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Fluvial system dynamics of Sudano-Sahelian zone during the Late Holocene. The Yamé River (Dogon Country, Mali)

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Abstract

In West Africa, most palaeoenvironmental studies have focused on the role of climatic change on the environment. Because of the richness of its deposits, the Yamé River (Mali), a tributary of the Niger River, offers an opportunity to reconstruct the evolution of this fluvial system in comparison with both climatic and anthropogenic changes during the Late Holocene. To investigate more closely the spatio-temporal response of the fluvial system, sedimentary analyses were conducted on seven reaches distributed along the 137 km length of the Yamé valley. This approach testifies of the possibility for each time slice and river reach (1) to reconstruct the fluvial style and processes and (2) to estimate the sediment storage volume reflecting sediment distribution patterns. Results reveal a wide variability of the sedimentary cascade suggesting contrasting responses to external and local controls. Humid (4200-2900 cal. BP ; 450-24 cal. BP) or arid (2350-1700 cal. BP) phases have been recorded in fluvial archives while an intensification in erosion and sediment supplies, even during the arid period (2900-2350 cal. BP and the 20th century), may be associated with an increase in human pressure. Two other periods are related to both climate and anthropogenic factors. During 1700-1400 cal. BP phase huge sediment supplies can be explained mainly by the reactivation of both hydrological processes and human occupation after an intense and long arid event. Dispersed sediment sinks recorded during the 450-24 cal. BP period originate from the combination of intensification of colluvial processes and a wet phase context originating from global climatic change. Thus, this study provides evidence that climate is the strongest driver for the fluvial response of these semi-arid and tropical rivers while human disturbance appear as a secondary factor due to the high sensitivity of the environment to climate variability in such areas.

1. Introduction

Because rivers are highly sensitive to environmental change, fluvial records are widely considered as a good indicator from which to reconstruct past landscapes. Global climatic and anthropogenic changes are considered as the strongest drivers of water discharge and sediment supply fluctuations on which fluvial system depends. However, local controls such as geological settings, geomorphological heritage, vegetation and land use are also relevant in determining fluvial system changes. A fluvial systems response to these forcing factors is extremely complex with considerable spatio-temporal variability (e.g. Knox, 1983; Notebaert and Verstraeten, 2010).

In West Africa, studies on Holocene fluvial system changes are rare and unevenly distributed across this geographical area and time period. Most of the studies have been conducted between latitudes 16°N and 22°N (Saharan and Sahelian zones) and have focused on the Early and Middle Holocene periods (11500 - 4200 BP). This focus can be explained by the orientation of research conducted in Africa during the last decades which have been mainly aimed at characterizing the spatial and temporal extension of the African humid Period ending around 5000 years ago (de Menocal et al., 2000; Hely et al., 2009; Lézine et al., 2011; Armitage et al., 2015; Shanahan et al., 2015). Thus, most of the previous fluvial studies have highlighted the role of climatic changes (Makaske, 1998; Makaske et al., 2007; Gumnior and Thiemeyer, 2003; Gumnior, 2008; Lespez et al., 2011). Only few studies were interested on the last three millennia and the question of the increasing human impact on the landscapes (e.g. the development of agricultural practices, extraction of raw materials for metallurgy and associated wood exploitation etc.; Garnier et al. 2018). Other palaeoenvironmental studies have mainly focused on lacustrine environments (Lézine et al., 2011; Shanahan et al., 2006, 2015) or marine cores taken from the mouths of the bigger rivers of West Africa such as the Niger River (Lézine et al., 2005; Collins et al., 2017) or the Sénégal River (Bouimetarhan et al., 2009; Niedermeyer et al., 2010). These lacunae in the literature stress the necessity of carrying out new high-resolution investigations into other deposition environments, such as fluvial environments, and more specifically focused on the Late Holocene period.

These were the objectives of this study conducted on the sedimentary records of the Yamé River, a tributary of the Niger River. Its catchment area, covering 4400 km², provided a diversity range of landscape units, geomorphological settings, fluvial styles and land use patterns (Garnier et al., 2014). Moreover, because of the exceptional preservation of the fluvial deposits including archaeological remains, the Ounjougou's reach, located in the upper Yamé valley, has already been subject to several palaeoenvironmental and archaeological studies (Huysecom, 2002; Huysecom et al., 2004, 2009; Mayor et al., 2005; Rasse et al., 2006; Lespez et al., 2008, 2011; Ozainne et al., 2009; Le Drézen et al., 2010; Garnier et al., 2013, 2015; Eichhorn and Neumann, 2013). A publication by Lespez et al. (2011) proposed a synthesis of fluvial changes during the Holocene of the Ounjougou's reach and discussed the role of climatic and anthropogenic controls. This study provide information about the local fluvial metamorphosis and the upper catchment landscapes changes. But, a multi-scale approach is necessary to understand the sedimentary responses of this type of medium-scale river basin. The study of six new reaches in the lower valley allows for the characterization of the general pattern of sedimentary dynamics and the longitudinal complexities of the alluvial filling during the Holocene. A particular focus of this research was on the internal arrangement of the catchment area and the flow connectivity at different spatio-temporal scales. In addition, estimation of the sediment storage for each reach provides information about the sediment delivery and the sedimentary cascade. From the onset of the Late Holocene onwards (4200-0 cal. BP), the Yamé fluvial system witnessed a wide variability of sedimentary cascade suggesting a contrasting response to external and local controls. A comparison of our data with those from other regional and local palaeoenvironmental studies allows for the examination and discussion of the role of each forcing factor in the geomorphological adjustment of the Yamé catchment area.

2. Study area and previous work

2.1. Study area

The Yamé River, a right-bank tributary of the Niger River, is the main stream of the Dogon Country (Mali) in the Sudano-Sahelian zone (Fig.1). Being 137 km long, from east to west, the longitudinal profile of the valley bottom is complex. Based upon classical morphological data (slope, channel / valley width, confined indice, sinuosity; Fig.1B), six river styles were identified and displayed a range of features and behaviors from confined valley to laterally unconfined valley settings (Garnier et al., 2014). These six river styles are displayed into four different river units: the headwater, midcatchment, lowland plain and inland delta domains (Fig.1). After crossing the sandstone plateau in the upper valley (500 m), on which remain many lateritic hills, the Yamé River flows in the midcatchment across the Pleistocene deposits resulting from the reworking of aeolian silts deposited during the last dry period (Rasse et al., 2006). The lower valley is characterized by a large glacis, common to the Sahelian zone, in which the Yamé River is slightly incised. Downstream, the Yamé flows at 267 m towards the Niger River in the Inland Delta.

The discharge regime of the Yamé is characterized by great spatial and temporal variability reflecting (1) the seasonal rainfall regime of the Sudano-Sahelian belt and (2) the local geological features. In the headwaters, until the Ounjougou's reach, the sandstone aquifers feed the river and enable low flow during the dry season (October to June). Otherwise, in the middle and lower valley the Yamé River dries up from the month of January onwards. The three month long rainy season (July to September), associated with the northward displacement of the monsoon, occurs as an intense rainstorm and generates all along the valley flood flows with a high velocity and channel avulsion within the valley bottom. Due to the orographic effect, regional rainfall amount is greatest on the sandstone plateau (563 mm/yr) and less in the Inland Niger Delta (520 mm/yr). As a result of this spatial and temporal discharge, the valley floor vegetation appears different upstream and downstream. Upstream, on the sandstone plateau, intense gardening by human groups occurs all year long thanks to the presence of water. Downstream, in the Inland Delta, the important water discharge and the slower receding waters of the Niger during the rainy season allow for rice cultivation. Otherwise, the whole catchment area is today covered by agricultural fields, mainly growing pearl millet (*Pennisetum glaucum*) and a Sahelo-Sudanian savanna strongly altered by humans (Eichhorn and Neumann, 2013).

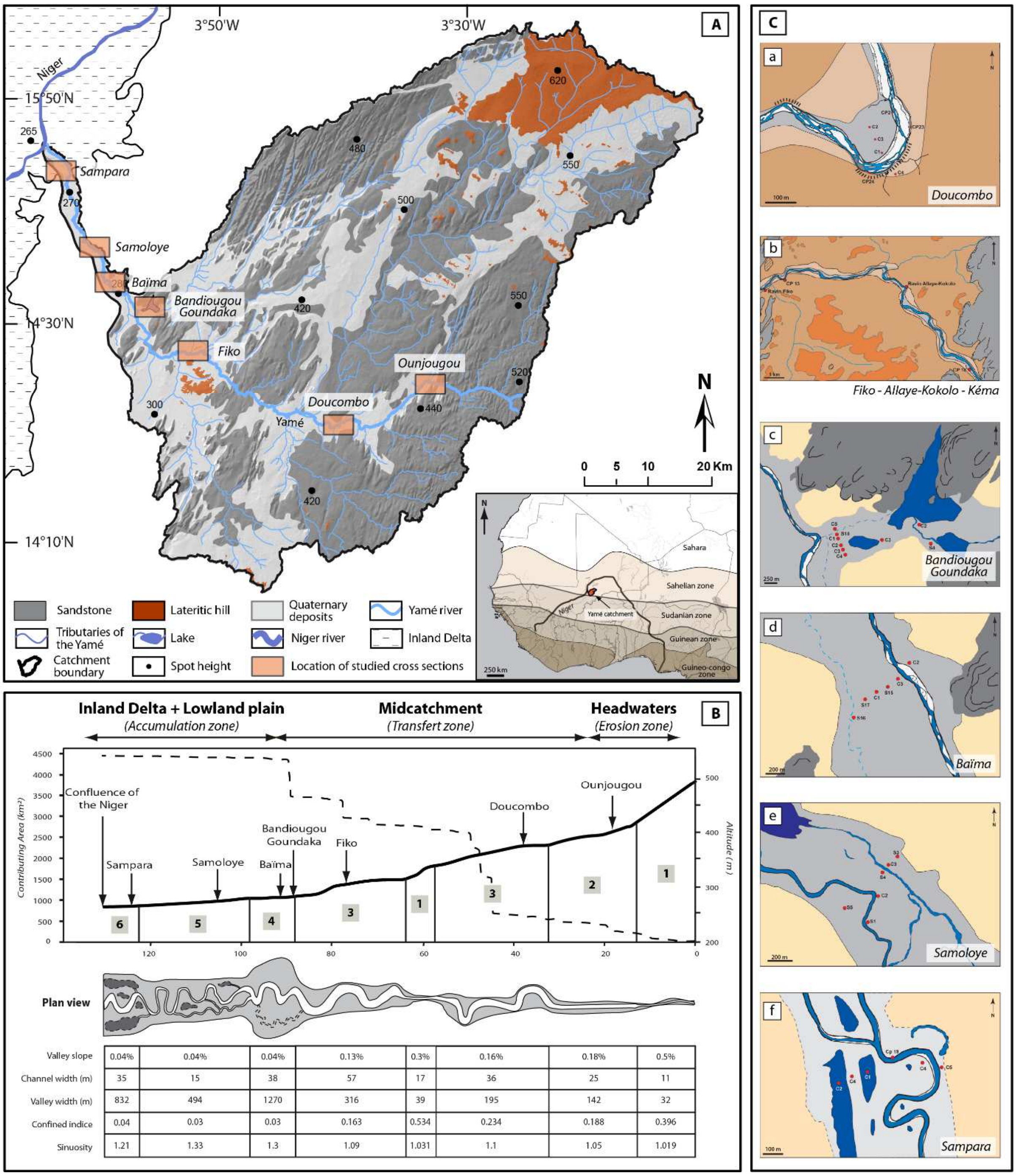

Fig. 1: **Geomorphological map of the Yamé valley**

A. Geomorphological map of the Yamé catchment; B. Description of the six River style (highlighted in grey) (1) The bedrock-controlled occasional floodplains River Style (2) The low sinuosity planform-controlled River style (3) The meandering irregular planform-controlled discontinuous floodplain River Style (4) Meandering channel in an extensive continuous floodplain (5) The multiple meandering channels (6) Meandering Rivers in a swampy floodplain associated to the Inland Niger Delta ; **C. Planform on the studied reaches and location of investigations** (a-b) River Style n°3; (c-d) River Style n°4; (e) River Style n°5; (f) River Style n°6.

2.2. Previous work

The previous research has focused on the Ounjougou reach situated 18 km from the spring of the river. The sedimentary succession is exceptionally long and has yielded archaeological materials from the Middle Palaeolithic to modern times (Huysecom et al., 2004). The geomorphological setting has been described in previous publications (Rasse et al., 2004, 2006 ; Lespez et al., 2008) and a final synthesis of the fluvial system changes published (Lespez et al., 2011). Thus, this reach represents a reference site for the fluvial system response to environmental changes in West Africa. Moreover, palaeobiological data, e.g. phytoliths, pollen and charcoal analyses, yielded additional information about the Holocene environmental changes for the Ounjougou's site (Neumann et al., 2009; Le Drézen et al., 2010, 2014; Eichhorn et al., 2010; Eichhorn and Neumann, 2013; Garnier et al., 2013). During the Late Holocene four major periods of fluvial change have been highlighted. At the beginning (4200-2350 cal BP), the sedimentation indicates a seasonal pattern with a drying up of the floodplain with active flood channels and drying up of ponds. This scenario is corroborated by the vegetation records with a disappearance of some Sudano-Guinean taxa and the gradual appearance of Sudano-Sahelian species (Eichhorn and Neumann, 2013). Locally, we observed on the surrounding plateau areas the development of colluvial deposits as recovered during the archaeological excavation (Ozainne et al., 2009). Later, between 2350 and 1700 cal. BP, a sedimentary hiatus and a deep incision in the earlier deposits was observed (Garnier et al., 2015). It can be interpreted as the result of the high-energy flood flows that occurred during a dry period. Then, the last two millennia were characterized by large variability of river dynamics reflecting a contrasted climatic period. Thus, there was an oscillation between a rhythmic sedimentation rate characterized by slow flows (1630-1410 and 930-690 cal. BP) alternates with periods of active flows (1320-910 and 700-450 cal. BP). Meanwhile, there was a widespread accumulation of colluvium over the past two millennia over the entire stretch of the Ounjougou, filling the valley floor. These thick colluvial deposits, reaching 4m locally, generated the formation of a sedimentary plug and forced the repositioning of the River path over the course of the four centuries. Finally, between 450-24 cal. BP a new metamorphosis occurred with the development of a large wetland in the valley bottom.

