.1), altitude white alder forests (unit 8.2) and other alluvial forests (unit 16.2) with pines.

2.3.2. The Ticino River

The third study area is located in the Southern Alps along the Ticino River between Iragna (275 m asl) and Castione (240 m asl) in the Canton of Ticino (fig. 2.24). In order to take into account the cultural and biogeographical diversity of Switzerland, a study site was chosen in the Southern region. The precise selection of this area is due to the sociological study also conducted in the Canton of Ticino. Moreover, projects were planned along this river (Carraro, pers. comm., 2004) that reinforced our selection. Similarities between this site and our main site along the Sarine River were not obvious in terms of geology, as well as flow discharge conditions. Anyway, this site was analysed as the others in order to study the diversity and similarities between the three cultural and geographical regions.

The Ticino River rises in the Gotthard Massif and flows through Lake Maggiore before entering Italy. It joins the Po River a few kilometers downstream of Pavia and is about 280 km long. Its total basin area is 6'598 km². It is the largest river in the canton of Ticino and its main tributaries are the Brenno River in the Blenio Valley and the Moesa River in the Mesolcina Valley in the Canton of

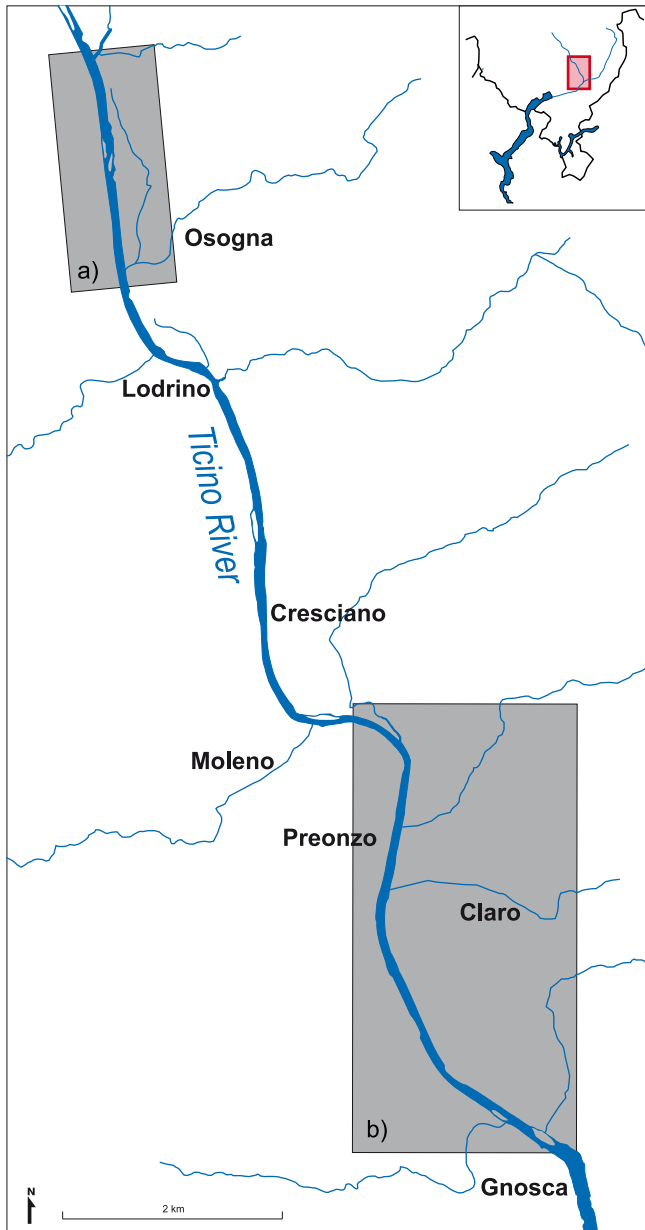


Fig. 2.24. The Ticino River area with its two major study zones: a) upstream area; b) downstream area.

Graubünden. The studied section has a length of 13 km (fig. 2.25).

From 1911 to 2005, the mean annual discharge in the measuring site of Bellinzona (situated about 5 kilometres downstream from our study section) was 69.2 m³/s with a maximum flow rate in June and a minimum in February (fig. 2.26). The climate is considered as insubrian and the Ticino region is known to receive among the highest annual precipitation in Switzerland ranging between



Fig. 2.25. View of the Ticino River from the heights of Claro.

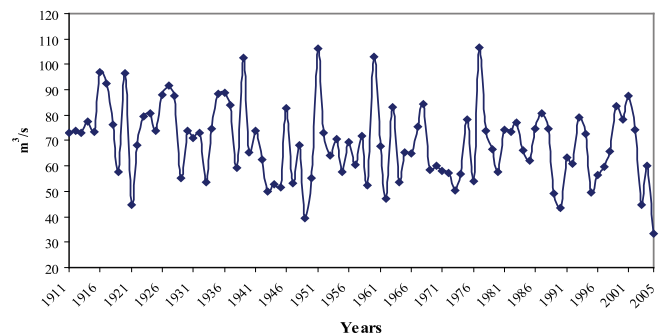


Fig. 2.26. Annual mean flow in m³/s from 1911 to 2005 at the measuring site of Bellinzona (source: Hydrological data, OFEG).

1000 and 2600 mm/year (Eggenberger and Kurz, 2000). These overall higher values are due to the geographic situation. The Ticino incorporates the first significant topographic elevations towards the Alps leading to the high precipitation values, strongly dependent on the precipitation–elevation relationship. The mean annual temperature (from 1961 to 1990) is 11.2°C with a minimum of 3.5°C in winter and a maximum of 19.5°C in summer (Atlas of Switzerland, 2004).

The study area is in the Alpine crystalline landscape and consists of crystalline basement nappes of pre- Carboniferous age, with para-mesozoic metamorphic rocks. The bottom of the valley is composed of alluvial deposits (Quaternary loose rocks) with sands and gravels, but with a low stone content (Atlas of Switzerland, 2004).

Concerning the vegetation, no alluvial zone of national importance lies along our study section. The forest zones in Claro and Lodrino are dominated by a mixing of willows (*Salix alba* or *S. elaeagnos*), ashes (*Fraxinus excelsior*), black locusts (*Robinia pseudoacacia*), poplars (mostly *Populus nigra*) and oaks (*Quercus* sp.). The very upstream part (Ca d'Ossola) present some alluvial natural characteristics with draped willows mixed with some black locusts and ashes. The Atlas of Switzerland (2004) indicates regular timber forests for the region of Claro and coppice with standards for the forest zone of Lodrino.

2.3.3. Data collection and analysis for the Rhine and Ticino River

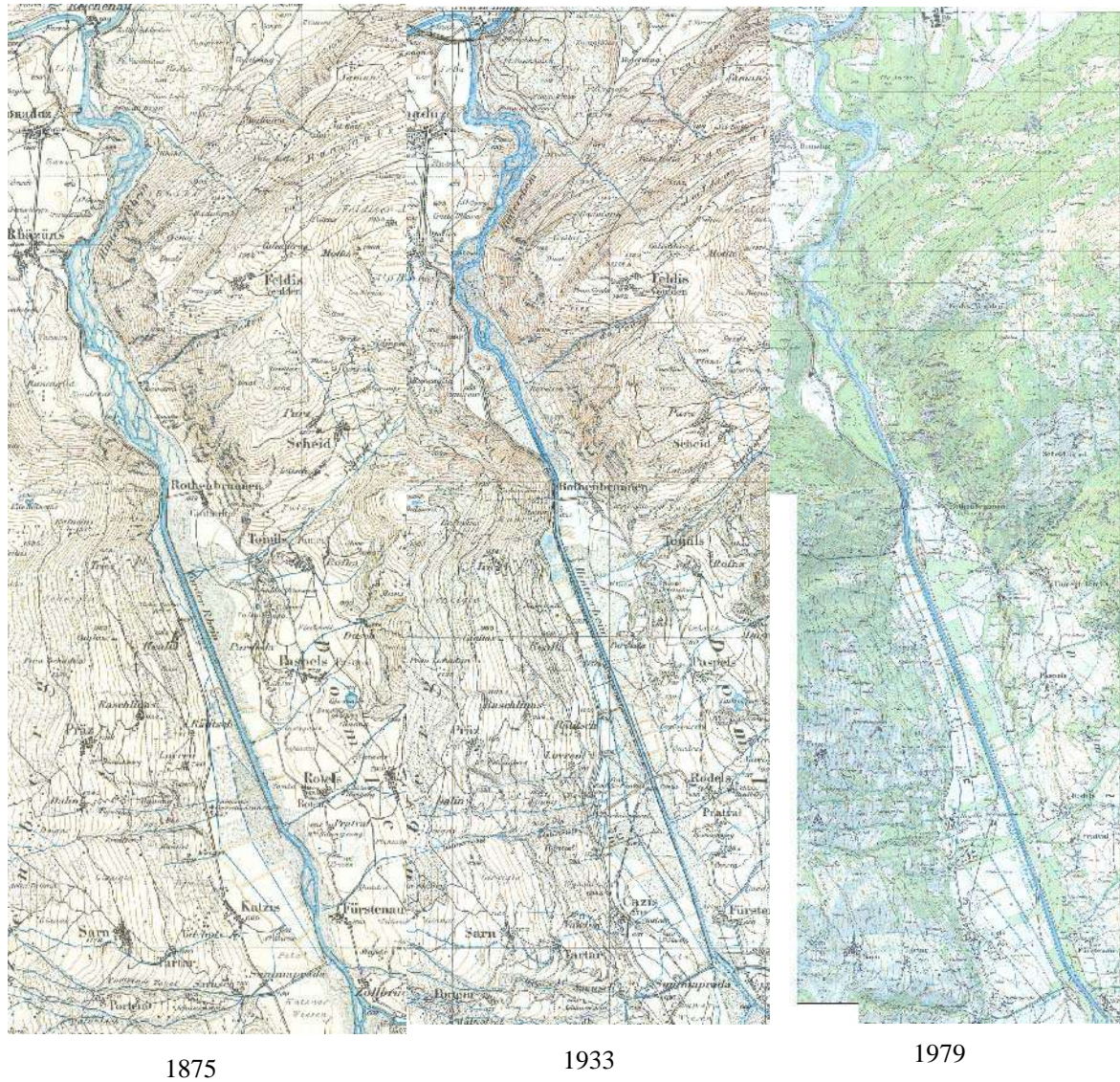
As these two last sites were considered as secondary, fewer landscape data than collected for the Sarine River were considered and analyzed. Nevertheless, some information was used to understand the evolution and the present state of each river. For the Upper Rhine study site, a comparison of three sets of maps (1875, 1933, and 1979) permitted to get the major landscape evolution. Moreover, an old drawn undated plan showing the Rhine correction in Domleschg valley was also studied, as well as some bibliographic information (Rougier, 1980; Ackermann *et al.*, 2000; Lippuner *et al.*, 2002). For the Ticino River, two sets of maps were used (1937 and 1983). Unfortunately, older maps were not available for our study section and few documents were found in the framework of the Flood'Alps project.

2.3.4. Historical and landscape evolution for the Rhine River

Concerning the Domleschg valley, the first notes about damages due to floods and inundations dated from the 11th century, but until the beginning of the 19th century, security was taken on by owners of lands bordered the river. From that period on, a new concept appeared that security became collective and had to be developed and supported by the community.

The first commission concerned with the Rhine correction appeared in 1821. It was asked to land owners to make their lands available to corrections. However, no arrangements were found. During that time the engineer Richard La Nicca started to work on the project of embanking the Upper Rhine River. The communities of Cazis and Rodels accepted to give their lands for the constructions started in 1832 and gone on for 60 years till 1892. On the map of 1875 (fig. 2.27), the Upper Rhine River was already embanked between Rodels (named Rodels now) and Rothenbrunnen. Downstream, the river kept a typical braided system with multiple channels and islands formed by gravels and sediments. Upstream, a braided system still exists, but corrections were previously completed on the left bank. The valley became progressively colonized by the forests (principally pines) that appeared in natural and artificial manner (fig. 2.28).

Locally the bottom of the valley became productive with the use of Nolla River sediments. This practice is called "warping" and consists of diverting water in successive settling tanks in order to provoke fine particle sedimentation and thus to improve and elevate the soil. In Domleschg valley, warping on large surfaces started only during the World War II. On the old drawn map (fig. 2.29) a project of warping is represented. We can see different canals used to guide the water charged in sediments to the different patches separated by small dikes. These techniques of silting were practiced in other European countries and particularly in France during the 19th century as mentioned by Girel (1994). He described warping ("*colmatage*" in French) as a method using sediments (clay, silt, sand and gravel) pulled from both the channel floor and banks or voluntarily thrown by farmers in artificial canals especially designed to lead water and matter flows over the areas that needed to be improved. It concerns the particular artificial silting method for filling and raising lower areas (marshes, swamps, gravel deposits) and transforming them into arable lands. This presence of artificial substratum generated by human perturbation has been well studied in France particularly along the Isère River valley, downstream from Albertville (Girel, 1994).



1875

1933

1979

Fig. 2.27. The set of maps (1875, 1933 and 1977) used to study the historical evolution of the Rhine River floodplain.



Fig. 2.28. View of pine forests in the active zone of Rhazuns.

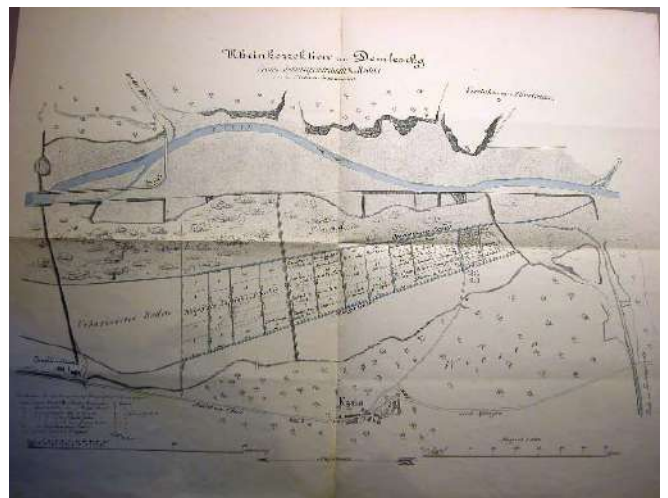


Fig. 2.29. Old drawn map "Rheinkorrektion im Domleschg. Section Summapraderbach bis Rodels" undating and unsigned (source: *Staatarchiv Graubünden, Chur, Plan 15.4.15*).

On the map of 1933 (fig. 2.27), a part of the floodplain was mostly covered by forest and the upstream section was completely embanked. The railroad was constructed on the left bank of the river. With the clearing carried out by the Polish internees and the widening of the Nolla River, rich in schist sediments (fig. 2.30), the warping became common on the left bank of the Upper Rhine River. Nowadays, the “Nollakanal” is still used by the Realta exploitation (fig. 2.31) and is visible on the third view (fig. 2.27). On that map of 1977, the highway was not yet finished, but the layout was already given. The tunnels between Rothenbrunnen and Reichenau were opened in 1980 after some very difficult discussions. Finally, the Swiss Confederation approved these constructions with the charge of keeping the different active environments intact and particularly the site “Auenlandschaft am Unterlauf des Hinterrheins” included in the federal inventory of landscape and natural monuments of national importance in 1977 (object n° 1903 of the BLN inventory; Ordinance RS 451.11 – OIFP – dating from 10th of August 1977). This site was then comprised in the national inventory of alluvial zones of national importance in 1991 (object n° 27 “Rhäzünser Rheinauen”; appendix 14).

From the last view on, the Rhine River landscape has only very little evolved. The same forest patches are visible and the upstream active section still presents a braided system with some channels and gravel islands (fig. 2.32). In 1988 a project was lead closed to the Rodels-Realta station in order to recreate some ponds (fig. 2.33). This site was a natural protected zone, but water was missing for amphibians and birds. In 1989, the government declared this area a natural zone of cantonal importance called “Reservat Munté”. A first step was made for the rehabilitation of the Rhine River, but at that time restoration was not yet taken into consideration. Actually, some restoration projects exist, but nothing in concrete has been lead.



Fig. 2.30. Sediments of the Nolla River rich in schist using for warping.



Fig. 2.31. Views of “Nollakanal” still using nowadays by the Realta exploitation.



Fig. 2.32. View of a braided system with some channels and gravel islands (active part of Rhäzuns).



Fig. 2.33. View of “Reservat Munté” recreated in 1988 and declared as a natural zone of cantonal importance for birds and amphibians.

2.3.5. Historical and landscape evolution for the Ticino River

Concerning the Ticino River area, available data were only very few. For a long time, the Ticino River and its tributaries have been an important source for hydroelectric power for Switzerland. Thus, major modifications to the flow discharge had been observed. Moreover, the Ticino River valley is the principal road across the Alps from North to South Europe and so, its landscape was early modified.

On the view of 1937 (fig. 2.34) embankments were already constructed and only few areas still

presented a braided system like in the very Southern part of the studied area or upstream. This could be explained by the fact that the railroad was already built and security was needed. The gained lands were then used for agriculture and forests were also visible. On the map of 1983 (fig. 2.34), it can be observed that the highway was constructed very close to the river implying dyke constructions. The forest patches were clearly delimited and represented about the same surface as before (except for the area on the left bank in the south of Cresciano). Some gravel bars were still present downstream close to the place named “Ca d’Ossola”. Upstream, the channel, which released in Ticino River water used for hydroelectricity, was then visible on the left bank (fig. 2.35). Nowadays, only 5 of the 17 m³/s flow through the Ticino River, the other 12 m³/s are discharged by the hydroelectric station. The river water level varies from 40-60 cm during the day according to the seasons (Carraro, pers. comm., 2003).

More generally, it can be observed that Ticino River has been completely disconnected from its nearby environment for more than a century. Water was progressively pushed back, became uninteresting and has visually and “psychologically” disappeared. Constructions have been made without any common development plan inducing a loss of relations with the landscape. Thus, dialogue must be rebuilt with water and global reflection about floodplain planning belongs to the Canton’s responsibility. At the present time, some restoration projects exist, but no concrete work has been done.

2.4. Conclusion

It has been shown that landscape modification processes were comparable for the three study areas, as seen in the majority of floodplains in Western Europe and USA. This was due to the high human pressure influencing spatial and temporal changes in channel morphology. The protection against floods was the first reason of embankment. The need of new lands, for agriculture and urbanisation, was also a central point. Nowadays in areas where economic activity is growing there are con-

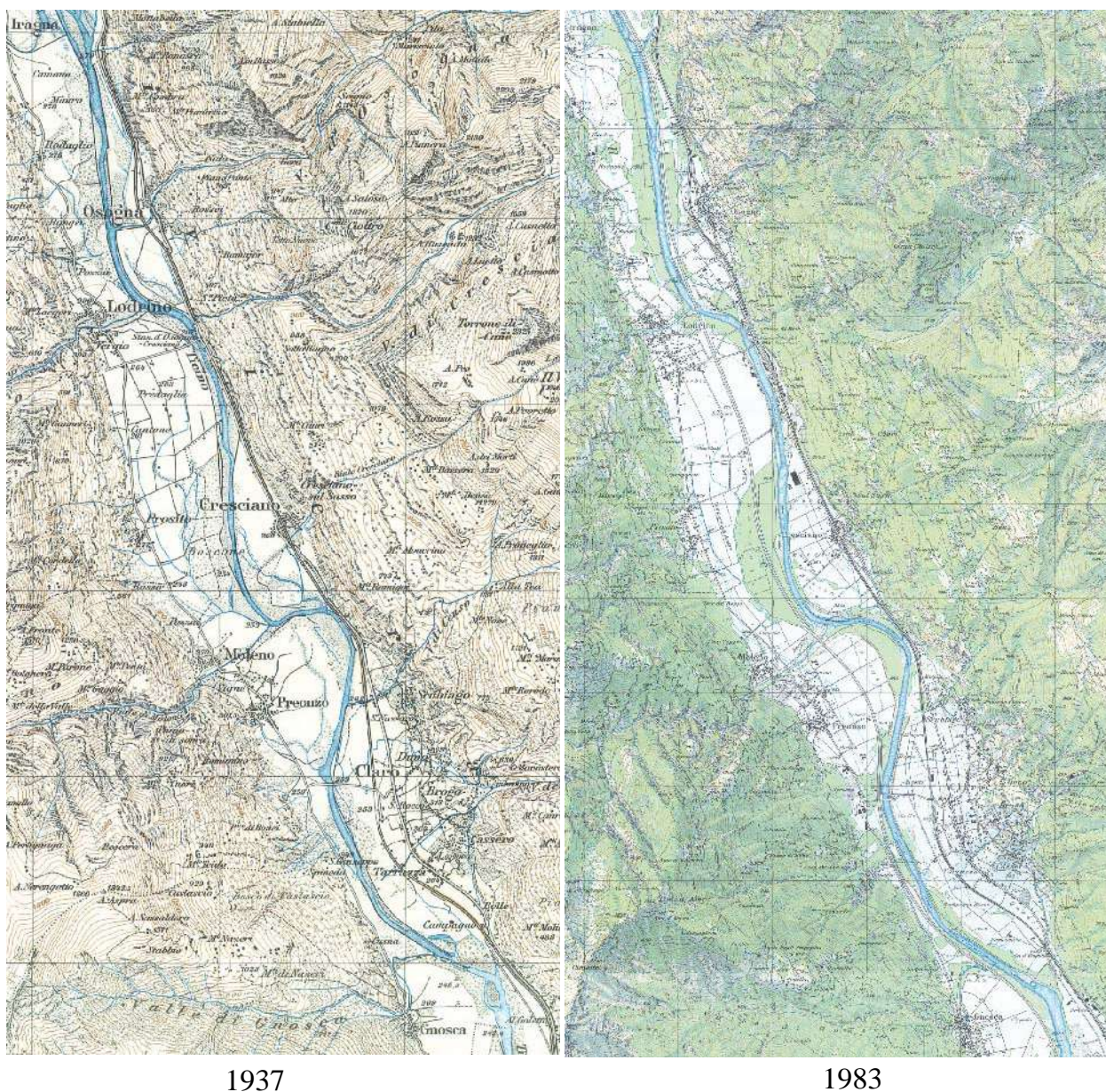


Fig. 2.34. The set of maps (1937 and 1983) used to study the historical evolution of the Ticino River floodplain.

stant pressures to intensify urban development on riverine banks or even more in the river bed. This intensification creates increased flood damage potential and may also amplify flood severity.

In this context notion of river restoration has progressively emerged. After having destroyed braided natural fluvial ecosystems, the idea of recovering the ecological integrity of rivers and creating natural reserves appears. Artificial rehabilitations are thus achieved by redesigning the floodplain morphology. After the “embankment period” we enter the “ecology period”. Anyway, and despite the ap-



Fig. 2.35. View of the channel releasing water used for hydroelectricity in Lodrino.

partition of restoration programmes, floodplains are high energy environments depending on several parameters where nature still decides.

As floodplain soils reflect in their profiles the character of environment changes, the different alternation of stages dominated by alluviation or pedogenesis are of great interest to understand soil

formation reproducing past history and dynamics. The consequences of human impacts may thus be detected in the soil sequence and explained more precisely what was happening in the study areas. Investigations based on geomorphological and pedological methods may also identify the differences or resemblances between the three study regions.

3. Alluvial soil formation in Sarine, Rhine and Ticino Rivers¹

3.1. Introduction

Soil is the superficial covering of most lands of the Earth. It is a natural body composed of minerals, organic compounds, living organisms, air and water in interactive combinations by physical, chemical and biological processes. It has a four-dimensional organisation including the factor of time. In a vertical direction it is organised in horizons of mineral and/or organic constituents of variable thickness (Gerrard, 2000). In lateral direction soil changes in response to variations of the major soil forming factors, such as climate, relief, vegetation and parent material. According to its organization and functioning, soil is an ecological system to which the usual defined properties of systems are applicable (e. g. the principles of thermodynamics, necessity for defining boundaries, spatio-temporal hierarchical organization, internal evolution, and opening to other systems; Gobat *et al.*, 2004).

3.1.1. Alluvial soils

Alluvial soils are considered being special soils that exhibit characteristics of both sediment transport and deposition, and *in situ* soil formation. They are related to specific landforms (flood-

plains) showing variable climatic conditions and classified as abnormal by Dokuchaev in 1879 (Gerrard, 1987). Actually, they are named Fluvisols in the World Reference Base for Soil Resources and are defined as genetically young and azonal soils in alluvial deposits (IUSS Working Group WRB, 2006). They are not limited only to river sediments, but also occur in lacustrine and marine deposits. Fluvisols are found on all continents and in all climate zones. Many of them are flooded periodically under natural conditions. The profiles present evidence of stratification with in general weak horizon differentiation, but a possible distinct topsoil horizon. In fact, the variability of alluvial soils is very difficult to understand without taking into account the transport and deposition processes in rivers (Gerrard, 1992). Thus, the position of alluvial soils in classifications was treated differently according to the local global conditions. For example, the FAO-UNESCO (1974) grouped alluvial soils in the category of Fluvisols with possible qualifiers such as “eutric” (with a base saturation greater than 50% between 20 cm and 50 cm from the surface, but not calcareous) or “calcaric” (calcareous between 20 cm and 50 cm from the surface).

¹ This chapter contains notably the paper: Bullinger-Weber G. and Gobat J.-M. 2006. Identification of facies model in alluvial soil formation: The case of a Swiss alpine floodplain. *Geomorphology*, 75 (1-4): 181-195, found in appendix 15.

In the “*Référentiel Pédologique*” (AFES, 1998), the definition of alluvial soils is comparable to the WRB’s one. They are classified in FLUVIOSOLS distinguished from other undeveloped or weakly developed soils by their low position in the landscape, their development from recent material (river alluvium) and the presence of a permanent or periodic water-table, and flood events. The FLUVIOSOLS are represented by three references of diagnostic sola. The first one is the FLUVIOSOL BRUT with coarse, riverside, alluvial deposits that may contain traces of organic matter and present *M* or *D* layers only. They are developed from recent riverside-alluvial deposits and seasonally flooded when the river is high and are then called FLUVIOSOL TYPIQUE with the following possible sequences: *Js* / *M* or *D* layers (thin soil less than 30 cm); *A* / *Jp* / *D* layers (relatively deep soils 30 to 80 cm depth); *A* / *Jp* / *M* / *D* (deep soils more than 80 cm). Finally, the FLUVIOSOL BRUNIFIÉ is developed from recent riverside-alluvial deposits that are fine, often clay or silty clay rich in organic matter that presents a well-developed structural horizon *S*. The diagnostic horizon sequence is *A* / *S* / *D* layers or *A* / *S* / *M* / *D* layers and the solum is deep (1 m or more) with a well-structured *A* horizon overlaying a *M*-layer that can be thick or directly a *D*-layer (alluvial gravel).

3.1.2. Ecological properties of alluvial soils

The integrity of the fluvial hydrosystem depends on the dynamic interaction between hydrological, geomorphological, and biological processes. The exploration and analysis of the multivariate and spatial data found in these ecological attributes of floodplains are commonly explored by standard methods, such as correspondence analysis or clustering and are widely used by ecologists. In this complex ecological system, alluvial soils are characterized by sediment transport and deposition, as well as by soil formation (Gerrard, 1987). They can be identified at the level of functional units according to Petts and Amoros (1996). In fact, these particular sequences evolve from a single origin by progressive changes over time-scales of 10^{-1} to 10^2

years. The processes involved include sedimentation or organic matter accumulation for example (Petts and Amoros, 1996). Thus, this combination of geomorphic and edaphic processes is the main property of alluvial soils providing good elements for the interpretation of past environmental changes (Daniels, 2003).

Moreover, alluvial soil morphology varies according to landscape position and overbank lithofacies (Autin and Aslan, 2001), but also from river modifications through time, such as embankments and dam constructions. These geomorphic processes produce a landscape mosaic reflected by abrupt juxtapositions of soils of different ages and degrees of profile development (McAuliffe, 1994). Stratification, formed by the alternation of pedological layers and layers with new material, is a particular characteristic of alluvial soils (Gerrard, 1987). New deposition may bury a pre-existing soil and move it away from the zone of active pedogenesis (Daniels, 2003).

Alluvial soils are good models to estimate the part of pedogenesis illustrating periods of stability with development of pedogenic features and pedoturbation, representing the overlay of sediments or instability periods (Paton *et al.*, 1995) in high or low energy depositional environments. High energy deposition contains coarse sediment deposited by traction currents (e. g. gravels and coarse sand deposition; fig. 3.1), whereas low energy deposition is reflected by fine grain sediment deposited by suspension settling. The size of particle possibly eroded and transported is a function of current velocity. The relation as presented by Allan (1995) between erosion, transportation and sedimentation and flow velocity is complex (fig. 3.2). For example, sand particles are most easily eroded while clay and silt particles need greater critical erosion velocities because of their cohesiveness. After transportation particles continue in motion at slower velocities than were necessary to initiate the movement and will settle at still lower velocities. Moreover, erosion rates depend on several factors such as lithology, climate, or relief (Campy and Macaire, 2003). For example, erosion rates are higher for loess or



Fig. 3.1. Example of coarse sands, gravels and pebbles.

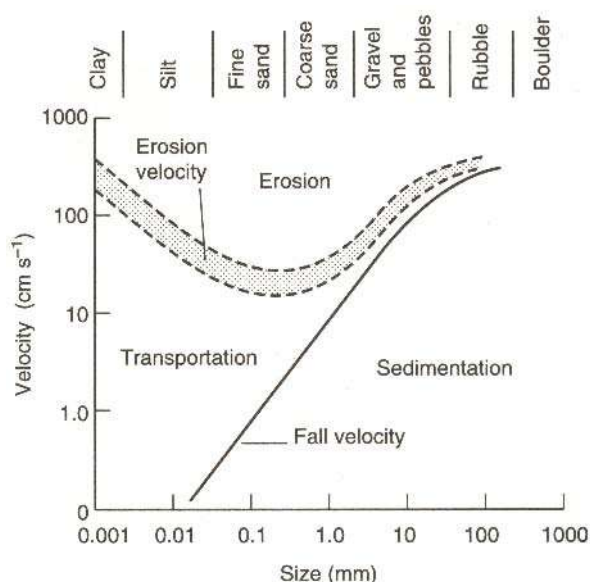


Fig. 3.2. Relation of mean current velocity in water at least 1 m deep to the size of mineral grains potentially eroded from a bed of material of similar size (source: Allan, 1995, p. 10).

crumbly materials while they are lower for granitic rocks. Climate, more precisely precipitation, strongly influences the mechanical erosion, because

surface runoffs increase with rain intensification. Finally, altitude influence has also to be taken in consideration, because steep slopes increase the runoff and limit infiltration of water.

3.1.3. Paleosols in floodplain¹

The process of soil cumulation is particularly important in a floodplain context, because all floodplains are exposed to pedogenesis during the stable intervals between periods of active sediment deposition. In cumulative soils, material accreted on surface becomes pedogenically assimilated into the soil profile and generates over-thickened horizon (Daniels, 2003). When an ancient buried soil, whose composition may reflect a climate significantly different from the climate now prevalent in the area, then this soil is called paleosol. It is composed of vertical successions of overbank deposits and pedogenic features (Kraus and Brown, 1988) generated by slow and sporadic aggradation and soil modification interrupted by more rapid deposition. Paleosols can be identified as buried soils determined by five groups of soil-forming factors: climate, organisms (including man), relief, parent material, and time (Bronger and Catt, 1998). They can also be regarded as polygenetic soils if they contain features formed during two or more periods of different environmental conditions and furthermore demonstrate an inverse relationship between soil maturity and sediment accumulation. Nevertheless, there is no agreement among earth scientists about what constitutes a paleosol, or how to define one (Follmer, 1998). In the French definition (Duchaufour, 1977), paleosols are really classified in a very general term to soils formed under climatic conditions different from that presently prevailing. Postglacial alluvial soils are mainly identified as buried soils or polyphasic soils corresponding to monocyclic soils with buried horizons under the same macro- or mesoclimatic conditions (Gobat *et al.*, 2004).

Nevertheless, paleosols are not restricted to alluvial context. The term pedofacies is mainly prefer-

¹ See also addenda 1a found in appendix 32.

red in order to delimit the lateral changes of adjacent packages of sedimentation rock when they vary in their ancient soil properties as a function of their distance from areas of relatively high sediment accumulation (Kraus and Brown, 1988). According to these authors, the concept of pedogenic maturity is used to infer sediment accumulation rates at different locations in ancient floodplain environments: weak soil development is assumed where sedimentation rates are rapid and events frequent. Strong development is presumed where sediment accumulation is slow. In a semiarid cut-and-fill floodplain context, Daniels (2003) defined three alluvial pedofacies (fig. 3.3). These three identical soils are shown to have developed different pedogenic features through time as a result of different aggradation rates. Daniels (2003) also defined A horizons as soil-stratigraphic markers and indicators of relative aggradation rates. They are identifiable in the field and their characterization permits to describe periods of stability. For example, the input of organic matter permits to keep biological processes for a while with the degradation of organic matter by fauna and the humification.

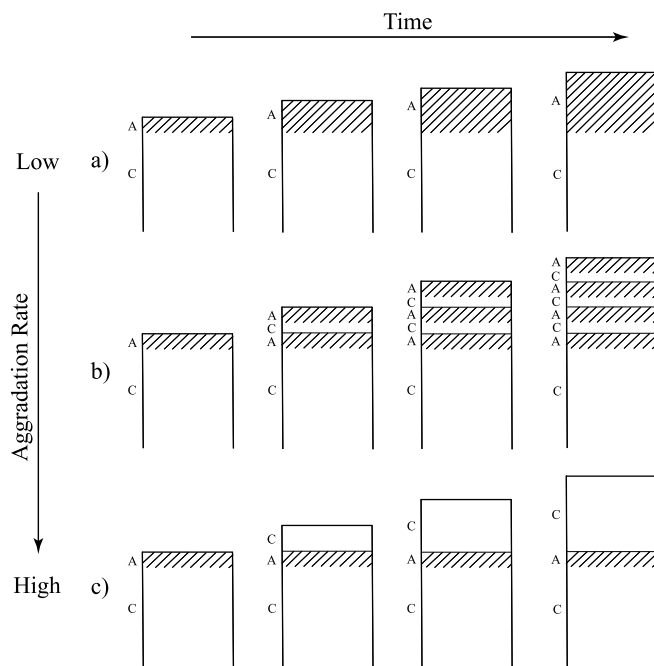


Fig. 3.3. Schematic diagram of three alluvial pedofacies common to semiarid cut and fill floodplains (source: Daniels, 2003, p. 227).

Thus, identification of the different horizons present in a pedon, reflecting different aggradation phenomena due to floods or development of a weak soil structure, seems to be the ideal level approach to describe precisely the variability and complexity of the alluvial soil profiles. The conceptual models of facies may then be adapted and used in other floodplain contexts, such as embanked zones. In these particular damaged systems, the lateral connectivity is broken resulting in a quasi complete isolation of the river from its floodplain and in a suspension of aggradation. Embanked river floodplain deposits are lithologically and sedimentologically different from natural (not human-influenced) floodplain deposits, and only pedogenic characteristics are then observed in the subsurface of paleosols.

Most studies of floodplains were undertaken to understand their morphology (e. g., Parsons and Gilvear, 2002; Richards *et al.*, 2002; Rinaldi, 2003; Steiger *et al.*, 2005; Gordon and Meentemeyer, 2006), sedimentology (Steiger and Gurnell, 2003; Vericat and Batalla, 2005; Krüger *et al.*, 2006; Rommens *et al.*, 2006) or hydrology (Pinter and Heine, 2004; Pinter *et al.*, 2006), but only few studies were lead in order to describe and understand the alluvial soil formation in a pedological way, and integrating all these disciplines.

3.2. The soil survey approach: goals

Using the concept of pedofacies defined by Kraus and Brown (1988) on the basis of differences in paleosol development, this study aims to develop a similar hierarchy - or similar facies models - including the lateral and vertical changes of soil development at different spatial and temporal scales. As embanked rivers represent a large part of the current floodplain cases, at least in Western Europe, a better comprehension of the aggradation and soil formation processes in the soils, nowadays disconnected from the current flow, as well as a better knowledge of their spatial distribution along the riparian corridor, is highly relevant to understand the global functioning of the floodplain. In order to un-

undertake a detailed examination of these properties, the vertical succession of the horizons (as defined by Gerrard, 2000)¹, presenting pedogenic features or consisting of overbank sediments, was used to describe the stratification of different alluvial soils at functional set and unit levels according to Petts and Amoros (1996). As these different sequences could be related to the concepts primarily used in ecological research (fluvial hydrosystem), analyses commonly used in ecology is appropriate in our context of pedology and geomorphology.

The case of the partially embanked Sarine River floodplain is first analyzed and results, giving

abstract categories and statistical abstractions of soil properties, are employed to establish modified simple conceptual models of alluvial soil formation used for describing in a rapid, simple, and inexpensive way the alluvial soils (fig. 3.4). These methods are then compared with other soil classifications or soil survey methods practiced in soil science. Simple indicators, mainly horizon and soil profile parameters (e. g. thickness of horizons, soil texture as defined in field; Gobat *et al.*, 2004), were used in order to identify the different mechanisms for floodplain soil formation and to understand the landscape evolution of an alpine floodplain altered by human activity.

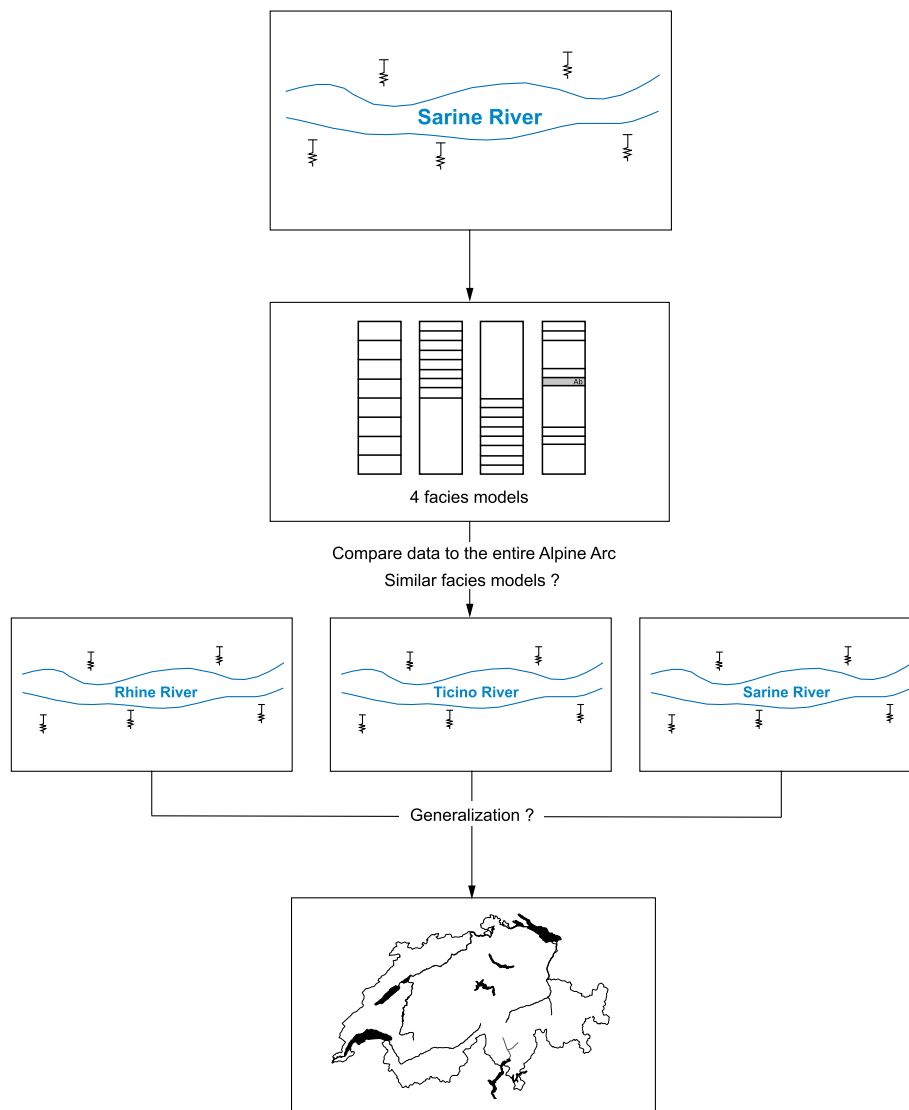


Fig. 3.4. Schematic representation of the methodological framework used to establish simple conceptual models of alluvial soil formation.

¹ See also addenda 1b, found in appendix 33.

In the second part, and in order to compare data from the entire Alpine Arc, results from the three studied alpine floodplains have been analyzed together (Sarine, Rhine and Ticino Rivers). We hypothesize that alluvial soil properties will be different in these three different systems, but processes and effects of human impact will be the same. By comparing these findings, and then with examples from other areas, results give general mechanisms of alluviation and floodplain pedogenesis in the Swiss Alpine area and significance in terms of understanding valley floor ecosystem structure and evolution.

3.3. Data acquisition

3.3.1. Soil of the Sarine River

Alluvial soils of the Sarine floodplain were surveyed by a detailed description of the morphology of different core samplings with a pedological auger throughout the two major study areas (upstream and downstream investigated zones in fig. 3.5). They were described according to the World Reference Base of Soil Resources (ISSS Working Group RB, 1998), using soil characteristics, properties and horizons. Soil characteristics, as well as soil properties, were measured in the field and emphasis was laid on describing the soil texture characteristics of the deposited sediments and the pedogenic layers. Pedogenic features were also observed (oxidation marks, organic matter, structure...). The different layers are called horizons (corresponding to the diagnostic horizons or reference horizons; AFES, 1998), which are three-dimensional bodies more or less parallel to the earth's surface characterized by morphological, chemical, and physical properties, and used to interpret the developmental history of the soil (Brakenridge, 1988; Bockheim *et al.*, 2004). They are defined as an ecological sampling unit that corresponds to Strong and La Roi (1988) definition. Their succession was named soil profile (or profile), by analogy with soil science concepts, and they defined the sequence of information related to a solum ordered from the land surface downwards (AFES, 1998).

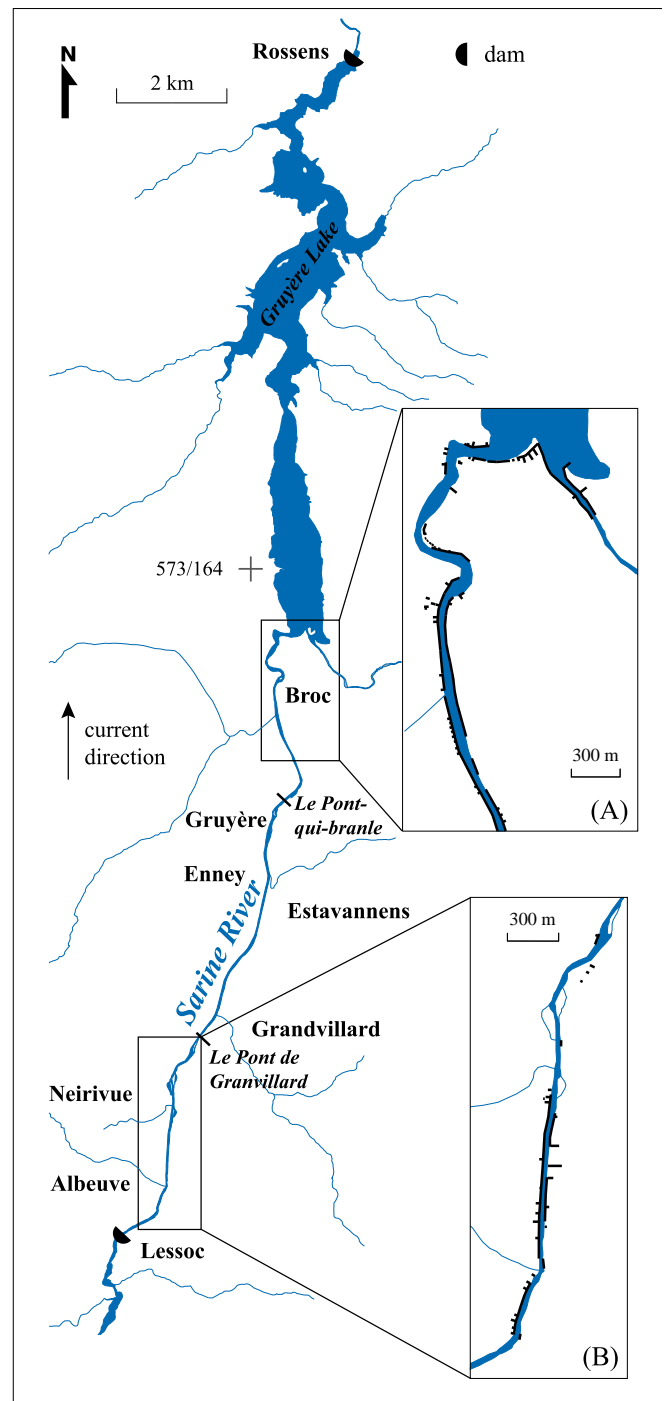


Fig. 3.5. Location and distribution of embankments built along the Sarine River in the two major study areas from 1917 to 1938 (and even to 1974; distribution not exhaustive because of missing archives; source: Guex, 2004).

A total of 143 points were surveyed with a pedological auger (fig. 3.6); only the ones reaching a calcareous pebble level were taken into consideration (109). This limit was chosen because it represents one event considering being the same layer throughout the study area. This soil cover named upper layer by Bernalov and Os'kina (2006) is defined as the upper aerated part of alluvial deposits. Its thickness varies from few centimetres to several meters in different areas. The sampling technique is commonly used to provide an indication of the soils represented in the field and to describe the soil types, if soil profiles have been previously determined (Cosandey *et al.*, 2003; Earl *et al.*, 2003; Bragato, 2004). This is the case for some areas of the Sarine site as previous studies have already published (Bureau *et al.*, 1995; Fierz *et al.*, 1995; Mendonça Santos *et al.*, 2000). The sediment cores were collected from representative locations and identified as being uncultivated and susceptible to



Fig. 3.6. Example of description using pedological auger sampling.

regular overbank flooding (forests, active zones), as well as cultivated and disconnected from the river (agricultural and embanked zones). In addition to precise geographical information and short vegetation description, the following characteristics and properties were recorded for each point:

- total thickness of the profile, from top surface to pebble limit (cm);
- number of horizons in each profile;
- depth (cm), thickness (cm) and texture of each horizon;
- presence or absence of oxidation marks (e. g. fig. 3.7), of coarse material (gravel and pebbles > 2 mm), and of organic macrorestes in each horizon; and
- soil structure of the topsoil horizon (e. g. particular, granular; Gobat *et al.*, 2004) illustrating the actual development of the soil.



Fig. 3.7. Example of oxidation marks.

Concerning the horizon thickness, it is considered in the case of alluvial soils, as a feature that can be linked to the duration and intensity of floods. The texture of each horizon was identified by hand in the field and no sample was taken for further analyses (sampling made with the auger core is approximate, especially for the depth, and sample may be contaminated by the surrounding soil). A total of 367 horizons were described.

In addition to these descriptive factors, two indexes were calculated for each soil profile, namely the number of horizons per total thickness (named nb/thick) and the number of horizons per meter (nb/m). All these data were introduced into a database to be studied and analysed (appendix 16).

3.3.2. The three floodplains

In order to compare the results found in the case of the Sarine River (Bullinger-Weber and Gobat, 2006), further surveys were conducted in the same way in the two other sites (Rhine and Ticino Rivers). Data of the three studied sites were then analyzed together. In this general approach, a total of 181 points were taken into account (the same 109 already described in the Sarine site, 47 new points in the Rhine site and 25 in the Ticino one). The same description method as seen in the case of the Sarine River was used (core sampling with pedological auger). Once again, only the cores reaching the basal gravels were taken into consideration.

For these 181 points, a total of 652 horizons were described (364 for Sarine, 211 for Rhine and 77 for Ticino) with the same features as presented above. Different representative locations were chosen for sampling: uncultivated and susceptible to regular overbank flooding (forests, active zones), as well as cultivated and disconnected from the river (agricultural and embanked zones; fig. 3.8). The same characteristics and properties as defined in the Sarine site were recorded for each point in addition to other properties.

3.4. Statistical analysis

The different attributes describing each horizon and profile were separated for statistical analysis. Horizon attributes are quantitative (depth and thickness), binary (presence or absence of oxidation marks, coarse material, and macrorestes), and qualitative (field texture). For quantitative analyses, each textural category identified in the field was replaced by an estimated proportion of silt and sand and a binary attribute (presence or absence of fine, medium or coarse sand particles). After standardization, these data were grouped by a hierarchical agglomerative clustering by means of Ward's minimum variance clustering with Euclidean distance (Legendre and Legendre, 1998) using Progiciel R software. As alluvial soils are characterized by stratification of different deposits and show weak horizon differentiation, it was decided that the horizon groups obtained after clustering were used as a categorization of horizons instead of the master horizon nomenclature (e. g. AFES, 1998 or ISSS Working Group RB, 1998). This permitted to conserve the particular characteristics of each horizon, particularly texture, depth and thickness that would have gone lost with other classifications.

The same hierarchical agglomerative clustering was applied to the different profile attributes, which are quantitative (total thickness, number of horizons, nb/thick, nb/m) and binary (presence or absence of horizon groups in the profile). This analysis calculates a matrix of proximity (here distance measures) between a set of two-by-two comparable elements of n samples, permitting to fuse horizons (and profiles), using stated criterion, into groups that respect the resemblance between them in a predefined optimal manner (Legendre and

Type of zone	Type of environment
Natural (67% of described points)	1 = open, no vegetation (1% of described points)
Embanked (33% of described points)	2 = open, with herbaceous vegetation (1%)
	3 = meadow and pasture land (19%)
	4 = field (5%)
	5 = bushes (4%)
	6 = forests (70%)

Fig. 3.8. Different types of zones and environments selected for sampling.

Legendre, 1998). In the common approach used in ecology the hierarchical agglomerative clustering considered the species as samples, but in this study the analysis was applied to horizon and soil attributes. The analyse used here with our soil data was particularly adapted because it permitted to extract relevant information among the large number of data sets that could be analysed in an independent way.

The dominance of the different horizon groups in each profile groups of the Sarine River was also calculated using an analysis of variance (ANOVA with Tuckey test) in order to test differences in profile parameters for each attribute (R software, version 2.0.1; R Development Core Team, 2004). Using the same R software, a regression tree analysis was applied to detect the more discriminating horizon attributes, as well as the repartition of each profile groups in the three rivers.

In order to investigate the contribution of the different profile factors, correlation analyses (using Pearson correlation) between these different soil factors, as well as other data summaries (principally means and standard deviations represented in histograms for data of the three floodplains) were also carried out by means of S-Plus software (version 6.0).

3.5. Results for the Sarine River soils

The Sarine soils have been identified as calcareous polygenetic Fluvisol or as Gleysol, according to the World Reference Base of Soil Resources (ISSS Working Group RB, 1998). The clustering separates 15 groups of horizons (named group I to group XV; fig. 3.9 and 3.10) and in a second step 10 groups of profiles (group 1 to group 10; fig. 3.11). Horizon groups differ from each other principally in their texture parameter (from medium and coarse sand to silt; fig. 3.10), and then in their thickness combined with oxidation marks. An absence of oxidation marks does not mean that there is no oxidation–reduction phenomenon, but only that these marks were not visible at the moment of field

observation or that particle size was too coarse for preservation. Group I consists of very thin layers with oxidation marks. Group II also presents oxidation marks, with a coarser silty sandy texture. Groups III, IV, and V are siltier and do not show any oxidation marks; they differ in the basis of mean depth. Group VI is an intermediate between groups III and V. The fine sandy textural horizons are represented by groups VII and VIII, which also do not show any oxidation marks. The presence of gravels is illustrated in groups IX and X, but the particle size varies: fine sand for IX and medium sand for X. Group XI is characterized by various soil texture distributions, but always with the presence of macrorests. Oxidation marks and medium sand define group XII, whereas groups XIII and XIV are only characterized by medium sand; the depth of each horizon differentiates these two groups. Coarse sand with very little silt differentiates group XV from all the others, independently of the other factors.

Topsoil horizon structure is mostly crumb and particular (63% and 25% of the horizons respectively). The crumb horizons are mainly represented by horizons of group VIII (26%), group V (25%) and group XIV (22%). Most of the particular horizons are found in group XIV (63%) corresponding to a medium sandy texture. The thickness of those topsoil horizons are various (1 to 37 cm), but is generally thicker for the crumb horizons than for the particular ones (mean of 12 and 8 cm respectively).

Profile groups are separated by the factors of total thickness (28 to 97 cm) and number of horizons (2 to 7 horizons; fig. 3.11). Relative location of different groups within the floodplain landscape is shown in fig. 3.12. In this last figure, the distribution of abstract representations of real soil profiles is illustrated and does not necessarily correspond to any of the 109 real profiles. Groups 1 to 5 are quite similar, but differ from each other in the parameter of the dominant horizons. They reveal soil covers with few horizons and are not very thick. Group 1 differs from the other groups by a dominant presence of the horizons from group XV. Group 2 ge-

Parameters	Group I (2% of samples)	Group II (8% of samples)	Group III (4% of samples)	Group IV (2% of samples)	Group V (7% of samples)
Oxidation marks ^a	0 (0%); 1 (100%)	0 (0%); 1 (100%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)
Gravels and pebbles ^a	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)
Silt (%)	Mean = 70 ± 0	Mean = 34 ± 22	Mean = 70 ± 0	Mean = 70 ± 0	Mean = 70 ± 0
Fine sand ^a	0 (100%); 1 (0%)	0 (3%); 1 (97%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (0%); 1 (100%)
Medium sand ^a	0 (100%); 1 (0%)	0 (97%); 1 (3%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)
Coarse sand ^a	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)
Depth (cm)	Mean = 39 ± 32	Mean = 35 ± 28	Mean = 4 ± 8	Mean = 48 ± 19	Mean = 3 ± 7
Thickness (cm)	Mean = 13 ± 9	Mean = 15 ± 10	Mean = 11 ± 5	Mean = 12 ± 6	Mean = 12 ± 7
Macrorestes ^a	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)
Parameters	Group VI (5% of samples)	Group VII (5% of samples)	Group VIII (21% of samples)	Group IX (4% of samples)	Group X (2% of samples)
Oxidation marks ^a	0 (72%); 1 (28%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (77%); 1 (33%)	0 (89%); 1 (11%)
Gravels and pebbles ^a	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (0%); 1 (100%)	0 (0%); 1 (100%)
Silt (%)	Mean = 61 ± 20	Mean = 24 ± 10	Mean = 23 ± 10	Mean = 38 ± 19	Mean = 17 ± 20
Fine sand ^a	0 (39%); 1 (41%)	0 (0%); 1 (100%)	0 (1%); 1 (99%)	0 (8%); 1 (92%)	0 (67%); 1 (33%)
Medium sand ^a	0 (89%); 1 (11%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (22%); 1 (78%)
Coarse sand ^a	0 (89%); 1 (11%)	0 (100%); 1 (0%)	0 (99%); 1 (1%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)
Depth (cm)	Mean = 23 ± 19	Mean = 34 ± 34	Mean = 12 ± 14	Mean = 8 ± 10	Mean = 15 ± 12
Thickness (cm)	Mean = 41 ± 15	Mean = 26 ± 11	Mean = 13 ± 7	Mean = 20 ± 9	Mean = 26 ± 18
Macrorestes ^a	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)
Parameters	Group XI (3% of samples)	Group XII (2% of samples)	Group XIII (3% of samples)	Group XIV (22% of samples)	Group XV (10% of samples)
Oxidation marks ^a	0 (45%); 1 (55%)	0 (0%); 1 (100%)	0 (83%); 1 (17%)	0 (99%); 1 (1%)	0 (86%); 1 (14%)
Gravels and pebbles ^a	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (81%); 1 (19%)	0 (92%); 1 (8%)
Silt (%)	Mean = 39 ± 30	Mean = 10 ± 0	Mean = 10 ± 0	Mean = 10 ± 2	Mean = 10 ± 3
Fine sand ^a	0 (55%); 1 (45%)	0 (78%); 1 (22%)	0 (67%); 1 (33%)	0 (38%); 1 (62%)	0 (100%); 1 (0%)
Medium sand ^a	0 (91%); 1 (9%)	0 (0%); 1 (100%)	0 (0%); 1 (100%)	0 (18%); 1 (82%)	0 (100%); 1 (0%)
Coarse sand ^a	0 (91%); 1 (9%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (81%); 1 (19%)	0 (0%); 1 (100%)
Depth (cm)	Mean = 47 ± 26	Mean = 39 ± 19	Mean = 83 ± 19	Mean = 12 ± 15	Mean = 35 ± 33
Thickness (cm)	Mean = 15 ± 8	Mean = 8 ± 3	Mean = 9 ± 5	Mean = 11 ± 8	Mean = 10 ± 6
Macrorestes ^a	0 (0%); 1 (100%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)

^a 0 = absence, 1 = presence

Fig. 3.9. Characteristics of horizon groups as identified by Ward’s minimum variance clustering (n = 367).

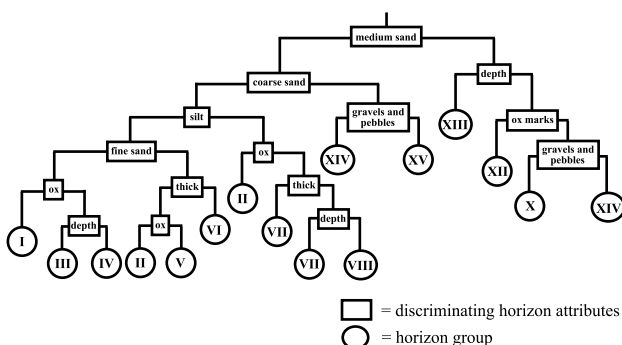


Fig. 3.10. Simplified dendrogram for 367 soil horizons obtained by means of Ward’s minimum variance clustering and described in the 109 profiles from the Sarine floodplain. The group fusion level is defined by a distance and the discriminating horizon attributes are obtained after a regression tree in R Software version 2.0.1. Some horizon groups could appear twice in the dendrogram or not at all. See fig. 3.9 for parameter designation (in this figure “ox” means oxidations marks).

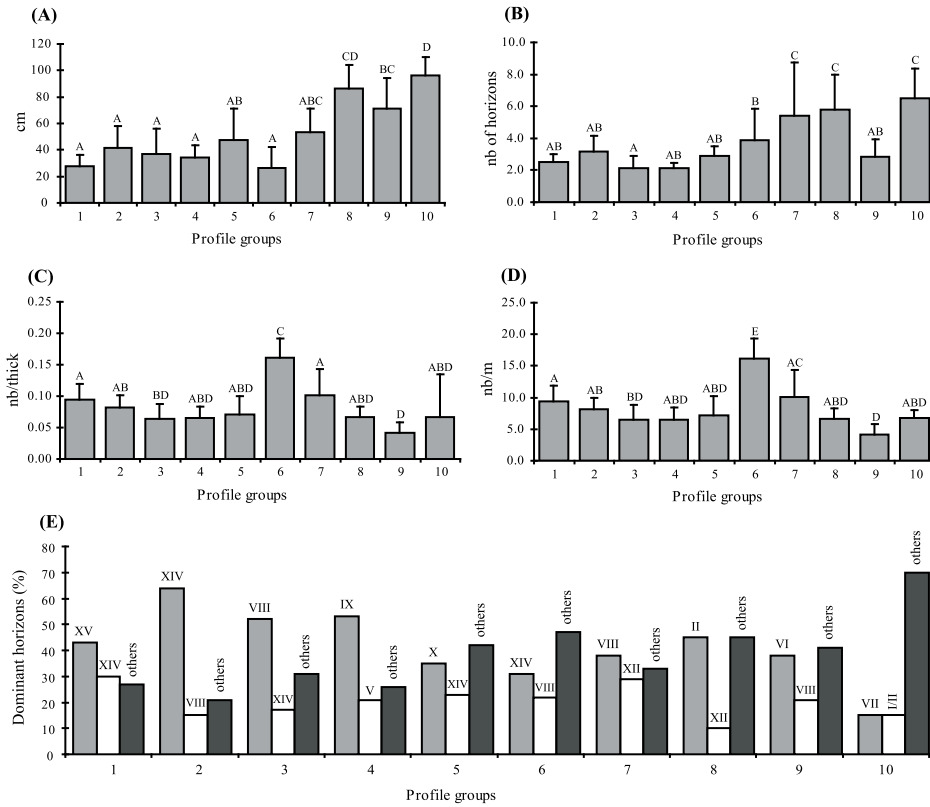


Fig. 3.11. Average values of profile parameters in the 10 profile groups (n = 109), a) total thickness of profile, b) number of horizons found in profile groups, c) index “number of horizons on the total thickness”, d) index “number of horizons per meter”, and e) dominance of horizon groups in profile groups. Capital letters above bars indicate significant differences among profile groups (Tuckey significant difference).

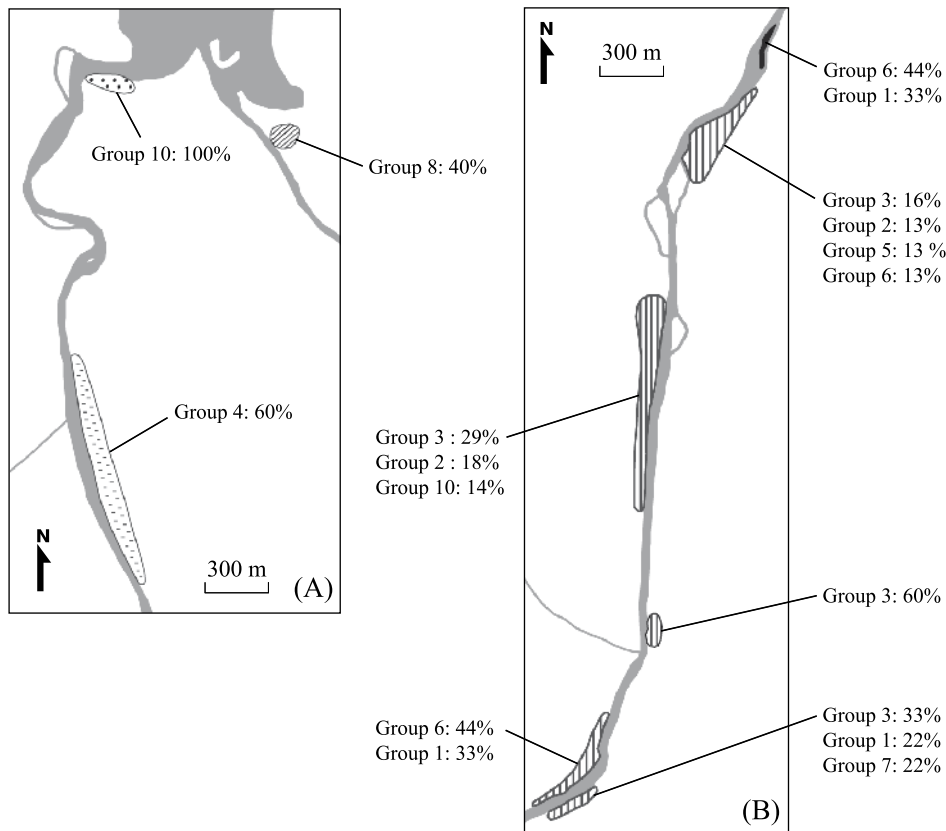


Fig. 3.12. Relative location of different profile groups within the two major study areas of floodplain landscape: a) downstream area; b) upstream area. This distribution reflects the location of the statistical abstractions of soil properties, rather than distributions of real soils. Dominant profile groups are calculated for each distinct investigated zone.

nerally shows profiles with one or more horizons from groups XIV and VIII, which are also typical for group 3. Most of the profiles are found in this last group where intermediate values are observed between groups 1–2 and 4, except for the number of horizons (1 to 4). Group 5 is characterized by various total thickness (but thicker than groups 1 to 4) and the number of horizons. Horizons from group X (medium coarse sand with oxidation marks) are not seen in group 6. The high values of indexes are very typical for groups 6 and 7, but to a lesser extent in the latter. The particularity of groups 7 and 8 is the presence of horizons of group XII, illustrating visible hydromorphic conditions. In addition, group 8 shows a high total thickness and the presence of more than one horizon of group II.

The index nb/m is also a discriminating factor for some groups, for example this index is quite low for group 9, which is also characterized by a few numbers of horizons (similar to groups 1 to 5) classified in group VI. The presence of a temporary or seasonal water table, shown with the presence of horizons of groups I and II, is a characteristic of group 10. In this last group, the number of horizons is high with a great variety, and the profiles are quite deep.

The results in fig. 3.13 show significant correlations between some horizon factors. The texture parameters vary differently with the depth, the thickness and the macrorest factor. The most striking relation is the positive correlation between the oxidation marks and the depth of the horizon. Fig. 3.14 exposes other positive correlations for the profile parameters. The important correlation between the total thickness and the number of horizons is particularly interesting ($r = 0.667$).

3.6. Discussion

3.6.1. Profiles description

The results of the clustering show different groups of alluvial soils, corresponding to the different processes of erosion and deposition combined with those of gleying, as well as the spatial variability of fluvial soils. The abstract representations show the discriminating parameter between the different types of soils being mainly the soil texture of the horizons, reflecting the variety of alluvial deposits. The 10 profile groups illustrate different types of sedimentation, when terraces reached by floods, and the various natures of these fluvial deposits.

	Silt	Fine sand	Medium sand	Coarse sand	Gravels and pebbles	Oxidations marks
Depth	-0.11*	0.25***	-0.17**	0.17**		0.30***
Thickness	0.19**				0.10*	
Macrorestes						0.16**

(*** p-value < 0.001, ** p-value < 0.01, * p-value < 0.05)

Fig. 3.13. Pearson moment correlation (r) between the horizon factors (Sarine River alone).

1	Total thickness			
2	Number of horizons	0.67**		
3	I horizon	0.34**	0.59**	
4	VII horizon	0.51**	0.25**	0.22*
5	XIII horizon	0.49**	0.52**	0.48**
		1	2	3

(** p-value < 0.01, * p-value < 0.05; in bold = value used for discussion)

Fig. 3.14. Pearson moment correlation (r) between the profile factors (Sarine River alone).

Among the 109 profiles described in the field, a representative real profile of each group has been chosen and is roughly and schematically drawn in fig. 3.15. Fig. 3.16 shows a summary of their particular characteristics. The presence of coarse material suggests a sedimentation process with a rapid flow velocity. Thick horizons covering the pebble limit and only buried by a topsoil horizon with weak soil structure means that the zone is still submitted to intense flooding (representative profiles of groups 2 and 3). Fine, thin sediment layers describe an active sedimentation, but with a slow flow velocity, as seen in a representative profile of group 6 (Gerard, 1987; Bridge and Gabel, 1992; Owens *et al.*, 1999). A vertical sequence, with several thin horizons at the bottom and a well-developed A horizon on the top, can be explained by floodplain stability sufficiently long to generate pedogenic features as soil structure. This stability could be due to the construction of embankments and dams built since about 1920 along the Sarine River. These structures have progressively modified the flow patterns and the spatial distribution of deposits, hence influencing soil formation (as seen in representative profiles of groups 7 and 8). Thick deposits with clear boundary distinctness, as seen in representative profile 9, suggest important events of smooth sedimentation with slow flow velocity. The representative profile of group 10 is deep, indicating an important sedimentation process as well as the presence of fluctuating waterlogging identified by oxidation features. This variation of the water table is due to the exploitation of the Rossens dam situated at the north shore of the Gruyère Lake. Every summer, the lake level increases (up to 15 m higher than the winter level) and slightly inundates the zone covered with various textural sediments.

3.6.2. Soil formation

The parameters distinguishing the formation of these different profiles are dominated by sedimentologic rather than pedogenic features, except for topsoil or buried organo-mineral horizons. The variable stratification found among the profiles suggests a spatial variation throughout the study area

and is involved in the soil formation. The vertical sequences of distinct layers contain features reflecting the complex history of the site and should be clearly identified and explained. For example, oxidation marks are preferably found in the deeper zones where coarse sands are more frequently described. This means an active sedimentation with high flows in the depth, thus in the past, with processes of hydromorphism. Even if fine-textured deposits (silts) are more frequently detected on the top, no oxidation marks are visible by the naked eye.

The results of the correlation analyses between the different descriptive factors show a close linear relationship between the total thickness of the profile and the number of horizons. This result may be obvious in many cases, but not in an alluvial context, characterized by a very important spatial and vertical heterogeneity. In the case of the Sarine floodplain, this relationship is relevant to identify the sedimentary processes and can be explained by two schematic types of stratification: the regular and the irregular type.

The regular type, homogeneous option with facies model 1 in fig. 3.17, suggests that fluvial deposits are equally distributed in space and time. The number of horizons grows regularly with soil thickness formation and the thickness of each horizon is still equivalent. However, except for a few cases, this possibility seems to be very unlikely in the field because of various changes taken place since the beginning of the 20th century (Mendonça Santos and Claramunt, 2001; Guex *et al.*, 2003). These changes are both hydrological (current speed, processes of sedimentation modified by the construction of embankments and dams) and historical (land-use and management).

The irregular type, combined option, with facies models 2 to 4 in fig. 3.17, is indicative of distinct units in space and time. It presents an obligatory combination of several kinds of formations, inducing a soil mosaic. For example, several thin layers can (over time) cover a thick deposit (facies model 2, e. g., profile group 3) or, on the contrary, be covered by a thick layer (facies model 3, represented for example by profile group 9). Multiple thick and

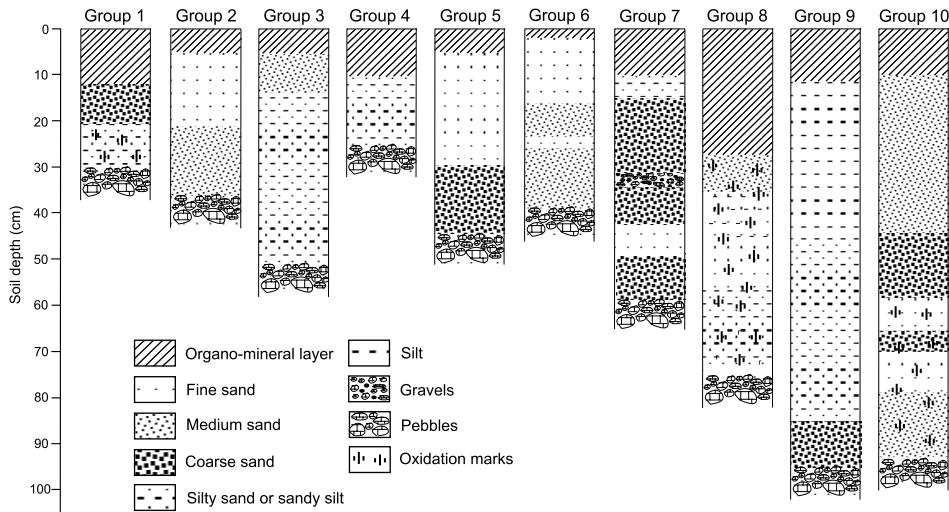


Fig. 3.15. Most representative profile of each group (group 1 to group 10).

Representative profiles	Vertical sequence	Texture parameter	Other parameters	Type of alluvial zone	Velocity of current and duration of flood
Group 1 n = 12	Reduced thickness; few horizons	Coarse material	Oxidation marks	Active zone	Rapid flow velocity and short flood duration
Group 2 n = 11	Reduced thickness; quite few horizons	Medium coarse material	Reduced A horizon development	Active zone	Medium flow velocity and flood duration
Group 3 n = 24	Reduced thickness; few horizons	Fine sediment at the bottom and medium on the top	Reduced A horizon development	Active zone or embanked zone potentially reached by flood	Slow flow velocity first, then faster
Group 4 n = 9	Reduced thickness; few horizons	Fine material	Development of A horizon	Past active zone, but embanked now	Slow flow velocity and quite long flood duration, no more events now
Group 5 n = 9	Moderate thickness; few horizons	Coarse material at the bottom and finer on the top	Reduced A horizon development	Past zone or embanked zone potentially reached by flood	Slow flow velocity and long flood duration
Group 6 n = 13	Reduced thickness; many horizons	Medium to fine material	Reduced A horizon development	Active zone	Slow flow velocity, but short flood duration
Group 7 n = 6	Moderate thickness; many horizons	Very coarse material at the bottom and finer on the top	Development of A horizon	Past active zone, but embanked now	First, rapid flow velocity, then slower; various flood duration
Group 8 n = 3	High thickness; many horizons	Alternation of medium and fine material	Oxidation marks and thick A horizon	Past active zone, but embanked now	Slow flow velocity, with quite long floods ; no more event now
Group 9 n = 12	High thickness; few horizons	Coarse material at the bottom and fine material on the top	Development of A horizon	Past active zone, but embanked now	Important events of sedimentation with slow flow and smooth sedimentation
Group 10 n = 10	High thickness; many horizons	Alternation of coarse and fine material	Oxidation marks	Past active zone, but embanked now, potentially reached by floods	Important sedimentation processes with alternation of rapid and slow flow velocity and long and short flood periods

Fig. 3.16. Summary of representative profile characteristics (see also fig. 3.11).

thin buried depositions can also be superposed as illustrated by facies model 4 (e. g., profile group 7). Periods of stability can be identified by the presence of a buried A horizon (*Ab* according to the World Reference Base of Soil Resources, ISSS Working Group, 1998) and succeed to periods of sedimen-

tation. Gerrard (1987) explained this succession of buried (or multiple buried) soils as a recurrent cycle of stable and unstable phases of landscape evolution. Thus, the combined option integrating facies models 2, 3, and 4 seems to be more relevant for explaining the general increase of number of horizons with thickness than the homogeneous option (facies model 1). The explanations are hydrological (river flow instability), geological, and geomorphological (variable floodplain morphology), as well as historical (human disturbance). Moreover, to follow the particular relationship between the profile thickness and the number of horizons throughout the studied area, only some combinations of these four models can be taken into account (fig. 3.18).

