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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.

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 m^3/s in 1974, and the mean annual discharge was 217 m^3/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 Gruyere 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.

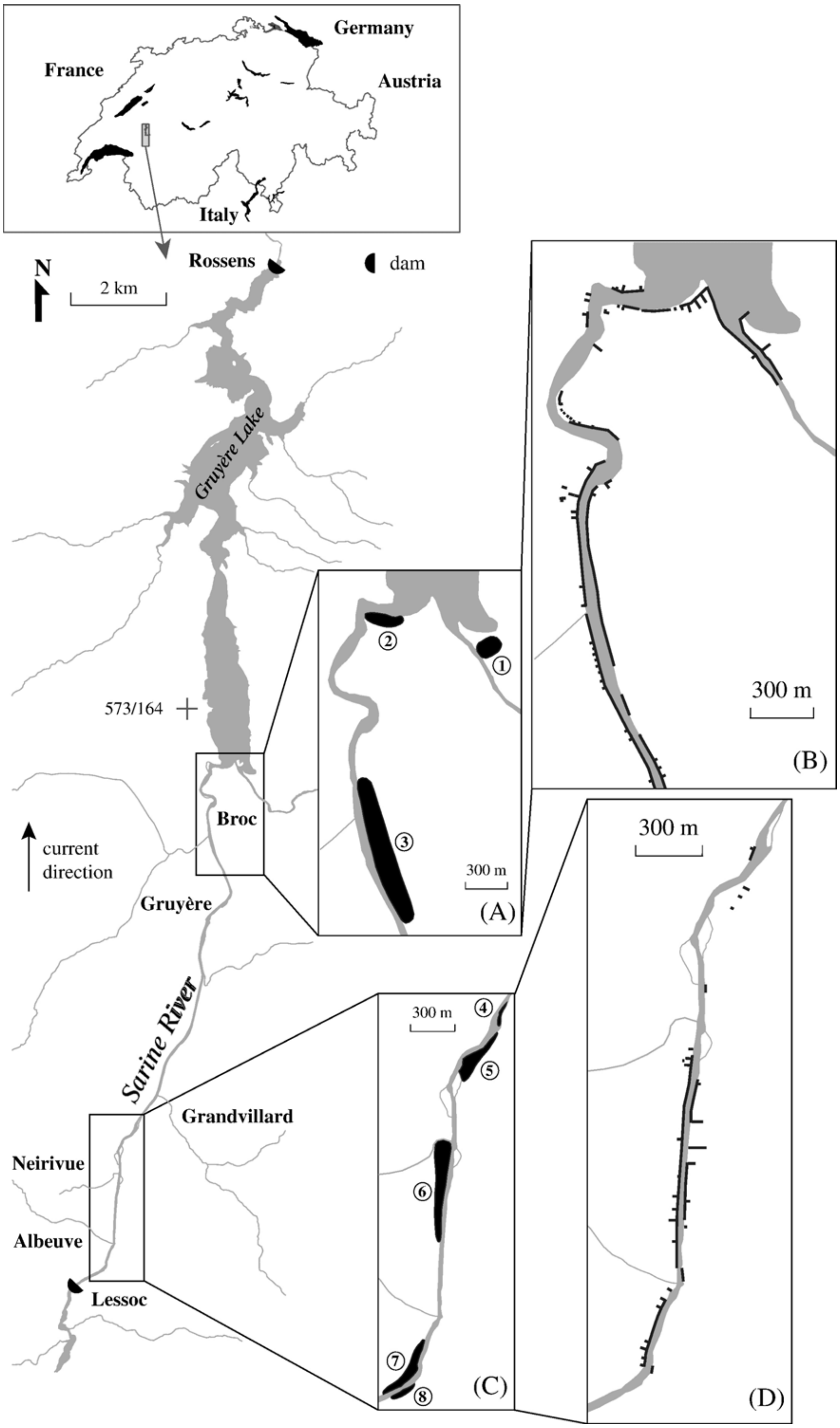


Fig. 1. Localisation of the Sarine floodplain with two major study areas: (A) downstream area with investigated zones in black (sites 1 to 3); (B) location and distribution of embankments throughout the downstream area; (C) upstream area with investigated zones in black (sites 4 to 8); (D) location and 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), 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; 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 (18%); 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