3. Materials and methods

In order to investigate the entire fluvial system, new geomorphological investigations were undertaken along the Yamé valley. The first step was to identify homogeneous landscapes units and hydro-geomorphological processes. Thus, the valley floor and channel surface areas were digitalized for the entire valley and split into 500m long sections (see Garnier et al., 2014). Then, for each 500m section, five classical morphological indices have been calculated (channel and valley floor width, confined indices, sinuosity and secondary channel area). Discontinuities within the longitudinal series of geomorphological parameters were identified by a Pettitt rupture test (Pettitt, 1979). This methodology allowed to dissociate eight different sections grouping elementary segments with similar morphological characteristics and six river styles (Garnier et al., 2014). Except in the bedrock-controlled occasional floodplains River Style (N° 1; Fig.1) where alluvial deposits are absent or very current, investigations were conducted in each River Style. From upstream to downstream, seven cross sections were surveyed by laser range meter while the architecture of alluvial filling was established through , thirty-two outcrop profiles (1-4m deep), fourteen hand augers (4-6m deep) and twenty-two boreholes (4-10m deep). Boreholes have been recovered along the cross-sections with a portable Cobra vibracorer using a 1m long steel drill-pipe.

3.1. Granulometry

Eighty-nine sediment samples from all lithofacies of the different sections were analyzed and compared with sixty modern samples from the valley floor (Fig. 2).

Granulometry was measured by laser particle analyser (Coulter Counter LS 200), adjusted for measurements from the ≤ 2 mm fraction. Coarse material was removed and grain-size was determined using a series of sieves ranging from 2 to 5 mm. In particular, the C-M pattern (Passega, 1957, 1964; Bravard and Peiry, 1999) in which C is the one-percentile and M the median of the grain size distribution, was used to distinguish the depositional environments by the criteria of competence and mode of sediment transport. Including the previously studied Ounjougou's samples (Lespez et al., 2011), a C-M diagram of 253 samples from the whole Yamé valley was constructed and allowed for the identification of six depositional environments (Fig. 2).

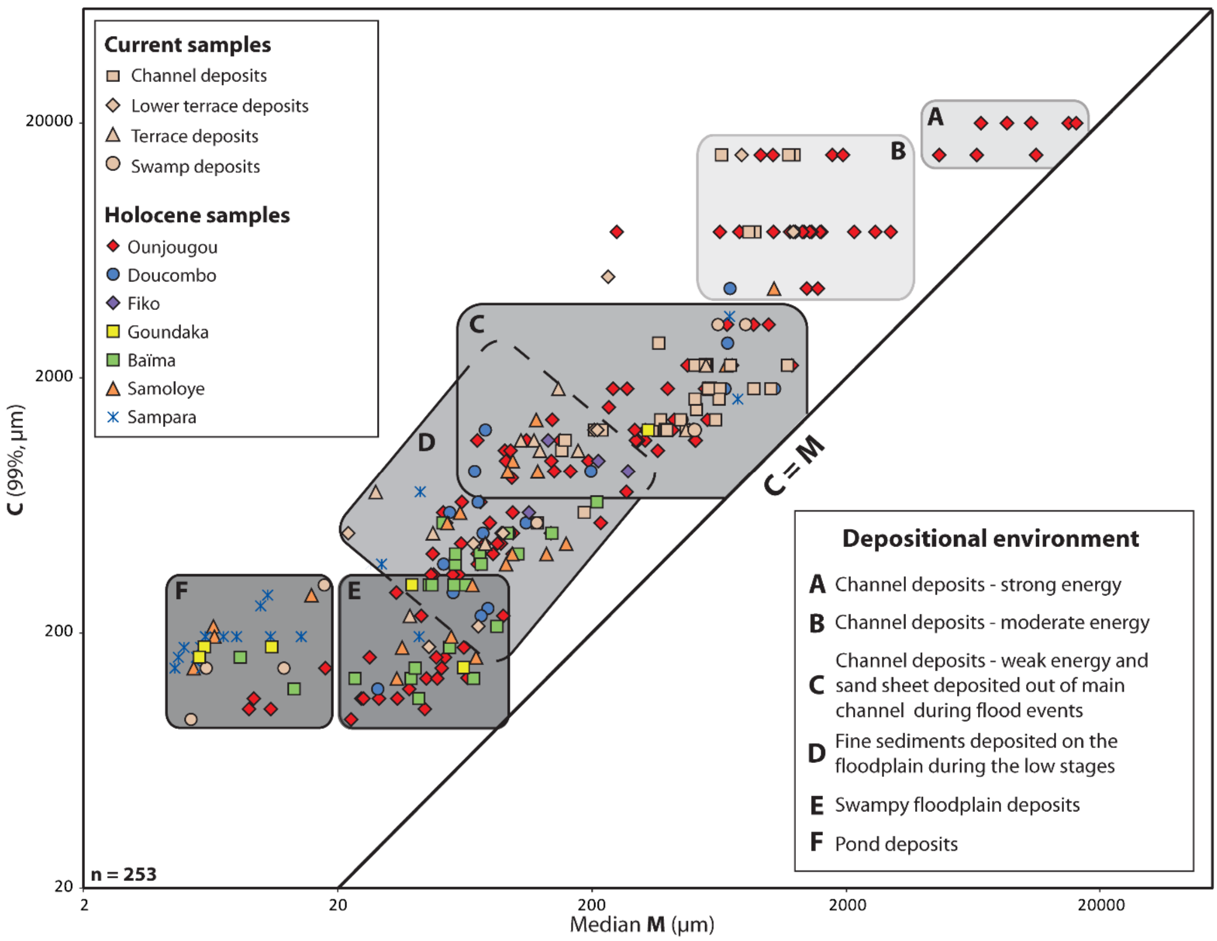

Fig. 2: C-M diagram of Holocene and modern alluvial deposits of the Yamé valley

3.2. Facies identification

The approach used in this study is based on an accurate classification of the sedimentary facies for the Yamé valley deposits, established from the architectural element analysis of Miall (1996) and combined with grain-size analyses (Table 1, Fig. 2).

Lithofacies assemblages (Miall, 1996)	Description	Other features	M	C99	Grain Size Group	Dessication index *	Current mode of transport	Depositionnal environment interpretation
Gh, Gt	Horizontal to cross-bedded gravel with cobbles and mud balls		600-2000	4000-20000	A, B	-	Rolling, saltation	Midchannel, lateral gravel bars and bedforms
Sp, Sl	Horizontal to cross-bedded coarse sand with gravels		300-1200	1000-4000	B, C	-	Saltation and rolling	Midchannel, lateral sand bars and bedforms
Sh	Laminated fine sand to coarse sand	Alternating with Fl	70-300	400-2500	C	-	Saltation and suspension	Sand sheet deposited out of main channel during flood events
Sm	Massive sandy-silt to medium sand	Redoximorphic features	50-300	300-700	C	2	Suspension and saltation	Sand flooded out over the alluvial plain
Fl	Laminated silty sand to fine sand	Alternating with Sh	15-200	300-700	D	1,2	Suspension	Fine sediments deposited in floodplain /pond during the low stage
Fsm	Laminated greyish silt to silty sand	Organic remains, redoximorphic features	20-100	100-250	E	1-3	Suspension	Swampy floodplain or/and ponds
Fm	Massive dark organic silt	Rich in organic matter / sometimes desiccation cracks	4-20	80-250	E, F	0,2,3	Uniform suspension during falling	Standing pools of water
-	Massive sandy silt to coarse sand	Sometimes with paedogenic features	100-300	800-1200	D	-	-	Colluvial deposits

***** Level of desiccation of floodplain and pond (Lespez et al., 2011): 0 = lack of dessication figures and seasonal pattern; 1 = rhythmic sediments testify to a seasonal pattern of sedimentation; 2 = development of oxidation borders; 3 = desiccation cracks; 4 = floodplain paleosoil***

Table 1: Sedimentary facies, description and interpretation

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Facies assemblages were classified based on their grain-size, texture, structure, colour and biogenic remains and composition of alluvia that are characteristic of the context of sediment deposition (channel, floodplain, pond, etc.) and fluvial style (braided, wandering, meandering, floodout, etc.). Facies are subdivided into four depositional environments distinguished by their modes of deposition (Fig. 2). Four facies are interpreted as channel deposits (Gh, Gt, Sp, Sl), four as floodplain deposits (Sh, Sm, Fl, Fsm) and one facies is characteristic of standing pools of water (Fm). One other facies is interpreted as colluvial deposits. It includes various facies formations with a silty matrix without clear sediment organization. For the channel deposits, the different subfacies permit the qualification of the stream power of the river (high, medium, low energy) (Fig. 2). For the floodplain deposits, another feature has been used to refine interpretation, the desiccation index (DI), developed by Lespez et al. (2011). Based upon the identification of the effects of the intensity and/or length of the dry season on the floodplain and pond deposits this index compares the impact of the dry season on the floodplain landforms during the Holocene. This index has four levels for intensity of desiccation (Table 1; Lespez et al., 2011). It is a good indicator of the characteristics of the dry season and reveals the hydrological level of the valley floor for the different sections and time slices.

3.3. Chronology and sediment storage estimation

The chronology of this study is based on 27 additional radiocarbon dates obtained on charcoal or on sediments (Table 2). The measurements were performed by the AMS ^{14}C laboratories in Erlangen (Erl), Germany and in Miami, United States (Beta). Radiocarbon dates were calibrated using Oxcal (4.2 version) with the IntCal13 atmospheric calibration curve (Reimer et al., 2013). The chronology used in this paper was identified in accordance with the chronological pattern previously established at Ounjougou (Huysecom et al., 2009; Ozainne et al., 2009).

Location	Lab.code	Section	Depth (cm)	Material	Method	Depositional environment	BP +/-	Δ ^{13}C ‰	Calibrated dates BP (2σ)
Doucombo	Erl-14729	CP34	283	Wood	AMS	Channel	6066 +/- 46	-24,42	7155-6786
Doucombo	Erl-14728	CP 33	292	Charcoal	AMS	Channel	4468 +/- 38	-25,68	5291-4972
Doucombo*	Erl-15477	C1	537 -539	Sediment	AMS	Pond	2695 +/- 56	-18,3	2925-2738
Doucombo*	Erl-15479	C3	668	Charcoal	AMS	Channel	1645 +/- 43	-26,8	1690-1413
Doucombo	Erl-14726	CP 24	206	Charcoal	AMS	Colluvial	416 +/- 35	-23,84	526-326
Doucombo	Erl-15478	C3	335	Charcoal	AMS	Floodplain	216 +/- 42	-25,3	425--4
Doucombo	Erl-14727	CP 23	288	Charcoal	AMS	Colluvial	138 +/- 34	-23,86	281-6
Doucombo	Erl-14723	CP 2	165	Charcoal	AMS	Floodplain	52 +/- 39	-25,91	261-24
Allaye	Erl-14717	CP 16	180	Charcoal	AMS	Colluvial	4377 +/- 36	-26,64	5041-4858
Fiko*	Erl-13738	CP4	226	Charcoal	AMS	Colluvial	2442 +/- 53	-27,4	2709-2353
Fiko*	Erl-13402	CP1	170	Charcoal	AMS	Colluvial	2085 +/- 44	-23,3	2292-1933
Fiko	Erl-13740	CP13	240	Charcoal	AMS	Colluvial	893 +/- 40	-25	916-732
Fiko	Erl-13739	CP13	220	Charcoal	AMS	Colluvial	845 +/- 40	-24,2	904-681
Kéma	Erl-14720	CP 18	290	Charcoal	AMS	Floodplain	479 +/- 37	-25,42	619-479
Fiko	Erl-13401	CP2	111	Charcoal	AMS	Colluvial	339 +/- 39	-22,9	488-308
Kéma	Erl-14718	CP 18	161	Charcoal	AMS	Floodplain	203 +/- 34	-24,61	307--4
Kéma	Erl-14719	CP 18	194	Charcoal	AMS	Floodplain	127 +/- 38	-27,21	278-8
Baïma*	Beta-298317	C1	750-752	Sediment	AMS	Swampy floodplain	2460+/-30	-16,4	2716-2357
Baima*	Beta-298316	C1	570-572	Sediment	AMS	Floodplain	1930+/-30	-17,5	1947-1820
Baïma*	Erl-15486	C1	420-422	Sediment	AMS	Wetland	1630 +/- 66	-16,4	1695-1385
Baïma	Erl-15487	C3	238-240	Sediment	AMS	Wetland	923 +/-43	-14,3	926-681
Baïma	Erl-13741	C1	256	Charcoal	AMS	Wetland	281 +/- 42	-24,6	473- -1
Samoloye	Beta-298318	C2	265-267	Sediment	AMS	Wetland	1100 +/-30	-14,7	1063-937
Sampara	Erl-15488	C3	354-356	Sediment	AMS	Channel	4055 +/-47	-20,1	4808-4421
Sampara	Erl-13745	C2	371 - 375	Sediment	AMS	Wetland	3316 +/- 41	-21,9	3676-3449
Sampara*	Erl-13744	C2	264 - 266	Sediment	AMS	Wetland	2473 +/- 40	-16,7	2715-2364
Sampara*	Erl-15489	C4	440	Charcoal	AMS	Channel	1664 +/-43	-27	1695-1418

**** Published in Garnier et al., 2015***

Table 2: Radiocarbon dates obtained on deposits of the Yamé valley

Setting aside Ounjougou, seven complete cross-sections surveys have also been carried out in the Yamé valley: two in the middle valley, four in the lower valley and one in the inland delta domain (Fig.1). The stratigraphic study of deposits, established from the investigations carried out in the field and laboratory and from available dating, allows for the characterization of the thickness of the sedimentary fill for each period and reaches studied. Because the fluvial architecture is relatively stable and coherent within each different scale, we decided to quantify the volume of sediment stored for the whole valley. For each reach, the fluvial architecture observed was extrapolated from boreholes and outcrops data. Despite its exploratory nature, this analysis provides an idea of the valley floor filling rhythms over the last millennia. The calculating method is based on five steps. The first two steps were conducted in the field. For each studied reach (1) the identification of the geomorphological units and (2) the establishment of the chronostratigraphy was undertaken. The next step consists of extrapolating the thickness of the sediment storage for all 500m sections and calculating the volume for different time slices. However, some adjustments were made based on local observations. For example, periods of incision do not concern the entire surface of the floodplain but only of the channel. Thus, the thickness of the removed sediment was multiplied by the surface of the channel to estimate the alluvial storage in the valley floor. Similarly, for section 2, sediment storage was only calculated for the Ounjougou's reach because storage is effective only there due to favorable local geomorphological conditions (Rasse et al., 2006; Lespez et al., 2008, 2011). However, in order to compare the volumes and improve interpretation, the data were normalized. The volume of stored sediment is indicated per year and per km.