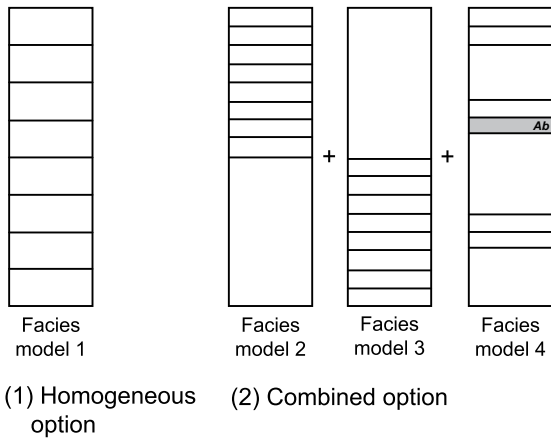
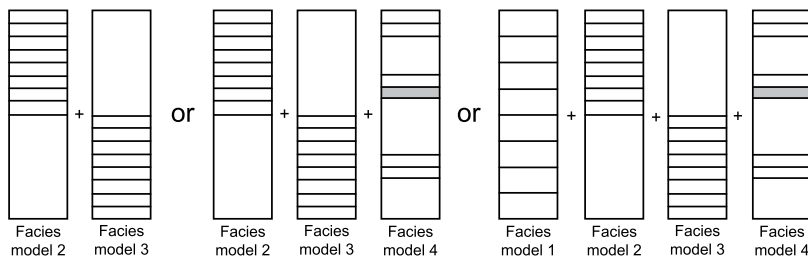


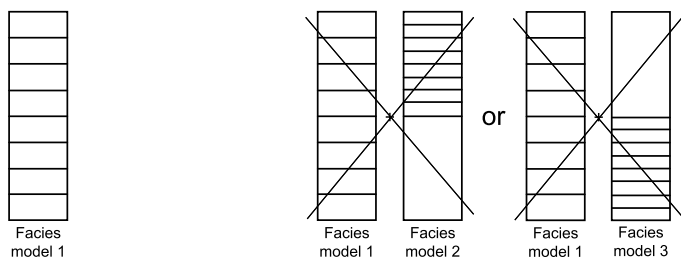
Fig. 3.17. Representation of two types of stratification - options 1) and 2) - illustrated by four facies models (1 to 4) and due to the linear relationship between the total thickness of the profile and the number of horizons found in the vertical sequence. The homogeneous option means that fluvial deposits are regular in space and time. The combined option suggests distinct units in space and time that should be combined to induce soil mosaic (*Ab* = buried organo-mineral horizon, according to ISSS Working Group RB, 1998).

3.6.3. Validation of facies models

In order to explain the soil formation in the valley, these schematical facies models, describing superficial deposits overlaying past conditions because of natural floods or human interventions, have now to be distinguished at a larger scale. In fact, our results can be explained at the Sarine floodplain scale level representing the functional set according to Petts and Amoros (1996). The four facies models show different alluvial formation contexts associating regular sedimentation with cumulative and multiple buried soils, illustrated by succession of



(A) Combinations explaining the particular relationship between the profile thickness and the number of horizons



(B) Unlikely combinaison

(C) Impossible combinaisons

Fig. 3.18. Combinations of the four models that can be taken into account to explain the particular relationship between the profile thickness and the number of horizons. These four extreme schemas (three for a, and one for b) represent conceptual explanatory facies models, but some intermediate cases certainly exist.

stable and unstable phases of deposition. In case of stability, soil pedogenic features with development of recognizable A horizon and accumulation of organic carbon provide evidence of periods of variable stability. At the temporal scale this periodic alternation of stable and unstable phases (meaning regularity and irregularity) is considered as stable in medium and long term and guarantees the maintenance of stability in the river environment.

It is thus fundamental to observe both regular (meaning development of soil pedogenic features) and irregular (in term of natural floods) periods at the functional set level of the river environment. This temporal hierarchy can also be related to the spatial hierarchy with the same succession of stability and instability periods (Auger *et al.*, 1992). The temporal process is, however, also stable at a long-term scale (or large spatial scale) with a combination of short-term instabilities regularly occurring in different habitats (Naiman and Bilby, 1998).

As seen above, each facies model can be used to explain concrete situations at a small scale in the field. They permit also generalization at a larger scale and may be used as “erasers” of local differences. What is important in the differentiation between these two situations is the scale.

3.6.4. Facies models and other soil classifications

Facies models illustrated in this study with the use of simple indicators help to describe in a rapid, simple and inexpensive way the soils of the Sarine floodplain. This method could be compared to the organization of References and Types of the “*Référentiel Pédologique*” (AFES, 1998) that is not necessarily associated to a spatial analysis, but assemble groups recognized as being associated although having ill-defined limits. Thus, it is not a new soil mapping technique (using kriging and GIS methods like fuzzy soil mapping), but a soil survey method that could help to investigate rapidly the soils of an entire floodplain valley. Nevertheless, it could be compared with the fuzzy soil mapping as mentioned by Shi *et al.* (2004) or the indicator kriging approach (Bierkens and Burrough, 1993) that

exclude the problems related with the high costs (on money, labour and time) and the high subjectivity associated with the standard soil surveys. These approaches, using mathematical equations, share some similarities with our facies models in terms of soil properties and combinations. They can be used to show the depth of different horizons or the texture of A horizon (Shi *et al.*, 2004). If the indicator kriging approach can be used for predicting categorical soil data and producing maps with defined boundaries, our facies models can interpret soil data at different scale levels - in space and time - and relate these levels to ancient landscape descriptions and floodplain evolution.

3.7. Results for the three rivers

3.7.1. Evaluation of the horizon parameters

The results presented in fig 3.19 show significant correlations between some of the horizon parameters. For example, coarse sand content, oxidation marks and macrorests are more present in the deepest horizons. These results are comparable to those found in the Sarine River (see paragraph 3.5).

The clustering separates 11 groups of horizons (named group I to XI; fig. 3.20). They differ from each other principally in the presence of macrorests (group VII), their texture and then in their thickness combined with the presence of oxidation marks. Group I consists of relatively thin and deep layers with a very coarse texture (gravels and pebbles, coarse sand). Group II also presents a coarse texture (coarse sand with no fine sand), but without any gravel and pebble. Groups III and IV are characterized by medium sand, but fine sand defines also group III that is found on the top of the solum while group IV is present deeper. Some oxidation marks can be found in these four first groups. Group V and VI do not show any oxidation marks, as well as medium and coarse sand. Group V is the shallowest and the thinnest group, while group VI is the most represented one (15%). Group VII is the only one that shows macrorests and is more found in the depth. Its texture is quite coarse with

	Ox	Pebbles	Silt	Fine sand	Medium sand	Coarse sand	Depth	Macrorest
Fine sand		-0.18***						
Medium sand			-0.35***	-0.25***				
Coarse sand		0.26***	-0.26***	-0.56***	-0.19***			
Depth	0.29***	0.08*			-0.10***	0.19***		0.13***
Thickness	0.14***						-0.09*	

*** p-value < 0.0001 * p-value < 0.01

Fig. 3.19. Pearson moment correlation (*r*) between the horizon factors (the three study areas; n = 652).

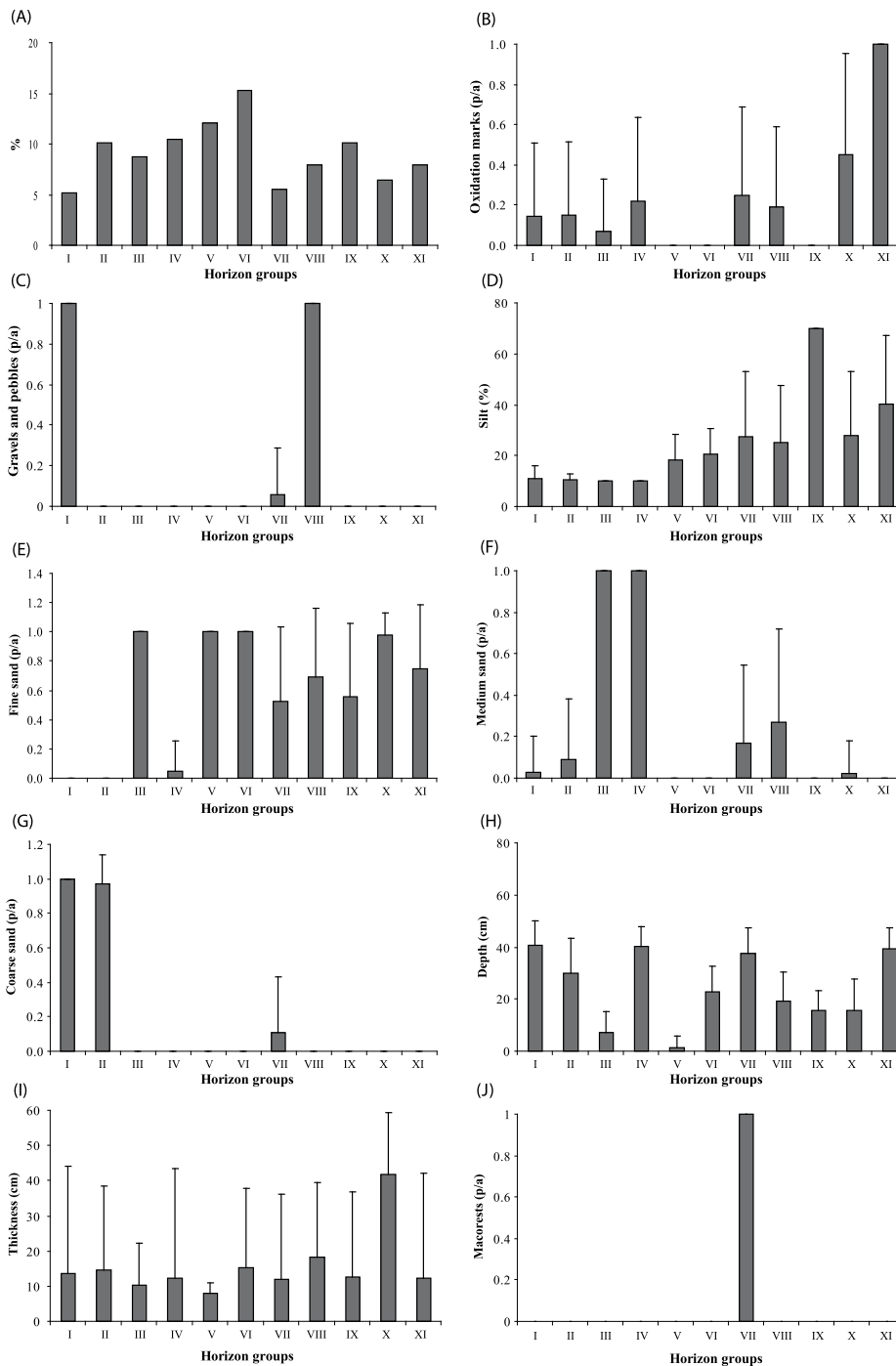


Fig. 3.20. Characteristics of the different horizon groups as identified by Ward's minimum variance clustering. Average values for each group, a) occurrence of horizon groups (in %), b) presence/absence of oxidations marks (0/1), c) presence/absence of gravels and pebbles (0/1), d) silt proportion (in %), e) presence or absence of fine sand (0/1), f) presence or absence of medium sand (p/a), g) presence or absence of coarse sand (p/a), h) upper limit of the horizon (in cm), i) thickness of the horizon (in cm), j) presence or absence of macrorests (0/1). Standard deviation in bars (n = 652).

presence of gravels and pebbles, as well as some coarse sand. Group VIII is characterized by gravels and pebbles with some oxidation marks. The silty textural horizons without any oxidation mark are represented by group IX, while the thickest group X is defined by a fine sandy texture with oxidation marks. Finally, group XI is found in the depth and is also illustrated by a fine sandy texture with oxidation marks.

3.7.2. Comparison between horizon groups of the three systems

Concerning the distribution of each group in the different rivers (fig. 3.21), a differential table (or synoptic table, built according to the phytosociological methodology as seen in Decocq, 2002) was established in order to find the differential horizon groups (fig. 3.22). In this figure, we observe that groups III, VI and IX (little oxidation marks, silty to fine sandy texture and not very deep) are present more frequently in the Sarine site. Groups VII and VIII (gravels and pebbles, medium oxidation marks and presence of macrorests) differentiate the Rhine River while groups V and X (fine sandy texture without any coarse material, variable oxidation marks and thickness, but shallower) are more present at the Ticino site. Finally, groups I, II and IV, found in depth with coarse textural parameter gravels and

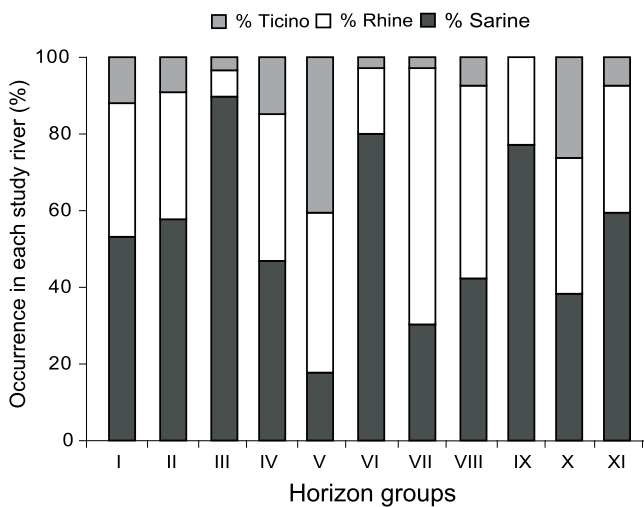


Fig. 3.21. Occurrence of horizon groups in the different study rivers (n = 652).

Horizon group	Sarine River	Rhine River	Ticino River
III	* 89 ¹⁾		
VI	* 80		
IX	* 77		
VII	+	* 67	
VIII	+	* 50	
V			* 41
X		+	* 26
XI	x	x	
II	x	x	x
I	x	x	x
IV	x	x	x

¹⁾ number of horizon occurrence
 * = horizon dominance
 + = horizon presence

Fig. 3.22. Differential table permitting to detect horizon groups characteristic or common to each study area (n = 652).

pebbles, coarse sand and medium sand, are described in the three sites.

3.7.3. Evaluation of the different soil profile parameters

The results in fig. 3.23 show significant positive correlations between some profile parameters. The most interesting one is the relationship between the number of horizons and the total depth of the profile ($r = 0.64$). We can also notice that some horizons are preferentially found in the depth, like for example groups I and IV characterized by coarse material. The number of horizons is also positively correlated with groups I, II, IV and VII, which are defined as deep horizons.

Profile groups are separated by the factors of total thickness (16 to 93 cm) and number of horizons (2 to 8 horizons; fig. 3.24). Groups 1 and 2 reveal profiles with several horizons (8) and a relatively high total thickness (71 to 93 cm). Moreover, group 1 is characterized by the horizon VII that reflects the presence of macrorests, while the horizon XI is distinctive of group 2. Horizon X is typical of group 3, in which most of the profiles are found (18%), as group 4 is particularly shallow with a high nb/thick index (0.16). Groups 5 and 6 represented each 17% of the total profiles and the group 6 is defined by the horizon VI. Horizon V is characteristic of groups 7

	A	B	C	D	E	F	G	I	Depth	Indice
E			-0.23**							
F					-0.21**					
G	0.16*	0.29***		0.26***						
H			-0.16*	-0.22**		-0.20**				
I	0.22**				-0.20**					
Depth	0.25***			0.38***		0.16*	0.24**	0.24***		
Indice		0.41***	0.22**				0.19**		-0.44***	
Nb	0.45***	0.46***		0.50***		0.32***	0.48***	0.33***	0.64***	0.28***

*** p-value < 0.0001 ** p-value < 0.001 * p value < 0.01

Fig. 3.23. Pearson moment correlation (r) between the profile factors (the three study areas; $n = 181$).

and 8, this last one is in addition very deep (mean of 78 cm). Groups 9 and 10 present intermediate values for the total thickness and the number of horizons, but with a high presence of horizon VIII in group 9. We can also observe that groups 1 and 4 are only found in natural zones, while groups 7 and 8 where more observed in embanked zones (fig. 3.25). Finally, open environment without vegetation is only found in group 1, as every point described in group 4 is found in forested vegetation (fig. 3.26). Most of the points described in meadow and pasture environments are present in groups 8, 9 and 10, while group 9 is only characterized by forest and meadow and pasture land points.

3.7.4. Distribution of soil groups among the three systems

About the repartition of each group in the different rivers (fig. 3.27), it appears that groups 4, 5, 6, and 10 are more present in the Sarine River. Groups 1, 8 and 9 occur particularly in the Rhine River, while groups 3, 7 and 8 are more abundantly found in the Ticino River.

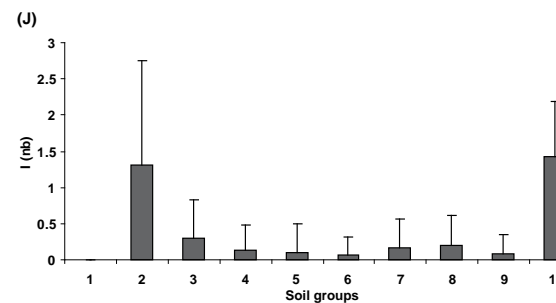
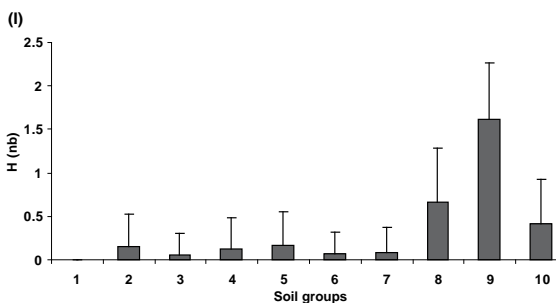
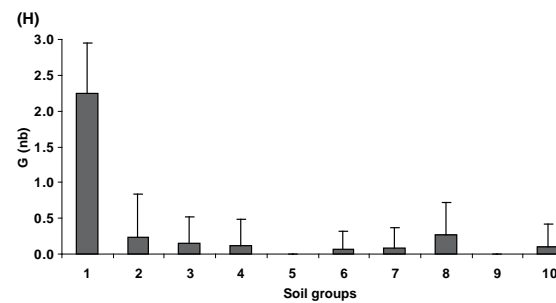
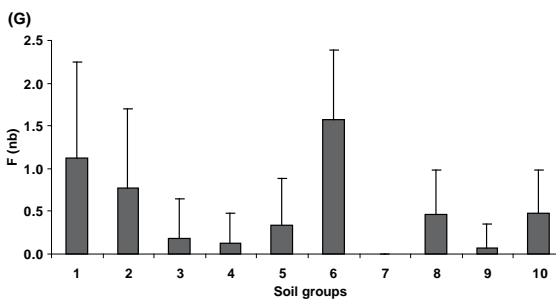
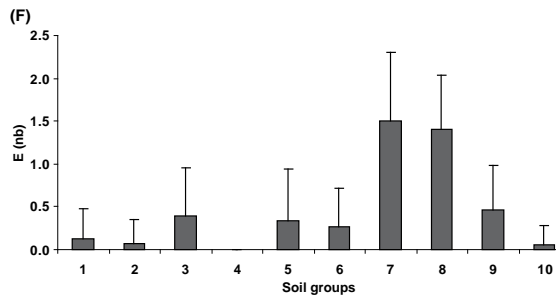
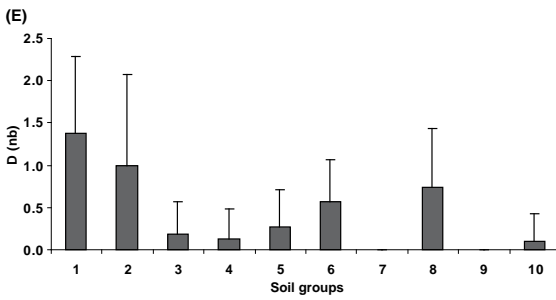
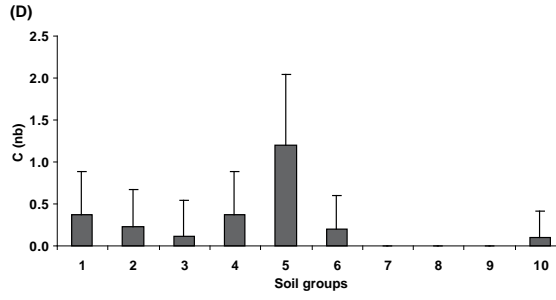
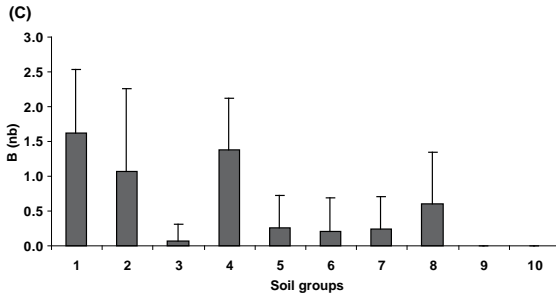
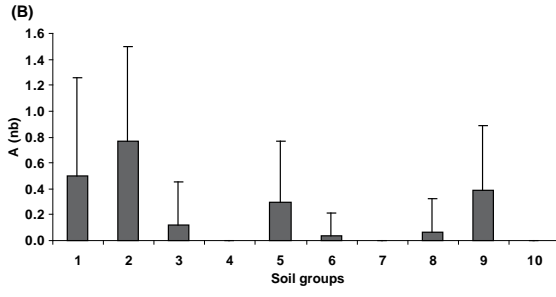
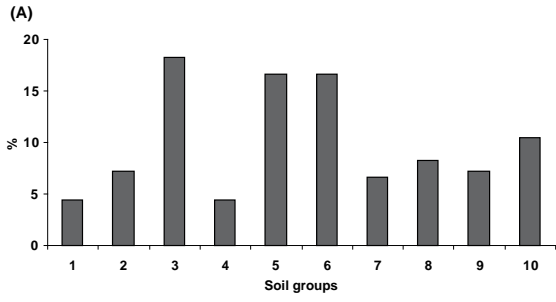
3.8. Discussion

3.8.1. Horizons parameters

A high degree of horizon variability is observed in the three sampled areas. This study shows that coarse material is rather found in the deepest horizons reflecting a past alluvial activity with transport of gravels and pebbles, as well as coarse sand. This was only possible when environmental conditions were disturbed with high-velocity flood flows. Indeed, in the past (before the 20th century) no embankment or dam was built, causing a stron-

gest flow discharge and the highest rate of coarse material transported (OFEG, 2003). The same observation was made in the Lower Missouri, where a decrease in flow velocity appears over time (Pinter and Heine, 2004; Steiger *et al.*, 1998), or in the Rhone River, where a decrease of sediment load was observed up to a mean of 78% between 1895 and 1995 (Arnaud-Fassetta, 2003). He explained this change by a reduction of runoff and of the occurrence of large flooding events in relation with the end of the Little Ice Age and also by major human disturbances. Since the rivers have been controlled, flow and sediment supply have been modified, and gravel bars were colonized by vegetation playing the role of filter for finer sediments and retaining them. Thus, the upper horizons show finer texture sediments (fine sand) that can be accentuated by the establishment of vegetation and shrubs (Gilvear and Willby, 2006). Then, newly created land surfaces on floodplains can be colonized by plants whose seeds can be transported by wind, animal vectors or water (Brown, 1996).

Another factor studied here are the oxidations marks, which in our study are generally found in the deepest soil horizons. This observation reflects that hydromorphic phenomena take place in the deepness. Texture is therefore not the only parameter concerned in oxidation-reduction processes. In spite of coarse particle size, oxidation marks are visible in the deepness when nothing is really detected on surface despite a finest texture. So, possibility of perched ground water may then be excluded. Indeed, retention in water requires even finest particles (fine silt and clay), which are transported downstream, and thus not found in torrential flows.



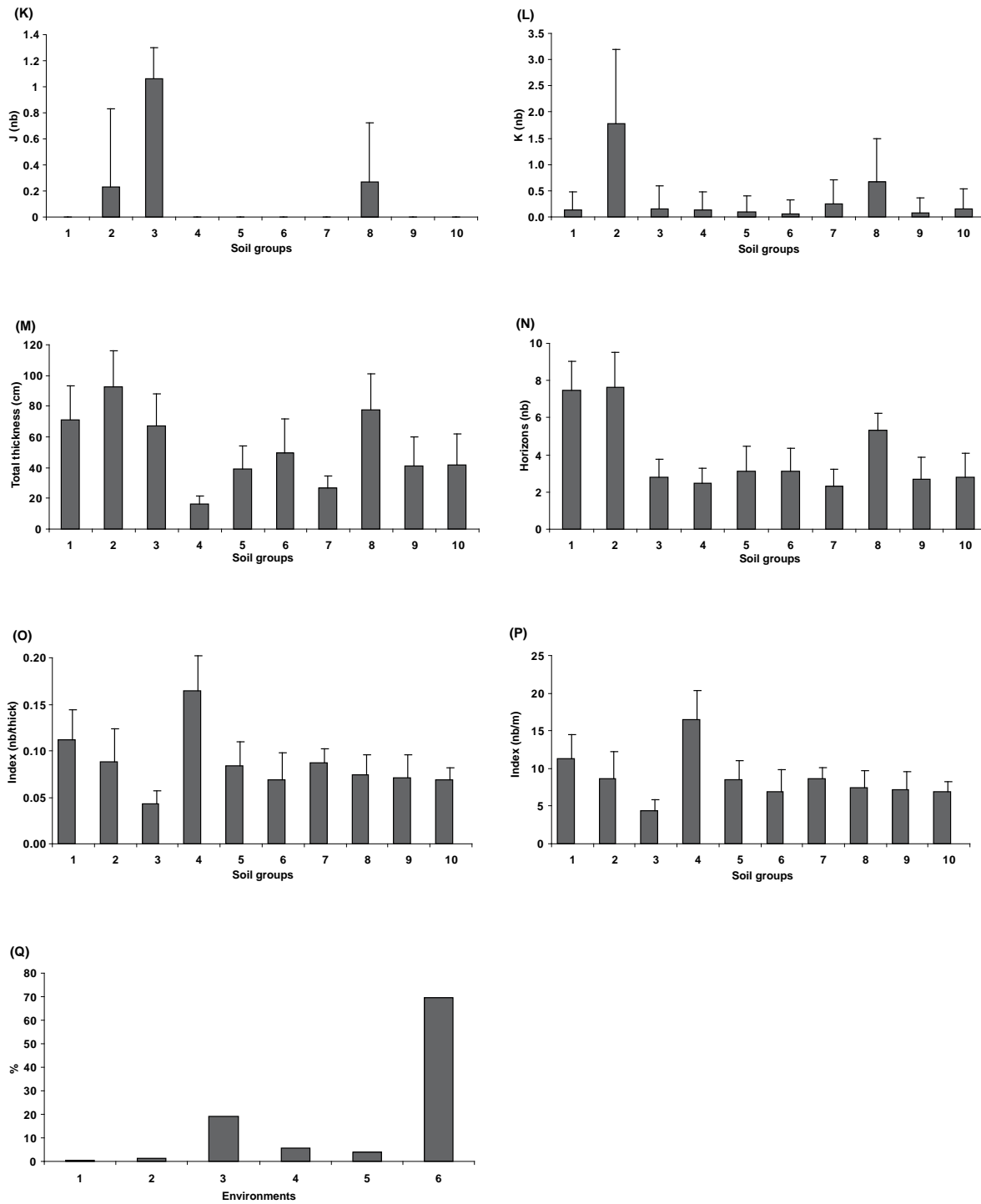


Fig. 3.24. Characteristics of the different soil groups as identified by Ward's minimum variance clustering. Average values for, a) occurrence of soil groups (in %), b-l) number (nb) of horizon groups in each soil group, m) total thickness of profile groups (in cm), n) number of horizons in each soil group (nb), o) index "number of horizons on the total thickness" (nb/thick), p) index "number of horizons per meter" (nb/m), and q) proportion of each studied environment type (in %). Standard deviation in bars (n = 181).

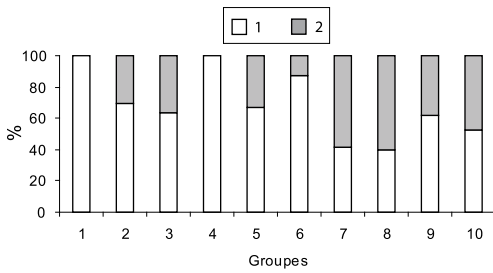


Fig. 3.25. Repartition of soil groups in each zone type (1 = natural; 2 = embanked; n = 181).

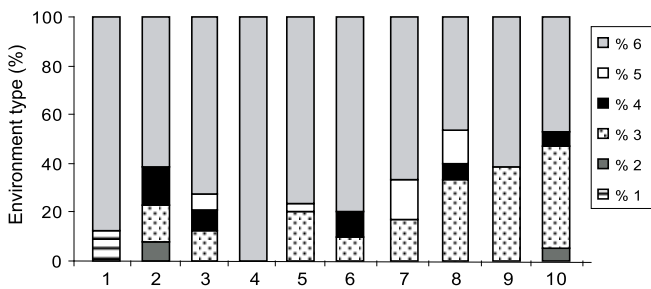


Fig. 3.26. Repartition of each soil groups in each environment type (1 = open, no vegetation, 2 = open, with herbaceous vegetation, 3 = meadow and pasture, 4 = field land, 5 = bushes and 6 = forests; n = 181).

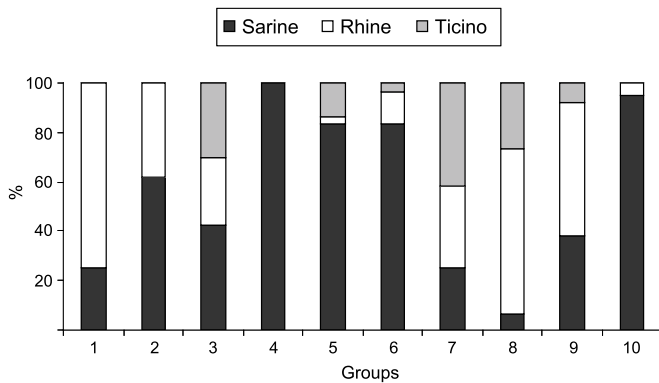


Fig. 3.27. Repartition of each soil group in the different river systems (n = 181).

Another factor, horizon thickness, is also correlated with oxidation marks (an increase of oxidations marks is observed with an increase of horizon thickness). This result could be explained by the fact that in a thick horizon oxidation marks are more easily visible to the naked eye. Nevertheless, this result is surprising especially as horizon thick-

ness is negatively correlated with deepness. We could then propose an explanation that in the depth the horizons are compressed because of the effect of auger sampling. This technique of description is easy, time-less, but still approximate.

The other material that is also found in the depth is macrorests proving an occurrence of alluvial activity in the past, when erosion and sedimentation were sufficient. In fact, the presence of weakly developed organic matter or debris reflects rapid deposition of sediment (McCarthy and Plint, 1999) and a presence of water permitting to conserve them. Moreover, these organic fragments were not degraded, reflecting unstable conditions (hydromorphy, frequent sedimentation) preventing organic matter degradation and humification (Gobat *et al.*, 2004).

3.8.2. Horizon group distribution among the three rivers

The results show that horizons found in the *Sarine River* present a silty-fine sandy texture with little coarse material (groups III, VI, and IX). In addition, these horizons are found on the top of the soil with a medium thickness, proving a reduction in sediment supply due to the construction of dams in the upper course, and because of colonization by forests. Once again, these results could be explained by the filter function of the vegetation, causing a deposition of the finest particles giving good conditions for seeds to germinate (Girel, 1996). This has already been demonstrated on the same river, but at a finer scale, with the filter effect of the mosses contributing to the thickening of the organo-mineral horizon (Arnold and Gobat, 1998). In this last study, the filter effect leads to a modification of the original texture with the deposit of finest sediments, which allows the settlement of mosses and stabilises the ground. The formation of a thin organo-mineral horizon is then progressively enriched in organic matter and fine mineral particles. Thus, on an alluvial ground composed of rocks, stones and gravels deposited by strong currents, the bryophytes play a major role in the very initial stages of the pedogenesis.

In the case of the *Rhine River*, horizons exhibit a coarse texture (gravels and coarse sand) with macrorests and some oxidation marks (groups VII and VIII). As overbank deposition is largely related to the magnitude and frequency of flood discharges (Benedetti, 2003), these parameters suggest a past and current activity even if the Upper Rhine River has been modified and embanked. In a study carried out in Wisconsin (USA), overbank deposits were characterized showing complete different results (Lecce and Pavlowsky, 2004). They found that throughout the historical period floodplain (settlement and agricultural development of the region appeared in the 1830s) deposits have become increasingly rich in sand. They give the explanation that historical change in land use practises, increasing surface runoff, produced higher flood discharges capable to suspend and transport coarser sediment. These variations in space and time of deposited materials can indicate, in the Rhine River, that the development of agricultural practices have not changed the characteristics of the valley in such a point that discharge flows got higher. On the contrary, due to diversion of streams in high-altitude stations, water budget has been completely altered and very little water is left.

In the *Ticino River*, horizons present a fine texture (fine sand) without coarse material, but with variable oxidations marks and thickness (groups V and X). These types of horizons are more found on the top of soil and look like horizon groups of Sarine River. The main difference lies in the hydrological regime that differs from one river to another. In Ticino River, the input of lateral streams is regular with more or less stable discharge flows. This river may be assimilated to meandering rivers found in the plain. Moreover, the characteristics of bed and bank material also differ: gneiss for Ticino and calcareous and loam rocks for Sarine study site. The gneiss forms an impermeable funnel where flow discharges could be very rapid, even if granite materials have low erosion rates (Campy and Macaire, 2003), as the karst substratum of the Gruyère area allows a better regulation of the current. These differences in hydrology and geology are thus detected in the succession of horizons at the regional level.

Another group (group XI) reflects at the same time horizons from the Sarine and Rhine sites, but is absent in the Ticino site, as seen in the differential table (fig. 3.22). Its texture is fine (silt and fine sand) with oxidations marks and is more found in depth. These parameters (fine-textured, oxidation-reduction phenomena and deepness) could be a feature of the Northern Alps.

Three groups are common for the three studied areas (groups I, II, and IV) showing a coarse texture (gravels and pebbles, coarse and medium sand) more in the depth. They represent invariants for the Alpine floodplain conditions. We could then conclude that the three studied floodplains were active in the past, and because of human modifications the alluvial activity, as well as the channel morphology, had changed. These changes have also been described for other rivers in Europe (Arnaud-Fassetta, 2003; Surian and Rinaldi, 2003; Owens and Walling, 2002) or in the United States (Florsheim and Mount, 2003; Pinter and Heine, 2004). It appears clearly that general changes have been detected for a variety of world areas where observed modifications are diverse (Gregory, 1977). Our findings detected in the Alpine Arc are not exceptions and can be generalised to other floodplain systems, even in plains.

3.8.3. Profile parameters

The results of observations made in the field and statistical analyses suggest that the number of horizons strongly depends on the total thickness of the profile, as already observed for the Sarine River (Bullinger-Weber and Gobat, 2006). Thus, our facies models found in the case of the Sarine River are still valuable for our general analysis (see paragraph 3.6.2). The same mechanisms are then observed with different alluvial formation contexts associating regular sedimentation, with cumulative and multiple buried soils illustrated by succession of stable and unstable phases of deposition.

Some groups of horizon found in the three study areas (groups I, IV) also increase significantly with the increase of the thickness. This illustrates again a past alluvial activity (coarse material in depth) in

the three study sites even if time is not directly correlated to the depth. Changes in flow discharge or reworking could have happened and modified the general conditions.

3.8.4. Profile group distribution among the three rivers

The analysis of the distribution of each group in the three studied sites shows that profiles in Sarine River (groups 4, 5, 6, and 10) present a thinner total thickness than profiles of Rhine (groups 1, 8, and 9) and Ticino River (groups 3, 7, and 8). This trend is confirmed by group 8, common to these two last rivers, presenting deep profiles with presence of horizon V (no oxidation mark, fine sand, and on the top of soil) and XI (oxidation marks are found in the depth), and reflecting one more time a high alluvial activity in the past. This tendency is confirmed in fig. 3.28, where horizon V is defined as the discriminating horizon group between the Sarine River and the Rhine and Ticino Rivers. The difference between profiles found in Rhine River and those in Ticino River is the total thickness, but this result is not clearly laid down (fig. 3.29).

However, groups described in Sarine and Rhine sites (groups 1 and 4 for example) are found in natural environment, while those from Ticino are more in embanked zones. This observation may also be due to a sampling effect, because less auger cores in natural environment were described in the

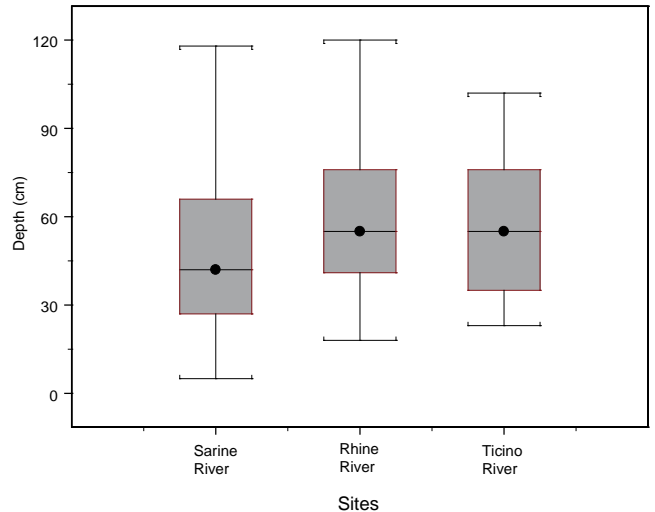


Fig. 3.29. Total thickness means of described auger sampling in the three study river systems. Error bars indicate standard error, and median is also illustrated in each box plot (n = 181).

Ticino site (only 12% of the auger cores described) than in the Sarine and Rhine sites (58% and 57% respectively). This difference is due to the thickness of soil profiles higher in Ticino site implying that a lot of cores were exceeded the auger limit, and could then not be used for the statistical analysis. An elimination of 40% of described points was necessary for the Ticino site, when only 19% (for the Rhine River) and 18% (for the Sarine River) of the total points have been excluded for the analysis.

In our study, we illustrate that soil cover is thicker in the Sarine River area than in the two other sites. Alluvial soils are not only indicators of the

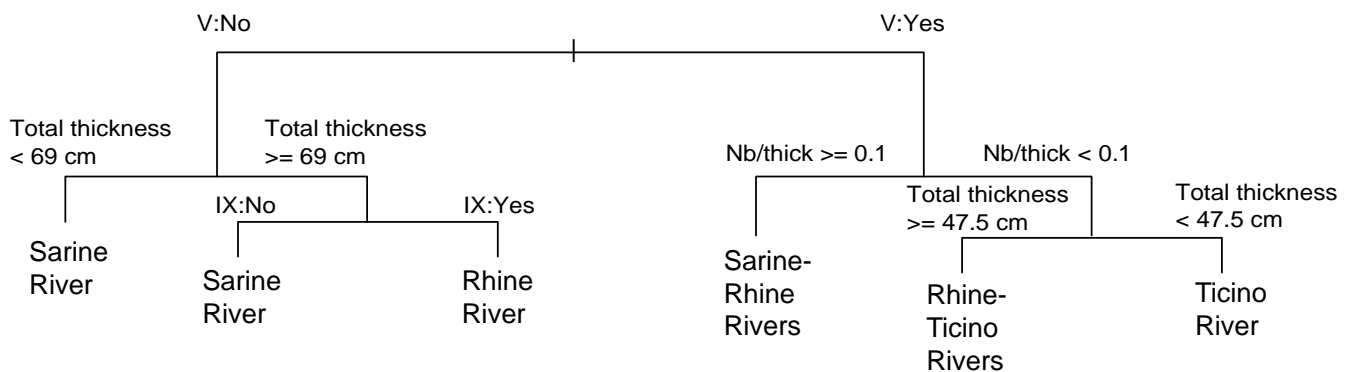


Fig. 3.28. Simplified dendrogram obtained by means of Ward’s minimum variance clustering and taken account of the different group parameters of the three river floodplains. The group fusion level is defined by a distance and the discriminating attributes are obtained after a regression tree in R Software (version 2.0.1; R Development Core Team, 2004). See fig. 3.24 for parameter designation.

local landscape evolution, but also reflect, in their horizon stratification, the local hydro-geological conditions of their catchment areas. This is the reason why alluvial soils are such original soils that differentiate them from others soils like brown soils or luvisols, depending essentially from pedogenic features and processes.

3.9. Conclusion

Firstly, the example of the Sarine River valley in the NW of the Swiss Alps shows that the soil formation in alluvial environment is highly heterogeneous and reveals distinctive sedimentologic and pedogenetic characteristics. Frequent depositional disturbances from flooding, as well as erosional processes that are very difficult to exhibit, create a complex mosaic of soil conditions that fundamentally influences vegetation colonization and establishment. Moreover, embanked zones show completely different conditions such as isolation of the river from its floodplain and suspension of

aggradation. This study provides abstractions of field information documenting different models of sedimentation that are necessary to improve our understanding on development and evolution of embanked floodplains. Consequently, the studied Sarine floodplain can be described schematically as a mosaic of four major facies models of soil development (fig. 3.30). It represents a combination of sedimentation and soil development. Buried soils are thus formed, which characterize particular functional floodplain units. The study of these different conceptual facies representing the evolution in time is an essential contribution to explain landscape history of each unit of the Sarine floodplain and to fix the more appropriate size with a view to global management of the whole floodplain.

By recognizing the combination of some facies models and the impossibility of combining others, the processes leading to soil establishment can be inferred at the functional set level. Therefore, this paper postulates that this full representation of four facies models in the Sarine River indica-

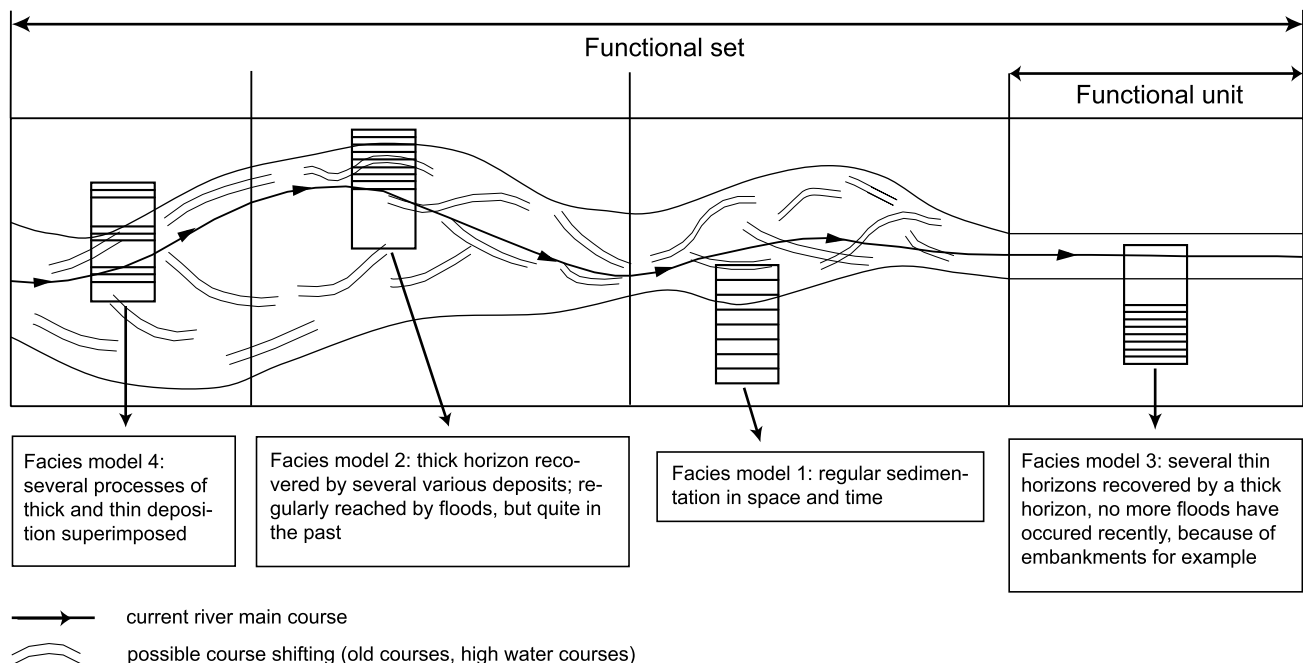


Fig. 3.30. Schematic representation of a possible spatial mosaic of the four facies models along the studied section (facies model 1 to facies model 4). Facies model is described at the functional unit level (Petts and Amoros, 1996) and the combination of facies models has to be considered at the higher functional set level.

tes the conservation of the general alluvial diversity of the entire floodplain. This conservation of riverine ecosystem patterns exists in spite of human modifications over the last 150 years and suggests a high potential for an eventual revitalisation of embanked zones. However, this occurrence of all alluvial facies models at the functional set level does not prevent appearance of “unbalanced” zones at a smaller spatial scale level where only one or two facies models remain. Thus, the *entire floodplain (functional set level), and not only the smaller scale functional alluvial unit, is the seemingly obvious pertinent level needed to understand for the long-term conservation of a complete alluvial system*. A real space - time balance should then exist between the different facies models at a larger scale. This spatial or temporal proportion between models also depends on the damages that the system underwent. Results documenting the different sedimentation models have then great significance for river management and restoration activities in the alpine floodplain context. For example, restoration management in a floodplain section - true and durable - should find the balance between facies models by recreating one model or even more. Improved scientific understanding of sedimentation and soil formation within the embanked fluvial hydrosystem will enhance effective management by finding equilibrium inside all types of floodplain ecosystems.

Secondly, confrontations of the three study areas highlighted similar modifications of soil formation, represented by the description of the same

four facies models. The human role in changing river channels has induced the same consequences, which is now taken into consideration for management of river channels. In the three study sites horizons with coarse material are found in the depth illustrating a past alluvial activity. Nevertheless, it appears clearly distinct particularities among each study area related to the local and regional properties (e. g. geology, hydrology). In the Sarine River, environment is calcareous, relatively natural and pebble layer is rapidly reached. In the case of the Rhine River, soil profiles are thicker, but sands are well represented. However, in the Ticino River, soil profiles are particularly thick, with dominance of silts and fine sands. This last river presents less natural environments and exhibits some properties of a meandering system from hill or plain level.

Auger core samplings permit to get, in a quick and inexpensive manner, results about the soil formation and the general functioning of Alpine floodplain at the river section level (functional set level). Nevertheless, these descriptions are only preliminary steps and are used to choose localisations (at the functional unit or even more the mesohabitat level) for precise typology descriptions. Moreover, genetic interpretation of particular soil properties and features remains rather ambiguous because of the subjective approach of soil descriptions. So, excavation of soil profiles with precise description and specific physicochemical analyses may lead to the identification of soil features prevailing at a specific location in the field.

4. Soil typology of the Sarine River

4.1. Introduction

As seen in the previous chapter, alluvial soils are considered as special soils that exhibit characteristics of both sediment transport and deposition and soil formation (Gerrard, 1987). Their variability is difficult to understand without taking in account the transport and deposition processes in rivers. The soil survey based on auger sampling provided an indication about general variation in soil factors and spatial extent of soils, but did not give precise information about soil properties. Thus, as mentioned by Earl *et al.* (2003), targeted excavations permit to establish soil types and soil variability factors at specific locations within a field. As they are time consuming, profile pits are only practical for a limited number of pits that have to be chosen carefully.

4.1.1. Soil typology

The term “soil types” was first adopted in the United States as a label for mapping units in the first surveys made in 1899 (Eswaran *et al.*, 2003). Later, soil series were introduced in order to group types. The input of Dokuchaev’s concepts of soil formation and distribution has strongly influenced how soils were described and classified (Gerrard, 2000). His classification used names for soil types based on the superimposing of the diagnostic hori-

zons. Nevertheless, soil types were considered to be the base upon which the whole structure of classification rested.

Several studies have already been made on soil classification, among them the Legend of the Soil Map of the World (FAO-UNESCO, 1974; Sumner, 2000) was of great significance. Its specific objectives were numerous, but principally to develop an internationally acceptable framework for delineating soil resources serving of guideline and to which national classifications can be attached and related. It also provided a sound scientific base that can be used in different fields (hydrology, geology, agriculture and ecology). The lateral distribution of soils and soil horizons in a topo- and chronosequences, as well as emphasize of the morphological characterization of soil rather than only analytical approach, were also developed.

About soil typology studies have been carried out in different parts of the world (e. g. Havlicek, 2004; Fiedler *et al.*, 2002; Murashkina *et al.*, 2005), but only few concerned alluvial soils in a pedogenic way (Bureau, 1995; Fierz, 1997; Mendonça Santos, 1999; Alexandrovskiy *et al.*, 2004; Sheremet, 2006), even if several studies have been carried out in sedimentology or geomorphology (see 3.1.2). Detailed information on soil physical and chemical properties provide a good understanding of the relationships between these particular soils and their

historical and geomorphological situation. Pedogenetic features, such as texture, colour or presence of organic layers, have already been used to reconstruct the flood periods (Saint-Laurent and Lavoie, 2004). Then, it appears interesting to establish a soil typology of the Sarine River.

In the framework of the Flood'Alps project, it also emerged important to identify the present-day state of the soil, as well as to understand what was happening in deepness reflecting the history of the study site. Thus, a descriptive typology based on the identification of pedological parameters could indicate some evolution of the soil (morphological and physicochemical parameters), and a comparison to site history was made. To our knowledge, very few studies take these considerations into account and present a combination of soil science and history in an alluvial environment.

4.1.2. Hypothetical model for the soil typology

The aim of this study was to understand the functioning of a floodplain ecosystem. The typology and the sampling were guided by two hypotheses presented in a model containing two axes (fig. 4.1). The horizontal gradient represents a progression between the “lake” situation (“quiet” side where the influence of chemical processes is higher) and the “river” situation (“disturbed” side where physical processes are predominant). The intermediate situation is the case of oxbow (50% water chemistry and 50% physics). The vertical gradient represents a transition between the natural (e. g. willow forest) and the agricultural environments (e. g. field of maize). Thus, a balance between open and forested environments was made. We suppose so that soil alluvial formation depends on these two processes, however, several intermediate forms exist.

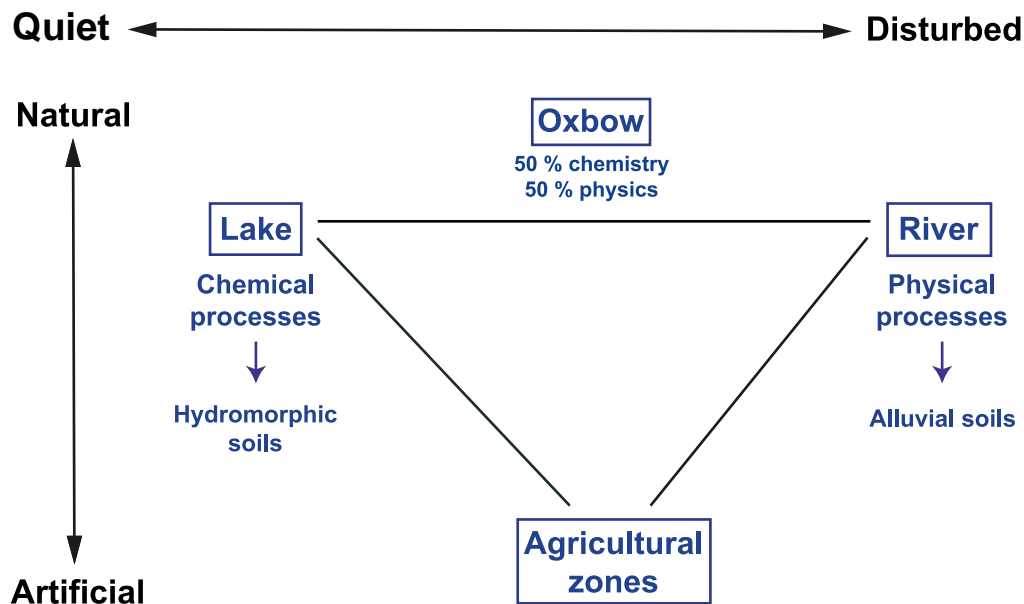


Fig. 4.1. Hypothetical model for the soil typology containing two axes: horizontal gradient representing a progression between the “lake” situation and the “river” situation, and vertical gradient meaning a transition between the natural (e. g. willow forest) and the agricultural environments (e. g. field of maize).

4.2. Material and methods

4.2.1. Selection and characterisation of the soil profiles

Based on the first auger explorations realized along the Sarine River in 2002 (see 3.3.1), a selection of 14 different locations was made on the two studied gradients in order to analyse in detail the pedogenesis of alluvial soils and to understand the

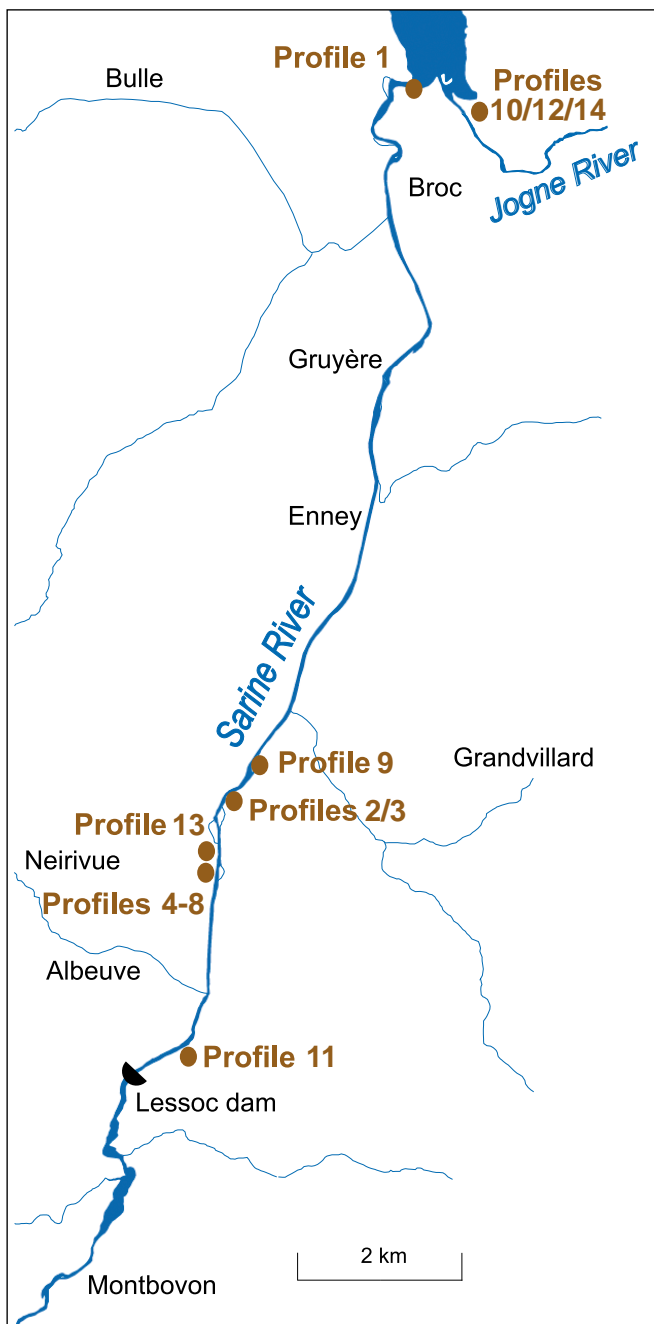


Fig. 4.2. Geographical locations of the soil profiles along the Sarine River.

geomorphological evolution and the present state of the ecosystem. This preferential method was used in order to incorporate the most representative soils present in the valley and to demonstrate a variation of soil types and alluvial conditions.

The different geographical locations, as well as a view of each soil profile situations are presented in fig. 4.2 and 4.3. The major characteristics of each site are given in the different soil profile descriptions found in appendix (17 to 30). Profiles 3 to 7 were dug along two transects forming a cross parallel to a drying oxbow (profiles 3 to 5 with a distance of 5 m) and perpendicular to the oxbow (profiles 6 to 7 with also a distance of 5 m; fig. 4.4).

4.2.2. Descriptions and physicochemical analysis

The profiles were described in 2003 and 2004 according to the “*Référentiel Pédologique*” (AFES, 1998). The detailed description of each profile was given in French, but the references for the soil and horizon names were translated. A special attention was holding on the characterization of buried organic matter by recognizing different types. Visual distinction was made between organic matters buried by earthworms (bioturbed zones) that presents round dark brown marks, organic matters found along roots showing vertical distribution, or laminated macrorests representing ancient debris deposits. Moreover, buried A horizon presenting crumb structure with stable aggregates may be recognized as horizontal buried organo-mineral horizon, when isolated marks could often be found throughout the soil profile in case of degradation of small amount of organic matter.

One more time, gravels and pebbles were considered as the bottom of the system and profiles were excavated down to this limit. For each horizon, samples were taken in the middle of the layer. The different physicochemical analyses were performed on air-dried and sieved soil (mesh size 2 mm), when others were carried out on ground soil samples (soil particles < 200 µm). Note that unfortunately no measurement of aggregate stability, giving indications about soil structure, has been carried

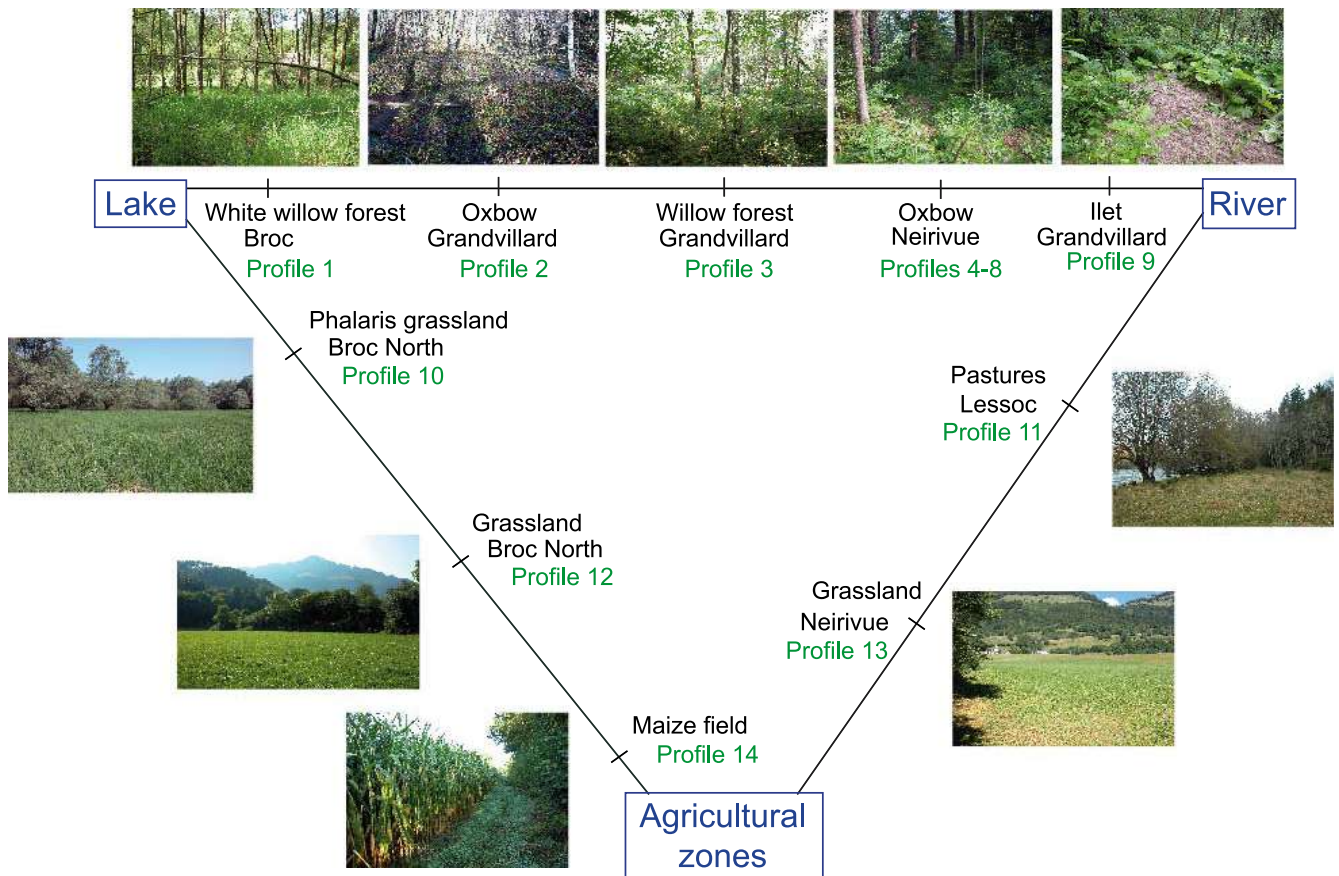


Fig. 4.3. View of each soil profile situation selected for the soil typology following the hypothetical model (see fig. 4.1).

out because of problems during the apparatus construction.

The following analyses were performed on all samples:

4.2.2.1. pH

The pH of a soil indicates the strength of acidity or alkalinity in the soil solution, which bathes soil constituents, plant roots and soil micro-organisms. Soil is neutral when pH is 7, it is acid when pH is lower than 7 and alkaline when it is higher than 7. The pH scale is logarithmic, so a difference of a unit is a tenfold difference in acidity or alkalinity (e. g. pH 5 is ten times more acid than pH 6). Traditionally, soil pH has been measured in the laboratory by inserting a pH electrode into a suspension of one part soil and two and a half parts water (1:2.5; pH H₂O). The same measure is made with a KCl solution, which is used to determine exchangeable

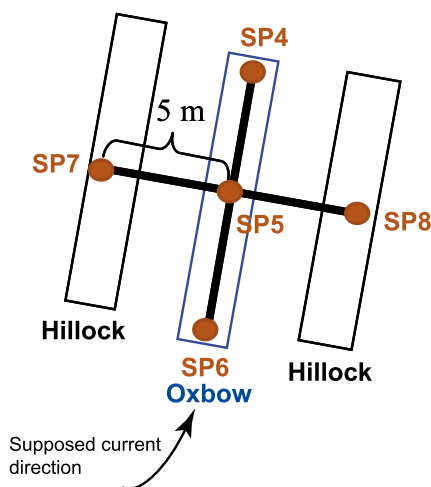


Fig. 4.4. Schema of the two transects forming a cross parallel to a drying oxbow and perpendicular to the oxbow.

acidity (pH KCl). K^+ ions displace H^+ ions from the soil cation exchange sites, so the results are usually slightly lower than obtained with method pH water.

4.2.2.2. Particle-size distribution

The particle-size distribution was measured using a modified Robinson pipette method followed by a sieving separation and a laser diffraction analysis. The samples were treated with hydrogen peroxide 10%, in order to remove organic material from the sediment by heating it on a stove for several hours. The particles were then centrifuged and dispersed with a sodium hexametaphosphate solution.

After this, the samples were placed on an automatic sieving platform, which separates under water coarse sand (500-2000 μm), medium sand (200-500 μm) and a part of fine sand ($> 125 \mu m$). The solution was then analyzed using a laser diffraction grain size analyzer, which separated the following sizes: 100-125 μm and 50-100 μm (the other part of fine sand), 20-50 μm (coarse silt), 8-20 μm and 2-8 μm (fine silt), and $< 2 \mu m$ (clay). The laser diffraction particle size analysis method was chosen for this study, because it is considerably faster than the other alternative, the sieve-pipette method.

Finally, note that 23 horizons were analyzed with an older method where coarse sands were not separated from the medium sands (profile 1: horizons 1, 2, 9, 11, 12, 13, 14, 15; profile 2: horizons 1, 3, 4, 5, 6; profile 3: horizons 3, 4, 5, 6, 7, 9, 10, 11, 12, 13). In order to visualize the particle-size distribution of each horizon in a single profile, a soil textural triangle was plotted using SigmaPlot 10.0 (Systat Software, Inc., 2006).

The following analyses were performed only on samples supposing to contain organic matter (*A*, *J_s* and *J_p* horizons):

4.2.2.3. Organic carbon (simplified Anne method)

The organic carbon content was determined by a potassium dichromate reduction. This method quantifies the amount of oxidizable organic matter, in which organic matter is oxidized with a known amount

of $Cr_2O_7^{2-}$ in the presence of sulphuric acid (Baize, 2000). The remaining Cr^{3+} chromate is determined by titration with a solution “*Sel de Mohr*” (ferrous ammonium sulphate solution) composing of $(NH_4)_2SO_4$ $FeSO_4 \cdot 6H_2O$ diluted in water and sulphuric acid.

4.2.2.4. Total nitrogen (Kjeldahl mineralization)

The Total Kjeldahl Nitrogen (TKN) method is based on a digestion with a sulphuric acid solution containing potassium sulphate, and using mercuric sulphate as a catalyst, making the conversion of organic nitrogen to the ammonium form (Baize, 2000). The sample solution was then steam distilled and received in a H_3BO_4 solution. The distillate was titrated with a HCl 0.01M solution in presence of a colored indicator (Tashiro indicator).

4.2.2.5. Total phosphorus

The Kjeldahl mineralization was used first to oxidize phosphorus into orthophosphate by a sulphuric acid oxidant. The digested solution was analyzed spectrophotometrically in presence of a 4-nitrophenol indicator with a pH adjustment. The PO_4^{3-} reacts with ammonium molybdate in the presence of H_2SO_4 to form a phosphomolybdenum complex. Potassium antimonyl tartrate and ascorbic acid were then used to reduce the complex, forming a blue color, which is proportional to the total phosphorus concentration.

4.2.2.6. Available phosphorus (Olsen method)

The extraction of plant available phosphate was based on an alkaline extraction by 0.5 N $NaHCO_3$. The method (Olsen and Sommers, 1982) consists of an ascorbic acid reduction of phosphomolybdate complex and estimates the relative bioavailability of inorganic ortho-phosphate (PO_4 -P) in soils. The method is based on the extraction of phosphate from the soil by 0.5 N sodium bicarbonate solution adjusted to pH 8.5. In the process of extraction, hydroxide and bicarbonate competitively desorbed phosphate from soil particles and secondary absorption is minimized because of high pH. The

orthophosphate ion reacts with ammonium molybdate and antimony potassium tartrate under acidic conditions to form a complex. This complex is reduced with ascorbic acid to form a blue complex which absorbs light at 880 nm. The absorbance is proportional to the concentration of orthophosphate in the sample.

4.2.3. Statistical analysis

In order to investigate the contribution of the different soil profile parameters, correlation analyses (using Pearson correlation) between the different factors, as well as other data summaries, were performed. Firstly, the whole horizons were taken into consideration for calculation of correlations between pH values and particle-size distribution of each horizon. Then, only data described as containing organic matter traces were used for further statistical analyses. After standardization, data were grouped by a hierarchical agglomerative clustering by means of Ward's minimum variance clustering with Euclidean distance (Legendre and Legendre, 1998), using R software (version 2.4.1; R Development Core Team, 2006). This analysis calculating matrix of proximity (here distance measures) between a set of two-by-two comparable elements of n samples, permitted, using stated criterion, to fuse horizons A and/or J into groups (assign cases to groups) respecting the resemblance between them in a predefined optimal manner (Legendre and Legendre, 1998). This non-parametric method is not often used in soil classification (Gerrard, 2000), but may be applied when divisions between individuals or determination of the degree of similarity are needed (Sheremet, 2006). A test was then applied on groups to know the discriminating factors (package "r-part" in R software), as well as a principal component analysis (PCA) in order to detect the similarities and dissimilarities in soil horizons. Some other calculations (regression tree method) were also applied to data in order to test the hypothesis of the two gradients (natural and artificial) using also R software (packing "r-part").

4.3. Descriptions of the soil profiles

4.3.1. Soil typology

Observed soils found along the Sarine River were attributed to eight different references according to the "Référentiel Pédologique" (AFES, 1998); two of them needed double attribution (fig. 4.5). Furthermore, the use of qualifiers to complete the description of a reference horizon is recommended for several soil types (Gobat *et al.*, 2004). All our soils were calcareous, but this adjective was not added to each reference in order to simplify the nomenclature.

Single attribution:

REDUCTISOL TYPIQUE: This soil is characterized by the presence of a G horizon related to a deep water-table, usually due to a local drainage system (streams, ponds or lakes) or a sea. Hydromorphic features are present at less than 50 cm depth and the excess water is considered to be predominant. All textures can be found and the permeability is variable. The micromorphology of these horizons is the result of the predominance of reduction processes and iron mobilization, but varies throughout the year depending on the seasonal characteristics of the saturation. *Go* horizon is temporarily re-oxidized and periodically unsaturated. The colour is light, and reddish-brown mottles may sometimes be observed along roots and ped faces. *Gr* horizon is characterized by their colour either bluish to greenish or evenly white, black or grey.

REDUCTISOL TYPIQUE polyphasic: This solum is also characterized by hydromorphic processes and presents *Go*, *Gr*, or *g* horizon at a depth of less than 50 cm. Moreover, the characteristic of this solum is a continual covering of buried horizons by new material under the same macro- or mesoclimatic conditions (monocyclic soil).

REDOXISOL: This reference occurs only on alluvial and/or colluvial deposits presenting a texture discontinuity, which supports a perched water-table. It is characterized by a *g* horizon, located at a depth of around 50 cm, resulting from the successive re-

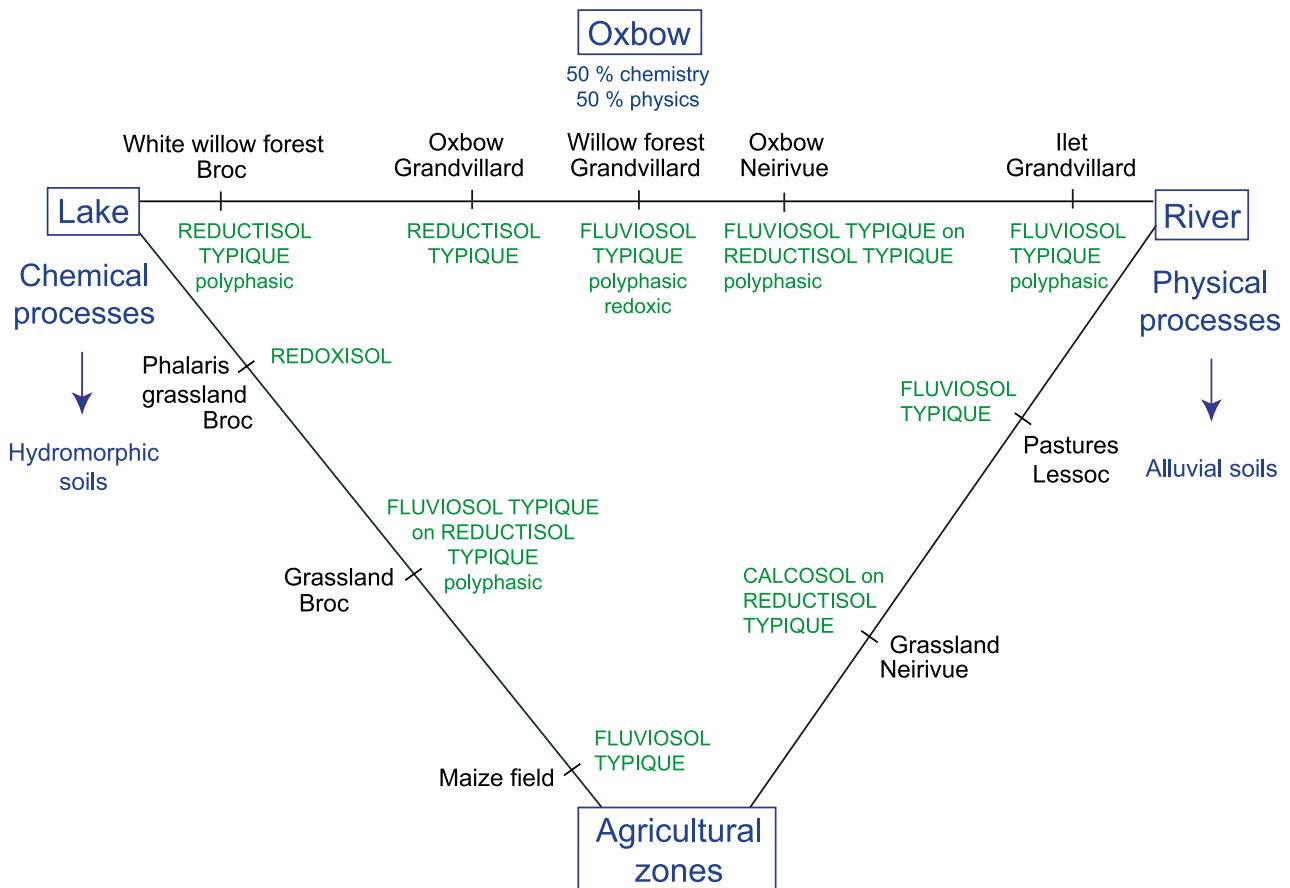


Fig. 4.5. References of the 14 soil profiles according to the “Référentiel Pédologique” (AFES, 1998).

duction and mobilization of iron and its oxidation and immobilization due to a temporary waterlogging.

