Chapter 16

Fluvial risk in rural areas from the Greek period to the early Middle Ages

The case of the Rhône delta (France)

Introduction

The Rhône delta (Fig. 1A) is a vast Holocene plain (~1700 km^2), which results from the interaction between several physical factors (alluviation, eustasy, soil movements). Hydrological and sediment-yield variability has played a major role in its morphological evolution. Exposed to flooding, avulsions, crevassing, and freshwater/saltwater interactions, the delta is an unstable physical environment (Arnaud-Fassetta, 1998, 2007). Yet despite severe natural constraints, the Rhône delta was an area of active settlement in antiquity and the Middle Ages (Landuré *et al.*, 2004). Faced with floods and hydrological variability of the Rhône River, the inhabitants of the delta have been exposed to hydroclimatic hazards, both physically and mentally and to varying degrees (Arnaud-Fassetta and Landuré, 2003).

In this chapter, we characterise the principal natural hazard as the Rhône River floods and their morphological effects on the deltaic plain. Closely linked to climate variability, flood events are here considered to be a hydroclimatic hazard. Vulnerability relates to societies, which in this case have developed on ancient alluvial ridges of the Rhône River. Our study will focus on the nature of the fluvial risk during the two millennia around 0 AD (800 BC-AD 1000). What influence did flooding exerted on the economic and rural development of the delta? Was it a perennial factor? Have the social group living on the delta always taken the risk into account?

Since 1995, two collaborative research projects of the Ministry of Culture ['*Rhône delta*' (1995/1998) and '*Rhône of Ulmet*' (1999/2001)], respectively coordinated by Michel Pasqualini and Corinne Landuré (Regional Archaeology Service, Regional Directorate of Cultural Affairs - Provence-Alpes-Côte d'Azur), and the ACI Young Researchers project ['*The hydrological risk in the Rhône delta in the Middle Ages. Assessment, management, and impact on land-use dynamics*' (2002-2004), coordinated by Gilles Arnaud-Fassetta (University of Paris 7/PRODIG)] have made progress in this area of research, particularly in our understanding of societies development on the Rhône delta and their interactions with the hydrosystem and river regime. Through the results of fifteen years of research, we discuss specifically (i) the characterisation and phasing of hydroclimatic hazards in the Rhône delta, (ii) the nature of the habitat, modes of occupation, which are linked to it, and the vulnerability of sites, and (iii) changes in fluvial risk between the Greek period and the early Middle Ages.

Hydroclimatic hazard in the Rhône delta

Palaeohydrographical framework

From the Rhône delta, palaeohydrographical data were derived from the interpretation of several stratigraphic sections and sedimentary cores coupled with the photointerpretation of visible, surficial fluvial forms (Fig. 2). The hydrographical network was formed in the deltaic environment in association with its continental margins. Palaeohydrographical maps show, since the Protohistory, the rhythm at which the river system developed before the completion of river dyking (embanking) in the late 19th c. During the period studied here, the hydrographical network was composed of the palaeo-Rhône of Ulmet in the east, the palaeo-Rhône of Saint-Ferréol in the central part, and the palaeo-Rhône of Albaron-Peccaïs in the west of the Rhône delta (Fig. 3). The extension of the hydrographical network was associated with the progradation of the delta plain, controlled by the slowing of relative sea-level rise and siltation of the Rhône River. Drainage density (*i.e.*, number and length of palaeochannels) evolved, which with