4. Results and interpretation

4.1. Chronostratigraphy of the deposits by reach

4.1.1. The midcatchment

The midcatchment, located between Bandiagara and Goundaka, corresponds to a meandering irregular planform-controlled discontinuous floodplain River Style (Fig. 1). The investigations were primarily conducted by cores in meandering lobes and by outcrop profiles in ravines and along the Yamé River. The sedimentary filling, about 3–4m deep above sandstone, corresponds to a stacking of alluvial sequences fed by colluvial deposits.

4.1.1.1. Doucombo cross-section

The cross section of Doucombo corresponds to a meander characterized by a wide floodplain and alluvial sedimentation on the convex side (Figs. 1 and 3). Four boreholes and several outcrop profiles permitted the identification of five sedimentary sequences. On the convex bank, a detrital sequence, 1.5m thick, has been identified at the bottom.

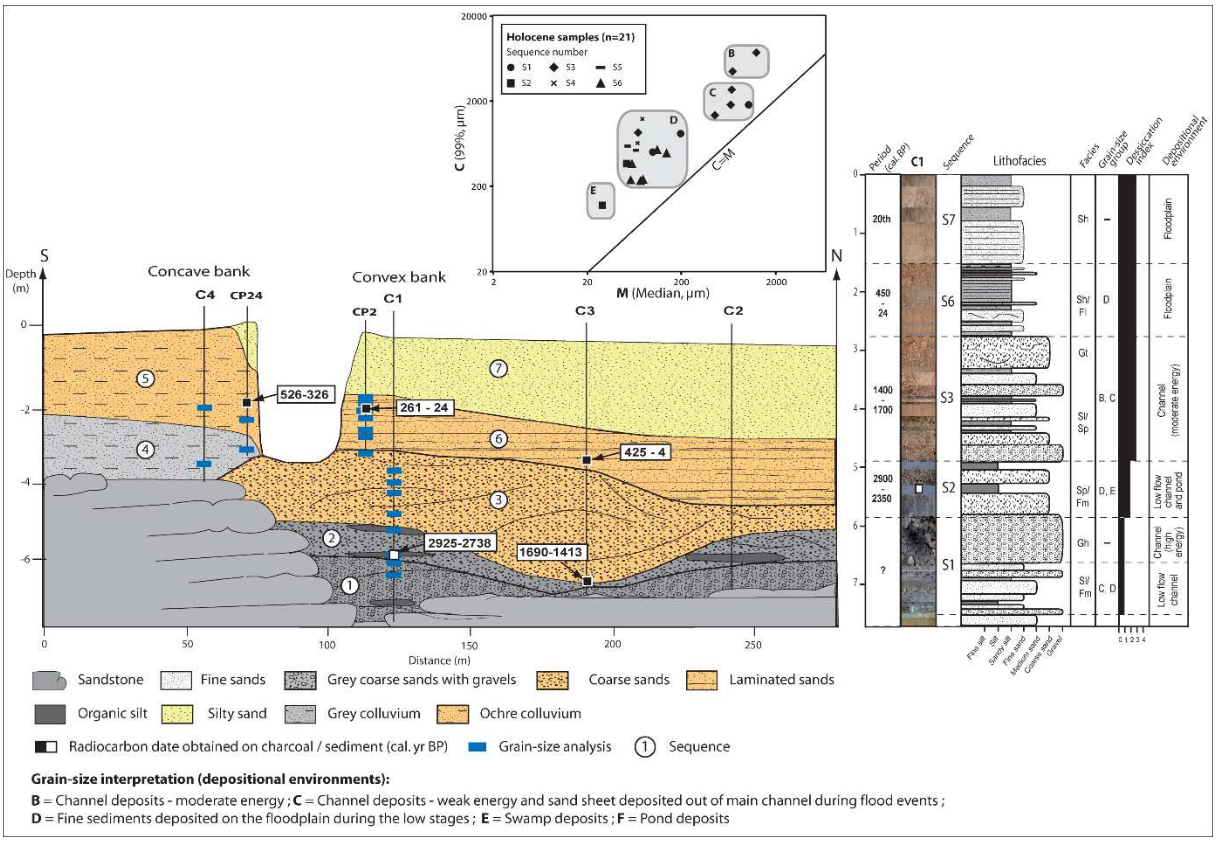


Fig. 3: The cross-section of Doucombo

The lower sequence (S1), 90 cm thick and not dated, can be characteristized by fine sand beds (Sl) with some blue compact laminated organic silts, indicating waterlogged and reducing conditions (Fm). It is overlain by blue-grey coarse sands to gravels (Gh). In contrast, the second sequence (S2), 60 cm thick and dated to 2925-2738 cal. BP, contains finest sandy deposits with a planar structure (Sp), intercalated with compact organic silts (Fm). These deposits reflect the channel's sediments transported during high flood flows for the coarser layers (Gh) or during more moderate flooding for the finest deposits (Sl/Sp). However, the color of the deposits and the presence of several dark organic silty layers without desiccation cracks (Fm) indicates a high water table all year round with many standing pools in the valley bottom. The contact with the next sedimentary sequence (S3) is clearly erosional. This incision, 1.5m deep in cross section into older deposits, corresponds to a period between 2925-2738 and 1690-1413 cal BP, a date obtained from the bottom of the top sequence. This second detrital sequence, 3m thick, corresponds to ochre coarse sand and gravels with planar or cross-bedding structure (Sl/Sp/Gt). The red - rust color of the deposits indicates an iron oxidation state reflecting contact of the sediments with air. Thus, compared to the previous period, there was a drop in the water table level. Sediments correspond to coarse sand containing some gravel beds that reflect the development of medium and lateral bars and a moderate flood energy. On the concave bank, a colluvial sedimentation 3m thick has been updated (S4 and S5). The oldest sequence is constituted by grey silty sands containing pulverulent iron concretions, while the following one, dated to 526-326 cal BP, is characteristic of an alternation of ochre-brown silty sand layers with numerous iron concretions. On the convex bank, the sedimentation is characterized by a much more recent laminated sequence (S6), showing the alternation of silty sand to fine sands (Sh/Fl). Two dates are available for this sequence, 425-4 cal BP and 261-24 cal. BP. These deposits, 1m thick, are interpreted as sand sheet deposits spread outside of the main channel on the floodplain during moderate-energy flood flows. At the top of both banks, a sequence (S7) 1 to 2m thick, corresponds to the current hydro-sedimentary pattern revealed by laminated silty sands (overbank deposits).

4.1.1.2. Fiko cross section

In this part of the valley, three topographic levels have been identified: the upper glacis, the low glacis and a low terrace (Fig. 4). Nineteen outcrop profiles were carried out along the Yamé River and in the ravines. For the glacis, the earliest available date, 5041-4858 cal. BP, comes from the ravine of Allaye-Kokolo, located on the right bank of the Yamé. The sedimentary sequence, 1 to 4m thick, is characteristic of ochre silty sands containing gravels. The nature and sedimentary structure indicates a leached ferruginous paleosol developed on the erosional levels of Pleistocene glacis.

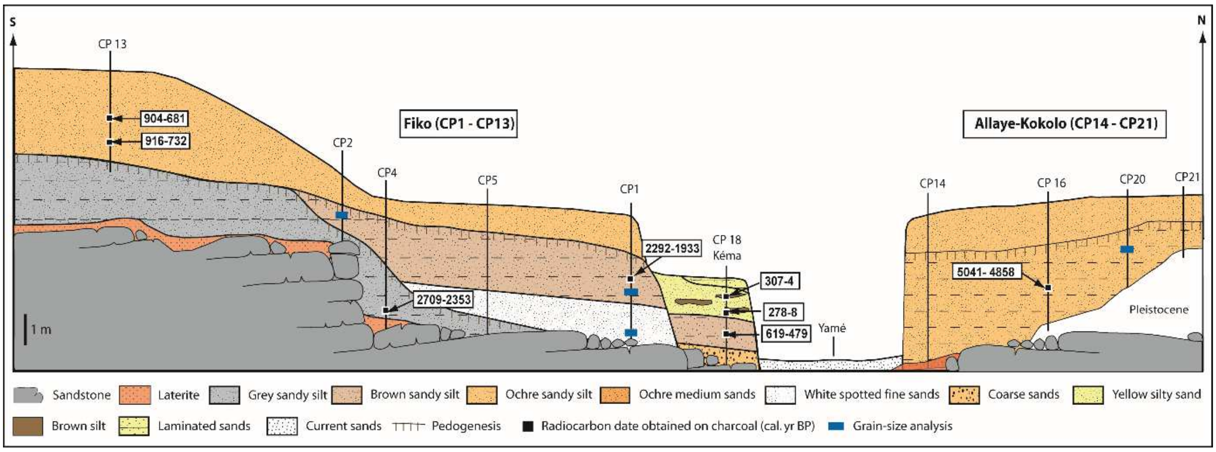


Fig. 4: Composite cross-section of Fiko

From the edges of the Holocene floodplain, eleven outcrop profiles were identified in the Ravine of Fiko, located a few kilometers downstream on the left bank of the Yamé. The oldest sequence recorded at the bottom corresponds to grey sandy silt, 1 to 2m thick, including many charcoal particles. The date of this sequence, rich in pottery sherds, has been established by radiocarbon dating to 2709-2356 cal. BP. The sedimentary characteristics and the grey-blue color of these deposits suggest a pseudo-gley paleosoil dominated by an excess of water. This sequence is covered by white fine sands with numerous ochre marks. These sediments can be interpreted as overbank deposits fed by colluvial sediments which were thereafter subject to pedogenic processes. The characteristics of the basal mass of these deposits is probably the result of an oblique leaching. This paleosoil is then topped by a relatively homogeneous sequence characterized by medium to coarse sands, dated to 2292-1933 cal. BP.

At the top of the glacis, there is a sequence of fine red sands reaching a thickness of 2m dated by two charcoal samples to 916-732 cal. BP and 904-681 cal. BP. Similar deposits have been observed on the right bank at Allaye-Kokolo.

The low terrace, located at Fiko on the right bank and on the left bank at Kéma upstream, is much more younger. At the bottom, it corresponds to ochre coarse sand. Above, there are colluvial sediments dating to 619-479 cal BP. They are overlain by floodplain deposits characterized by fine to medium sand containing lenses of brown silt. Two dates place its establishment around the last three centuries (Tab. 1; 307-4 cal. BP and 278-8 cal. BP).

4.1.2. The lowland plain

From Goundaka, the fluvial morphology of the landscape changes. The sandstone plateau is replaced by glacis, which now occupy the whole landscape. We observed the development of an unconfined valley whose width increased greatly. Moreover, the very low slope (0.4 ‰) of this zone promotes sediment storage. Two river styles can be differentiated in this section of the valley (Fig. 1).

4.1.2.1. Goundaka-Bandiougou cross section

Located upstream of the lower valley, the Goundaka-Bandiougou section is characterized by specific hydro-sedimentary dynamics. Situated on the left bank of the Yamé, the Bandiougou's wetland is approximately 1 km² during the wet season. The lake is fed by two major tributaries coming from the north of the watershed (Fig.1). However, during large floods, the Yamé River can flow into the lake and become a tributary of the Bandiougou's Lake. The Goundaka's reach is located at the interface between the Yamé River and the lake.

At Goundaka, eight boreholes and two auger holes were undertaken. The chronostratigraphy study indicates seven different sequences (Fig. 5). The oldest one, 2m thick, corresponds to grey sandy silt with ferruginous concretions (Sm). These sediments are not dated but are older than 2956-2181 cal. BP, the first date provided by the upper sequence. They are overlain by heterometric yellow-brown sands. This sequence can be interpreted as sediments carried by flows that lose their velocity and competence as they spread over a flat floodplain and deposit their sediment load (Sm).