FLUVIOSOL TYPIQUE: This soil, found in a low position in the landscape and depending on recent material (river alluvium), is undeveloped or weakly developed. They are also characterized by the presence of a permanent or periodic water-table with marked fluctuations. FLUVIOSOL do not present any specific diagnostic horizons, but the FLUVIOSOLS TYPIQUES have three diagnostic horizon sequences:

Js/M or D: thin and slightly developed solum with possible large quantities of coarse gravel derived from the *D* layer.

A/Jp/D: relatively deep soils (30 to 80 cm depth) including a typical *A* horizon and a “juvenile” *Jp* horizon in the depth. The transition between the *Jp* and *D* layers is sometimes gradual, but the contact is most often sharp and wavy.

A/Jp/M/D: deep soil (> 80 cm) in which the *Jp* horizon lies on a thick *M* layer composed of alluvial deposits of variable texture. The *M* layer lies on a *D* layer.

FLUVIOSOL TYPIQUE polyphasic: This solum presents the same characteristics as the FLUVIOSOL TYPIQUE, but buried horizons are detected.

FLUVIOSOL TYPIQUE polyphasic redoxic: This soil shows a superimposing of several distinct horizons with the presence of *g* or *-g* horizon between 50 and 80 cm. In this case, excess water is considered as a secondary factor indicated by the use of redoxic qualifier.

Double attribution:

FLUVIOSOL on REDUCTISOL polyphasic: This soil exhibits in the depth excess water considered as predominant with hydromorphic features and buried horizons. This system is superimposed by different

recent material, which is undeveloped or weakly developed, present typically in riverine soils.

CALCOSOL on REDUCTISOL: This solum is characterized by a predominance of hydromorphic features with presence of a water-table in depth upon which a calcareous brown soil has evolved. CALCOSOL is defined with the obligatory presence of a *Sca* horizon giving effervescence with HCl when cold. This diagnostic horizon contains a minimum CaCO_3 content of 5% and the adsorbing complex is saturated mainly by Ca^{2+} (S/T ratio > 95%). The structure is blocky resulting from physical processes affecting clay minerals like the swelling and shrinking of smectites.

4.3.2. First interpretations

The different soil profile descriptions are given in the “natural-artificial” and “quite-perturbed” gradient orders (first from the left to the right side of the hypothetical model represented in fig. 4.1, and then from the height to the bottom of this same diagram). The detailed description of each soil profile, as well as the pedological characteristics, is given in French in the different figures (appendixes 17 to 30), but the discussion of each profile is written in English. For a reason of legibility, the horizon names are not followed by the “ca” suffix indicating presence of carbonates, but every horizon is carbonated. At the end of each description, the profile is assimilated to one of the four facies models defined in chapter 3 (see fig. 3.17 in chapter 3.6). Finally, notice that in some case it was technically not possible to sample the alluvial pebble layers.

Soil profile 1 – REDUCTISOL TYPIQUE polyphasic

This soil profile was realized in the white willow forest of Broc, on the right bank of the Sarine mouth, at about 50 m from the Gruyère Lake. The description permits to detect horizons deposited before the Rossens dam construction (up to 75 cm) with medium sand texture reflecting an active sedimentation with high flow discharge (fig. 4.6, appendix 17). The horizon 11, dark brown with stable aggregates and organic matter content, seems to

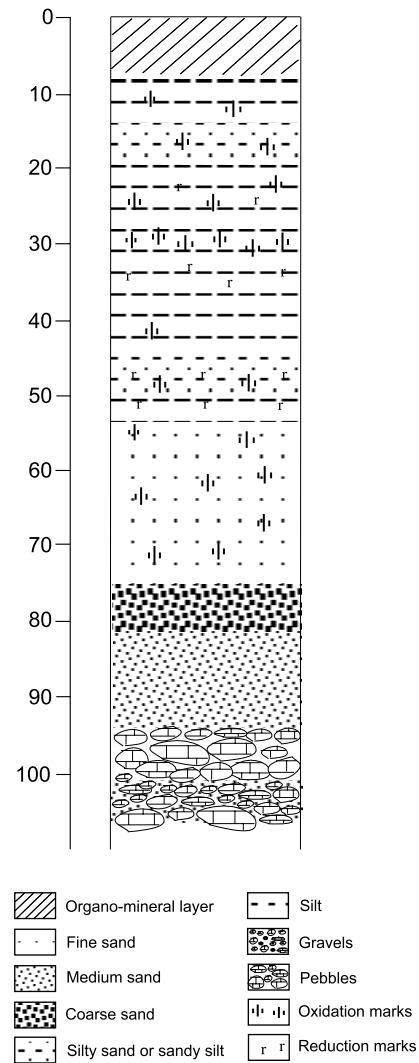


Fig. 4.6. Schematic description of soil profile 1.

have been the top soil horizon for a while (fig. 4.7). The upper layers, formed of different particle-size particles, but often fine (fine silt), reflect a smooth sedimentation and are due to the water retention at the Rossens dam provoking a permanent and quasi annual inundation from May to about September throughout this area (fig. 4.8). Oxidation marks observed throughout the profile indicate a fluctuating water-logging, even if the white willow forest was exceptionally not inundated in 2003, a particularly dry year.

This profile is an illustration of the facies model 4.

Soil profile 2 – REDUCTISOL TYPIQUE

This profile was made in the active zone of Grandvillard at about 1 m from the oxbow. The water table is already visible at a 60 cm depth complicating

Sample	Horizons	Depth (cm)	pH water	pH KCl	Coarse sand (%)	Coarse silt (%)	Fine sand (%)	Fine silt (%)	Clay (%)	OC (%)	OM (%)	Tot N (%)	C/N	Olsen P (mg/g)	Tot P (mg/g)
P1/h1	Ag	0-8	7.7	7.2	0	17	8	46	5	4.0	6.9	0.38	11	0.044	0.49
P1/h2	Jpg	8-14	8.0	7.4	0	4	0	85	10	1.8	3.1	0.18	10	0.025	0.38
P1/h3	Mg	14-19	8.1	7.5	0	29	0	63	7	1.3	2.3	0.12	11	0.035	0.35
P1/h4	IIMg	19-28	8.2	7.5	0	4	0	87	9	ND	ND	ND	ND	ND	ND
P1/h5	IIIGo	28-31	8.2	7.4	0	20	0	73	6	ND	ND	ND	ND	ND	ND
P1/h6	IVMg	31-36	8.2	7.5	0	19	1	73	7	ND	ND	ND	ND	ND	ND
P1/h7	VMg	36-43	8.2	7.5	0	10	0	81	8	ND	ND	ND	ND	ND	ND
P1/h8	VIMg	43-46	8.2	7.5	0	45	1	49	4	ND	ND	ND	ND	ND	ND
P1/h9	VIIIGoGr	46-50	8.2	7.5	0	37	6	52	5	ND	ND	ND	ND	ND	ND
P1/h10	VIIIIGr	50-52	8.2	7.4	0	26	10	58	5	ND	ND	ND	ND	ND	ND
P1/h11	ApG	52-75	8.1	7.4	0	9	0	82	9	1.4	2.4	0.14	10	0.019	0.30
P1/h12	IXM	75-81	8.6	7.9	0	5	9	2	0	ND	ND	ND	ND	ND	ND
P1/h13	XM	81-94	8.6	7.8	0	7	17	5	0	ND	ND	ND	ND	ND	ND
P1/h14	XIM	94-102	8.5	7.8	0	7	7	6	0	ND	ND	ND	ND	ND	ND
P1/h15	XIID	> 102	8.7	8.1	0	4	6	3	0	ND	ND	ND	ND	ND	ND

Fig. 4.7. Pedological characteristics of the soil profile 1. Abbreviations: OC = organic carbon; OM = organic matter; Tot N = total nitrogen; Olsen P = Olsen phosphorus; Tot P = total phosphorus.



Fig. 4.8. View of the permanent inundation in the white willow forest of Broc (August 2002).

strongly the description (fig. 4.9, appendix 18). Under the water table we observe a laminated layer with a silty-sand matrix containing organic macrorests relatively well preserved thanks to humidity (fig. 4.10). This layer made of leaves and twigs was probably brought by a flood. The other layers with various texture (sandy and silty) and thickness prove an active erosion and sedimentation dynamics, especially on the surface (fig. 4.11).

This profile is an illustration of the facies model 2.

Soil profile 3 – FLUVIOSOL TYPIQUE polyphasic redoxic

This soil profile was situated in the active zone of Grandvillard in a white alder forest constituted of high draped willows in the tree stratum. It was located at about 10 m from the oxbow of Grandvillard on a slightly elevated terrace. It presents typical characteristics of aggradation with notably very diverse textured horizons at the profile bottom (fig. 4.12, appendix 19). This indicates various floods in intensity and duration. On the top, horizons tend to be standardized with the development of a crumbly structure. The lack of regular deposits permits the development of pedogenic processes, like structuration by soil fauna. Surprisingly, the top soil horizon (*Js*) contains less organic matter than the layer situated just below (*Ap*; fig. 4.13). This is probably due to a thin recent mineral deposit containing few or no organic matter, which is mixed with the below layer under root and bioturbation effects. Oxidation

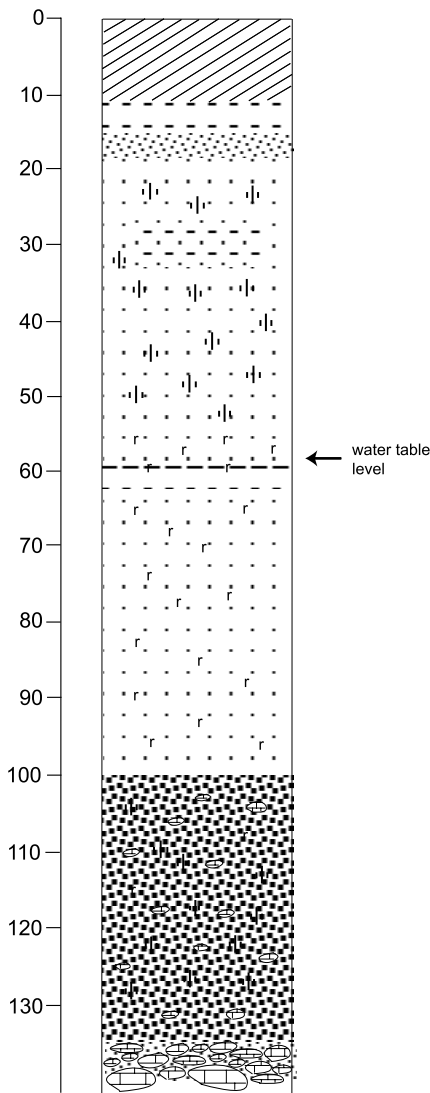


Fig. 4.9. Schematic description of soil profile 2 (see fig. 4.6 for legends of the description).



Fig. 4.10. Organic macrorests found in silty-sand matrix between 60 and 61 cm in the soil profile 2.

Sample	Horizons	Depth (cm)	pH water	pH KCl	Coarse sand (%)	Medium sand (%)	Fine sand (%)	Coarse silt (%)	Fine silt (%)	Clay (%)	OC (%)	OM (%)	Tot N (%)	C/N	Olsen P (mg/g)	Tot P (mg/g)
P2/h1	A	0-9	7.9	7.3	1	12	7	25	49	6	3.1	5.3	0.26	12	0.03	0.36
P2/h2	Jp	9-13	8.1	7.4	1	15	11	26	41	5	1.7	2.9	0.16	10	0.02	0.34
P2/h3	IIM	13-18	8.3	7.6	1	25	31	28	14	1	ND	ND	ND	ND	ND	ND
P2/h4	IIMg	18-30	8.4	7.7	0	5	28	45	21	1	ND	ND	ND	ND	ND	ND
P2/mark	[Mg]	[26-32]	8.4	7.8	0	6	45	36	12	0	ND	ND	ND	ND	ND	ND
P2/h5	IVGoGr	30-54	8.3	7.7	0	7	63	24	6	0	ND	ND	ND	ND	ND	ND
P2/h6	VGr	54-58	8.0	7.7	0	4	31	38	25	2	ND	ND	ND	ND	ND	ND
P2/h7	VIGr	58-60	7.8	7.5	0	2	19	55	23	1	ND	ND	ND	ND	ND	ND
P2/h8	OLpVIIGr	60-61	7.7	7.5	1	10	23	43	22	1	2.3	3.9	0.13	17	0.02	0.30
P2/h9	VIIIGr	61-100	7.8	7.5	2	8	31	41	17	2	ND	ND	ND	ND	ND	ND
P2/h10	IXGo	100-135	8.6	8.2	64	13	8	8	6	0	ND	ND	ND	ND	ND	ND

Fig 4.11. Pedological characteristics of the soil profile 2. Abbreviations : OC = organic carbon; OM = organic matter; Tot N = total nitrogen; Olsen P = Olsen phosphorus; Tot P = total phosphorus.

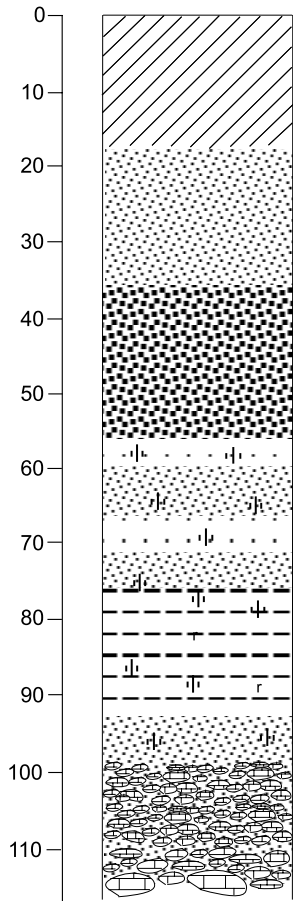


Fig. 4.12. Schematic description of soil profile 3 (see fig. 4.6 for legends of the description).



Fig. 4.14. View of the bottom layers of soil profile 3 with presence of oxidation marks.

Sample	Horizons	Depth (cm)	pH water	pH KCl	Coarse sand (%)	Medium sand (%)	Fine sand (%)	Coarse silt (%)	Fine silt (%)	Clay (%)	OC (%)	OM (%)	Tot N (%)	C/N	Olsen P (mg/g)	Tot P (mg/g)
P3/h1	Js	0-18	7.8	7.3	2	11	6	38	40	3	1.1	1.9	0.10	12	0.027	0.31
P3/h2	Ap	18-35	8.2	7.6	3	19	9	32	34	3	2.7	4.7	0.25	11	0.019	0.38
P3/h3	IIM	35-55	8.7	8.2	30	54	7	7	2	0	ND	ND	ND	ND	ND	ND
P3/h4	IIIMg	55-59	8.3	7.6	0	11	59	23	6	0	ND	ND	ND	ND	ND	ND
P3/h5	IVMg	59-66	8.4	7.6	1	39	29	23	8	0	ND	ND	ND	ND	ND	ND
P3/h6	VMg	66-70	8.2	7.3	0	4	9	52	30	4	ND	ND	ND	ND	ND	ND
P3/h7	VIMg	70-76	8.3	7.5	1	31	12	27	26	3	ND	ND	ND	ND	ND	ND
P3/h8	VIIMg	76-92	8.2	7.4	0	2	18	49	28	3	ND	ND	ND	ND	ND	ND
P3/h9	VIIIMg	92-98	8.4	7.7	2	26	33	28	10	0	ND	ND	ND	ND	ND	ND
P3/h10	IXMg	98-110	8.3	7.7	13	34	17	20	16	1	ND	ND	ND	ND	ND	ND
P3/h11	XD	>110	8.4	7.8	28	32	12	16	11	1	ND	ND	ND	ND	ND	ND

Fig. 4.13. Pedological characteristics of the soil profile 3. Abbreviations : OC = organic carbon; OM = organic matter; Tot N = total nitrogen; Olsen P = Olsen phosphorus; Tot P = total phosphorus.

marks indicate a fluctuating water table due to the adjacent oxbow (fig. 4.14).

This profile is an illustration of the facies model 3.

Soil profile 4 - FLUVIOSOL TYPIQUE on REDUCTISOL TYPIQUE polyphasic

This soil profile, as well as the followings (soil profiles 5 to 8), was carried out in Neirivue on the left bank of the Sarine River in an embanked zone in a poplar plantation. Two transects were determined, one parallel to an old oxbow (soil profiles 4 to 6) and the other perpendicular (soil profiles 6, 7). The profiles are separated by 5 m and formed a cross (fig. 4.4).

Profile 4 present two different superimposed functionings (fig. 4.15; appendix 20). Hydromorphic processes are particularly visible at the bottom where water table influence is strong, despite embankments (fig. 4.16). The water comes probably from the Neirivue Stream not far away. The entire profile is developed on deposited materials reflecting a great heterogeneity in texture (medium sandy to fine silty). The top soil horizon, 24 cm thick and presenting stable aggregates, shows no flood events happened recently. Moreover, the layer below (*Jp*) also presents marks of diffusion organic matter probably due to roots and soil fauna (fig. 4.17). This stable period makes it possible the pedogenetic processes to take place.

The horizon 8 (*OLpVIIM*) presents a juxtaposition of plant residues scarcely decomposed and of silty sands. This layer was brought by a flood occurring before embankment construction. These macrorests are still well conserved because of the constant soil humidity.

This profile is an illustration of the facies model 3.

Soil profile 5 - FLUVIOSOL TYPIQUE on REDUCTISOL TYPIQUE polyphasic

From the functional point of view this soil profile is comparable to soil profile 4 (two functionings superimposed; fig. 4.18; appendix 21), but differs by the absent macrorest layer and a lower humidity. A *Jp* horizon is described between 87 and 90 cm exhibiting organic matter (fig. 4.19), but only one

macrorest. The smaller water content has increased the almost all decomposition rate of plant residues.

The same particle-size sequence is observed with alternation of fine sands, medium sands, sandy silts, coarse sands and clay (from 20 cm) as soil profile 4 (fig. 4.20).

This profile is an illustration of the facies model 3.

Soil profile 6 - FLUVIOSOL TYPIQUE on REDUCTISOL TYPIQUE polyphasic

The upper layer shows an unusual low content of organic carbon, explaining its name (*Js*; fig. 4.21; appendix 22), especially compared with the horizon just below (*Ap*) presenting a high organic matter content with some aggregates (fig. 4.22). The horizons 9 and 10 are named *Jp* and *Jpg*, because they exhibit organic matter marks, but no crumbly structure.

About particle-size distribution and stratification this soil profile is also comparable to the two previous ones with various textural layers at the bottom (fig. 4.23). The same functioning superposition is detected.

This profile is an illustration of the facies model 3.

Soil profile 7 - FLUVIOSOL TYPIQUE on REDUCTISOL TYPIQUE polyphasic

Digged on a small hillock, this profile is particularly deep, but the same features as the ones made along the old oxbow are observed (fine and coarse layers alternation; oxidation marks; fig. 4.24; appendix 23). The horizons 5 and 6 between 80 and 95 cm with gravels and coarse material > 2 mm indicate a high flow discharge flood in the middle of the profile (fig. 4.25). The absence of this layer in the four other soil profiles is not easy to explain, but erosion phenomena might happen at different places except at this specific point on a small hillock. This may be particularly plausible because of the marked deepness of this pedon due to the position of soil profile 7, situated outside the supposed ancient current of the lateral channel. It has already been shown that erosion and sedimentation may occur at particular locations in different events and also that a flood of a particular magnitude has

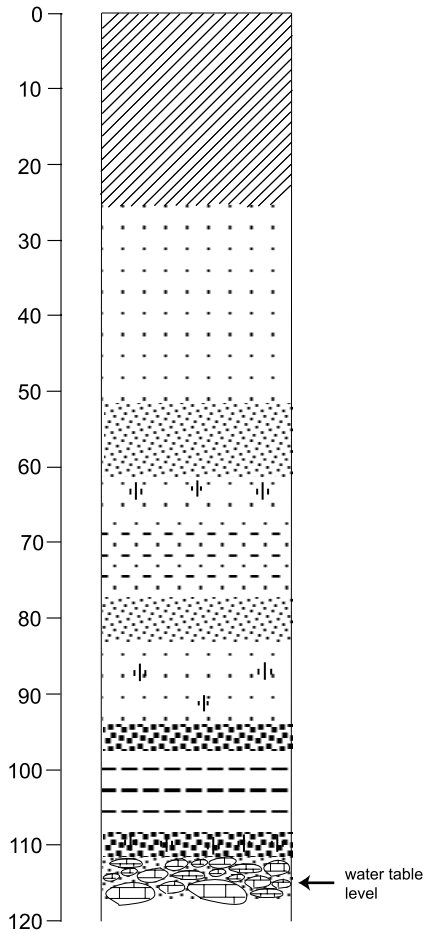


Fig. 4.15. Schematic description of soil profile 4 (see fig. 4.6 for legends of the description).

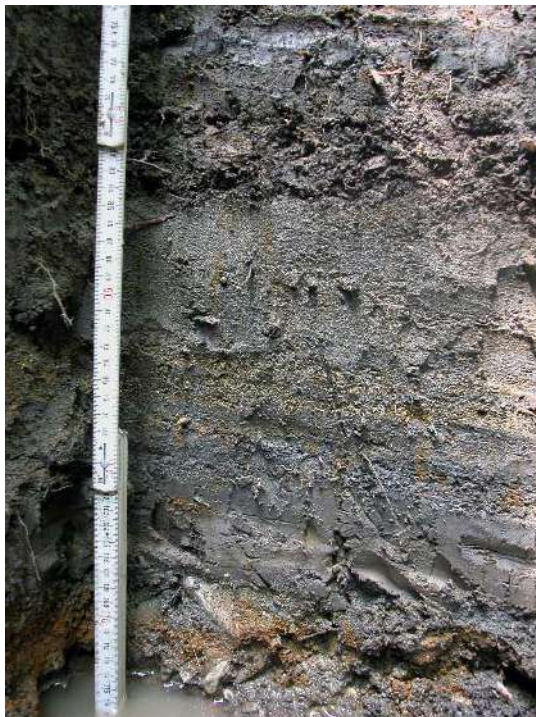


Fig. 4.16. View of the bottom layers of soil profile 4 with strong influence water table.

Sample	Horizons	Depth (cm)	pH water	pH KCl	Coarse sand (%)	Medium sand (%)	Fine sand (%)	Coarse silt (%)	Fine silt (%)	Clay (%)	Corg (%)	OM (%)	Ntot (%)	C/N	Polsen (mg/g)	Ptot (mg/g)
P4 / h1	A	0-24	7.9	7.3	1	6	17	28	44	5	2.4	4.1	0.20	12	0.027	0.33
P4 / h2	M	24-51	8.2	7.5	1	16	16	26	37	4	1.2	2.0	0.10	12	0.020	0.28
P4 / h3	IIIM	51-59	8.5	7.9	0	71	19	6	4	0	ND	ND	ND	ND	ND	ND
P4 / h4	IIIM	59-62	8.3	7.6	0	34	21	22	21	2	ND	ND	ND	ND	ND	ND
P4 / h5	IVMg	62-66	8.3	7.6	0	21	23	19	34	3	ND	ND	ND	ND	ND	ND
P4 / h6	VMg	66-74	8.2	7.5	0	2	9	25	58	6	ND	ND	ND	ND	ND	ND
P4 / h7	VIM	74-77	8.1	7.7	0	12	31	32	23	2	ND	ND	ND	ND	ND	ND
P4 / h8	OLpVIIM	77-83	7.8	7.2	1	25	15	19	35	4	4.7	8.2	0.24	20	0.020	0.31
P4 / h9	VIIIMg	83-94	8.2	7.6	0	17	33	17	29	3	0.8	1.3	0.05	16	0.019	0.23
P4 / h10	IXMg	94-97	8.3	7.7	0	49	15	16	17	2	ND	ND	ND	ND	ND	ND
P4 / h11	XMg	97-108	8.0	7.3	0	1	2	35	57	5	ND	ND	ND	ND	ND	ND
P4 / h12	XIGo	108-112	8.6	8.2	0	94	4	2	1	0	ND	ND	ND	ND	ND	ND
P4 / h13	XIIDg	>112	8.3	7.9	0	70	6	12	11	1	ND	ND	ND	ND	ND	ND

Fig. 4.17. Pedological characteristics of the soil profile 4. Abbreviations : OC = organic carbon; OM = organic matter; Tot N = total nitrogen; Olsen P = Olsen phosphorus; Tot P = total phosphorus.

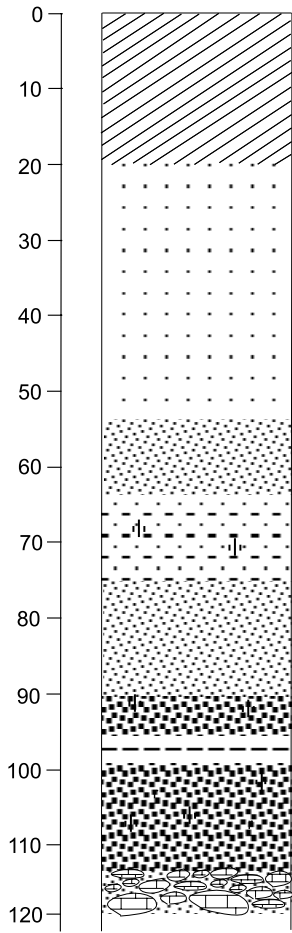


Fig. 4.18. Schematic description of soil profile 5 (see fig. 4.6 for legends of the description).



Fig. 4.19. View of the *Jp* horizon of soil profile 5 with orga-

Sample	Horizons	Depth (cm)	pH water	pH KCl	Coarse sand (%)	Medium sand (%)	Fine sand (%)	Coarse silt (%)	Fine silt (%)	Clay (%)	Corg (%)	OM (%)	Ntot (%)	C/N	Polsen (mg/g)	Ptot (mg/g)
P5 / h1	A	0-18	7.8	7.3	1	10	3	7	68	10	2.7	4.7	0.23	12	0.023	0.34
P5 / h2	M	18-53	8.1	7.5	2	13	3	10	65	7	1.4	2.5	0.12	12	0.018	0.29
P5 / h3	IIM	53-63	8.4	7.9	25	47	3	17	7	1	ND	ND	ND	ND	ND	ND
P5 / h4	IIIMg	63-74	8.1	7.5	0	6	8	22	58	6	ND	ND	ND	ND	ND	ND
P5 / h5	IVMg	74-87	8.2	7.6	1	53	6	23	16	2	0.7	1.3	0.05	14	0.010	0.20
P5 / h6	Jp	87-90	8.0	7.5	6	24	8	6	49	6	2.5	4.4	0.16	16	0.017	0.24
P5 / h7	VMg	90-94	8.0	7.5	8	26	5	11	45	5	ND	ND	ND	ND	ND	ND
P5 / h8	VIM	94-99	7.9	7.4	2	1	0	25	65	7	ND	ND	ND	ND	ND	ND
P5 / h9	VIIMg	99-112	8.3	8.0	77	8	2	7	5	0	ND	ND	ND	ND	ND	ND

Fig. 4.20. Pedological characteristics of the soil profile 5. Abbreviations : OC = organic carbon; OM = organic matter; Tot N = total nitrogen; Olsen P = Olsen phosphorus; Tot P = total phosphorus.

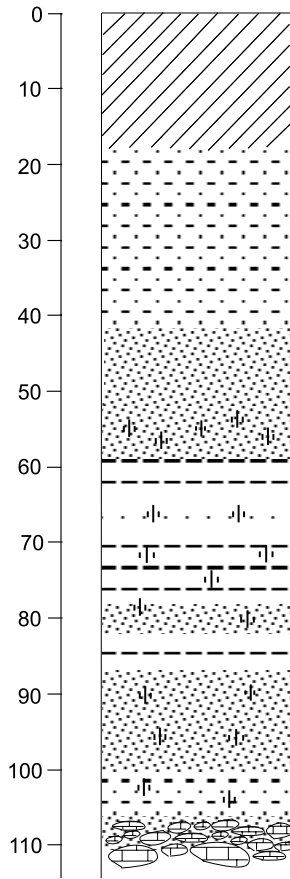


Fig. 4.21. Schematic description of soil profile 6 (see fig. 4.6 for legends of the description).



Fig. 4.23. View of the bottom layers of soil profile 6 showing various textural layers.

Sample	Horizons	Depth (cm)	pH water	pH KCl	Coarse sand (%)	Medium sand (%)	Fine sand (%)	Coarse silt (%)	Fine silt (%)	Clay (%)	Corg (%)	OM (%)	Ntot (%)	C/N	Polisen (mg/g)	Ptot (mg/g)
P6/h1	Js	0-17	8.1	7.4	2	7	5	23	56	8	1.1	1.9	0.09	12	0.031	0.28
P6/h2	Ap	17-41	8.3	7.6	2	15	8	9	61	5	3.2	5.6	0.29	11	0.016	0.34
P6/h3	Mg	41-51	8.8	8.2	29	56	9	5	1	0	ND	ND	ND	ND	ND	ND
P6/h4	IIGo	51-59	8.7	8.2	44	39	5	6	5	0	ND	ND	ND	ND	ND	ND
P6/h5	IIIM	59-63	8.2	7.6	1	6	23	45	24	1	ND	ND	ND	ND	ND	ND
P6/h6	IVM	63-68	8.6	7.9	2	61	22	10	5	0	ND	ND	ND	ND	ND	ND
P6/h7	VMg	68-78	8.0	7.5	1	4	9	27	53	6	ND	ND	ND	ND	ND	ND
P6/h8	VIMg	78-82	8.3	8.1	3	39	47	9	2	0	ND	ND	ND	ND	ND	ND
P6/h9	Jp	82-86	8.1	7.5	1	5	13	40	39	3	2.5	4.3	0.15	17	0.018	0.27
P6/h10	Jpg	86-100	8.5	7.9	1	57	27	13	3	0	2.8	4.8	0.16	17	0.016	0.26
P6/h11	VIIMg	100-105	7.7	7.4	1	19	35	32	13	1	0.5	0.9	0.04	14	0.018	0.18
P6/h12	VIIDG	>105	8.6	8.2	71	17	5	3	3	0	ND	ND	ND	ND	ND	ND

Fig. 4.22. Pedological characteristics of the soil profile 6. Abbreviations : OC = organic carbon; OM = organic matter; Tot N = total nitrogen; Olsen P = Olsen phosphorus; Tot P = total phosphorus.

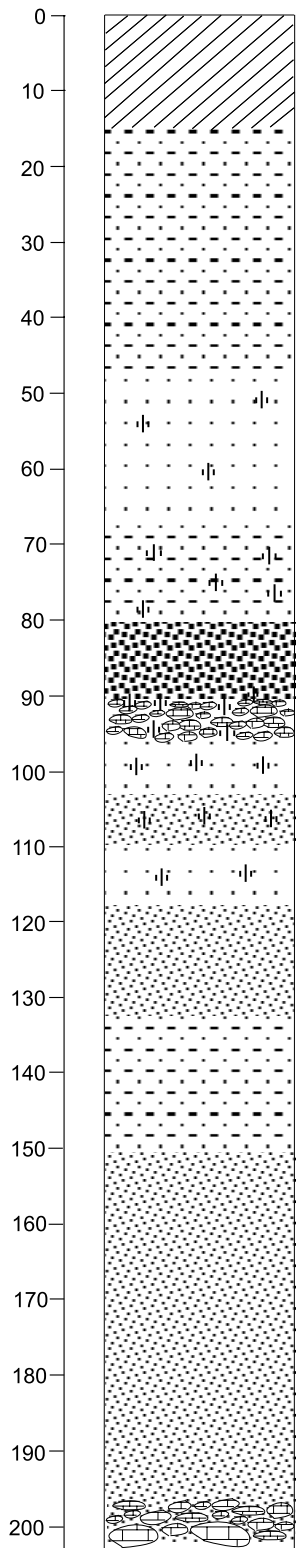


Fig. 4.24. Schematic description of soil profile 7 (see fig. 4.6 for legends of the description).



Fig. 4.25. View of gravels and coarse material found between 80 and 95 cm in the soil profile 7 indicating a high flow discharge flood in the middle of the profile.

Sample	Horizons	Depth (cm)	pH water	pH KCl	Coarse sand (%)	Medium sand (%)	Fine sand (%)	Coarse silt (%)	Fine silt (%)	Clay (%)	Corg (%)	OM (%)	Ntot (%)	C/N	Polsen (mg/g)	Ptot (mg/g)
P7/h1	A	0-14	7.8	7.2	0	3	5	30	55	7	3.6	6.2	0.30	12	0.039	0.38
P7/h2	M	14-47	8.3	7.5	1	11	21	36	29	1	0.9	1.5	0.09	10	0.026	0.28
P7/h3	IIM	47-67	8.2	7.5	0	10	13	33	40	3	ND	ND	ND	ND	ND	ND
P7/h4	IIIMg	67-80	8.3	7.5	1	3	27	42	26	2	ND	ND	ND	ND	ND	ND
P7/h5	IVM	80-90	8.7	8.1	35	43	14	7	2	0	ND	ND	ND	ND	ND	ND
P7/h6	VGo	90-95	ND	ND	39	31	4	13	13	0	ND	ND	ND	ND	ND	ND
P7/h7	VIGo	95-103	8.2	7.5	3	20	18	31	26	2	ND	ND	ND	ND	ND	ND
P7/h8	VIIGo	103-109	8.4	7.7	1	29	38	19	13	1	ND	ND	ND	ND	ND	ND
P7/h9	VIIIMg	109-118	8.3	7.7	0	19	32	31	16	1	0.5	0.8	0.02	29	0.025	0.29
P7/h10	IXM	118-132	8.3	7.7	13	50	7	14	14	2	ND	ND	ND	ND	ND	ND
P7/h11	XM	132-150	8.2	7.6	2	35	14	21	26	2	0.9	1.6	0.06	15	0.025	0.23
P7/h12	XIMh	150-195	7.8	7.4	1	14	20	36	25	2	2.5	4.2	0.13	19	0.024	0.29

Fig. 4.26. Pedological characteristics of the soil profile 7. Abbreviations : OC = organic carbon; OM = organic matter; Tot N = total nitrogen; Olsen P = Olsen phosphorus; Tot P = total phosphorus.

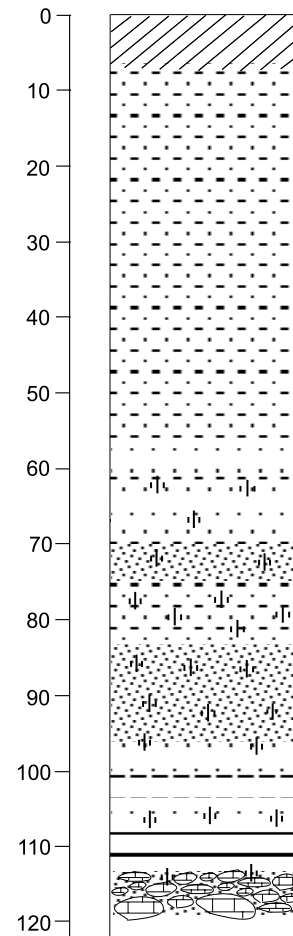


Fig. 4.27. Schematic description of soil profile 8 (see fig. 4.6 for legends of the description).

different effects on channel dynamics (Richards *et al.*, 2002).

The horizon 12 (*IXCh*) presenting organic matter marks do not show any aggregation feature excluding a buried top soil horizon. Organic matter content observed in this layer (2.46%; fig. 4.26) is probably due to accumulation of undecomposed plant debris. The bottom of the profile was very difficult to describe and to sample because of the deepness.

This profile is an illustration of the facies model 3.

Soil profile 8 - FLUVIOSOL TYPIQUE on REDUCTISOL TYPIQUE polyphasic

Situated on the opposite hillock this soil profile also exhibit alternation of fine and coarse materials, but is not so deep as the previous one (fig. 4.27; appendix 24). A different past sedimentation happened from one side of the oxbow to the other. The organic carbon content of horizon 2 (*AM*) is here higher than the content of top soil horizon (*A*; fig. 4.28), but this last one presents a lower pH and higher biodisponible phosphorus, strongly characteristic of surface horizons where fixing is possible with the clay-humus complex notably (Duchaufour, 2001). This is the reason why this nomenclature has been chosen (*A/AM*).

This profile is an illustration of the facies model 3.

Soil profile 9 – FLUVIOSOL TYPIQUE polyphasic

This soil profile was carried out on the Grandvillard islet during July 2004, so after the flood occurred in January 2004 (see 2.2.6.). The relating deposit is represented by horizon 1 (*M*) containing coarse sands (fig. 4.29; appendix 25). Horizons with organic matter (*Jp1*, *Jp2*, *Jp3*) are well separated by various coarse sediments (high content of coarse silts and coarse sands; fig. 4.30). They reflect certain stability between the different flood events, but not enough to stabilize the clay-humus complex. Organic carbon analyses show a relatively low content of organic matter for these three layers suggesting a rapid decomposition of the litter, as well as a quick organic matter mineralization

(fig. 4.31). No visible structure has been observed implying the choice of the reference FLUVIOSOL TYPIQUE polyphasic.

This profile is an illustration of the facies model 4.

Soil profile 10 - REDOXISOL

This profile was described in a *Phalaris* (or reed canary grass) grassland on the right bank of the Jogne River in an embanked zone, but regularly inundated by the rise in Gruyère Lake water level. There is no sharp limit between the different horizons and transitions are blurred and wavy (fig. 4.32; appendix 26). The texture of horizons composed of fine silts to clays reflects a quite inundation with low flow discharge generating slow and regular sedimentation. The top soil horizons present a relatively high content in organic carbon and in Olsen phosphorus resulting from the litter accumulation (caused by a slow *Phalaris* leaves decomposition; Kao *et al.*, 2003) and slow decomposition due to the inundation (fig. 4.33). The impact of embankments is not evident on this pedon, but the fluctuations of the Gruyère Lake water-table are predominant.

This profile is an illustration of the facies model 1.

Soil profile 11 – FLUVIOSOL TYPIQUE

This description was carried out in Lessoc on the right bank of the Sarine River in an embanked zone at about 10 m from the principal stream. This area is used as pasture, essentially for sheeps. In spite of dike constructions, layers with various texture and thickness indicate a zone regularly reached by floods (fig. 4.34; appendix 27). These rather fine deposits (silty sands or fine sands) reflect a calm inundation (fig. 4.35). Few oxidation marks are detected, but the presence of a water-table on the top soil is not obvious (fig. 4.36). These marks are rather the consequence of water trapping due to trampling even if the grazing influence is rather weak. Moreover, texture is sandy at these specific zones. In this area, pasture pressure due to sheeps do not have the influence observed in other conditions where perturbation affecting vegetation and soil due to trampling is noticed (Abdelmagid *et al.*, 1987) provoking a compressing of the ground, influencing the water regime.

This profile is an illustration of the facies model 4.

Sample	Horizons	Depth (cm)	pH water	pH KCl	Coarse sand (%)	Medium sand (%)	Fine sand (%)	Coarse silt (%)	Fine silt (%)	Clay (%)	Corg (%)	OM (%)	Ntot (%)	C/N	Polsen (mg/g)	Ptot (mg/g)
P8/h1	A	0-7	7.6	7.2	1	5	6	18	58	12	1.6	2.7	0.14	11	0.039	0.28
P8/h2	AM	7-31	8.0	7.5	0	8	25	37	29	1	4.1	7.1	0.35	12	0.024	0.35
P8/h3	M	31-55	8.1	7.6	1	18	9	17	48	7	ND	ND	ND	ND	ND	ND
P8/h4	IIM	55-60	8.2	7.7	1	21	30	31	18	0	ND	ND	ND	ND	ND	ND
P8/h5	IIIMg	60-63	8.1	7.6	0	4	16	39	37	3	ND	ND	ND	ND	ND	ND
P8/h6	IVM	63-66	8.2	7.7	0	5	28	42	23	1	ND	ND	ND	ND	ND	ND
P8/h7	VM	66-69	8.2	7.6	0	4	15	40	38	2	ND	ND	ND	ND	ND	ND
P8/h8	VIM	69-74	8.4	7.9	2	40	21	19	17	1	ND	ND	ND	ND	ND	ND
P8/h9	VIIMg	74-83	8.1	7.5	1	11	25	30	32	2	ND	ND	ND	ND	ND	ND
P8/h10	VIIIGo	83-96	8.5	8.0	15	66	12	4	2	0	ND	ND	ND	ND	ND	ND
P8/h11	IXM	96-98	7.9	7.4	1	10	18	40	28	3	ND	ND	ND	ND	ND	ND
P8/h12	XM	98-100	8.5	7.9	5	51	27	11	7	0	ND	ND	ND	ND	ND	ND
P8/h13	XIM	100-102	8.2	7.6	0	3	47	42	7	0	0.9	1.5	0.07	12	0.017	0.29
P8/h14	XIIM	102-107	8.4	7.8	1	29	18	34	16	1	ND	ND	ND	ND	ND	ND
P8/h15	XIIIGoGr	107-112	8.2	7.5	5	8	16	25	42	4	1.7	2.9	0.13	13	0.019	0.30
P8/h16	XIVDg	>112	8.4	8.1	51	29	16	4	1	0	ND	ND	ND	ND	ND	ND

Fig. 4.28. Pedological characteristics of the soil profile 8. Abbreviations : OC = organic carbon; OM = organic matter; Tot N = total nitrogen; Olsen P = Olsen phosphorus; Tot P = total phosphorus.

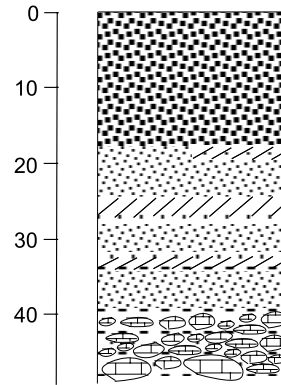


Fig. 4.29. Schematic description of soil profile 9 (see fig. 4.6 for legends of the description).



Fig. 4.30. View of the different *Jp* horizons, separated by coarse sand layers, found in the soil profile 9.

Sample	Horizons	Depth (cm)	pH water	pH KCl	Coarse sand (%)	Medium sand (%)	Fine sand (%)	Coarse silt (%)	Fine silt (%)	Clay (%)	Corg (%)	OM (%)	Ntot (%)	C/N	Polsen (mg/g)	Ptot (mg/g)
P9/h1	M	0-18	8.8	8.3	79	12	1	1	7	1	ND	ND	ND	ND	ND	ND
P9/h2	[Jp1]	[18-19]	8.3	7.9	40	32	2	6	18	2	0.9	1.5	0.09	10	0.009	0.16
P9/h3	IIM	18-23/25	8.5	8.0	47	38	3	5	6	1	ND	ND	ND	ND	ND	ND
P9/h4	Jp2	23/25-28/30	8.1	7.6	44	20	2	16	16	2	0.7	1.3	0.14	5	0.006	0.22
P9/h5	IIM	28/30-32	8.4	7.8	48	34	1	4	12	1	ND	ND	ND	ND	ND	ND
P9/h6	Jp3	32-34.5	8.1	7.6	46	20	2	12	18	2	1.2	2.1	0.12	11	0.006	0.21
P9/h7	IVM	34.5-39	8.5	7.9	24	55	5	3	11	1	ND	ND	ND	ND	ND	ND
P9/h8	VM	39-41	8.1	7.5	3	18	35	25	17	2	ND	ND	ND	ND	ND	ND
P9/h9	VID	>41	8.4	7.9	52	25	5	8	8	1	ND	ND	ND	ND	ND	ND

Fig. 4.31. Pedological characteristics of the soil profile 9. Abbreviations : OC = organic carbon; OM = organic matter; Tot N = total nitrogen; Olsen P = Olsen phosphorus; Tot P = total phosphorus.

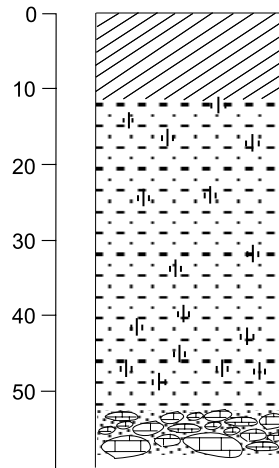


Fig. 4.33. Pedological characteristics of the soil profile 10. Abbreviations : OC = organic carbon; OM = organic matter; Tot N = total nitrogen; Olsen P = Olsen phosphorus; Tot P = total phosphorus.

Fig. 4.32. Schematic description of soil profile 10 (see fig. 4.6 for legends of the description).

Sample	Horizons	Depth (cm)	pH water	pH KCl	Coarse sand (%)	Medium sand (%)	Fine sand (%)	Coarse silt (%)	Fine silt (%)	Clay (%)	Corg (%)	OM (%)	Ntot (%)	C/N	Polsen (mg/g)	Ptot (mg/g)
P10/h1	Ag	0-11	7.7	7.1	0	1	1	0	80	18	4.5	7.8	0.43	11	0.043	0.48
P10/h2	Jpg	11-19	7.9	7.1	0	2	3	11	72	13	3.1	5.4	0.34	9	0.029	0.42
P10/h3	Mg	19-26	8.0	7.2	0	3	5	2	78	12	ND	ND	ND	ND	ND	ND
P10/h4	IIMg	26-37	8.1	7.3	0	5	7	4	74	10	ND	ND	ND	ND	ND	ND
P10/h5	IIMg	37-52	8.2	7.4	0	12	9	1	68	11	ND	ND	ND	ND	ND	ND
P10/h6	IVD	>52	8.6	7.9	0	80	3	3	12	1	ND	ND	ND	ND	ND	ND

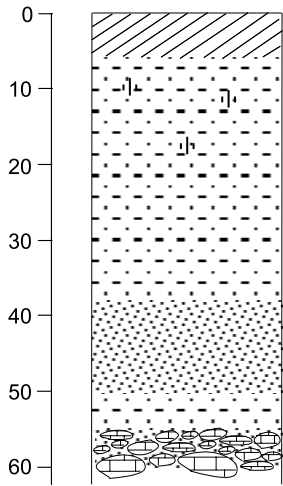


Fig. 4.34. Schematic description of soil profile 11 (see fig. 4.6 for legends of the description).

Sample	Horizons	Depth (cm)	pH water	pH KCl	Coarse sand (%)	Medium sand (%)	Fine sand (%)	Coarse silt (%)	Fine silt (%)	Clay (%)	Corg (%)	OM (%)	Ntot (%)	C/N	Polsen (mg/g)	Ptot (mg/g)
P11 / h1	A	0-5	8.0	7.3	6	14	8	36	33	3	2.3	4.0	0.21	11	0.028	0.40
P11 / h2	M	5-14/20	8.1	7.4	3	17	30	35	14	1	1.3	2.2	0.13	10	0.020	0.29
P11 / h3	IIM	14/20-29/38	8.3	7.6	3	16	33	30	17	1	ND	ND	ND	ND	ND	ND
P11 / h4	IIIM	29/38-34/50	8.4	7.7	1	35	34	17	11	1	ND	ND	ND	ND	ND	ND
P11 / h5	IVM	34/50-38/54	8.2	7.5	2	14	19	41	23	2	ND	ND	ND	ND	ND	ND

Fig. 4.35. Pedological characteristics of the soil profile 11. Abbreviations : OC = organic carbon; OM = organic matter; Tot N = total nitrogen; Olsen P = Olsen phosphorus; Tot P = total phosphorus.



Fig. 4.36. View of the few oxidation marks found on the top of soil profile 11.

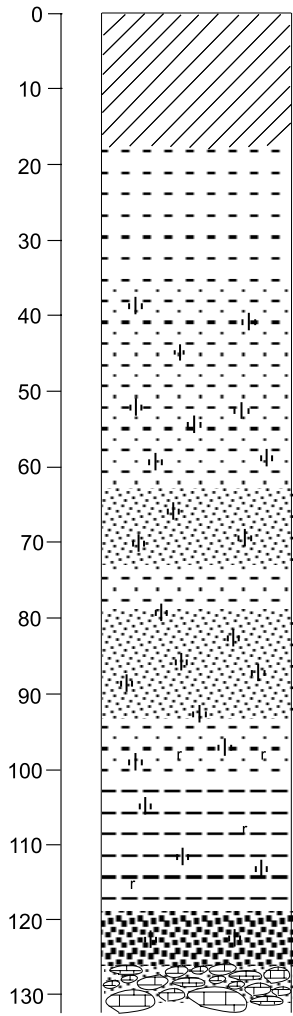


Fig. 4.37. Schematic description of soil profile 12 (see fig. 4.6 for legends of the description).

Sample	Horizons	Depth (cm)	pH water	pH KCl	Coarse sand (%)	Medium sand (%)	Fine sand (%)	Coarse silt (%)	Fine silt (%)	Clay (%)	Corg (%)	OM (%)	Ntot (%)	C/N	Polisen (mg/g)	Ptot (mg/g)
P12 / h1	A	0-17	7.8	7.2	2	7	6	30	48	7	3.3	5.6	0.38	9	0.038	0.56
P12 / h2	Jp1	17-36	8.1	7.3	1	6	15	43	31	4	1.4	2.4	0.15	9	0.022	0.30
P12 / h3	IIM	36-48	8.4	7.5	1	13	10	44	28	5	ND	ND	ND	ND	ND	ND
P12 / m.o.1	[Jp2]	[35-43]	8.0	7.2	1	11	7	40	35	6	2.0	3.5	0.22	9	0.038	0.38
P12 / h4	IIM	48-63	8.4	7.5	0	7	10	41	37	4	ND	ND	ND	ND	ND	ND
P12 / m.o.2	[Jp3]	[58-63]	8.1	7.3	1	7	13	46	29	4	1.8	3.1	0.21	9	0.023	0.34
P12 / h5	IVMg	63-73	8.5	7.7	0	20	21	35	21	3	ND	ND	ND	ND	ND	ND
P12 / h6	VM	73-79	8.4	7.6	0	9	13	46	29	3	ND	ND	ND	ND	ND	ND
P12 / h7	VGo	79-92	8.5	7.6	1	38	15	17	26	3	ND	ND	ND	ND	ND	ND
P12 / h8	VIIGoGr	92-101	8.4	7.4	0	6	16	29	44	5	ND	ND	ND	ND	ND	ND
P12 / h9	VIIIGoGr	101-119	8.4	7.4	4	4	6	35	44	7	ND	ND	ND	ND	ND	ND
P12 / h10	IXMg	>119	8.5	7.6	41	16	4	20	17	2	ND	ND	ND	ND	ND	ND

Fig. 4.38. Pedological characteristics of the soil profile 12. Abbreviations : OC = organic carbon; OM = organic matter; Tot N = total nitrogen; Olsen P = Olsen phosphorus; Tot P = total phosphorus.



Fig. 4.39. View of the bioturbated zones found in soil profile 12.

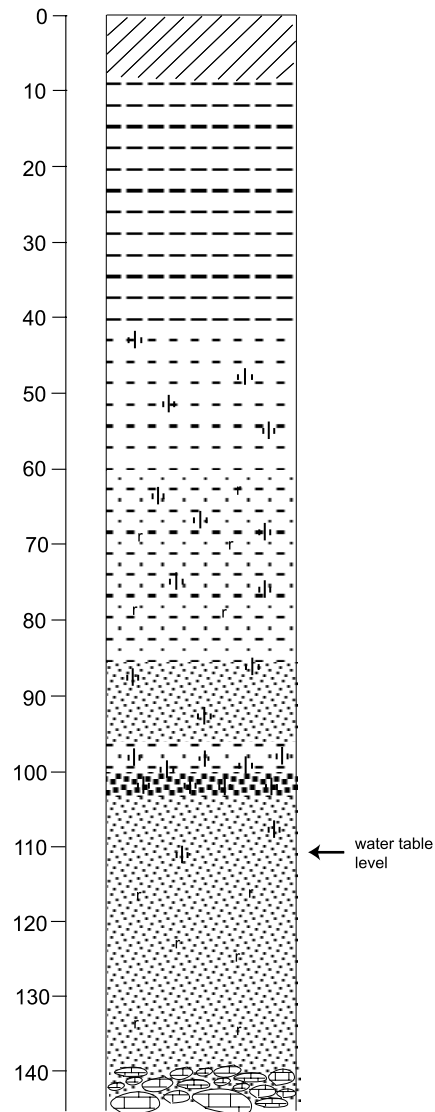


Fig. 4.40. Schematic description of soil profile 13 (see fig. 4.6 for legends of the description).



Fig. 4.41. View of the bottom layers of soil profile 13 showing coarse deposits, as well as a fluctuating water table.

Soil profile 12 – FLUVIOSOL on REDUCTISOL polyphasic

This soil profile was realized on the right bank of the Jogne River in grassland (belated pasture). The zone is named embanked, but is still potentially reached by Gruyère Lake overflowings. In the deepest part, horizons of various texture and thickness are observed (coarse sands to silts) reflecting a past alluvial dynamics relatively important in this area (fig. 4.37; appendix 28). Absence of recent flood permits the development of a well-structured top horizon (A) with stable aggregates and a high content in organic matter for alluvial context (3.26%; fig. 4.38). Between 40 and 60 cm, traces of organic matter are detected, probably due to the action of burrowing earthworms and/or roots (fig. 4.39). This presence of bioturbated zones suggests that this zone has been stable for a prolonged period (McCarthy and Plint, 1999). The hypothesis of a buried surface horizon is not maintained because no horizontality has been detected and the distribution of the traces is quite heterogeneous in the upper part of the profile. Oxidation marks found throughout the soil profile indicate water circulation probably due to temporary water table, but not observed at the description moment.

This profile is an illustration of the facies model 3.

Soil profile 13 – CALCOSOL on REDUCTISOL TYPIQUE

This soil profile was made in Neirivue on the left bank of the Sarine River at about 2 m on the left bank of the Neirivue Stream. The zone is embanked and used as hay field and belated pasture. Analysis of the different layers permit to show again two different superimposed functionings (fig. 4.40; appendix 29). On the bottom, mainly coarse deposits (sands to silty sands) reflect regular flood events (fig. 4.41). On the contrary, the top of the profile (between 0 and 40 cm) indicates pedogenic features with apparition of subangular blocky structure (horizon AS; fig. 4.42). Structure of this type is due to physical processes affecting clay minerals by swelling and shrinking of smectites (Gobat *et al.*, 2004). This is the result of the current field use (grassland and pasture), as well as the disconnec-

tion of this zone with the Sarine River. A fluctuating water table linked to the Neirivue Stream is also observed.

This profile is an illustration of the facies model 3.

Soil profile 14 – FLUVIOSOL TYPIQUE

This soil profile was described in a maize field and was situated in an embanked zone on the right bank of the Jogne River at about 20 m from soil profile 12. Even if no more impact of the river is visible in the field, this pedon still presents some aggradation marks. Nevertheless, layers are not well differentiated by their texture (more silty) indicating a past calm and regular sedimentation (fig. 4.43; appendix 30) as already seen in soil profile 10.

Here, the land-use obstructs the development of a good crumbly structure, but no hardpan is visible. This is probably due to the texture not fine enough to get compacted. According to the analyses, the horizons 1 and 2 seem to constitute a same and unique layer, differences observed in the field could be due to the very dryness of the surface horizon when excavation was made (during August 2003; fig. 4.44).

This profile is an illustration of the facies model 1.

4.3.3. Preliminary discussion

Basing on fig. 4.45, we may give some preliminary conclusions about soil typology. Hypothesis that alluvial soil formation is depending on two chemical and physical processes is verified. When soils are regularly saturated with water (e. g. soil profiles 1 and 2), high hydromorphism processes take place resulting in the formation of distinctive gley horizons. Soil profiles 3 and 10 also present hydromorphic features, but the impact of the river becomes predominant in the willow forest of Grandvillard (soil profile 9).

The impact of physical processes of the river is still present even if zones got artificial. For example soil profile 14 carried out in a maize field is described as a FLUVIOSOL TYPIQUE. On the other hand, constructions of embankments influence the connectivity between the river and its environment in

Sample	Horizons	Depth (cm)	pH water	pH KCl	Coarse sand (%)	Medium sand (%)	Fine sand (%)	Coarse silt (%)	Fine silt (%)	Clay (%)	Corg (%)	OM (%)	Ntot (%)	C/N	Polsen (mg/g)	Ptot (mg/g)
P13 / h1	A	0-8	7.7	7.2	1	7	5	27	54	6	2.8	4.9	0.32	9	0.041	0.52
P13 / h2	AS	8-40	8.0	7.4	1	8	8	14	61	9	1.5	2.5	0.18	8	0.015	0.37
P13 / h3	IIMg	40-60	8.2	7.5	1	17	11	1	61	10	ND	ND	ND	ND	ND	ND
P13 / h4	IIIMg	60-73	8.3	7.6	1	13	8	26	47	5	ND	ND	ND	ND	ND	ND
P13 / h5	IVMg	73-76	8.4	7.6	0	5	14	27	48	6	0.5	0.8	0.06	8	0.010	0.26
P13 / h6	VMg	76-86	8.4	7.7	0	13	28	29	27	3	0.4	0.6	0.04	9	0.018	0.24
P13 / h7	VIMg	86-95	8.4	7.7	0	10	4	14	64	7	ND	ND	ND	ND	ND	ND
P13 / h8	VIIMg	95-100	8.4	7.6	0	9	17	32	39	4	ND	ND	ND	ND	ND	ND
P13 / h9	VIIIGo	100-103	8.6	7.9	15	42	12	10	19	3	ND	ND	ND	ND	ND	ND
P13 / h10	IXGr	103-140	8.0	7.7	0	13	16	45	24	2	ND	ND	ND	ND	ND	ND
P13 / h11	-	at 125	7.9	7.8	3	19	9	36	31	2	ND	ND	ND	ND	ND	ND

Fig. 4.42. Pedological characteristics of the soil profile 13. Abbreviations : OC = organic carbon; OM = organic matter; Tot N = total nitrogen; Olsen P = Olsen phosphorus; Tot P = total phosphorus.

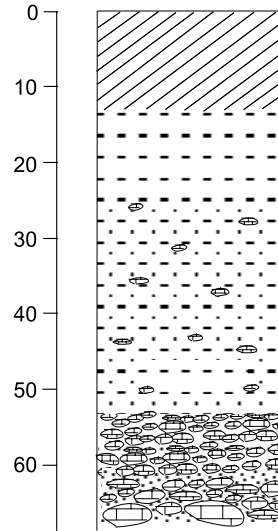


Fig. 4.43. Schematic description of soil profile 14 (see fig. 4.6 for legends of the description).

Sample	Horizons	Depth (cm)	pH water	pH KCl	Coarse sand (%)	Medium sand (%)	Fine sand (%)	Coarse silt (%)	Fine silt (%)	Clay (%)	Corg (%)	OM (%)	Ntot (%)	C/N	Polsen (mg/g)	Ptot (mg/g)
P14 / h1	LA	0-12	8.0	7.3	8	2	36	9	40	5	2.4	4.1	0.26	9	0.09	0.61
P14 / h2	Jp	12-23	8.0	7.3	7	2	30	10	45	5	2.4	4.1	0.27	9	0.09	0.59
P14 / h3	M	23-46	8.2	7.4	4	5	6	3	72	11	ND	ND	ND	ND	ND	ND
P14 / h4	IIM	46-52	8.2	7.4	4	6	35	2	47	5	ND	ND	ND	ND	ND	ND
P14 / h5	IIIM	52-62	8.2	7.5	6	20	15	6	48	5	ND	ND	ND	ND	ND	ND
P14 / h6	IVD	>62	8.1	7.5	7	21	15	3	47	7	ND	ND	ND	ND	ND	ND

Fig. 4.44. Pedological characteristics of the soil profile 14. Abbreviations : OC = organic carbon; OM = organic matter; Tot N = total nitrogen; Olsen P = Olsen phosphorus; Tot P = total phosphorus.

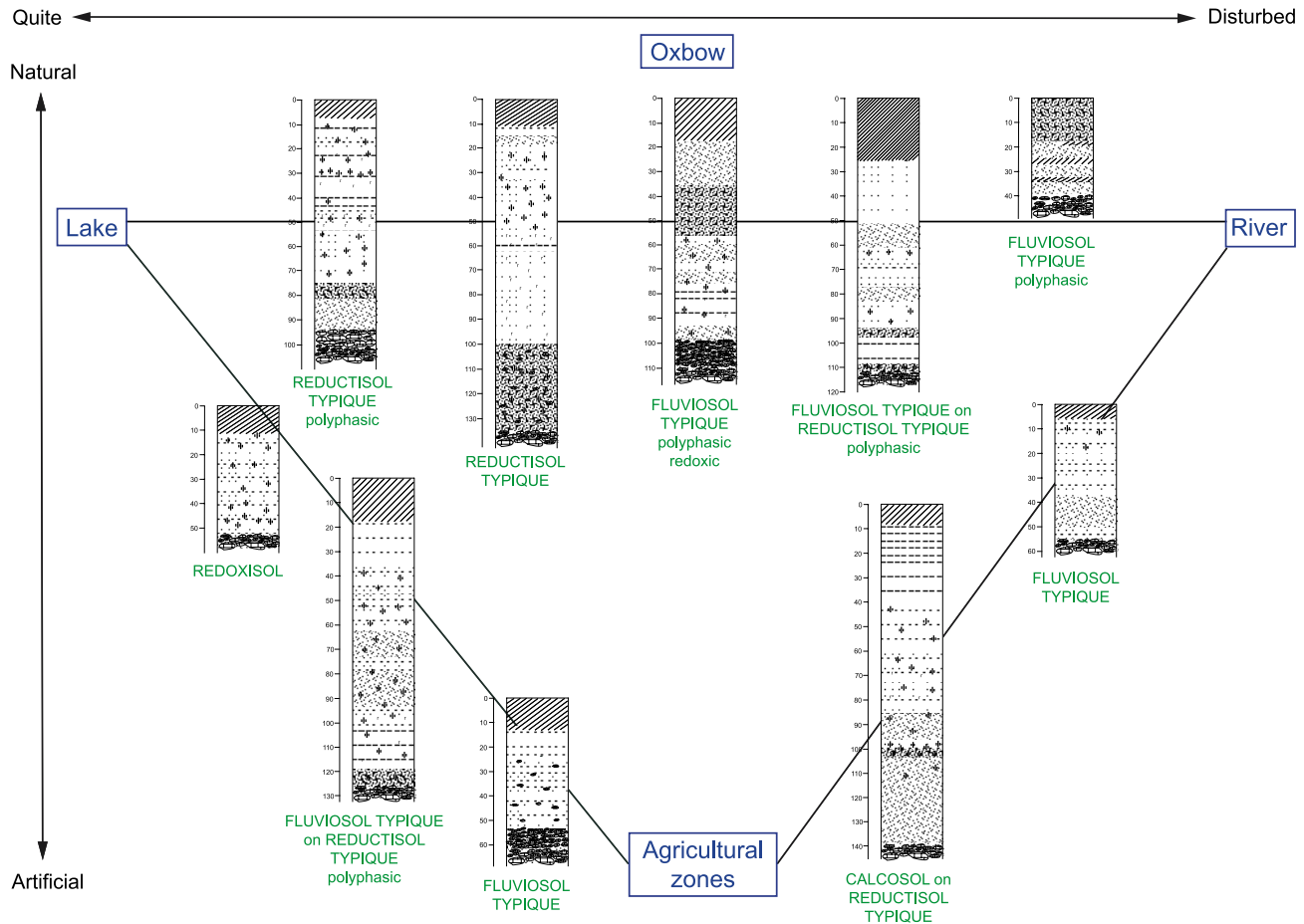


Fig. 4.45. Synthesis of the soil typology of the Sarine River following the hypothetical model.

natural and artificial zones. The cases of profiles 4 to 8, as well as 12 and 13, present the superposition of two different functionings clearly separated. We may illustrate that soil record its own ecological and hydrological history, traduced by different phases of development, as well as changes in landscape and land-use. More generally, soils reflect their flood-plains, which are especially sensitive to changes and more changeable over time than most other terrestrial ecosystems due to both autogenic and allogenic factors (Brown, 1996).

4.4. Particle-size distribution analysis and pH values

4.4.1. Results

The results of analyses of particle-size distribution, as well as data concerning pH H₂O and pH KCl, are given in 4.3.2. Correlations between these factors are found in fig 4.46. Additionally, for each soil profile, a textural triangle is presented (fig. 4.47). About the texture values in the soil profile 1, we may observe a steep separation between the bottom of the profile (h12 to h15) presenting a high

	Depth	Clay	Fine silt	Coarse silt	Fine sand	Medium sand	Coarse sand
pH H ₂ O	0.30***	-0.53***	-0.56***	-0.35***		0.58***	0.38***
Depth		-0.44***	-0.41***		0.18*	0.32***	

(*** p-value < 0.001, * p-value < 0.05)

Fig. 4.46. Pearson moment correlation (*r*) between some profile parameters (concerning texture and pH values).

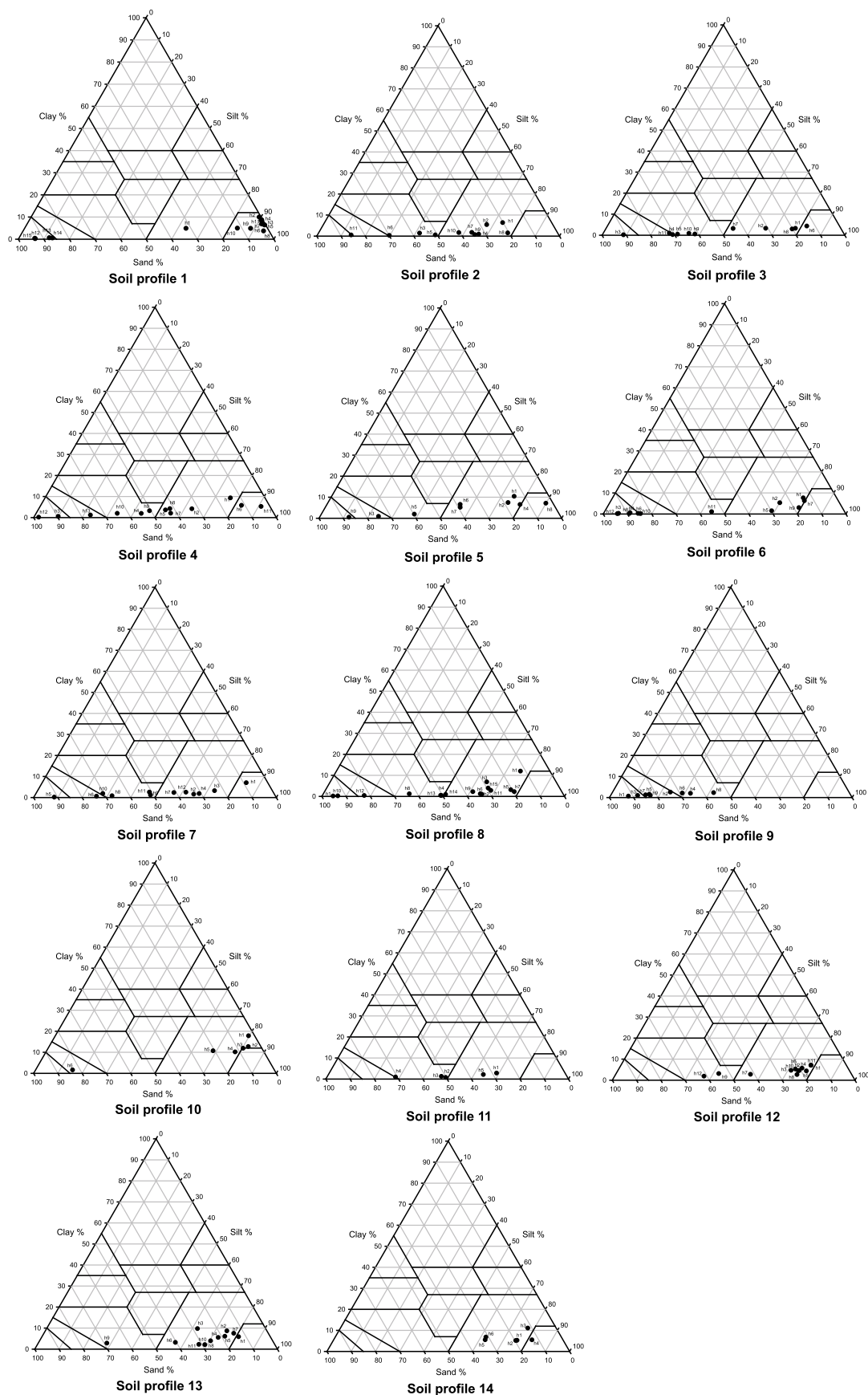


Fig. 4.47. Soil texture classes for soil profiles 1 to 14 (in %; after USDA, 1975).

content of sands, and the above layers generally in the silt category (or silt loam for h1). The pH H₂O values range from 7.7 to 8.7 (7.2 to 8.1 for pH KCl) with the minimum observed for the upper layer. Profile 2 presents texture categories from silt loam to loamy sand, which are quite similar, except for the deepest horizon containing a high sand proportion (85%). The lowest pH H₂O values are measured for h8 (7.7), corresponding to an organic layer with macrorests in a silty matrix (*VIIOLpGr*), and for h9 (7.8), a fine sandy layer with reduction process characteristics. The profile 3 presents textures from silt to sand categories with little clay content. About pH H₂O values, they range from 7.8 for *J_s* to 8.7 for h3 (*IIM*).

Concerning the profile 4, various texture classes are represented between silt to sand with clay content less than 10% (0-6%). pH values are also quite similar to other profiles with the lowest ones observed for the surface and organic layers (7.9 and 7.8 for pH H₂O, and 7.3 and 7.2 for pH KCl). Horizons of profile 5 present also texture categories from silt to sand with horizon A presenting a clay content of 10% and horizon h3 (*IIM*) with a high content of sand (almost 80%). pH H₂O values vary from 7.8 to 8.4 (7.3 to 8.0 for pH KCl). For the soil profile 6, alternation of silt loam (horizons h1, h2, h5, h7, h9) and sand categories (horizons h3, h4, h6, h8, h10) is obvious. Horizon h11 is an intermediate between these two classes with a sand loam texture. pH H₂O and KCl values for silty layers are lower than those for sandy layers (fig. 4.48). The texture categories are also quite diverse for soil profile 7 from silt or silt loam on the top (h1, h2, h3, h4, and h7 with silt content >50%) to sandy loam or

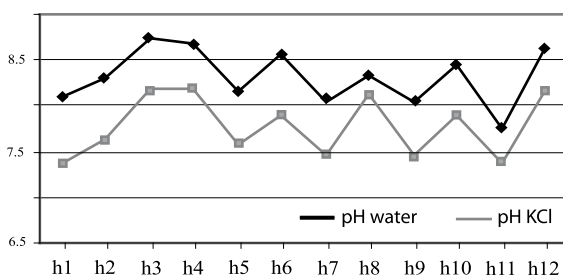


Fig. 4.48. pH values (water and KCl) for the different horizons of soil profile 6.

sand in the bottom. pH values range from 7.8 (for h1 and h12 presenting macrorests, to 8.4). Finally, the last profile of the two transects present also texture classes of silt loam mostly on the top (h1 to h7, except h4). From about 70 cm, an alternation of silt loam, sandy loam/loam sandy and sand categories is visible. The same tendency can be observed for the pH H₂O and KCl values.