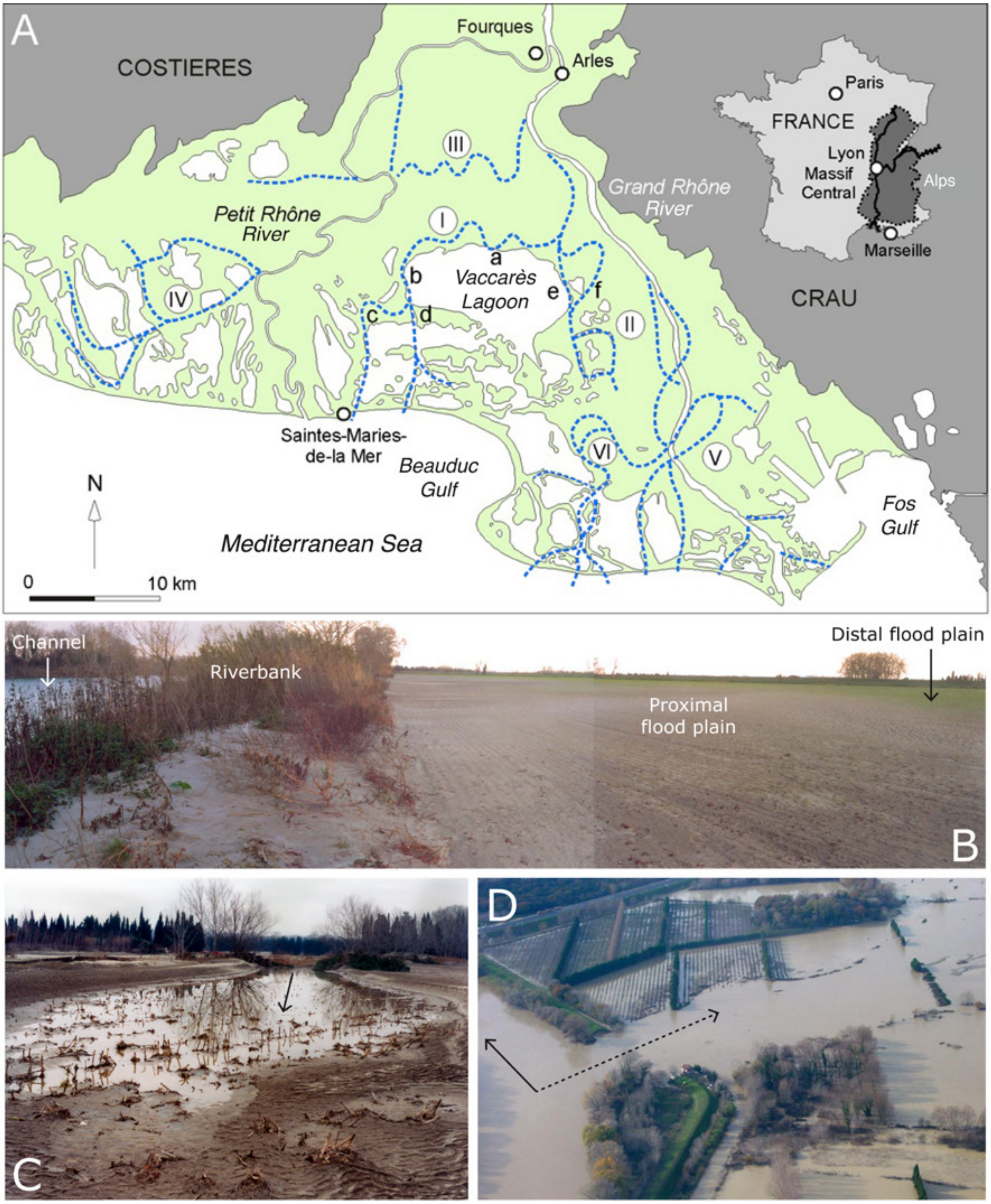


Fig. 1. Location of studied geoarchaeological sites and contemporaneous morpho-sedimentary analogs. A: The Rhône delta. I: palaeo-Rhône of Saint-Ferréol; II: paleao-Rhône of Ulmet; III: palaeo-Rhône of Albaron; IV: palaeo-Rhône of Peccaïs; V: palaeo-Rhône of Grand Passon; VI: palaeo-Rhône of Bras de Fer; a: site of Cabassole; b: site of Le Carrelet; c: site of Les Combettes; d: site of Mornès; e: site of Le Pont Noir; f: site of La Capelière. B: Riverbank and flood-plain sediments deposited during the flood event of Decembre 2003 in the Rhône delta, site of Fourques, Petit Rhône River (photo: G. Arnaud-Fassetta, Décember 2003). C: Crevasse channel opened during the December 2003 flood in the Rhône delta, site of Petit Argence, Petit Rhône River (photo: G. Arnaud-Fassetta, December 2003). D: Crevasse channel opened during the December 2003 flood in the Rhône delta, site of Petit Argence, Petit Rhône River. Human intervention and the infilling of the breach opened in the dyke of the Rhône River have prevented its possible avulsion (photo: Syndicat mixte de protection et de gestion de la Camargue gardoise, December 2003).

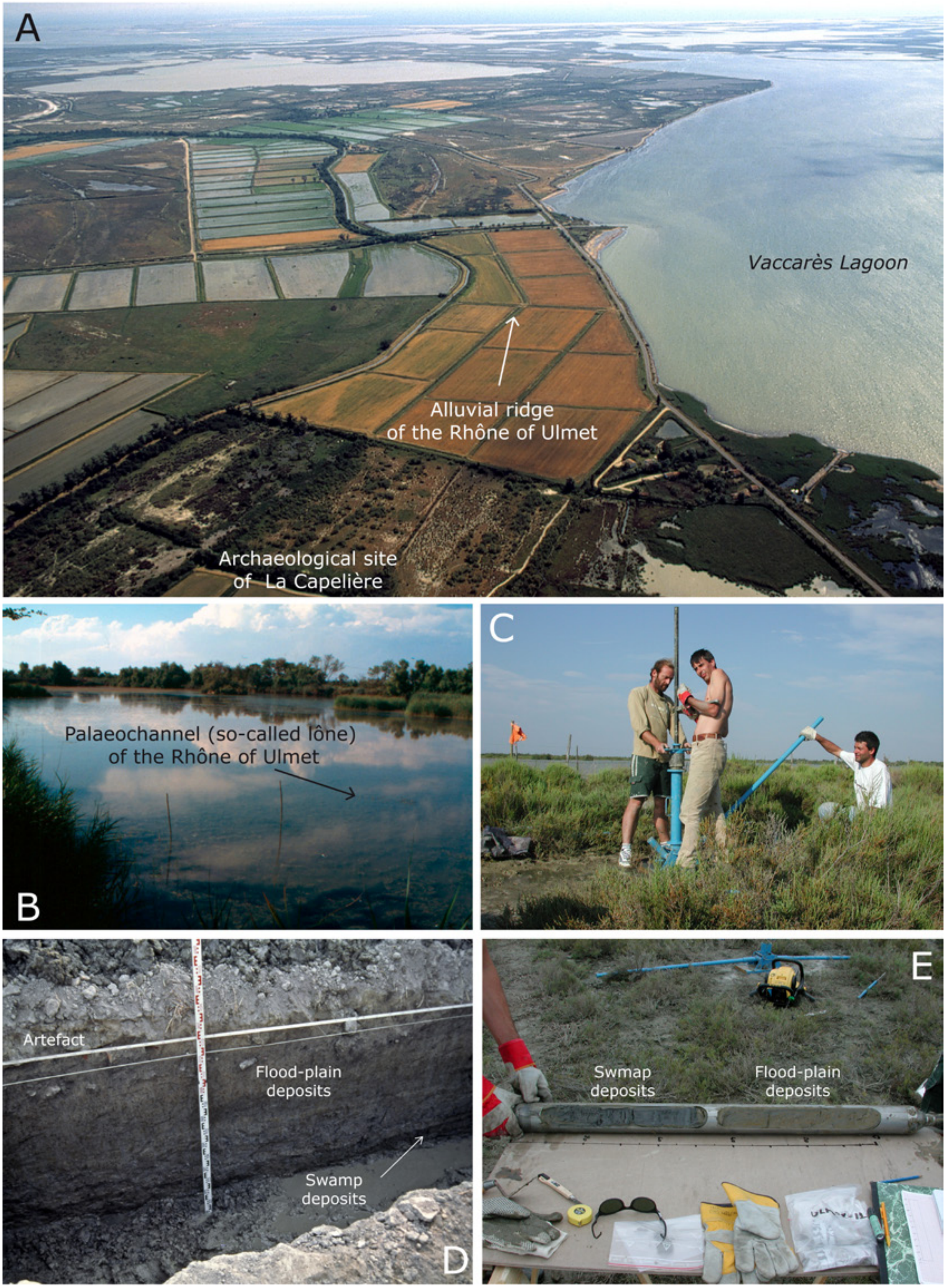


Fig. 2. Acquisition of hydrogeomorphological data (example of the palaeo-Rhône of Ulmet). A: Aerial photoraph of the archaeological site of La Capelière in its (palaeo)environmental context (photo: C. Hussy, June 1998). B: The ancient channel (lône) of the Rhône of Ulmet in La Capelière (photo: G. Arnaud-Fassetta, July 2001). C: The use of a motorised auger on the site of Abbaye d'Ulmet (photo: M. Charlet, July 2002). D: Stratigraphic section in La Capelière (photo: C. Landuré, July 1999). E: Sediment core extracted from the site of Abbaye d'Ulmet (photo: G. Arnaud-Fassetta, July 2002).