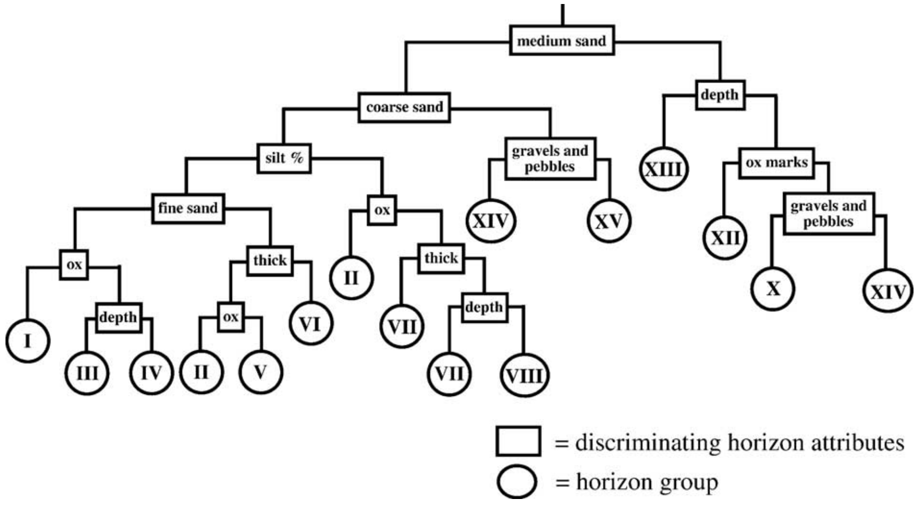


Fig. 2. Simplified dendrogram for 367 soil horizons obtained by means of Ward's minimum variance clustering and described in the 109 profiles from the Sarine floodplain. The group fusion level is defined by a distance and the discriminating horizon attributes are obtained after a regression tree in R 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).