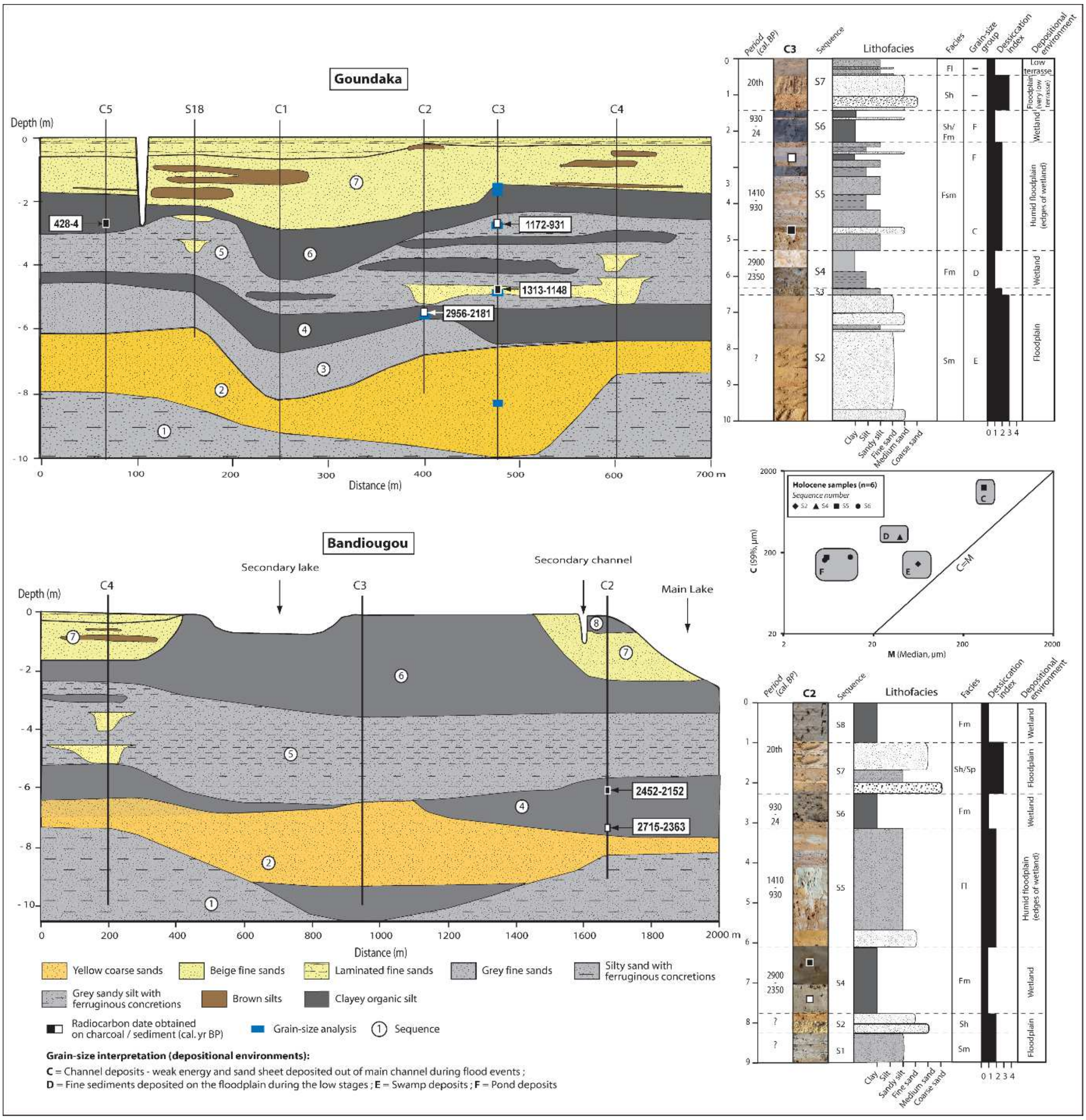


Fig. 5: Cross sections of Bandiougou and Goundaka

Sedimentary records of the following sequence are thinner in depth (m) and organic. In the lower part, there is a layer of grey sands (Sm) covered with organic silt (Fm). These were deposited by decantation in wetland environment such as lake or ponds.

The above sedimentation corresponds to silty sandy deposits including finer layers. It is dated to the top of 1172-931 cal. BP. This evidence suggests a swampy, depositional environment of wetland margins that are subject to low flood flows (Sf). However, these deposits are also impregnated by ochre-rust marks indicating an oxidizing environment. There is, in some places (C3, C4 and S18), a sandy layer indicating a return to fluvial dynamics dating to 1313-1148 cal. BP at C3.

The following sequence reveals organic silt deposited by decantation (Fm). This corresponds to the development of swampy - lacustrine conditions for all of the Goundaka reach. These deposits are dated at C5 to 428-4 cal. BP. They are also intercalated with sandy deposits (Sp) suggesting the presence of a wandering channel throw into the lake.

Finally, the top of the sedimentary filling is composed of an alternation of laminated sands (Fl), that come from the overflow of the Yamé and its tributaries during contemporary flood episodes.

At Bandiougou, the same alluvial pattern as at Goundaka is observed (Fig. 5). At the bottom, we observed grey sandy silt sediments (Facies Fl), reflecting a wide floodplain inundated by low flows. At the core C3, a fine silty clay sequence (Fm) indicates the development of a wetland. It is overlaid for all cores by yellow-red sands suggesting a suspended load deposition. Thus, we can assume they have been deposited by overflows within this vast floodplain (floodout). Two dates are available (2715-2363 cal. BP and 2452-2152 cal. BP) which are similar to Goundaka for the same sequence. This indicates the presence of a large wetland during the first millennia BCE.

The next sequence, 3m thick, consists of grey fine sand and has also been observed at Goundaka. This sedimentary facies is associated with the sequence 5 (Fig. 5). The structure correspond to massive sands (Sm) that have been transported by overflow and deposited in the floodplain by the reduction of the flow velocity. However, in the west, near the presentday Yamé, sedimentation appears different. This sequence of grey silty sand is intercalated with detrital laminae (Sp), characteristic of channel deposits during episodes of flooding and organic clay lenses (Fm) that suggests the presence of wetlands in the floodplain. They can also result in sedimentation in pools or from an extension of Lake Bandiougou for certain periods of time.

They are then topped by an organic clay sequence usually thick depending on the location of the coring (1-3m). According to the dates available at Goundaka, we assume that this sequence corresponds to the last millennium. The fine organic sedimentation without desiccation cracks (Fm) indicates the development of a permanent wetland from this time onwards. To the west, the last meter observed corresponds to the establishment of the current system with sandy sediments that originated from the overflow of the Yamé during the last few centuries. However, to the east, near the present lake, alluvial sediments with coarse beige sands (Sl / Sh) have been identified. These probably came from the channel of the tributary, now located just a few meters from the C2 core. At the top, contemporaneous lacustrine deposits are observed (Fm).

Thus, for at least the last two millennia the Goundaka's reach was characterized by sedimentation that fluctuated between alluvial or swampy-lacustrine sequences.

4.1.2.2. Baïma cross section

The Baïma cross-section is located at the beginning of the lower valley, just after the confluence with the last tributary of the Yamé River. Hand auger (S16, S17 and S15) and boreholes (C1, C2, and C3) enabled the identification of five sedimentary sequences (Fig. 6). The sedimentation of the bottom sequence was composed of 5m thick massive fine silty-sand (Sm) with some silty sand patches with ferruginous concretions (Fsm). These are interpreted as swamp deposits in an alluvial plain overlaid by sand sheet flooded out during low energy flood flows. It can be related to a suspended load transported by a energic fluvial system. This sequence dated to 2716-2357 cal BP and is characterized by a strong 2m thick erosion occurring between 2716-2357 and 1947-1820 cal BP. However, this period is recorded in the sedimentation filling by coarse sand (Sp) transported in a channel by medium energy flood flows. It is overlaid by 2m thick sandy silt sediments (Fsm) interpreted as swampy floodplain deposits and dated from 1947-1820 to 1695-1385 cal BP. Thus, a system of lower energy characterized by the development of wetlands with 1m thick fine and organic sedimentation (Fm) was recorded and dated between 1695-1385 and 473-1 cal BP. The last sequence, 2m thick, corresponds to the alternation of fine sands and sandy silt (Fl) which are the current overbank deposits.

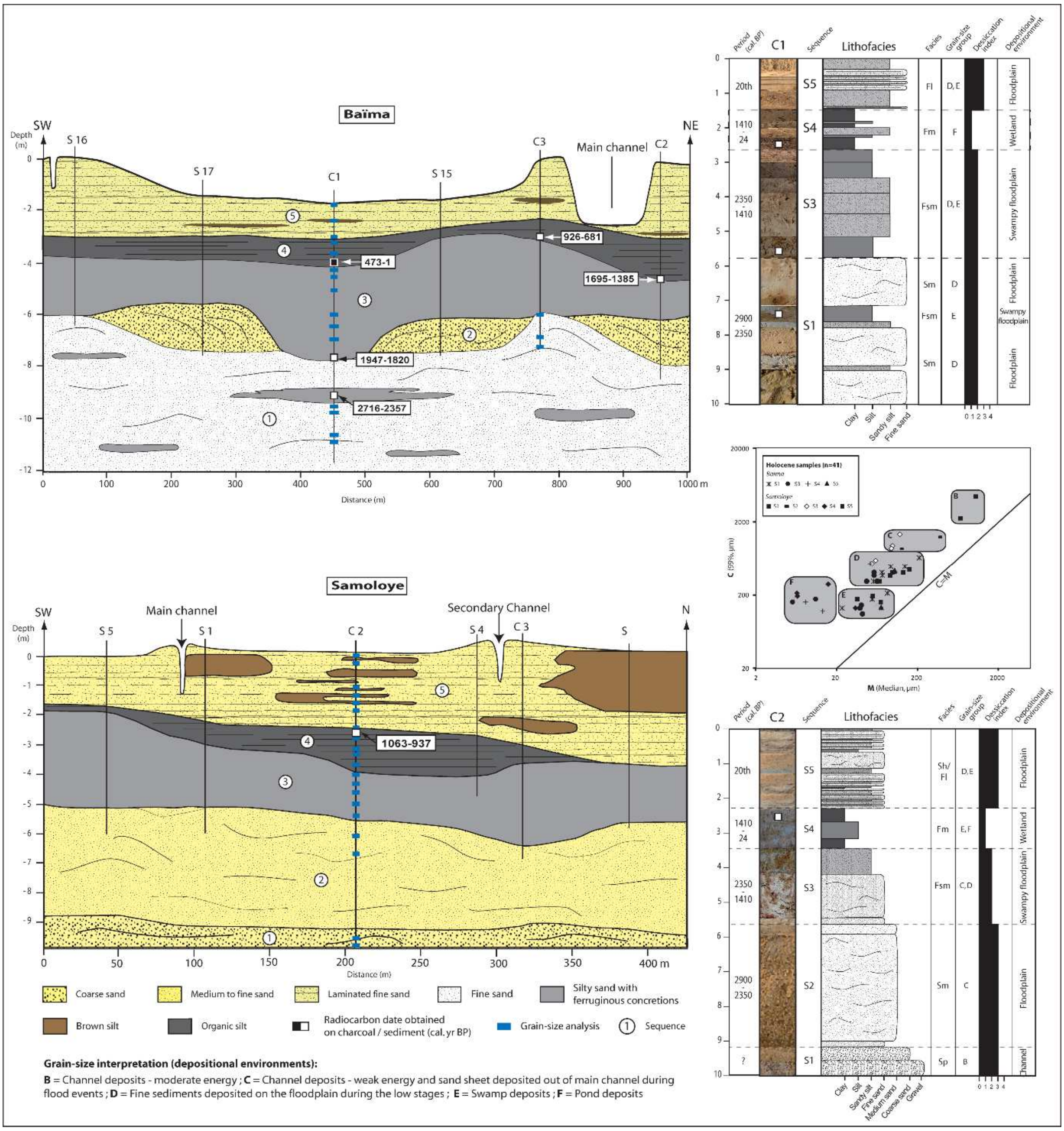


Fig. 6: Cross sections of Baïma and Samaloye

4.1.2.3. Samoloye cross section

The Samoloye's reach is located 15 km downstream of Baïma. The architecture of the alluvial filling was established by four hand auger (S1, S3, S4 and S5) and two boreholes (C2 and C3) (Fig. 6). Four sequences have been identified. Setting apart the two bottom sequences, the infill is similar to those observed for the section at Baïma. At the bottom, sediments correspond to coarse sand (Sp) interpreted as channel bars transported by high energy flood flows. It is overlaid by a 4m thick medium sand sequence with massive structure (Sm) which indicates a deposition by suspension during low energy velocity. Before 1063-937 cal BP, a 2m thick sandy silt (Fm) sequence was covered by a 1m thick dark organic silt (Fm) which has been interpreted as swamp deposits and dated to 1063-937 cal BP. Finally, from the top we observe a filling of the valley bottom with sand sheet and ponds deposits (Sh/Fl) corresponding to the current pattern.

4.1.3. The Niger Inland Delta domain

Downstream of the valley of the Yamé River, a few kilometers away from the confluence with the Niger River, the reach of Sampara has been the subject of five boreholes (C1, C2, C3, C4, C5) and one outcrop profile (CP19) (Fig. 7). These investigations permit the identification of five sedimentary sequences. At the bottom, lateritic deposits are overlain by two detrital sequences. The oldest one is mainly developed on the west side of the cross-section and is characterized by a 4m thick ochre coarse sand (Sp) transported in a meandering channel during high energy flood flows. The upper surface of this sequence is dated to 4808-4421 cal BP. The following one is slightly incised within on the east side of the cross section. The 2m thick blue-green coarse sand to gravels (Gh) including some layers of organic clayey deposits (Fm) is interpreted as deposits characteristics of wandering channels including many standing pools in the valley bottom. It is covered by 1.5m thick silty clayey sediments

(Fm) interpreted as standing pool. This sequence, rich in organic matter, was dated on the base to 3676-3449 cal BP and at the top to 2715-2364 cal BP. The contact with the following sequence is erosional on the east of the cross-section. The incision is dated between 2715-2364 cal BP and 1695-1418 cal BP. This 1.5m thick, sequence developed east of the cross section, corresponds to medium yellow sands planar structure (Sp), and intercalated with organic silt lenses (Fm). Interpreted as a return towards a fluviatile system with an average energy, this meandering system is dated to 1695-1418 cal. BP. Finally, the last sequence, 4m thick, presents overbank silt deposits (Fsm) corresponding to the current hydro-sedimentary pattern, a swampy environment that dries up seasonally as shown by the oxidation marks. Thus, these sediments, deposited since the middle of the second millennium CE, come from the overflow by slow currents during the flood of the Yamé and Niger and have remained suspended in water for several months.