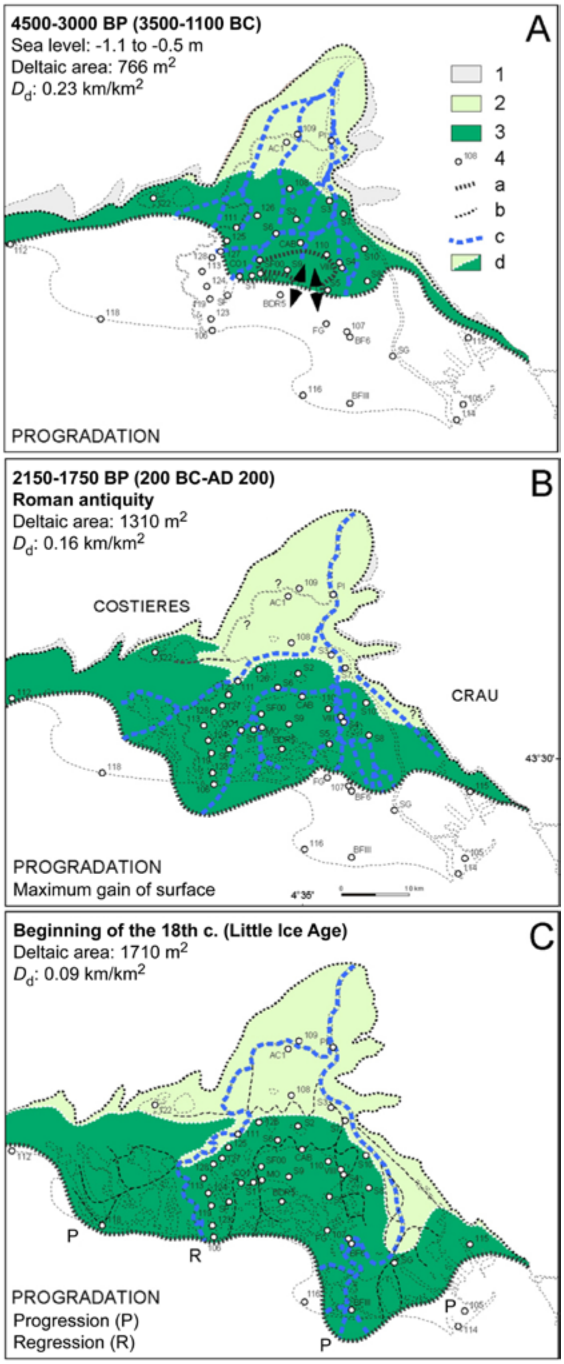


Fig. 3. Hydrogeomorphological and palaeohydrographical changes in the Rhône delta from Protohistoric to Modern times. 1: freshwater, continental environment; 2: freshwater, deltaic environment; 3: brackish-salted, deltaic environment; 4: sediment core; a: coastal fringe; b: Rhône palaeochannel; c: deltaic area boundary; d: hypothetical "fresh-water/brackish-salted" environments boundary. Note the maximum rate of deltaic progradation between 3500-1100 BC and 200 BC-AD 200, and the decrease of the drainage density during Modern times of anthropogenic origin.

changes in hydrological regime, altered the impact of floods on communities living near the river.

Flood magnitude/frequency, typology, and hydromorphological impact of a natural, physical phenomenon

Flooding is the major hydroclimatic hazard in the Rhône River deltaic area. In the lower part of the Rhône valley, river-floods are mainly Mediterranean origin but, due to the large size and diversity of the catchment, flood events can be generalised from the whole hydrological network and they can be responsible for huge overbank flows. Nowadays, these events generally occur every thirty years to every hundred years. Less abrupt than flash floods that characterise Rhodanian and Mediterranean tributaries like the Ardèche and Ouvèze rivers, the consequence of fluvial floods on the delta is prolonged flooding. The reason for this is the inevitable delay in the concentration of the discharge in this large catchment. The velocity of the stream flow is low but the hydromorphological effects of floods can produce significant damage in the deltaic plain during riverbanks breaching, as was the case in 1993-1994 and 2003 (Arnaud-Fassetta, 1996, 2013).

In the Rhône delta, the magnitude/frequency and hydromorphological impact of hydroclimatic hazard depend on five factors:

(i) The hydrological regime: its variability in the lower Rhône valley determines the frequency of extreme flows and the height of floodwaters on the flood plain. Thus, the flood hazard is highly dependent on historical climate variability; it is more frequent during periods of high hydrological levels (flood periods).

(ii) The hydrography: the subdivision of the hydrographical network, resulting in a hierarchisation of different branches (major, minor), determines the geography of fluvial risk.

(iii) The channel geometry: its maximal capacity to contain flood flows depends on the bankfull cross sectional area (bankfull capacity). This value depends on the density of fluvial bars and islands; it also varies depending on the type of channel section (straight, wandering or meandering section, mouth section) and the height of the river banks.

(iv) The sensitivity of the floodplain to submersion: this depends on floodplain relief (*sensu stricto*), the channel geometry (see above), and hydrological connectivity between the channel and the alluvial aquifer. In the Rhône delta, groundwater levels generally adjust to the average height of water flows in the channel (*i.e.*, mean discharge). However, other factors may interact such as the permeability of the floodplain deposits and seasonal water balance.

(v) The rate of evacuation of floodwaters out of the deltaic plain: this is rapid in areas with steeper slopes, but slower when the channel slope decreases nearer to the river mouth. Meteorological-marine conditions also play an important role in increasing (NW winds, surges) or reducing (SE or SW winds, sea-level fall) the duration of flooding in the deltaic plain.

Although the hydroclimatic hazard depends on these five key factors, its geomorphological features are based on the isolated or the combined occurrence of three main process phenomena: floodplain deposition, crevasse splay activity, and avulsion (Arnaud-Fassetta, 2000; Crichton and Siboni, 2001).

Flood-plain deposition

Floodplain deposits results from fine sediment deposited by river floods. The volume and texture of these alluvial units is directly related to the relief of the floodplain, the stream power, the transport capacity, and organic productivity. All these parameters depend on the distance of deposits from the trunk river channel. They include proximal and distal floodplain deposits (Arnaud-Fassetta, 1996; Fig. 1B).

In the proximal floodplain (*i.e.*, close to the channel and its banks), deposits accumulate in the form of sprays, leveees or fans of variable irregularity. These sediments are composed of silt with variable amounts of sand, transported by suspension. The percentage of sand varies between 25 and 35%, with a grain-size median varying between 0.01 mm and 0.05 mm. Grain-size variability of deposits is often a function of the stream power of floodwaters. Average sedimentation rates are generally low (<2 mm yr^{-1}) across several centuries but several decimetres of sediment can accumulate during a single event (Arnaud-Fassetta, 1996, 2013). Soil-forming processes and bioturbation destroy almost entirely the primary sedimentary structures in these deposits.

In the distal floodplain, sediments consist of the finest grains deposited by settling through the water column (decantation). Their grain size is more homogeneous, dominated by silty clay with a median varying between 0.005 and 0.01 mm. The sand fraction is negligible, rarely exceeding 10%. The high organic productivity, low sedimentation rates, and the presence of perennial groundwater are favourable for the preservation of organic debris and the development of peat layers.

Crevasse splays

Crevasse splays are related to the breaching of the riverbanks during morphogenetic flood events. Located along the distributary channels, they form large crevasse lobes of variable thickness (0-4 m) in the form of sandy tongues perpendicularly or tangentially developed to the main channel and towards the flood basin (Arnaud-Fassetta, 2013; Fig. 1C). Crevasse splays are connected to the main channel by a distributary channel associated with a complex system of secondary, anastomosing or wandering channels, leading the floodwaters to the floodbasin. The competence of floodwaters therefore decreases from the levee breach to the distal zones. The percentage of sand varies from 35 to 95% (crevasse channels) and from 70 to 100% (crevasse lobes), with a grain-size median varying respectively from 0.2 mm to 0.5 mm and from 0.1 to 20 mm. Crevasse splays can form vary rapidly (up to 4 m/few hours) accelerating the sedimentation rates in the deltaic plain. The dominant processes are firstly the aggradation by deposition of bed-material load associated with the saltation and suspension, and secondly progradation towards the floodbasin and interfluvial lagoons. They can form rapidy, from few days in anthropogenic hydrosystems to a few years in "natural" conditions (Smith *et al.*, 1989).