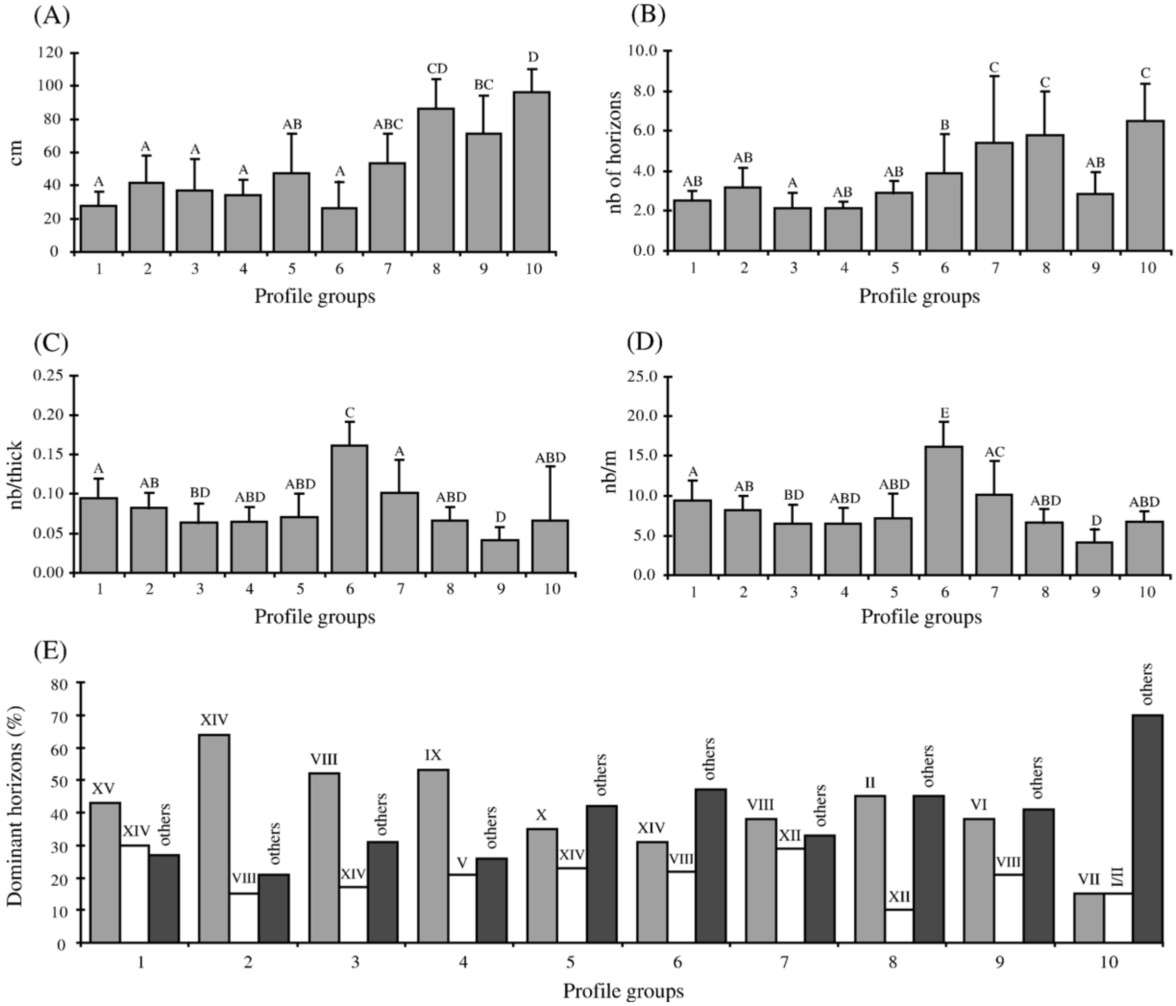


Fig. 3. Average values of profile parameters in the 10 profile groups, (A) total thickness of profile, (B) number of horizons found in profile groups, (C) index "number of horizons on the total thickness", (D) index "number of horizons per meter", and (E) dominance of horizon groups in profile groups.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

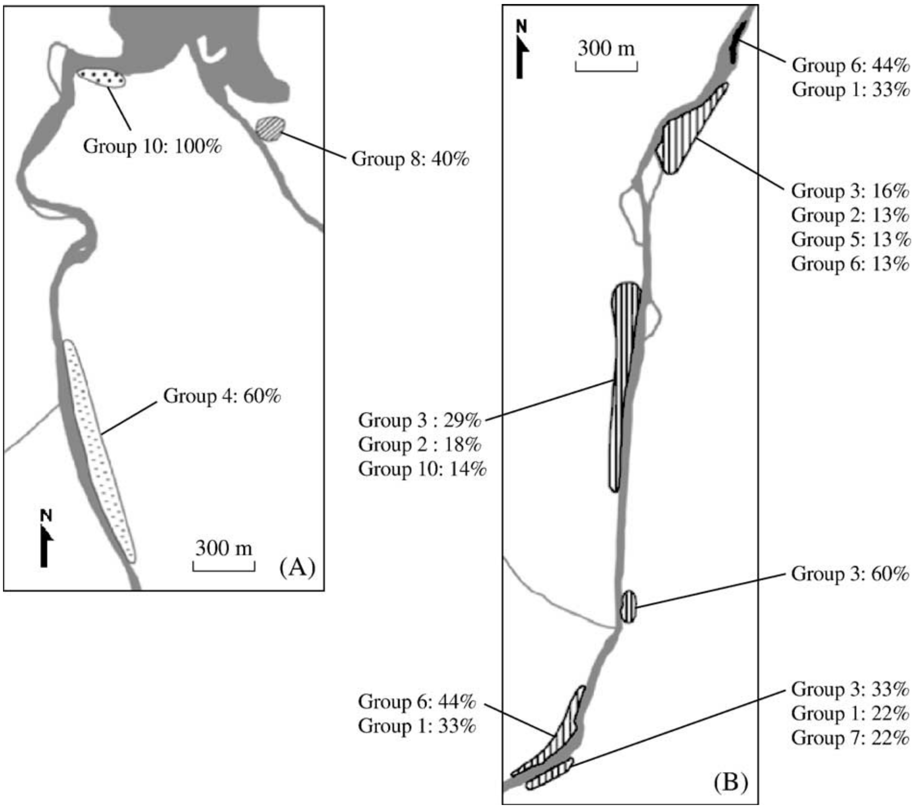


Fig. 4. Relative location of different profile groups within the two major study areas of floodplain landscape: (A) downstream area; and (B) upstream area. This distribution reflects the location of the statistical abstractions of soil properties, rather than distributions of real soils. Dominant profile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

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.