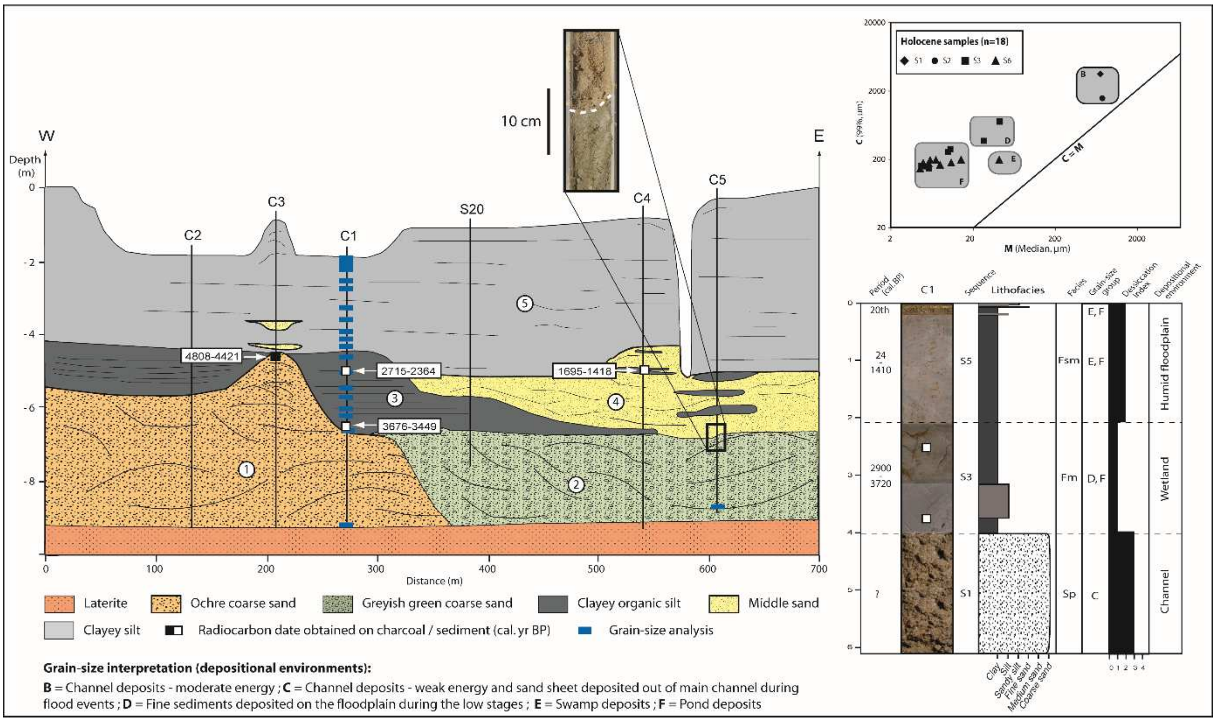


Fig. 7: Cross-section of Sampara

4.2. From upstream to downstream: fluvial dynamics and sediment

From the Late Holocene onwards (4200 cal. BP to today) sedimentary archives have been preserved for the whole Yamé valley and have allowed the reconstruction of the longitudinal fluvial dynamics. The total Holocene sediment stored in the Yamé valley is estimated at 292 million m^3 (Fig. 8.a). Most of the sedimentary filling has been recorded in the lower valley (sections 4 and 5) with an estimation of about 200 million m^3.

According to the same time slices dating from the beginning of the Late Holocene onwards, figure 8 shows the sedimentary storage of each section estimated per year and per 500m section. Figure 9 depicts the changing nature of river style and process zones (alluvial sediment accumulation, transfer and source zones) within the Yamé fluvial system.

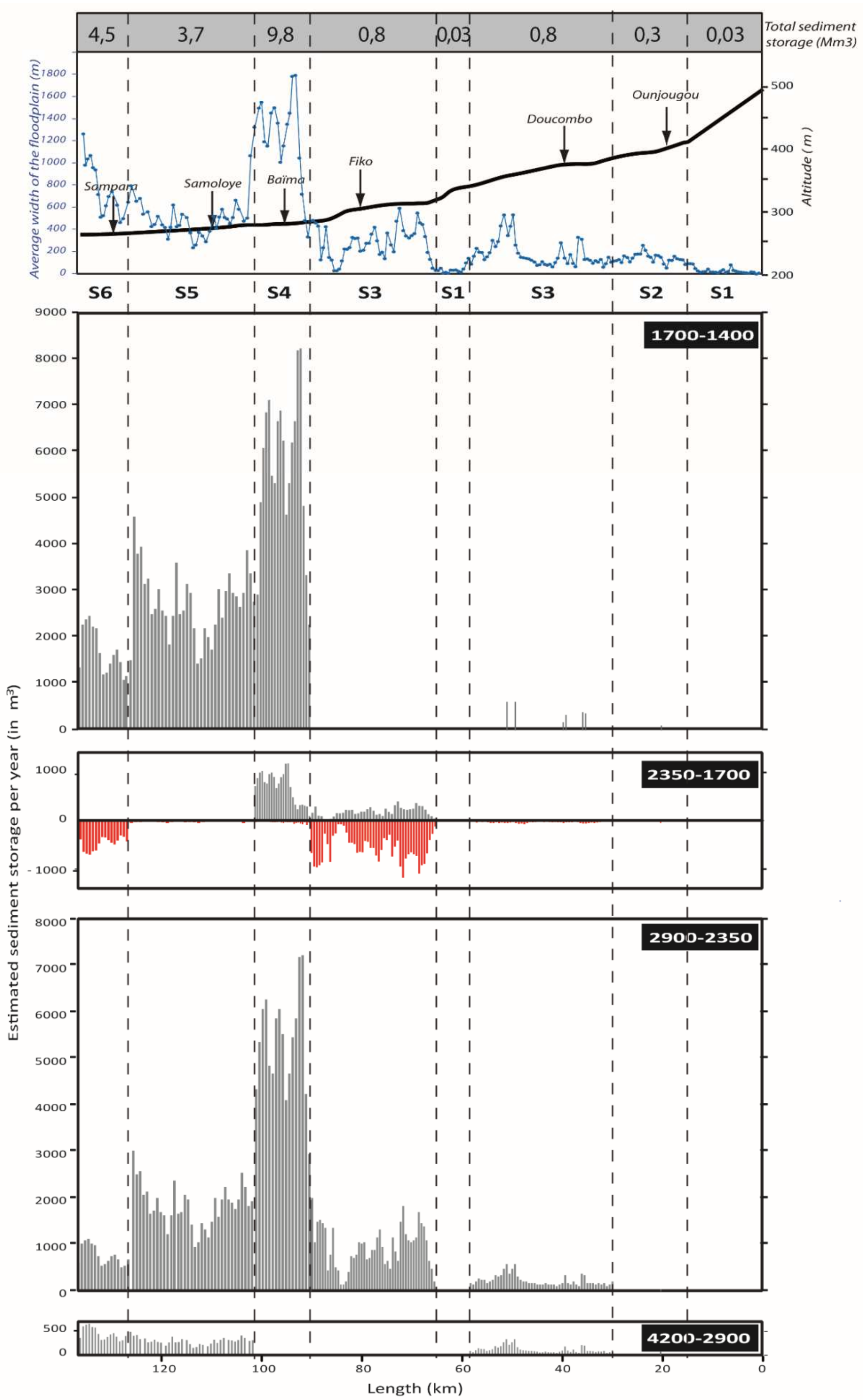


Fig. 8.a: Yamé valley estimated sediment storage (in m3/year) for each 500m section long (input in grey bars and output in red bars). Time scale in cal. BP.

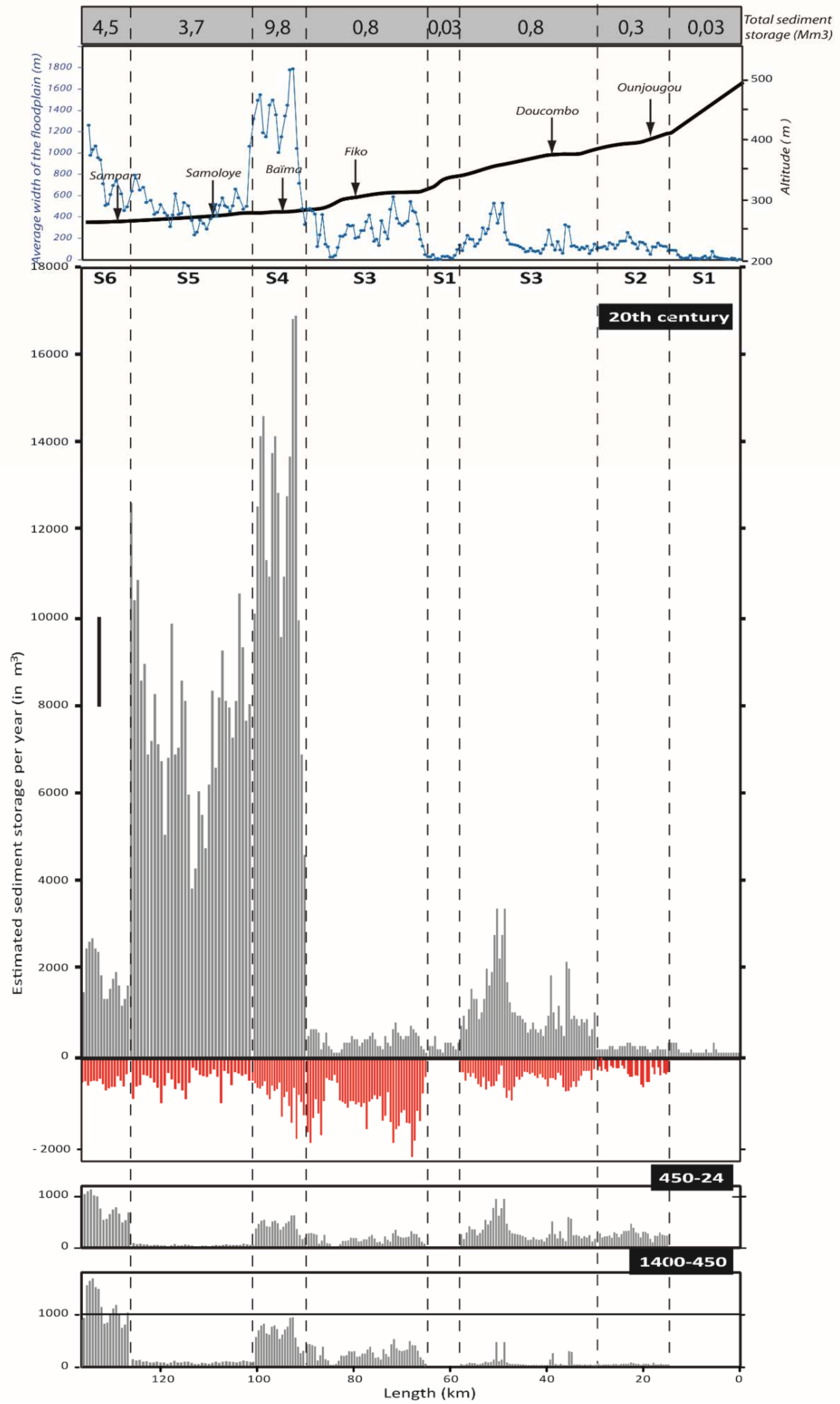


Fig. 8.b: Yamé valley estimated sediment storage (in m3/year) for each 500m section long (input in grey bars and output in red bars). Time scale in cal. BP.

At the beginning of the Late Holocene (**4200-2900 cal. BP**), the sediment cascade indicates an idealized river system pattern with an increase of sediment storage in the downstream direction. The estimated volume of stored sediment is approximately 24 000 m^3/year for the whole valley and progressed from 4 m^3/year/km at Ounjougou to 700 m^3/year/km by average for section 6 (Fig. 9.a). The middle and lower valley acted as sediment transfer zones as illustrated by their river style, which was characterized by a wandering river in the middle valley and meandering style in the lower valley.

During the next period (**2900-2350 cal. BP**) an important change occurred in the pattern of the Yamé valley as shown by the volume of stored sediment which sharply increased, reaching a total of 221 000 m^3/year. First, colluvial deposits have been observed revealing the onset of a new process of sediment production. Thus, the sandstone plateau remained as a source and transfer zone while the lower valley was transformed into an accumulation zone. For section 4, sedimentation of fine sands was very important representing an average of 8234 m^3/year/km. Then, sedimentation in the valley bottom decreases progressively downstream to an average of 2757 m^3/year/km for section 5 and finally almost 1148 m^3/year/km for section 6.

The following period (**2350-1700 cal. BP**) is a key phase in the evolution of the Yamé River system. It corresponds to a deep incision of the channel in the earlier deposits for the entire valley. The total volume of sediment pulsed is about 38 000 m^3/year more than the sediment volume stored (24 100 m^3/year). This incision is particularly important in the middle valley for section 3, with the export of more than 29 000 m^3/year (540 m^3/year/km) (Fig. 9.a). It is relatively weak in the lower valley where the export is an average volume of 71 m^3/year/km and 40 m^3/year/km for sections 4 and 5, respectively. Finally, incision is more intense downstream with a discharge of 745 m^3/year/km of sediments. Thus, except for section 4, all sections acted as sediment source areas. However, lateral supplies, attested by the observation of colluvial deposits allowing sediment storage in the middle valley at 9102 m^3/year (170 m^3/year/km). In section 4, sediment storage is about 15 000 m^3/year (1 300 m^3/year/km).