Profile 9 shows appreciable amounts of sand with texture classes from sandy loam to sand. Horizon h8 presents the highest proportion of silt (more than 40%). pH H₂O varies in alternation from 8.8 to 8.1 (8.3 to 7.6 for pH KCl). For soil profile 10, the texture is in the silt loam class, except for the pebbles layer (loamy sand). pH H₂O values increase from 7.7 for the surface horizon to 8.6 for the pebble layer (7.1 to 7.9 for the pH KCl). Horizons of soil profile 11 are in silt loam categories for horizons h1 and h5 with silt proportion between 60% and 70%, and in the sandy loam one for the others. pH H₂O values increase from 8.0 to 8.4 (7.3 to 7.7 for pH KCl) from the top to the depth, with a slight drop (0.2 pH unit) in the deepest layer. For profile 12, silt loam class is well represented, particularly on the top. Horizons h5, h7, and h10 are sandier (sandy loam category for these two last layers). pH H₂O values slightly increase from the top to the depth (7.8 to 8.5; 7.2 to 7.6 for pH KCl).

Particle-size distribution for profile 13 is clearly in the silt loam class, except for horizon h9 containing the highest proportion of sand (almost 70%). Horizons h2 and h3 with almost 10% of clay and 60% of fine silt are the finest textured layers. pH H₂O values show a slight increase from 7.7 to 8.6 (7.2 to 7.9 for pH KCl). Finally, soil profile 14 described in a maize field presents a texture found in silt (h3) and silt loam classes. pH H₂O measures are quite similar throughout the profile (8.0 to 8.2).

4.4.2. First discussion

Correlations analyses expose a strong correlation between coarse and medium sands and pH H₂O values ($r = 0.38$ and $r = 0.57$ respectively). The drainage effect of sand particles can be an explanation. In fact, desiccation due to sands provokes a

re-saturation of the calcium complex increasing pH value. This fact is due to the correlation existing between pH and base saturation percentage (Gobat *et al.*, 2004). On the contrary, pH is lower in presence of silts or clays. This could be due to organic matter preferentially linked to the finest particles of the soil, and decreasing thus the soil pH because of organic acids.

The analyses of particle-size distribution reflect descriptions made in the field. Sands are preferentially found in the depth as also seen in the core sampling study (see 3.5 and 3.7.1). This fact is particularly obvious in the different soil profiles excavated in Neirivue, in the poplar plantation (profiles 4 to 8) or in the grassland (profile 13), which are now disconnected from the main river. The construction of dikes involved stable conditions allowing the formation of pedogenic features, such as angular or crumb structural organization. This isolation of environments due to river regulation was first studied in term of habitat mosaic for biota (Petts, 1996). Organism situations in such stabilized dynamics may be especially critical because of the lack of lateral connections between patches, provoking extinctions. The same phenomenon may be applied to vegetation or soils where “extinction” of alluvial dynamic has been observed for a while.

In soil profile 12, biological features are observed below the organic layers. This biological homogenization is part of the initial soil formation, when animals and plants start to inhabit the soils (Edelman and Van der Voorde, 1987). The stratification of alluvial deposits is progressively destroyed by the combined activity of animals and plants in the solum. This phenomenon also reflects the stabilisation of alluvial environment and the evolution toward different soil types.

4.5. Physicochemical parameters of the soil profiles

4.5.1. Physicochemical factors

The different physicochemical analyses are given in fig. 4.49. Only horizons described with traces of organic matter were taken into consideration

($n = 48$), because the others had missing values. Summaries of the different parameters for these organic horizons are also given in fig. 4.50. A general statistical analysis allows the identification of some significant correlations between soil factors. The most relevant relations (fig. 4.51) are the positive correlation between the total amounts of nitrogenous (total N) and phosphorus (total P), as well as organic carbon content (OC) with the clay proportion ($r = 0.46$, $r = 0.41$, and $r = 0.32$, respectively). Total P and OC are also correlated with the fine silts ($r = 0.42$, and $r = 0.30$, respectively). Strong relations are also observed between organic carbon and total nitrogen and phosphorus contents ($r = 0.89$, and $r = 0.58$, respectively). About textural categories, we can observe that clays and fine silts are correlated positively ($r = 0.88$), while they are negatively related with the four other ones. Negative correlations are also found between total P and the different sand proportions (coarse: $r = -0.33$, medium: $r = -0.41$, and fine: $r = -0.28$). Moreover, pH values are negatively correlated with OC, total N, and total P contents ($r = -0.51$ for the first two, and $r = -0.42$, for total P), as well as with the fine silt and clay contents.

4.5.2. Clustering analysis¹

The cluster analysis separates 7 groups of organic horizons (named AJ1 to AJ7; fig. 4.52). Their different characteristics are shown in fig 4.53 a and b. We can observe that group AJ1 present a high content of coarse sand and some medium sand, but very little clay, total and Olsen phosphorus. Group AJ2 shows the highest content of medium and fine sand and some coarse silts. Group AJ3 is characterized by a high proportion of medium sand and again little clay. These three groups present relatively high pH H₂O and pH KCl values and very little organic matter content, even if group AJ3 present a high C/N ratio is characteristic of the group AJ3. AJ4 presenting one of the highest proportions of coarse silt is also characterised by very high contents of total and Olsen phosphorus. The texture in group AJ5 is clearly silty (mostly fine)

¹ See also addenda 2, found in appendix 34.

Sample	Horizons	Depth (cm)	pH water	pH KCl	C. sand (%)	M. sand (%)	F. sand (%)	C. silt (%)	F. silt (%)	Clay (%)	OC (%)	OM (%)	Tot N (%)	C/N	Olsen P (mg/g)	Tot P (mg/g)
P1 / h1	Ag	0-8	7.7	7.2	0	24	8	17	46	5	4.0	6.9	0.38	11	0.044	0.49
P1 / h2	Jpg	8-14	8.0	7.4	0	0	0	4	85	10	1.8	3.1	0.18	10	0.025	0.38
P1 / h3	Mg	14-19	8.1	7.5	0	0	0	29	63	7	1.3	2.3	0.12	11	0.035	0.35
P1 / h11	IXApg	52-75	8.1	7.4	0	0	0	9	82	9	1.4	2.4	0.14	10	0.019	0.30
P2 / h1	A	0-9	7.9	7.3	1	12	7	25	49	6	3.1	5.3	0.26	12	0.03	0.36
P2 / h2	Jp	9-13	8.1	7.4	1	15	11	26	41	5	1.7	2.9	0.16	10	0.02	0.34
P3 / h1	Js	0-18	7.8	7.3	2	11	6	38	40	3	1.1	1.9	0.10	12	0.027	0.31
P3 / h2	Ap	18-35	8.2	7.6	3	19	9	32	34	3	2.7	4.7	0.25	11	0.019	0.38
P4 / h1	A	0-24	7.9	7.3	1	6	17	28	44	5	2.4	4.1	0.20	12	0.027	0.33
P4 / h2	M	24-51	8.2	7.5	1	16	16	26	37	4	1.2	2.0	0.10	12	0.020	0.28
P4 / h8	OLpVIIM	77-83	7.8	7.2	1	25	15	19	35	4	4.7	8.2	0.24	20	0.020	0.31
P4 / h9	VIIIMg	83-94	8.2	7.6	0	17	33	17	29	3	0.8	1.3	0.05	16	0.019	0.23
P5 / h1	A	0-18	7.8	7.3	1	10	3	7	68	10	2.7	4.7	0.23	12	0.023	0.34
P5 / h2	M	18-53	8.1	7.5	2	13	3	10	65	7	1.4	2.5	0.12	12	0.018	0.29
P5 / h5	IVMg	74-87	8.2	7.6	1	53	6	23	16	2	0.7	1.3	0.05	14	0.010	0.20
P5 / h6	Ap	87-90	8.0	7.5	6	24	8	6	49	6	2.5	4.4	0.16	16	0.017	0.24
P6 / h1	Js	0-17	8.1	7.4	2	7	5	23	56	8	1.1	1.9	0.09	12	0.031	0.28
P6 / h2	Ap	17-41	8.3	7.6	2	15	8	9	61	5	3.2	5.6	0.29	11	0.016	0.34
P6 / h9	Jp	82-86	8.1	7.5	1	5	13	40	39	3	2.5	4.3	0.15	17	0.018	0.27
P6 / h10	Jpg	86-100	8.5	7.9	1	57	27	13	3	0	2.8	4.8	0.16	17	0.016	0.26
P6 / h11	VIIIMg	100-105	7.7	7.4	1	19	35	32	13	1	0.5	0.9	0.04	14	0.018	0.18
P7 / h1	A	0-14	7.8	7.2	1	3	27	42	25	2	3.6	6.2	0.30	12	0.039	0.38
P7 / h2	M	14-47	8.3	7.5	1	11	21	36	29	1	0.9	1.5	0.09	10	0.026	0.28
P7 / h9	VIIIMg	109-118	8.3	7.7	0	19	32	31	16	1	0.5	0.8	0.02	29	0.025	0.29
P7 / h11	XM	132-150	8.2	7.6	2	35	14	21	26	2	0.9	1.6	0.06	15	0.025	0.23
P7 / h12	XIMh	150-195	7.8	7.4	1	14	20	36	25	2	2.5	4.2	0.13	19	0.024	0.29
P8 / h1	Js	0-7	7.6	7.2	1	5	6	18	58	12	1.6	2.7	0.14	11	0.039	0.28
P8 / h2	Ap	7-31	8.0	7.5	0	8	25	37	29	1	4.1	7.1	0.35	12	0.024	0.35
P8 / h13	XIM	100-102	8.2	7.6	0	3	47	42	7	0	0.9	1.5	0.07	12	0.017	0.29
P8 / h15	XIIIGoGr	107-112	8.2	7.5	5	8	16	25	42	4	1.7	2.9	0.13	13	0.019	0.30
P9 / h2	[Jp1]	[18-19]	8.3	7.9	40	32	2	13	18	1	0.9	1.5	0.09	10	0.009	0.16
P9 / h4	Jp2	23/25-28/30	8.1	7.6	44	20	2	18	16	2	0.7	1.3	0.14	5	0.006	0.22
P9 / h6	Jp3	32-34.5	8.1	7.6	46	20	2	17	18	2	1.2	2.1	0.12	11	0.006	0.21
P10 / h1	Ag	0-11	7.7	7.1	0	1	1	0	80	18	4.5	7.8	0.43	11	0.043	0.48
P10 / h2	Jpg	11-19	7.9	7.1	0	2	3	11	72	13	3.1	5.4	0.34	9	0.029	0.42
P10 / h8	Apg	60-61	7.7	7.5	1	10	23	43	22	1	2.3	3.9	0.13	17	0.02	0.30
P11 / h1	A	0-5	8.0	7.3	6	14	8	36	33	3	2.3	4.0	0.21	11	0.028	0.40
P11 / h2	M	5-14/20	8.1	7.4	3	17	30	35	14	1	1.3	2.2	0.13	10	0.020	0.29
P12 / h1	A	0-17	7.8	7.2	2	7	6	30	48	7	3.3	5.6	0.38	9	0.038	0.56
P12 / h2	Jp1	17-36	8.1	7.3	1	6	15	43	32	4	1.4	2.4	0.15	9	0.022	0.30
P12 / m.o.1	[Jp2]	[35-43]	8.0	7.2	1	11	7	40	35	6	2.0	3.5	0.22	9	0.038	0.38
P12 / m.o.2	[Jp3]	[58-63]	8.1	7.3	1	7	13	46	29	4	1.8	3.1	0.21	9	0.023	0.34
P13 / h1	A	0-8	7.7	7.2	1	7	5	27	54	6	2.8	4.9	0.32	9	0.041	0.52
P13 / h2	AS	8-40	8.0	7.4	1	8	8	14	61	9	1.5	2.5	0.18	8	0.015	0.37
P13 / h5	IVMg	73-76	8.4	7.6	0	5	14	3	48	6	0.5	0.8	0.06	8	0.010	0.26
P13 / h6	VMg	76-86	8.4	7.7	0	13	28	29	27	3	0.4	0.6	0.04	9	0.018	0.24
P14 / h1	LA	0-12	8.0	7.3	2	8	9	36	40	5	2.4	4.1	0.26	9	0.09	0.61
P14 / h2	M	12-23	8.0	7.3	2	7	10	30	45	5	2.4	4.1	0.27	9	0.09	0.59

Fig. 4.49. Physicochemical analysis for horizons containing organic matter (A, J, OL, some M and S; n = 48). Abbreviations: C. sand = coarse sand; M. sand = medium sand; F. sand = fine sand; C. silt = coarse silt; F. silt = fine silt; OC = organic carbon; OM = organic matter; Tot N = total nitrogen; Olsen P = Olsen phosphorus; Tot P = total phosphorus.

	pH H ₂ O	pH KCl	Coarse sand (%)	Medium sand (%)	Fine sand (%)	Coarse silt (%)	Fine silt (%)	Clay (%)	OC (%)	OM (%)	Tot N (%)	C/N	Olsen P (mg/g)	Tot P (mg/g)
Min.	7.6	7.1	0	0	0	0	3	0	0.4	0.6	0.02	5	0.006	0.16
Median	8.1	7.4	1	11	9	26	38	4	1.8	3	0.15	11	0.022	0.3
Mean	8.0	7.4	3.9	13.5	13	25	40	5	2.0	3.5	0.18	12	0.026	0.33
Max.	8.5	7.9	46	57	47	46	85	18	4.7	8.2	0.43	29	0.09	0.61

Fig. 4.50. Summaries of the different soil parameters for horizons containing organic matter (A, J, OL, some M and S; n = 48). Abbreviations: OC = organic carbon; OM = organic matter; Tot N = total nitrogen; Olsen P = Olsen phosphorus; Tot P = total phosphorus.

	pH H ₂ O	Clay	Fine silt	Fine sand	Medium sand	Coarse sand	OC
OC	-0.51***	0.32*	0.30*				
Total N	-0.51***	0.46***					0.89***
Total P	-0.42***	0.41**	0.42**	-0.28*	-0.41**	-0.33*	0.58***

(*** p-value < 0.001, ** p-value < 0.01, * p-value < 0.05)

Fig. 4. 51. Pearson moment correlation (r) between the profile factors for horizons containing organic matter (*A, J, OL*, some *M* and *S*; $n = 48$).

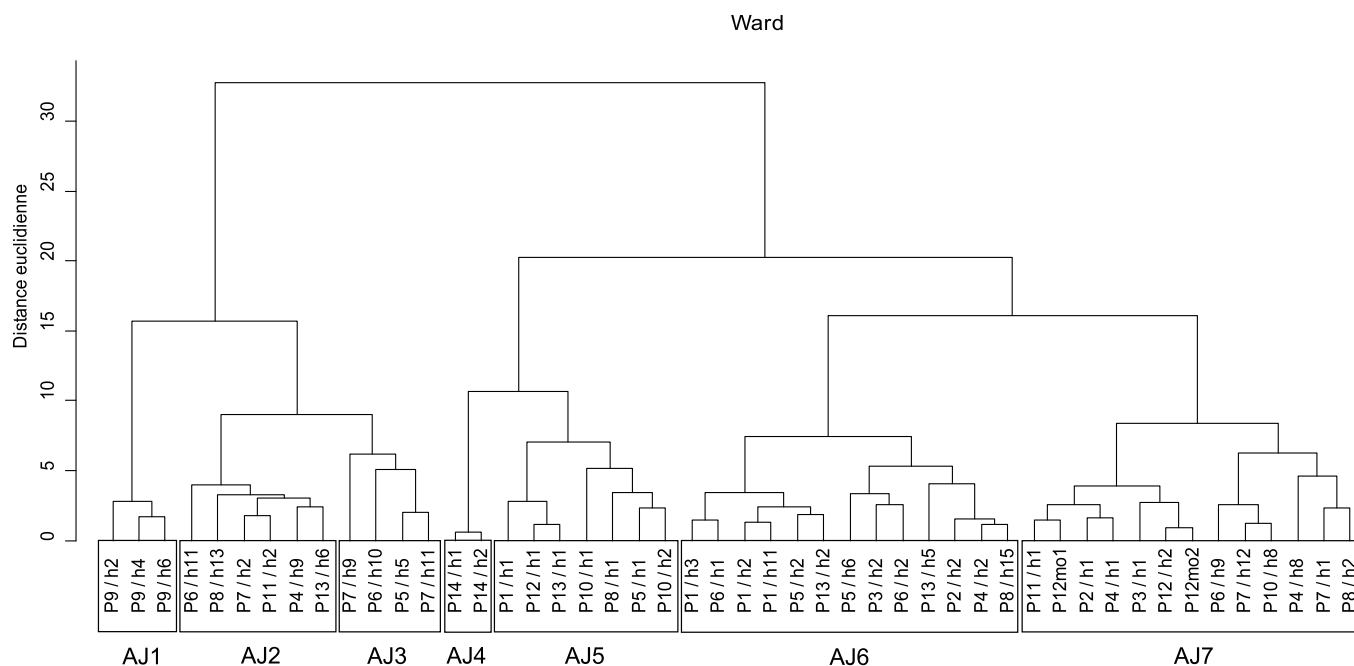


Fig. 4.52. Simplified dendrogram for 48 horizons containing organic matter obtained by means of Ward's minimum variance clustering and described in the 14 soil profiles. The group fusion level is defined by a distance (R Software, version 2.4.1; R Development Core Team, 2006). Seven AJ groups are then defined.

with a lot of clays; it also presents high proportions of total phosphorus, total nitrogenous and organic carbon. Moreover, the two pH values are quite low. Group AJ6 is dominated by a fine texture with high proportions of fine silt and clay. Similarly, group AJ7 presents high contents of coarse silt, organic matter and total nitrogenous. The statistical analysis reveals the proportion of fine silt as the most discriminating factor for the clustering analysis (more or less than 21%), then the organic carbon content (more or less than 1.15%).

About the repartition of each horizon in the different groups, we observe that only two profiles are represented in the same group (profiles 9 – ilet

with draped willows, horizons found in group AJ1 - and 14 – maize field, horizons of AJ4 group). The others are distributed in the different groups. Top soil horizons (h1) are more represented in the groups AJ5 and in AJ7 for a lesser extent. The second horizons just below the surface (h2) are rather found in groups AJ6, whereas the buried ones are characteristic of groups AJ2, AJ3 and AJ7 to a lesser extent. Correspondence to groups of genetic horizons as distinguished in the field is not obvious. Once again, the part of external factors (nature of deposited sediments) and internal pedogenetic processes (incorporation of organic matter) enhances of great importance in the horizon development.

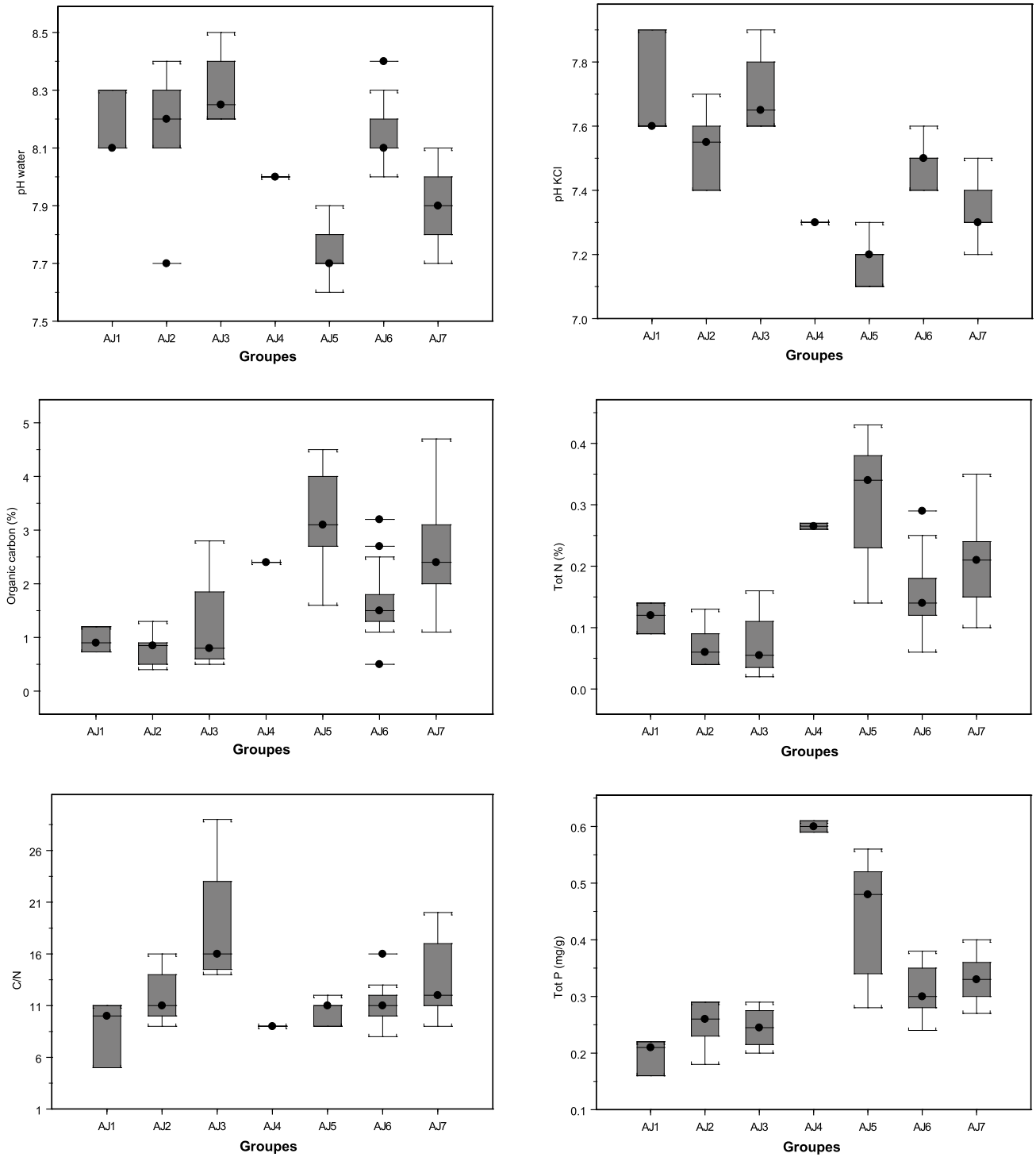


Fig. 4.53 a. Summaries of the different chemical analyses for groups AJ1 to AJ7 as identified by Ward’s minimum variance clustering (see fig. 4.52). Error bars indicate standard error, and median is also illustrated in each box plot.

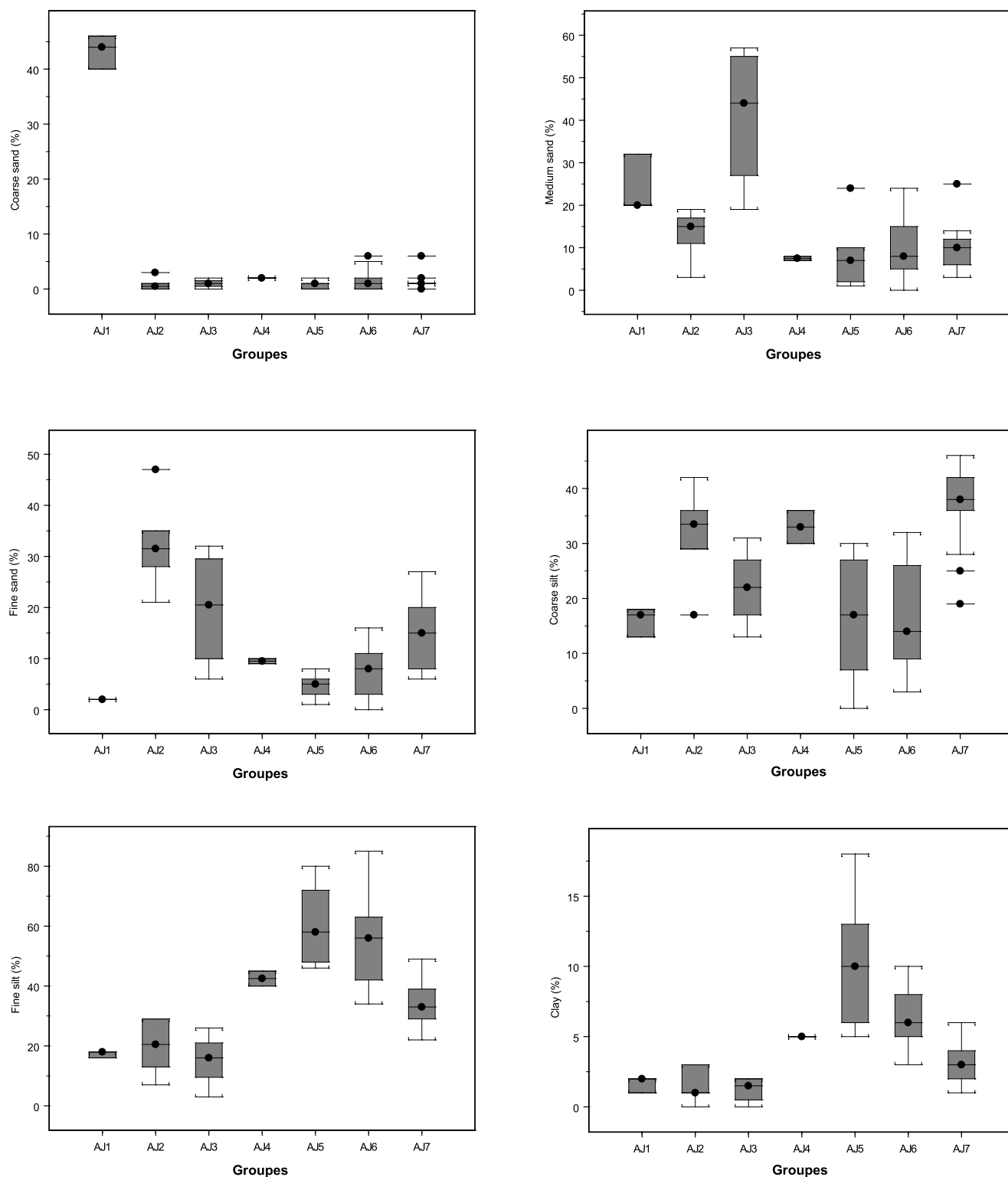


Fig. 4.53 b. Summaries of the different physical analyses for groups AJ1 to AJ7 as identified by Ward’s minimum variance clustering (see fig. 4.52). Error bars indicate standard error, and median is also illustrated in each box plot.

4.5.3. Other analysis

The PCA illustrates in a two-way axis the relationships between measured variables (Fig. 4.54). The first principal component axis PC1 (explaining 42% of the total variance) separated the samples according to the chemical parameters (total nitrogen and pH KCl principally, and then total phosphorus and organic carbon). The second axis PC2 (explaining 16% of the total variance) discriminated the texture with coarse silt and fine sand on one side and fine silt and clay on the other side. The different groups show again a repartition in relation with total organic matter

content and texture. For example, group AJ5 is clearly related to fine silt and clay texture, when AJ2 and AJ3 are more closed to fine sand and coarse silt one.

Regression trees were calculated to test the two hypothetical gradients. Concerning the natural-artificial gradient, it appears that soils in the bottom of the model triangle (profiles 12 to 14) present generally an index C/N lowers than 10. The discriminating factors for the upper layers (h1 and h2) compared to the buried ones are the Olsen phosphorus values. Indeed, Olsen P over 0.026 mg/g is characteristic of upper layers.

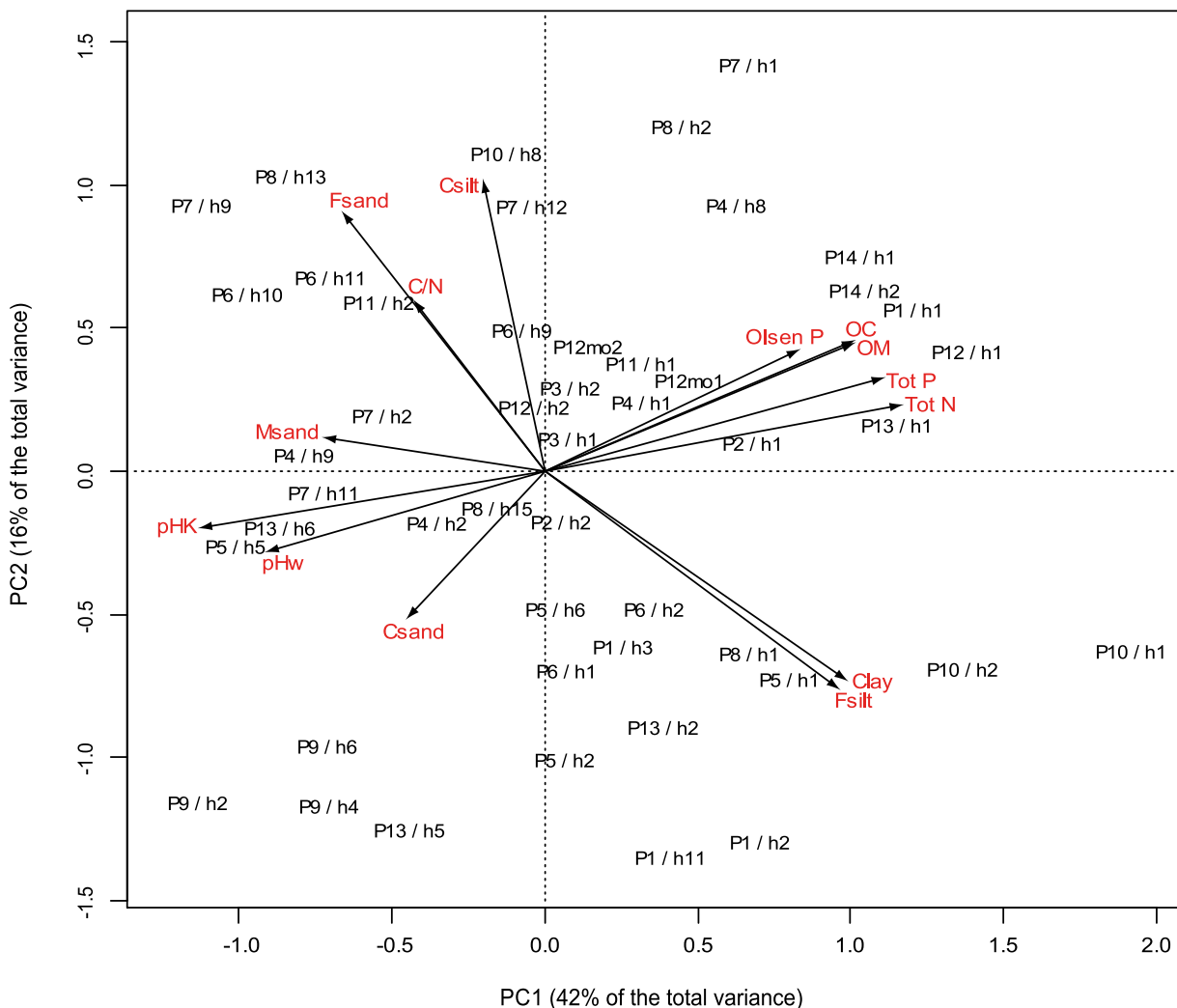


Fig. 4.54. Results of the principal component analysis (PCA): ordination of the samples (horizons containing organic matter; n = 48) and soil parameters in the plane defined by the axis PC1 and PC2. Abbreviations: Csand = coarse sand; Msand = medium sand; Fsand : fine sand; Csilt = coarse silt; Fsilt = fine silt; OC = organic carbon; OM = organic matter; Tot N = total nitrogen; Olsen P = Olsen phosphorus; Tot P = total phosphorus.

4.6. Interpretation of the soil profile parameters

Concerning the soil profile parameters, our results follow those already found in the Sarine River (Bureau, 1995; Mendonça Santos, 1999; Augsburger, 2004) or in other alluvial systems (e. g. Mann and Plug, 1999; Daniels, 2003). Fang *et al.* (2002) studied calcareous soils in the Minnesota River Basin and found slightly highest content of organic matter (3.8-8.3%), but in silty clay and clay soils with pH values ranging between 5.8 and 8.0. They also found highest proportions of phosphorous (1.1 to 0.35 mg/g for total phosphorus, and 0.006 to 0.097 mg/g for Olsen phosphorus). In another research, monitoring the dynamics of phosphorus availability in soils following the application of phosphorus fertilizer and using alluvial soils, proportions of 5.3% of organic matter and 0.021 mg/g of Olsen phosphorus are found with a pH of 7.89 (12.7% of sand, 21.8% of silt and 65.5% of clay; Huang *et al.*, 2005), and are once again slightly higher than our values (except for the phosphorous content). In China, a study concerning of soil phosphorus forms in riparian freshwater wetlands found also contents of total phosphorus between 0.427 and 0.811 mg/g.

Thus, our results show relatively low organic, phosphorus and nitrogenous contents in the top-soil horizon and various proportions of the different textural classes. This may be due to the river regime that still transported and deposited coarse materials as seen in soil profile 9, which presents particularly low proportions of nutrients and high sand content. Moreover, the low clay content prevents the humus-clay complex to retain organic matter. Nevertheless, in case of gley soils subjected to permanent reducing conditions, concentrations of phosphorus and nitrogen are under influence of floods, which maintain the nitrogen and phosphorus filtering of riparian zones, and thus the effectiveness of processes in nutrient retention and removal (Takatert *et al.*, 1999). The lower concentrations in P and N in the Sarine River soils may be rather due to the chemical and physical properties and pH value in particular. In very acid or very calcareous environments, phosphorus evolves under influence

of alternation of soaking and desiccation towards crystalline insoluble forms with reduced availability (Duchaufour, 2001). Moreover, organic carbon and nitrogen storage seems to be strongly related to fine particle concentrations and fine-textured soils had greater nitrogen with slower turnover (Bechtold and Naiman, 2006).

The particularly high proportion of phosphorus (total P and Olsen P) in the maize field (soil profile 14) is certainly due to soil improvement. Agricultural fertilizers contain effectively a high proportion of phosphorus, as well as nitrogenous also found in high proportion in this profile, and are used to accelerate the turnover and activate the humus formation (Duchaufour, 2001). Because of the calcareous substratum found in the Sarine River valley, the mineralogical origin could not be taken into consideration. Effectively, only apatite rocks contain a high content of phosphorus, and these rocks are not detected in the present study area; Le Bayon, pers. comm., 2007). The particularities of these two soil profiles (9 and 14) explain the clustering separation of their horizons in different groups (AJ1 and AJ4).

Calculated correlations suggest that organic matter, as well as total phosphorus, is more related to a fine texture (fine silt and clay) allowing formation of soil structure. In presence of organic matter, and thus organic acids, pH is lower than in coarse textured horizons. This result display the similar trend already found for the whole horizons (see 4.4.1). Sandy horizons are also shown as presenting a low total phosphorus proportion. This is quite obvious when we know that phosphorus in soil depends on accumulation of organic matter. Moreover, phosphorus availability is determined by absorbing power, which varies in relation with the nature and state of absorbing agent (Duchaufour, 2001). When absorbing power is high, like in presence of clay-humus complex, phosphorus is retained by the substrate and could then become available for plants. In the case of coarse sandy texture, absorbing power is low and the compounds such as phosphorus are not maintained (Gobat *et al.*, 2004). The same process is known for nitrogen

whose stocks in soil are also distributed in organic matter (Duchaufour, 2001).

The PCA reinforces these considerations by opposing organic matter (total phosphorus, nitrogenous and organic carbon in a lesser extend) to pH KCl values on the first axis, and coarse silt and fine sand to fine silt and clay on the second axis. About texture, we observe a strong relation between very fine particles of soil (fine silt and clay). This is probably due to the mineralogical nature of these particles and particularly to the clay minerals preferentially found in the finest silt fraction. In our case, fine silt particles present the same properties as clay particles, particularly electronegativity and hydrophilicity (Gobat *et al.*, 2004). The first property permits to retain cations and anions and thus to increase plant nutrient release and soil fertility, when the other creates hydric reserve of the soil. Moreover, the best combination of physical and chemical properties for crop growth and cultivation is supposed to be the loams corresponding to a soil texture with 40% of silt and sand and 20% of clay (Gerrard, 2000). In this case, particles allow easy drainage of excess water and retain enough water for plant use. Soil porosity is also dependent on texture. In the case of fine silt soils, pores seem to be large enough to allow root penetration and water movements. It is not the case if texture is heavy with a high content of clay for example (Gerrard, 2000). Nevertheless, this situation never appears in the studied soils because of the high torrential regime of the rivers.

The cluster analysis indicates that even if organic matter is present in the horizon, the ones found in depth present a coarser texture than the top soil ones. Organic matter may thus be detected in soil layers only after periods of certain stability. Unstable periods provoke deposition of coarse material not favourable for soil structuring. This phenomenon of alternation of stable and unstable periods is rarely found in soil formation. In general, profiles tend to get more differentiated with time with an increase of complexity of soil profiles (Gerrard, 2000). Young soils have generally a higher pH and a lower percentage of carbon. In our case, it is effectively due to the youth of the soils, but different pedogeneses are su-

perimposed that could modify the time scale dimension. Combinations of particles, preferably fine silts and clays, but with some sands, linking with steady environmental conditions, seem to be the situation for concentration of organic matter and thus formation of soil structure.

4.7. Soils variability in the Sarine River system

Regarding the diversity of soil types throughout the study area, it appears that soils submitted to effects of the Gruyère lake really present hydromorphic features predominating in the soil functioning (presence of *Go* and *Gr* horizons, as well as “g” suffix). When the effects of the river become progressively evident, relatively to the lake’s ones, soil types are more influenced by alluvial dynamics and the phenomena of deposition and erosion (succession of different *M* horizons). When regular alluviation processes happen (like in soil profile 9) succession to climax may be reversed and to initial stage is observed. The evolution is then called regressive (Duchaufour, 2001). The evolution could be progressive (leading to the climax) in the case of agricultural environments, where zones become stable with the apparition of bioturbated zones (e. g. in soil profile 12) or blocky structure on the top of the profile (e. g. in soil profile 13 – CALCOSOL on REDUCTISOL TYPIQUE).

The double attributions applied to some soil profile references reflect the effects of embankments on soil functioning. Before the construction of dikes, the soils could be attributed to the alluvial dynamics with hydromorphic and sedimentologic characteristics. Afterwards, the zone is no more reached by floods, disconnected from its river and thus developed another pedogenesis. As seen in other studies (Gordon and Meentemeyer, 2006), construction of dam coupled with agricultural practices has a great impact on the riparian environment. The variability in bankfull area decreases and stable conditions for vegetation growth are provided. Observation of stratified sediments may then be used as time marker in order to detect events in the floodplain chronology. This double attribution corresponds to

a drift in the environmental conditions leading to changes in soil evolution. In this case, we are not talking about regressive evolution, but about degradation meaning a new evolution of ecosystem causing by human impact or climate change, leading to a complete transformation of vegetation, humus and soil (Duchaufour, 2001). Here, the transformation is not total, but a new soil pedon is superimposed to an older one forming polyphasic soils.

Such polyphasic development has already been studied in the Loir low-lying valley (France), but on quaternary siliceous alluvial formations (Rosignol *et al.*, 2006). These soils, originating from different periods, but made up of material showing little variation from one terrace to another, do not show the same characteristics in the pedological profiles. The older soils present the greater evolution, but this evolution can be incorporated into the same type of chronosequence (brunification, clay-leaching, rubefaction and hydromorphy). Anyway, our soils are not evolved enough to show such characteristics and only marks of brunification was detected in the soil profile 13.

It has been shown that different rate of soil formation and alluviation could be observed (Alexandrovskiy *et al.*, 2004). Some periodicity in the rates of alluvial sedimentation (and thus pedogenesis) may explain the variability of deposit sediments. They detected that when rate of alluviation exceeds 3 mm/year, well-developed soils cannot be formed and a unit of stratified sediments is produced. On the other hand, when the rate of alluviation is less than 1 mm/year, well-developed soils can be formed. Between 1-3 mm/year distinct stratification is developed. This phenomenon is observed in active alluviation soils that we described (in soil profile 9 for example), where thick sand layers alternate with weak-developed organic matter layers meaning an alternation of high and low rate events. In the lower part of the polyphasic soils (e. g. soil profiles 4 and 5) an alternation of thin and thick layers of different texture is also observed, meaning rates of alluviation between 1-3 and 3 mm/year, but layer with organic matter is not regularly found. This may be due to erosion that transports downstream this organic

layer or to frequent and regular floods preventing the formation of this particular layer. Nevertheless, soil profile 1 is the only one to present a real buried organic-mineral horizon indicating a long period of stability in that zone (before the construction of Rossens dam and the annual inundations).

Concerning the natural-artificial gradient, soils in the bottom of the model triangle (profiles 12 to 14) present an index C/N of 8-9, representing a high turnover of organic matter even in the buried horizon. Other sites, particularly the ones of the two transects (4 to 7), present a high C/N (more than 14) for buried layers. This could be explained one more time by the past dynamics happening in the deepest layers as a result of organic debris deposition. These plant tissues were not decomposed because of certain water content present, sufficient to conserve them.

The discriminating factors for the upper layers (h1 and h2) compared to the buried ones are the Olsen phosphorus values. The feedback effect happening in the topsoil permits to make the phosphorous form more available for plants. The roots secretions and soil fauna exudates enriching the upper layers may be an explanation. Moreover, pH values are often lower in the surface horizon.

4.8. Evolution of soils and link with vegetation

Some studies have been made on alluvial vegetation in the Sarine River (Werfelli *et al.*, 1997; Roulier, 1998; Gremaud, 2004) or in other floodplain systems (Bravard *et al.*, 1986; Hughes and Cass, 1997; Deiller *et al.*, 2001; Capon, 2005) with the main conclusion of a frequent floristic shift between vegetation layers, as well as a great impact of historical events on vegetation (Tremolières *et al.*, 1998; Kamisako *et al.*, 2007). For example, the herbaceous layer of a given forest community (e. g. willow forest) might contain several species of an older dynamic stage (e. g. beech or spruce shrubs). In this case, environmental changes, due mainly to human impact, induce differential stability of the vegetation layers, and thus, communities of plant

species evolve quite rapidly in the time scales (from months for moss layers to several decades for tree layers). This time scale is different for soil evolution and soil may stay in connection with the underlying sediments and evolve quite slowly.

Others studies, like the one carried out in Russia (Alexandrovskiy *et al.*, 2004), showed that soils developing under herbaceous vegetation usually have a shallow profile. On the contrary, soils developing under forest vegetation have a thicker profile with humus accumulation and eluvial and illuvial horizons. In this last case, alluvial stratification is often destroyed by the processes of illuviation and structuring leading to the destruction of previously buried soils. The soil profiles of the Sarine River are not stabilized for enough time to present this type of evolution. Anyway, features of humus accumulation and structuring have already been detected.

Even if embankments, built since the beginning of the 20th, permit to keep riverside lands out of flood reach, these constructions have lead to a decrease in alluvial environment species. Forests got more uniform, losing their alluvial character (see 2.2.6). Soil evolution is thus happening independently of vegetation colonisation, as well as soil age. On the other hand, vegetation reacts mainly to the functioning of the soil, and to a lesser extent to its morphology (Gobat *et al.*, 2004). Indeed, vegetation responds often to a single limiting edaphic factor and not to the horizon morphology. Apparition of pedological features due to new conditions implies adaptation for horizons that takes time. This notion of time has thus to be taken at a different way if vegetation or soil is concerned.

4.9. Conclusion

In the Sarine River floodplain, soils of different genesis have been discovered. Weakly developed buried soils found in active alluvium accumulation zones (soil profile 9) alternated with buried soils showing pedogenesis features described in more stable zones (soil profile 13). Anthropogenic loads on the fluvial environment have enhanced the modifications of soil evolution. Construction of

embankments, forest cutting and land-use changes have significantly redesigned the pattern of alluvial soil evolution. These variations have thus provoked standardization in the vegetation types, which become uniform and loose their alluvial characters.

Alluvial soils are unique soils depending on accumulation of materials transported by streams. These deposited materials coming from upstream erosion may often lead pedogenesis to another direction and change local conditions. Observation of these drifts could then give relevant information about how system (here soil pedon) has the ability to adapt its structure and functioning in order to survive changes and perturbations, and thus to aim a certain equilibrium. These changes in stability, considered as markers detectable inside the profile, give also information about the chronology and so about the history of the study area. This distinguishes alluvial soils from other soils such as BRUNISOL or NEOLUVISOL, also found in temperate climate zones, but in which pedological features are mainly occurred from the top to the bottom of the soil pedon.

The significant particularity of alluvial soils is also the fact that they show a part of inheritance linking to abiotic processes (sedimentation) and a part of *in situ* processes taking account of pedogenetic processes such as structure development. These two kinds of processes have been observed in the Sarine River with a relative strength of one phenomenon or a mix of both leading to polyphasic references. Soils evolve and develop over time and their formation is under influence of changes to the controlling factors, which could be external or internal.

As alluvial soil evolution depends strongly on what happened on the top of soil (deposition, erosion or development of structure), a special attention to the properties of the surface layer is then necessitated. Soil surface layers influence plant growth and are the seat of biological activity. Moreover, they store a large part of plant nutrients and contain a major portion of the roots of annual plants. In this way, a better knowledge of the very first steps of soil formation happening in the context of undeveloped and young soils is of great interest.

5. Soil structure processes of the Sarine River¹

5.1. Introduction

Soil is considered as an ecological system (see 3.1), comprising the community together with the physical environment and taking account of fluxes of energy and matter. The system theory follows some fundamental laws, among them thermodynamics. In fact, in thermodynamic terms, a growing system is moving away from thermodynamic equilibrium (Jorgensen and Marques, 2001). Soil formation represents a thermodynamic process where the contribution of energy is highest at the surface. Recent developments in soil science and ecosystem dynamics suggest that humus forms play a central role in the functional biodiversity of terrestrial ecosystems and are in crossroads of interactions between living organisms and inert constituents (Ponge, 2003; Coleman *et al.*, 2004; Gobat *et al.*, 2004). They determine the development of terrestrial plant, animal and microbial communities, in a feedback process.

The humiferous episolum, assembling the upper horizons of a solum containing organic matter (*O*, *H* and *A* horizons; AFES, 1998), strongly depends on biological activity, creating soil structure. It is a

perfect integrator of environmental conditions (Zanella *et al.*, 2001). It illustrates the recent ecosystem memory and reflects the state of the relation between soil and vegetation. It exposes different hierarchical levels between soil and vegetation and reveals also time gaps between the morphology of the solum and its functioning (Gobat *et al.*, 2004), particularly visible in an alluvial context for example. By linking the temporal development of the vegetation to the temporal development of soil, the humiferous episolum constitutes an irreplaceable temporal and spatial pivot in the ecosystem.

Several studies have already been carried out on humus forms (e. g. Bernier and Ponge, 1994; Deschaseaux and Ponge, 2001; Loranger *et al.*, 2003; Seeber and Seeber, 2005), on soil structure (e. g. Roger-Estrade *et al.*, 2004; Sarah and Rodeh, 2004; Pagliai *et al.*, 2004; Bronick and Lal, 2005) or on relations between fauna and humiferous episolum (e. g. Michalet *et al.*, 2001; Cassagne *et al.*, 2003; Salmon *et al.*, 2006). Edwards and Bohlen (1996) reported that earthworms are influenced by soil type and texture, but only few studies of the direct influence of soil type on earthworm populations exist (Baker *et al.*, 1998; Nachtergale *et al.*, 2002;

¹ This chapter is an adaptation of the paper: Bullinger-Weber G., Le Bayon R.C., Guenat C. and Gobat J.-M. 2007. Influence of some physicochemical and biological parameters on soil structure formation in alluvial soils. *European Journal of Soil Biology*, 43: 57-70, found in appendix 31.

Räty, 2004). Linking vegetation, fauna and humus forms with the soil structuring in alluvial environment is quite unusual and unknown. This chapter is thus dedicated to biological, chemical and physical characterization of humus forms through different sedimentation conditions and vegetation (Bullinger-Weber *et al.*, 2007).

5.1.1. Soil structuring processes

Soil structure is influenced by different properties of soil constituents and by its environment (Cammeraat and Imeson, 1998). Soil aggregation is related to basic soil properties, such as texture and type of parental material. The amount of clay, as well as the presence of calcium carbonates and iron acting as cementing material, influences the aggregate formation and stabilisation (Emerson and Greenland, 1990). Soil carbonates usually work as a source of Ca^{2+} -ions helping to flocculate clay particles and stabilizing the exchange complex. Moreover, calcium carbonates preserve the flocculated structure of the clay in soil surface aggregates by neutralizing acids produced by fungi, microbes and roots. A high content of iron oxides also favours a stable structure and may be more concentrated in the fine clay particles. Oades (1990) also found that in temperate regions the interactions of oxides with clays may be reversed in the presence of humic substances and that contribution of these iron oxides is often difficult to separate from the stability attributable to organic matter. Anyway, organic matter is an important factor in soil aggregation, correlated with the organic carbon content (Tisdall and Oades, 1982). Soil organic matter is assumed to stabilize aggregates against disruptive processes, such as slaking, by increasing the cohesion of aggregates through the binding of mineral particles by organic polymers. It could also decrease the wettability of aggregates, thus reducing their rates of wetting and the extent of slaking (Chenu *et al.*, 2000). Organic substances are very repellent to water and several organic fractions are responsible for this hydrophobicity of soils, e. g. humic acids, aliphatic fractions or plant litter debris.

5.1.2. The role of soil biota

Soil aggregate formation is not only determined by the physical or chemical properties of the soil, but also by biological soil processes. Soil biota is numerous and diverse and is mainly represented by earthworms (macrofauna), enchytraeids and collembolans, diplopoda (mesofauna), nematodes and rotifers (microfauna), as well as fungi and bacteria (microflora). Living organisms, especially worms (Oligochaeta), play a major role in soil structure. For instance, the action of enchytraeids contributes to litter degradation and nutrient mobilization, particularly in acid soils with a high organic content (Bauer *et al.*, 1994; Marinissen and Didden, 1997; Schrader *et al.*, 1997; van Vliet *et al.*, 1997). In addition, soil bioturbation by earthworms is essential and produces very stable casts, as well as a large burrow network (Oades, 1993; Shipitalo and Le Bayon, 2004). Earthworms affect soil physical properties by ingesting and egesting soil, but their effects on soil aggregation is specific and depends on the species ecological strategy (Shipitalo and Le Bayon, 2004). While epigeic individuals feed mainly on organic matter, the material ingested by endogeic and anecic species is mainly mineral matter, which is mixed with organic matter in digestive tracts and then egested as casts on the soil surface or below ground. The quality of the ingested material, as well as the contribution of earthworms to cast production and aggregation is well documented (Coleman *et al.*, 2004; Garvin *et al.*, 2001; Marinissen *et al.*, 1997; Shipitalo and Le Bayon, 2004). Furthermore, Marinissen and van den Bosch (1992) proposed a simple model on the colonization of new habitats by earthworms such as grasslands, while Zorn *et al.* (2005) examined the earthworm population dynamics in a floodplain system in relation to frequency and duration of flooding events. However, the colonization of young environments by different worm species and the first interactions between mineral and organic materials under the influence of soil fauna in the upper soil layers are not well known, particularly in the first steps of soil formation and aggregation.

5.1.3. Humus forms as indicator of soil structure

At the top of soil profiles, humus forms function as the habitat of decomposer organisms and as a nutrient sink and source (Klinka *et al.*, 1990). These properties are reflected in morphological characteristics of humus form horizons manifested by the mode and the rate of decomposition and they can then be defined as a morphological pattern observed in the association of organic and mineral matter. It has been demonstrated that humus forms play a central role in the functional biodiversity of terrestrial ecosystems. Actually, they are stable and display a visible result of the activity of the soil animal and microbial life (Ponge, 2003). Moreover, small-scale variations in the topsoil profile composition may occur under the influence of several conditions, such as vegetation, soil properties or microtopography (Patzel and Ponge, 2001). Humus forms can then be considered as excellent tools to investigate the first interactions between mineral and organic materials under colonizing fauna.

5.1.4. The model of FLUVIOSOL

Alluvial soils have already been described as reliable models to detect the influence of both abiotic and biotic mechanisms involved in soil structure (Guenat *et al.*, 1999). They are considered as young soils depending on a complicated genesis (interaction between inheritance and in situ evolution) and situated in a heterogeneous environment (i. e. herbaceous vegetation, tree population, alluvium), where early stages of soil formation are represented. Moreover, carbonate-rich alluvial soils are relevant for the study of soil structuring because they contain a high proportion of calcium (Ca^{2+} ions) helping to establish an intimate relation within the clay-humus complex in an aerated granular structure that is particularly favourable to the general biological activity (Gobat *et al.*, 2004). As a consequence, we studied alluvial soils to investigate the relative importance of abiotic (texture, different types of carbonate and iron forms, organic matter) and biotic (enchytraeids and earthworms) mechanisms on initial soil aggregation.

5.1.5. Aims of the research

Our research focused on the humus form, which is considered as a good indicator of short-term and small-scale variations under the influence of vegetation or sedimentation changes. We hypothesized that the soil structure formation was mainly determined by the nature of the recent alluvial deposits with little influence of alluvial gravel or underlying mineral sediments. This upper mineral part, directly in contact with organic matter, affects in turn the colonization by the soil fauna (earthworms and enchytraeids), and alters the distribution of the different iron forms, with little forest type influence, which are, in our case, pioneer communities of willow and alder. We concentrated this study on six sampling plots differentiated mainly by recent alluvial deposits and by the age of the tree populations. Alluvial gravels, as well as other underlying mineral horizons, were considered as similar for the six plots. We characterized these soils biologically, chemically and physically and observed the heterogeneous spatial distribution of humus forms throughout the alluvial study area, regarding earthworms (abundance, biomass and species), enchytraeids, soil textural parameter and iron forms.

5.2. Material and methods

5.2.1. Site description and sampling method

The active part of “*Les Auges de Neirivue*” of the Sarine River (close to Grandvillard; zones 4 and 5, see the description of the Sarine River in 2.2.1.) was used for this part of the research. Our study was based on the comparison of humus forms of six sampling plots located on a riverbank potentially inundated. These sampling plots were selected along a transect according to the vegetation type, the age of the present tree population (Guenat *et al.*, 1999), and the visual heterogeneity of alluvial deposition. Two different types of softwood forest community were chosen, representing two stages of vegetation succession in alluvial ecosystems, with three plots in each type (fig. 5.1; Petts and Amoros, 1996): the willow type, the old gravel bars have been colonized by willow shrubs for

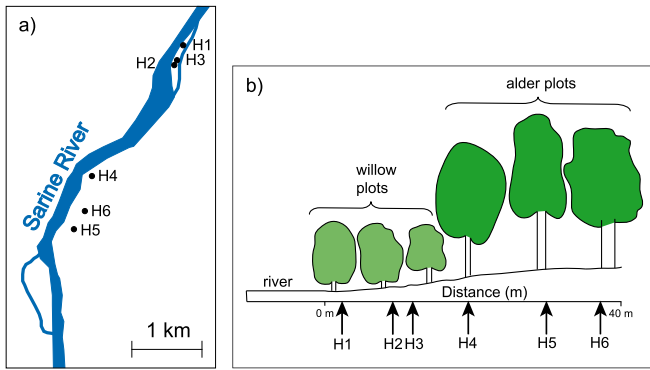


Fig. 5.1. Localisation the 6 humus forms along the river (a) and schematic representation of the Sarine River in the study section with two stages of vegetation succession in alluvial ecosystems (b).

about 20 years (H1 to H3), and the alder type, colonized for about 25 to 30 years (H4 to H6). Inside each vegetation type, plots were chosen according to the environment heterogeneity (herbaceous plants, soil texture, etc.).

Soils were FLUVIOSOLS TYPIQUES according to the "Référentiel pédologique" (AFES, 1998). The humus profile of each location was described and named using the classification system of the "Référentiel pédologique". From each profile, the organo-mineral layers *A* and/or *J* and the mineral horizons *M* were sampled for further analyses.

5.2.2. Soil fauna extraction

Enchytraeids were sampled from three plots of 25 x 25 cm inside whose three soil cores (6 cm diameter x 10 cm deep) were mixed together. Sampling was made only one time in August 1997 during and after a fairly dry period. Counting was performed after extraction using the wet funnel technique (Didden *et al.*, 1995; O'Connor, 1967). Earthworms were sampled from each soil (three squares of 50 x 50 cm) using the ethophysical method (Bouché and Gardner, 1984). Sampling was realized only one time in September and October 1997 after a relative dry summer combining a formalin extraction followed by hand-sorting (soil depth 0-20 cm). All worms were weighed and identified to the species level with the help of Thiabaud Decaens (University of Rouen, France). Small and/or juvenile individuals were classified either in

their ecological type (anecic, endogeic or epigeic) or at the genus level. No major flooding event took place during the months before sampling, thus we suppose that flooding did not influence our sampled area.

5.2.3. Soil analysis

Samples for soil analysis were taken in May and June 1997 at a different place than those for fauna extraction to avoid perturbing the soil communities. Physicochemical analyses were performed on air-dried and sieved soil (mesh size 2 mm) from the layers *A* and/or *J* and *M*. Water pH (ratio 1:2.5), particle size distribution (modified Robinson pipette method for: fine silts 2-20 μm , coarse silts 20-50 μm , clays 0-2 μm ; and sieving for: fine sands 50-200 μm , coarse sands 200-2000 μm ; Pansu and Gautheyrou, 2003), and active carbonate content (CaCO_3 ; modified Drouineau and Galet method; X31-105, 1987) were measured. Other analyses were carried out on ground soil samples (soil particles <200 μm), like carbonate content (reaction with H_3PO_4 and titration of the CO_2 released with a Carmograph Wösthoff 8-ADG), organic carbon content (C_{org} ; combustion and titration of the CO_2 released with a Carmograph Wösthoff 8-ADG), and total nitrogen content (N_{tot} ; Kjeldahl mineralization, Technicon colorimetric titration). In addition, and only for *A* and/or *J* horizons, iron forms were quantified as amorphous iron species (Fe_0 ; iron extractable by oxalate using Tamm method modified by Schwertmann, 1964), crystallized iron species (Fe_d ; iron extractable by dithionite-citrate-bicarbonate modified from Mehra and Jackson method; Mehra and Jackson, 1960) and total iron content (Fe_t ; metaborate fusion method; Rouiller, 1981). In general, Fe_0 is considered as "active", Fe_d minus Fe_0 ratio as "less active" (Arduino *et al.*, 1986), and Fe_0/Fe_d ratio estimates the degree of the soil evolution (Dolui and Bera, 2001). Three replicates were carried out for the quantification of iron forms while one measurement was made with other methods. Aggregate stability was determined on *A* and/or *J* horizons by wet sieving using 1.00, 0.50 and 0.25 mm mesh sizes (method adapted from Kemper and Rosenau, 1986) on 1-2 mm calibrated aggregates.

The mean weight diameter (MWD) was calculated on three replicates per soil using a correction index for the coarse sand content (Angers and Mehuys, 1993).

5.2.4. Statistical analysis

Statistical analyses were performed using Pearson correlations and principal component analysis (PCA). The data were previously standardized to make the variance more homogeneous across the range of the data. The software used was R (version 2.0.1; R Development Core Team, 2004). Earthworm data were grouped in ecological categories before statistical analysis.

5.3. Humus form descriptions

Three different humus forms were observed and described in the transect (fig. 5.2 and 5.3): eumull for H1, H2, H3 and H5; oligomull for H4; and dysmull for H6. Two types of calcareous organo-mineral horizons located just under the soil surface were observed (*J_{ca}* and *A_{ca}*). The *A* horizons is biomacrostructured while the *J_s* horizons were “young”, weakly differentiated and containing small amounts of organic matter (AFES, 1998).

The *M* horizons are sandy for each plot, but fine sand was observed for the *M* horizon of plot H4 and for the *IIM* horizon of H5 and H6. The thickness of these different mineral horizons, down to the gravels, was almost the same for the six sampling plots.

5.4. Enchytraeids and earthworm communities

Despite no significant differences, the abundance of enchytraeids (fig. 5.4) tended to be twice lower in H2 compared to other plots. Regarding the earthworm diversity (fig. 5.5), 11 different species were recorded: *Lumbricus castaneus*, *Lumbricus terrestris*, *Lumbricus rubellus*, *Dendrobaena octaedra*, *Dendrobaena pygmaea*, *Dendrobaena rubida*, *Aporrectodea rosea*, *Nicodrilus caliginosus caliginosus*, *Nicodrilus nocturnus*, *Octolasion cya-*

Sites	Humus forms	Horizons	Thickness (cm)
H1	Eumull	(OLn)	0.5
		<u>J_{sca}</u>	1
		<u>M_{ca}</u>	14
H2	Eumull	(OLn)	0.5
		<u>J_{sca}</u>	0.5
		<u>M_{ca}</u>	8.5
H3	Eumull	(OLn)	0.5
		<u>A_{ca}</u>	5
		<u>M_{ca}</u>	11
H4	Oligomull	OLn	0.5
		(OFr)	0.5
		<u>A_{ca}</u>	5.5
		<u>M_{ca}</u>	12
H5	Eumull	OLn	0.5
		(OLt)	0.5
		<u>A_{ca}</u>	7
		<u>M_{ca}</u>	3
		<u>IIM_{ca}</u>	10
H6	Dysmull	OLn	1
		OFr	0.5
		(OFm)	1
		<u>J_{sca}</u>	7
		<u>M_{ca}</u>	8
		<u>IIM_{ca}</u>	2

Fig. 5.2. Site descriptions according to the “Référentiel pédologique” (AFES, 1998) and thickness of each horizon. The suffix “ca” underlines the presence of carbonates.

neum, *Octolasion tyrtaeum lacteum*. Earthworms from H2, H4, H5 and H6 were almost exclusively epigeic and/or endogeic and contained a lot of juveniles (fig. 5.6). Anecic species were recorded in H1 and H3, *L. terrestris* in both plots while *N. nocturnus* was only found in H1. Earthworm abundance (fig. 5.5) was higher in H1, H3 and H4 (182.0, 191.6 and 202.7 individuals m⁻² respectively) compared to H5 and H2 (32.0 and 61.3 individuals m⁻², respectively). Epigeic species were highest in H4 and H6, while endogeic species were more present in H3 and H1. Regarding the identified species, *O. tyrtaeum lacteum* was dominant in H3 and H4 and *D. octaedra* in H3. However, and because of a high proportion of juveniles, it should be noted a

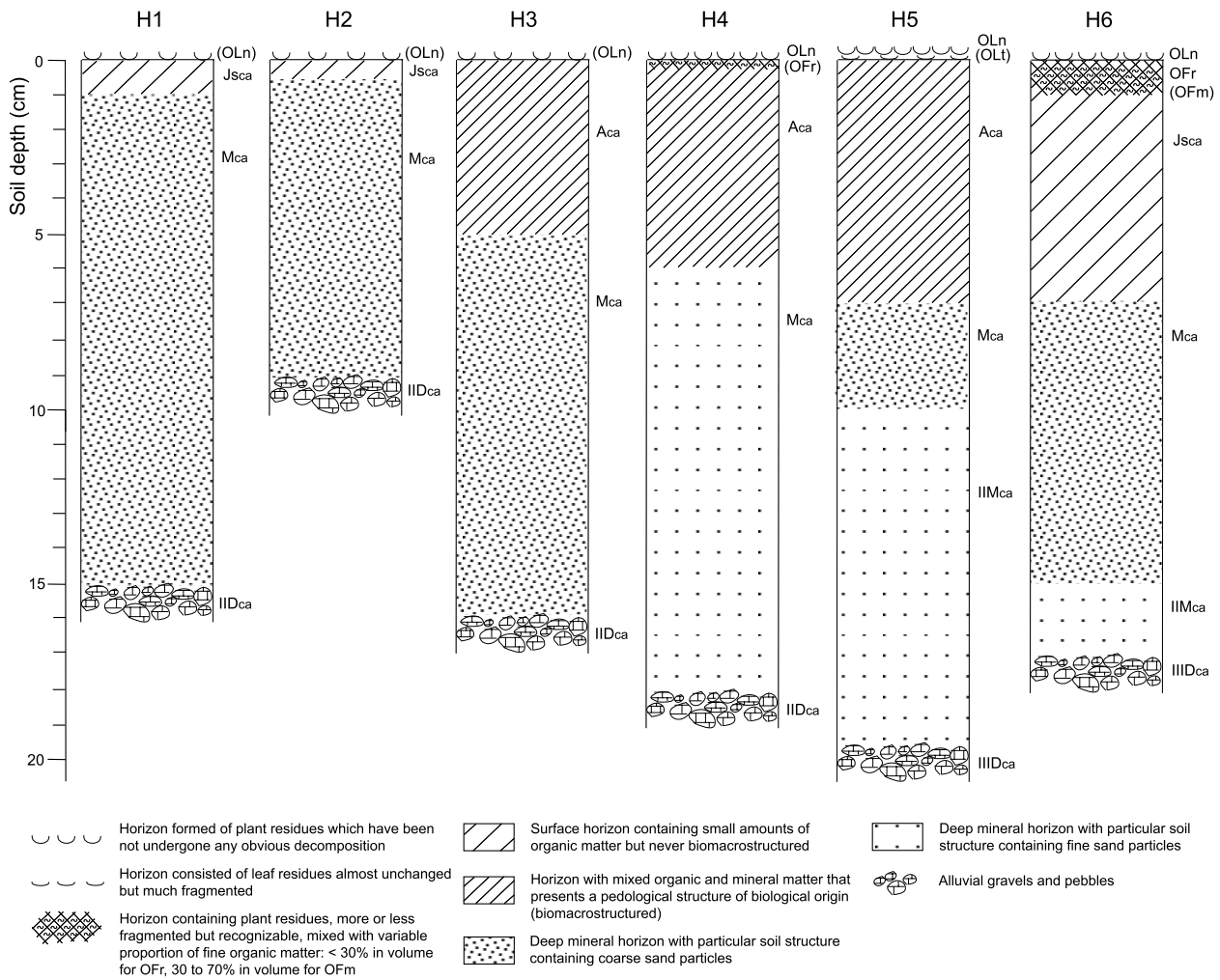


Fig. 5.3. Schematic diagram of the six sites and their first 10 centimetres. *OLn* = horizon formed of plant residues which have not undergone any obvious decomposition; *OLv* = horizon formed of plant residues which show little fragmentation, but have clearly been altered since falling to the ground; *OFr* = horizon consisting of easily identifiable leaf fragments which are more or less fragmented with a small proportion of fine organic matter; *OFm* = horizon containing equal quantities of fragmented leaf residues and messes of fine organic matter; *Js* = horizon containing small amounts of organic matter but never biomacrostructured; *A* = horizon with mixed organic and mineral material with generally a pedological structure of biological origin; *M* = friable or soft, unbroken or broken rock horizon; *ca* = presence of carbonates (denomination after AFES, 1998). H1 to H3 are situated in the willow plots colonized by vegetation for about 20 years, while H4 to H6 are located in the alder plots colonized for 25-30 years.

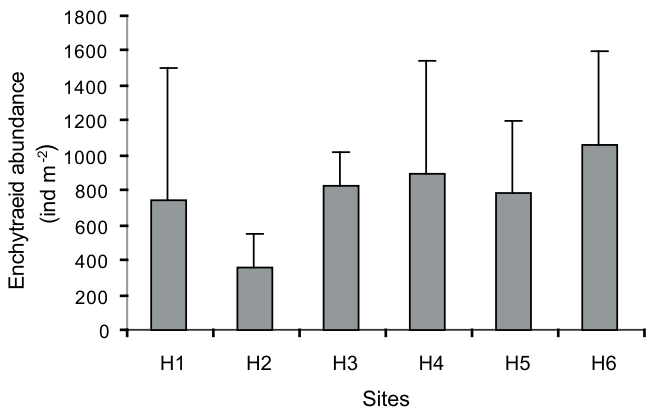


Fig. 5.4. Mean abundance of Enchytraeids (ind m⁻²) in the different sites H1 to H6. Bars indicate the standard deviations.

Sites	Species	Ecol. cat.	Numbers no m ⁻²	% of total number	Biomass g m ⁻²	% of total biomass	Ratio g ind ⁻²
H1	<i>Dendrobaena octaedra</i>	epi	50.67	28	3.37	7	0.07
	<i>Lumbricus rubellus</i>	epi	1.33	1	0.43	1	0.32
	<i>Dendrobaena rubida</i>	epi	2.67	1	0.15	0.5	0.06
	Epigeic sp juv.	epi	9.33	5	2.10	4.5	0.23
	<i>Lumbricus terrestris</i>	ane	2.67	1	13.16	28	4.93
	<i>Nicodrilus nocturnus</i>	ane	12.67	7	20.24	4	1.60
	<i>Nicodrilus</i> spp juv.	ane	19.33	11	5.90	12.5	0.31
	<i>Octolasion tyrtaeum lacteum</i>	endo	21.33	12	6.18	13	0.29
	<i>Nicodrilus caliginosus caliginosus</i>	endo	8.00	4.5	3.11	10	0.39
	<i>Aporrectodea rosea</i>	endo	12.67	7	3.42	7	0.27
	<i>Octolasion cyaneum</i>	endo	13.33	7	4.03	8.5	0.30
	Endogeic sp juv.	endo	28.00	15.5	1.92	4	0.07
	Total ± SD			182.00 ± 42	100	64.01 ± 41.97	100
H2	<i>Lumbricus castaneus</i>	epi	6.67	11	0.78	12	0.12
	<i>D. octaedra</i>	epi	4.00	6.5	0.41	6	0.10
	Epigeic sp juv.	epi	45.33	74	2.08	31	0.05
	<i>Lumbricus</i> spp juv.	ane	1.33	2	0.67	10	0.50
	<i>O. tyrtaeum lacteum</i>	endo	4.00	6.5	2.69	41	0.67
	Total ± SD			61.33 ± 14	100	6.63 ± 3.74	100
H3	<i>D. octaedra</i>	epi	22.00	11	2.17	1	0.10
	<i>L. rubellus</i>	epi	10.67	6	7.57	8	0.71
	Epigeic sp juv.	epi	30.67	16	1.94	2	0.06
	<i>L. terrestris</i>	ane	10.00	5	34.64	36	3.46
	<i>Lumbricus</i> spp juv.	ane	2.97	2	3.48	4	1.17
	<i>O. tyrtaeum lacteum</i>	endo	88.00	46	34.86	36	0.40
	<i>N. caliginosus caliginosus</i>	endo	17.33	9	9.38	10	0.54
	<i>A. rosea</i>	endo	4.67	2	1.90	2	0.41
	Endogeic sp juv.	endo	5.33	3	0.86	1	0.16
	Total ± SD			191.64 ± 80	100	96.8 ± 65.87	100
H4	<i>D. octaedra</i>	epi	8.67	4	0.63	2	0.07
	<i>L. rubellus</i>	epi	2.67	1.5	2.07	7	0.78
	<i>Dendrobaena pygmea</i>	epi	4.00	2	0.05	0.5	0.01
	<i>D. rubida</i>	epi	24.00	12	1.26	4	0.05
	Epigeic sp juv.	epi	91.33	45	4.02	14	0.04
	<i>O. tyrtaeum lacteum</i>	endo	40.00	20	15.61	53	0.39
	<i>N. caliginosus caliginosus</i>	endo	1.33	0.5	0.41	1.5	0.31
	<i>A. rosea</i>	endo	8.00	4	3.29	11	0.41
	Endogeic sp juv.	endo	22.67	11	1.95	7	0.09
	Total ± SD			202.67 ± 71	100	29.29 ± 3.51	100
H5	<i>D. octaedra</i>	epi	3.33	10.5	0.25	6	0.08
	<i>D. pygmea</i>	epi	1.33	4	0.02	0.5	0.02
	Epigeic sp juv.	epi	7.33	23	0.33	7.5	0.05
	<i>O. tyrtaeum lacteum</i>	endo	6.67	21	2.74	65	0.41
	Endogeic sp juv.	endo	13.33	41.5	0.88	21	0.07
	Total ± SD			31.99 ± 14	100	4.22 ± 2.31	100
H6	<i>D. octaedra</i>	epi	10.67	8.5	1.07	7.5	0.10
	<i>L. rubellus</i>	epi	1.33	1	0.99	7	0.74
	<i>D. rubida</i>	epi	6.67	5	0.72	5	0.11
	Epigeic sp juv.	epi	95.33	74.5	3.97	27.5	0.04
	<i>O. tyrtaeum lacteum</i>	endo	12.67	10	7.52	52	0.59
	Endogeic sp juv.	endo	1.33	1	0.11	1	0.08
Total ± SD			128.00 ± 32	100	14.38 ± 6.35		0.11

Fig. 5.5. Ecological categories (Ecol. cat.; epi = epigeic forms; ane = anecic forms; endo = endogeic forms; juv. = juveniles), numbers (no m⁻², %), biomass (g m⁻², %) and ratio biomass (Ratio; g ind⁻¹) of earthworms in the six sites H1 to H6 (SD = standard deviation).