Avulsions

An avulsion reflects the abandonment of a fluviatile channel in favour of another channel. This phenomenon results from rapid lateral channel displacement, or a slower process associated with the development of a crevasse splay in the context of floodbasin aggradation and the coalescence of several channels. The avulsions fall into two categories, those related to the reoccupation of a former channel and those derived from the division of the hydrographical network in a floodbasin (Fig. 1D). The former channel can be reactivated if the aggradation process is gradual, generally where the sediment yield constrains the increase of the accommodation space (*i.e.*, space for the development of the sedimentary prism). Avulsions linked to the division of the channels in the floodbasin are common when moderate aggradation rates deliver sufficient accommodation space. Avulsion frequency (*i.e.*, the time required for an avulsion to occur and a new channel to develop) is highly variable. In the Rhine-Meuse Delta, avulsion frequency depends on five interacting factors during the Holocene: positive fluctuations of relative sea level, neotectonics, increased river discharges, channel sedimentogenesis, and human activities (Stouthamer and Berendsen, 2000). These authors highlighted the importance hydrological-sedimentary variability between 2800 and 1000 BP, which corresponds to the period studied here. Work carried out in the Rhône delta showed that avulsion frequencies have varied from 850 years to 2300 years (mean: 1450 years) during the last eight millennia (Arnaud-Fassetta, 2004).

Consequently, flood deposits, crevasse splays and avulsions present different types of constraint for rural societies living in the Rhône delta. Floodplain deposits not only represent a high fluvial constraint, but also an agricultural advantage. What is restrictive is less the result of river alluviation than the height, the power and the time of inundation by flood flows. Both crevasse splays and avulsions represent a severe fluvial constraint because of (i) the energy that is liberated by the hazard in this form (*e.g.*, >10 W/m^2 during crevassing events of December 2003; Arnaud-Fassetta, 2013), (ii) spatial and geomorphological changes caused by the hazard, and (iii) the unpredictability of this event. Traces of ancient floodplain deposits, crevasse splays and avulsions are numerous. Using contemporary analogues to aid interpretation (Fig. 1 B to D; Arnaud-Fassetta, 2007), their study can facilitate the characterisation of the hydrographical network, the hydrological regime, and the hydraulic conditions of the deltaic palaeo-Rhône River.

How to characterise the complexity/ variability of the hydrological regime of the Lower Rhône River?

Depending on the period, the hydrological regime of the Lower Rhône River, which results from glacier-melting, snowmelt and rains with mixed oceanic and Mediterranean influences, exhibit three alternating types of regime: "flood-dominated regime" (FDR), "irregular flood-dominated regime" (IFDR), and "low-water-dominated regime" (LWDR; Arnaud-Fassetta, 1998).

The FDRs

FDRs are linked to high hydrodynamic activity. The Rhône's hydrological regime is characterised by high mean discharge combined with frequent high-energy flood events.

In the channel, aggradation is associated with frequent and abundant sedimentary deposition, which promotes the development of a typical wandering pattern (*i.e.*, the "*tressage deltaïque*" of Arnaud-Fassetta, 1998), and which is characterised by several shallow river channels enclosing sandy bars. The sands of which they are made have a median to fine grain-size distribution, and imply a high competence of Rhône flows, which can transport material of 0.61 mm in diameter. The in-filled channels allow the development of avulsions and crevasse splays.

In the floodplain, FDRs are favourable to the extension of swamps and the general rise of the water table, related to a shallow channel and a high mean discharge. The frequent waterlogging of soils hinders the development of pedogenesis and alluvial units are characterised by a large homogeneous grain-size distribution. Coarse granular particles (fine sand and silt) are well represented, indicating flood flows of high maximum competence (0.2-0.27 mm). High sedimentation rates (2-5 mm yr^{-1}) are linked to high transport capacity and/or to the frequent overflows resulting from infilled channel.

The IFDRs

During IFDRs, the hydrological regime of the Rhône River is characterised by a relatively low mean discharge with a few large flood events that temporarily involve the rise of hydrological levels.

In the channel, alluvial deposits are characterised by sand units (high-energy flood events) or silty-sand units (low-energy flood events). The maximum competence of the Rhône River never reaches more than 0.5 mm. Moreover, flood deposits are insufficient to fill in the channel over a long time, which is why vertical incision still occurs.

In the floodplain, the high inter-annual variability of the overflows is revealed by significant oscillations of grain-size distribution between two flood periods. Coarse deposits (silty sand) are alternately laid down with fine deposits (clayey silt). The maximum competence of the floods has been measured at 0.19 mm to 0.26 mm. Channel incision (i) restricts overbank flows – which results in low sedimentation rates (0.6-1.6 mm yr^{-1}) – and (ii) involves the lowering of the water table. Efficient draining of the floodplain also allows the activity of burrowing animals and the development of biosoils.

The LWDRs

During LWDRs, the hydrological regime is regular and large events are very rare, or nearly non-existent.

In the channel, sediments are finer, composed of fine sand and enriched with an abundant silt fraction, as the Rhône maximum competence is low (0.4-0.46 mm). The mean discharge is low because of reduced water peak in the catchment and/or channel incision. Insufficient sediment yield is responsible for the lack of sandy bars and channel pattern seems to evolve towards meandering or anastomosing.

In the floodplain, the settling of very fine deposits (clayey silt) is linked to the prevailing still-water sedimentation (decantation) processes. The competence of maximum overbank flows is low (0.12-0.2

mm) and is related to the low hydraulic power of the Rhône River. Sedimentation rates are very low (0.5-0.6 mm yr^{-1}) because overbank flowi is exceptional and transport capacity is reduced. The result is weak alluviation processes and a low water table, which allow the development of pedogenesis.

Measurement of hydraulic conditions of the fluviatile palaeochannels

Palaeohydraulic estimates were used to quantify the channel capacity, the discharge, and the specific stream power of the Rhône palaeochannels dating from late Antiquity, early Middle Ages and high/late Middle Ages (Fig. 4). Hydraulic characteristics of palaeochannels were derived from an analysis integrating bed geometry, hydraulic slope, and grain size of the alluvial infils. Calculations derived from the hydraulic geometry of the present-day deltaic Rhône River served as control. The results show that today, the bankfull capacity of both Rhône channels approximate 8895 m^2 (average of 140 cross sections). During the late Antiquity, the three distributaries of the Rhône River (Saint-Ferréol, Ulmet, and Peccaïs) had a combined bankfull-channel capacity (8695 m^2) very close to the present-day. During the high/late Middle Ages, the bankfull capacity of the Rhône palaeochannels (Grand Passon, Saint-Ferréol, Ulmet, Peccaïs) was only 3890 m^2. This lower value means that a large part of the drainage of the deltaic area occurred by overbank process during flood events, and not only through the main distributaries. In this case, the fluvial risk was greater for each large flood overflow. These results are confirmed by the palaeodischarge estimations. The evolution of the specific stream powers shows that in the late Antiquity, they were distributed well on the whole deltaic plain. In the high/late Middle Ages, specific stream powers increased and concentrated in the east part of the Rhône delta, thereby increasing both the fluvial hazard and the induced hydrological risk.