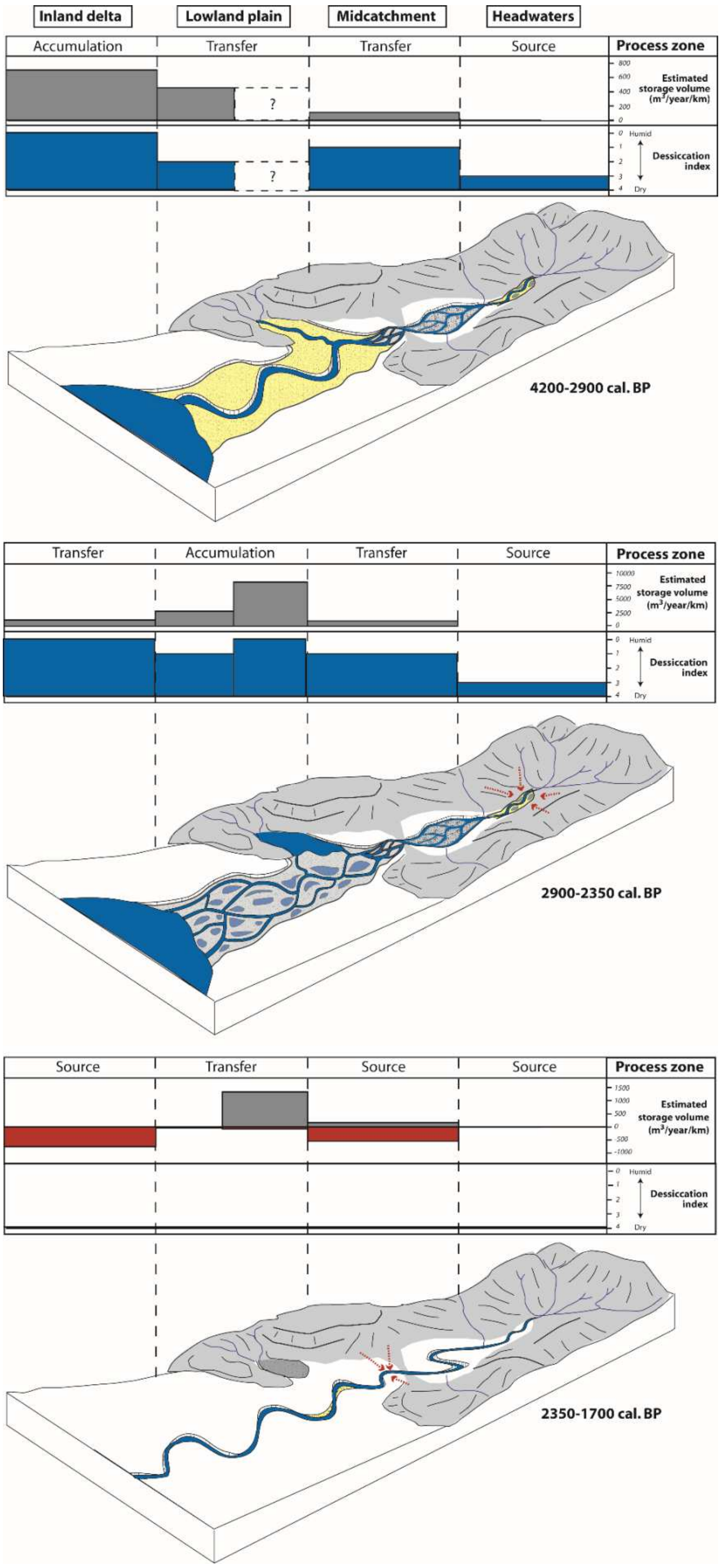


Fig. 9.a: Fluvial dynamics reconstruction along the Yamé valley during 4200-1700 cal. BP. Sediment storage is indicated for each section by an average of m³ per year and km.

The **1700-1400 cal. BP** period indicates a return to an alluvial aggradation into the catchment with the volume of stored sediment slightly higher than during the 2900-2350 cal. BP period with a total of 234 500 m^3/year. In the headwaters, the function of the valley remained as a sediment source while the middle valley and the inland delta section were transformed into sediment transfer zones. In response to this sediment influx, the lower valley became again an accumulation zone. The average volume stored in sections 4 and 5 was 9357 m^3/year/km and 4234 m^3/year/km, respectively.

The sediment records of the **1400-450 cal. BP** period show an idealized river system pattern with a downstream sediment conveyance throughout the valley. On the sandstone plateau (upper and middle valley), the fluvial style is a meandering river system fed by colluvial deposits indicating a lateral sediment supply. The lower valley was transformed into a sediment transfer zone while the inland delta domain shifted to sediment sinks. Hence, the sediment supply was less important than the previous period as demonstrated by the total volume of stored sediment reaching about 54 800 m^3/year.

Over the past five centuries (**450-24 cal. BP**), the fluvial system was quite similar to the previous period except for the upstream zone which switched from a source zone to a sediment accumulation zone. Swamp deposits associated with an increase in sediment storage rate indicate that these local swamps acted as sediment sinks. However, the middle valley, illustrated by a meandering channel river style remained a transfer zone. The high record of sediment storage in the inland delta section, reaching on average around 1500 m^3/year/km, indicates that this section continued to act as a sediment storage zone. For the last few centuries, the upper and middle valley experienced greater aggradation which was almost equivalent to all the volume of the others sections added. The total volume of stored sediments was about 63 900 m^3/year.

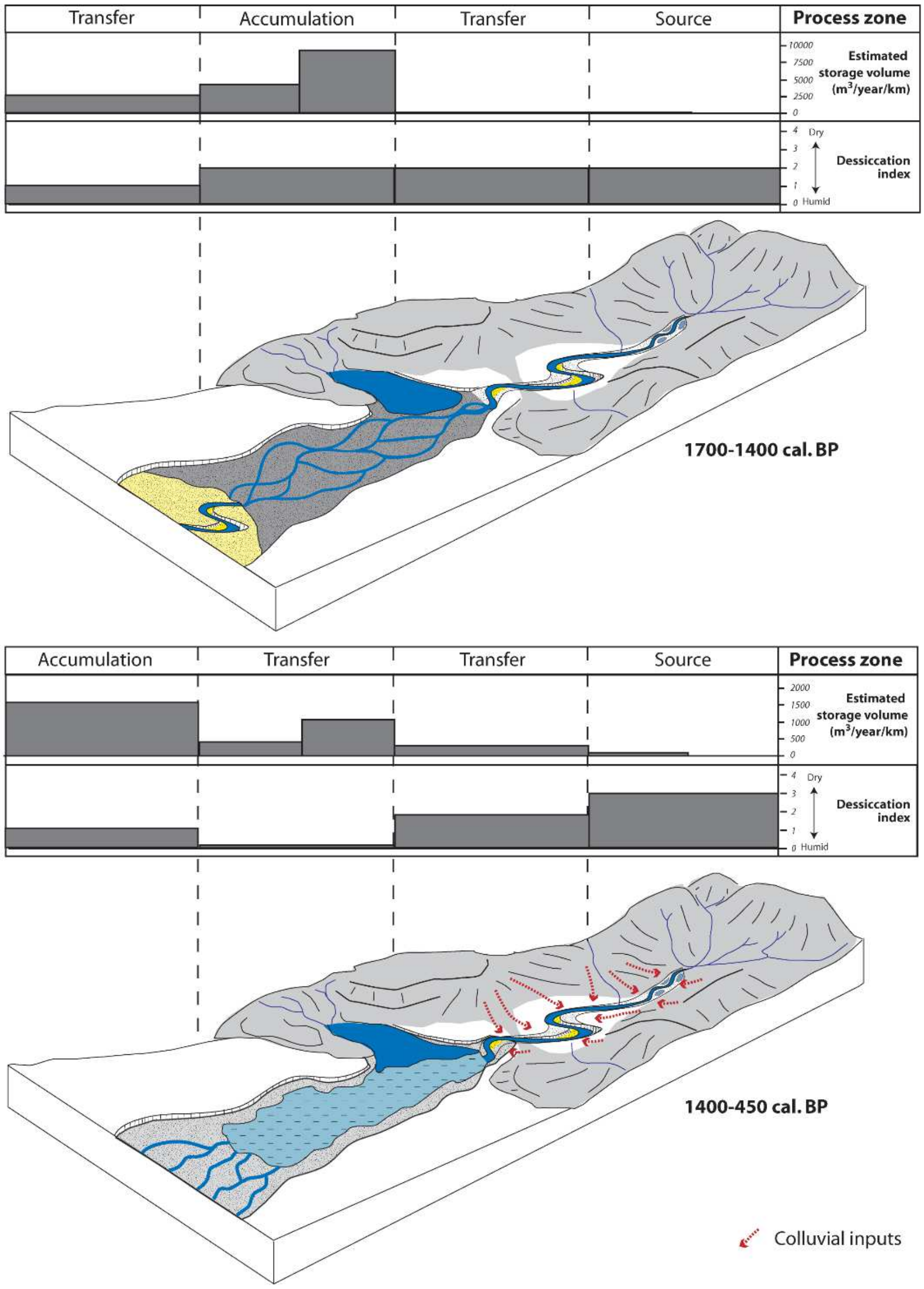


Fig. 9.b: Fluvial dynamics reconstruction along the Yamé valley during 1700-450 cal. BP. Sediment storage is indicated for each section by m^3 an average of year and km.

During the last decades (**post 1936 CE**), the Yamé River has experienced a new metamorphosis of fluvial style. A huge incision observed at the valley head reached a thickness of 12m at Ounjougou (see above). For the rest of the valley, a strong lateral erosion of river banks occurred. During the year or decades that followed this event, pulsed sediments were transferred downstream and promoted an aggradation of the valley bottom mainly in the lower valley which acted as a sediment storage zone. This erosion is equivalent to a volume of 10 million m^3. Parallel to this event is a significant aggradation of 596 000 m^3/year for the whole valley.

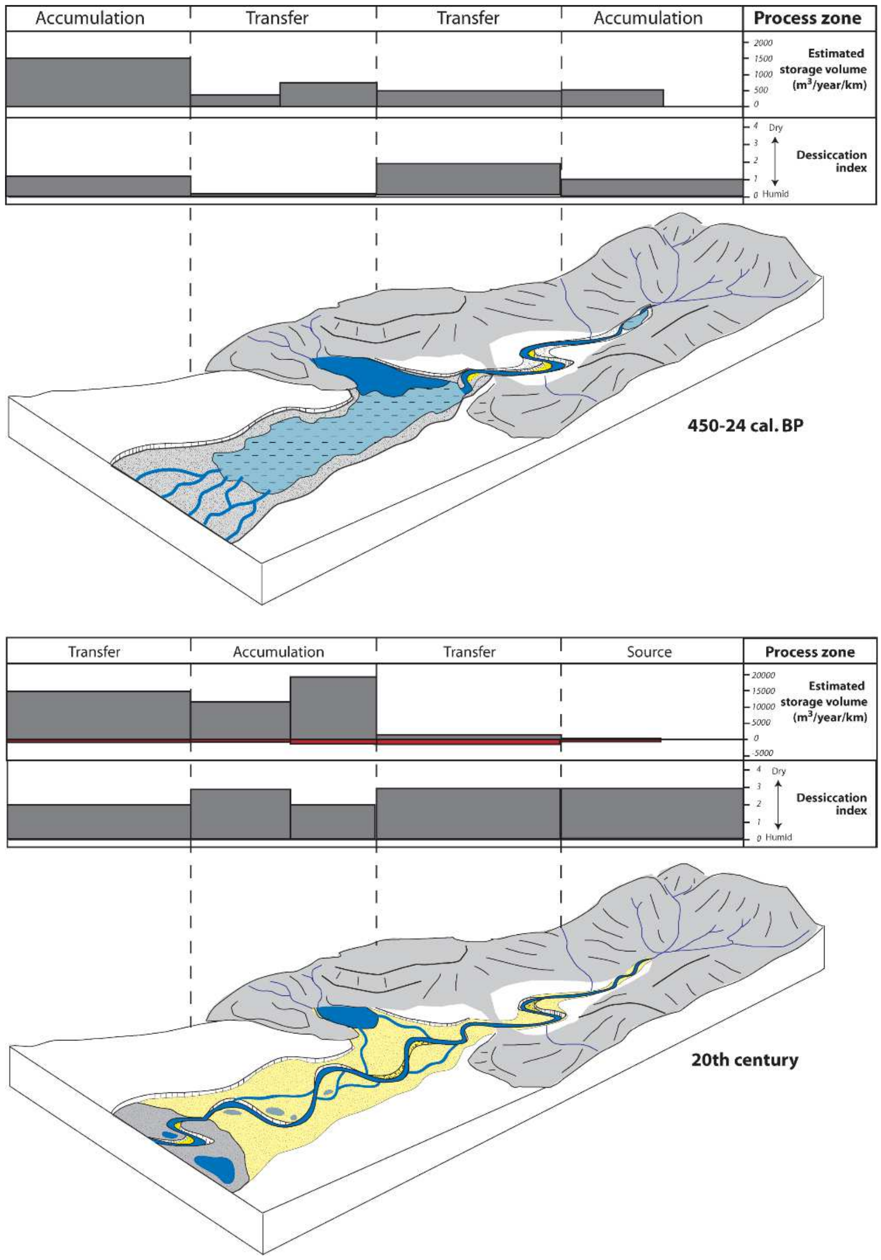


Fig. 9.c: Fluvial dynamics reconstruction along the Yamé valley during 450 cal. BP-20th century. Sediment storage is indicated for each section by m^3 an average of year and km.

5. Discussion: Understanding changes in the sediment distribution patterns: which factors and which scales matter?

According to the idealized fluvial system concept by Schumm (1977) sediment storage increases progressively along the valley floor from source zones in headwaters to accumulation zones located downstream. Continuity of sediment movement along the fluvial system reflects the availability of water energy to mobilize sediments (Fryirs et al., 2007; Fryirs, 2013). Our results show that sometimes the Yamé fluvial system response can be jerky reflecting a disconnectivity between different compartments of the catchment sediment cascade. Analysis of the spatio-temporal variability of sediment storage or incision for the late Holocene has helped to characterize the pattern and processes of sediment movement within a catchment (e.g. Schumm, 1977; Trimble, 1981; Schumm and Rea, 1995; Fryirs and Brierley, 2001). In this study, four distinct sediment distribution patterns have been highlighted during the Late Holocene (Fig. 10). These patterns reveal changes in sediment and water discharge whose origin may be from external triggers such as climatic events or oscillations, or from internal changes such as land use, or a combination of the two.