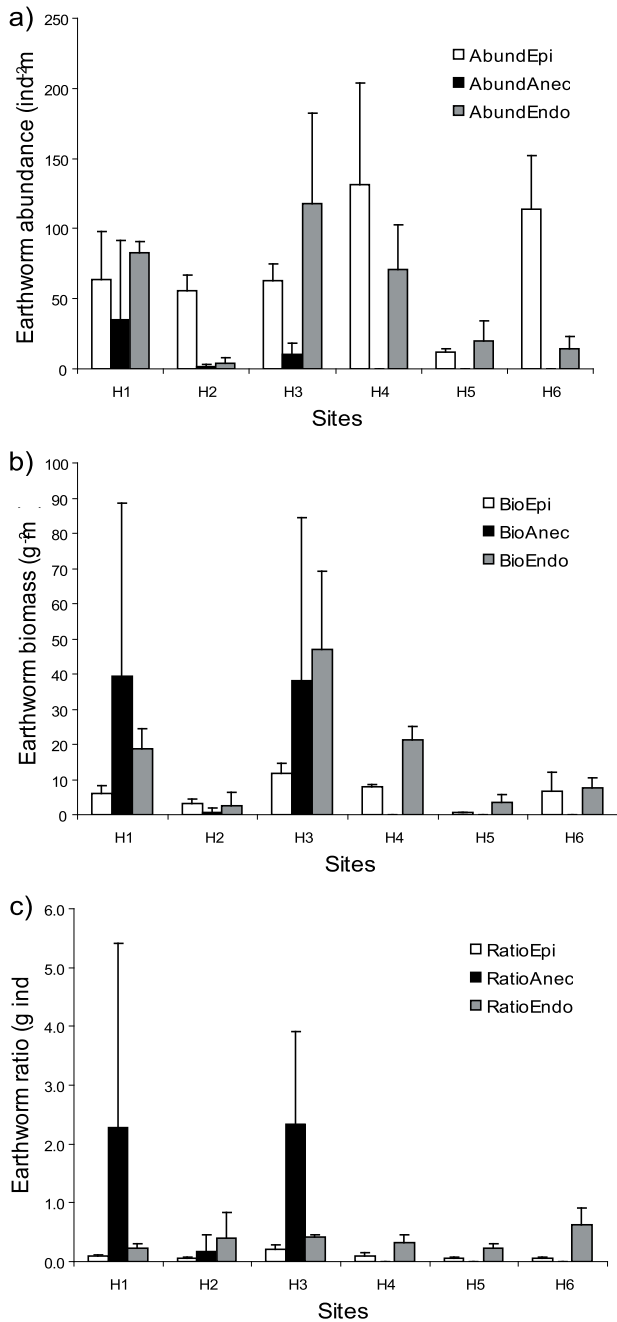


Fig. 5.6. Mean (a) abundance of epigeic earthworms (ind m⁻²), (b) biomass (g m⁻²) and (c) earthworm ratio (g ind⁻¹) in the studied sites H1 to H6 (standard deviation in bars).

high proportion of unidentified epigeic species in H2 and H6 (74%), H4 (45%) and H5 (23%), as well as the proportion of unidentified endogeic species in H5 (41.5%). In terms of biomass (fig. 5.5), the global mean values were lowest in H2 and H5 (6.6 and 4.2 g m⁻², respectively), while it was largest in H3 (96.8 g m⁻²). The endogeic and anecic biomasses were the highest in H3, followed by H1, but a high

standard deviation was observed probably due to the extreme heterogeneity of the different sampling plots. Looking at the ratio biomass giving the mean weight of all individuals in each plot, it appears clearly that the largest worms were located in H3 (0.51 g ind⁻¹), the smallest in H2, H4, H5 and H6 (0.11, 0.14, 0.13 and 0.11 g ind⁻¹, respectively), and that an intermediate ratio was found in H1 (0.35 g ind⁻¹). The same tendency was observed when ecological categories were studied separately, but with a high standard deviation. Not only the number of worms, but also the individual biomass contributed to the relative percentage of the total biomass. No significant correlation was found between abundance and biomass of each ecological category on the one hand and other biotic or abiotic parameters on the other hand.

5.5. Soil analysis

The six organo-mineral horizons *Aca* and/or *Jsca* differed in the physicochemical values, especially with regard to the particle size distribution (fig. 5.7). Despite a different tree cover and a different location within the transect, the *Jsca* horizons of H2 and H6 were enriched in coarse sand (74.7% and 51.8%, respectively). In contrast, H3 contained the highest proportion of clay (23.1%) and almost no coarse sand (7.4%). H1, H4 and H5 had medium values of each particle size (fig. 5.7). The *M* horizons were particularly rich in coarse sand, but poor in clay and silt compared to the upper layers. Thus, the nature (texture, carbonate content) and the thickness of these underlying deposits were similar for the six plots. The mean weight diameter (MWD) of soil aggregates was negatively correlated with the sand content ($r = 0.96$, 95%, $P < 0.01$), while an opposite tendency was observed for both fine silt and clay contents ($r = 0.94$ and 0.95 , respectively, 95%, $P < 0.01$).

The amount of total carbonate was higher in willow plots H2 (67%), H1 (56.4%), H3 (44.6%) than in other ones (around 35%). In addition, the relatively high content of active carbonate (20%) found in H1, H3, H4 and H5 was negatively correlated with the coarse sand content ($r = 0.89$, 95%,

Sites	Horizons	pH	Total CaCO ₃ (%)	Active CaCO ₃ (%)	Fe _t (g kg ⁻¹)	SD	Fe _o (g kg ⁻¹)	SD	Fe _d (g kg ⁻¹)	SD	Fe _d -Fe _o /Fe _t ratio	Fe _o /Fe _d ratio
H1	JS _{ca}	7.9	56.4	20.0	14.8	0.12	1.4	0.009	4.1	0.02	18.2	34.1
	M _{ca}	8.6	66.2	13.8	-	-	-	-	-	-	-	-
H2	JS _{ca}	8.1	67.0	10.9	10.1	0.05	0.5	0.0002	2.2	0.001	16.8	22.7
	M _{ca}	8.3	72.4	7.5	-	-	-	-	-	-	-	-
H3	A _{ca}	7.9	44.6	20.8	19.7	0.04	2.2	0.002	6.5	0.02	21.8	33.8
	M _{ca}	8.5	76.1	10.4	-	-	-	-	-	-	-	-
H4	A _{ca}	7.9	35.0	18.0	22.6	0.07	2.5	0.014	5.7	0.015	14.2	43.9
	M _{ca}	8.3	39.4	16.2	-	-	-	-	-	-	-	-
H5	A _{ca}	7.8	35.0	19.4	21.7	0.14	2.3	0.017	5.7	0.02	15.7	40.3
	M _{ca}	8.5	54.5	8.9	-	-	-	-	-	-	-	-
	IIM _{ca}	8.3	43.5	18.1	-	-	-	-	-	-	-	-
H6	A _{ca}	7.4	33.9	10.5	18.3	0.04	2.0	0.007	4.8	0.03	15.3	41.7
	M _{ca}	8.1	56.5	10.1	-	-	-	-	-	-	-	-
	IIM _{ca}	8.2	43.9	15.0	-	-	-	-	-	-	-	-

Sites	Horizons	C _{org} (%)	N _{tot} (%)	C/N	Coarse sand (%)	Fine sand (%)	Coarse silt (%)	Fine silt (%)	Clay (%)	MWD (mm)	SD
H1	JS _{ca}	2.8	0.2	14	33.2	20.9	12	18.9	15	0.908	0.023
	M _{ca}	0.6	0.04	-	72.4	15.6	3.7	5.7	2.6	-	-
H2	JS _{ca}	1.2	0.1	12	74.7	5.9	4.6	9.9	4.9	0.389	0.004
	M _{ca}	0.2	0.03	-	93.7	3.5	0.9	2.0	0	-	-
H3	A _{ca}	3.5	0.2	17	7.4	21.7	17.2	30.6	23.1	1.168	0.031
	M _{ca}	0.4	0.3	-	84.1	9.5	1.8	4.3	0.2	-	-
H4	A _{ca}	2.9	0.2	13	20.6	32.2	18.8	17.2	11.2	0.868	0.037
	M _{ca}	1.2	0.08	-	35.5	35.8	12.8	11.4	4.6	-	-
H5	A _{ca}	5.4	0.4	15	20.7	27	12.8	22.1	17.3	1.039	0.007
	M _{ca}	0.8	0.05	-	76.8	12.3	2.6	6.8	1.5	-	-
	IIM _{ca}	1.5	0.1	-	42.1	25.2	11.3	12.9	8.5	-	-
H6	A _{ca}	12.1	0.9	13	51.8	9.7	10.3	15.5	12.7	0.733	0.007
	M _{ca}	1.5	0.1	-	63.9	17.9	5.0	8.8	4.4	-	-
	IIM _{ca}	1.1	0.08	-	37.0	40.3	9.1	9.8	3.7	-	-

Fig. 5.7. Physicochemical characteristics in the different horizons (see fig. 5.2) from the six sites H1 to H6: pH, total and active carbonates (Total CaCO₃ and Active CaCO₃, in %), iron forms (Fe_o: amorphous iron, Fe_d: crystallised iron, Fe_t: total iron, in g kg⁻¹), iron form ratios (Fe_d-Fe_o/Fe_t, Fe_o/Fe_d), organic carbon (C_{org}, in %), total nitrogen (N_{tot}, in %) and C/N ratio, soil texture (coarse and fine sand, coarse and fine silt, clay, in %), mean weight diameter (MWD, in mm). Iron forms were only measured on organo-mineral horizons and the C/N ratio and MWD were only calculated for JS_{ca} and/or A_{ca} horizons. Standard deviations (SD) are given for iron forms and MWD.

$P < 0.05$). The organic matter showed great variations along the transect, with high contents in H6 (12.06% and 0.91% for C_{org} and N_{tot}, respectively). However, the C/N ratios remained quite constant, except for H5 (15.2) compared to a value of around 13-14 for the other plots. As for iron forms, concentrations of total iron Fe_t were highest in the alder community plots H4 (22.6 g kg⁻¹) and H5 (21.7 g kg⁻¹) compared for instance to H2 (10.1 g kg⁻¹). These values were inversely proportional to coarse sand content. A significant positive correlation was found between Fe_t, Fe_o, Fe_d and the coarse silt

content (respectively $r = 0.85$, $r = 0.87$, $r = 0.89$, 95%, $P < 0.05$), but no other significant correlation was found with another mineral fraction.

The values of Fe_d were low for H2 (2.2 g kg⁻¹) and high for H3 (6.5 g kg⁻¹) and showed a positive correlation with the MWD ($r = 0.91$, 95%, $P < 0.05$). The same tendency could be observed for the values of Fe_o (low for H2 and H1; 0.5 and 1.4 g kg⁻¹, respectively). On the other hand these two iron forms showed a significantly negative correlation with the coarse sand amount ($r = 0.92$, 95%, $P < 0.01$ for Fe_d; $r = 0.82$, 95%, $P < 0.05$ for Fe_o). The

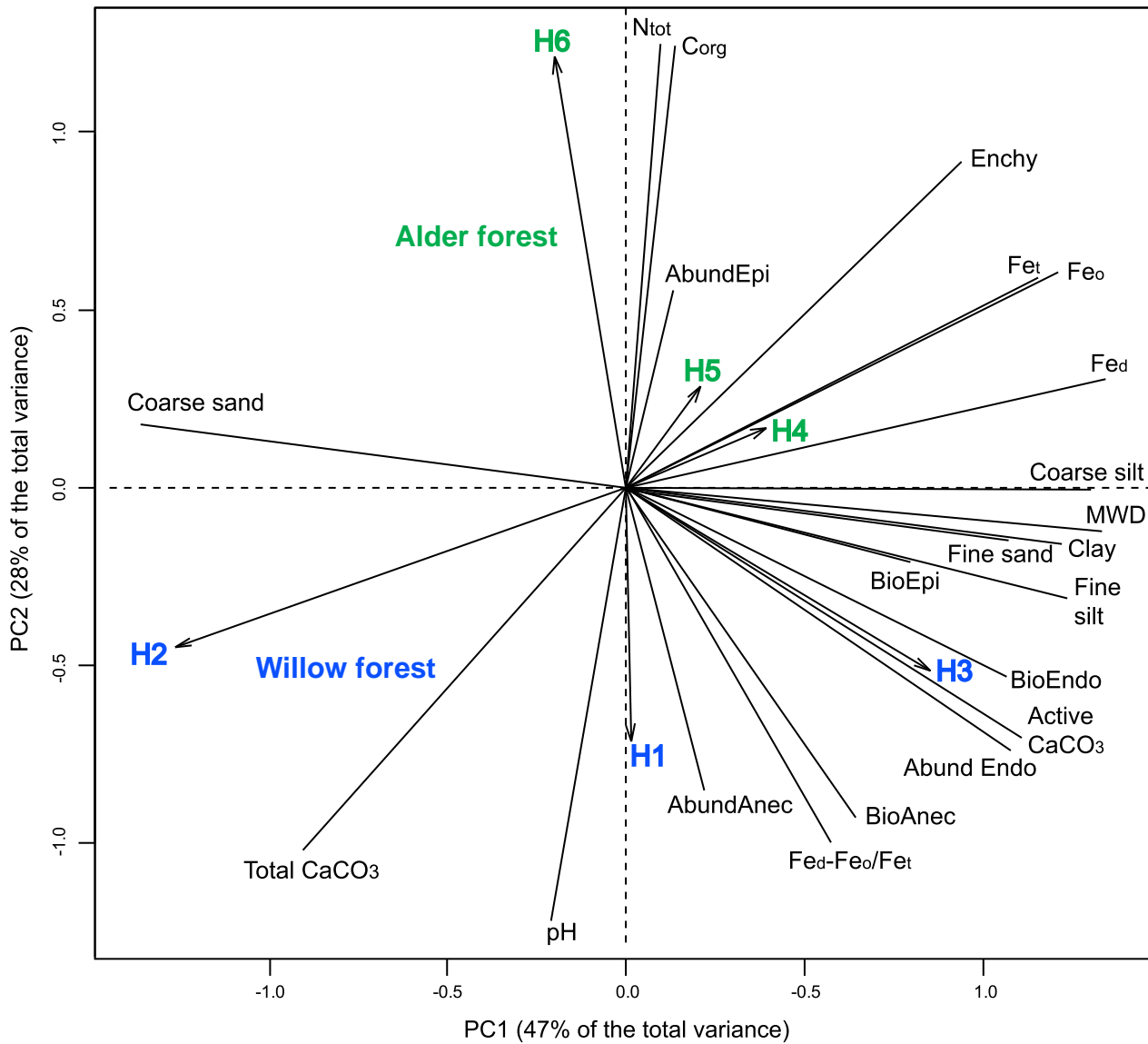


Fig. 5.8. Results of the principal component analysis (PCA): ordination of the samples (H1 to H3: willow plots, H4 to H6: alder plots) and the variables in the plane defined by the axis PC1 and PC2 (variables: codes as in Table 3; Enchy = enchytraeid abundance; AbundEpi = epigeic earthworm abundance; BioEpi = epigeic earthworm biomass; AbundAnec = anecic earthworm abundance; BioAnec = Anecic earthworm biomass; AbundEndo = endogeic earthworm abundance; BioEndo = endogeic earthworm biomass).

ratio Fe_o/Fe_d increased gradually from H2 (22.7) to H5 (40.4) with a peak in H4 (43.9) and a negative correlation was observed between Fe_o/Fe_d and the total carbonate content ($r = 0.94$, 95%, $P < 0.01$).

As a complement to biological variables, the $Fe_d - Fe_o/Fe_t$ ratio, which represents an index of the soil evolution and increases with time, was positively related to the biomass of anecic earthworms ($r = 0.85$, 95%, $P < 0.05$) while the abundance of enchytraeids was negatively correlated to the total carbonate amount ($r = 0.88$, 95%, $P < 0.05$).

5.6. PCA synthesis

The principal component analysis (PCA, fig. 5.8) illustrates in a two-way axis the relationships between all measured variables. The first principal component axis PC1 (explaining 47% of the total variance) separated the samples according to the particle-size distribution (except the coarse sand), the MWD and the biomass of epigeic and endogeic earthworms on the right side. The second axis PC2 (explaining 28% of the total variance) discriminated the forest types with alder plots at the top and willow plots at the bottom. Along this same axis, differences were also visible between pH values (at the bottom) and contents of C_{org} and N_{tot} (on the top).

The PCA showed a relationship between most of the biological parameters (biomass and abundance of worms) and the plot H3, as well as H1 to a lesser extent. However, no strong relations appeared between earthworm's criteria and the different iron forms, except for $Fe_d - Fe_o/Fe_t$ ratio more related to anecic earthworms. The plots H4 and H5 were more related to the number of enchytraeids, the abundance of epigeic earthworms and the different iron forms. These iron forms were also more associated with the coarse silt content than other particle size parameters and were closed to the MWD. No strong relations appeared between the soil texture and the concentrations of C_{org} and N_{tot} , revealing no evident difference between H3 and the alder plots (H4, H5 and H6).

5.7. Discussion

5.7.1. Biological parameters

5.7.1.1. Enchytraeids

Enchytraeids are an important group of the soil mesofauna in most temperate terrestrial biotopes (O'Connor, 1967). The density of enchytraeids is generally higher in acid soils with important organic content (Coleman and Crossley, 1996). Thus, the high pH values found in our soils could explain the low average abundance of enchytraeids compared to the values reported for an intensively cultivated agricultural soil, dry sclerophyll forests or a peat moor (Coleman and Crossley, 1996; Didden *et al.*, 1997). The slightly greater abundance in H6 could be due to the highest content of organic carbon found in that plot. As enchytraeid densities are usually associated with soil moisture and silty particles, their low abundance in our case may also be due to the unfavourable conditions of humidity due to the particle size distribution (sandy soils are drier than silty soils). Another reason for this low abundance could be the competition with earthworms, since they have been often reported to have a considerable effect on enchytraeid populations: in an acid (pH 4.5) deciduous forest (Räty, 2004), they were shown to drastically decrease their abundance, while other authors also suggested a negative relationship between enchytraeids and earthworms at different acidities (pH 4.9 and pH 6.1 in unlimed or limed forest soil respectively; Räty, 2003). Moreover, an antagonistic relationship was also found in a polder soil, which showed less enchytraeids upon inoculation with earthworms (Didden *et al.*, 1997). Nevertheless, this last author also demonstrated that both groups showed optimal population development at different temperatures and moisture levels, suggesting different ecological niche occupations in natural environments. This last assumption is probably the reflection from what occurs in the present study. As enchytraeids, which can resist rough conditions caused by flooding and drought, colonize first the environments forming by new deposits, earthworms, particularly the anecic ones, appear later when conditions are less harsh. Sometimes, favourable environment is

immediately created, like in plot H3 where high colonization levels of earthworm communities can be observed.

Another reason for the relatively low abundance of enchytraeids could be the sampling period. Samples were collected during summer time and high temperatures may have killed or forced a part of the population to move to the deeper soil layers. Due to a variable abundance of enchytraeids (see the high standard deviations), no statistical difference between the six soils was found. As soil structure actors, and even if the abundance is low, enchytraeids affect soil structure by producing faecal pellets influencing aggregate stability by creating favourable habitats for microorganisms (Coleman and Crossley, 1996). These microorganisms are also known to have a great influence on the decomposition of freshly fallen leaf litter (Wolter, 1988) and form micro-aggregates after soil organic matter consumption. Particle aggregation is then stimulated, which greatly improves the soil structure (Koutika *et al.*, 2001). This influence is particularly relevant in initial stages of soil structure formation, as investigated here, where earthworm communities are still not well developed.

5.7.1.2. Abundance and biomass of earthworms

In the present study, abundance and biomass of earthworms were similar to those recorded in a subtropical forest in Athens (GA, USA) with sandy loam to sandy clay loam soils (Callaham and Hendrix, 1997) or in various woodland types on clay or limestone soils (Cuendet, 1984). A study of earthworm distribution within different humus forms in beech forests (Staaf, 1987) gave a mean abundance of 220 individuals m^{-2} and a mean biomass of 116 g m^{-2} for a rich mull humus form. These data are comparable to our plot H3 and to H1 and H4 for the mean abundance.

However, our results were much higher than those of Zorn *et al.* (2005) in the Netherlands, who observed only five different species in an active floodplain system. This low diversity was explained by the climatic conditions with long periods of flood-

ing. Our study site could then not be considered as an active floodplain system, but in contrast, as a stable dynamic alluvial system. On the other hand, the white willow forest of Broc (see description in 2.2.1.) may be compared to such flooding conditions. Unfortunately, no extraction was carried out in this area. In Edwards and Bohlen (1996) a study on the main soil types in Scotland showed a population of 44 individuals m^{-2} in alluvium. Our results present a higher abundance except for sampling plot H5. The relative contribution of juveniles to the average abundance and biomass of our studied plots is quite similar to a study conducted in a deciduous forest in the United States (Snider and Snider, 1988), where juveniles accounted for approximately half of the total biomass and of the total number of individuals.

Concerning the *epigeic* category, the preponderance of *D. octaedra* in H1, H3, H4 and H6 indicated a higher degree of organic matter humification than in other plots (Snider and Snider, 1988). The other epigeic species, *L. rubellus*, indicating less humified conditions, was also present in H1, H3, H4 and H6, but to a lesser extent. This species plays a major role in the first steps of aggregation, because it adds numerous secretions to soil as it passes through the gut and thus increases the organic carbon content in casts (Shipitalo and Protz, 1988). Moreover, it breaks up and incorporates litter into underlying horizons if present in great numbers (Deleporte, 2001). The absence of this species in H2, associated with a sandy texture difficult to ingest and to stabilize in aggregates could explain the lower aggregate stability reflected by the low MWD. In addition, *L. castaneus*, which indicates reduced organic matter content, dominated in H2. In contrast, the presence of *D. pygmea* in H4 is a sign of high content of organic matter and possibly a sign of sand as well (Bouché, 1972). The high number of *D. rubidus* in H4 and in H6 to a lesser extent indicated a good biological activity in the upper layers. This species is known to be ubiquitous and very mobile in the superficial layers of soil and has been reported to consume a proportionately greater amount of organic matter than deeper-burrowing species (Langdon *et al.*, 2001).

The *anecic* category was only present in H1 and H3. The deep-burrowing *L. terrestris* was dominant in H3 and represented one third of the total biomass. This species is known to have a positive effect on soil structure by creating mixing casts of organic and mineral particles. These casts may then be hardened into stable soil aggregates and provide a food source for other animals in deeper soil strata (Schaefer and Schauermaun, 1990). The massive abundance and biomass of *L. terrestris* in H3 and the smallest abundance in H1 can be explained by the soil texture. According to Cuendet (1984), this species prefers a soil formed of limestone layer instead of clay, and Curry (2004) demonstrated a positive relationship between clay content and different species including *L. terrestris*. Thus, a sandy texture is not favourable for worms because the low water content does not maintain the hydrostatic pressure and then does not prevent desiccation (Zorn *et al.*, 2005). In abrasive gravelly soils the earthworm skin could be injured because of its softness (Coleman and Crossley, 1996; Curry, 2004). This constraint is particularly true for the anecic category (but also for the endogeic one), which contributes also to the mixing of organic and inorganic material in deep layers (bioturbation). Thus, the soil texture can explain the absence of anecic earthworm in H4, H5 and H6 despite the oldest age of tree population, compared with the three other ones.

The *endogeic* category was mostly present in H1, H3 and H4 with the dominance of *O. t. lacteum*. This neutrophilous species plays a major role in the stabilization of organic matter by incorporating litter fragments into the mineral layers. This bioturbation is a key process in the formation of mull humus forms (Edwards and Bohlen, 1996) and the presence of anecic and endogeic earthworms in soils, as observed for H1, H3 and H4, has a critical impact on soil structure, aggregate formation and stability.

We suggest that, in terms of soil biota succession, epigeic earthworms are probably the first engineers, with enchytraeids, in the initial steps of soil structuring. Then, if the soil texture is favourable, the anecic and endogeic earthworms rapidly invade

the different soil layers and improve the physical and nutrient conditions. So, fauna succession does not necessarily follow primary or secondary succession, but show different steps not successive and depending on various relative exogenous and endogenous factors.

It is well known that earthworm spatial distribution is aggregated and follows the local conditions, in particular available food supplies. Earthworms are very selective and avoid rough conditions by moving up to several meters during a night when most suitable conditions for activity are found (Edwards and Bohlen, 1996). As plots H1, H2 and H3 are separated by about 30 m (only 5 m between H2 and H3) we may suppose that individuals move horizontally to find best local conditions. In our case, invasion may be due to the sediment deposits, in which cocoons are probably transported from upstream. When optimal conditions are brought together, lumbricids can start their growth period.

5.7.2. Physicochemical characteristics

5.7.2.1. Features of soil aggregation

In this study the effect of the particle size distribution of the surface horizons on soil structure was evident. As the nature and thickness of the underlying mineral horizons (alluvium gravel and *M* horizons) were similar, we could then exclude in our case their influence on the structure of the upper horizons. Thus, aggregate stability, illustrated by MWD, is strongly dependent on the particle size distribution of the recent deposits and not only on the duration of soil evolution. We did not find, in contrast to many authors (Elliot, 1986; Puget *et al.*, 1995; Tisdall and Oades, 1982), a positive correlation between organic carbon content and aggregation. In our case, the aggregate stability was positively correlated with enchytraeid abundance, coarse and fine silt, and clay content of *A* and/or *J* horizons, as well as with different iron forms and negatively correlated with coarse sand content. The “young” plot H3 showed the highest MWD value with fine sand, fine silt and clay contents. It is well recognized that clay particles are particularly involved in the soil structure with an increase of ag-

gregate stability when clay content increases (Le Bissonnais, 1996). *Anyway it has until now never been demonstrated that the fine parts of sand particles as well as the silt particles also participate to aggregate stability.* Boix-Fayos *et al.* (2001) showed a positive correlation between large aggregates (>5 mm) and amount of sand, but this occurred in the presence of earthworms producing casts. It has already been shown that medium-textured soils appear to be more favourable to earthworms than sandy soils or soils with high clay content (Curry, 2004). Shipitalo and Protz (1988) also showed a significantly lower sand content and greater clay content in casts of small worms such as *L. rubellus*, than in casts of the large worm *L. terrestris*. In our case, the plot H3 presented these expected conditions and was indeed rapidly colonized by anecic earthworms producing stable aggregates in spite of a recent and silty sand deposit.

5.7.2.2. Relationships between iron and texture

Data for iron forms found in this work were quite similar to other studies (Kahle *et al.*, 2002) or a little lower (Arduino *et al.*, 1984). Our data showed that among the “youngest” (in terms of sediment deposition and age of present tree population) sampling plots H1, H2 and H3, the stability of aggregates increased with the increase of various iron form proportions. These iron forms and particularly the Fe_o type (amorphous form) are usually considered as cement particles in water-stable aggregates (Elliott, 1986) and are related here to the fine particles of soil (fine silts). Bera *et al.* (2005) mention larger proportions of amorphous iron form in the illuvial horizons of a soil series indicating translocation of iron. In our case Fe_o form is actually more present in the advanced stages of soil formation (H3 to H6). Here again, H3 is comparable to the alder sampling plots. However, Arduino *et al.* (1984) have another point of view and found that amorphous iron is lowest in samples from the oldest terraces and highest in those from youngest ones. This opposition may be due to parent material with nearly no carbonate and pH H_2O values ranging from 4.9 to 7.0 (7.8 in presence of lower content of carbonates),

as well as to the high content of clay (between 7.5 and 57.5%) and the age of terraces formed during the Middle Pleistocene and Upper Pleistocene-Holocene periods. No recent sedimentation seems to have taken place for a while.

It is known that clay and Fe_d (crystalline form) contents are significantly and positively correlated in the upper layers (Oades, 1990; Kahle *et al.*, 2002), but it was revealed by our correlation analysis that the coarse silt fraction was the prime supplier of the different forms of iron. We discern an increase of Fe_d with increasing soil formation age (Bera *et al.*, 2005), associating to the silt particles in our alluvial context. Clearly, fewer proportions of various iron forms were extracted from the coarse sandy H2, implying a reduced aggregate stability. Our sampling plot H3 is once more comparable to the most evolved soils.

Nevertheless, degree of soil development does not give the same trend when $Fe_d - Fe_o/Fe_t$ and Fe_o/Fe_d ratios are studied. On the contrary, $Fe_d - Fe_o/Fe_t$ ratio usually increase with degree of development (Arduino *et al.*, 1986). According to Dolui and Bera (2001), Fe_o/Fe_d ratio should decrease with the increase of soil age. Thus, Sarine River alluvial soils show tendency in soil evolution with amounts of Fe_o and Fe_d , but we presume that these soils are finally too young to really show progressive evolution in degree of development and time series.

5.7.2.3. The role of the calcium carbonates

Calcium carbonates are also known to act as cementing agents by maintaining the flocculated structure or the clay in soil-surface aggregates through acid neutralization (Emerson and Greenland, 1990). In our study, this content was not correlated to any textural classes and calcium carbonates were distributed equally among the different textural fractions. On the other hand, the negative correlation with Fe_t and Fe_o forms revealed a weak iron content in the carbonated part of soil. Moreover, the active calcium carbonates, which represent the finest fraction of total calcium carbonate and

binding particles, showed low calcium availability in the coarse sand fraction. In our study, this coarse sand fraction played clearly a major role in the aggregate stability and influenced strongly the humus form evolution.

5.7.3. Synthesis

The study of soil biological and physicochemical processes on initial stages of soil structure formation in two different tree population types brought new observations to light:

1. The distribution of earthworm categories depends on the soil texture of recent deposits and not only on the soil age reflecting by the colonizing age of tree populations. Soil biota succession appears in two steps: epigeic earthworms with enchytraeids are the first engineers producing in a short-term soil structure and then, if texture is favourable, anecic and endogeic earthworms invade the different soil layers improving physical and nutrient conditions and creating long-term stable aggregates. This invasion is possible by lateral travelling and probably also by inflow of cocoons due to sedimentation. When environmental conditions are favourable the juveniles emerge and migrate horizontally to invade the adequate soil types.

2. Particle size distribution of the upper horizon strongly influences aggregate stability that is weak in the presence of coarse sand content and stronger with fine silt and clay contents. When the structure stability increases, a positive feedback appears (probably due to soil fauna activity) and accelerates the formation of large aggregates despite a recent and silty sand deposit. No strong influence of the underlying mineral horizons (alluvial gravel or buried mineral horizon) was found. The role of barrier expecting from a sharp limit between deposits of various textures does not seem to appear here. Even if texture plays a major role in soil structure, porosity, ion exchange and hydric regime in particular, only the upper layer texture class is implied in the structure formation.

3. Iron forms acting as cementing agents in soil aggregation are observed in the coarse silt frac-

tion representing the prime supplier of iron and are found in low amounts in the coarse sand fraction. This may be due to the mineralogy of silts allowing better availability of iron, which is highest in presence of clay. However, degree of soil development is not progressed enough to detect reprecipitated forms of iron that generally increase with pedogenic processes and soil age (e. g. in case of weathering). Tendencies have already been visible, but pedogenesis still starts out.

4. Calcium carbonates are equally distributed among the different textural fractions. However, the negative correlation between active calcium carbonate fraction, representing the finest part of total calcium carbonate, and the coarse sand content could also explain a lack of aggregate stability in this textural class. Active calcium carbonate seems to be a good agent for binding organic matter with mineral components. Further analysis specifying the chemical nature of soil organic matter, especially the one implied in the very first processes of soil structuring in the youngest and the least developed soils, are thus needed to precisely understand these fundamental processes.

5.8. Conclusion

We showed here that the tree population age cannot be used alone as an indicator of the humus form formation and evolution. Biological and physicochemical parameters, especially particle size distribution and earthworm categories, also strongly influence aggregation in the initial phases of soil structure formation in an alluvial context, such as the Sarine River. In this case, aggregate stability is not correlated to organic matter, but mainly to fine parts of sands and silts deposited by floods. Fauna succession is then not clearly established and also depends on texture classes. If initial conditions are suitable for anecic earthworms, spatial invasion and colonization may happen implying soil structure formation. These differences in soil development induce a heterogeneous distribution of the humus forms increasing the ecological value of the alluvial zone and the continuity of ecosystem functions.

It also appears that in these very different initial conditions, due to various deposits, the first steps of soil evolution present particular stages of development, sometimes different from the evolution of older ones. In fact, ecosystems tend to evolve more or less rapidly to a site climax and the dynamics towards this climax are under the control of numerous processes relevant to homoeostasy on

the sense of ability of system to maintain its functioning constant against changes in the external environment. Nevertheless, in our toposequence through the alluvial zone, soil fauna does not follow the same sequence than vegetation or even more soil age and development. The evolution depends mainly on exogenous factors represented by sediment deposits.

6. Conclusions and perspectives

This chapter aims to discuss how each objective defined in chapter 1 is answered. Contributions of the different chapters towards the objective (chapter 2 to 5) will be outlined. A general synthesis combining each scale level is presented in order to have an overview in space and time on this thesis. Finally, some limits and perspectives for continuing research are suggested.

6.1. Main research objectives

Within the frame of the multi-level scale approach, from general interdisciplinary study on landscape to particular specialized processes of soil structuring, results from each scale level is reevaluated and added with some interesting information.

6.1.1. 150 years of floodplain landscapes evolution

Our results highlighted major changes in fluvial systems mainly due to human impacts, such as embankments and dam constructions. The flow regime has therefore been changed causing incision and modifications of deposition and erosion processes, and thus evolution in the vegetation mosaic. Softwood forests have been progressively replaced by hardwood forests. Moreover, the surrounding lands have been disconnected from their rivers and used for other purposes (agricultural practices,

wood exploitation or urbanisation) leading to a reduction of alluvial forest surface towards a narrow ribbon along the riverbanks.

Our brief landscape evolution study showed also that despite geological, geographical or climatic differences between the three study systems, rivers have reacted in a similar way to human perturbations. Even if human presence was earlier in the Ticino River Valley, due to the important role of this valley in connecting North of Europe to South, similar morphological transformations has been observed in both Rhine and Sarine River valleys. Natural landscape elements have mostly disappeared in favour of landscape elements guided by anthropic processes. Only some small sections have remained in a natural state, areas that are always under high human pressure. Biodiversity is still decreasing and economic worth is prioritised compared to ecological values.

In ecological terms floodplains are regarded as an essential component of the system with intrinsic properties and ability to survive changes and perturbations in its structure and functioning. Nevertheless, damages caused to floodplains are generally irreversible and initial stage could never be found again. Thus, restoration efforts related to the recreation of natural morphological characteristics, as well as water quality improvement, have to be taken into consideration. In practice, only

restricted zones may be concerned by restoration, and common baseline management should conduct the different involved disciplines. Moreover, appropriate scientific monitoring has to be an integral component of sample projects in order to evaluate the recovering of the interface between terrestrial and aquatic environments.

The principle limiting factor is without any doubt the financial restrictions of the restoration projects. This kind of works costs a lot of money and measures are not always well understood. In Switzerland, and particularly in the Canton of Graubünden, several restoration projects were achieved with the development of security arguments (in the area of Chur and in the Mesolcina Valley). With the help of motivated persons having decision power, restoration projects could respond to local expectations in terms of land development, leisure, gravel extraction, but little importance has been laid on ecological principle.

Despite the Swiss Order on the protection of the alluvial zones of national importance (RS 451.31, 1992; www.admin.ch), the protection of alluvial zones is not easy because of their multiple uses, such as urbanisation, production of energy or gravel supply. Alluvial zones are submitted to high pressures, and with intensification of violent flood events, are now in the heart of human society debate. Nevertheless, the examples of our three floodplain systems have proved that a work of information is still needed, notably at the level of the general public. It is necessary to conserve available natural zones in order to absorb intense events of floods and by the same occasion to recreate a link with the river.

6.1.2. Alluvial soil development and human impact

The soil cover differentiation throughout the study areas depends on the diverse processes taking place in our selected rivers. Human activities have affected streams by direct or indirect causes and may only be detected at a long term. Time is thus a predominant parameter to be taken in consideration. In the present study, we brought to light that river regulation occurring since the middle of

the 19th century has modified the alluvial soil formation. By disconnecting the river from its floodplain, constructions along the stream have changed soil stratification. Periods of stability, succession of buried (or multiple buried) soils, as well as high rates of sedimentation, are summarized in our four facies models (see 3.6.2).

At the functional unit level, facies models may be found alone or combined with others. A stable alluvial section (for example at the functional unit level) may be related to one and an unstable to another, but at the functional set level, each of these four facies models must be represented throughout the area in order to approach the ecosystem equilibrium. The representation of these facies models have to be balanced in space, but also in time to achieve a continuing equilibrium.

Our results showed also that the four facies models detected in the Sarine River are also identified in the two other study areas. So, a general consideration for the entire Alpine region may be considered. They reflected the recent history of the rivers and the human role in changing river channels. It has been illustrated that alluvial soils are formed by violent and irregular events depositing sediments. Their particle size distribution depends on the energy of the flow discharge. Nevertheless, alluvial soil is not necessary a continuous sequence and some missing events may appear in the stratification. Thus, we showed that alluvial soils are not only indicators of the local landscape evolution, but above all, reflect, in their horizon stratification, the local hydro-geological conditions of their catchment areas.

6.1.3. Alluvial soil evolution

Soil typology of the Sarine River showed highly variable soil development within the study area, as already highlighted. Frequent erosion and deposition disturbances create a complex mosaic of soil conditions influencing vegetation colonization and establishment. This heterogeneous distribution of soil conditions permits the maintenance of high plant diversity. Nevertheless, human activity greatly modified these local conditions at the soil level,

but also at the landscape level due to farming, grazing and deforestation.

Such modifications of rivers and their impact on soil development have also been observed in the Sarine River. Changes in soil evolution may be detected in the soil profile. For example, a double attribution, such as CALCOSOL on REDUCTISOL described in the grassland of Neirivue, reflects a drift in the chronological development of soil and may thus be used as marker in space and time. It is proved once again that the abruptness of any transitions noted is a powerful field tool for the differentiation of soil horizon boundaries from sedimentary unit boundaries. It permits to illustrate the described model of soil development on aggrading floodplain, where materials go through a succession of development (fig. 6.1). On the top of soil, original sediment is deposited with its own properties, which will decline with time. Therefore, through processes of gleying, decalcification or clay translocation, sediments will evolve and be recovered by other alluvial deposits. Floodplain surface will then approach a hypothetical level of aggradation from which intensity of soil-forming processes should increase. Greater horizon development at the top of the alluvial sequence would be observed. *This model of soil development may be applied to our soil development by substituting the hypothetical level of aggradation by human modifications, such as embankments.* The same processes are observed

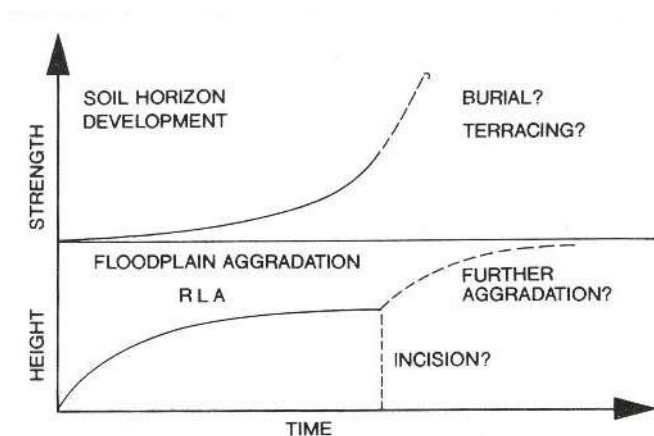


Fig. 6.1. Model of soil development on an aggrading floodplain (source: Gerrard, 1992, p. 95).

with an increase in thickness of top soil horizon and development of some pedogenic features.

Nevertheless, in the case of Sarine River soils, pedogenesis is not developed enough to really contain a progressive pedogenesis compared for example to the Loir valley (see 4.7), where successive pedogenesis processes are described in the pedological chronosequence. Sarine River soils are still young and not-well developed, and some of them even present a regressive pedogenesis. Moreover, it has to be noticed that this study only focused on lower terraces closed to the river implying that some more evolved soils were probably neglected.

6.1.4. Alluvial soil structuring fauna and deposition mechanisms

The present study allowed us to attest that different initial conditions, due to various deposits, influence soil structuring processes in the first steps of soil evolution. Nature of sediments induces the colonization of fauna, the succession of which starts with enchytraeids and epigeic earthworms. This colonization may then be accelerated by favourable conditions. In our case, fine parts of sand particles, as well as silt compounds, participate to aggregate stability and promote anecic earthworms, when organic carbon content has no visible influence.

In alluvial context, the dynamics towards the equilibrium and the periodic fluctuations of the systems are under the control of numerous processes, and thus succession, from one development phase to another, does not follow the typical evolution of alluvial succession. Fauna toposequence observed through the study alluvial zone of the Sarine River does not follow the same sequence as the vegetation or even more the soil. The evolution depends mainly on exogenous factors represented by sediment deposits.

Moreover, no strong influence of the underlying mineral horizons was found in structure stability. The barrier role, which may represent a sharp transition between one layer to another, seems not to be important for the upper soil development. If conditions are combined on the top, no influence

of bellow layers is detected, and soil structuring processes appear.

Therefore, the question of how is made gradually the convergence towards the state of balance of the dynamic equilibrium may be asked. It probably exists several ways to reach this equilibrium state and several relative rates of the ecosystem compartments. Indeed, various initial physicochemical situations (notably texture) may evolve through different intermediate states to finally achieve the same hypothetical result (fig. 6.2). This hypothetical final state depends on two scales of time: season, decade or century for the development time of the vegetation, and decade to millennium for a slower development time of the soil. The humiferous episolium depends then on these two time-scales that, in the case of alluvial soils, may be interrupted by

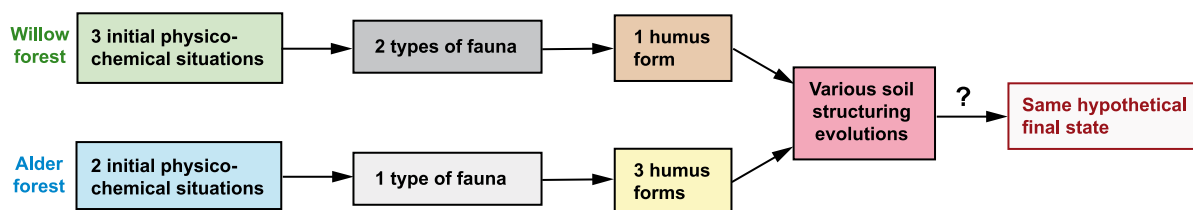


Fig. 6.2. Schema of the hypothetical evolution from various initial physicochemical situations through different intermediate states to the same hypothetical result depending on two scales of time from vegetation and soil.

new fluvial deposits. The different system compartments have their own relative speeds evolving in parallel. Vegetation evolves faster than humiferous episolium, which reacts faster than soil, but with time equilibrium may be reached if no exogenous factor happens.

Conclusively from all results of the thesis, we found that the combination of various scales and techniques allowed the connection between the dynamics of soil structuring processes in described humiferous episolium and the general fluvial mechanisms due to river regulation and management. Human impact have great importance on alluvial zones functioning and damages caused to floodplains are generally irreversible and initial stage could never been found again, unless restoration efforts are taken into account.

6.2. Limits and perspectives

When a study at large scale is useful to understand landscape evolution, research at the scale of microsites is important to understand the basic processes of the fluvial environment. Recently, there has been a higher interest for studying the alluvial soil ecosystems to get the knowledge of their multiple importances. Monitoring the environmental impact of anthropic disturbance on soil ecosystem is of great importance for optimizing strategies for soil use, conservation and remediation. Soils are complex open processes and response systems, which continuously adjust by varying degrees, scales and rates to assume the changes of energy, mass fluxes, thermodynamic gradients, as well as other environmental conditions. Getting a complete view on these systems is rather difficult and focus has to be made on precise themes.

In this research, emphasis was made on soil formation and humus form description, with the conclusion that soil evolution reflects the history of fluvial disturbance, but vegetation was rather neglected. More detailed examination of the interrelationships between vegetation and historical events should be necessary to better identify the floodplain functioning in response to perturbation. Moreover, a detailed local vegetation survey should be carried out at the scale of the soil typology level in order to improve the evolution model of alluvial zones.

In a general way, and at the end of this research, some limits may be exposed. Firstly, at the level of humiferous episolium, only two different steps of alluvial soil evolution were presented here. A precise study on how evolves fauna towards the dyna-

mic equilibrium state and what is the hypothetical final state should be carried out. Some questions could be asked, notably about the possible change of fauna type and/or functions during evolution towards the final state. Moreover, some further analysis concerning fauna and fungal diversity and functioning implying in soil structure formation should also be very indicative of this soil evolution. Our results highlighted at the mountain level the importance of taking into account the various initial physicochemical conditions, similar questions should be asked at the subalpine level or at lower levels such as hill or plain.

About the typology of the Sarine River, the survey was exclusively carried out on the lower terraces of the three floodplain systems. An extension of this investigation to sites situated on higher terraces would allow a better overall view on floodplain valley functioning. Moreover, pit excavations should be carried out in other fluvial systems in order to specify the alluvial soil typology. Another attempt will be to study the variations of the trace element and nutrient concentrations in layers of various profiles along a river segment in relation to the anthropic impact. The use of lead isotopes would allow dating precisely the different deposited sediments and thus flooding events. Furthermore, research on association between trace elements and organic matter may give important information for floodplain management in terms of water and soil pollution.

The soil survey approach based on auger sampling presented in this thesis is still approximate and subjective notably for the horizon thickness and the texture. Despite everything, this method is very useful and little expensive to get a rapid assessment of the spatial distribution of soil types across the field. Furthermore, it permits to obtain indications on the general functioning of the entire floodplain valley at the level of functional set level. Other prospecting in different floodplain systems

would allow verifying the hypothesis of the obligatory combination of our four facies models.

Riverine ecosystems are not only species-rich ecosystems and hot-spots of biodiversity, but they also represent essential processes such as carbon stockage. In the context of global change, the loss of such ecosystem processes is a serious threat for ecological services on which humans depend. Developing sustainable approaches to such systems implies understanding what maintains its resilience, its structural or functional stability and how human intervention might affect it through time. Further research on carbon cycling or a better understanding of the amount and the chemical composition of soil organic matter, which is also essential in storage and supplying of nutrients, such as nitrogen and phosphorus, are of great importance.

In the present study, rich-carbonated environments showing coarse texture in mountain level were favoured. Nevertheless some elements about non-carbonated systems may be found in the Ticino River study area (see 3.8.2.) showing points of similarity with meandering systems of plain level. While a thin total thickness has been found in the Sarine River, deeper profiles were described in the Ticino River with horizons of finest texture. Emphasis has thus to be made on systems of lower altitude level, such as hill or plain, with the use of the same methodological tools.

With considering actual evolution of floodplains and always important damages caused by the exceptional events, a change of paradigm, as mentioned in the Flood'Alps project, is inevitable. Landscape modifications reveal not only floodplain changes due to natural (sedimentation, soil and vegetation development) or anthropic processes (embankment, channel straightening), but also changes in perceptions, representations, and legal directives. Ecological management based on detailed information about processes concerned by the fluvial hydrosystem is important for conservation and restoration of floodplains.

7. References

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8. Appendixes

Cadre législatif : Rapport interne du projet Flood'Alps (Service conseil Zones Alluviales, 2004)

1. Législation fédérale

L'évolution des bases constitutionnelles présente une vue synthétique de l'évolution de la politique en matière de protection de la nature et d'aménagement des cours d'eau :

1874 – art. 24 Cst: haute surveillance de la Confédération sur la police des endiguements et des forêts dans les régions élevées.

1897 – Modification de l'article 24 Cst: Haute surveillance de la Confédération sur la police des endiguements et des forêts sur tout le territoire suisse.

1908 – art. 24bis Cst: haute surveillance de la Confédération sur l'utilisation des forces hydrauliques

1953 – art. 24 quater Cst: protection qualitative des eaux

1962 – art. 24 sexies Cst: protection de la nature et du paysage

1971 – art 24 septies Cst: protection de l'environnement

1975 – art. 24bis Cst: protection qualitative et quantitative des eaux

Cependant, l'application de ces principes n'est pas immédiate et il faut souvent plusieurs années avant la mise en œuvre des lois conséquentes. Par exemple, le principe de protection quantitative institué en 1975 n'est appliqué qu'en 1991 avec la loi sur la protection des eaux (LEaux) (RO 1992 1860).

Une autre vue synthétique est présentée dans une étude de l'IDHEAP qui analyse le « Développement historique des régimes institutionnels de la ressource en eau en Suisse entre 1870 et 2000 ». L'étude de l'IDHEAP propose une périodisation des politiques publiques régulant la ressource naturelle en 4 phases:

- 1871-1908 : Phase de protection contre les eaux (Wasserbau). L'objectif principal durant cette période est la réduction des dégâts dus aux inondations par une politique d'intervention centralisée sur les torrents et forêts de montagnes. C'est également durant cette période que sont jetées les premières bases de la politique de protection des eaux qui sera développée principalement après 1950.
- 1908-1953 : Phase d'exploitation économique des eaux (Wassernutzung). L'augmentation des besoins en énergie de la Suisse incite la Confédération à développer une politique « rationnelle » de mise en valeur du potentiel hydraulique des cours d'eau du pays. Parallèlement, la politique d'approvisionnement autarcique en produits agricoles incite à la mise en valeur de nouvelles terres agricoles par le drainage des zones humides.
- 1953-1991 : Phase de protection qualitative des eaux (Wasserschutz). Durant cette phase, la Confédération met en œuvre une politique de protection des eaux contre les atteintes polluantes de la société. La pollution diffuse agricole est explicitement exclue de cette politique.
- 1991-2000 : Phase de protection quantitative et qualitative des eaux. Durant la dernière décennie du 20^{ème} siècle, la politique de l'eau en Suisse vise à protéger la ressource de manière globale par la mise en œuvre de principe de causalité et par la protection globale du système hydrologique naturel.

2. Législation fribourgeoise

Au début de notre période d'étude, la législation fribourgeoise précède la législation fédérale. Dans le canton de Fribourg, un code forestier est édicté en 1850 et une loi sur le dessèchement des marais, le redressement des cours d'eau et les endiguements en 1852 (ROF 1853 20) alors que la loi fédérale concernant la haute surveillance de la Confédération sur la police des forêts dans les régions élevées (RO 1876 250) et celle sur la police des eaux (RO 1877 130) datent respectivement de 1876 et 1877.

Cependant, les cantons sont chargés de l'exécution des lois fédérales et dès qu'une loi fédérale est élaborée les lois cantonales doivent être adaptées en conséquence. Souvent, un arrêté pare au « plus pressé » alors que la création d'une loi peut prendre beaucoup plus de temps. Par exemple, la loi fédérale sur la protection de la nature de 1966 (RS 451) est exécutée au niveau cantonal dès 1968 au moyen d'un arrêté (RSF 721.0.12) qui renvoie à la législation existante, soit le règlement d'exécution de la loi sur les constructions de 1965. D'autres arrêtés ont suivi (ROF 1994 389), et la protection de la nature est actuellement régie sur le plan cantonal par diverses dispositions se trouvant dans la loi du 9 mai 1983 sur l'aménagement du territoire et des constructions (ROF 1983 199).

3. Evolution de la législation vers le principe de conservation de la biodiversité

Les premières législations liées à la protection de la biodiversité visent à réglementer l'utilisation de certaines **ressources**. Au niveau fédéral, il s'agit des lois fédérales sur la pêche en 1888 (RO 1876 74) et sur la police des forêts dans les régions élevées en 1876 (RO 1876 250) dont le champ d'application est étendu à l'ensemble de la Suisse en 1902 (RS 1848-1947 511). Dans la loi sur la pêche, l'intérêt piscicole est prépondérant mais des principes intéressants y figurent : maintien de la circulation des poissons (Art. 6), protection qualitative des eaux poissonneuses (Art. 21, al. 1 et 2). La police sur les forêts insiste sur leur rôle protecteur des forêts mais il établit le principe de maintien de l'aire forestière (Art. 11 de la loi de 1876 et Art. 31 de la loi de 1902).

Le principe de protection de la nature n'apparaît qu'au début du 20^{ème} siècle dans la mesure où certaines espèces deviennent protégées. En 1904, la loi fédérale sur la chasse et la protection des oiseaux (RO 1904 126) assure une protection à certains oiseaux (Art. 17) et permet au conseil fédéral d'interdire localement ou temporairement la chasse du gibier ou de certaines espèces (Art. 7). Suite à la révision de cette loi en 1925 (RS 1848-1947 535), des districts francs seront créés (Art. 15, al.1). Dans le canton de Fribourg, certaines espèces végétales sont protégées dès 1912 par un arrêté.

Un grand pas pour la protection de la nature est réalisé, en 1914, avec l'arrêté fédéral concernant la création d'un parc national suisse dans la Basse-Engadine (RS 1848-1947 269) où « L'ensemble des animaux et des plantes compris dans ce territoire sera abandonné entièrement à son développement naturel et soustrait d'une manière absolue à toute influence humaine qui s'exercerait en dehors du but poursuivi par la création du parc. » (Art. 1^{er}, al.1).

A cette même époque, on commence à protéger les sites (en allemand *Naturschönheiten* et *landschaftliches Bild*), principalement pour des raisons esthétiques, dans les législations relatives à différentes activités. L'article 22 de la loi fédérale sur l'utilisation des forces hydrauliques de 1916 (RS 1848-1947 761) règle les relations avec d'autres intérêts, notamment la « *protection des sites* ». On retrouve ce terme dans l'article 79, al. 1 de la loi sur l'agriculture de 1951 (RO 1953 1095). Dans le canton de Fribourg, la protection de la nature est mentionnée dès 1960 dans la loi sur les améliorations foncières (ROF 1960 93) puis dans le règlement d'exécution de la loi sur les constructions de 1965.

En 1966, la loi fédérale pour la protection de la nature et du paysage (RS 451) est édictée. La notion de protection des biotopes est intégrée avec l'article 18 alinéa 1. Il précise que « *La disparition d'espèces animales et végétales indigènes doit être prévenue par le maintien d'un espace vital suffisamment étendu (biotopes), ainsi que par d'autres mesures appropriées.* ». L'application de la loi fédérale dans le canton de Fribourg est assurée, dès 1968, par un arrêté (ROF 1968 134). Actuellement, la protection de la nature et du paysage dans le canton de Fribourg est régie par diverses dispositions se trouvant dans la loi du 9 mai 1983 sur l'aménagement du territoire et les constructions (ROF 1983 199) et dans plusieurs arrêtés d'exécution (ROF 1973 50, ROF 1994 389).

Parallèlement à la protection de la nature, la protection de l'environnement, notamment la protection qualitative des eaux se met en place. Elle apparaît en 1943 dans le canton de Fribourg avec la loi sur la santé. En 1955, une loi fédérale sur la protection des eaux contre la pollution est édictée (RO 1956 1635). Toutes les eaux sont protégées ; les eaux superficielles et souterraines, naturelles et artificielles, publiques et privées, y compris les sources (Art. 1). La loi protège la santé de l'homme et des animaux, assure que l'eau soit propre à la boisson, au bain, que les poissons puissent subsister et que le paysage ne soit pas enlaidi (Art. 2, al.1). La loi d'application dans le canton de Fribourg date de 1964. La loi fédérale est révisée en 1971 (RO 1972 958) quand le principe de l'épuration centralisée des eaux usées est instauré.

En 1983, la loi fédérale sur la protection de l'environnement (RS 814.01), établit le principe de causalité et intègre plusieurs politiques sectorielles relatives à la protection de l'environnement. Elle introduit l'alinéa 1bis de l'article 18 de la loi sur la protection de la nature et du paysage (RS 451) : « *Il y a lieu de protéger tout particulièrement les rives, les roselières et les marais, les associations végétales forestières rares, les haies, les bosquets, les pelouses sèches et autres milieux qui jouent un rôle dans l'équilibre naturel ou présentent des conditions particulièrement favorables pour les biocénoses.* » En 1986, la loi fédérale sur la chasse et la protection des mammifères et des oiseaux sauvages (RS 922.0) introduit en ses articles 1 et 7 alinéa 4 les notions de diversité des espèces et diversité des biotopes.

En 1987, l'acceptation par le peuple de l'initiative Rothenthurm marque un tournant dans les effets de la politiques agricoles et de la politique d'aménagement des cours d'eau sur le fonctionnement de l'hydrosystème, en mettant un frein à la politique poursuivie jusque-là, au détriment de la protection des milieux humides et des paysages qui leurs sont liés. La loi fédérale sur la protection de la nature est révisée en 1988 (RO 1988 254). Les nouveaux articles 18a, 18b introduisent la notion de biotopes d'importance « nationale » (art. 18a) et d'importance « régionale et locale » (art. 18b). Ces biotopes sont placés sous une protection totale. Le financement des mesures de protection et d'entretien est légiféré dans l'article 18d. La protection des biotopes « d'importance nationale », notamment des zones alluviales, est assurée par le biais d'ordonnances (RO 1992 2080, RO 1994 2092, RO 1996 1839) édictées dans les années 1990. L'article 4 de l'ordonnance sur la protection des zones alluviales de 1992 (RO 1992 2080), précise le but visé par la protection : la flore et la faune indigène typique, la dynamique naturelle du régime des eaux et du charriage et les particularités géomorphologiques doivent être conservés intacts.

En 1991, la loi sur la protection des eaux (RO 1992 1860) est révisée. On y instaure le principe d'une protection qualitative et quantitative des eaux avec le maintien de débits résiduels convenables (Art. 29-35). Simultanément, les lois fédérales sur la police des eaux (RO 1993 234), sur la pêche (61) et sur les forêts (62) sont révisées. Ainsi, une politique globale de l'eau est mise en place. Initialement, l'ensemble de ces révisions faisait partie du second train de mesures pour une nouvelle répartition des tâches entre la Confédération et les cantons. Cependant, les révisions de la loi sur les forêts et celle de la loi sur la protection des eaux ont été traitées séparément (FF 1988 II 1293). La révision de la loi sur la protection des eaux fut soumise comme contre-projet indirect à l'initiative populaire « pour la sauvegarde de nos eaux » (FF 1987 II 1081). Avec la révision de la loi sur les forêts (RO 1992 2521), on reconnaît également à la forêt une valeur « *en tant que milieu naturel* » (Art. 1)

L'ordonnance sur la protection de la nature et du paysage du 16 janvier 1991 (OPN; RS 451.1) utilise en son article 14 alinéa 2 la notion de diversité biologique. On retrouve ce terme dans la toute récente loi fédérale sur le génie génétique du 21 mars 2003 (RS 814.91). La diversité biologique doit entre autres être conservée à long terme (art. 1 al. 2). Suite à l'introduction de cette loi, les lois sur la protection de la nature (Art. 1) et sur la protection de l'environnement (Art. 1) protègent également la « diversité biologique ».

4. Evolution de la législation liée à la protection contre les crues

La législation sur la protection contre les crues débute dans le canton de Fribourg en 1850 avec le code forestier et en 1852 avec la loi sur le dessèchement des marais, le redressement des cours d'eau et les endiguements (ROF 1852 79). Au niveau fédéral, la protection contre les crues est également liée à la gestion des forêts. En 1876/77, on se focalise sur les régions élevées avec la loi concernant la haute surveillance de la Confédération sur la police des forêts (RO 1876 250) et la loi fédérale sur la police des eaux (RO 1877 130). La loi sur la police des forêts définit (Art. 4) et régit l'exploitation (Art. 11) des forêts protectrices. La loi sur la police des eaux stipule « *qu'aucun usage nuisible aux intérêts publics ne soit fait des cours d'eau placés sous la haute surveillance de la Confédération* » (Art. 3, al.1), de plus, « *Les travaux de défense, d'endiguements et de correction exigés par l'intérêt public, ou toutes les autres mesures propres à empêcher des mouvements de terrain, seront exécutés le plus tôt possible sur les cours d'eau soumis à la haute surveillance de la Confédération* » (Art. 5, al.1).

En 1885, une loi concernant la police des eaux dans les régions élevées est créée dans le canton de Fribourg (ROF 1885 58). Les travaux affectant les cours d'eaux du domaine public ne peuvent être exécutés qu'avec l'autorisation du Conseil d'Etat (Art. 1^{er}). « [...] *Le Conseil d'Etat veille spécialement à ce que les dits travaux rentrent dans les conditions d'un endiguement général et rationnel du cours d'eau ou ne puissent constituer une entrave à un endiguement ultérieur ni éventuellement en aggraver les charges. [...]* » (Art. 2). Les champs d'application des textes fédéraux sont étendus à l'ensemble du territoire suisse avec l'article constitutionnel de 1897. Ainsi la loi fédérale sur la police des forêts est créée en 1902 (RS 1848-1947 511). On y classe l'ensemble des forêts suisses en forêts protectrices et en forêts non protectrices (Art. 3, al. 1). Les défrichements dans les forêts protectrices sont soumis à autorisation du Conseil fédéral (Art. 31, al. 2). L'exécution de cette loi dans le canton de Fribourg est assurée par un arrêté en 1904 (ROF 1905 5). La loi fédérale sur la police des eaux est uniquement complétée en 1953 (RO 1953 970) pour coordonner les mesures destinées à la protection contre les crues avec l'économie hydraulique et avec les intérêts militaires. L'article 3bis règle de façon concrète les modalités de la surveillance exercée par le Conseil

Fédéral dans l'exécution, l'entretien et le comportement des grands barrages. Sinon, au niveau fédéral, ces textes feront foi jusque dans les années 90.

Dans le canton de Fribourg, une loi sur l'aménagement des eaux est créée en 1975 (ROF 1975 307). Elle préconise un maintien en bon état des cours d'eau (Art.3) et une prise en compte d'autres intérêts, « *en particulier de ceux de la protection de la nature et du paysage* » (Art. 45).

Dans les années 90, une gestion globale de la politique de l'eau est mise en place, comme nous l'avons expliqué ci-dessus. Elle comprend les lois fédérales sur la protection des eaux (RO 1992 1860), sur l'aménagement des cours d'eau (RO 1993 234), sur la pêche (RO 1991 2259) ainsi que, dans une moindre mesure, la loi sur les forêts (RO 1992 2521). Cette nouvelle politique accorde de l'importance à la protection de la nature. Dorénavant, la loi sur la protection des eaux vise également à « *c) sauvegarder les biotopes naturels abritant la faune et la flore indigène ; [...] e) sauvegarder les eaux en tant qu'élément du paysage, [...] h) assurer le fonctionnement naturel du régime hydrologique.* » (Art. 1).

En matière d'endiguement et de correction des cours d'eau, de fortes restrictions sont émises « *Les cours d'eau ne peuvent être endigués ou corrigés que si ces interventions : a) s'imposent pour protéger des personnes ou des biens importants (art. 5, al. 1bis, de la LF du 22 juin 1877 sur la police des eaux) ; b) sont nécessaires à l'aménagement de voies navigables ou à l'utilisation de forces hydrauliques dans l'intérêt public ; c) permettent d'améliorer au sens de la présente loi l'état d'un cours d'eau déjà endigué ou corrigé.* » (Art. 37, al. 1). La manière de procéder pour protéger contre les crues est intégrée dans la loi fédérale sur l'aménagement des cours d'eau de 1991 (57). Il s'agit de protéger « *des personnes et des biens matériels importants* » (Art. 1). La compétence de protéger contre les crues incombe aux cantons (Art. 2). Dans cette loi, les mesures d'entretien et de planification deviennent prioritaires par rapport aux interventions et « *le tracé naturel doit être autant que possible respecté* » (Art. 4). De plus, l'ordonnance sur l'aménagement des eaux (58) est modifiée en 1999 (RS 721.100). Elle précise dorénavant que « *Les cantons [...] déterminent l'espace minimal des cours d'eau nécessaire à la protection contre les crues et à la préservation des fonctions écologiques.* » (Art. 21 al. 1, 2.). Concrètement, cela signifie que les surfaces correspondantes doivent être intégrées dans les plans directeurs et les plans d'affectation des cantons et des communes, et qu'elles doivent être prises en compte dans le cadre des activités ayant un effet sur l'organisation du territoire (LAT Art. 3., 51a)

Malgré l'intégration de considérations écologiques, la sécurité des personnes ou des biens importants reste prioritaire en matière d'aménagement des cours d'eau (LEAUX Art. 37, al. 1 lit. a, voir ci-dessus). Pour les zones alluviales d'importance nationale, l'article 4 de l'ordonnance sur les zones alluviales (RS 451.31) donne des lignes directrices pour pondérer les intérêts publics de sécurité et de protection de la nature. Il précise que des dérogations au but visé par la protection ne sont admises que « *pour des projets dont l'emplacement s'impose directement par leur destination et qui sont destinés à assurer la sécurité de l'homme face aux effets dommageables de l'eau ou qui servent un autre intérêt public prépondérant d'importance nationale également* ». (OZA Art. Art. 4 al. 2).

5. Liens entre l'évolution des lois et les événements majeurs

La série de catastrophes de la période 1827-1875 (notamment les inondations catastrophiques de 1868) et la constatation de gros déboisements dans les Alpes sont à l'origine de la mise en œuvre d'une politique publique spécifique en matière de protection contre les crues. Le lien entre la surexploitation des forêts et l'augmentation des inondations fut établi dans plusieurs études scientifiques. Ainsi, en 1876/77, les lois concernant la haute surveillance de la Confédération sur la police des forêts (RO 1876 250) et sur la police des eaux (RO 1877 130) sont édictées. Depuis lors d'innombrables corrections de cours d'eau ont été réalisées en montagne et dans la plaine.

Notons encore que de grands travaux de correction ont été entrepris avant la mise en place de la loi sur la police des eaux de 1877, sur la base d'arrêtés fédéraux : Linth (1804), Rhin (1854), Eaux du Jura (1857, 1863, 1867), Rhône (1863, 1870). Ces arrêtés s'appuyaient sur l'article 21 de la Constitution fédérale (1848). « *La Confédération peut ordonner à ses frais ou encourager par des subsides les travaux publics qui intéressent la Suisse entière ou une partie considérable du pays* ».

Dans les années 80, on constate que malgré des décennies d'effort et de lourds investissements, une protection absolue contre les crues ne peut être atteinte. Et ce n'est pas seulement les événements majeurs

de 1987 qui ont révélé brutalement ce fait. Tous les événements de moindre ampleur de ces dernières années ont fait la démonstration que les conséquences d'événements exceptionnels ne se laissent qu'en partie influencer par les mesures de protection structurelles. Un réexamen de la protection contre les crues a alors été conduit et les causes des crues ont été analysées. On aboutit aux deux constats suivants :

- En matière de sécurité, un effort doit être porté sur la diminution du potentiel de dommages.
- De plus, la perte de diversité liée aux aménagements entrepris par le passé doit être freinée.

Ainsi une nouvelle stratégie est mise en place : on ne parle plus uniquement de défense contre les dangers, mais plus exactement d'acceptation raisonnable de risques connus : que peut-il se passer et où ? Toutes ces nouvelles connaissances ont influencé les bases légales mises en place au début des années 90, soit les lois fédérales sur la protection des eaux (RS 814.20), sur l'aménagement des cours d'eau (RS 721.100), sur la pêche (RS 923.0) ainsi que, dans une moindre mesure, la loi sur les forêts (RS 921.0).

6. Evolution d'autres sécurités dans la législation ; leur importance vis-à-vis de la protection contre les crues et de la protection de la biodiversité

Sécurité énergétique¹

Les relations entre protection contre les crues et utilisation des cours d'eau sont régies dans la loi fédérale concernant la police des eaux dans les régions élevées de 1877 (RO 1876 250) par l'article 3. Dans les cours d'eau aménagés avec des subsides de la Confédération, la protection contre les crues est prioritaire car l'utilisation « *dans un but industriel* » est restreinte « *aux conditions protectrices qui seront fixées par le Conseil fédéral* ».

Dès le début du 20^{ème} siècle, la politique mise en œuvre par la Confédération vise une utilisation maximale de la force hydraulique des cours d'eau. La première loi fédérale en matière de force hydraulique date de 1916 (RS 1848-1947 761). Elle vise une « *utilisation rationnelle des forces hydrauliques* » (Art. 5) mais la protection contre les crues reste prioritaire. Il est précisé dans l'article 21 alinéa 1 que « *Les usines hydrauliques doivent être établies conformément aux prescriptions fédérales et cantonales sur la police des eaux* ». De plus, « *Sur les cours d'eau corrigés à l'aide de subventions fédérales, l'établissement des usines est subordonné à l'autorisation du Conseil Fédéral* » (Art. 21, al.3). Après la 2^{ème} guerre mondiale, les intérêts de la défense nationale sont pris en compte dans la gestion des forces hydrauliques. En 1953, une loi fédérale (RO 1953 970) complète celle qui concerne la police des eaux de 1877 en y ajoutant l'article 3bis. Des mesures doivent être prises « *pour prévenir le plus possible les dangers et les dommages qui pourraient résulter de leur (des ouvrages) mode de construction, de leur entretien insuffisant ou de faits de guerre.* »

La loi fédérale de 1916 sur l'utilisation des forces hydrauliques est révisée en 1985 (RO 1985 1839) et en 1996 (RO 1997 991) sans conséquences pour la protection contre les crues ni pour la protection de la nature.

Les intérêts de l'écologie sont intégrés dans la gestion des forces hydrauliques avec la loi fédérale sur la protection des eaux de 1991 (RO 1992 1860) et l'instauration de maintien de débits résiduels convenables (art. 29-35). Ce principe avait été inscrit dans la Constitution en 1975 (FF 1975 II 197) ! Cependant, si l'intérêt public l'exige, l'utilisation des forces hydrauliques permet un endiguement ou une correction des cours d'eau (LEAUX Art. 37, al. 1. Let. b).

Sécurité alimentaire

Au début de notre période d'étude, les intérêts de l'agriculture sont très forts. Le but de la loi fribourgeoise sur le dessèchement des marais, le redressement des cours d'eau et les endiguements (ROF 1852 79) de 1852 est clairement de gagner des terres agricoles « *et en même temps entourer la propriété des garanties nécessaires* ». A cette époque, on retrouve également de nombreux actes concernant les corrections des eaux du Jura (ROF 1857 97, ROF 1866 366, ROF 1867 177, ROF 1867 183, ROF 1869 195, ROF 1872 4). Dès 1893, la loi fédérale concernant l'amélioration de l'agriculture par la Confédération (RS 1848-1347 555) accorde des subventions fédérales pour améliorer le sol ou en faciliter l'exploitation.

¹ Ce paragraphe ne contient aucune information sur le canton de Fribourg car nous n'y avons pas effectué de recherche sur les forces hydrauliques.

Pendant la 2^{ème} guerre mondiale la politique agricole prend une nouvelle tournure avec les Arrêtés du Conseil fédéral sur l'extension de la culture des champs (24, 25, 26). Un maximum de terrain doit être cultivé « *en vue d'assurer l'approvisionnement du pays* ». La sécurité alimentaire prend de la place par rapport à la protection contre les crues dans le sens où le défrichement des forêts est autorisé. Dans le canton de Fribourg, la législation sur les forêts est adaptée pour faciliter l'augmentation des surfaces agricoles avec l'arrêté de 1941 concernant la création d'un fond cantonal de reboisement (ROF 1941 24). Les défrichements entrepris pour étendre les cultures sont dispensés du reboisement, s'ils ne peuvent le faire facilement. A la fin de la guerre (1946), l'Arrêté fédéral concernant la compensation de défrichements et de surexploitations forestières (RS 1848-1947 531) impose une compensation à ces défrichements par une afforestation dans des régions de montagne et une restauration des forêts protectrices (Art. 1).

Dès 1951, le drainage des terrains incultes est favorisé avec le développement des mesures d'amélioration foncières liées à l'entrée en vigueur d'une nouvelle loi fédérale sur l'agriculture (RO 1953 1095). Les intérêts de la protection de la nature sont considérés dans l'article 79 puisqu'il « *sera tenu compte [...] de la protection des sites* ».

En 1998, cette politique agricole est stoppée radicalement avec la loi fédérale sur l'agriculture (RO 1998 3033) où l'agriculture est « *écologisée* ». La Confédération verse des contributions écologiques (Art. 76) et la remise de petits cours d'eau à un état proche des conditions naturelles est promue (Art. 87, al. 1, let. e).

7. Conclusion : évolution de la législation

Protection de la biodiversité

Dans la législation suisse, l'évolution vers la protection de la biodiversité est à peu près la suivante : Protection d'espèces, protection isolées des sites, prise de connaissance de la nécessité de protéger des biotopes des espèces ; → protection nature intégrée ; → utilisation durable, etc. Actuellement, le terme de « *biodiversité* » est encore peu répandu dans la législation. Ce n'est pas surprenant si l'on considère que la législation suit (i) la perception sociale des dangers pour la nature et (ii) les connaissances scientifiques. Or, en science, la notion de biodiversité n'a été « *créée* » que dans les années 80 !

Au niveau international, un pas important a été la convention de la biodiversité (1992)². Il semble qu'en considérant le sens matériel des normes plutôt que le terme même il n'était pas nécessaire de changer les normes (lois) pour des raisons de terminologie seulement. Les bases légales existantes étaient considérées suffisantes pour faire des ordonnances.