Variability of hydroclimatic hazards from 800 BC to AD 1000

From 800 BC to AD 1000, the hazards in the Rhône delta show a typical hydrological behaviour characterised by three FDRs, interrupted by periods of lower hydrological activity, typically IFDR or LWDR (Fig. 5). Downstream from Arles, the Rhône River flows through three major branches (Ulmet in the east, Saint-Ferréol in the centre, and Albaron-Peccaïs in the west), all of which were affected by significant hydrological-sedimentary variability.

800-500 BC: FDR 1

As revealed by the great lateral instability of the palaeo-Rhône of Ulmet in La Capelière; the channels are affected by avulsions, crevasse splays and the formation of large sandy deposits in the proximal floodplain. The high water table favours the extension of swamps from the north to the south of the delta (Cabassole, La Capelière).

500-400 BC: LWDR 1

This happens when Rhône alluvial activity slows down. The channel of the palaeo-Rhône of Ulmet is affected by several major floods, causing the deposition of sandy loam in the proximal floodplain in La Capelière. In Cabassole, sedimentary deposits of the palaeo-Rhône of Saint-Ferréol are very fine and the maximum competence does not exceed 0.12 mm in the flood plain.

400-100 BC: IFDR 1

The Rhône hydraulic behaviour becomes more variable and powerful. In the floodplain (Cabassole), the heterogeneity of sedimentary deposits is a sign of a calm hydrological regime with only a few violent flood events. Maximum competence (0.24 mm) rises but the sedimentation rates remain moderate (0.6-1.2 mm yr^{-1}). This implies a relatively low sediment yield from the catchment and/or rare overbank flows. The same trend is observed at La Capelière.

100 BC-AD 200: FDR 2

In this time window there are two flood periods (FDRa, FDRb), separated by a short period (a few decades) of LWDR2 between AD 75 and 125 (Arnaud-Fassetta, 2002).

- FDR 2a (100 BC-AD 75). Around 100 BC, the development of crevasse splays in Mornès and La Capelière highlights significant channel instability of the Rhône River. Between 30 BC and AD 110, the Rhône's mean discharge rises and involves lateral aggradation of the palaeochannel of Saint-Ferréol in Le Carrelet. Steep river banks are elevated and strengthened with a boulder armouring (see above). Between 100 BC and AD 75, the maximum competence of the flood flows rises, which can be seen in Cabassole. Significant sedimentation rates (2-4 mm yr^{-1}) are the sign of frequent overbank flows and/or high transport capacity with an abundant sediment yield. The development of hygrophilic species, which is synchronous with a significant deltaic progradation, shows that the Rhône delta is wetter and fresh water-dominated at this time.

- LWDR 2 (AD 75-125). A brief period of weak fluvial activity involves a decrease in the maximum

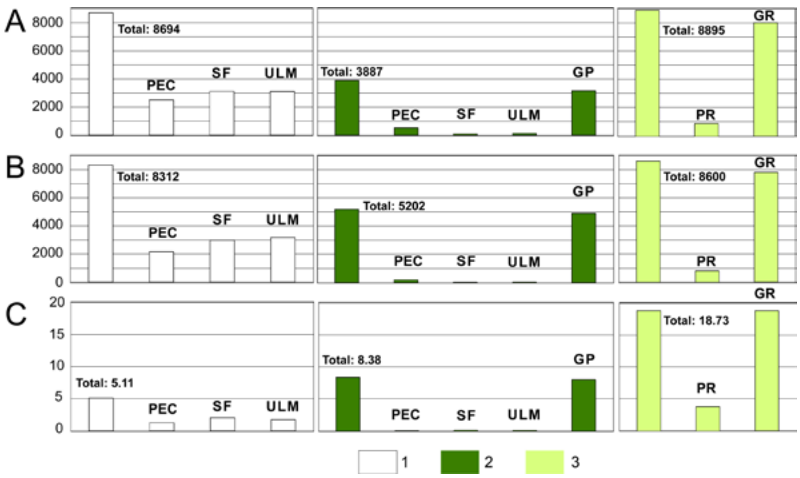


Fig. 4. Palaeohydraulics of some ancient Rhône channels in the deltaic plain. A: Bankfull channel capacity (in m^2); B: Bankfull discharge (in m^3/s); C: Bankfull specific stream power (in W/m^2); 1: late Antiquity/early Middle Ages; 2: high/late Middle Ages; 3: present-day; SF: palaeo-Rhône of Saint-Ferréol; ULM: palaeo-Rhône of Ulmet; PEC: palaeo-Rhône of Peccaïs; GP: palaeo-Rhône of Grand Passon (Escale meander); GR: Grand Rhône River; PR: Petit Rhône River.