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

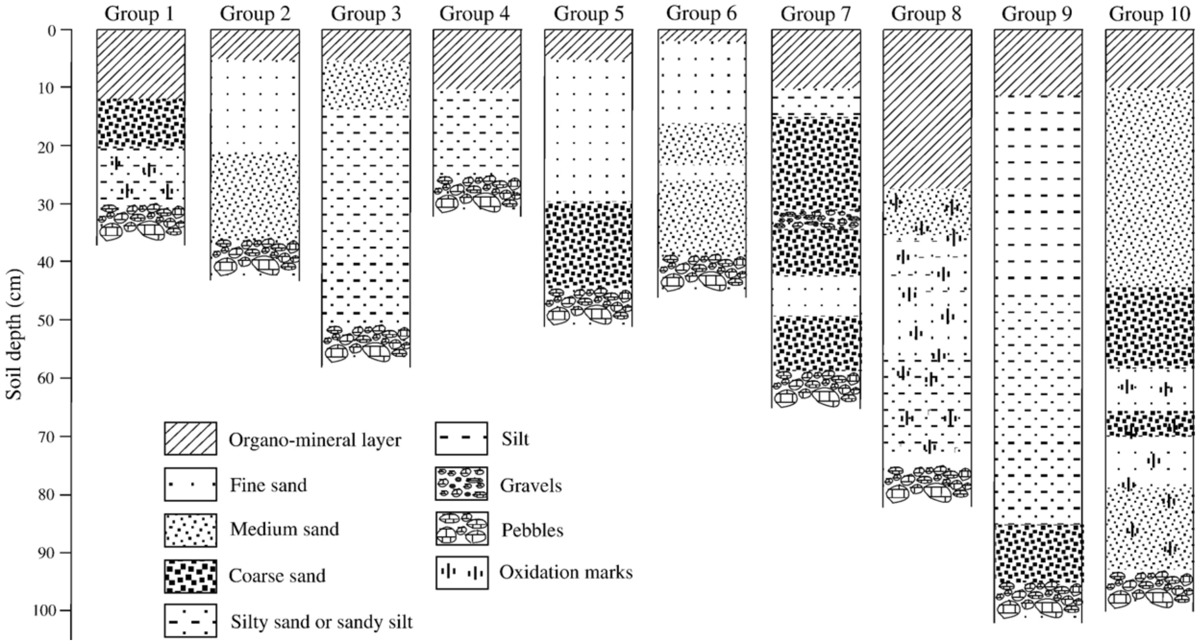


Fig. 5. Schema of a representative real profile of each group (group 1 to group 10).

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

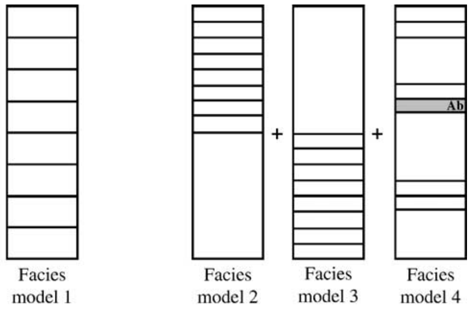
Table 3
Summary of representative profiles' characteristics (see also Fig. 3)

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



(1) Homogeneous option (2) Combined option

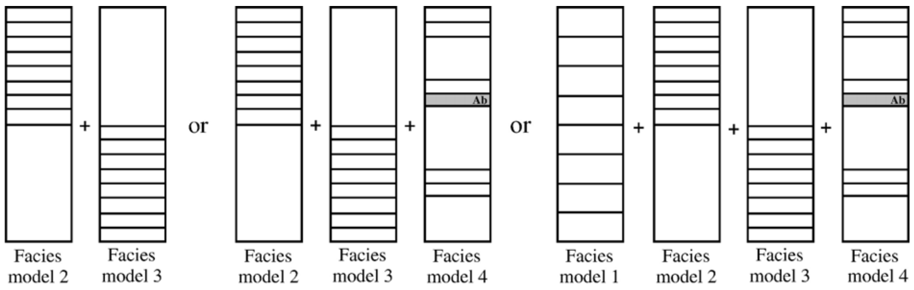
Fig. 6. Representation of two types of stratification — options (1) and (2) — illustrated by four facies models (1 to 4) found in the vertical sequence and, because of the linear relationship between the total thickness of the profile and the number of horizons. The homogeneous option means that fluvial 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).