Relation Biodiversité/Sécurité

Par rapport à la protection de la biodiversité, la sécurité des biens et des personnes est prioritaire durant toute notre période d'étude. La sécurité énergétique et la sécurité alimentaire ont également une grande importance, en particulier durant et peu après la deuxième guerre mondiale. Contrairement à la protection de la biodiversité, des lois spécifiques à ces différentes sécurités (bien et personnes, alimentaire, énergétique) sont édictées très tôt (RO 1877 130, RS 1848-1947 3, RS 1848-1947 511, RS 1848-1947).

Avec la nouvelle politique introduite au début des années 90 la sécurité des biens est « *relativisée* ». C'est l'apparition du « *nouveau paradigme* ». On différencie les objectifs de protection en fonction du risque que l'on admet pour différentes utilisations du sol. C'est à ce moment que les intérêts de la nature sont pris en compte dans la gestion des cours d'eau. A cette période également, la politique agricole change radicalement de direction. Des prestations écologiques sont indemnisées.

Pour évaluer si les bases légales sont suffisantes pour intégrer la protection de la biodiversité (ou leur utilisation durable, qui comprend aussi le facteur économique !) dans le cadre de la gestion des cours d'eau, il faudrait étudier comment les lois sont appliquées, notamment la fameuse pondération des intérêts, en particulier l'article 37 de la loi sur la protection des eaux (LEaux). Pour cela il serait intéressant d'étudier la juridiction actuelle (voir DEP (Droit de l'environnement dans la pratique) 5/2003 : Dix années de jurisprudence relative à la nouvelle loi sur la protection des eaux).

² Elle définit : *Diversité biologique*: variabilité des organismes vivants de toute origine y compris, entre autres, les écosystèmes terrestres, marins et autres écosystèmes aquatiques et les complexes écologiques dont ils font partie; cela comprend la diversité au sein des espèces et entre espèces ainsi que celle des écosystèmes.

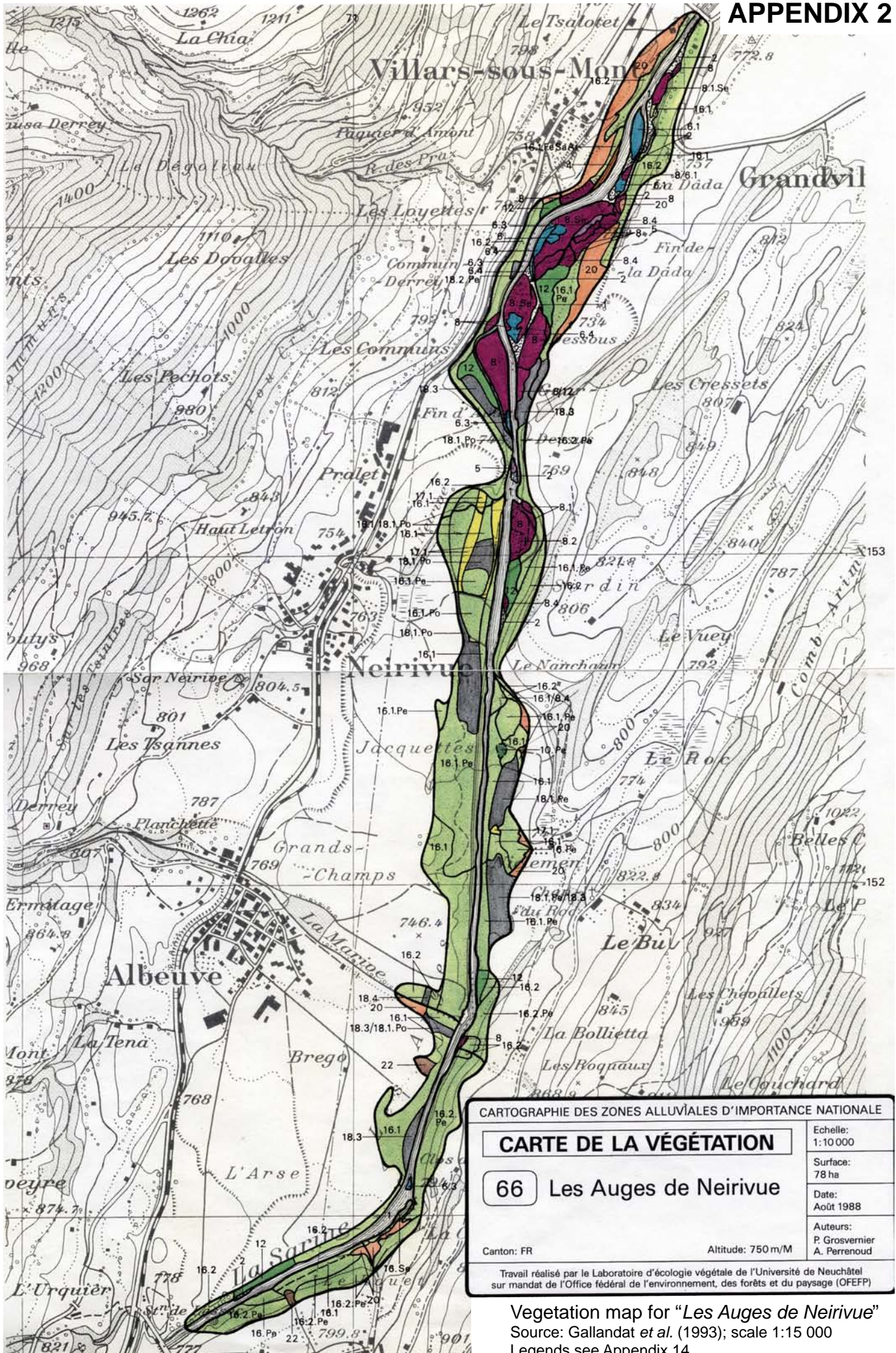
8. Contraintes exigées par la législation actuelle

Les principales contraintes liées à la gestion et à l'utilisation des cours d'eau proviennent de la loi sur la protection des eaux (RS 814.20). Le principe de causalité « Celui qui est à l'origine d'une mesure prescrite par la présente loi en supporte les frais. » est établi dans l'article 3a. Le titre 2 définit les modalités liées à la sauvegarde de la qualité des eaux (Chapitre 1), au maintien de débits résiduels convenables (Chapitre 2, art. 29 et ss.) et à la prévention d'autres atteintes nuisibles aux eaux (endiguement et correction, introduction de substances solides, curage et vidange, exploitation de graviers ...) (chapitre 3). Les contraintes liées au maintien des débits résiduels convenables (Art. 29 et ss.) ne sont à appliquer que dans le cas de nouveaux prélèvements. Les articles 80 et suivants définissent les mesures d'assainissement transitoires pour les prélèvements existants. Elles sont beaucoup moins contraignantes. Un cours d'eau « sensiblement influencé par un prélèvement doit être assaini, [...], sans que les droits d'utilisation existants soient atteints d'une manière qui justifierait un dédommagement » (Art. 80, al.1). La loi est plus exigeante en ce qui concerne les biotopes répertoriés dans un inventaire national ou cantonal. Dans ce cas, des mesures d'assainissement sont ordonnées par l'autorité (Art. 80, al. 2).

De manière générale, les biotopes répertoriés dans les inventaires imposent des contraintes plus exigeantes. Pour les zones alluviales d'importance nationale « les exploitations existantes ou futures, notamment l'agriculture et la sylviculture, l'utilisation des forces hydrauliques, l'exploitation des eaux souterraines et de graviers, la navigation et les activités de loisirs, y compris la pêche, (doivent être) en accord avec le but visé par la protection; » (OZA, Art. 5 al.2 let. C). Le taux de financement de la Confédération pour les mesures de protection et d'entretien des biotopes d'importance nationale (60 à 90 % des frais) et régionale et locale (jusqu'à 50% des frais) est précisé dans l'article 18d de la loi sur la protection de la nature et du paysage.

D'autres contraintes sont impliquées par d'autres normes fédérales (notamment les directives de l'OFEG parues en 2000) :

- loi fédérale sur l'aménagement du territoire (RS 700). Au niveau cantonal, la planification de l'aménagement des cours d'eau est partie intégrante du plan directeur et du plan d'affectation, elle doit s'accorder aux exigences territoriales revendiquées dans d'autres domaines dans le cadre d'une pesée d'intérêt.
- loi fédérale sur la pêche (RS 923.0). Toute intervention touchant aux cours d'eau nécessite une autorisation relevant du droit de la pêche
- loi fédérale sur les forêts (RS 921.0) La loi prévoit une interdiction de principe des défrichements. Des dérogations à ce sujet ne sont accordées qu'à des conditions très restrictives.
- loi fédérale sur la protection de l'environnement (RS 814.01). Le principe de précaution prévu par la loi se manifeste dans l'étude d'impact sur l'environnement (EIE) ; cette étude doit être entreprise en cas de mesures d'aménagement de cours d'eau importantes.
- loi fédérale sur la chasse et la protection des mammifères et oiseaux sauvages (RS 922.0). Lors de projets d'aménagements susceptibles de porter atteinte aux réserves de sauvagines et d'oiseaux migrateurs, une prise de position de l'office compétent (OFEFP) est requise.
- loi sur l'agriculture (RS 910.1) définit les conditions requises pour recevoir des paiements directs écologiques (Art. 76).
- loi sur la protection de la nature (RS 451) accorde un statut spécial aux zones alluviales d'importance nationale et demande des mesures de compensation ou de remise en état lorsque des interventions s'avèrent inévitables.



CARTOGRAPHIE DES ZONES ALLUVIALES D'IMPORTANCE NATIONALE

CARTE DE LA VÉGÉTATION

66 Les Auges de Neirivue

Canton: FR Altitude: 750 m/M

Echelle: 1:10 000

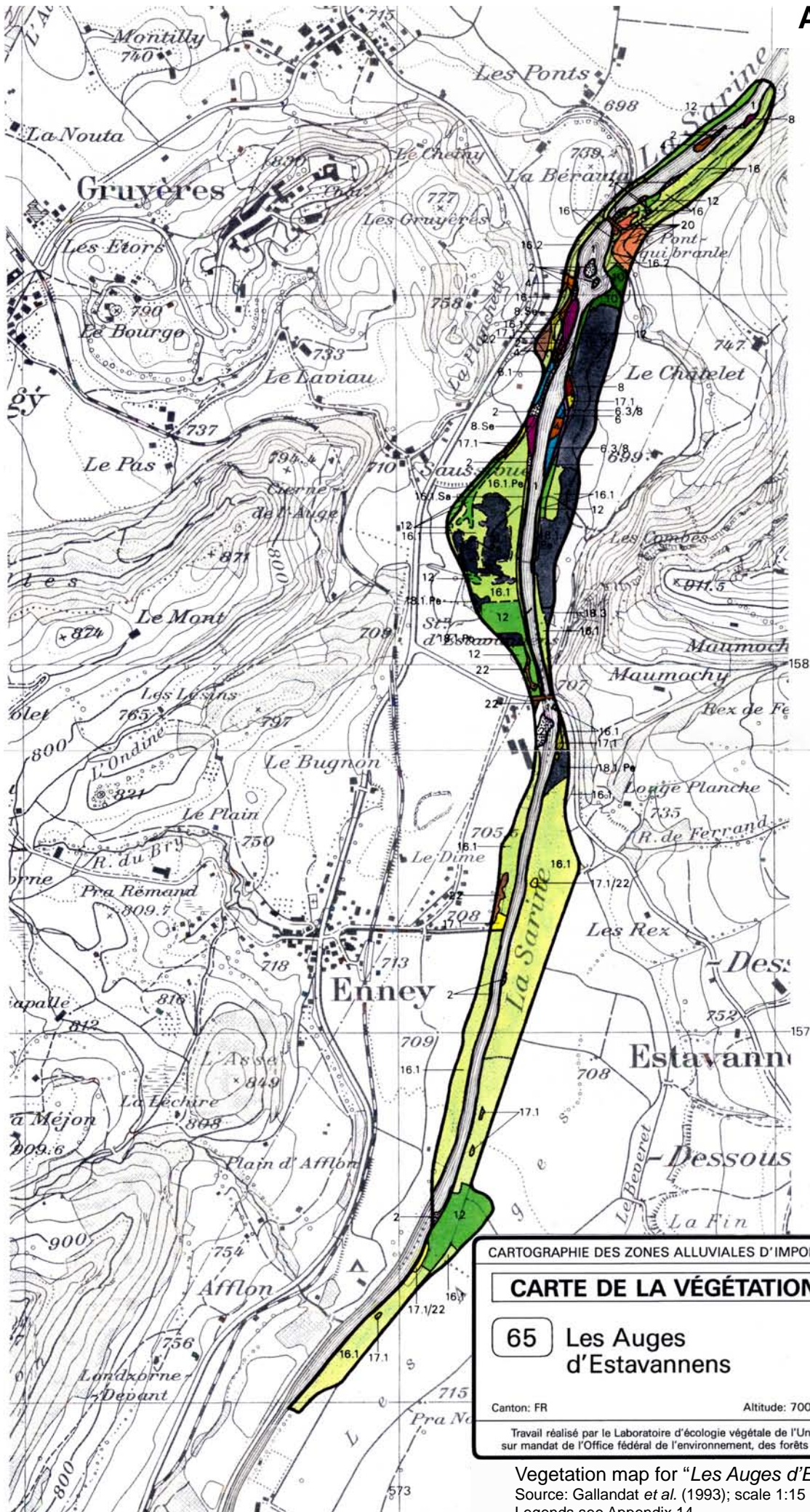
Surface: 78 ha

Date: Août 1988

Auteurs: P. Grosvernier, A. Perrenoud

Travail réalisé par le Laboratoire d'écologie végétale de l'Université de Neuchâtel sur mandat de l'Office fédéral de l'environnement, des forêts et du paysage (OFEFP)

Vegetation map for "Les Auges de Neirivue"
 Source: Gallandat et al. (1993); scale 1:15 000
 Legends see Appendix 14

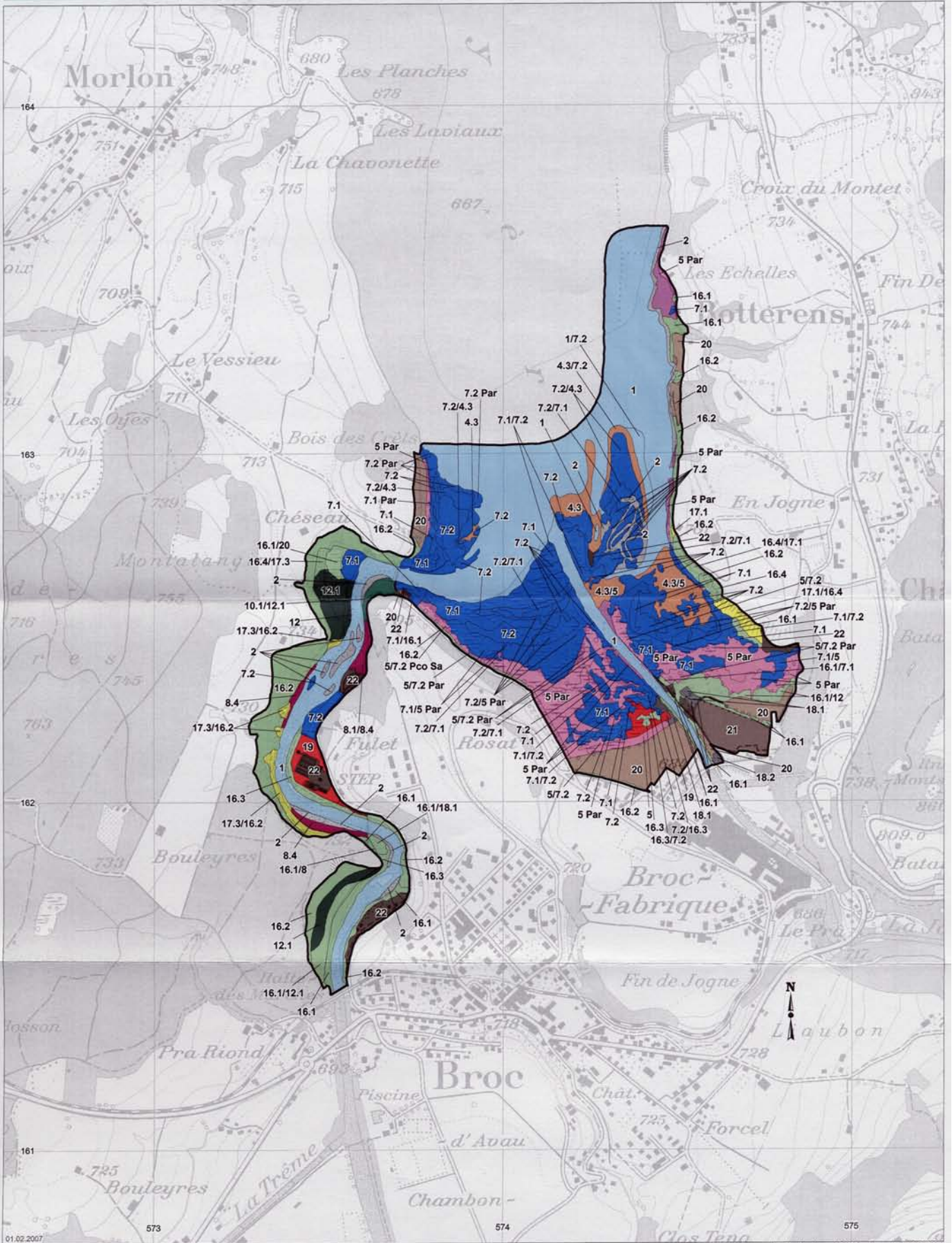


CARTOGRAPHIE DES ZONES ALLUVIALES D'IMPORTANCE NATIONALE	
CARTE DE LA VÉGÉTATION	
65	Les Auges d'Estavannens
Canton: FR	Altitude: 700 m/M
Travail réalisé par le Laboratoire d'écologie végétale de l'Université de Neuchâtel sur mandat de l'Office fédéral de l'environnement, des forêts et du paysage (OFEFP)	

Echelle: 1:10 000
Surface: 50 ha
Date: Août 1988
Auteurs: P. Grosvernier, A. Perrenoud

Vegetation map for "Les Auges d'Estavannens"
 Source: Gallandat et al. (1993); scale 1:15 000
 Legends see Appendix 14

Echelle 1:10'000 Etat cartographié: Septembre 1998 (Terrain) Photos aériennes: Juillet 1997



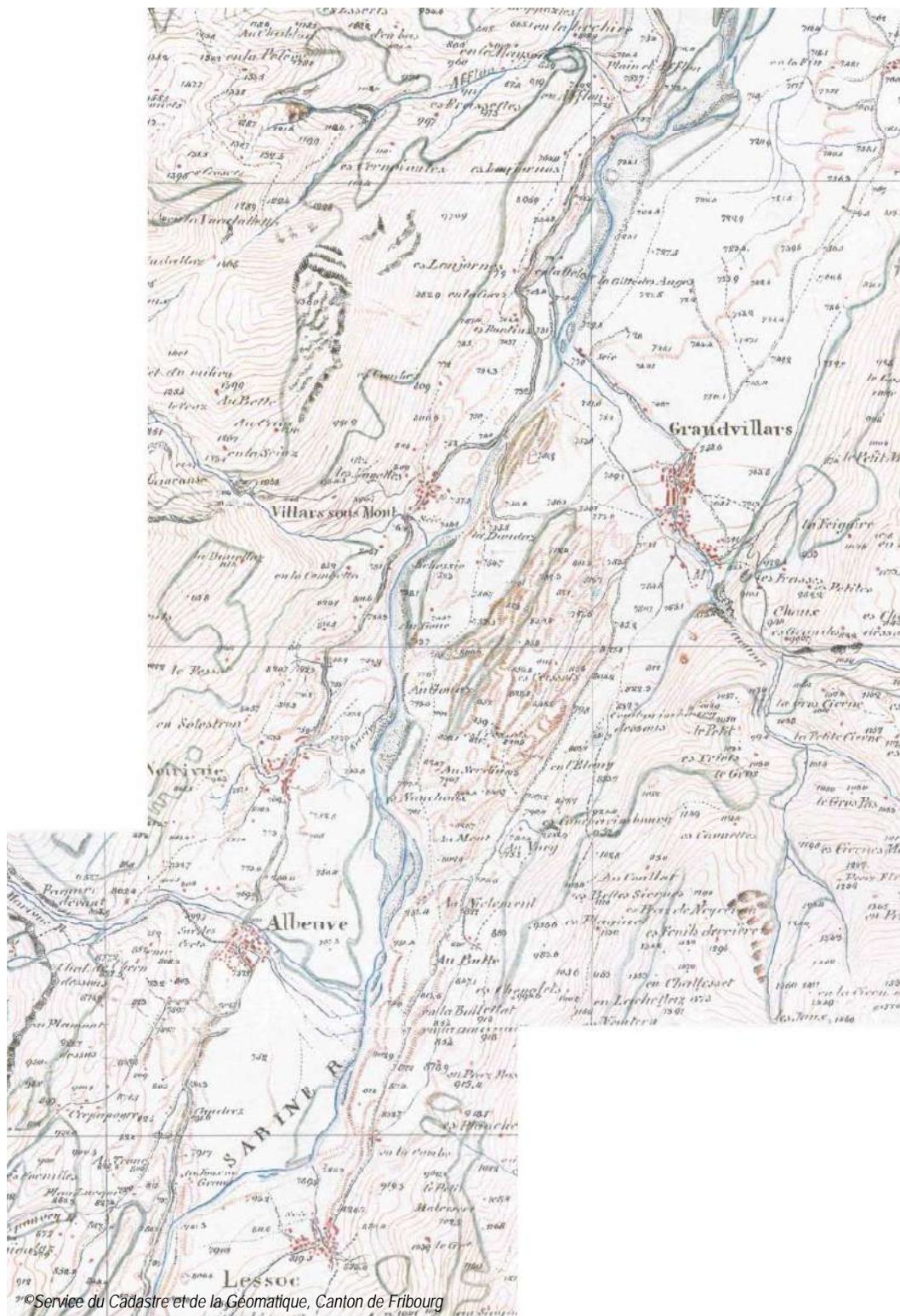
01.02.2007 573 574 575 PK25, reproduit avec l'autorisation de Swisstopo (BA067794)

Surface: 91.9 ha Altitude: 670 m/M Auteur: A. Perrenoud
sur mandat de
Office fédéral de l'environnement (OFEV)

Vegetation map for "Broc"
Source: Thielen et al. (2002); scale 1:15 000
Legends see Appendix 14

Réalisation
Service conseil Zones alluviales

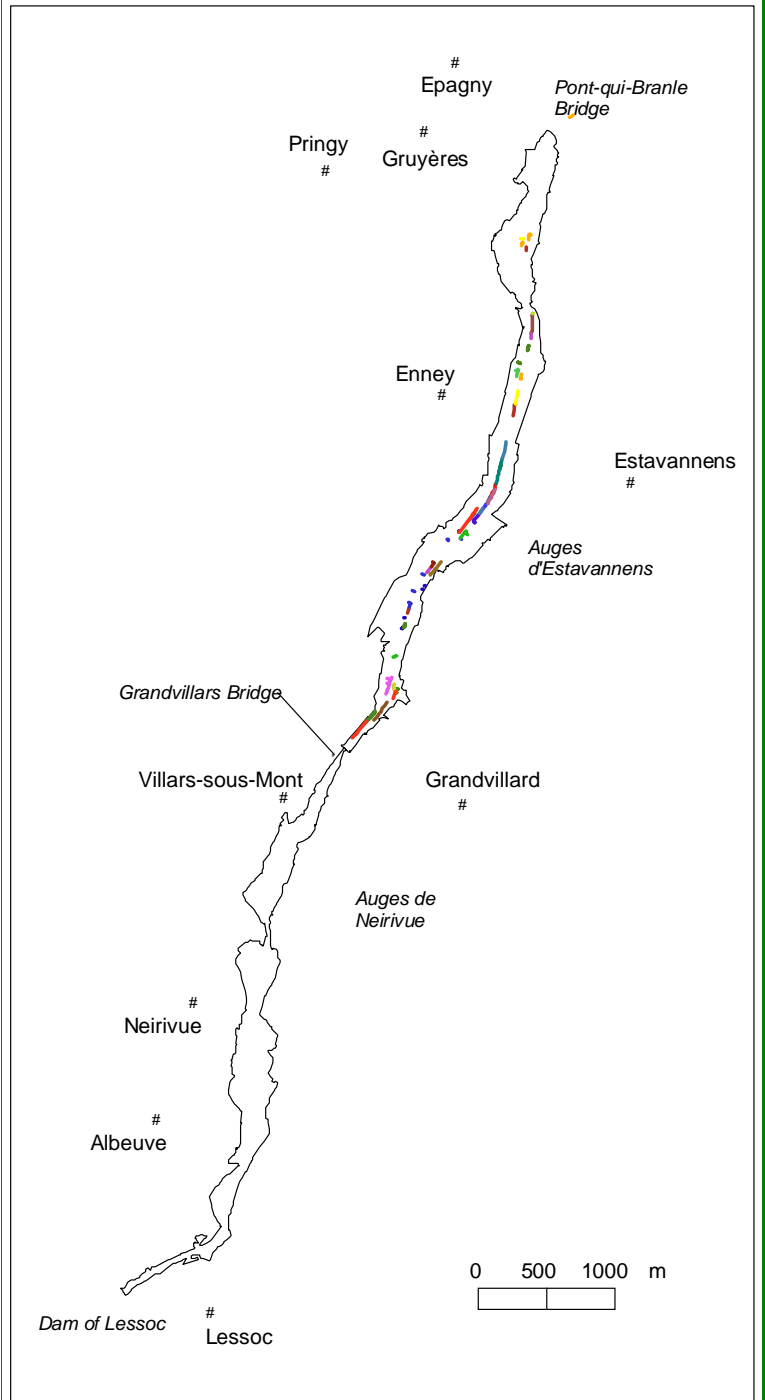
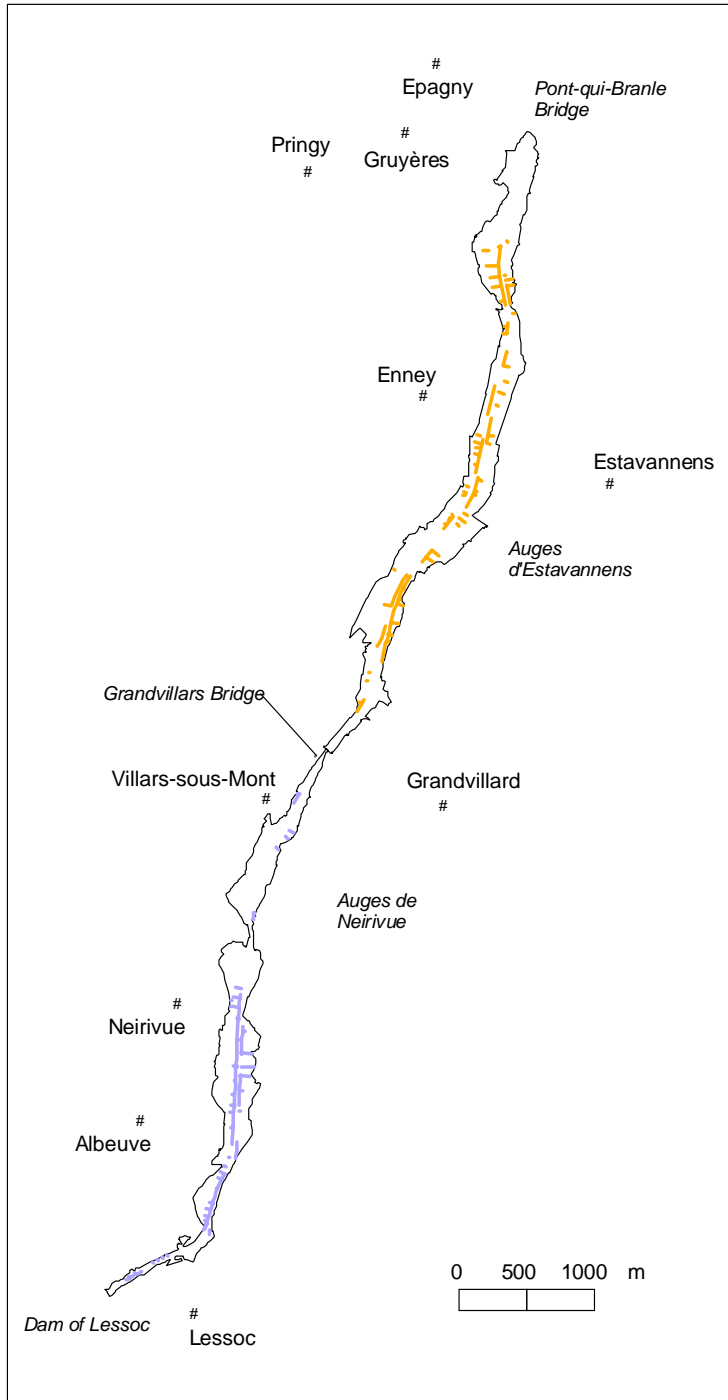
STRIENSKY MAP


























Extract of the map of the canton of Fribourg, drawn by Alexander Strienksy between 1844 and 1851.

Source: Dupertuis (2005)

EMBANKMENTS



 Dignes 1930
 1917-1938

 1948	 1957-1958	 1958-1959
 1947	 1955-1956	 1958-1961
 1946	 1954-1955	 1964-1965
 1945	 1954	 1963-1964
 1942	 1953	 1962-1963
 1941	 1952	 1961-1962
 1940	 1951	 1960-1961
 1939	 1949	 1959-1960

Plans of the embankments achieved in the study site from 1917 to 1965

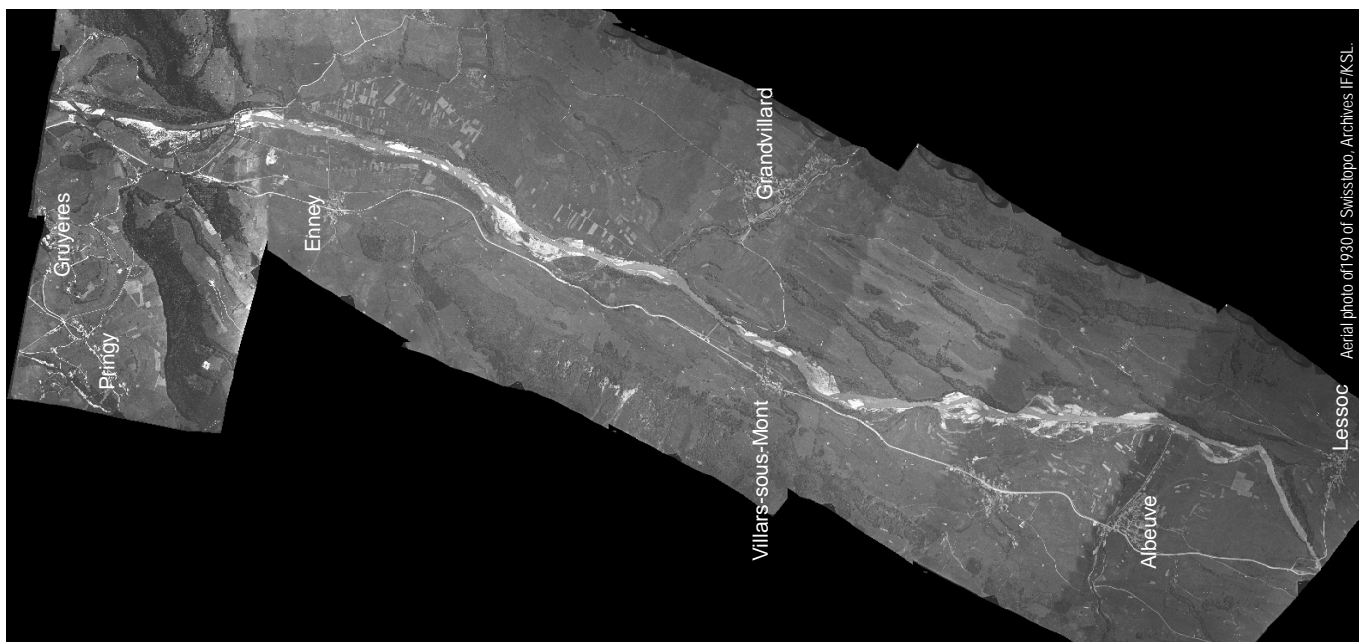
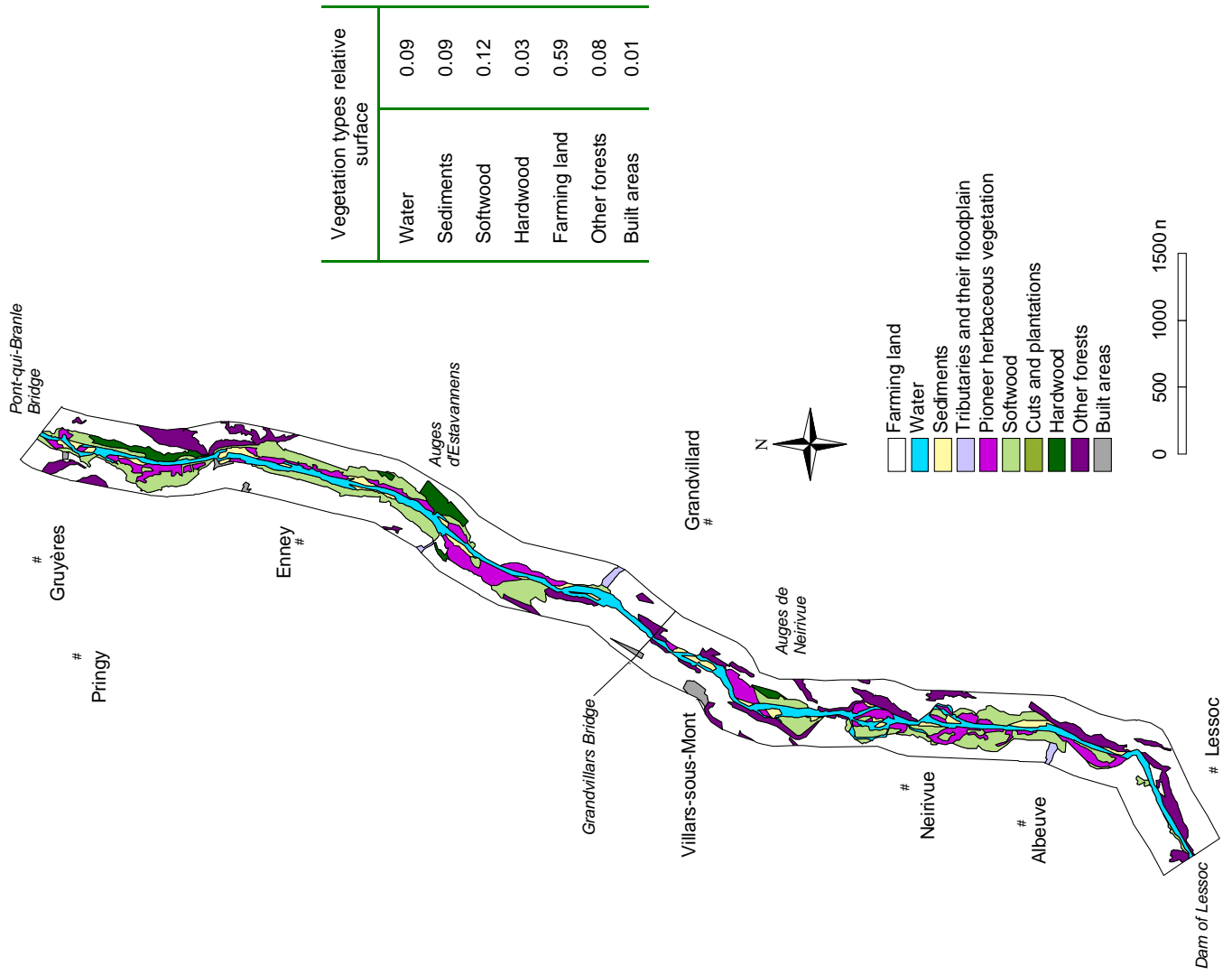
Source: Dupertuis (2005)

CLEARANCES



Aerial photo of 1998 of Swissstop Archives IF/KSL.

1930

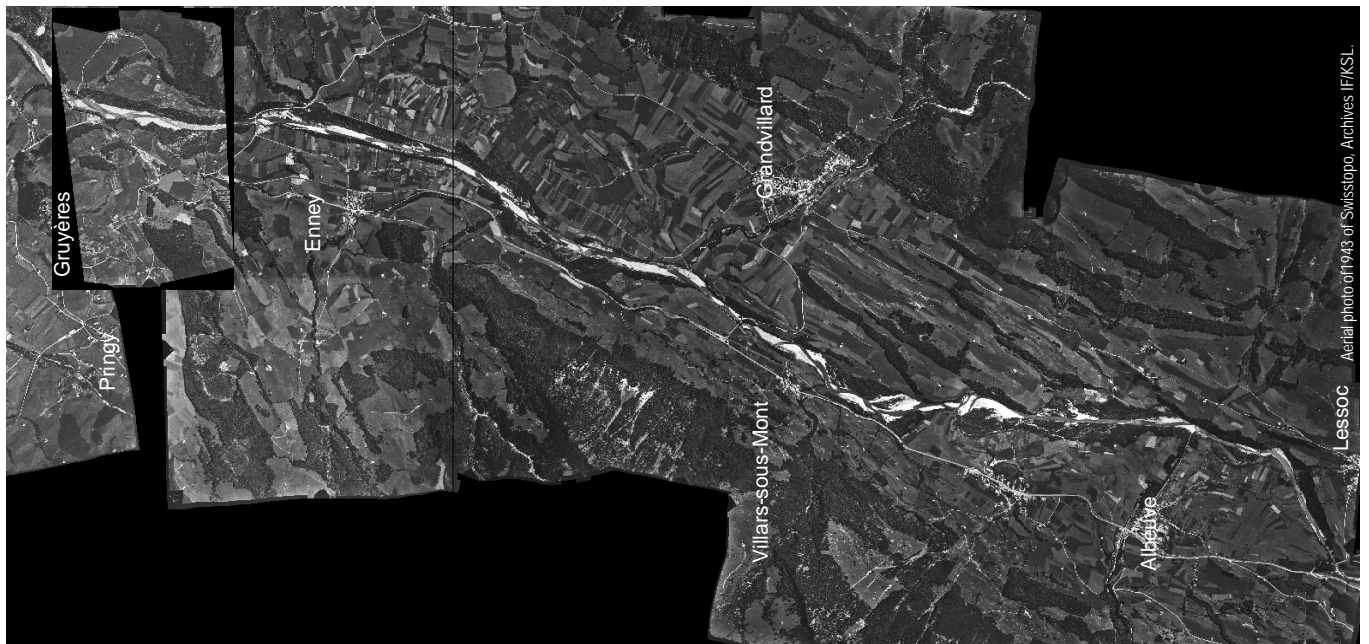


Vegetation map

Aerial photo

Source: Dupertuis (2005)

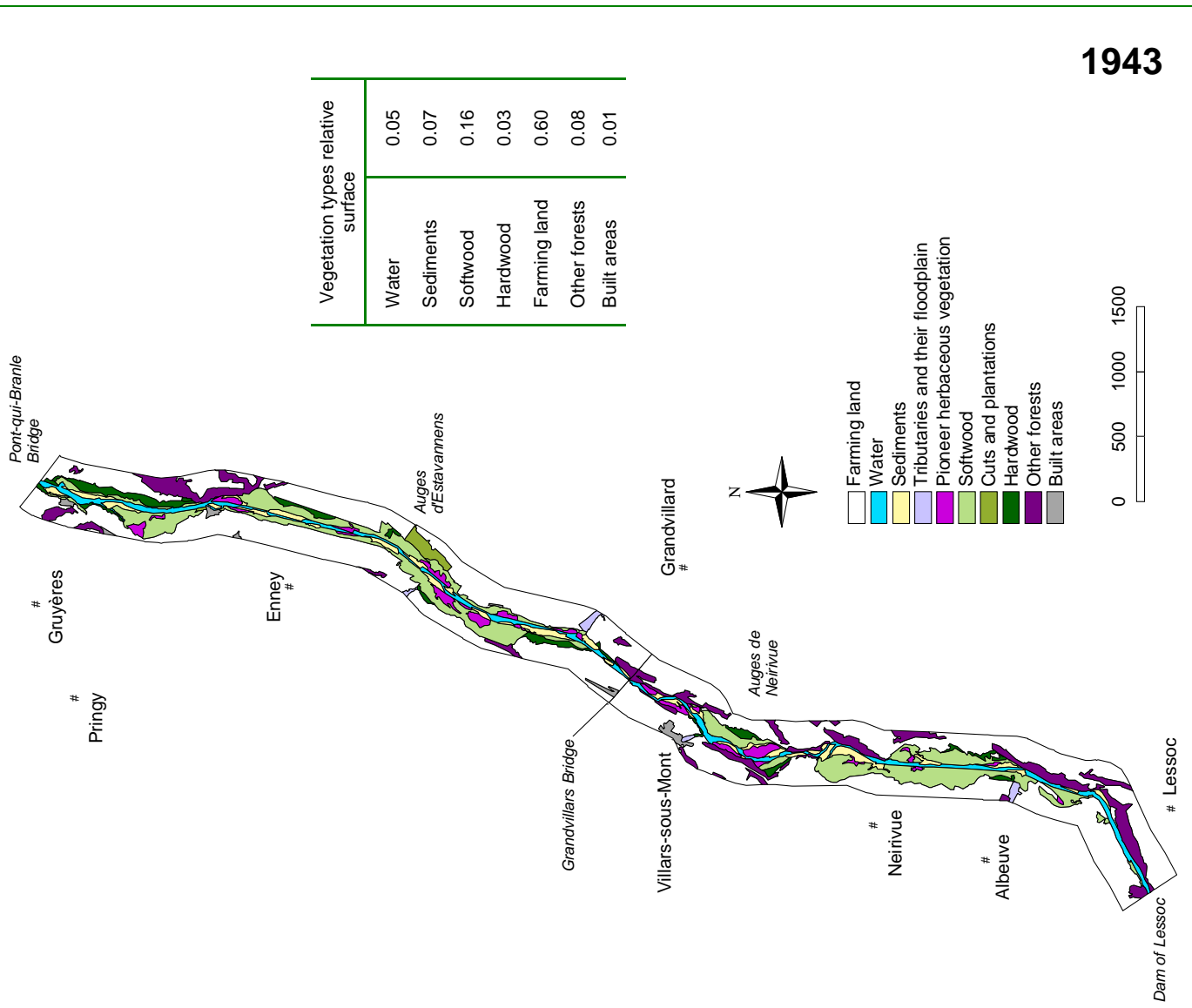
Aerial photo of 1930 of Swiss topo. Archives IFKSL



Aerial photo of 1943 of SwissTopo. Archives IF/KSL.

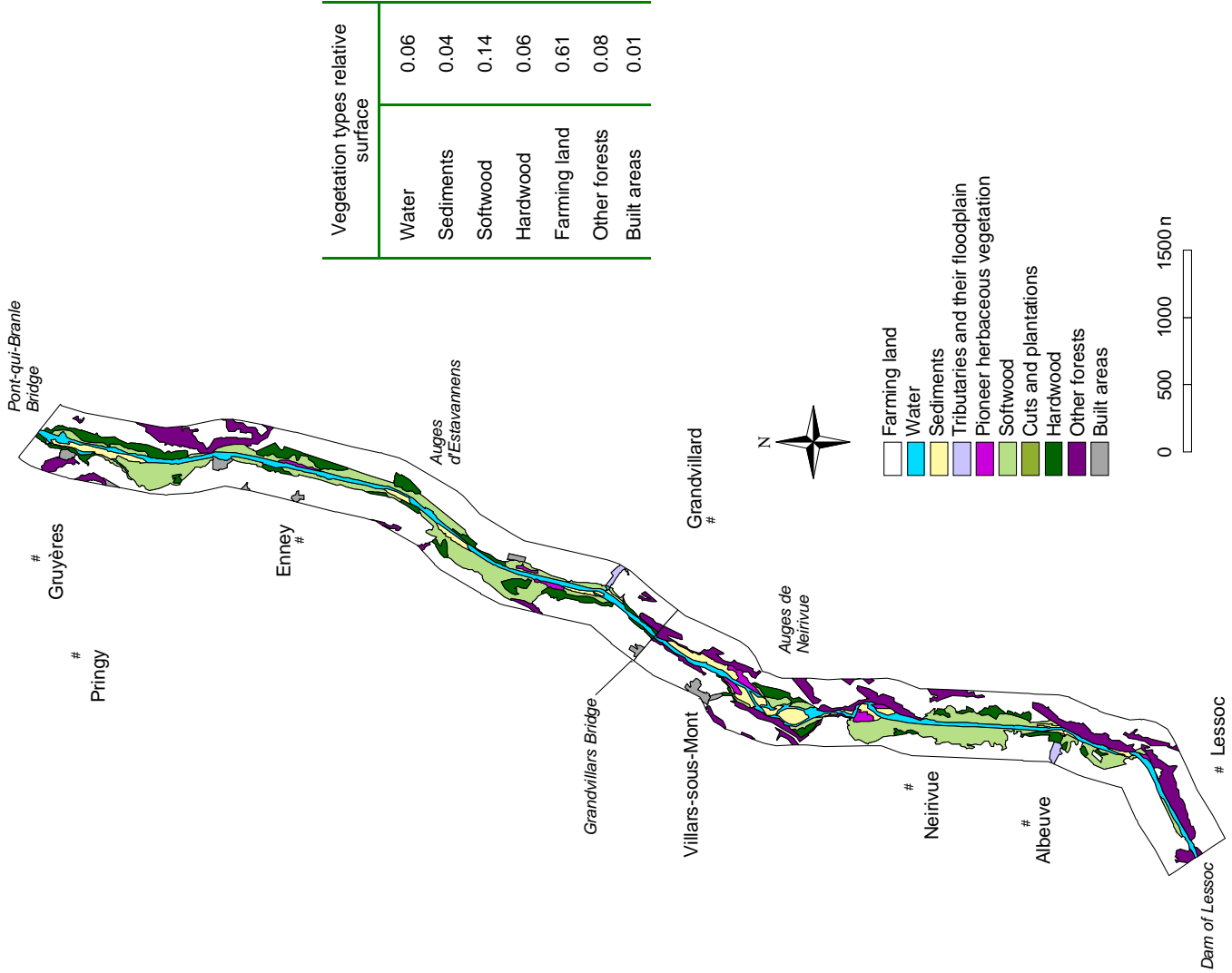
Aerial photo

Source: Dupertuis (2005)

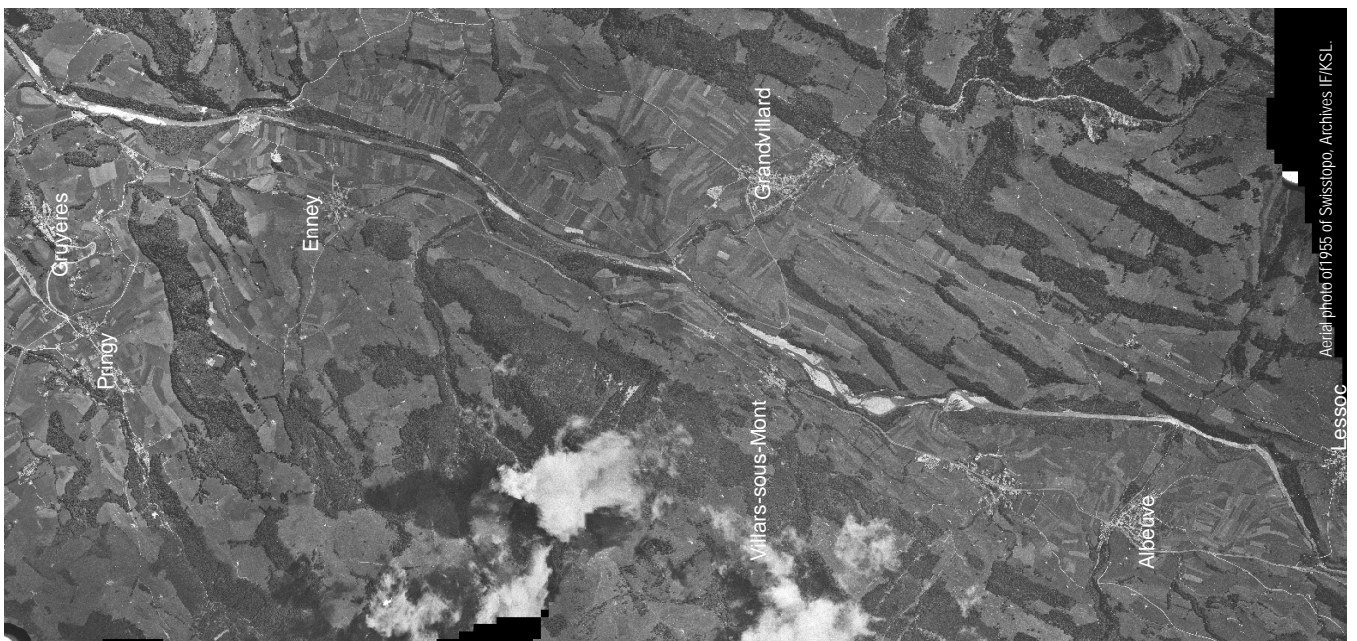


Vegetation map

1955



Vegetation map



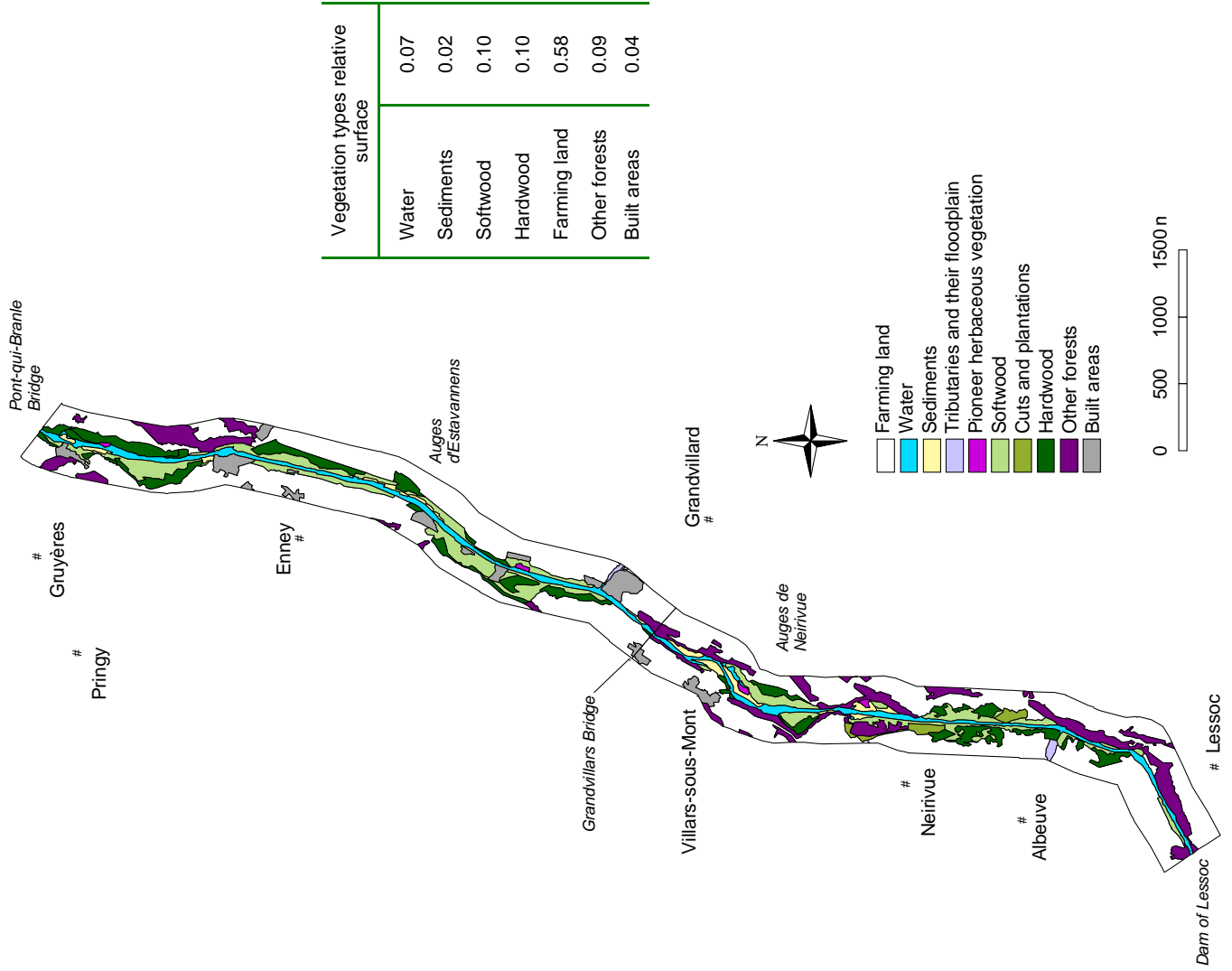
Aerial photo

Source: Dupertuis (2005)

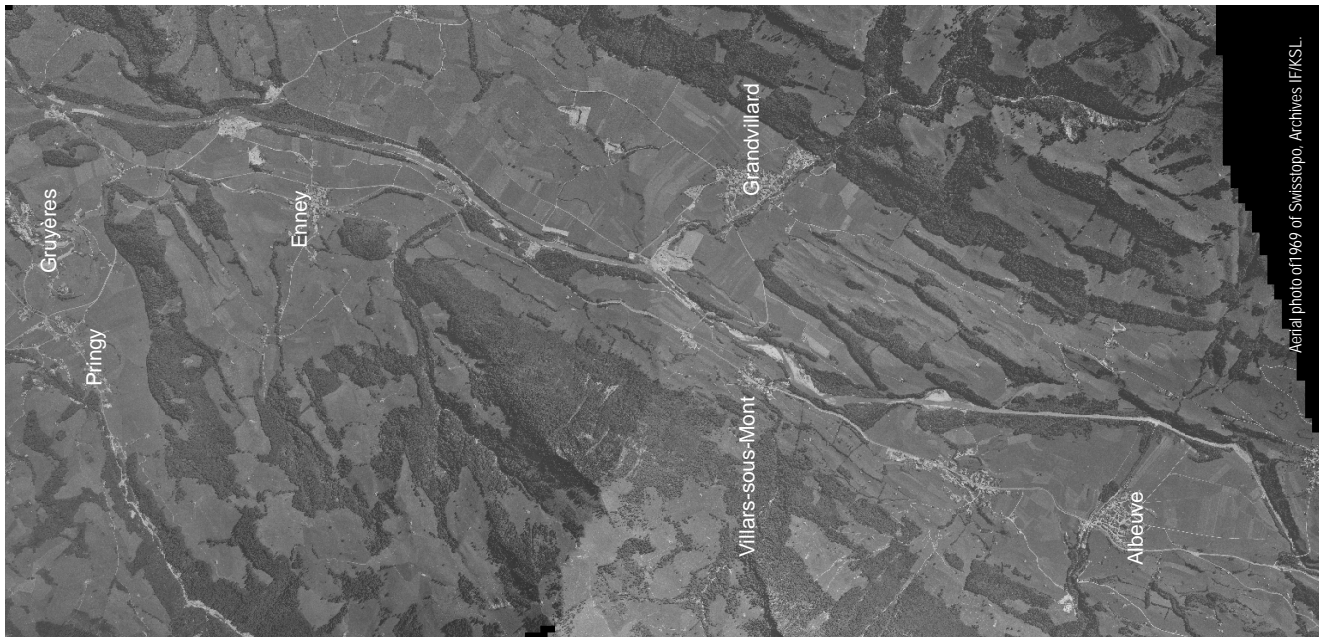
Aerial photo of 1955 of Swissstopo, Archives IF/KSL

LESSOC

1969

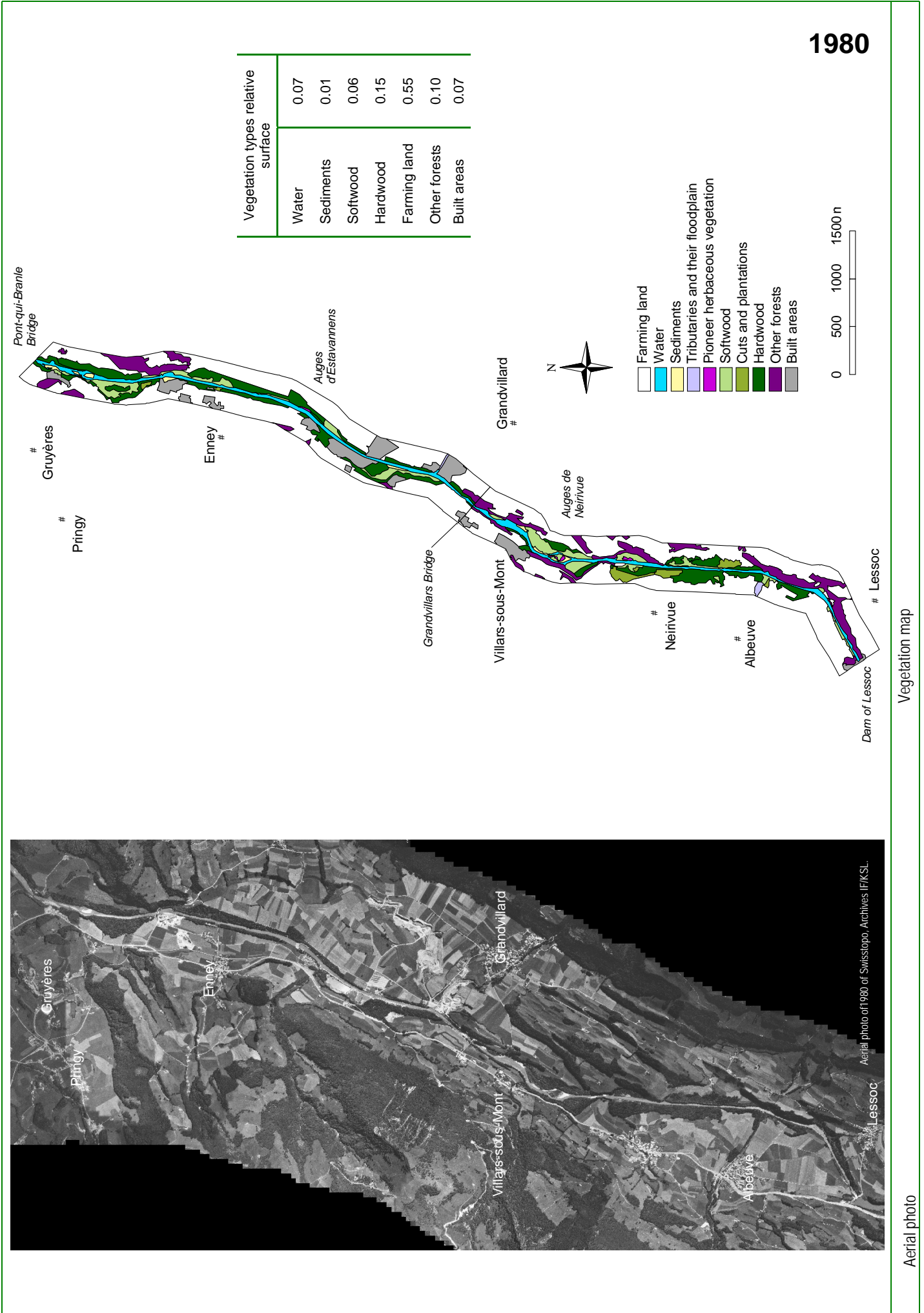


Vegetation map



Aerial photo

Source: Dupertuis (2005)

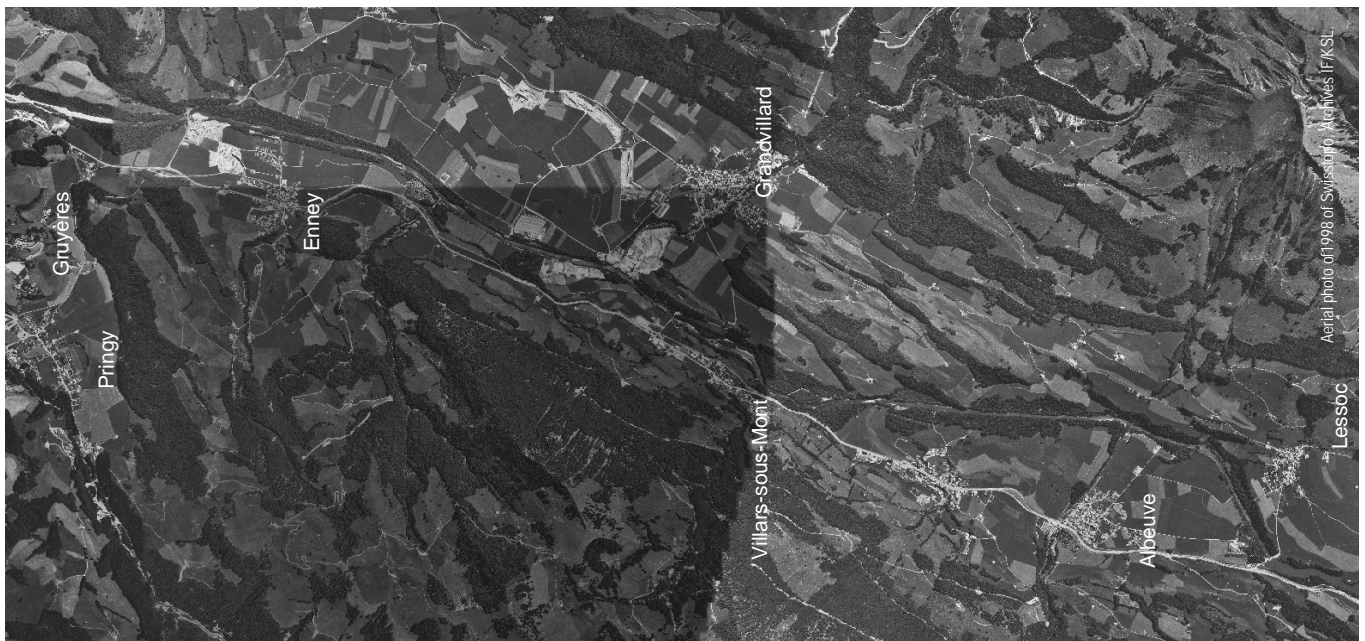
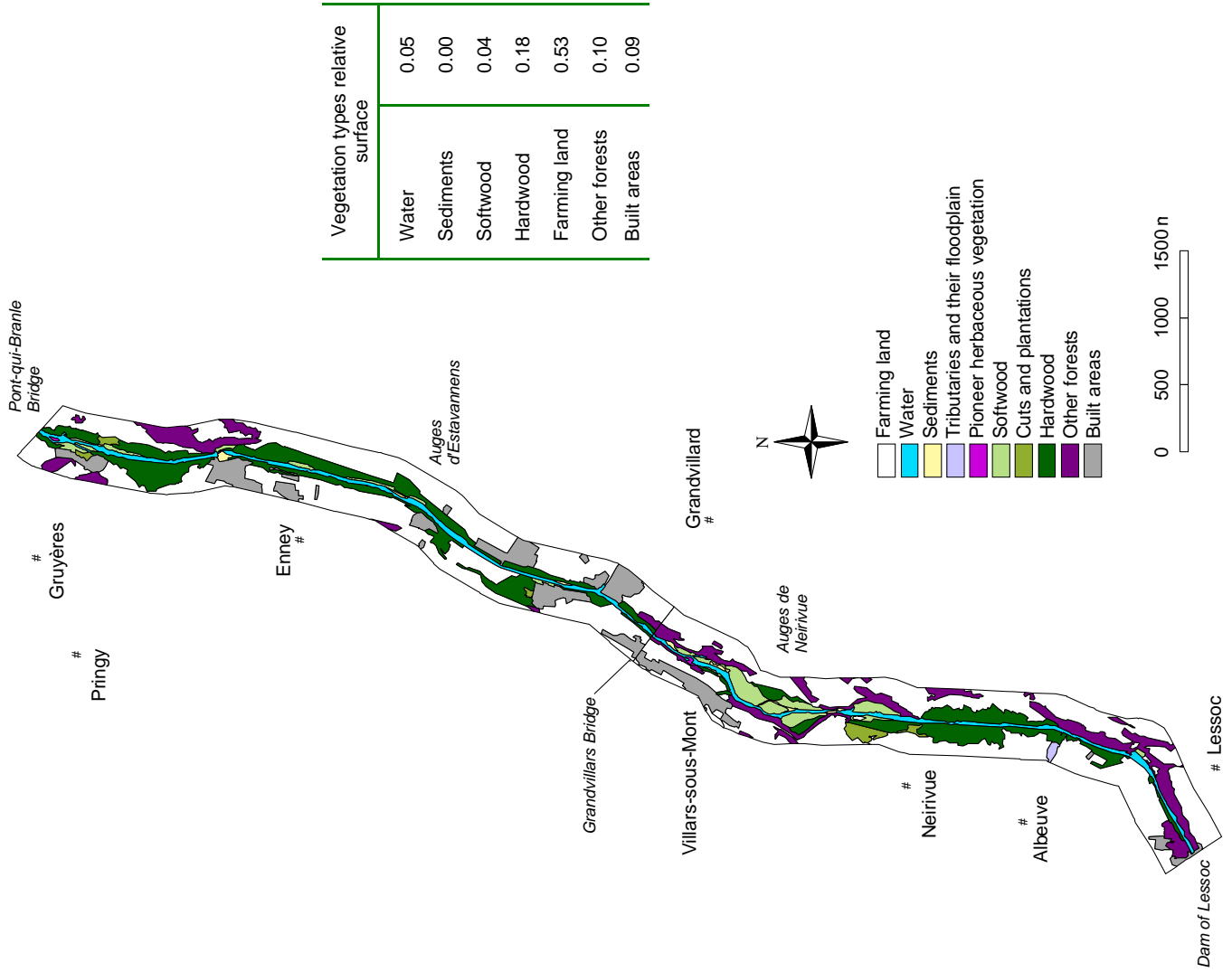


Vegetation map

Aerial photo

Source: Dupertuis (2005)

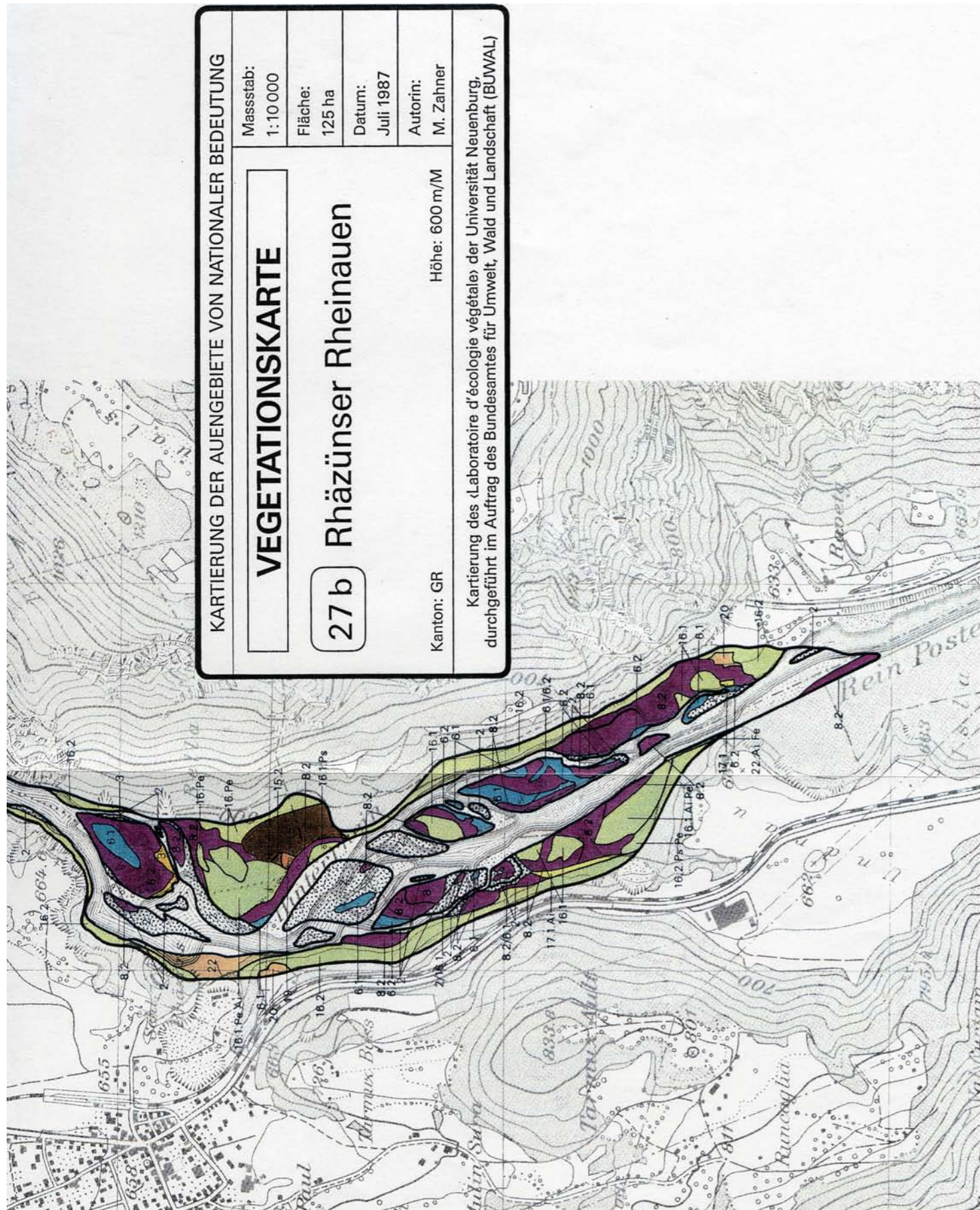
1998



Vegetation map

Aerial photo

Source: Dupertuis (2005)



Vegetation map for "Rhäzünser Rheinauen"
 Source: Gallandat et al. (1993); scale 1:13 000

CARTOGRAPHIE DES ZONES ALLUVIALES D'IMPORTANCE NATIONALE

Légende de la carte de la végétation

- | | |
|---|---|
| <ul style="list-style-type: none"> 1. Eau 2. Sédiments nus 3. Végétation herbacée pionnière d'altitude <ul style="list-style-type: none"> 3.1 Végétation pionnière des alluvions graveleuses grossières (<i>Epilobion fleischeri</i>) 3.2 Végétation pionnière des alluvions graveleuses fines (<i>Caricion atrofusco-saxatilis</i>) 4. Végétation herbacée pionnière de plaine <ul style="list-style-type: none"> 4.1 Végétation de hautes herbes nitrophiles (<i>Artemisietea vulgaris</i>) 4.2 Végétation piétinée (<i>Polygono-Poetea annuae</i>) 4.3 Végétation d'annuelles nitrophiles (<i>Bidentetea tripartitae</i>) 5. Bas-Marais 6. Fourrés et manteaux de saules d'altitude <ul style="list-style-type: none"> 6.1 Fourrés de saule drapé (<i>Salicetum elaeagno-daphnoidis</i>) 6.3 Variante eutrophe 6.2 Manteau à myricaire (<i>Salici-Myricarietum</i>) 6.4 Fourrés ouverts de saule drapé à espèces thermophiles (steppe) 6.5 Fourrés de saules des altitudes supérieures 7. Fourrés, manteaux et forêts de saules de plaine <ul style="list-style-type: none"> 7.1 Forêt de saule blanc (<i>Salicetum albo-fragilis</i>) 7.3 Variante appauvrie 7.2 Manteau à osier blanc (<i>Salicetum triandro-viminalis</i>) 7.4 Groupement arbustif à saule cendré 8. Forêts d'aulne blanc et manteaux <ul style="list-style-type: none"> 8.1 Forêt d'aulne blanc de plaine (<i>Equiseto-Alnetum incanae</i>) 8.3 Variante appauvrie 8.6 Manteau à viorne obier (<i>Salici-Viburnetum</i>) 8.2 Forêt d'aulne blanc d'altitude (<i>Calamagrostio-Alnetum incanae</i>) 8.4 Variante eutrophe 8.7 Manteau à saule noirissant (<i>Salicetum alpicolae</i>) 8.5 Forêt d'aulne blanc à saule drapé 9. Forêts d'aulne noir 10. Forêts de frêne et manteaux des substrats grossiers <ul style="list-style-type: none"> 10.1 Forêt de frêne et d'orme (<i>Ulmo-Fraxinetum</i>) 10.2 Variante sèche 10.3 Manteau à noisetier (<i>Pado-Coryletum</i>) 11. Forêts de frêne des substrats fins <ul style="list-style-type: none"> 11.1 Forêt de frêne et d'aulne noir (<i>Carici remotae-Fraxinetum</i> et <i>Pruno-Fraxinetum</i>) 11.2 Variante appauvrie 11.3 Variante sèche 12. Ripisylves de transition de rivière <ul style="list-style-type: none"> 12.1 Ripisylve de transition de la forêt de frêne et d'orme 12.3 Ripisylve de transition de la forêt d'aulne blanc 12.4 Ripisylve de transition à saule drapé 13. Ripisylves de transition de lac et de cours d'eau lents <ul style="list-style-type: none"> 13.1 Forêt de frêne 13.2 Ripisylve de transition de la forêt d'aulne blanc 14. Forêts de chêne | <ul style="list-style-type: none"> 15. Forêts de pin sylvestre et manteaux <ul style="list-style-type: none"> 15.1 Forêt de pin sylvestre 15.2 Manteau à épine-vinette (<i>Hippophao-Berberidetum</i>) 15.3 Forêt de pin sylvestre à pyrole (<i>Pyrolo-Pinetum</i>) 16. Autres forêts, manteaux et groupements arbustifs <ul style="list-style-type: none"> 16.1 Forêts et manteaux de la zone alluviale à statut indéterminé 16.2 Forêts et manteaux non alluviaux 16.3 Groupements arbustifs et manteaux alluviaux 16.4 Groupements arbustifs et manteaux non alluviaux 17. Autres Groupements <ul style="list-style-type: none"> 17.1 Autres groupements herbacés 17.2 Végétation herbacée alpine 17.3 Rochers et éboulis 18. Sylviculture intensive <ul style="list-style-type: none"> 18.1 Plantation en zone alluviale 18.2 Plantation en zone non alluviale 18.3 Coupe forestière en zone alluviale 18.4 Coupe forestière en zone non alluviale 19. Prairies maigres 20. Prairies grasses 21. Cultures 22. Sites construits, végétation artificielle |
|---|---|
-
- | | |
|---------|---|
| — | Limite de l'objet |
| — | Limite de l'eau |
| — | Limite de la végétation |
| - - - | Limite imprécise de la végétation |
| - · - · | Coupure artificielle dans la végétation |
| — | Chemin de fer |
-
- Conventions (illustrées par des exemples):
- 8.Se Forêt d'aulne blanc; strate arborescente dominée par *Salix elaeagnos*
 - 8/18 Mélange ou mosaïque
 - 18.Fe Plantation de *Fraxinus excelsior*
-
- Abréviations
- | | |
|-----|-----------------------------|
| Ag | <i>Alnus glutinosa</i> |
| Ai | <i>Alnus incana</i> |
| Fe | <i>Fraxinus excelsior</i> |
| Ld | <i>Larix decidua</i> |
| Pe | <i>Picea excelsa</i> |
| Po | <i>Populus sp.</i> |
| Ps | <i>Pinus silvestris</i> |
| Sa | <i>Salix alba</i> |
| Sc | <i>Salix cinerea</i> |
| Se | <i>Salix elaeagnos</i> |
| Par | <i>Phalaris arundinacea</i> |
| Pco | <i>Phragmites communis</i> |
| Phy | <i>Petasites hybridus</i> |

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Identification of facies models in alluvial soil formation: The case of a Swiss alpine floodplain

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Abstract

This paper describes different conceptual facies models intervening in alluvial soil formation in the case of the Sarine River floodplain, a partially embanked floodplain situated in the northwest of the Swiss Alps. Alluvial soils are submitted to processes of deposition and erosion and exhibit various characteristics reflecting the composition and properties of the material transported. Moreover, these processes of sedimentation and erosion vary in space and time and contribute thus to the heterogeneity of the whole floodplain system. Detailed analyses of the different soil layers permit a precise description of the variability and complexity of soil formation. In addition, the vertical succession of the horizons is useful to reconstruct the different natural or artificial events that occurred in this alluvial valley since the nineteenth century. On a larger scale, this study aims to contribute to floodplain management by identifying zones for restoration. The investigation was undertaken using data from 109 auger borings carried out in the Sarine River valley. Several morphological attributes of the different horizons and of the different profiles were first reduced in number and then grouped by a hierarchical agglomerative clustering. Profile factors were analysed by means of correlation analyses as well as other data summaries. The results showed positive correlations between several factors, particularly between the total profile thickness and the number of horizons found in the profile. Four facies models of alluvial soil formation are then proposed to illustrate and explain the variability of alluvial soil formation in the Sarine floodplain. Finally, these facies models are placed into the context of the Sarine floodplain scale case, according to the levels of organization of the alluvial system. © 2005 Elsevier B.V. All rights reserved.