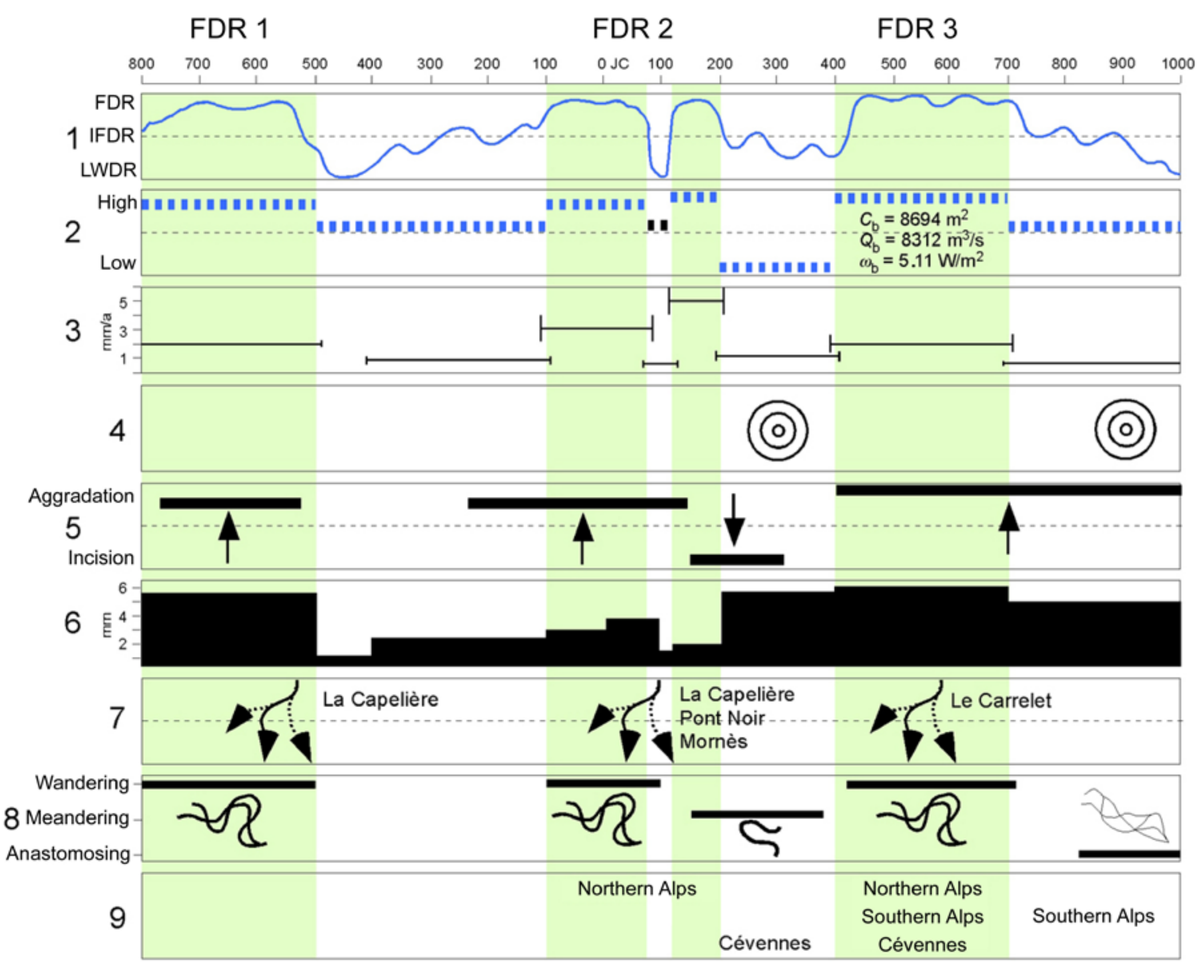


Fig. 5. Outcome of the palaeohydrological functioning of the Rhône River in its delta, showing the existence of three periods of "flood-dominated regime" (FDR) from 800 BC to AD 1000 (after Arnaud-Fassetta and Landuré, 2003, modified). 1: hydrological regime; 2: mean discharge and water table; 3: sedimentations rates in the flood plain; 4: soil development in the flood plain; 5: channel geometry; 6: channel competence; 7: avulsions and crevasse splays; 8: fluvial pattern; 9: source zones of channel sands.

competence (0.16 mm) of Rhône's overbank flows in Cabassole and Les Combettes.

- FDR 2b (AD 125-200). During this period, alluvial activity rises in Le Carrelet. At the same time, very thick silty deposits (0.85 m) are laid in the floodplain of the palaeo-Rhône of Saint-Ferréol. The maximum competence of the overbank flow waves is constant but does not exceed 0.2 mm; therefore, it remains beneath the competence level reached during the FDR 2b. The very high sedimentation rates (6-13 mm yr^{-1}) indicate either the importance of the sediment supply or the rapidity of the aggradation of the floodplain, which responds to the rapid creation of accommodation space.

AD 200-450: IFDR 2

Rhône sediment yield is not in equilibrium with water discharge. In this context, between AD 150 and 310, the palaeochannel of Saint-Ferréol is affected by a strong incision of the alluvial floor, which reaches -12 m in Le Carrelet. However, the Rhône's maximum competence stays high (0.6 mm). In the floodplain (Cabassole, Le Carrelet, Les Combettes), maximum competence does not exceed 0.19 mm, moreover sedimentary deposits are mainly composed of fine particles, in spite of some layers with coarser particles, which indicate higher floods. Backwater decantation facies are very rare because of rare overbank flows. This situation corresponds to an IFDR with only a few violent floods. Sedimentation rates are generally low (0.8-1.6 mm yr^{-1}) in association with the incised channel, which reduce overbank flows. Between the middle of the 4th c. AD and the beginning of the 5th c. AD, a rural construction in Cabassole seems indicate efficient drainage of the lowest part of the flood plain.

AD 450-700: FDR 3

In most of the sites on the Camargue, hydrological conditions worsen in this period. The palaeochannel of Saint-Ferréol undergoes an important in-filling of more than 6 m in Le Carrelet that involves the development of crevasse splays (Le Carrelet, Les Combettes). Maximum competence of the Rhône River reaches 0.61 mm whereas its discharge and specific stream power at bankfull stage are 8310 m^3/s and 5.1 W/m^2, respectively. The analysis of heavy minerals showed that sediments carried by the Lower Rhône River originated from the whole catchment, *i.e.* from the Alps and Massif Central (Arnaud-Fassetta, 2000). In the floodplain, deposits become coarser with maximum competence rising up to 0.24 mm. Sedimentation rates are high (1.3-2.7 mm yr^{-1}) in connection with a channel with greater overbank flows. The growing of riparian forest shows that more fresh water is present in the floodplain system.

AD 700-1000: IFDR 3

During this period, the Rhône hydraulic activity slows down irregularly in the whole of the Camargue. This however, reflects a situation typical for the delta, and is the result of the gradual reduction in activity of the palaeochannels of Saint-Ferréol and Ulmet and the hydrological functionning of the palaeo-Rhône of Grand Passon, active since the end of the 10th c. AD. In the channel, maximum competence is reduced to 0.5 mm. In Cabassole and Le Carrelet, the maximum competence of overbank flow waves raises falls to 0.2 mm. Sedimentation rates decrease as well (0.5-0.7 mm yr^{-1}). During the high/late Middle Ages, both discharge and specific stream power values at bankfull stage scarcely exceed 35 m^3/s and 0.15 W/m^2 (Saint-Ferréol), 50 m^3/s and 0.1 W/m^2 (Ulmet), and 200 m^3/s and 0.1 W/m^2 (Peccaïs), whereas the palaeo-Rhône of Grand Passon becomes the most active branch (5595 m^3/s and 8.1 W/m^2) in the deltaic plain.

In conclusion, three FDRs characterise the palaeohydrology of the Rhône delta from 800 BC to AD 1000. They are associated with phases of degradation of climatic conditions, exacerbated by human activities (Bravard *et al.*, 1992; Magny, 1992 a and b; Stuiver and Braziunas, 1993; Patzelt, 1994; Berger, 1996; Jorda and Provansal, 1996; Arnaud-Fassetta, 1998):

- Intensive swamp extension, which is characteristic of the FDR 1 (800-500 BC), and could be the sign of an excessive pluviometric balance as may be the case for most of the catchment (Magny, 1992b; Jorda and Provansal, 1996; Bravard *et al.*, 1997; Bruneton, 1999). It is also associated with a well-known climatic oscillation at a Western European scale (Van Geel *et al.*, 1996).

- The two phases of FDR 2 (100 BC-AD 75 and AD 125-200) could be induced by the more unstable climatic conditions (*i.e.*, more frequent events of large rainfall). Note that it was in phase with the palaeohydrological functioning of the Upper-Middle Rhône River (Bravard *et al.*, 1997) and its Alpine tributaries (Peiry, 1997), but also downstream of the catchment (Provansal *et al.*, 1999; Bruneton *et al.*, 2001). However, it varies out-of-phase with rivers of the Durancian Alps and Provence (Provansal, 1995; Jorda and Provansal, 1996).