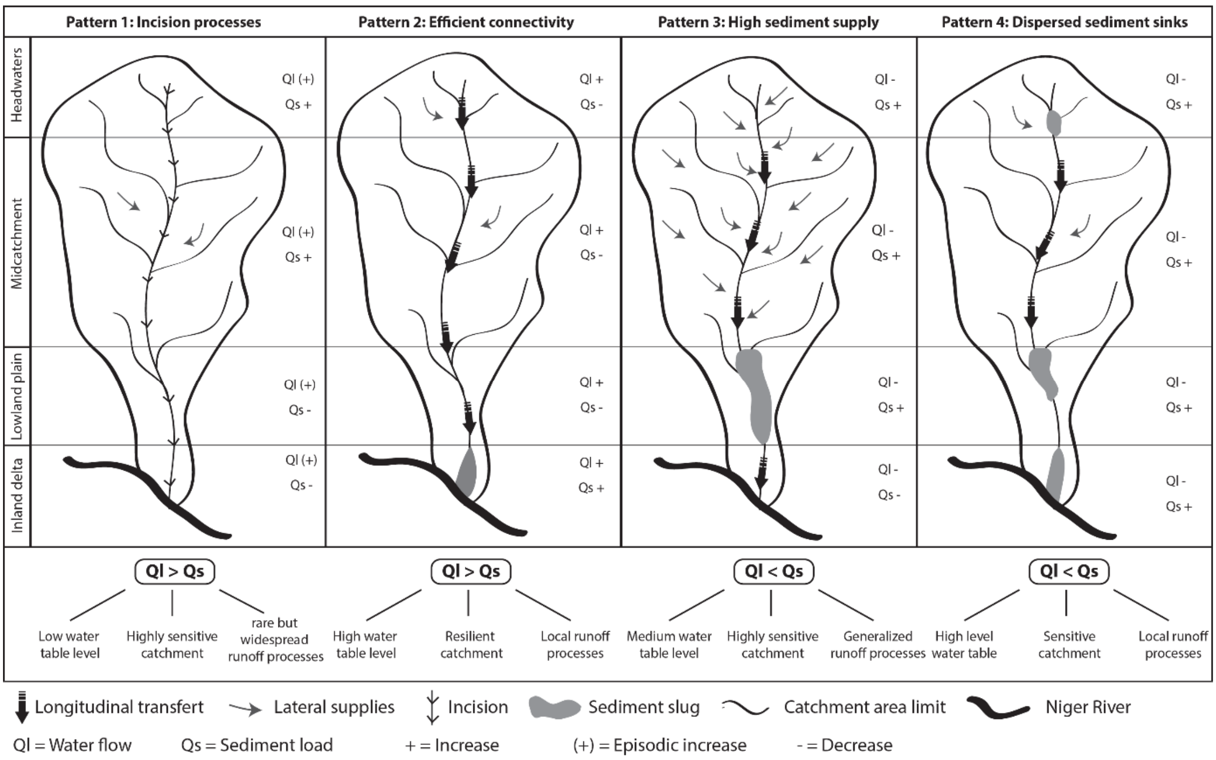
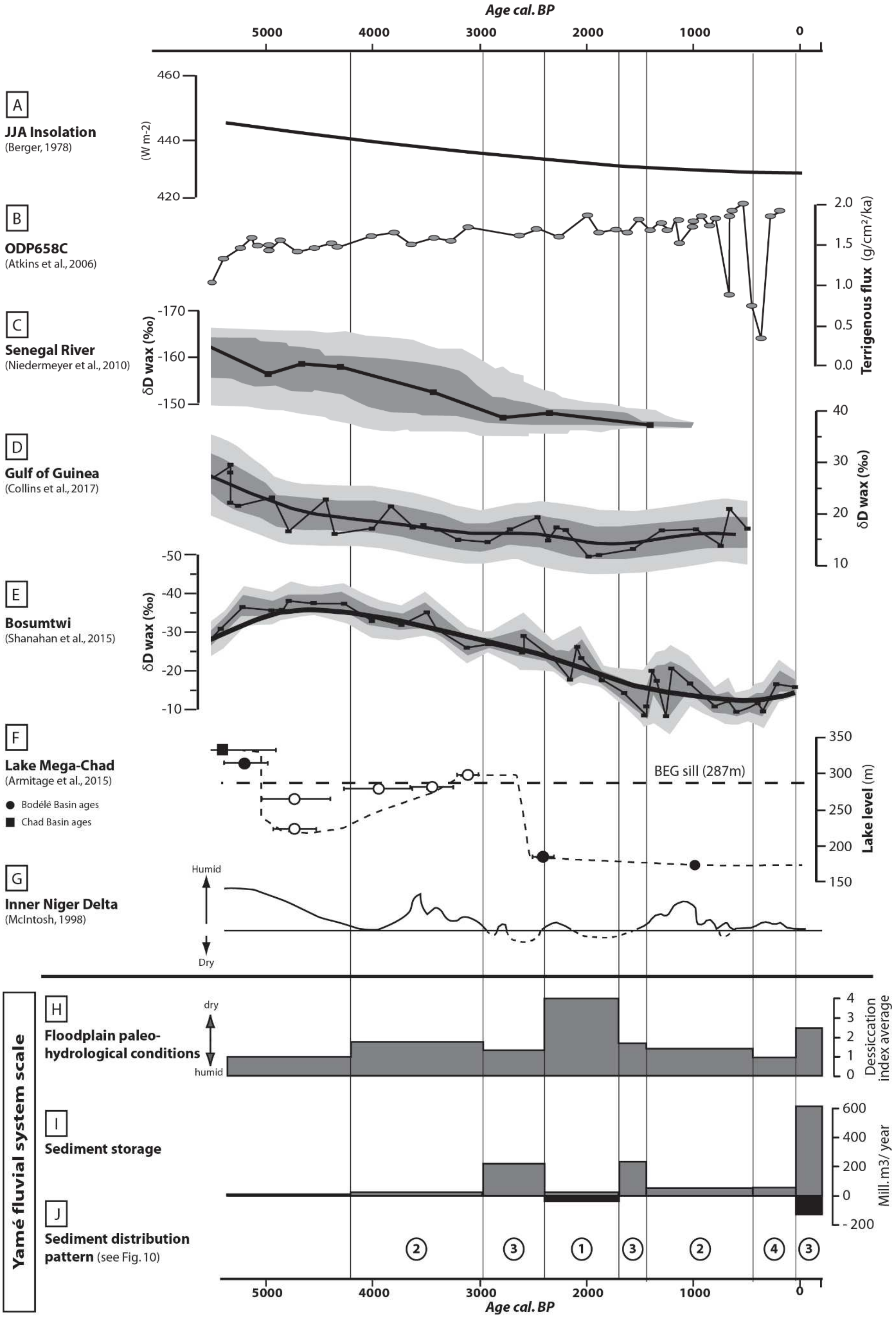


Fig. 10: Schematic sediment distribution patterns in the Yamé valley during the Late Holocene.

In semi-arid catchment areas, because of the high sensitivity of the vegetation and the strong connectivity between slopes and channels, the effects of climatic or anthropogenic changes are particularly rapid (Knighton, 1998; Frankl et al., 2011). To evaluate the sediment and water supplies changes more accurately, we applied to each studied fluvial zone and pattern, the equations of Frankl et al. (2011) based on the concept of Schumm (1977) and Knighton (1998). Channel aggradation (d-) results from an increase in sediment supply (Qs+) and/or a decrease of water flows while channel incision (d+) signals an increase in water flow (Ql) and/or a decrease of sediment load (Qs-). A comparison with available palaeoenvironmental datasets from the end of the African Humid period from the region is necessary to discuss the role played by different factors in these morphological adjustments (Fig. 11).



Age cal. BP
5000
4000
3000
2000
1000
0
A
JJA Insolation
(Berger, 1978)
(W m-2)
460
440
420
B
ODP658C
(Atkins et al., 2006)
Terrigenous flux (g/cm²/ka)
2.0
1.5
1.0
0.5
0.0
C
Senegal River
(Niedermeyer et al., 2010)
δD wax (‰)
-170
-160
-150
D
Gulf of Guinea
(Collins et al., 2017)
δD wax (‰)
40
30
20
10
E
Bosumtwi
(Shanahan et al., 2015)
δD wax (‰)
-50
-40
-30
-20
-10
F
Lake Mega-Chad
(Armitage et al., 2015)
Bodélé Basin ages
Chad Basin ages
BEG sill (287m)
Lake level (m)
350
300
250
200
150
G
Inner Niger Delta
(McIntosh, 1998)
Humid
Dry
Yamé fluvial system scale
H
Floodplain paleo-hydrological conditions
dry
humid
Dessiccation index average
4
3
2
1
0
I
Sediment storage
Mill. m3/ year
600
400
200
0
- 200
J
Sediment distribution pattern (see Fig. 10)
2
3
1
3
2
4
3
5000
4000
3000
2000
1000
0
Age cal. BP

Fig. 11: Comparison of fluvial record of the Yamé with local regional climatic data

A. Mean June-August Insolation at 10°N (Berger, 1978); **B.** Terrigenous flux record from ODP Site 685C (Adkins et al., 2006); **C-E.** δD wax from the Senegal River from core GeoB9508-5 (**C.** based on the C_{31} n-alkane; ice-volume and vegetation adjusted - Niedermeyer et al., 2010); The Gulf of Guinea from core GeoB4905-4 (**D.** based on the C_{29} n-alkane; ice-volume and vegetation adjusted **-** Collins et al., 2017); The Bosumtwi Lake (**E.** based on the C_{31} n-alkane; ice-volume and vegetation adjusted - Shanahan et al., 2015). Shading reflects 66% (dark) and 95% (light) uncertainty bounds. **F.** Lake Mega Chad levels. Point data are from the Bodélé Basin, whereas square ones are from the Chad Basin. Open data points represent Aeolian sediments, which were deposited above the contemporaneous lake level. Closed data points represent shorelines and therefore contemporaneous lake level. The black dashed line indicates lake-level changes while the the horizontal dashed line represents the elevation of the Bahr El Ghazal sill whioch separates lakes exist in the Chad ans Bodelé basin. So lake-level changes below this line represent the Bodelé basin only. **G.** Climatic variations of the Inner Niger delta after McIntosh, 1998. **H-J**: Yamé river data. **H**. Dessication index average reflecting floodplain paleohydrological conditions of the whole valley; **I:** Sum of sediment storage per period for the valley (in mill.m^3/year); **J.** Sediment distribution pattern per period.

5.1. Intense and widespread incision in the valley during the 2350-1700 cal. BP: climate crisis?

This sediment distribution pattern (pattern 1; Fig. 10) is characteristic of a major down cutting of the channel bed occurring ca. 2350-1700 and signifies a hydro-sedimentary crisis (Garnier et al., 2015). This geomorphological adjustment, synchronous for the whole valley, is the result of a dysfunction of the flow-sediment balance and a high sensitivity of the watershed. In particular, it reflects a significant increase in the water supply of the river compared to sediment load (Ql>Qs). Generally, a rise in water flow compared to sediment supply may originate from increased precipitation and/or dense vegetation cover. But conversely, it can also be linked to the action of consecutive flash floods on a sensitive watershed during an arid period. This latter scenario has been suggested for the Ounjougou's reach (Lespez et al., 2011) and has already been observed in other semi-arid regions (Berger et al., 2012) and also more recently in the Sahelo-Sudanian region during the 70-80's. Despite a decrease in rainfall, studies suggest an increase of flow coefficients (Valentin et al., 2004; Garnier et al., 2015). During droughts, sporadic rains result in an increase of hortonian runoff because of the low infiltration capacity of the soils. The decline in vegetation cover promotes soil crust formation and makes these soils more sensitive to an extreme climatic event (Casenave and Valentin, 1992; Wilcox et al., 1998). This hypothesis of a more arid oscillation is supported in the lower valley by the drying up of the Bandiougou's Lake which became a swampy area.

In West Africa, some studies argue that this period was arid (Lézine., 1989, 2011; Shanahan et al., 2006; Armitage et al., 2015). A significant decrease of flow rates of the Senegal River is observed between 2500-2200 cal. BP (Bouimetarhan et al., 2009). Between ca. 2200 and 2100 cal yr BP, a rapid increase in sedimentation rates and important proxies percentage fluctuations (fern spores, pollen, dinocysts, etc.) suggests high magnitude river discharge which can be interpreted as the result of episodic flash-flood events of the Senegal River (Bouimetarhan et al., 2009). This period is also associated with a greater peak in terrigenous fluxes indicating more arid conditions (Fig. 11B; Adkins et al., 2006). In the Middle Niger an arid phase called the "Big Dry" is recorded (McIntosh, 1998; Makaske, 1998) while the Inland Niger Delta is subject to a long period of drought (Makaske et al., 2007). Water levels from Chad Lake fell after 3 ka. BP. On 2400 cal. BP, it reached the sill of 287m, which is the limit to feed northward the Bodelé basin by overflow through the Bahr el Ghazal (Fig.11F; Armitage et al., 2015). According to Maley and Vernet (2015) a significant erosive phase occurred south of the Sahara between 2400-1800 cal. BP. Indeed, an incision of several tens of meters is observed along the Bahr el Ghazal even to the Congo basin, with the identification of coarse deposits associated with erosive dynamics (Maley, 2010). Nevertheless, the archives from the current Sudano-Guinean zone show no change in the vegetation cover for this period, with palynological and phytoliths records of the Sudano-Sahelian zone indicating a permanent opening of the vegetation (Maley, 1981; Lézine, 1988, 1989; Alexandre et al., 1997). Ngomanda et al., (2009) demonstrate a significant increase in Poaceae around 2,500 years old. BP. Gulf Guinea δDwax record are the lowest during this period suggesting a decrease in antecedent rainfall (Fig.11D; Collins et al., 2017). Palaeoenvironmental studies concur that this period was determinant in the history of the

Holocene in West Africa. Archaeological studies also testify to the importance of population dynamics during this dry period, particularly in wetland areas such as the Inner Niger Delta, the Senegal delta (McIntosh and McIntosh, 1983; McIntosh, 1999, 2005; Mayor et al., 2005) or local refuge areas with permanent water sources (Garnier et al., 2015).

5.2. Efficient connectivity within the catchment basin reflecting humid phases (4200-2900 cal. BP and 1400-450 cal. BP)

Two periods testify to an efficient sediment conveyor belt with a sediment wave that operated from headwaters to the Inland Niger Delta (Pattern 2; Fig. 10). This fluvial pattern suggests that the competence and capacity of flow are sufficient to transport sediments along the valley to the storage basin downstream. Alluvial records of these time slices reflect the same geomorphological conditions. Desiccation indexes around 1.8 and 1.25 on average attest to the presence of a moderate to high water table in the whole valley (Fig. 11H). However, the most conspicuous feature of this fluvial system pattern is the weakness of the sediment supply. The storage record for both of these periods is the lowest of the Late Holocene with <500 m3/yr/km on average for the whole basin. Indeed, the combination of moderate and stable water flow is sufficient to transfer sediment and relatively low sediment supply could explain the good connectivity between landscapes units, from headwater to accumulation zone, downstream.