Keywords: Facies models; Alluvial soil; Soil formation; Hierarchical levels; Floodplain; Switzerland

1. Introduction

Floodplains are ecotones forming a transition between aquatic and terrestrial environments. They are characterized by complex ecological systems and are dynamic spatial mosaics, more or less connected with the active channel of the river. These lateral connections

are essential for the functioning and integrity of a floodplain (Thoms, 2003), and the various landscape patches induce a hierarchical system that can be considered at different levels. Thoms (2003) also reported that many floodplain management strategies often fail to provide scientific knowledge at the appropriate scale. The approach described by Petts and Amoros (1996) is based on the fluvial hydrosystem. This one is defined as an eco-complex forming by different environments that are dependent to a greater or lesser degree on connectivity with the active channel of the river, just like the character of this main channel also depends on interac-

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tions with those environments. In other words, the fluvial hydrosystem may be viewed as a nested hierarchy of subsystems with different levels controlled by different rates and types of processes. Five distinct levels are then described:

- the drainage basin, delineated by a topographic divide (the watershed) that results from geological processes and climatic changes;
- the functional sectors, delimited by changes in valley width and gradient due to different flow, water-quality and sediment regimes draining subbasins of different geological, climatic and biogeographical character;
- the functional sets, defined as sections of typical ecological units associated with specific landforms (e.g. major cutoff meander, aggrading floodplain, main channel);
- functional units, characterized by a typical animal and plant community that is indicative of the habitat conditions at the site that are generally arranged in spatial successions along topographic gradients; and
- the mesohabitats, subdivisions of functional unit that are particularly sensitive to variations of the control variables and may change from year to year.

The integrity of the fluvial hydrosystem depends then on the dynamic interaction between hydrological, geomorphological, and biological processes. The exploration and analysis of the multivariate and spatial data found in these ecological attributes of floodplains are commonly explored by standard methods such as correspondence analysis or clustering and are widely used by ecologists.

In this complex ecological system, alluvial soils are characterized by sediment transport and deposition, as well as by soil formation (Gerrard, 1987), and could be identified at the level of functional units. In fact, these particular sequences evolve from a single origin by progressive changes over time-scales of 10^{-1} to 10^2 years and the processes involved include sedimentation or organic matter accumulation for example (Petts and Amoros, 1996). Thus, this combination of geomorphic and pedologic processes is the main property of alluvial soils providing good elements for the interpretation of past environmental changes (Daniels, 2003). Moreover, alluvial soil morphology varies according to landscape position and overbank lithofacies (Autin and Aslan, 2001), but also from river modifications through time, such as embankments and dam constructions. These geomorphic processes produce a landscape mosaic reflected by abrupt juxtapositions of

soils of different ages and degrees of profile development (McAuliffe, 1994).

Stratification, formed by the alternation of pedological layers and layers with new material, is a particular characteristic of alluvial soils (Gerrard, 1987). New deposition may bury a pre-existing soil and move it away from the zone of active pedogenesis (Daniels, 2003). Alluvial soils are good models to estimate the part of pedogenesis illustrating periods of stability with development of pedogenic features and pedoturbation, representing the overlay of sediments or instability periods (Paton et al., 1995) in high or low energy depositional environments. High energy deposition contains coarse sediment deposited by traction currents, whereas low energy deposition is characterised by fine-grain sediment deposited by suspension settling.

The process of soil cumulization is particularly important in a floodplain context because all floodplains are subject to pedogenesis during the intervals between periods of sediment deposition. These vertical successions of overbank deposits and pedogenic features are defined as paleosols by Kraus and Brown (1988) and are generated by slow and sporadic aggradation and soil modification interrupted by more rapid deposition. Paleosols can be identified as buried soils determined by five groups of soil-forming factors: climate, organisms (including man), relief, parent material, and time (Bronger and Catt, 1998). They can also be regarded as polygenetic soils if they contain features formed during two or more periods of different environmental conditions and they demonstrate moreover an inverse relationship between soil maturity and sediment accumulation. But, paleosols are not restricted to alluvial context, so the term *pedofacies* is mainly preferred in order to delimit the lateral changes of adjacent packages of sedimentation rock when they vary in their ancient soil properties as a function of their distance from areas of relatively high sediment accumulation (Kraus and Brown, 1988). According to these last authors, the concept of pedogenic maturity is used to infer sediment accumulation rates at different locations in ancient floodplain environments: weak soil development is assumed where sedimentation rates are rapid and strong development is presumed where sediment accumulation is slow. In a semiarid cut-and-fill floodplain context, Daniels (2003) defined three alluvial pedofacies. These three identical soils are shown to have developed different pedogenic features through time as a result of different aggradation rates. Daniels (2003) also defined A horizons as soil-stratigraphic markers and indicators of relative aggradation rates. Thus, identification of the different horizons present

in a soil, reflecting different aggradation phenomena due to floods or development of a weak soil structure, seems to be the ideal level approach to describe precisely the variability and complexity of the alluvial soil profiles. The conceptual models of facies may then be adapted and used in other floodplain context, such as embanked zones. In these particular damaged systems, the lateral connectivity is broken resulting in a quasi complete isolation of the river from its floodplain and in a suspension of aggradation. Embanked river floodplain deposits are lithologically and sedimentologically different from natural (not human-influenced) floodplain deposits and only pedogenic characteristics are then observed in the subsurface of paleosols.

Using the concept of pedofacies defined by Kraus and Brown (1988) on the basis of differences in paleosol development, this study aims to develop a similar hierarchy—or similar facies models—including the lateral and vertical changes of soil development at different spatial and temporal scales in the case of the embanked Sarine River floodplain. As embanked rivers represent a large part of the actual floodplain cases, at least in Europe, a better comprehension of the aggradation and soil formation processes in the soils that are now disconnected from the current flow, as well as a better knowledge of their spatial distribution along the riparian corridor, is highly relevant to understand the global functioning of the Sarine River floodplain. In order to undertake a detailed examination of these properties, the vertical succession of the horizons (as defined by Gerrard, 2000), presenting pedogenic features or consisting of overbank sediments, were used to describe the stratification of different alluvial soils at functional set and unit levels according to Petts and Amoros (1996). As these different sequences could be related to the concepts primarily used in ecological research (fluvial hydrosystem), analysis commonly used in ecology is appropriate in our context of pedology and geomorphology. Results from this research, giving abstract categories and statistical abstractions of soil properties, are then employed to establish modified simple conceptual models of alluvial soil formation used for describing in a rapid, simple, and inexpensive way the soils of the Sarine floodplain. These methods are then compared with other soil classifications or soil survey methods practiced in pedology. Simple indicators, mainly horizon and soil profiles parameters (e.g., thickness of horizons, soil texture as defined in field; Gobat et al., 2004), were used in order to identify the different mechanisms for floodplain soil formation and to understand the landscape evolution of an alpine floodplain altered by human activity.

2. Materials and methods

2.1. Study area description

The Sarine River is situated in the NW of the Swiss Alps (canton Fribourg) and is a tributary of the Aare River, which flows into the Rhine River (Fig. 1). The length of the study section is 12 km between Lessoc (770 m) and the Gruyère Lake near Broc (670 m) with an average slope of 0.0006 m m^{-1} . The hydrological regime is an intermediate nival regime with a maximum flow in spring and a minimum flow in January. The catchment area covers 639 km^2 with an average altitude of 1520 m. From 1972 to 2001, the maximum annual peak discharge was $400 \text{ m}^3/\text{s}$ in 1974, and the mean annual discharge was $217 \text{ m}^3/\text{s}$.

The geomorphology of the section is characterized by a succession of alluvial basins separated by rocky constrictions, and the deposits are calcareous (Mendonça Santos et al., 1997). But some geomorphological particularities are observed. For example, the sites 1 and 2 (see (A) in Fig. 1) were formed, before the construction of the Rossens dam and the formation of the Gruyère Lake in 1948, of gravel bars colonized by pioneer annual herb communities or willow shrubs that covered the entire base bed of that part of the valley. Nowadays, and despite an artificial origin, this area is characterized by a dynamic system of slow velocity river and lake environments with slow sedimentation. Site 3 was considered before the embankments as a “lake” where regular floods appeared. This section is constituted of flat fields laid on a gravel substrate. About the upstream area, the site 4 (see (C) in Fig. 1) is situated on gravel bars that have been colonized by willow shrubs for about 20 years. Differences in micro-geomorphology are visible inside that site: natural levees and channel fills. The site 5 is also located in a natural environment but colonized by tree population for 20 to 100 years. Micro-geomorphological conditions are also contained inside the site: natural levees, channel fills, active or abandoned channel fills. Site 6 is situated under a mature forest but with different morphological characteristics such as abandoned channel fills and natural levees. Sites 7 and 8 are closed to the river main channel and do not show any particular features. All the sites are situated on the first terrace that is only a few meters above river level (from 50 cm to 2 m) and a distance of few meters to about 100 m from the main river channel. The total thickness above basal gravel varies slightly throughout the study area but these variations should not interfere in the results.

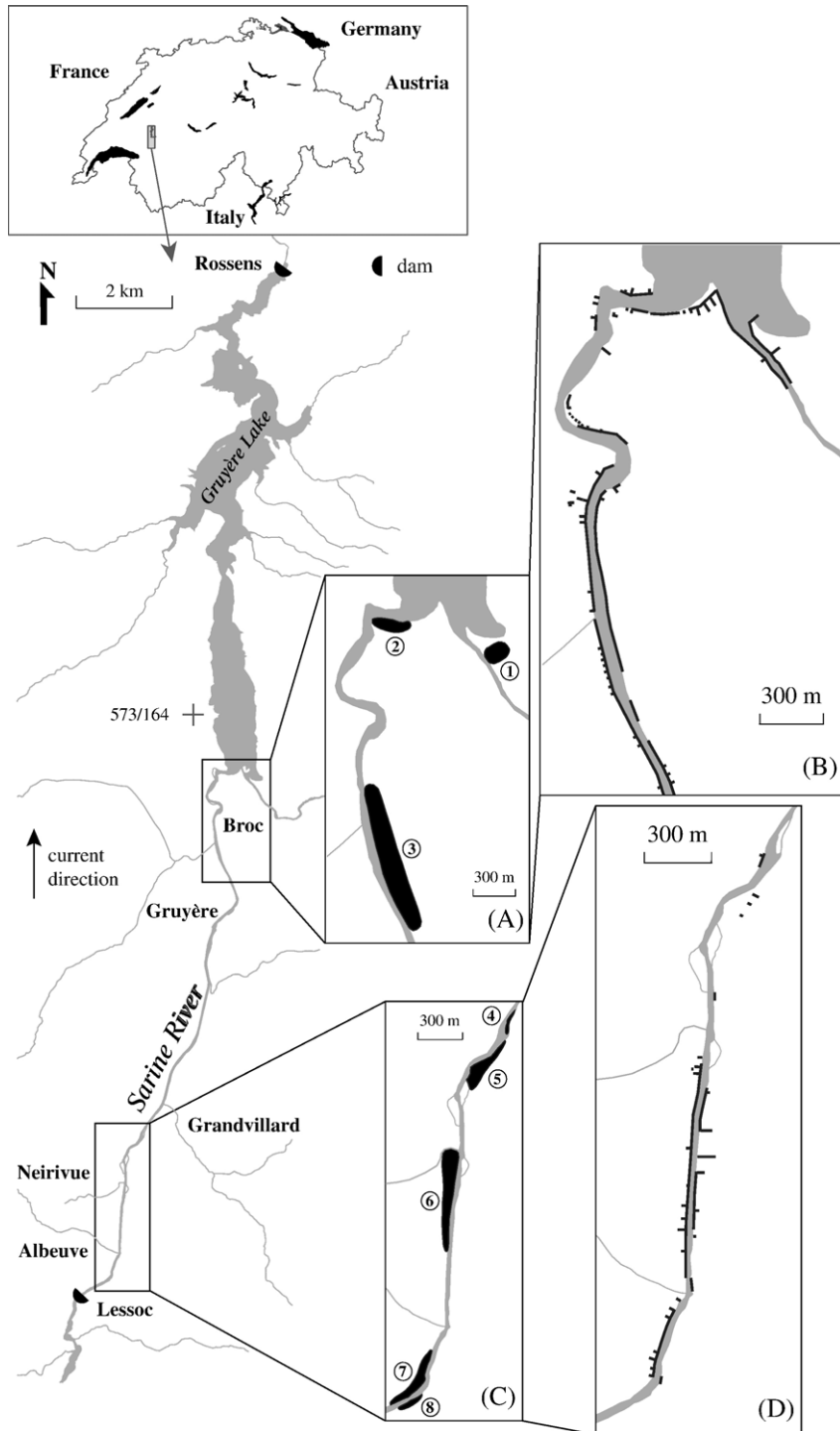


Fig. 1. Localisation of the Sarine floodplain with two major study areas: (A) downstream area with investigated zones in black (sites 1 to 3); (B) location and distribution of embankments throughout the downstream area; (C) upstream area with investigated zones in black (sites 4 to 8); (D) location and distribution of embankments built from 1917 to 1938 (and even to 1974) throughout the upstream area (distribution not exhaustive because of missing archives). Cross: Swiss coordinate system (in km) for orientation.

Historical descriptions revealed that because of the catastrophic flood of 1913, important engineering and regulation works were necessary to strengthen the Sarine riverbanks (Guex et al., 2003). Thus, a general diking and canalisation with one pair of continuous and unsinkable dikes were made to transform the braided channel system to a single uniform channel (Fig. 1). Further embankment projects were undertaken during the twentieth century to reconstruct the damaged structures and to build new structures, but sometimes and particularly in the upstream area (part D) in Fig. 1, the archives miss that makes difficult to recall the real embankment history of the zone. These works progressively caused the modification of the sedimentation–erosion phenomena by interrupting the flooding and disconnected the Sarine River from its floodplain. Moreover, the creation of the Gruyère retention lake in 1948 caused the nearly complete disappearance of a very dynamic floodplain, except for a reduced area close to Broc and a second one upstream near Grandvillard situated in the two major study areas (Fig. 1).

After 1960, two main human activities related to river systems, gravel mining and water retention by dams in the upper catchments, increased the bed incision and the disconnection of the river from its floodplain. Between 1960 and 1976, gravel was removed directly from the riverbed, and the combination of this activity with the sediment retention upstream accelerated the riverbed incision process already initiated by the systematic river embanking.

2.2. Data acquisition

Alluvial soils of the Sarine floodplain were surveyed by a detailed description of the morphology of different core samplings throughout the two major study areas (investigated zones (A) and (C) in Fig. 1). They were identified according to the World Reference Base of Soil Resources (ISSS/ISRIC/FAO, 1998) using soil characteristics, properties and horizons. Soil characteristics, as well as soil properties, were measured in the field and emphasis was on describing the soil texture characteristics of the deposited sediments and the pedogenic layers, but the pedogenic features were also observed. The different layers were called horizons (corresponding to the diagnostic horizons or reference horizons; AFES, 1998), which are three-dimensional bodies more or less parallel to the earth's surface, characterized by one or more properties and a variable thickness. Their succession was named soil profile (or profile), by analogy with soil science concepts, and defined the sequence of information related to a

solum ordered from the land surface downwards (AFES, 1998).

A total of 143 points were surveyed with a pedological auger; and 109 of them, the ones reaching the basal calcareous gravels, were taken into consideration. This limit was chosen because it represents the bottom of the studied system and was considered as almost similar throughout the study area. This sampling technique is commonly used to provide an indication of the soils represented in the field and to describe the soil types, if soil profiles have been previously determined (Cosandey et al., 2003; Earl et al., 2003; Bragato, 2004). This is the case for this site where previous studies have already been published (Bureau et al., 1995; Fierz et al., 1995; Mendonça Santos et al., 2000). The sediment cores were collected from representative locations and identified as being uncultivated and susceptible to regular overbank flooding (forests, active zones), as well as cultivated and disconnected from the river (agricultural and embanked zones). In addition to precise geographical information and short vegetation description, the following characteristics and properties were recorded for each point:

- (i) total thickness of the profile, from top surface to pebble limit (cm);
- (ii) number of horizons found in the profile;
- (iii) depth (cm), thickness (cm), and texture of each horizon; horizon thickness is considered in the case of alluvial soils as a feature that can be linked to the duration and intensity of floods; the texture was identified by hand in the field; a total of 367 horizons were described;
- (iv) presence or absence of oxidation marks, of coarse material (gravel and pebbles >2 mm), and of organic macrorestes in each horizon; and
- (v) soil structure of the topsoil horizon (e.g. particular, granular; Gobat et al., 2004) illustrating the actual development of the soil.

In addition to these descriptive factors, two indexes were calculated for each soil profile, namely the number of horizons per total thickness (named *nb/thick* in Fig. 3) and the number of horizons per meter (*nb/m* in Fig. 3). All these data were introduced into a database to be studied and analysed.

2.3. Statistical analyses

The different attributes describing each horizon and profile were separated for statistical analysis. Horizon attributes were quantitative (depth and thickness), bi-

nary (presence or absence of oxidation marks, coarse material, and macrorestes), and qualitative (field texture). For quantitative analyses, each textural category identified in the field was replaced by an estimated proportion of silt and sand and a binary attribute (presence or absence of fine, medium or coarse sand particles; Table 1). After standardization, these data were grouped by a hierarchical agglomerative clustering by means of Ward's minimum variance clustering with Euclidean distance (Legendre and Legendre, 2000) using ProGiciel R software. As alluvial soils are characterized by stratification of different deposits and show weak horizon differentiation, it was decided that the horizon groups obtained after clustering were used as a categorization of horizons instead of the master horizon nomenclature (e.g. AFES, 1998 or ISSS/ISRIC/FAO, 1998). This permitted to conserve the particular characteristics of each horizon, particularly the texture, the depth and the thickness, that would be lost with other classifications.

The same hierarchical agglomerative clustering was applied to the different profile attributes, which are quantitative (total thickness, number of horizons, nb/thick, nb/m) and binary (presence or absence of horizon groups in the profile). This analysis that calculates matrix of proximity (here distance measures) between a set of two-by-two comparable elements of n samples, permitted, using stated criterion, to fuse horizons (and profiles) into groups that respect the resemblance between them in a predefined optimal manner (Legendre and Legendre, 2000). In the common approaches used in ecology the hierarchical agglomerative clustering considered the species as samples, but in this study the analysis was applied to horizon and soil attributes. This approach used here with our soil data was particularly adapted because it permitted to extract relevant information among the large number of data sets that could be analysed in an independent way.

The dominance of the different horizon groups in each profile groups was also calculated using an analysis of variance (ANOVA with Tuckey test) in order to test differences in profile parameters for each attribute (R software, version 2.0.1; Ihaka and Gentleman, 1996). Using the same R software an analysis of regression tree was applied to detect the more discriminating horizon attributes.

In order to investigate the contribution of the different profile factors, correlation analyses (using Pearson correlation) between these factors, as well as other data summaries were carried out by means of S-Plus software (version 6.0).

Table 1
Characteristics of horizon groups as identified by Ward's minimum variance clustering

Parameters	Group I (2% of samples)	Group II (8% of samples)	Group III (4% of samples)	Group IV (2% of samples)	Group V (7% of samples)	Group VI (5% of samples)	Group VII (5% of samples)	Group VIII (21% of samples)	Group IX (4% of samples)	Group X (2% of samples)	Group XI (3% of samples)	Group XII (2% of samples)	Group XIII (3% of samples)	Group XIV (22% of samples)	Group XV (10% of samples)
Oxidation marks ^a	0 (0%); 1 (100%)	0 (0%); 1 (100%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (72%); 1 (28%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (77%); 1 (33%)	0 (89%); 1 (11%)	0 (45%); 1 (55%)	0 (0%); 1 (100%)	0 (83%); 1 (17%)	0 (99%); 1 (1%)	0 (86%); 1 (14%)
Gravels and pebbles ^a	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (0%); 1 (100%)	0 (0%); 1 (100%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (81%); 1 (19%)	0 (92%); 1 (8%)
Silt (%)	Mean = 70 ± 0	Mean = 34 ± 22	Mean = 70 ± 0	Mean = 70 ± 0	Mean = 70 ± 0	Mean = 61 ± 20	Mean = 24 ± 10	Mean = 23 ± 10	Mean = 38 ± 19	Mean = 17 ± 20	Mean = 39 ± 30	Mean = 10 ± 0	Mean = 10 ± 0	Mean = 10 ± 2	Mean = 10 ± 3
Fine sand ^a	0 (100%); 1 (0%)	0 (3%); 1 (97%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (0%); 1 (100%)	0 (39%); 1 (41%)	0 (0%); 1 (100%)	0 (1%); 1 (99%)	0 (8%); 1 (92%)	0 (67%); 1 (33%)	0 (55%); 1 (45%)	0 (78%); 1 (22%)	0 (67%); 1 (33%)	0 (38%); 1 (62%)	0 (100%); 1 (0%)
Medium sand ^a	0 (100%); 1 (0%)	0 (97%); 1 (3%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (89%); 1 (11%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (22%); 1 (78%)	0 (91%); 1 (9%)	0 (0%); 1 (100%)	0 (0%); 1 (100%)	0 (0%); 1 (82%)	0 (100%); 1 (0%)
Coarse sand ^a	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (89%); 1 (11%)	0 (100%); 1 (0%)	0 (99%); 1 (1%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (91%); 1 (9%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (81%); 1 (19%)	0 (0%); 1 (100%)
Depth (cm)	Mean = 39 ± 32	Mean = 35 ± 28	Mean = 4 ± 8	Mean = 48 ± 19	Mean = 3 ± 7	Mean = 23 ± 19	Mean = 34 ± 34	Mean = 12 ± 14	Mean = 8 ± 10	Mean = 15 ± 12	Mean = 47 ± 26	Mean = 39 ± 19	Mean = 83 ± 19	Mean = 12 ± 15	Mean = 35 ± 33
Thickness (cm)	Mean = 13 ± 9	Mean = 15 ± 10	Mean = 11 ± 5	Mean = 12 ± 6	Mean = 12 ± 7	Mean = 41 ± 15	Mean = 26 ± 11	Mean = 13 ± 7	Mean = 20 ± 9	Mean = 26 ± 18	Mean = 15 ± 8	Mean = 8 ± 3	Mean = 9 ± 5	Mean = 11 ± 8	Mean = 10 ± 6
Macrorestes ^a	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (0%); 1 (100%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)	0 (100%); 1 (0%)

^a 0 = absence, 1 = presence.

3. Results

The soils have been identified as calcareous polygenetic Fluvisol or as Gleysol due to the World Reference Base of Soil Resources (ISSS/ISRIC/FAO, 1998). The clustering separates 15 groups of horizons (named group I to group XV; Table 1, Fig. 2) and then 10 groups of profiles (group 1 to group 10; Fig. 3).

Horizon groups differ from each other principally in their texture parameter (from medium and coarse sand to fine silt; Fig. 2), and then in their thickness combined with the oxidation marks. Note that an absence of oxidation marks does not mean that there is no oxidation–reduction phenomenon, but only that these marks were not visible at the moment of field observation or that particle size was too coarse for preservation. Group I consists of very thin layers with oxidation marks. Group II also presents oxidation marks, with a coarser silty sandy texture. Groups III, IV, and V are siltier and do not show any oxidation marks; they differ on the basis of mean depth. Group VI is an intermediate case between these last three groups. The fine sandy textural horizons are represented by groups VII and VIII, which also do not show any oxidation marks. The presence of gravels is illustrated in groups IX and X, but the particle size varies: fine sand for IX and medium sand for X. Group XI is characterized by various soil texture distributions but always with the presence of macrorestes. Oxidation marks and medium sand define group XII, whereas groups XIII and XIV are only characterized by medium sand; the depth of

each horizon differentiates these two groups. Coarse sand with very little silt differentiates group XV from all the others, independently of the other factors.

Topsoil horizon structure is mostly granular and particular (63% and 25% of the horizons respectively). The granular horizons are mainly represented by horizons of group VIII (26%), group V (25%) and group XIV (22%). Most of the particular horizons are found in group XIV (63%) corresponding to a medium sandy texture. The thickness of those topsoil horizons are various (1 to 37 cm) but is generally thicker for the granular horizons than for the particular ones (mean of 12 and 8 cm respectively).

Profile groups are separated by the factors of total thickness (28 to 97 cm) and number of horizons (2 to 6.5; Fig. 3). Relative location of different groups within the floodplain landscape is shown in Fig. 4. In this last figure, the distribution of abstract representations of real soil profiles is illustrated and does not necessarily correspond to any of the 109 real profiles. Groups 1 to 5 are quite similar but differ from each other by the parameter of the dominant horizons. They reveal profiles with few horizons and are not very thick. Group 1 differs from the other groups by a dominant presence of horizons of group XV. Group 2 generally shows profiles with one or more horizons of group XIV and VIII, which are also typical of group 3. Most of the profiles are found in this last group where intermediate values are observed between groups 1–2 and 4, except for the number of horizons (1 to 4). Group 5 is characterized by various total thicknesses (but thicker than groups 1

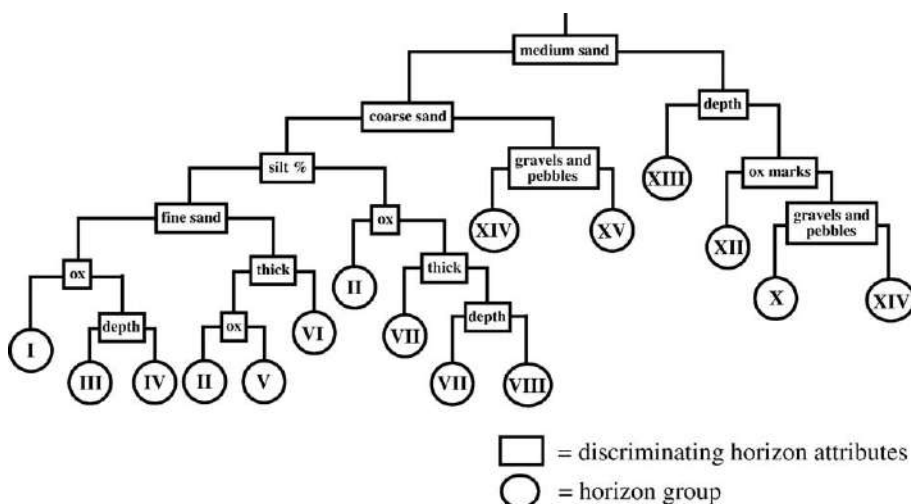


Fig. 2. Simplified dendrogram for 367 soil horizons obtained by means of Ward's minimum variance clustering and described in the 109 profiles from the Sarine floodplain. The group fusion level is defined by a distance and the discriminating horizon attributes are obtained after a regression tree in R Software version 2.0.1. Some horizon groups could appear twice or not at all in the dendrogram. See Table 1 for parameter designation (in this figure "ox" or "oxmarks" means oxidation marks).

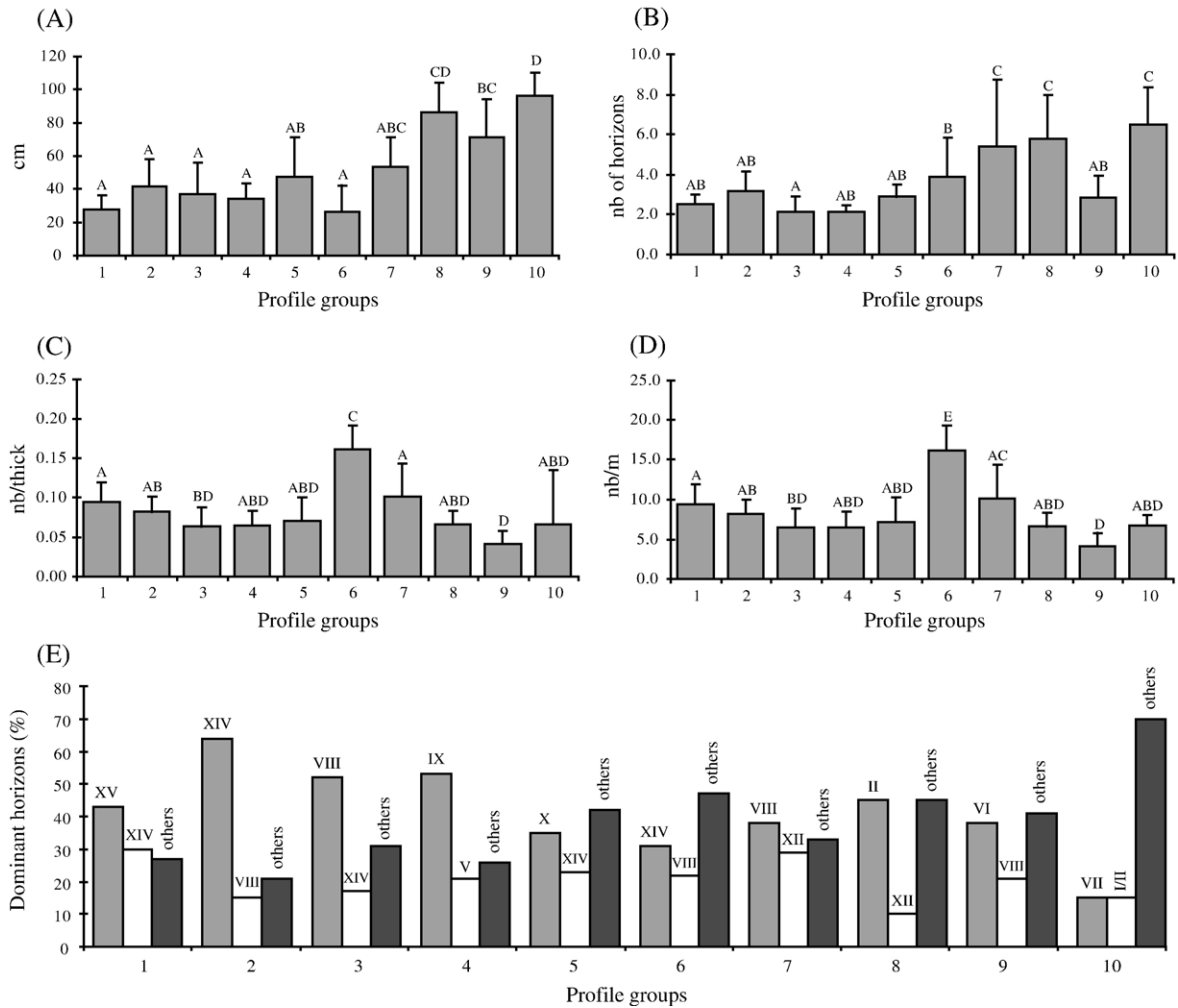


Fig. 3. Average values of profile parameters in the 10 profile groups, (A) total thickness of profile, (B) number of horizons found in profile groups, (C) index “number of horizons on the total thickness”, (D) index “number of horizons per meter”, and (E) dominance of horizon groups in profile groups. Capital letters above bars indicate significant differences among profile groups (Tukey significant difference).

to 4) and the number of horizons. Horizons from group X (medium coarse sand with oxidation marks) are observed that are not seen in group 6. The high values of indexes are very typical of groups 6 and 7, but to a lesser extent in the latter. The particularity of groups 7 and 8 is the presence of horizons of group XII illustrating visible hydromorphic conditions. In addition, group 8 shows a high total thickness and the presence of more than one horizon of group II. The index *nb/m* is also a discriminating factor for some groups, for example this index is quite low for group 9, which is also characterized by a few numbers of horizons (similar to groups 1 to 5) classified in group VI. The presence of a temporary or seasonal water table, shown with the presence of horizons of groups I and II, is a characteristic of group 10. In this last group, the number of

horizons is high with a great variety, and the profiles are quite deep.

The results in Table 2 show positive correlations between some factors. Significant correlation occurs between the total thickness and the number of horizons ($r=0.667$).

4. Discussion

4.1. Profiles—description

The present study examines pedogenesis in space and time of alluvial soils situated along the Sarine River. The results of the clustering show different groups of alluvial soils corresponding to the different processes of erosion and deposition combined with

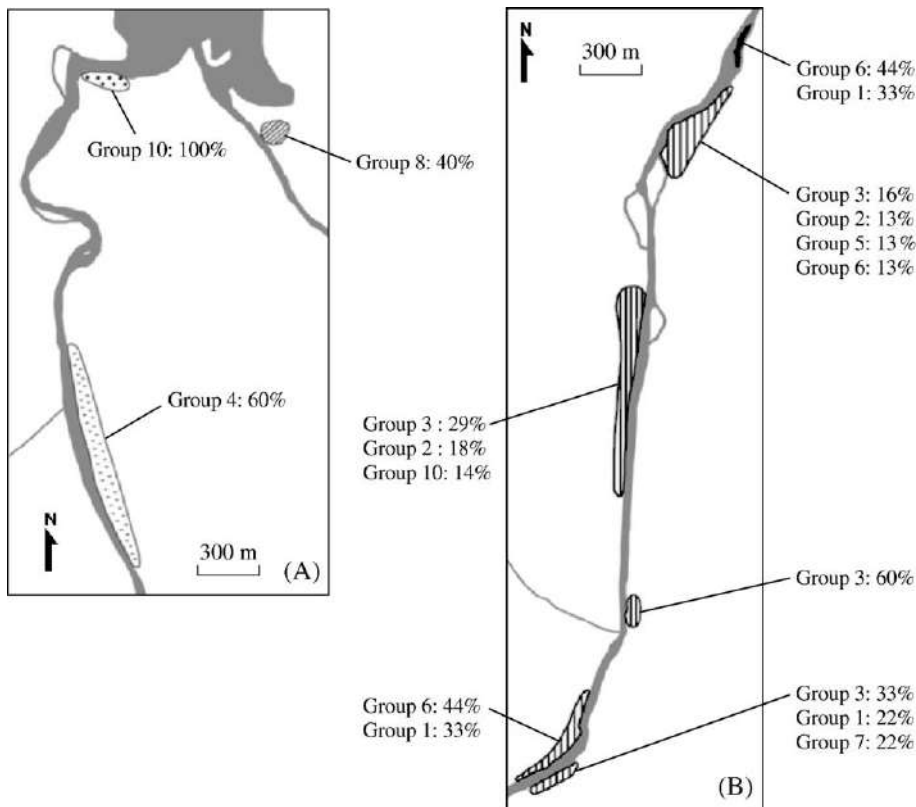


Fig. 4. Relative location of different profile groups within the two major study areas of floodplain landscape: (A) downstream area; and (B) upstream area. This distribution reflects the location of the statistical abstractions of soil properties, rather than distributions of real soils. Dominant profile groups are calculated for each distinct investigated zone.

those of gleying, as well as the spatial variability of fluvial soils. These results are statistical abstractions of soil properties obtained in the field and do not exactly correspond to the real profiles. These abstract representations show that the discriminating parameter between the different types of soils is mainly the soil texture of the horizons, reflecting the variety of alluvial deposits. The 10 profile groups illustrate different types of sedimentation, when terraces are/were reached by flood, and the various natures of these fluvial deposits. Among the 109 profiles described in the field, a representative real profile of each group has been chosen and is roughly and schematically

drawn in Fig. 5. Table 3 shows the summary of their particular characteristics.

The presence of coarse material suggests a sedimentation process with a rapid flow velocity (Gerrard, 1987; Bridge and Gabel, 1992; Owens et al., 1999). Thick horizons covering the pebble limit and only buried by a topsoil horizon with weak soil structure means that the zone is still submitted to intense flooding (representative profiles of groups 2 and 3). Fine, thin sediment layers describe an active sedimentation but with a slow flow velocity, as seen in a representative profile of group 6. A vertical sequence, with several thin horizons at the bottom and a well developed A horizon on the top, can be explained by floodplain stability sufficiently long to generate pedogenic features as soil structure. This stability could be due to the construction of embankments and dams built since about 1920 along the Sarine River. These structures have progressively modified the flow patterns and the spatial distribution of deposits, hence influencing soil formation (as seen in representative profiles of groups 7 and 8). Thick deposits with clear boundary distinctness, as seen in representative profile

Table 2
Pearson moment correlation (*r*) between the profile factors

1	Total thickness			
2	Number of horizons	0.67**		
3	I horizon	0.34**	0.59**	
4	VII horizon	0.51**	0.25**	0.22*
5	XIII horizon	0.49**	0.52**	0.48**
		1	2	3

***p*-value<0.01, **p*-value<0.05; in bold=value used for discussion.

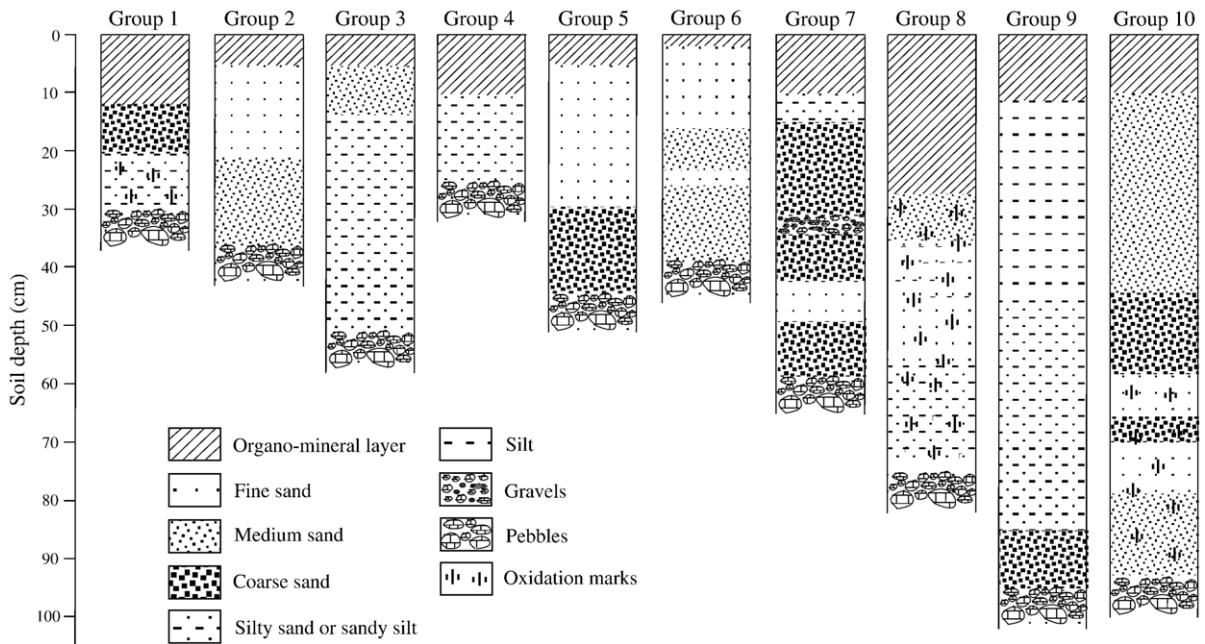


Fig. 5. Schema of a representative real profile of each group (group 1 to group 10).

9, suggest important events of smooth sedimentation with slow flow velocity. The representative profile of group 10 is deep, indicating an important sedimentation process as well as the presence of fluctuating waterlogging identified by oxidation features. This variation of the water table is due to the exploitation of the Rossens dam situated at the north shore of the Gruyère Lake. Every summer, the lake level increases (up to 15 m from upper the winter level) and slightly inundates the zone covered with various textural sediments.

4.2. Soil formation

The parameters distinguishing the formation of these different profiles are dominated by sedimentologic rather than pedogenic features, except for topsoil or buried organo-mineral horizons. The variable stratification found among the profiles suggests a spatial variation throughout the study area and is involved in the soil formation. The vertical sequences of distinct layers contain features reflecting the complex history of the site and should be clearly identified and explained.

The results of the correlation analyses between the different descriptive factors show a close linear relationship between the total thickness of the profile and the number of horizons found in the vertical sequence. This result may be obvious in many cases but not in an

alluvial context characterized by a very important spatial and vertical heterogeneity. Actually, in the case of the Sarine floodplain, this relationship is relevant to identify the sedimentary processes and can be explained by two schematic types of stratification: the regular and the irregular type.

The regular type, i) homogeneous option with facies model 1 in Fig. 6, suggests that fluvial deposits are regular in space and time. The number of horizons grows regularly with soil thickness formation and the horizon thickness remains. However, except for a few cases, this possibility seems to be very unlikely in the field because of various changes that have taken place since the beginning of the twentieth century (Mendonça Santos and Claramunt, 2001; Guex et al., 2003). These changes are both hydrological (current speed, processes of sedimentation modified by the construction of embankments and dams) and historical (land-use and management).

The irregular type, ii) combined option, with facies models 2 to 4 in Fig. 6, is indicative of distinct units in space and time. It presents an obligatory combination of several kinds of formations, inducing a soil mosaic. For example, several thin layers can (over time) cover a thick deposit (facies model 2, e.g., profile group 3) or, on the contrary, be covered by a thick layer (facies model 3, represented for example by profile group 9). Multiple thick and thin buried depositions can also be superimposed as illustrated by

Table 3
Summary of representative profiles' characteristics (see also Fig. 3)

Representative profiles	Vertical sequence	Texture parameter	Other parameters	Type of alluvial zone	Velocity of current and duration of flood
Group 1	Reduced thickness; few horizons	Coarse material	Oxidation marks	Active zone	Rapid flow velocity and short flood duration
Group 2	Reduced thickness; quite few horizons	Medium coarse material	Reduced A horizon development	Active zone	Medium flow velocity and flood duration
Group 3	Reduced thickness; few horizons	Fine sediment at the bottom and medium on the top	Reduced A horizon development	Active zone or embanked zone potentially reached by flood	Slow flow velocity first, then faster
Group 4	Reduced thickness; few horizons	Fine material	Development of A horizon	Past active zone, but embanked now	Slow flow velocity and quite long flood duration, no more events now
Group 5	Moderate thickness; few horizons	Coarse material at the bottom and finer on the top	Reduced A horizon development	Past active zone or embanked zone potentially reached by flood	Slow flow velocity and long flood duration
Group 6	Reduced thickness; many horizons	Medium to fine material	Reduced A horizon development	Active zone	Slow flow velocity, but short flood duration
Group 7	Moderate thickness; many horizons	Very coarse material at the bottom and finer on the top	Development of A horizon	Past active zone, but embanked now	First, rapid flow velocity, then slower; various flood duration
Group 8	High thickness; many horizons	Alternation of medium and fine material	Oxidation marks and thick A horizon	Past active zone, but embanked now	Slow flow velocity, with quite long floods; no more events now
Group 9	High thickness; few horizons	Coarse material at the bottom and fine material on the top	Development of A horizon	Past active zone, but embanked now	Important events of sedimentation with slow flow and smooth sedimentation
Group 10	High thickness; many horizons	Alternation of coarse and fine materials	Oxidation marks	Past active zone, but embanked now, potentially reached by floods	Important sedimentation processes with alternation of rapid and slow flow velocity and long and short flood periods

facies model 4 (e.g., profile group 7). Periods of stability can be identified by the presence of a buried A horizon (Ab according to the World Reference Base of Soil Resources, [ISSS/ISRIC/FAO, 1998](#)) and succeed to periods of sedimentation. [Gerrard \(1987\)](#) explained this succession of buried (or multiple buried) soils as a recurrent cycle of stable and unstable phases of landscape evolution. Thus, the combined option integrating facies models 2, 3, and 4 seems to be more relevant for explaining the general increase of number of horizons with thickness than the homogeneous option (facies model 1). The explanations are hydrological (river flow instability) and geological and geomorphological (variable floodplain morphology), as well as historical (human disturbance). Moreover, only some combinations of these four models can be taken into account to explain the particular relationship between the profile thickness and the number of horizons throughout the studied area ([Fig. 7](#)).

4.3. Validation of facies models

In order to explain the soil formation in the valley, these schematically facies models, describing superficial deposits overlaying past conditions because of natural floods or human interventions, have now to be distinguished at a larger scale. In fact, our results can be explained at the Sarine floodplain scale level representing the functional set according to [Petts and Amoros \(1996\)](#). The four facies models show different alluvial formation contexts associating regular sedimentation, with cumulative and multiple buried soils illustrated by succession of stable and unstable phases of deposition. In case of stability, soil pedogenic features with development of recognizable A horizon and accumulation of organic carbon provide evidence of variable stability periods combined over time with instability periods. At the temporal scale this periodic alternation of stable and unstable phases (meaning regularity and irregularity respectively) is considered

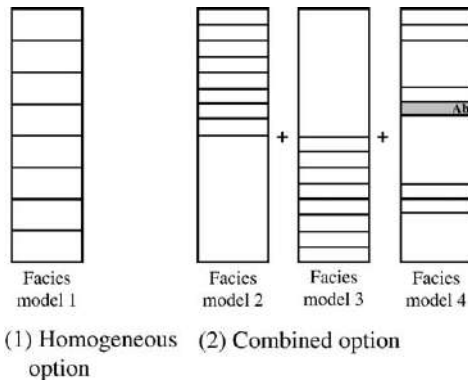


Fig. 6. Representation of two types of stratification — options (1) and (2) — illustrated by four facies models (1 to 4) found in the vertical sequence and, because of the linear relationship between the total thickness of the profile and the number of horizons. The homogeneous option means that fluvial deposits are regular in space and time. The combined option suggests distinct units in space and time that should be mixed to induce soil mosaic (Ab=buried organo-mineral horizon, according to *ISSS Working Group RB, 1998*).

as stable in medium and long term, and guarantees the maintenance of stability in the river environment. Thus, it is fundamental to observe both regular (meaning development of soil pedogenic features) and irregular (in term of natural floods) periods at the functional set

level of the river environment. This temporal hierarchy can also be related to the spatial hierarchy with the same succession of stability and instability periods (*Auger et al., 1992*). The temporal process is, however, also stable at a long-term scale (respectively large spatial scale) with a combination of short-term instabilities regularly occurring in different reaches or habitats (*Naiman and Bilby, 1998*).

As seen above, each facies model can be used to explain concrete situations at a small scale in the field. They can also permit generalization at a larger scale and be used as “erasers” of local differences. What is important in the differentiation between these two situations is the scale taken into consideration.

4.4. *Facies models and other soil classifications*

Facies models illustrated in this study, with the use of simple indicators, help to describe in a rapid, simple, and inexpensive way the soils of the Sarine floodplain. This method could be compared to the organization of References and Types of the “Référentiel Pédologique” (*AFES, 1998*) that is not necessarily associated to a spatial analysis but assemble groups recognized as being associated but having

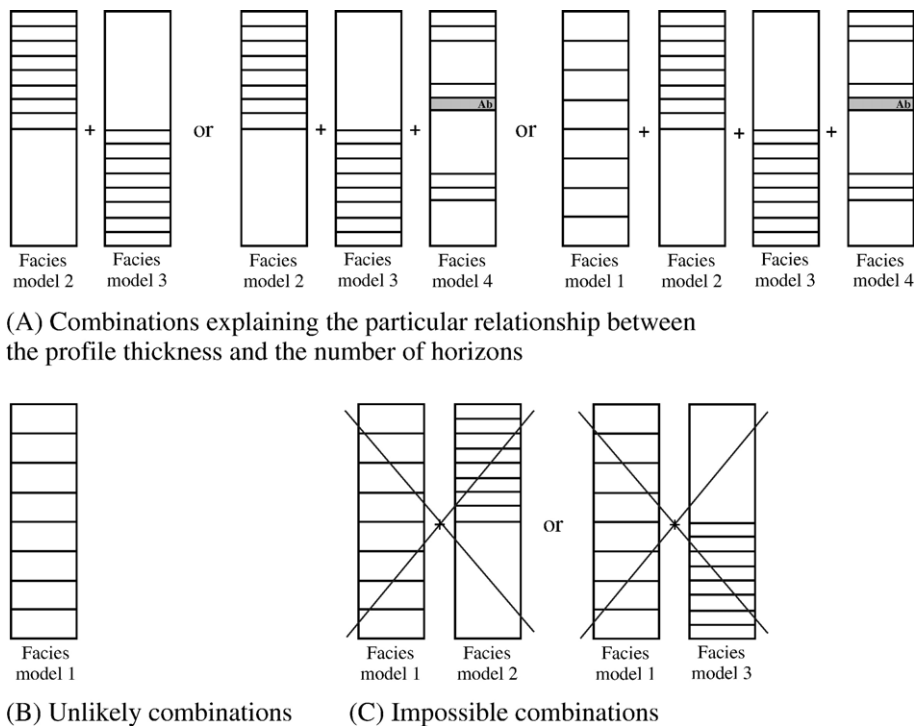


Fig. 7. Combinations of the four facies models that can be taken into account to explain the particular relationship between the profile thickness and the number of horizons. These four extreme schemas (A and B) represent conceptual explanatory facies models, but some intermediate cases certainly exist.

ill-defined limits. Thus, it is not a new soil mapping technique (using kriging and GIS methods like fuzzy soil mapping) but a soil survey method that could help to investigate rapidly the soils of an entire floodplain valley. Nevertheless, it could be compared with the fuzzy soil mapping as mentioned by Shi et al. (2004) or the indicator kriging approach (Bierkens and Burrough, 1993) that exclude the problems related with the high cost (on money, labour, and time) and the high subjectivity associated with the standard soil surveys. These approaches, using mathematical equations, share some similarities with our facies models in terms of soil properties and combinations. They can be used to show the depth of different horizons or the texture of A horizon (Shi et al., 2004). But if the indicator kriging approach can be used for predicting categorical soil data and producing maps with defined boundaries, our facies models can interpret soil data at different scale levels—in space and time—and relate these to ancient landscape descriptions and floodplain evolution.

5. Conclusions

The example of the Sarine River valley in the NW of the Swiss Alps shows that the soil formation in alluvial environment is highly heterogeneous and reveals distinctive sedimentologic and pedologic characteristics. Frequent depositional disturbances from flooding, as

well as erosional processes that are very difficult to exhibit, create a complex mosaic of soil conditions that fundamentally influences vegetation colonization and establishment. Moreover, embanked zones show completely different conditions such as isolation of the river from its floodplain and suspension of aggradation. This study provides abstractions of field information documenting different models of sedimentation that are necessary to improve our understanding on development and evolution of embanked floodplains. Consequently, the studied Sarine floodplain can be described schematically as a mosaic of four major facies models of soil development (Fig. 8.). It represents a combination of sedimentation and soil development. Buried soils are thus formed, which characterize particular functional floodplain units. The study of these different conceptual facies representing the evolution in time represents an essential contribution to explain landscape history of each unit of the Sarine floodplain.

By recognizing the combination of some facies models and the impossibility of combining others, the processes leading to soil establishment can be inferred at the functional set level. Therefore, this paper postulates that this full representation of four facies models in the Sarine River indicates the conservation of the general alluvial diversity of the entire floodplain. This conservation of riverine ecosystem patterns exists in spite of human modifications over

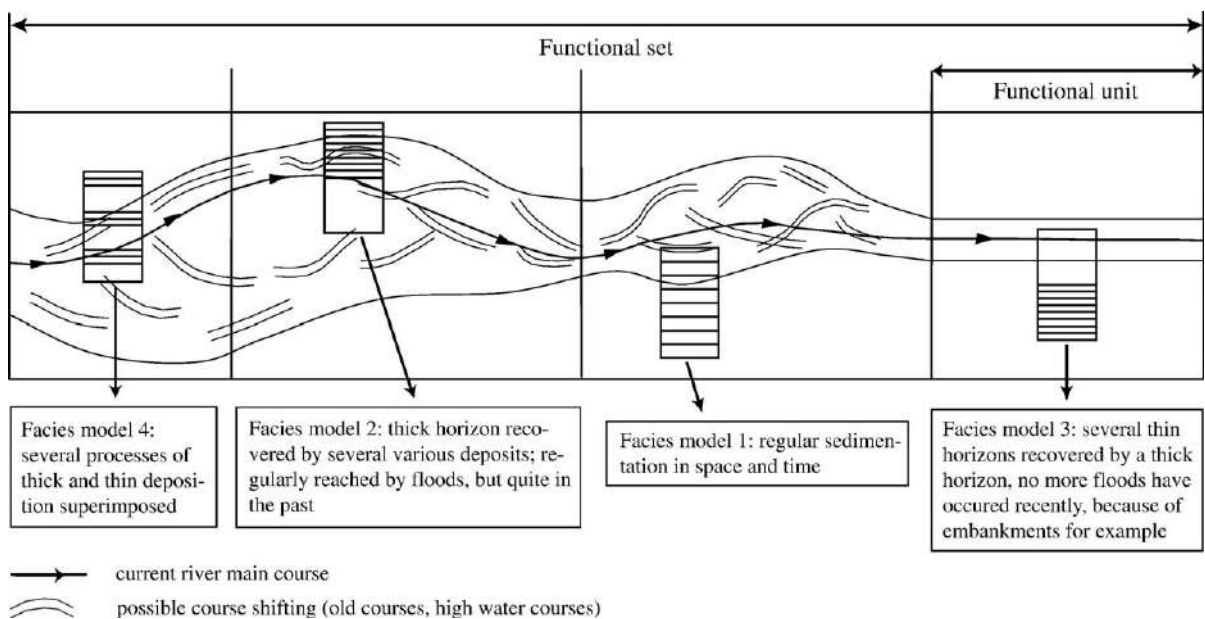


Fig. 8. Schematic representation of a possible spatial mosaic of the four facies models along the studied section (facies model 1 to facies model 4). Facies model is described at the functional unit level (Petts and Amoros, 1996) and the combination of facies models has to be considered at the higher functional set level.

the last 150 yr and suggests a high potential for an eventual revitalisation of embanked zones. However, this occurrence of all alluvial facies models at the functional set level does not prevent appearance of “unbalanced” zones at a smaller spatial scale level where only one or two facies models remain. Thus, the entire floodplain (functional set level), not only the smaller scale functional alluvial unit, is the seemingly obvious pertinent level needed to understand for the long-term conservation of a complete alluvial system. A real space–time balance should then exist between the different facies models at a larger scale. This spatial or temporal proportion between models also depends on the damages that the system underwent. Results documenting the different sedimentation models have then great significance for river management and restoration activities in the alpine floodplain context. For example, restoration management in a floodplain section — “true and durable” — should find the balance between facies models by re-creating one model or even more. Improved scientific understanding of sedimentation and soil formation within the embanked fluvial hydrosystem will enhance effective management by finding equilibrium inside all types of floodplain ecosystems.

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Microsoft Access
 : Fichier Edition Affichage Insertion Format Enregistrements Outils Feuille 2
 Tapez une question

Sondages

S1 - Gour-Dessous, Grandvillard, Fribourg

Sondage

Sondage **S1** Canton **Fribourg** Commune **Grandvillard** Lieu-dit **Gour-Dessous**

Carte **1245** Altitude **725** Coord X **571630** Coord Y **153840** Date **18.07.2002**

Profondeur **30** Grève atteinte Zone endiguée Zone non endiguée

Situation **dans bras mort bord N**

Code végétation Végétation **frêne - hêtre - pétașites**

Type de zone **1** Type de litière **3** Macrorrestes **1**

Recouvrement frac. grossière **6** Horizon humifère **2** Taches d'oxydo-réduction

Granulométrie frac. grossière **1** Matière organique **3** Profondeur oxydation **23-25**

Recouvrement litière **3** Structure horizon humifère **2** Profondeur réduction

Texture horizon humifère **3** Texture horizon humifère **2**

Remarques

Recherche sondage Nb. Horizons **Description des horizons**

Enr : **1** sur **226**

Horizon A Texture **S**

meleuse

Echantillons

Horizon C Texture **Sg**

Echantillons

Horizon IIAG Texture **S-L**

10 cm

Echantillons

Description **str grumeleuse; text. S-L; grosses concrétions d'ox. à 23-25**

Sommet 20 Base **30**

Horizon IIID Texture

cm

Echantillons

Description **grève alluviale**

Sommet 30 Base

Profondeur totale : **30 cm**

Mode Formulaire **démarrer**

Database used for the input and analysis of the different auger sampling data (using Microsoft Office Access 2003)



Soil profile 1

Commune : Broc

Lieu-dit : Broc-Fabrique

Coordonnées : 573'835/162'565, Alt. : 650 m

Milieu : Saulaie blanche

Végétation dominante : *Phalaris arundinacea*, *Salix alba*

Profondeur totale : 102 cm

Date : 23.05.2003

REDUCTISOL TYPIQUE polyphasic

- 0-8 : limons, str grumeleuse, bien agrégée, agrégats stables de 2-4 mm, brun, radicelles, pas de graviers, racines env. 1 mm, transition nette et horizontale
- 8-14 : limons argileux, gris brun, avec ox, qq de racines 1-2 mm, pas de graviers, qq nodules de m.o., limite peu nette et onduleuse
- 14-19 : limons sableux, gris brun, ox, qq nodules m.o., pas de graviers, peu de racines (*Salix* ?) 0,5-1 cm, limite peu nette et ondulée
- 19-28 : argiles limoneuses, gris, ox-red, pas de graviers, peu de racines 1 cm, limite nette et horizontale
- 28-31 : limons argileux, brun clair à orange, bcp ox (red), pas de graviers, peu de racines 1-2 mm, limite nette et horizontale
- 31-36 : argiles limoneuses, gris, (ox-) red, qq racines jusqu'à 2 cm, pas de graviers, 1 galet trouvé à plat à 35 cm
- 36-43 : argiles limoneuses, stratifiées/feuilletées, cassantes, str polyédrique, pas collant, brun orange, limite nette et horizontale
- 43-46 : limons, gris, stratifiés en microcouches annuelles, peu de racines, limite nette et horizontale
- 46-50 : sables limoneux, gris orange, alternance red-ox, pas de graviers, qq racines 0.5 - 1 cm, limite nette et horizontale
- 50-52 : argiles limoneuses, gris, red (-ox), peu de racines, pas de graviers, limite nette et horizontale
- 52-75 : sables (limoneux), str grumeleuse, agrégats stables 2-3 mm, brun foncé, ox, qq rares graviers 1-2 cm (gravillons), qq radicelles, mollusques, os de limace, un niveau de graviers à 65 cm, limite nette et ondulée, pas horizontale
- 75-81 : sables grossiers, qq graviers jusqu'à 1 cm, gris, pas de racines, 1 galets de 3-5 cm, limite nette et ondulée
- 81-94 : sables moyens, gris brun, limite nette
- 94-102 : galets 5-10 cm, limite nette
- > 102 : graviers, galets, sables, tous calibres





Soil profile 2

Commune : Grandvillard

Lieu-dit : Fin de la Dâda

Coordonnées : 571°803/154°047, Alt. : 733 m

Milieu : Aulnaie blanche à saules; à 1,5 m du bras mort

Végétation dominante : impatient, reine-des-prés

Profondeur totale : 135 cm

Date : 21.11.2003

REDUCTISOL TYPIQUE

- 0-9 : limons, brun, str grumeleuse, qq racines 1-5 mm jusqu'à 1 cm, limite diffuse et +/- horizontale
- 9-13/15 : limons, brun clair, avec m.o., qq racines
- 13/15-17/18 : sables moyens, gris, peu de racines
- 17/18-30 : sables fins, gris, ox, limite nette et biseauté
- 26-32 : beige plus clair
- 30-54 : sables fins, bcp ox dès 30 cm avec red, qq racines, limite nette +/- horizontale
- 54-58 : sables fins, red, qq racines
- 58-60 : argiles limoneuses, gris foncé, limite de la nappe
- 60-61 : couche organique foncée avec macro-restes, matrice limoneuse
- 61-100 : sables fins, gris foncé
- 100-135 : graviers et sables grossiers avec grosses taches d'ox
- 135-... : galets





Soil profile 3

Commune : Grandvillard

Lieu-dit : Fin de la Dâda

Coordonnées : 571°765/154°125, Alt. : 731 m

Milieu : Aulnaie blanche à saules

Vég. dominante : saules blancs, ormes, petites hêtres et érables

Profondeur totale : 110 cm

Date : 19.08.2003

FLUVIOSOL TYPIQUE polyphasic redoxic

- 0-18 : sables limoneux, str grumeleuse, brun, racines 1-5 mm, pas de graviers, limite peu nette et +/- horizontale
- 18-35 : sables, brun, avec m.o., racines 1mm - 1 cm, poches plus sableuses, limite nette et +/- horizontale
- 35-55 : sables grossiers avec graviers, gris, peu de racines 1-3 mm, couche disparaissant sur la gauche du profil, limite nette et +/- horizontale
- 55-59 : sables fins, gris beige plus clair, début ox, très peu de racines, limite nette et horizontale
- 59-66 : sables moyens, gris, qq racines plutôt grosses 3-5 mm, limite nette et horizontale
- 66-70 : sables fins, gris beige plus clair, qq racines 1-3 mm, limite nette et horizontale
- 70-76 : sables moyens, qq racines 3-5 mm, limite nette et horizontale
- 76-92 : limons argileux, brun gris bleu, bcp de racines 1 mm - 1 cm, limite nette et horizontale
- 92-98 : sables moyens, gris, qq racines, limite nette et horizontale
- 98-110 : graviers, galets et sables grossiers
- 110-... : grève alluviale





Soil profile 4

Commune : Neirivue

Lieu-dit : Jacquettes

Coordonnées : 571'332/152'678, Alt. : 752 m

Milieu : Plantation de peupliers

Vég. dominante : jeunes épicéas, frênes, chèvrefeuilles

Profondeur totale : 112 cm

Date : 05.06.2003

**FLUVIOSOL TYPIQUE on REDUCTISOL TYPIQUE
polyphasic**

- 0-24 : sables limoneux, str grumeleuse, brun +/- foncé, racines petites à moyennes 1-5 mm, pas de graviers, 1 escargot, limite ondulée et moyennement nette
- 24-51 : sables fins avec un peu de m.o. de diffusion, faiblement agrégés, brun, racines 1 mm - 1 cm, pas de graviers, limite nette et ondulée
- 51-59 : sables moyens, gris, qq racines 1-3 mm, limite nette et horizontale
- 59-62 : sables moyens, orange, peu de racines 1 mm, pas de m.o., pas de graviers, limite nette et +/- horizontale
- 62-66 : sables fins, ox, avec taches beige gris, peu de racines 1-2 mm, pas de graviers, limite nette et +/- horizontale
- 66-74 : limons sableux (à sables limoneux), gris brun, avec taches d'ox, racines 1-5 mm, pas de graviers, limite peu nette et ondulée
- 74-77 : sables limoneux, gris brun, racines 1-5 mm, pas de graviers, limite nette et horizontale
- 77-83 : sables moyens, brun, avec bcp de m.o. et de macrorestes, racines abondantes 1 mm - 1 cm, limite nette et horizontale
- 83-94 : sables fins, gris, avec qq ox, qq racines 1-3 mm, limite nette et horizontale
- 94-97 : sables grossiers, gris orange, qq racines 1-3 mm, pas de graviers, limite nette et horizontale
- 97-108 : limons argileux, brun gris et orange, lités feuilletés, peu de racines 1-3 mm, pas de graviers, avec un peu de m.o. piégée, limite nette et horizontale
- 108-112 : sables grossiers, très oxydés, orange, qq graviers tous petits, pas de racines, limite floue
- 112-... : grève alluviale, avec sables grossiers orange et gris, nappe à 115 cm





Soil profile 5

Commune : Neirivue

Lieu-dit : Jacquettes

Coordonnées : 571'335/152'673, Alt. : 756 m

Milieu : Plantation de peupliers

Vég. dominante : jeunes épicéas, frênes, chèvrefeuilles

Profondeur totale : 112cm

Date : 05.06.2003

**FLUVIOSOL TYPIQUE ou REDUCTISOL TYPIQUE
polyphasique**

- 0-18 : sables limoneux, grumeleux, stabilité moyenne, agrégation moyenne, racines 1-5 mm avec qq grosses 2 cm, escargots, pas de graviers, limite diffuse, peu nette et floue
- 18-53 : sables fins limoneux, brun, avec m.o. de diffusion, racines 1-5 mm, qq grosses racines 1 cm, pas de graviers, limite nette et ondulée (moins limoneux que couche sus-jacente)
- 53-63 : sables moyens (à grossiers), gris, très peu de racines 0.5 cm, pas de graviers, limite nette et horizontale
- 63-74 : limons sableux fins, brun gris, peu de racines 1-5 mm, qq taches d'ox, pas de graviers, limite nette et horizontale
- 74-87 : sables moyens, gris, avec bcp de macrorestes, racines 1-2 mm, 1 grosse racine 2 cm, présence de bois mouillé, pas de graviers, limite +/- nette et horizontale
- 87-90 : sables, brun gris, avec bcp de m.o. et de macrorestes, 1 gros macroreste, qq racines, pas de graviers, limite nette et +/- horizontale
- 90-94 : sables moyens à grossiers, gris, taches oranges en surface de la couche, pas de racines, pas de graviers, limite nette +/- horizontale
- 94-99 : limons argileux, lités en 3 couches, brun-gris/brun beige/brun et gris, pas de racines, pas de graviers, limite nette +/- horizontale
- 99-112 : sables grossiers, gris et orange, bois à 105 cm, sables plus fins vers le bas de la couche
- 112-... : grève alluviale avec galets et graviers





Soil profile 6

Commune : Neirivue

Lieu-dit : Jacquettes

Coordonnées : 571°341/152°673, Alt. : 753 m

Milieu : Plantation de peupliers

Vég. dominante : jeunes épicéas, frênes, chèvrefeuilles

Profondeur totale : 105 cm

Date : 09.07.2003

**FLUVIOSOL TYPIQUE on REDUCTISOL TYPIQUE
polyphasie**

- 0-17 : sables limoneux, brun, grumeleux, bcp de racines 1mm - 2 cm, pas de graviers, limite diffuse et ondulée
- 17-41 : sables limoneux, avec m.o. de diffusion, brun beige, faible structuration, avec poches de sables fins, moins de racines que couche sus-jacente 1mm - 2 cm, ox dès -30 cm, limite nette et ondulée
- 41-51 : sables moyens, gris clair, peu d'ox, peu de radicelles 1-2 mm, limite nette et ondulée
- 51-59 : sables moyens, orange, bcp ox, peu de radicelles 1-2 mm, limite nette et horizontale
- 59-63 : argiles limoneuses, gris brun foncé, quelques racines 1-3 mm, limite nette et horizontale
- 63-68 : sables fins, gris avec taches oranges, peu de racines 1-2 mm, limite nette et horizontale
- 68-78 : argiles limoneuses, gris foncé, avec poches de sables fins, bcp de microcouches, ox, qq racines 1-3 mm, limite nette et horizontale
- 78-82 : sables moyens à sables fins, petits gravillons, couche biseauté, orange, limite nette et +/- horizontale
- 82-86 : argiles limoneuses, gris foncé, avec taches noires de m.o., 1 racine, limite nette et horizontale
- 86-100 : sables moyens, gris orange avec grosses taches d'ox, peu de racines, limite nette et horizontale
- 100-105 : sables limoneux, gris foncé, couche organique, qq taches oranges, pas de racines, pas de graviers, limite nette et ondulée
- 105-... : grève alluviale avec ox, 1 grosse racine à - 105 cm





Soil profile 7

Commune : Neirivue

Lieu-dit : Jacquettes

Coordonnées : 571°328/152°675, Alt. : 744 m

Milieu : Plantation de peupliers

Vég. dominante : jeunes épicéas, frênes, chèvrefeuilles

Profondeur totale : 195 cm

Date : 19.09.2003

**FLUVIOSOL TYPIQUE on REDUCTISOL TYPIQUE
polyphasic**

- 0-14 : limons sableux, grumeleux, brun, bcp de racines 1 mm - 3 cm, limite diffuse et horizontale
- 14-47 : limons sableux, avec poches de sables fins, brun, racines 1 mm - 3 cm, limite diffuse et horizontale
- 47-67 : sables fins, avec poches de sables moyens, brun clair, qq ox, qq racines 1-3 mm, limite diffuse et horizontale
- 67-80 : sables très fins limoneux, gris beige, ox, avec petits niveaux de limons argileux plus foncés, qq racines 1-3 mm, limite nette et horizontale
- 80-90 : sables grossiers avec galets, limite diffuse, lenticulaire (sur un côté de la coupe)
- 90-95 : graviers oxydés, limite nette, lenticulaire (sur un côté de la coupe)
- 95-103 : sables fins, gris, avec ox, peu de racines 1-5 mm, limite nette et horizontale
- 103-109 : sables moyens, gris, ox, racines 1 mm - 1 cm, limite nette et horizontale
- 109-118 : sables fins, gris brun, avec m.o., un peu d'ox, racines 1 mm - 1 cm, limite nette et horizontale
- 118-132 : sables moyens, gris brun, racines 1-5 mm, limite diffuse
- 132-150 : sables limoneux, brun, avec m.o., racines 1-5 mm
- 150-195 : m.o. à environ 155 cm, restes de roseaux entre 175-195
- 195-... : grève alluviale





Soil profile 8

Commune : Neirivue

Lieu-dit : Jacquettes

Coordonnées : 571°340/152°672, Alt. : 758 m

Milieu : Plantation de peupliers

Vég. dominante : jeunes épicéas, frênes, chèvrefeuilles

Profondeur totale : 112 cm

Date : 27.06.2003

FLUVIOSOL TYPIQUE ou REDUCTISOL TYPIQUE polyphasic

- 0-7 : sables limoneux, grumeleux, brun, bcp racines 1-5 mm, limite peu nette-diffuse et ondulée
- 7-31 : sables limoneux, brun gris, encore un peu de m.o., bcp de racines 1 mm - 3 cm, pendage vers la gauche de la coupe (coupe N-S), limite peu nette et ondulée
- 31-55 : sables limoneux, gris brun avec poches de sables fins gris, bcp de racines 1 mm - 3 cm, pendage, limite peu nette et ondulée
- 55-60 : sables fins, gris (-beige), qq racines 1-5 mm, limite nette et en pendage
- 60-63 : sables fins limoneux, gris beige, début ox, peu de racines 1-2 mm, limite nette et en pendage
- 63-66 : sables fins, gris (-beige), peu de racines 1-2 mm, limite nette et en pendage
- 66-69 : sables fins limoneux, gris beige, peu de racines 1-2 mm, limite nette et en pendage
- 69-74 : sables fins à moyens, gris beige, 1 ou 2 radicelles < 1 mm, limite nette et horizontale
- 74-83 : limons sableux, gris foncé, avec lentilles de sables fins très oxydés, qq radicelles 1-3 mm, limite nette et horizontale
- 83-96 : sables moyens, gris orange, oxydés, qq radicelles 1-2 mm, limite nette et ondulée
- 96-98 : limons sableux (idem 74-83), gris foncé, 1 grosse racine 2 cm, limite nette et horizontale
- 98-100 : sables fins à moyens, gris, qq radicelles 1-2 mm, limite nette et ondulée
- 100-102 : limons, avec sables, un peu de m.o., qq radicelles 1-2 mm, limite nette et ondulée
- 102-107 : sables fins, gris plus foncé, peu de radicelles 1-2 mm, limite nette et ondulée
- 107-112 : argiles, gris foncé avec taches d'ox, radicelles 1-2 mm, m.o., sables moyens en contact avec la grève
- 112-... : grève alluviale avec petits galets, graviers et gravillons très oxydés





Soil profile 9

Commune : Grandvillard

Lieu-dit : La Dâda

Coordonnées : 571°850/154°220, Alt. : 730 m

Milieu : Saulaie de l'île (traces de crue de janv. 04)

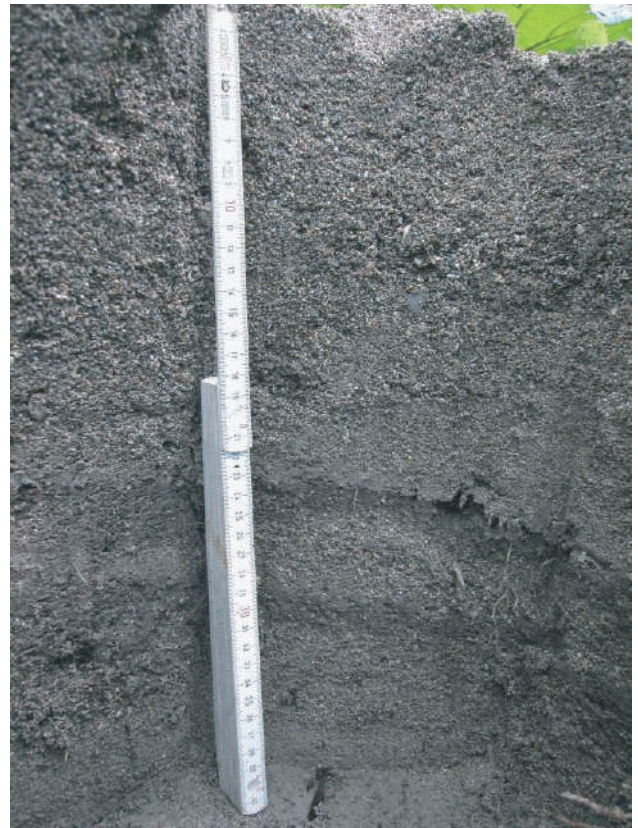
Végétation dominante : saules drapés, pétasites

Profondeur totale : 41 cm

Date : 09.07.2004

FLUVIOSOL TYPIQUE polyphasique

- 0-18 : dépôt de sables grossiers gris (probablement crue janvier 2004), pas de racines, petits graviers
- [18-19] : petite poche organique brune de matériel fin sur la partie droite du profil
- 18-23/25 : sables moyens, limite nette et non horizontale
- 23/25-28/30 : couche organique brune sableuse fine avec qq racines 1 mm, 1 grosse racine, limite nette et non horizontale
- 28/30-32 : sables moyens, apparition des racines
- 32-34 : limons sableux, couche organique brune, qq racines 2-3 cm
- 34-39 : sables moyens, qq racines 2-3 mm, limite floue
- 39-41 : couche limono-sableuse sur les galets
- 41-... : galets dans matrice limono-sableuse





Soil profile 10

Commune : Broc
 Lieu-dit : Broc-Fabrique
 Coordonnées : 571'332/152'678, Alt. : 677 m
 Milieu : Prairie à *Phalaris*
 Végétation dominante : *Phalaris arundinacea*
 Profondeur totale : 52 cm
 Date : 29.05.2003

REDOXISOL

- 0-11 : argiles limoneuses, str grumeleuse, agrégats 1-2 mm, moyennement stables, brun foncé, ox, petites racines 1-2 mm, dans zone supérieure 3-5 mm, pas de graviers, limite nette et ondulée
- 11-19 : limons sableux, brun, un peu de m.o. de diffusion, transition avec minéral, toujours ox, qq racines fines 1-2 mm, limite floue et ondulée
- 19-26 : limons sableux, brun plutôt clair, peu de racines 2-3 mm, limite floue et ondulée
- 26-37 : sables limoneux, brun clair, peu de racines 2-3 mm, structure plus aérée que couche sus-jacente, galeries de vers de terre, limite floue et ondulée, vers 31 cm: niveau de galets sporadique sur description à droite du profil
- 52-... : grève alluviale, galets, graviers, gris brun, gros galets jusqu'à 30 cm





Soil profile 11

Commune : Lessoc

Lieu-dit : Le Rouet

Coordonnées : 571'118/150'964, Alt. : 751 m

Milieu : Pâturage, à 10 m du cours d'eau

Profondeur totale : 54 cm

Date : 07.11.2003

FLUVIOSOL TYPIQUE

- 0-5 : limons argileux, str grumeleuse, brun foncé, qq racines fines/radicelles < 1 mm, limite peu nette et horizontale
- 5-14/20 (droite/gauche): sables limoneux, brun roux, charbons à 14 cm, qq taches d'ox, qq radicelles < 1 mm, 1 racine 3 mm, limite nette, limite en pendage vers le sens de la Sarine
- 14/20-29/38: limons sableux, brun, une poche de sables moyens, charbons à 23 cm, 1 racine de 1 cm, limite nette en pendage vers la Sarine
- 29/38-34/50: sables moyens, gris brun, peu de racines 1-3 mm, limite nette en pendage vers la Sarine
- 34/50-38/54: limons sableux, brun foncé, sur les galets, racines 1-2 mm, limite nette en pendage
- 54-... : gros galets 15-40 cm, qq rares à 5 cm, pas de sables ni de graviers, structuré avec m.o.