- The FDR 3 (AD 450-700) could be related to pluviometric change – maybe associated with a cold period – in the whole Rhône catchment (Zoller, 1977; Magny, 1992a; Patzelt, 1994).

During worsening climatic conditions, the hydroclimatic hazard and its effects (flooding, crevassing, avulsion) occurs more intensively and more frequently and can highlight the vulnerability of societies.

The vulnerability of societies faced with hydroclimatic hazard

The creation of an inventory archaeological sites in the Camargue (Landuré *et al.*, 2004) has enabled the examination of their nature and function and of the vulnerability of the antique and Mediaeval societies in relation to the Rhône River, its floods, its crevasse splays and its avulsions (Arnaud-Fassetta and Landuré, 2003).

The archaeological sites in the delta: Their location, nature, function, and evolution

The inventory of the archaeological sites, created by field-survey, revealed 155 sites, created between the 6th c. BC and the 10th c. AD (Fig. 6). In reality, the number of sites may have been underestimated if we take into account the fact that some are probably still buried, which is highly likely considering the deltaic context where the processes of alluviation remain very active.

A more or less continuous occupation during nearly sixteen centuries

The earliest traces of occupation in the Camargue may date from the 6th c. BC, with the (ancient) discovery of fragments of Attic ceramics (Gantès, 2004). However, recent excavations have not dated back further than the 5th c. BC. Five sites on the side of the lagoons of Vaccarès and of Le Fournelet illustrate the Greek occupation in the Rhône delta. The study of their palaeoenvironmental context shows that these sites were established in the floodplain of the palaeo-Rhône of Saint-Ferréol and palaeo-Rhône of Ulmet.

With 26 sites, dating from the period between the 3rd c. and the 1st c. BC appears to represent the beginning of a change in populating density. This is confirmed during the period between the 1st c. and the 3rd c. AD, with a strong increase in the number of sites (to eighty-six). Some can certainly be interpreted as important *villae*. Built in the flood plain, these *villae* seem to be disproportionately situated in the Upper Camargue, at a time when this region benefited from agricultural development in connection with the expansion of the Roman colony of Arles (Leveau, 1999).

The number of sites dating to between the 4th c. and 7th c. AD is less at 48. The most important settlements of the previous period are still inhabited while new settlements are created in the zones of the floodplain, which were till then unoccupied. These observations could confirm the continuity of the population, which it is tempting to interpret as being related to the importance of the city of Arles (Trément, 2001).

Concerning the 8th to 10th c. AD, the number of sites is continues to decrease (8). The paucity of sources may be due to the forms of construction emerging during this period, which, by favouring the use of earth and perishable material, leave little traces in the ground (Kotarba, 1988). One could also attribute the decrease in the number of sites to a phenomenon of restructuring of the spatial structure of the population (Fossier, 1992; Schneider and Paya, 1995).

Sites essentially established along the branches of the palaeo-Rhône River

Despite the assumed incomplete inventory of archaeological sites, superimposition of archaeological sites on the map of the Rhône palaeochannels shows human occupation had a distribution essentially controlled by the presence or absence of the river. Throughout the period concerned, most sites (79%) were situated along the three distributaries of the Rhône River that were active during the antiquity and the early Middle Ages.

Sixty-three sites (*i.e.*, 40% of the total) were located in the area under direct influence of the palaeo-Rhône of Saint-Ferréol – which was probably the most active distributary during the first part of the antiquity –, 29 (19%) were close to the palaeo-Rhône of Albaron, and 26 (17%) were close to the palaeo-Rhône of Ulmet (Fig. 6). Four sites were also established in the zone of the Saint-Ferréol/Ulmet palaeo-Rhône bifurcation (diffluence). Amongst the remaining sites, 13 (8%) were situated alongside the palaeocoast, and the last 20 (13%) seem to have been far from both the palaeocoast and the three palaeochannels of the Rhône River.

If we add up these values, the proportion of sites established in immediate proximity to the Rhône palaeochannels amounts to 79%, thereby confirming that the statistical proximity to the palaeo-Rhône River was indeed the main factor determining the choice made by the communities when establishing their sites in the delta. This result obviously poses the question of the vulnerability of these sites, which were settled in the flood-prone zone.