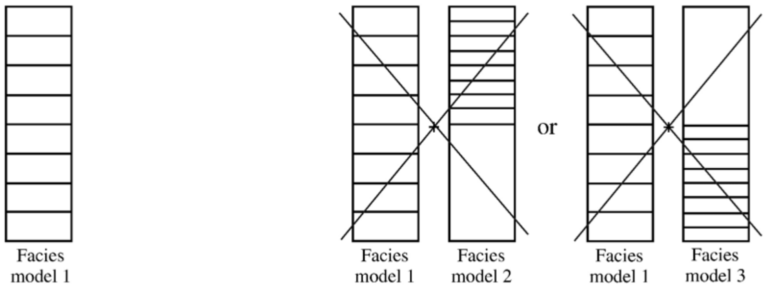
As seen above, each facies model can be used to explain concrete situations at a small scale in the field. They can also permit generalization at a larger scale and be used as "erasers" of local differences. What is important in the differentiation between these two situations is the scale taken into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



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



(B) Unlikely combinations (C) Impossible combinations

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

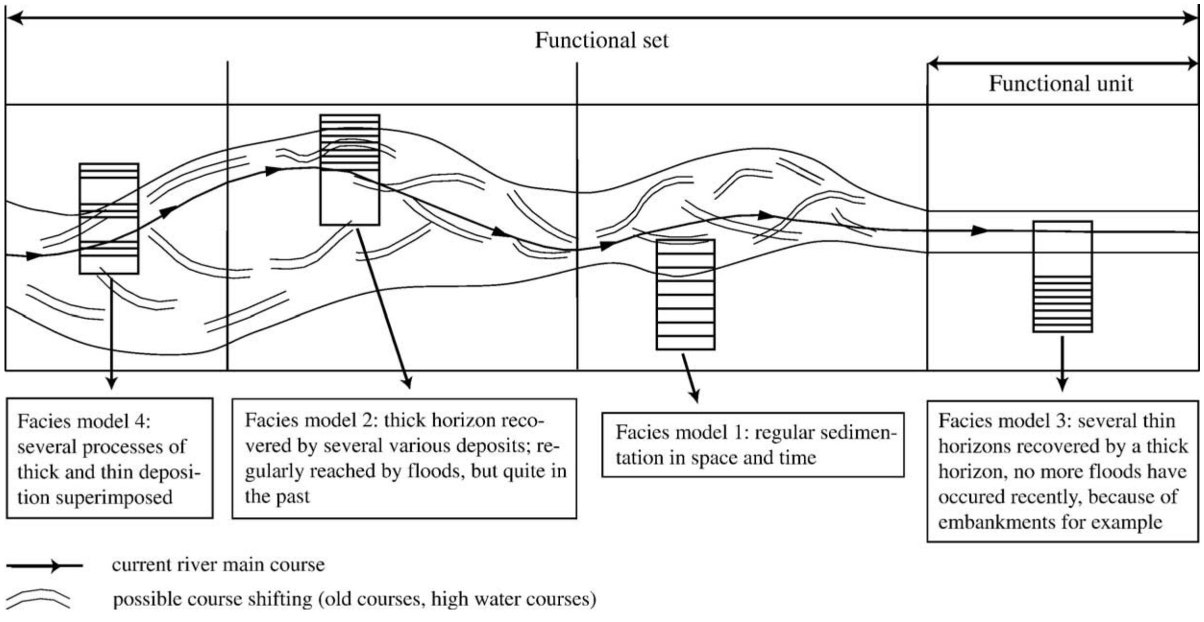


Fig. 8. Schematic representation of a possible spatial mosaic of the four facies models along the studied section (facies model 1 to facies model 4). Facies model is described at the functional unit level (Petts and Amoros, 1996) and the combination of facies models has to be considered at the higher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