Soil profile 12

Commune : Broc

Lieu-dit : Broc-Fabrique

Coordonnées : 574'690/162'262, Alt. : 688 m

Milieu : Prairie de fauche et pâturage

Profondeur totale : 125 cm

Date : 29.10.2004

**FLUVIOSOL TYPIQUE on REDUCTISOL TYPIQUE
polyphasic**

- 0-17 : limons sableux, str grumeleuse, brun, qq racines 0.2-1 mm, limite diffuse et +/- horizontale
- 17-36 : limons, brun clair, un peu de m.o., peu de racines 0.1-1 mm, limite diffuse et +/- horizontale
- 36-48 : sables fins limoneux, qq grosses taches d'ox, limite diffuse et +/- horizontale
- 35-43 : une grosse tache brune de m.o.
- 48-63 : limons sableux fins, brun clair, grosses taches d'ox, charbon à 53 cm côté gauche de la coupe, limite diffuse et horizontale
- 58-63 : une grosse taches brune
- 63-73 : sables moyens, gris, taches d'ox, limite diffuse et +/- horizontale
- 73-79 : limons sableux, brun clair, limite diffuse et +/- horizontale
- 79-92 : sables moyens, gris avec taches d'ox importantes, très peu de racines, qq taches entre 85-95 cm côté droite, limite diffuse et +/- horizontale
- 92-101 : limons sableux, brun clair, ox-red, limite diffuse et +/- horizontale
- 101-119 : limons argileux, brun clair, ox-red, limite nette et horizontale
- 119-125 : sables grossiers, gris, qq taches d'ox
- 125-... : galets dans matrice limoneuse brune: grève alluviale





Soil profile 13

Commune : Neirivue

Lieu-dit : Fin d'Avau

Coordonnées : 571°385/153°209, Alt. : 743 m

Milieu : Prairie de fauche, pâturage

Profondeur totale : 140 cm

Date : 20.06.2003

CALCOSOL on REDUCTISOL TYPIQUE

- 0-8 : limoneux, brun, grumeleux, agrégats 1-4 mm stables, qq racines 1-3 mm, pas de graviers, limite diffuse et non nette
- 8-40 : limons argileux, brun beige, début de structure polyédrique, peu de racines 1-2 mm, m.o. de diffusion, pas de graviers, limite diffuse et non nette
- 40-60 : limons, brun beige, ox, qq mollusques, pas de racines, pas de graviers, limite nette et +/- horizontale
- 60-73 : sables limoneux, brun gris, ox-red, bcp de mollusques, limite floue et diffuse
- 73-76 : limons sableux, toujours ox-red, taches brunes de m.o., mollusques, limite floue, diffuse et peu nette
- 76-86 : sables limoneux, gris, grosses taches d'ox oranges, qq taches de m.o., limite peu nette et diffuse
- 86-95 : sables moyens limoneux, gris, moins d'ox, bcp plus gris, limite peu nette et diffuse
- 95-100 : sables fins limoneux, gris, plus d'ox (pas comme 76-86), macrorestes à 95 cm,
- 100-103 : sables grossiers, bcp ox, couche biseauté en direction de la rivière)
- 103-140 : sables moyens, gris, red, bcp de macrorestes, nappe à 110 cm,
- 140-... : grève alluviale





Soil profile 14

Commune : Broc

Lieu-dit : Broc-Fabrique

Coordonnées : 574° 652/162° 256, Alt. : 684 m

Milieu : Champ de maïs

Profondeur totale : 62cm

Date : 18.08.2003

FLUVIOSOL TYPIQUE

- 0-12 : horizon de labour, limons à limons sableux, brun gris, grumeleux, racines 1-3 mm, limite +/- nette et horizontale
- 12-23 : limons à limons sableux, avec un peu de m.o., racines 1-3 mm, limite +/- nette et horizontale
- 23-52 : limons sableux, gris brun, qq racines 1-5 mm, qq rares graviers, mollusques, limite +/- nette et horizontale
- 46-50 : couche sporadique limoneuse, plus foncé (brun clair) à structure grumeleuse
- 52-62 : niveau de graviers et petits galets, avec un peu de terre fine
- 62-... : grève alluviale



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Original article

Influence of some physicochemical and biological parameters on soil structure formation in alluvial soils

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Abstract

This study examines the role of abiotic (texture, calcium carbonates or iron) and biotic parameters (earthworm and enchytraeid activities) on the initial phases of soil aggregation. Our research focused on humus forms in alluvial soils, which are considered as young and heterogeneous environments. We hypothesized that the soil structure formation is determined by both the nature of the recent alluvial deposits and the soil fauna. For this purpose, six sites were chosen throughout two types of softwood forests (willow and alder forest) representing two stages of vegetation succession. Evidence of soil texture influence on aggregate stability was observed. A dominance of a coarse sand fraction caused a quick colonization of enchytraeids and epigeic earthworms while a silty texture favoured the presence of anecic earthworms, thus increasing the aggregate stabilisation. Iron forms, acting as cementing agents, were observed in the coarse silt, while calcium carbonates were equally distributed among the textural fractions. Active calcium carbonate fraction, binding organic matter with mineral components, was not found in the coarse sand fraction. In conclusion, the tree age cannot alone be used as an indicator of the humus form evolution but biological and physicochemical parameters also influence the initial steps of soil structuration.

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Keywords: Soil aggregate stability; Earthworms; Enchytraeids; Physicochemical factors; Humus form; Alluvial soil; Softwood forest

1. Introduction

Soil structure is influenced by different properties of the soil constituents and by its environment [11]. Soil aggregation is related to basic soil properties such as the texture and the type of parental material. The amount of clay, as well as the presence of calcium carbonates

and iron acting as cementing material, influences the aggregate formation and stabilisation [21]. Soil carbonates usually work as a source of Ca^{2+} -ions that help to flocculate clay particles and then stabilize the exchange complex. Moreover, calcium carbonates preserve the flocculated structure of the clay in soil surface aggregates by neutralizing acids produced by fungi, microbes and roots. A high content of iron oxides also favours a stable structure and may be more concentrated in the fine clay particles. But Oades [35] also found that in temperate regions the interactions of oxides with clays may

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be reversed in the presence of humic substances and that the contribution of these iron oxides is often difficult to separate from the stability attributable to organic matter. As a matter of fact, organic matter is an important factor in soil aggregation, which is correlated with the organic carbon content [53]. Soil organic matter is assumed to stabilize aggregates against disruptive processes such as slaking, by increasing the cohesion of aggregates through the binding of mineral particles by organic polymers. It could also decrease the wettability of aggregates, thus reducing their rates of wetting and the extent of slaking [12]. Organic substances are very repellent to water and several organic fractions are responsible for this hydrophobicity of soils, e.g. humic acids, aliphatic fractions or plant litter debris.

Soil aggregate formation is not only determined by the physical or chemical properties of the soil, but also by soil biological processes. Soil biota is numerous and diverse and is mainly represented by earthworms (macrofauna), enchytraeids, collembolans, diplopoda (mesofauna), nematodes, rotifers (microfauna), as well as fungi and bacteria (microflora). Living organisms, especially worms (Oligochaeta), play a major role in soil structure. For instance, the action of enchytraeids contributes to litter degradation and nutrient mobilization, particularly in acid soils with a high organic content [5,32,47,55]. In addition, soil bioturbation by earthworms is essential and produces very stable casts as well as a large burrow network [36,49]. Earthworms affect soil physical properties by ingesting and egesting soil, but their effects on soil aggregation is species specific and depends on their ecological strategy [49]. While epigeic individuals feed mainly on organic matter, the material ingested by endogeic and anecic species is mainly mineral matter, which is mixed with organic matter in digestive tracts and then egested as casts on the soil surface or belowground. The quality of the ingested material, as well as the contribution of earthworms to cast production and aggregation are well documented [13,22,33,49]. Furthermore, Marinissen and van den Bosch [31] proposed a simple model on the colonization of new habitats by earthworms such as grasslands, while Zorn et al. [57] examined the earthworm population dynamics in a floodplain system in relation to frequency and duration of flooding events. However, the colonization of young environments by different worm species and the first interactions between mineral and organic materials under the influence of soil fauna in the upper soil layers are not well known, particularly in the first steps of soil formation and aggregation.

At the top of soil profiles, humus forms function as the habitat of decomposer organisms and as a nutrient

sink and source [27]. These properties are reflected in morphological characteristics of humus form horizons manifested by the mode and the rate of decomposition and they can then be defined as a morphological pattern observed in the association of organic and mineral matter. It has been demonstrated that humus forms play a central role in the functional biodiversity of terrestrial ecosystems. Actually they are stable and display a visible result of the activity of the soil animal and microbial life [41]. Moreover, small-scale variations in the topsoil profile composition may occur under the influence of several conditions such as vegetation, soil properties or microtopography [39]. Humus forms can then be considered as excellent tools to investigate the first interactions between mineral and organic materials under colonizing fauna.

Alluvial soils have already been described as reliable models to detect the influence of both abiotic and biotic mechanisms involved in soil structure [23]. They are considered as young soils depending on a complicated genesis (interaction between inheritance and in situ evolution) and situated in a heterogeneous environment (i.e. herbaceous vegetation, tree population, alluvium) where early stages of soil formation are represented.

As a consequence, we studied alluvial soils to investigate the relative importance of abiotic (texture, different types of carbonate and iron forms, organic matter) and biotic (enchytraeids and earthworms) mechanisms on initial soil aggregation. Our research focused on the humus form, which is considered as a good indicator of short-term and small-scale variations under the influence of vegetation or sedimentation changes. We hypothesized that the soil structure formation was mainly determined by the nature of the recent alluvial deposits with little influence of alluvial gravel or underlying mineral sediments. This upper mineral part, directly in contact with organic matter, affects in turn the colonization by the soil fauna (earthworms and enchytraeids), and the distribution of the different iron forms, with little influence of the forest types that are, in our case, pioneer communities of willow and alder. We concentrated our study on six sampling sites differentiated mainly by recent alluvial deposits and by the age of the tree populations. Alluvial gravel as well as other underlying mineral horizons were considered as similar for the six sites. We characterized these soils biologically, chemically and physically and observed that the spatial distribution of humus forms throughout the alluvial study area was very heterogeneous, regarding earthworms (abundance, biomass and species), enchytraeids, soil textural parameter and iron forms.

2. Material and methods

2.1. Site description and sampling method

The study site is an alluvial zone of national importance (Fig. 1) located in the northwest of the Swiss Alps (Swiss coordinate system in km: 571.5/154). It is a part of the floodplain of the Sarine River, tributary of the Aare River. The Sarine River is strongly confined between embankments except for the study area situated at 750 m above the sea level [9,23].

Our study was based on the comparison of humus forms of six sites located on a riverbank that can potentially be flooded. These sites were selected along a transect according to the vegetation type, the age of the present tree population [23], and the visual heterogeneity of alluvial deposition. Two different types of softwood forest community were chosen with three sites in each type (Fig. 1) representing two stages of

vegetation succession in alluvial ecosystems [40]: the willow type, old gravel bars that have been colonized by willow shrubs for about 20 years (H1 to H3), and the alder type, colonized for about 25 to 30 years (H4 to H6). Inside each vegetation type, sites were chosen according to the environment heterogeneity (herbaceous plants, soil texture, etc.).

Soils were FLUVIOSOL TYPIQUE according to the “Référentiel pédologique” [1]. The humus profile of each location was described using the classification system of the “Référentiel pédologique” [1]. From each profile, the organo-mineral layers A and/or J and the mineral horizons M were sampled for further analyses.

2.2. Soil fauna extraction

Enchytraeids were sampled from three plots of 25×25 cm inside whose three soil cores (6 cm diameter \times 10 cm deep) were mixed together. Sampling was

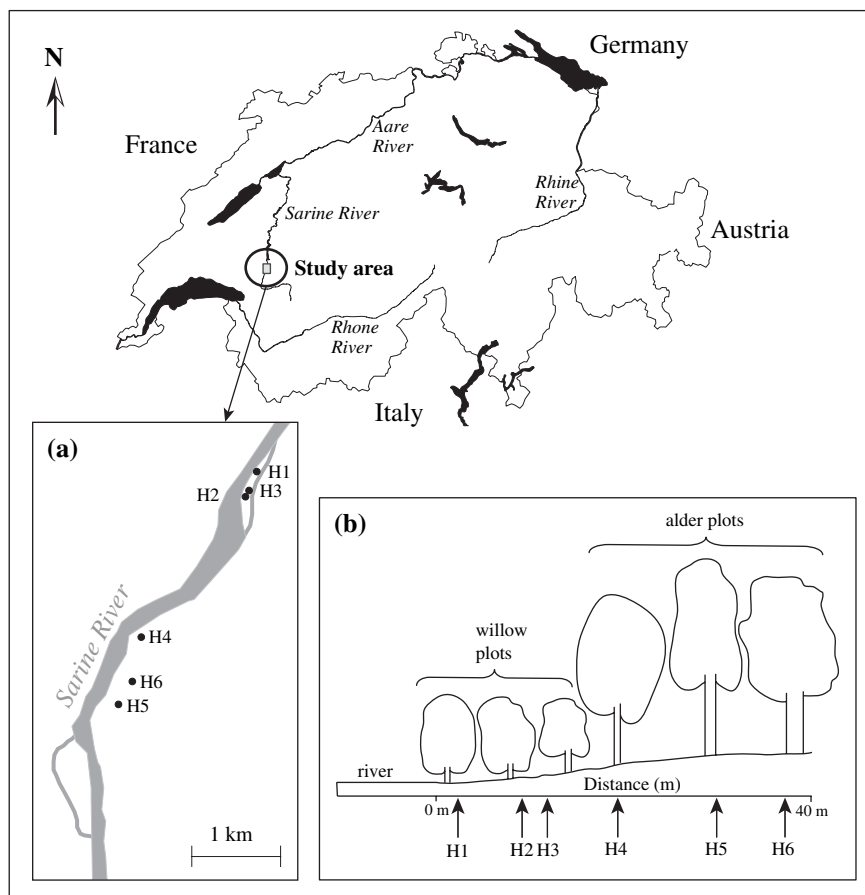


Fig. 1. The study area, the Sarine River, in the northwest of the Swiss Alps, with the location of the six sites along the river (a). (b) Schematic drawing of the Sarine River in the studied section with two stages of vegetation succession in alluvial ecosystems.

made only one time in August during and after a fairly dry period. Counting was performed after extraction using the wet funnel technique [16,37]. Earthworms were sampled from each soil (three squares of 50 × 50 cm) using the ethophysical method [8]. Sampling was realized only one time in September and October after a relative dry summer combining a formalin extraction followed by hand-sorting (soil depth 0–20 cm). All worms were weighed and identified to the species level. Small and/or juvenile individuals were classified either in their ecological type (anecic, endogeic or epigeic) or at the genus level. No major flooding event took place during the months before sampling, thus we suppose that flooding did not influence our sampled area.

2.3. Soil analysis

Samples for soil analysis were taken in May and June and at a different place than those for fauna extraction to avoid perturbing the soil communities. Physico-chemical analyses were performed on air-dried and sieved soil (mesh size 2 mm) from the layers A and/or J and M. Water pH (ratio 1:2.5), particle size distribution (modified Robinson pipette method for: fine silts 2–20 μm, coarse silts 20–50 μm, clays 0–2 μm; and sieving for: fine sands 50–200 μm, coarse sands 200–2000 μm [38]), and active carbonate content (modified Drouineau and Galet method [54]) were measured. Other analyses were carried out on ground soil samples (soil particles <200 μm), like carbonate content (reaction with H₃PO₄ and titration of the CO₂ released with a Carmograph Wösthoff 8-ADG), organic carbon content (combustion and titration of the CO₂ released with a Carmograph Wösthoff 8-ADG), and total nitrogen content (Kjeldahl mineralization, Technicon colorimetric titration). In addition, and only for A and/or J horizons, iron forms were quantified as amorphous iron species (Fe_o; iron extractable by oxalate using Tamm method modified by Schwertmann [52]), crystallized iron species (Fe_d; iron extractable by dithionite-citrate-bicarbonate modified from Mehra and Jackson method [34]) and total iron content (Fe_t; metaborate fusion method [45]). In general, Fe_o is considered as “active”, Fe_d minus Fe_o ratio as “less active” [4], and Fe_o/Fe_d ratio estimates the degree of the soil evolution [18]. Three replicates were carried out for the quantification of iron forms while one measurement was made with other methods.

Aggregate stability was determined on A and/or J horizons by wet sieving using 1.00, 0.50 and 0.25 mm mesh sizes (method adapted from Kemper and Rosenau

[26]) on 1–2 mm calibrated aggregates. The mean weight diameter (MWD) was calculated on three replicates per soil using a correction index for the coarse sand content [2].

2.4. Statistical analysis

Statistical analyses were performed using Pearson correlations and principal component analysis (PCA). The data were previously standardized to make the variance more homogeneous across the range of the data. The software used was R (version 2.0.1 [24]). Earthworm data were grouped in ecological categories before statistical analysis.

3. Results

3.1. Humus forms

Three humus forms were observed and described in the transect (Table 1, Fig. 2): eumull for H1, H2, H3 and

Table 1
Site descriptions according to the “Référentiel pédologique” [1] and thickness of each horizon

Sites	Humus forms	Horizons	Thickness (cm)
H1	Eumull	(OLn)	0.5
		J _{Sca}	1
		M _{ca}	14
H2	Eumull	(OLn)	0.5
		J _{Sca}	0.5
		M _{ca}	8.5
H3	Eumull	(OLn)	0.5
		A _{ca}	5
		M _{ca}	11
H4	Oligomull	OLn	0.5
		(OFr)	0.5
		A _{ca}	5.5
		M _{ca}	12
H5	Eumull	OLn	0.5
		(OLt)	0.5
		A _{ca}	7
		M _{ca}	3
		IIM _{ca}	10
H6	Dysmull	OLn	1
		OFr	0.5
		(OFm)	1
		J _{Sca}	7
		M _{ca}	8
		IIM _{ca}	2

The suffix “ca” underlines the presence of carbonates.

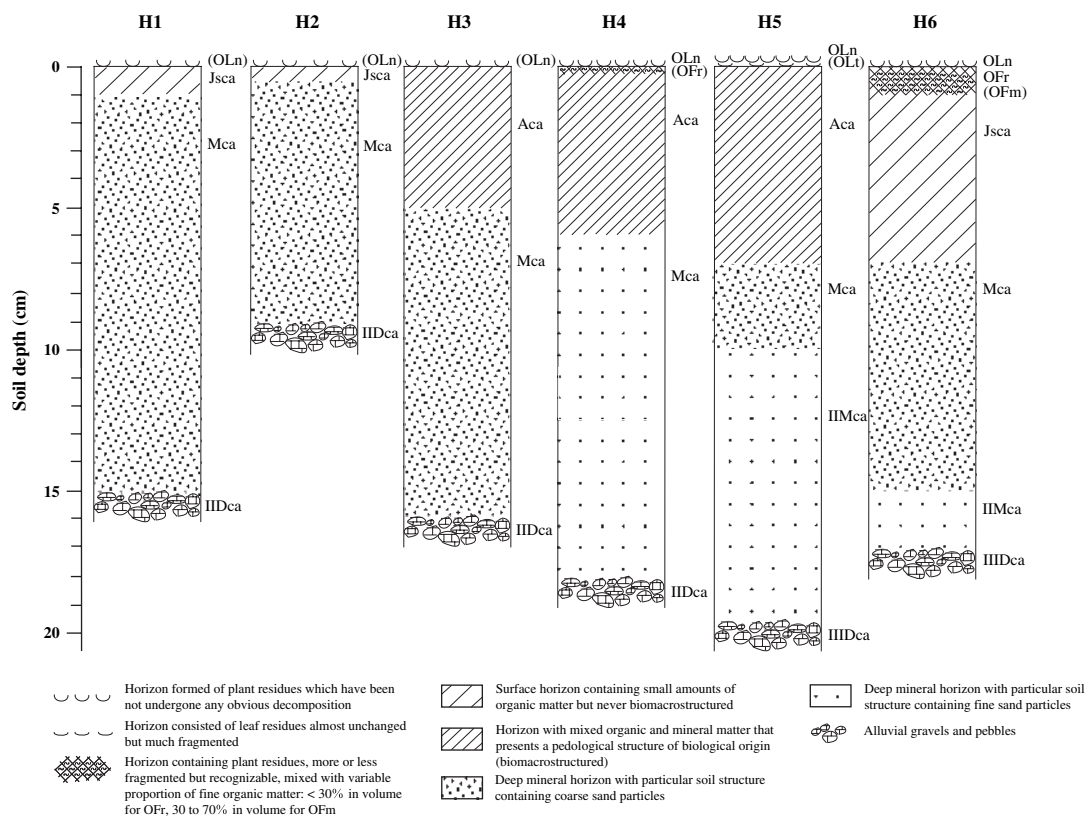


Fig. 2. Schematic diagram of the six sites. OLn, horizon formed of plant residues which have not undergone any obvious decomposition; OLv, horizon formed of plant residues which show little fragmentation, but have clearly been altered since falling to the ground; OFr, horizon consisting of easily identifiable leaf fragments which are more or less fragmented with a small proportion of fine organic matter; OFm, horizon containing equal quantities of fragmented leaf residues and masses of fine organic matter; Js, horizon containing small amounts of organic matter but never biotransformed; A, horizon with mixed organic and mineral material with generally a pedological structure of biological origin; M, friable or soft, unbroken or broken rock horizon; ca, presence of carbonates (denomination after [1]). H1 to H3 are situated in the willow plots colonized by vegetation for about 20 years, while H4 to H6 are located in the alder plots colonized for 25–30 years.

H5; oligomull for H4; and dysmull for H6. Two types of calcareous organo-mineral horizons located just under the soil surface were observed (J_{sca} and A_{ca}). The A horizons were biotransformed while the Js horizons were “young”, weakly differentiated and containing small amounts of organic matter [1].

The M horizons were sandy for each site, but fine sand was observed for the M horizon of site H4 and for the IIM horizon of H5 and H6. The thickness of these different mineral horizons was almost the same for the six sites.

3.2. Enchytraeid and earthworm communities

Despite no significant differences, the abundance of enchytraeids (Fig. 3) tended to be twice lower in H2 compared to other sites. With regard to earthworm diversity (Table 2), 11 different species were recorded: *Lumbricus castaneus*, *Lumbricus terrestris*, *Lumbricus rubellus*, *Dendrobaena octaedra*, *Dendrobaena pygmaea*,

Dendrobaena rubida, *Aporrectodea rosea*, *Nicodrilus caliginosus caliginosus*, *Nicodrilus nocturnus*, *Octolasion cyaneum*, *Octolasion tyrtaeum lacteum*. Earthworms from H2, H4, H5 and H6 were almost exclusively epigeic

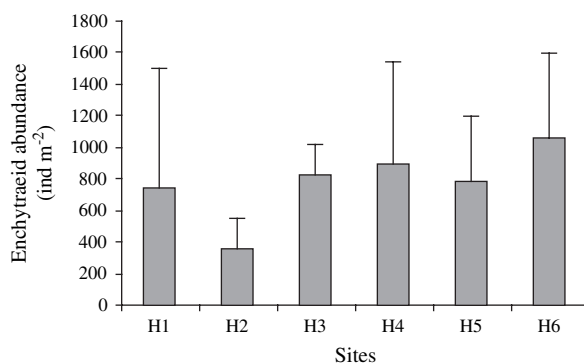


Fig. 3. Mean abundance of Enchytraeids (ind m⁻²) in the different sites H1 to H6. Bars indicate the standard deviations.

Table 2

Ecological categories (Ecol. cat.; epi, epigeic forms; ane, anecic forms; endo, endogeic forms; juv., juveniles), numbers (no m⁻², %), biomass (g m⁻², %) and ratio biomass (Ratio; g ind⁻¹) of earthworms in the six sites H1 to H6

Sites	Species	Ecol. cat.	Numbers, no m ⁻²	% of total number	Biomass, g m ⁻²	% of total biomass	Ratio, g ind ⁻¹
H1	<i>Dendrobaena octaedra</i>	epi	50.67	28	3.37	7	0.07
	<i>Lumbricus rubellus</i>	epi	1.33	1	0.43	1	0.32
	<i>Dendrobaena rubida</i>	epi	2.67	1	0.15	0.5	0.06
	Epigeic sp. juv.	epi	9.33	5	2.10	4.5	0.23
	<i>Lumbricus terrestris</i>	ane	2.67	1	13.16	28	4.93
	<i>Nicodrilus nocturnus</i>	ane	12.67	7	20.24	4	1.60
	<i>Nicodrilus</i> ssp. juv.	ane	19.33	11	5.90	12.5	0.31
	<i>Octolasion tyrteaum lacteum</i>	endo	21.33	12	6.18	13	0.29
	<i>Nicodrilus caliginosus caliginosus</i>	endo	8.00	4.5	3.11	10	0.39
	<i>Aporrectodea rosea</i>	endo	12.67	7	3.42	7	0.27
	<i>Octolasion cyaneum</i>	endo	13.33	7	4.03	8.5	0.30
	Endogeic sp. juv.	endo	28.00	15.5	1.92	4	0.07
	Total ± S.D.		182.00 ± 42	100	64.01 ± 41.97	100	0.35
H2	<i>Lumbricus castaneus</i>	epi	6.67	11	0.78	12	0.12
	<i>D. octaedra</i>	epi	4.00	6.5	0.41	6	0.10
	Epigeic sp. juv.	epi	45.33	74	2.08	31	0.05
	<i>Lumbricus</i> ssp. juv.	ane	1.33	2	0.67	10	0.50
	<i>O. t. lacteum</i>	endo	4.00	6.5	2.69	41	0.67
	Total ± S.D.		61.33 ± 14	100	6.63 ± 3.74	100	0.11
H3	<i>D. octaedra</i>	epi	22.00	11	2.17	1	0.10
	<i>L. rubellus</i>	epi	10.67	6	7.57	8	0.71
	Epigeic sp. juv.	epi	30.67	16	1.94	2	0.06
	<i>L. terrestris</i>	ane	10.00	5	34.64	36	3.46
	<i>Lumbricus</i> ssp. juv.	ane	2.97	2	3.48	4	1.17
	<i>O. t. lacteum</i>	endo	88.00	46	34.86	36	0.40
	<i>N. caliginosus caliginosus</i>	endo	17.33	9	9.38	10	0.54
	<i>A. rosea</i>	endo	4.67	2	1.90	2	0.41
	Endogeic sp. juv.	endo	5.33	3	0.86	1	0.16
	Total ± S.D.		191.64 ± 80	100	96.8 ± 65.87	100	0.51
H4	<i>D. octaedra</i>	epi	8.67	4	0.63	2	0.07
	<i>L. rubellus</i>	epi	2.67	1.5	2.07	7	0.78
	<i>D. pygmaea</i>	epi	4.00	2	0.05	0.5	0.01
	<i>D. rubida</i>	epi	24.00	12	1.26	4	0.05
	Epigeic sp. juv.	epi	91.33	45	4.02	14	0.04
	<i>O. t. lacteum</i>	endo	40.00	20	15.61	53	0.39
	<i>N. c. caliginosus</i>	endo	1.33	0.5	0.41	1.5	0.31
	<i>A. rosea</i>	endo	8.00	4	3.29	11	0.41
	Endogeic sp. juv.	endo	22.67	11	1.95	7	0.09
	Total ± S.D.		202.67 ± 71	100	29.29 ± 3.51	100	0.14
H5	<i>D. octaedra</i>	epi	3.33	10.5	0.25	6	0.08
	<i>D. pygmaea</i>	epi	1.33	4	0.02	0.5	0.02
	Epigeic sp. juv.	epi	7.33	23	0.33	7.5	0.05
	<i>O. t. lacteum</i>	endo	6.67	21	2.74	65	0.41
	Endogeic sp. juv.	endo	13.33	41.5	0.88	21	0.07
	Total ± S.D.		31.99 ± 14	100	4.22 ± 2.31	100	0.13
H6	<i>D. octaedra</i>	epi	10.67	8.5	1.07	7.5	0.10
	<i>L. rubellus</i>	epi	1.33	1	0.99	7	0.74
	<i>D. rubida</i>	epi	6.67	5	0.72	5	0.11
	Epigeic sp. juv.	epi	95.33	74.5	3.97	27.5	0.04
	<i>O. t. lacteum</i>	endo	12.67	10	7.52	52	0.59
	Endogeic sp. juv.	endo	1.33	1	0.11	1	0.08
	Total ± S.D.		128.00 ± 32	100	14.38 ± 6.35		0.11

S.D., standard deviation.

and/or endogeic and contained a lot of juveniles (Fig. 4). Anecic species were recorded in H1 and H3, *L. terrestris* in both sites while *N. nocturnus* was only found in H1. Earthworm abundance (Table 2) was higher in H1, H3 and H4 (182.0, 191.6 and 202.7 individuals m^{-2} ,

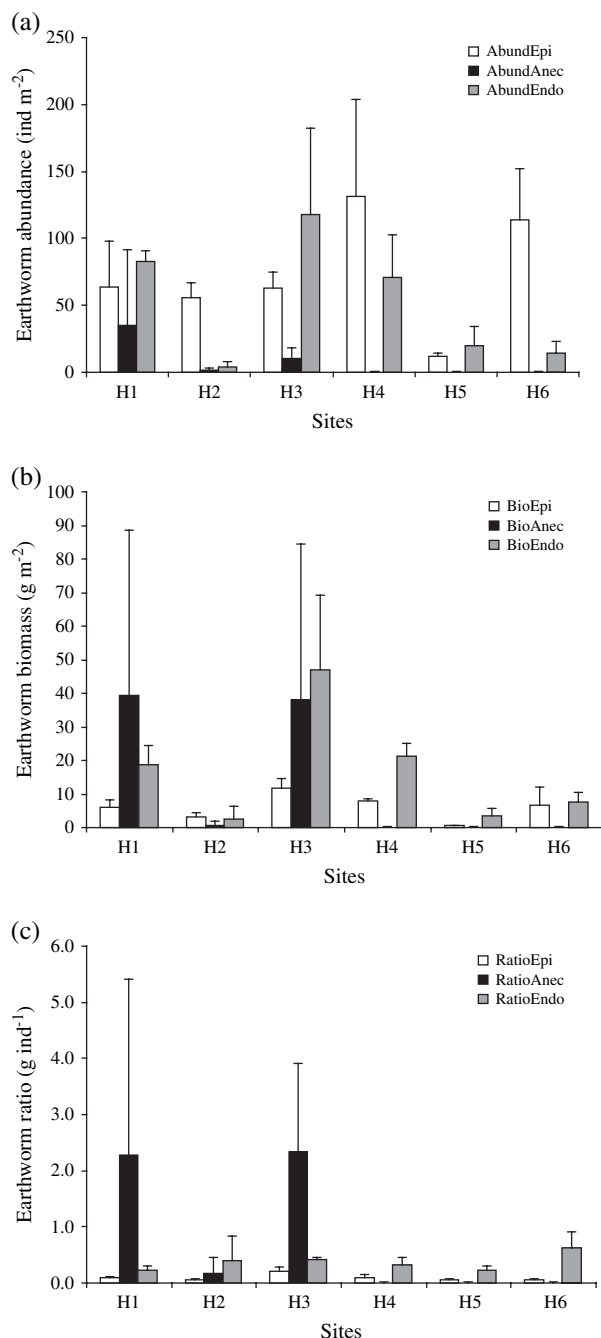


Fig. 4. Mean (a) abundance of epigeic earthworms (ind m^{-2}), (b) biomass (g m^{-2}) and (c) earthworm ratio (g ind⁻¹) in the studied sites H1 to H6 (standard deviation in bars).

respectively) compared to H5 and H2 (32.0 and 61.3 individuals m^{-2} , respectively). Epigeic species were highest in H4 and H6 while endogeic species were more present in H3 and H1. Regarding the identified species, *O. t. lacteum* was dominant in H3 and H4 and *D. octaedra* in H3. However, it should be noted that the proportion of unidentified epigeic species was very high in H2 and H6 (74%), H4 (45%) and H5 (23%), as well as the proportion of unidentified endogeic species in H5 (41.5%). In terms of biomass (Table 2), the global mean values were lowest in H2 and H5 (6.6 and 4.2 g m^{-2} , respectively) while it was largest in H3 (96.8 g m^{-2}). The endogeic and anecic biomasses were the highest in H3, followed by H1, but a high standard deviation was observed. Looking at the ratio biomass giving the mean weight of all individuals in each site, it appears clearly that the largest worms were located in H3 (0.51 g ind⁻¹), the smallest in H2, H4, H5 and H6 (0.11, 0.14, 0.13 and 0.11 g ind⁻¹, respectively), and that an intermediate ratio was found in H1 (0.35 g ind⁻¹). The same tendency was observed when ecological categories were studied separately but with a high standard deviation. Not only the number of worms but also the individual biomass contributed to the relative percentage of the total biomass.

No significant correlation was found between abundance and biomass of each ecological category on the one hand and other biotic or abiotic parameters on the other hand.

3.3. Soil analysis

The six organo-mineral horizons A_{ca} and/or J_{sca} differed in the physicochemical values especially with regard to the particle size distribution (Table 3). Despite a different tree cover and a different location within the transect, the J_{sca} horizons of H2 and H6 were enriched in coarse sand (74.7% and 51.8%, respectively). In contrast, H3 contained the highest proportion of clay (23.1%) and almost no coarse sand (7.4%). H1, H4 and H5 had medium values of each particle size (Table 3). The M horizons were particularly rich in coarse sand but poor in clay and silt compared to the upper layers. Thus, the nature (texture, carbonate content) and the thickness of these underlying deposits were similar for the six sites. The mean weight diameter (MWD) of soil aggregates was negatively correlated with the coarse sand content ($r = -0.96, 95\%, P < 0.01$) while an opposite tendency was observed for both fine silt and clay contents ($r = 0.94$ and 0.95 , respectively, $95\%, P < 0.01$).

The amount of total carbonate was higher in willow plots H2 (67%), H1 (56.4%), H3 (44.6%) than in other sites (around 35%). In addition, the relatively high

Table 3

Physicochemical characteristics in the different horizons (see Fig. 2) from the six sites H1 to H6

Sites	Horizons	pH	Total CaCO ₃ (%)	Active CaCO ₃ (%)	Fe _t (g kg ⁻¹)	S.D.	Fe _o (g kg ⁻¹)	S.D.	Fe _d (g kg ⁻¹)	S.D.	Fe _d - Fe _o / Fe _d ratio	C _{org} (%)	N _{tot} (%)	C/N	Coarse sand (%)	Fine sand (%)	Coarse silt (%)	Fine silt (%)	Clay (%)	MWD (mm)	S.D.	
H1	J _{ca}	7.9	56.4	20.0	14.8	0.12	1.4	0.009	4.1	0.02	18.2	34.1	2.8	0.2	14	33.2	20.9	12	18.9	15	0.908	0.023
	M _{ca}	8.6	66.2	13.8	-	-	-	-	-	-	-	-	0.6	0.04	-	72.4	15.6	3.7	5.7	2.6	-	-
H2	J _{ca}	8.1	67.0	10.9	10.1	0.05	0.5	0.0002	2.2	0.001	16.8	22.7	1.2	0.1	12	74.7	5.9	4.6	9.9	4.9	0.389	0.004
	M _{ca}	8.3	72.4	7.5	-	-	-	-	-	-	-	-	0.2	0.03	-	93.7	3.5	0.9	2.0	0	-	-
H3	A _{ca}	7.9	44.6	20.8	19.7	0.04	2.2	0.002	6.5	0.02	21.8	33.8	3.5	0.2	17	7.4	21.7	17.2	30.6	23.1	1.168	0.031
	M _{ca}	8.5	76.1	10.4	-	-	-	-	-	-	-	-	0.4	0.3	-	84.1	9.5	1.8	4.3	0.2	-	-
H4	A _{ca}	7.9	35.0	18.0	22.6	0.07	2.5	0.014	5.7	0.015	14.2	43.9	2.9	0.2	13	20.6	32.2	18.8	17.2	11.2	0.868	0.037
	M _{ca}	8.3	39.4	16.2	-	-	-	-	-	-	-	-	1.2	0.08	-	35.5	35.8	12.8	11.4	4.6	-	-
H5	A _{ca}	7.8	35.0	19.4	21.7	0.14	2.3	0.017	5.7	0.02	15.7	40.3	5.4	0.4	15	20.7	27	12.8	22.1	17.3	1.039	0.007
	M _{ca}	8.5	54.5	8.9	-	-	-	-	-	-	-	-	0.8	0.05	-	76.8	12.3	2.6	6.8	1.5	-	-
	IIM _{ca}	8.3	43.5	18.1	-	-	-	-	-	-	-	-	1.5	0.1	-	42.1	25.2	11.3	12.9	8.5	-	-
H6	J _{ca}	7.4	33.9	10.5	18.3	0.04	2.0	0.007	4.8	0.03	15.3	41.7	12.1	0.9	13	51.8	9.7	10.3	15.5	12.7	0.733	0.007
	M _{ca}	8.1	56.5	10.1	-	-	-	-	-	-	-	-	1.5	0.1	-	63.9	17.9	5.0	8.8	4.4	-	-
	IIM _{ca}	8.2	43.9	15.0	-	-	-	-	-	-	-	-	1.1	0.08	-	37.0	40.3	9.1	9.8	3.7	-	-

pH, total and active carbonates (Total CaCO₃ and Active CaCO₃, in %), iron forms (Fe_o: amorphous iron; Fe_d: crystallized iron; Fe_t: total iron, in g kg⁻¹), iron form ratios (Fe_d - Fe_o/Fe_d, Fe_o/Fe_d), organic carbon (C_{org}, in %), total nitrogen (N_{tot}, in %) and C/N ratio, soil texture (coarse and fine sand, coarse and fine silt, clay, in %), mean weight diameter (MWD, in mm). Iron forms were only measured on organo-mineral horizons and the C/N ratio and MWD were only calculated for J_{ca} and/or A_{ca} horizons. Standard deviations (S.D.) are given for iron forms and MWD.

content of active carbonate (20%) found in H1, H3, H4 and H5 was negatively correlated with the coarse sand content ($r = -0.89$, 95%, $P < 0.05$). The organic matter showed great variations along the transect, with high contents in H6 (12.06% and 0.91% for C_{org} and N_{tot} , respectively). However, the C/N ratios remained quite constant except for H5 (15.2) compared to a value of around 13–14 for the other sites.

As for iron forms, concentrations of total iron Fe_t were highest in the alder community sites H4 (22.6 $g\ kg^{-1}$) and H5 (21.7 $g\ kg^{-1}$) compared for instance to H2 (10.1 $g\ kg^{-1}$). These values were inversely proportional to coarse sand content. A significant positive correlation was found between Fe_t , Fe_o , Fe_d and the coarse silt content (respectively $r = 0.85$, $r = 0.87$, $r = 0.89$, 95%, $P < 0.05$), but no other significant correlation was found with another mineral fraction. The values of Fe_d were low for H2 (2.2 $g\ kg^{-1}$) and high for H3 (6.5 $g\ kg^{-1}$) and showed a positive correlation with the MWD ($r = 0.91$, 95%, $P < 0.05$). The same tendency could be observed for the values of Fe_o

(low for H2 and H1; 0.5 and 1.4 $g\ kg^{-1}$, respectively). But these two iron forms showed a significant negative correlation with the coarse sand amount ($r = -0.92$, 95%, $P < 0.01$ for Fe_d ; $r = -0.82$, 95%, $P < 0.05$ for Fe_o). The ratio Fe_o/Fe_d increased gradually from H2 (22.7) to H5 (40.4) with a peak in H4 (43.9) and a negative correlation was observed between Fe_o/Fe_d and the total carbonate content ($r = -0.94$, 95%, $P < 0.01$).

As a complement to biological variables, the $Fe_d - Fe_o/Fe_t$ ratio, which represents an index of the soil evolution and increases with time, was positively related to the biomass of anecic earthworms ($r = 0.85$, 95%, $P < 0.05$) while the abundance of enchytraeids was negatively related to the total carbonate amount ($r = -0.88$, 95%, $P < 0.05$).

3.4. PCA synthesis

The principal component analysis (PCA, Fig. 5) illustrates in a two-way axis the relationships between all measured variables. The first principal component

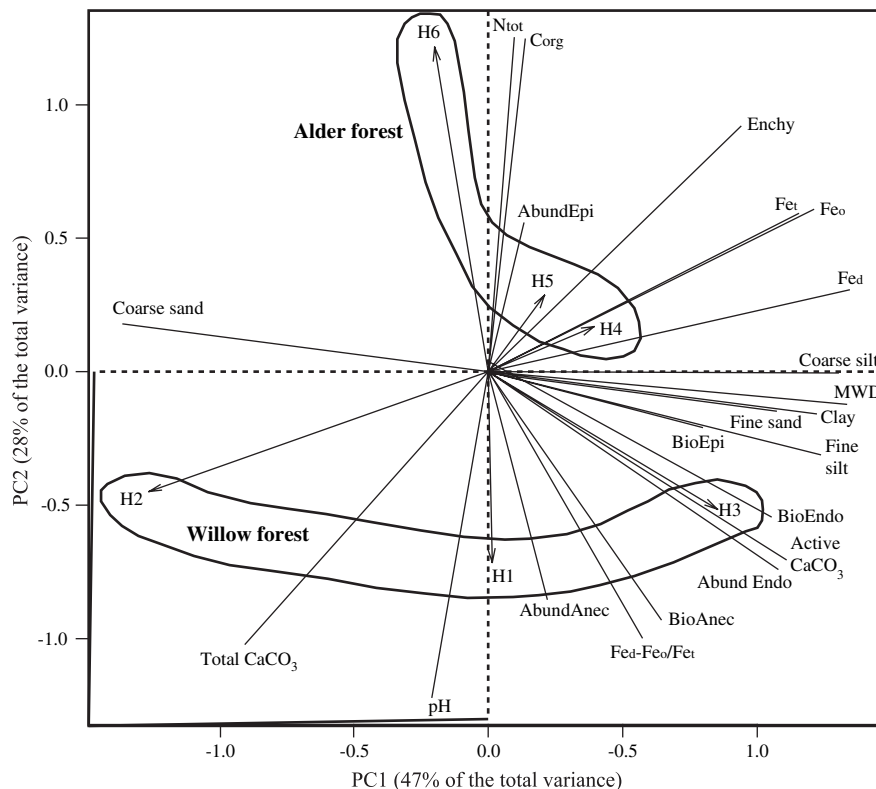


Fig. 5. Results of the principal component analysis (PCA): ordination of the samples (H1 to H3: willow plots; H4 to H6: alder plots) and the variables in the plane defined by the axis PC1 and PC2. Variables: codes as in Table 3; Enchy, enchytraeid abundance; AbundEpi, epigeic earthworm abundance; BioEpi, epigeic earthworm biomass; AbundAnec, anecic earthworm abundance; BioAnec, Anecic earthworm biomass; AbundEndo, endogeic earthworm abundance; BioEndo, endogeic earthworm biomass.

axis PC1 (explaining 47% of the total variance) separated the samples according to the particle size distribution (except the coarse sand), the MWD and the biomass of epigeic and endogeic earthworms on the right side. The second axis PC2 (explaining 28% of the total variance) discriminated the forest types with alder plots at the top and willow plots at the bottom. Along this same axis, differences were also visible between pH values (at the bottom) and contents of C_{org} and N_{tot} (on the top).

The PCA showed a relationship between most of the biological parameters (biomass and abundance of worms) and the sites H3, as well as H1 to a lesser extent. However, no strong relations appeared between earthworm's criteria and the different iron forms, except for $Fe_d - Fe_o/Fe_t$ ratio that was more related to anecic earthworms.

Furthermore, the site H2 was clearly correlated with the coarse sand and the carbonates, while H4 and H5 were more related to the number of enchytraeids, the abundance of epigeic earthworms and the different iron forms. These iron forms were also more associated with the coarse silt content than other particle size parameters and were closed to the MWD. No strong relations appeared between the soil texture and the concentrations of C_{org} and N_{tot} revealing no evident difference between H3 and the alder plots (H4, H5 and H6).

4. Discussion

4.1. Biological parameters

Enchytraeids are an important group of the soil mesofauna in most temperate terrestrial biotopes [37]. The density of enchytraeids is generally higher in acid soils with important organic content [13]. Thus, the high pH values found in our soils could explain the low average abundance of enchytraeids compared to the values reported for an intensively cultivated agricultural soil, dry sclerophyll forests or a peat moor [13,17]. The slightly greater abundance in H6 could be due to the highest content of organic carbon found in that site. As enchytraeid densities are usually associated with soil moisture and silty particles, their low abundance in our case may also be due to the unfavourable conditions of humidity due to the particle size distribution (sandy soils are drier than silty soils). Another reason for this low abundance could be the competition with earthworms, since they have been often reported to have a considerable effect on enchytraeid populations: in an acid (pH 4.5) deciduous forest [43], they were shown to drastically decrease their abundance, while

other authors also suggested a negative relationship between enchytraeids and earthworms at different acidities (pH 4.9 and pH 6.1 in unlimed or limed forest soil respectively) [44]. Moreover, an antagonistic relationship was also found in a polder soil, which showed less enchytraeids upon inoculation with earthworms [17]. Nevertheless, this last author also demonstrated that both groups showed optimal population development at different temperatures and moisture levels, suggesting that in natural environments, they occupy different ecological niches.

Another reason for the relatively low abundance of enchytraeids could be the sampling period. Samples were collected during summer time and high temperatures may have killed or forced a part of the population to move to the deeper soil layers. Due to a variable abundance of enchytraeids (see the high standard deviations), no statistical difference between the six soils was found. But as soil structure actors, and even if the abundance is low, enchytraeids affect soil structure by producing faecal pellets that influence aggregate stability by creating favourable habitats for microorganisms [13]. These microorganisms are also known to have a great influence on the decomposition of freshly fallen leaf litter [56] and form micro-aggregates after soil organic matter consumption. Particles aggregation is then stimulated, which greatly improves the soil structure [28]. This influence is particularly relevant in initial stages of soil structure formation, as investigated here, where earthworm communities are still not well developed.

In the present study, abundance and biomass of earthworms were similar to those recorded in a subtropical forest in Athens (GA, USA) with sandy loam to sandy clay loam soils [10] or in various woodland types on clay or limestone soils [14]. A study of earthworm distribution within different humus forms in beech forests [51] gave a mean abundance of 220 individuals m^{-2} and a mean biomass of 116 $g m^{-2}$ for a rich mull humus form. These data are comparable to our site H3 and to H1 and H4 for the mean abundance. However, our results were much higher than those of Zorn et al. [57], who observed only five different species in an active floodplain system. This low diversity was explained by the climatic conditions in the Netherlands with long periods of flooding. Our study site could then not be considered as an active floodplain system but, in contrast, as a stable dynamic alluvial system. The relative contribution of juveniles to the average abundance and biomass of our studied plots is quite similar to studies conducted in a deciduous forest in the United States [50] where juveniles accounted for

approximately half of the total biomass and of the total number of individuals.

Concerning the epigeic category, the preponderance of *D. octaedra* in H1, H3, H4 and H6 indicated a higher degree of organic matter humification than in other plots [50]. The other epigeic species *L. rubellus*, indicating less humified conditions, was also present in H1, H3, H4 and H6, but to a lesser extent. This species plays a major role in the first steps of aggregation because it adds numerous secretions to soil as it passes through the gut and thus increases the organic carbon content in casts [48]. The absence of this species in H2, associated with a sandy texture difficult to ingest and to stabilize in aggregates could explain the lower aggregate stability reflected by the low MWD. In addition, *L. castaneus*, which indicates a reduced organic matter content, dominated in H2. In contrast, the presence of *D. pygmaea* in H4 is a sign of high content of organic matter and possibly a sign of sand as well [7]. The high number of *D. rubidus* in H4—and in H6 to a lesser extent—indicated a good biological activity in the upper layers. This species is known to be ubiquitous and very mobile in the superficial layers of soil and has been reported to consume a proportionately greater amount of organic matter than deeper-burrowing species [29].

The anecic category was only present in H1 and H3. The deep-burrowing *L. terrestris* was dominant in H3 and represented one third of the total biomass. This species is known to have a positive effect on soil structure by creating mixing casts of organic and mineral particles. These casts may then be hardened into stable soil aggregates and provide a food source for other animals in deeper soil strata [46]. The massive abundance and biomass of *L. terrestris* in H3 and the smallest abundance in H1 can be explained by the soil texture. According to Cuendet [14], this species prefers a soil formed of limestone layer instead of clay, and Curry [15] demonstrated a positive relationship between clay content and different species including *L. terrestris*. Thus, a sandy texture is not favourable for worms because the low water content does not maintain the hydrostatic pressure and then does not prevent desiccation [57]. In abrasive gravelly soils the earthworm skin could be injured because of its softness [13,15]. This constraint is particularly true for the anecic category (but also for the endogeic one), which contributes also to the mixing of organic and inorganic material in deep layers (bioturbation). Thus, the soil texture can explain the absence of anecic earthworm in H4, H5 and H6 despite the oldest age of tree population, compared with the three other sites.

The endogeic category was mostly present in H1, H3 and H4 with the dominance of *O. t. lacteum*. This neutrophilous species plays a major role in the stabilization of organic matter by incorporating litter fragments into the mineral layers. This bioturbation is a key process in the formation of mull humus forms [19] and the presence of anecic and endogeic earthworms in soils, as observed for H1, H3 and H4, has a critical impact on soil structure, aggregate formation and stability.

Thus, the present paper suggests that, in terms of soil biota succession, epigeic earthworms are probably the first engineers, with enchytraeids, in the initial steps of soil structuring. Then, if the soil texture is favourable, the anecic and endogeic earthworms rapidly invade the different soil layers and improve the physical and nutrient conditions.

4.2. Physicochemical characteristics

In this study the effect of the particle size distribution of the surface horizons on soil structure was evident. As the nature and thickness of the underlying mineral horizons (alluvium gravel and M horizons) were similar, we could then exclude in our case their influence on structure of the upper horizons. Thus, aggregate stability, illustrated by MWD, is strongly dependent on the particle size distribution of the recent deposits and not only on the duration of soil evolution. We did not find, in contrast to many authors [20,42,53], a positive correlation between organic carbon content and aggregation. In our case, the aggregate stability was positively correlated with enchytraeid abundance, coarse and fine silt, and clay content of A and/or J horizons, as well as with different iron forms and negatively correlated with coarse sand content. The “young” site H3 showed the highest MWD value with fine sand, fine silt and clay contents. It is well recognized that clay particles are particularly involved in the soil structure with an increase of aggregate stability when clay content increases [30]. But it has until now never been demonstrated that the fine parts of sand particles as well as the silt particles also participate to aggregate stability. Boix-Fayos et al. [6] showed that large aggregates (>5 mm) were positively correlated with the amount of sand but this occurred in the presence of earthworms producing casts. It has already been shown that medium-textured soils appear to be more favourable to earthworms than sandy soils or soils with high clay content [15]. Shipitalo and Protz [48] also showed that sand content was significantly lower and the clay content greater in casts of small worms such as *L. rubellus*

than in casts of the large worm *L. terrestris*. In our case, the site H3 presented these expected conditions and was indeed rapidly colonized by anecic earthworms that produced stable aggregates in spite of a recent and silty sand deposit.

Data for iron forms found in this work were quite similar to other studies [25] or a little lower [3]. Our data showed that among the “youngest” (in terms of sediment deposition and age of present tree population) sites H1, H2 and H3, the stability of aggregates increased with the increase of various iron forms proportions. These iron forms and particularly the Fe_o type are usually considered as cement particles in water-stable aggregates [20] and are related here to the fine particles of soil. It is known that clay and Fe_d contents are significantly and positively correlated in the upper layers [25,35], but it was revealed by our correlation analysis that the coarse silt fraction was the prime supplier of Fe_t . In addition, Fe_d , which increases with increasing soil formation age, was also associated to the silt particles in our alluvial context. Clearly, fewer proportions of various iron forms were extracted from the coarse sandy H2, implying a reduced aggregate stability.

Calcium carbonates are also known to act as cementing agents by maintaining the flocculated structure or the clay in soil-surface aggregates through acid neutralization [21]. In our study, this content was not correlated to any textural classes and calcium carbonates were distributed equally among the different textural fractions. But the negative correlation with Fe_t and Fe_o forms revealed that the carbonated part of soil was characterized by a weak iron content. Moreover, the active calcium carbonates, which represent the finest fraction of total calcium carbonate and binding particles, showed a low calcium availability in the coarse sand fraction. In our study, this coarse sand fraction played clearly a major role in the aggregate stability and influenced strongly the humus form evolution.

5. Conclusions

The study of soil biological and physicochemical processes on initial stages of soil structure formation in two different tree population types brought new observations to light:

1. The distribution of earthworm categories depends on the soil texture of the recent deposits and not only on the soil age that is reflected by the colonizing age of tree populations. Soil biota succession

appears in two steps: epigeic earthworms with enchytraeids are the first engineers producing in a short-term soil structure and then, if texture is favourable, anecic and endogeic earthworms invade the different soil layers improving physical and nutrient conditions and creating long-term stable aggregates.

2. The particle size distribution of the upper horizon strongly influences aggregate stability that is weak in the presence of coarse sand content and stronger with fine silt and clay contents. When the structure stability increases, a positive feedback appears and accelerates the formation of large aggregates despite a recent and silty sand deposit. No strong influence of the underlying mineral horizons (alluvial gravel or buried mineral horizon) was found.
3. Iron forms acting as cementing agents in soil aggregation are observed in the coarse silt fraction representing the prime supplier of iron and are found in low amounts in the coarse sand fraction.
4. Calcium carbonates are equally distributed among the different textural fractions. However, the negative correlation between active calcium carbonate fraction, representing the finest part of total calcium carbonate, and the coarse sand content could also explain a lack of aggregate stability in this textural class. Active calcium carbonate seems to be a good agent for binding organic matter with mineral components.

In conclusion, we showed in our study that the tree population age cannot be used alone as an indicator of the humus form formation and evolution. Biological and physicochemical parameters, especially particle size distribution and earthworm categories, also strongly influence aggregation in the initial phases of soil structure formation in an alluvial context, such as the Sarine River. These differences in soil development induce a heterogeneous distribution of the humus forms that increases the ecological value of the alluvial zone and the continuity of ecosystem functions.

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Addenda 1a

In addition to the definition of paleosols found in 3.1.3, some other concepts of paleopedology should be given. For example, Kraus (2002) showed that in floodplain paleosols the same processes happen than in modern soils, but at different scale of time. Redoximorphic features resulted from the fluctuations in soil saturation may be detected. In the same way, earthworms produced burrows and permit an incorporation of organic matter in depth with help of roots. Moreover, degree of soil development is dependent on rates of sediment accumulation and attributed to different frequencies of channel avulsion, which differ throughout the entire floodplain. These processes are of course also visible in our contemporary alluvial soils.

It has also been showed that maturity of paleosols increases with longer periods of nondeposition (pedogenesis) and thus slower sediment accumulation (Kraus and Bown, 1993). Moreover, the nature of deposited sediments influence greatly rates of pedogenesis, and even more, two different depositional processes of same grain size parent material led to two major groups of paleosols (Kraus and Gwinn, 1997).

It is also interesting to notice that sedimentation and erosion episodes occupy very little time in any alluvial sequence (Kraus and Bown, 1986). Accumulation of alluvial sequences leads to a complete stratigraphic sequence of paleosols that may be compared to our modern soils. Indeed, each alluvial sequence of paleosol acts like each horizon in soil profile and evolves independently.

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Addenda 1b

Terminology in sedimentary environment

In order to specify the definitions given in the introduction of chapter 3, we have to precise that the “horizon” expression was taken with the pedological direction of the term. Indeed, it defines any layer of soil, roughly parallel to the land surface that may be distinguished from adjacent layers because it differs in physical, chemical or biological characteristics, e. g. colour, kinds and numbers of organisms present, soil structure, soil consistence, soil reaction. This definition has to be distinguished from the one given for “lamina” that may be considered as the smallest megascopic layer in a sedimentary sequence (Reineck and Singh, 1980). It is relatively uniform in composition and texture (with sometimes some gradational features) and is usually measured in millimetres or several centimetres. This lamina, assimilated to our pedological horizon, may be arranged with other units-laminae in order to compose a “bed” that presents various thickness limits and ranges widely in lateral extent. The composition and textures within the bed may be uniform or heterogeneous. This heterogeneity in texture represents the major feature, with the smaller lateral extent and the shorter period of formation, making a distinction between bed and lamina.

In alluvial context, and in order to compare our results with others pedological studies, we used the term horizon in the same direction as lamina defined in sedimentary studies. In French, the term “*lit sédimentaire*” is used to define bed or layer of low thickness (few centimetres to few decimetres) especially for the sedimentary rocks (Foucault and Raoult, 2000).

Effects of ground water

Moreover, it has to be specified that in our examination of the vertical succession of horizons, the effects of ground water were not really explained and taken in consideration. This is due to the fact that in the Flood’Alps project, another PhD thesis has been lead in hydrology and should have given precise information about presence or fluctuation, vertical depth or effects of ground water. Unfortunately, this study was delayed and much information thus missed. For reason of time, it was not possible at the end of this research to look further into this subject provoking lacks in some discussion of chapters 3 and especially 4.

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Addenda 2

In addition to the clustering analysis found in 4.5.2, another cluster using unweighted pair-group average (UPGMA) was applied to the *A/J* horizon data. In this method, the distance between two clusters is calculated as the average distance between all pairs of objects in the two different clusters. According to Legendre and Legendre (1998) this technique must be applied with caution in ecology because it gives equal weights to the original similarities and thus, objects in each group form a representative sample of the corresponding larger groups of objects in the reference population under study. It should only be used in connection with simple random or systematic sampling designs. Anyway, after having testing the cophenetic coefficient of each clustering methods, the UPGMA cluster showed a better coefficient (0.73) than the Ward's minimum variance method (0.58). A new principal component analysis (PCA) was then performed.

The UPGMA clustering separates also 7 groups of *A/J* horizons (called AJbis1 to AJbis7) presented in the figure 4.52bis. These groups differ from the ones presented in 4.5.2 at first by the repartition of each horizon in the different group. Groups AJbis1 and AJbis6 present only one horizon, when group AJbis7 only two horizons and groups AJbis2 and AJbis5 only three. Most of the samples are represented in the group AJbis3 characterized by a fine texture (mainly coarse and fine silt) and average values for the chemical parameters. These horizons were previously found in AJ2, AJ6 and a part of AJ7 of the Ward's clustering method. AJbis2 corresponds to the previous AJ1, as the horizons of AJbis4 were formerly associated to groups AJ4 and a part of AJ7. The statistical analysis (regression tree) indicates here again that fine silt content is the most discriminating factor for this new clustering analysis (more of less than 20%). The new calculated PCA (fig. 4.54bis) reflects the same repartition in the plane defined by the axis PC1 and PC2 for the different factors as the one found in figure 4.54. We may observe that organic matter factors (OC, OM, phosphorus forms and Tot N) do not seem to be correlated with fine mineral particles (particularly fine silt and clay). This is quite relevant and needs some further developments.

Thus, some horizons are found again in the same group, but other combinations are also given. In this way, we can observe that when a method is chosen, which seems appropriate to studied data, the responsibility lies with the researcher implying a notion of risk. Anyway, we can also conclude that with different methods used, the same global tendencies are obtained.

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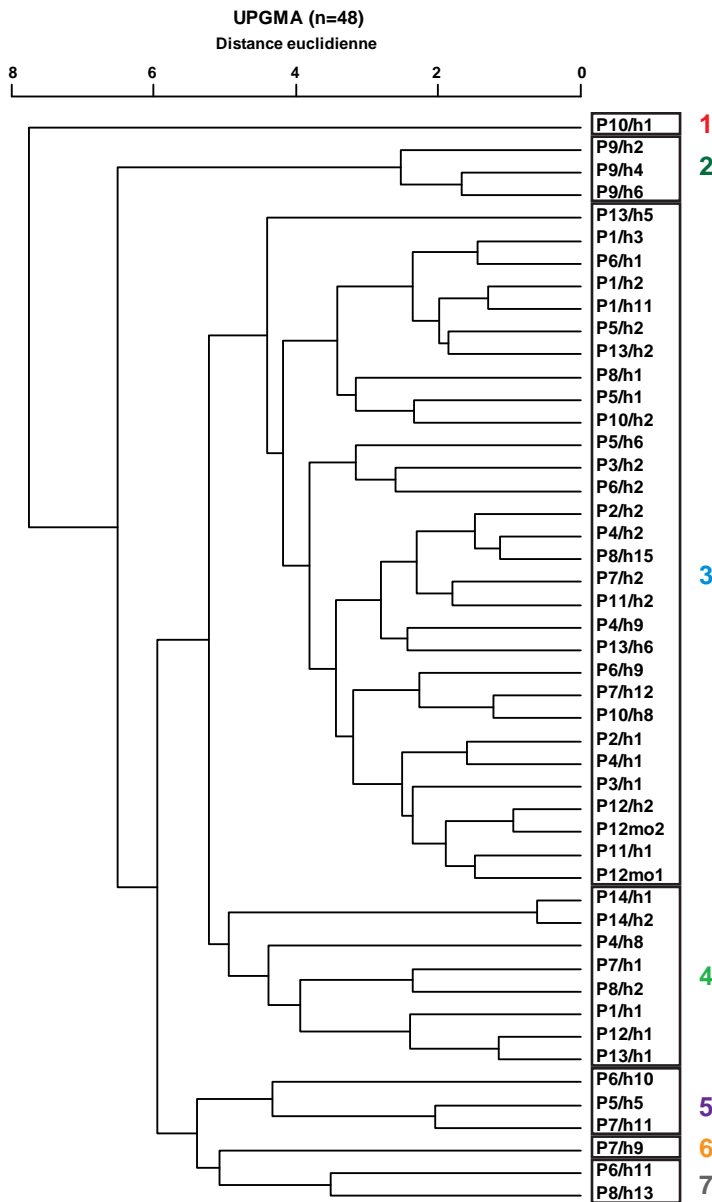


Fig. 4.52bis. Simplified dendrogram for 48 horizons containing organic matter obtained by means of UPGMA (unweighted pair-group average) clustering and described in the 14 soil profiles. The group fusion level is defined by a distance in R Software (version 2.4.1; R Development Core Team, 2006). Seven groups are then defined.

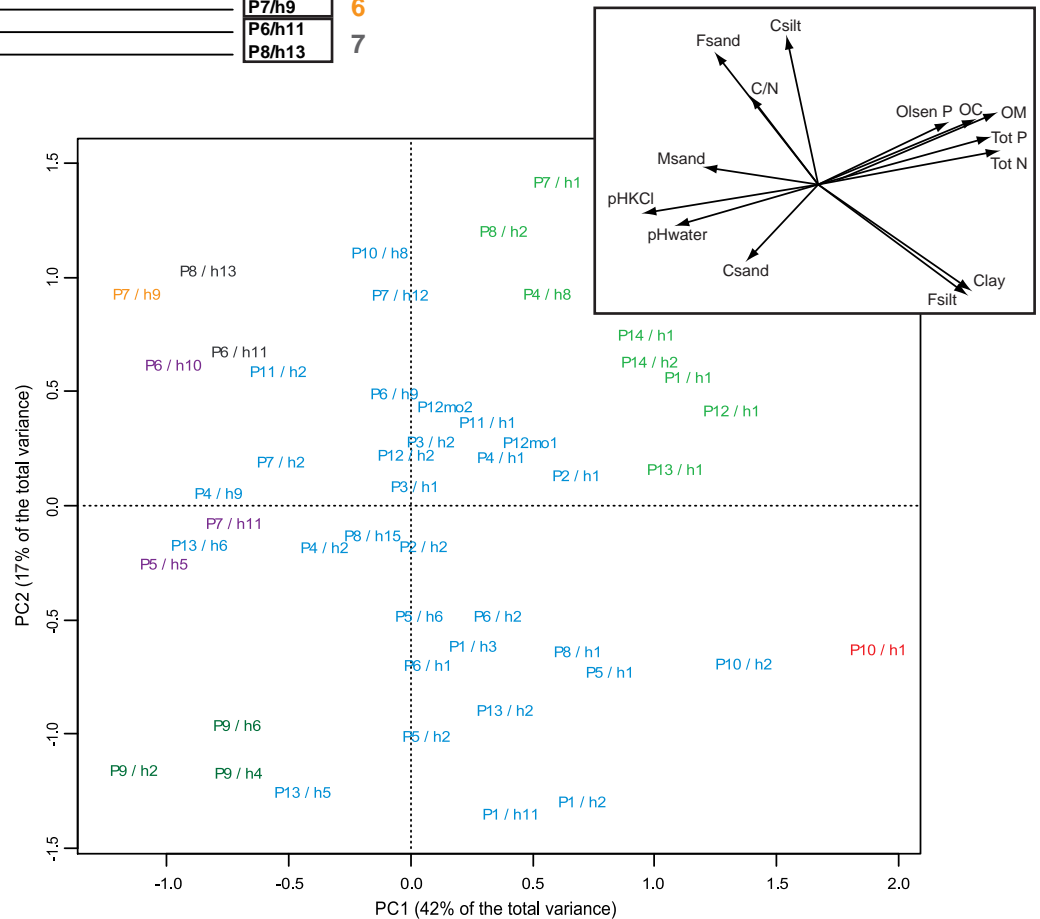


Fig. 4.54bis. Results of the principal component analysis (PCA): ordination of the samples (horizons containing organic matter; n=48) and soil parameters in the plane defined by the axis PC1 and PC2. Abbreviations: Csand = coarse sand; Msand = medium sand; Fsand = fine sand; Csilt = coarse silt; Fsilt = fine silt; OC = organic carbone; OM = organic matter; Tot N = total nitrogen; Olsen P = Olsen phosphorus; Tot P = total phosphorus. See fig. 4.52bis for color legends.