The weakness of sediment supply could also have been promoted by the presence of dense vegetation cover, sufficient to protect soils from runoff. This interpretation is in line with regional data that confirm the presence of a relatively humid period for the first period. Despite the fact that the 5th millennium is often described as the termination of the African Humid Period (Gasse, 2000; deMenocal et al., 2000; Salzmann et al., 2002; Lézine et al., 2005; Armitage et al., 2015; Collins et al., 2017), studies indicate some spatio-temporal variability with the identification of a new wet period during the 4th millennium BP. Lake Chad is lived his last transgression around 3000 cal. BP (Leblanc et al., 2006; Maley and Vernet, 2015; Armitage et al., 2015; Fig. 11F) while more locally, the level of the Niger, after a significant regression around 4000 cal. BP, became higher until ca. 2400 cal. BP in the Inland Niger Delta (McIntosh, 1998, 2005; Fig. 11G). The crater lake Bosumtwi δDwax records testify to a return to wet conditions around 5.5 ka and then a termination of the African Humid Period at ~3.5 ka (Fig.11E; Shanahan et al., 2015). More generally, Lézine et al. (2011) compiled the palaeohydrological proxies in lacustrine, fluvial or palustrine deposits and showed that the Sahel had a period of relative humidity between 3500 and 2500 cal BP.

On the other hand, it appears very different for the 1400-450 cal. BP period. Locally, many colluvial deposits have been observed on the sandstone plateau suggesting an increase in soil sensitivity (Fig. 9.b). Some regional environmental data postulate about a humid climate. After an arid period, an increase in water level is recorded between 1400-1000 cal. BP in the Inland Niger Delta (Fig. 11G; McIntosh, 1998) which than became more variable (Mayor et al., 2005). Nearby, in Saouga (Burkina Faso), this short climatic improvement was marked by the migration of various Sudanese plant taxa in a Sahelian floristic context (Neumann et al., 1998). Historical data also points to a more humid period around 900-1000 cal. BP (Reichelt et al., 1992). However, this short climatic pulse could have a local extent because further away other data testify to a continuous trend towards aridification. Indeed, this was confirmed by a regression of the Lake Chad level (Maley, 1981; Leblanc et al., 2006; Armitage et al., 2015) and stronger aeolian activity (Makaske, 1998; Adkins et al., 2006).

Despite a different environmental context, the good connectivity suggests that changes in the vegetation cover and in the catchment area sensibility are not the dominant driving factor and that climate was sufficiently wet to produce flows available to transfer sediment throughout the valley.

5.3. An increase in sediment supply: a result of a degraded catchment? (2900-2350 cal. BP; 1700-1400 cal. BP; 20th century)

The third sediment distribution pattern reveals a sediment wave from upstream with a substantial aggradation of sandy sediments downstream (Fig. 10). The volume of sediment storage in the low valley ranges between 8200 and 9300 m3/yr/km for the two older periods and more than 17000 m3/yr/km for the 20th century. The flow is inefficient to transport sediments that are trapped at the entrance into the lower valley that can be characterized by a decrease of the longitudinal slope and energy (Fig. 1). This geomorphic adjustment resulted in floodplain width expansion. This sediment slug acted as an obstacle to longitudinal sediment transfer altering the water-sediment balance with an increase of sediment load (Qs>Ql). This reflects a highly sensitive catchment originating from climate and/or vegetation cover changes. A decline of vegetation cover may induce intensified erosion on hillslopes and increased sediment delivery downstream.

For the older period (2900-2400 cal. BP), the geomorphological data signifies a relatively wet period with a desiccation index reaching 1.3 on average for the whole valley. However, this desiccation index can also be explained by the sudden aggradation of the valley floor in the lower valley creating a vast spreading watery area with some remaining small pools.. This also indicates a local geomorphological adjustment. Moreover, first colluvial deposits have been observed upstream and this suggests an increase in soil erosion. On a regional scale, some studies demonstrate a trend towards aridification for this period (Breuning and Neumann, 2002; Mayor et al., 2005). Re-activation of a dune system was recorded during 2700-2500 cal. BP in the Gourma (Stokes et al., 2004), in the Inland Niger Delta (Makaske, 1998), in Mauritania (Hanebuth and Lantzsch, 2008) and further north at Ounianga, north of Chad (Kröpelin et al., 2008). Vegetation data at Oursi dated to ca. 3000 cal. BP suggest a more arid period (Ballouche and Neumann, 1995). Other analyses conducted on marine cores retrieved off the Senegal River mouth reveal increased runoff from the Senegal River but was related however by authors to higher monsoonal precipitation (Bouimetarhan et al., 2009; Nizou et al., 2010). Niedermeyer et al. (2010) studying the δD record from a marine sediment core from the continental slope off Senegal showed a strong decrease in their results suggesting aridification during this period (Fig.11C).

Archaeological data highlight a possible role played by human activities in this significant increase in sediment delivery. Even if signs of agriculture are recorded at Ounjougou around circa 3900-3400 cal. BP (Ozainne et al., 2009; Garnier et al., 2013), it seems that this activity

was even more intense over a millennium later, and contributed towards accelerating soil erosion. Eichhorn and Neumann (2013) point to an openness in the vegetation cover and a diversification of habitats maybe promoted by agricultural practices. Hence, this period follows an increase in the archaeological record of artifacts which confirms the presence of farmers in the region, particularly on the sandstone plateau (Ozainne, 2013; Ozainne et al., 2009). Thus, drier climatic conditions associated with an increase in agriculture practices on the sandstone plateau would have probably favored high runoff on watershed slopes.
The second period (1700-1400 cal BP) is specific because it is the lag time or recovery period after an arid period (2350-1700 cal. BP). The rise of precipitation and the reactivation of the water flows resulted in an increase in sediment supply and water discharge. Sediment records at Bandiougou show an extension of the lake and wetlands and suggest the possibility of a wetter climate. This is in agreement with McIntosh (1998, 2005), who suggests an increase in the water table in the Inland Niger Delta (Fig.11G). A rise in the δDwax record of Gulf Guinean indicates as well an increase in past precipitation (Collins et al., 2017D). The recovery of more humid conditions would have been favorable to soil stability but we suggest that human activities would have certainly accelerated soil degradation. Local archaeological data points towards an expansion of human occupation and agro-pastoral activities during these centuries (Mayor et al., 2005, 2014; Mayor, 2011; Huysecom et al., 2009; Ozainne et al., 2009; Ozainne, 2013) while other palaeoenvironmental data suggest the development of a sedentary lifestyle in West Africa leading to the expansion of cultivated areas (Höhn and Neumann, 2012; Ozainne et al., 2014; Davidoux et al., 2018; Stern et al., in press). Land clearance and agricultural activities associated with hydrological reactivation created a direct impact on surface runoff and soils erosion. However, the frequency and intensity of flood flows were not sufficient to transfer all these sediments to the Inland Niger Delta.

More recently, the Yamé valley was subject to a cut and fill hydro-sedimentary pattern. At Ounjougou, this strong incision, around 10m in the Quaternary deposits, can be related to the oral tradition and dating back to 1936 (Rasse et al., 2006). According to the chronostratigraphy, the incision of around a few meters observed in the whole valley, occurred during the same period or slightly after (post 24 cal. BP). Despite the shortness of the period, the sediment volume stored is significant (49 million m³) and testifies to a high denudation rate and an increase in runoff coefficients. This intense degradation of vegetation cover might be the result of an increase of aridification as hinted at by the desiccation index reaching the highest level (2.7) since the beginning of the Late Holocene but also an increase promoted by human pressure. The local meteorological data point towards more arid conditions not seen since the second part of the 20th century (Garnier et al., 2014). In addition, Mayor (2005) noted an increase in the demographic pressure from the 18th century CE resulting from a new wave of migration from the populations of Mandé (South of Mali) to the Dogon Country. Most of the current villages were settled during this century. In Sahel, the second half of the 20th century is also characterized by one of the world's highest population growth episodes. Leblanc et al. (2008) show that 80% of their study area (500 km²) in SW Niger had been cleared between 1950 and 1992. First, to open up new areas for agricultural use but also for firewood supplies.

Despite different environmental conditions, the combination of both of these external and internal triggers played a role in this major geomorphological event. For both time periods, 2900-2400 cal. BP and the 20th century, the huge increase in sediment supply is the result of climate aridification associated with an increase of anthropogenic impact on the Yamé valley catchment. The fluvial response of the 1700-1400 cal. BP period is more complex because geomorphological inheritance of the preceding arid period and increases in human populations and agricultural practices must be taken into consideration. The aridification of the climate over more than seven centuries created a higher sensitivity of the landscapes with the opening of the vegetation and degradation of the soils. A more humid climate conducted to the reactivation of hydrological processes as well as the reoccupation by human populations in the Yamé valley increased substantially the runoff processes and sediment delivery.

5.4. Disperse sediment sinks : local adjustment to human disturbance and climatic pulse (450-24 cal. BP)

Sedimentary records of the last centuries (450-24 cal. BP) are representative of the last sediment delivery pattern (Fig. 10). This pattern is quite similar to the first one with a sediment slug processing from the sandstone plateau to the Inland Niger Delta. However, except in the middle valley which acted as a sediment transfer zone, some sections reveal the development of wetland environments throughout the valley, which acted as a storage area. The sedimentary facies and the desiccation index, which decreased to 1, suggest a rise in the water table level and increase in precipitation. According to McIntosh (1998), a wet phase occurred between 500-200 cal. BP in the Inland Niger Delta (Fig. 11G) and from 400 cal. BP to the beginning of the 20th century in Lake Chad (Maley, 1981). Terrigenous fluxes in sediments from the marine core ODP Site685C off Cape Blanc show a large drop (Fig.11B; Factor of 1.5-2.0 *vs.* factor of <1) at the beginning of this period suggesting important changes in vegetation cover and/or precipitation (Adkins et al., 2006; McGee et al., 2013). On a global scale, this period may be correlated with the last rapid climate change identified by Mayewski et al. (2004) and Wanner et al. (2011). It also corresponds in Europe to the 'Little Ice Age' which resulted in wetter conditions in the tropics ("Cool poles, wet tropics", Mayewski et al., 2004). Despite this well-recorded rapid climatic change across the world, studies reveal that this event has not been yet observed in West Africa. We can also suppose that the local swamps promoted by the expansion of the sediment slugs which acted as plugs to longitudinal sediment movement along channels and creating further vast swampy areas. Indeed, archaeological data is numerous for this period (Mayor et al., 2005). For example, the Dogon settlement developed during this time period and increased the impact of human activities on the environment in this region. Increases in sediment supplies and the local sediment delivery may have been plugged in the valley floor according to the topography features and the climatic conditions. Thus, these local swamps lasting several decades to a century in large unconfined reach formed due to climatic oscillations and sediment supply increases.

6. Conclusion

Just as Holocene fluvial system responses have already been well studied in temperate and Mediterranean zones (e.g: Faust and Wolf, 2017; Verstraeten et al., 2017; Brown et al., 2018), research conducted on medium size tropical rivers remain scarce, especially in Africa. The study of the Late Holocene sedimentary records of the Yamé valley provide new information about climatic and anthropogenic changes for a region and period poorly studied to date. Thus, the analyses of sediment archives for seven reaches distributed along the entire course of the 137km of the Yamé valley (Mali) is the first study to attempt to reconstruct the fluvial system operating from the source to the accumulation zone during the Holocene in tropical West Africa. This study has attempted to address questions of time and scale which are crucial to the understanding of fluvial archives and to interpreting themes in terms of system responses to different controls (e.g. Schumm, 1991; Harvey, 2002). This study demonstrates the possibility for each time slice and river reach (1) to reconstruct the fluvial style and processes and (2) to estimate the sediment storage volume reflecting sediment and water delivery changes whose origin may be from external (climatic events) or local (land use, etc.) controls or a combination of both. The results obtained from this research highlight the role of the wet oscillation (4200-2900 cal. BP, 450-24 cal. BP) and arid period (2350-1700 cal. BP). This study confirms that climatic factors play a crucial role in the timing of the fluvial system changes in semi-arid and tropical rivers (e.g. Thomas, 2008; Macklin et al., 2015; Faust and Wolf, 2017) while human disturbance appears as a secondary driver due to the high sensitivity of the environment to climate variability in such areas. If we can assume that human practices have certainly intensified runoff processes during the Late Holocene, it remains difficult to disentangle and quantify the role played by human activities. Nevertheless, we observe an intensification in erosion and sediment supplies, even during more arid periods. It can be interpreted as an increase in human pressure on the environment. This is the case during the 2900-2350 cal. BP period corresponding to the beginning of the agro-pastoral activities development but also more recently, during the demographic explosion of the 20th century generating an extension and intensification of agricultural practices (Garnier et al., 2014).

This study also highlights the role of sediment and geomorphic legacies in the response of the river system to environmental changes and emphasizes the necessity for understanding the trajectory of the fluvial system for interpreting the fluvial archive. For the 1700-1400 cal. BP period, fluvial archives record huge sediment supplies which can be explained mainly by the reactivation of both hydrological processes (on slopes and channels) and human occupation after an intense and long arid event. Thus, this record appears as a complex and strong response to long-term change in the environment not only proportional to the intensity of climate change but also subject to the state of the environment and fluvial system before this change occurred. On the other hand, the last sediment delivery pattern (450-24 cal. BP) testifies to the strong reactivity of the fluvial system with local fluvial adjustments to human disturbance. Fluvial archives demonstrate that for many reaches disperse sediment sinks result both from the combination of local intensification of colluvial processes andof global climatic change with wet phase occurring at the regional scale. These factors also have to be considered for the management and prediction of fluvial system changes due to global and local land use changes.

To conclude, the results from this study highlight the need for researchers to undertake new palaeoenvironmental analyses in order to better capture and characterize the vegetation cover changes. Certainly, these analyses will provide new information on human-environment interactions and enable researchers to discuss, more accurately, the role of these factors in changes in the fluvial landscapes during the Late Holocene. Furthermore, this kind of global fluvial system study should be developed South of the Sahara in order to make further comparisons useful to understand the role of geographical contexts and local controls *vs.* global changes in the river changes in Africa.

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