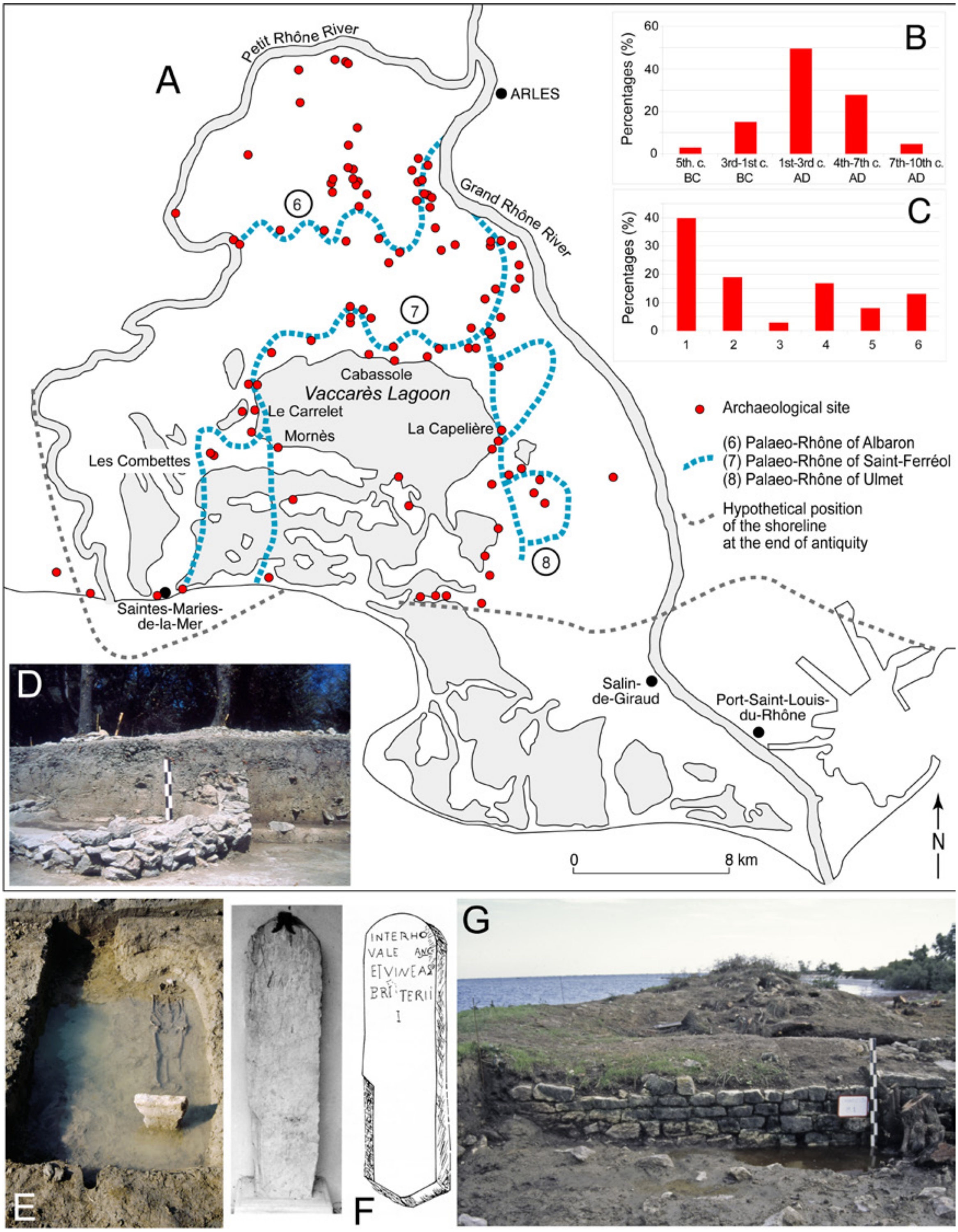


Fig. 6. Palaeohydrography and land use in Camargue (after Arnaud-Fassetta and Landuré, 2003, completed). A: General view of Camargue showing location of archaeological sites for the period 5th c. BC-10th c. AD. B: Evolution of the number (expressed as percentages) of archaeological sites from the 5th c. BC to the 10th c. AD. C: Location of archaeological sites in the deltaic plain. 1: sites near the palaeo-Rhône of Saint-Ferréol; 2: sites near the palaeo-Rhône of Ulmet; 3: sites in the zone of palaeo-Rhône diffluence Saint-Ferréol/Ulmet; 4: sites near the palaeo-Rhône of Albaron; 5: sites alongside the palaeocoast; 6: sites to be far from both the palaeocoast and the three above-mentioned palaeochannels of the Rhône River. D: La Capelière (photo: C. Landuré, July 2000). E: Cabassole (photo: A. Richier, July 1996). F: Carrelet "mas", landmark, drawn by M. Gayraud (1989), photo CNRS/CCJ. G: Le Carrelet (photo: L. Martin, July 1995).

Forms of occupation *vs.* economic resources/ activities

Geoarchaeological excavations revealed the forms of occupation and the nature of the economic activities of Camargue from 600 BC to AD 1000 at five sites situated on the riverbanks of two palaeochannels of the Rhône (Fig. 6): the palaeo-Rhône of Saint-Ferréol [Le Carrelet (Martin, 2004), Cabassole (Richier, 2004), Les Combettes (Landuré and Arnaud-Fassetta, 2004b), Mornès (Landuré and Arnaud-Fassetta, 2004a)], and the palaeo-Rhône of Ulmet [La Capelière (Landuré, 2000)].

As regards the land use, the sites of Les Combettes, Le Carrelet, and La Capelière have been interpreted as grouped settlements; the site of Mornès may be a temporary settlement, whereas Cabassole seems to correspond to a small rural settlement. The results of archaeological survey and recent research conducted on a Gallo-Roman site in south Camargue revealeds the existence of a mosaic of large *villae* richly decorated with mosaics and murals (Pasqualini, 1999; Excoffon *et al.*, 2004).

Concerning economic activities, the societies that settled in the delta initially practised agriculture. The Rhône flood plain enabled (i) cereal growing, as evidenced by palynological analyses (Arnaud-Fassetta *et al.*, 2000) and the discovery of millstones, and (ii) the development of viticulture as revealed at Le Carrelet where a boundary stone was discovered marking the limits of a property and mentioning the presence of vines and gardens (Gayraud, 1989; Fig. 6F). As a complement to agriculture, the populations also practised stock breeding, as from the 5th c. BC, as shown by the first results of the excavations of La Capelière (Forest, 2004).

Other economic activities have been identified, and most of all, handicrafts. In Le Carrelet, traces of metallurgy have been dated from the end of the 4th c.-beginning of 5th c. AD (Martin, 2004) and an activity linked to the manufacturing of soda or glass seems to have developed in Cabassole in the 9th-10th c. AD (Amouric and Foy, 1991; Richier, 2004).

Furthermore, the exploitation of salt and fish was revealed at Le Carrelet thanks to the discovery of salting basins dating from the 5th c. AD (Martin, 2004). This salting industry was most probably favoured by the geography of the site – the proximity of fishing areas, lands favourable to salt evaporation-based extraction, and a navigable channel, which ensured the distribution of the production. Moreover, the presence of salterns as from the 5th c. AD is likely, considering that some are mentioned in the texts, although with no precise locations (Benoit, 1959). Stouff (1986) hypothesised that the documented Mediaeval saltworks on the banks of the Vaccarès lagoon were probably exploited before the 13th c. AD.

Finally, the Rhône River probably facilitated contacts between the sites of the delta and their and their abilities to secure supplies of construction materials, namely the stones that were transported from Arles, and various other goods. The river's role as an interface between the sites is also revealed by the variety and abundance of ceramic material found, which reflect the privileged exchange networks between the sea and the continent *via* the ports of Marseilles and Arles (Hirbec, 2004).

Assessment of societal vulnerability

A strong vulnerability, lessened by settling on the highest points of the flood plain

The proximity of the Rhône River, although economically, made these societies vulnerable being situated in the zones liable to flooding, they were exposed to devastating peaks in water levels and to unpredictable river avulsions and crevassing. This societal vulnerability was, however, lessened by settlements chosen on the higher points of the floodplain when topography (*i.e.*, the relief *sensu stricto*) allowed it. Four sites exemplify this spatial logic of settlement.

At La Capelière, traces of a swamp with fresh to brackish water, dating from the 8th-5th c. BC (Lyon-1497/1498) were found between -1.5 m and -1 m. Then, during a phase when the palaeo-Rhône of Ulmet came closer (by avulsion?), the swamp was covered over with sandy-silt flood deposits. The latter contributed towards creating a considerable relief to the floodplain and little by little formed a dominant point between the main channel situated to the west of the site and a secondary channel situated to the north. At the top of this knoll, at an altitude of -0.5 m some buildings on sand deposited soil and load-bearing posts were installed around 500-475 BC, forming the first traces of occupation of the site (Fig. 7).

At Cabassole, the results of the geoarchaeological investigations illustrate comparable settlement conditions (Richier, 2004). The human settlement on this site dates from the Greek period (5th-4th c. BC). It is represented by a layer of ceramics of approximately 300 m^2 in area on floodplain deposits whose top is situated at -0.4 m. Again, two factors favoured human settlement: (i) the transition from a paludal environment to a better-drained floodplain and (ii) the raising of the topographical surface of the floodplain as the result of the 0.2 m deposit of silt.

At Les Combettes, the arrival of communities in the 6th c. AD was favoured by the same palaeoenvironmental conditions. Around AD 90-190 (Ly-7760),

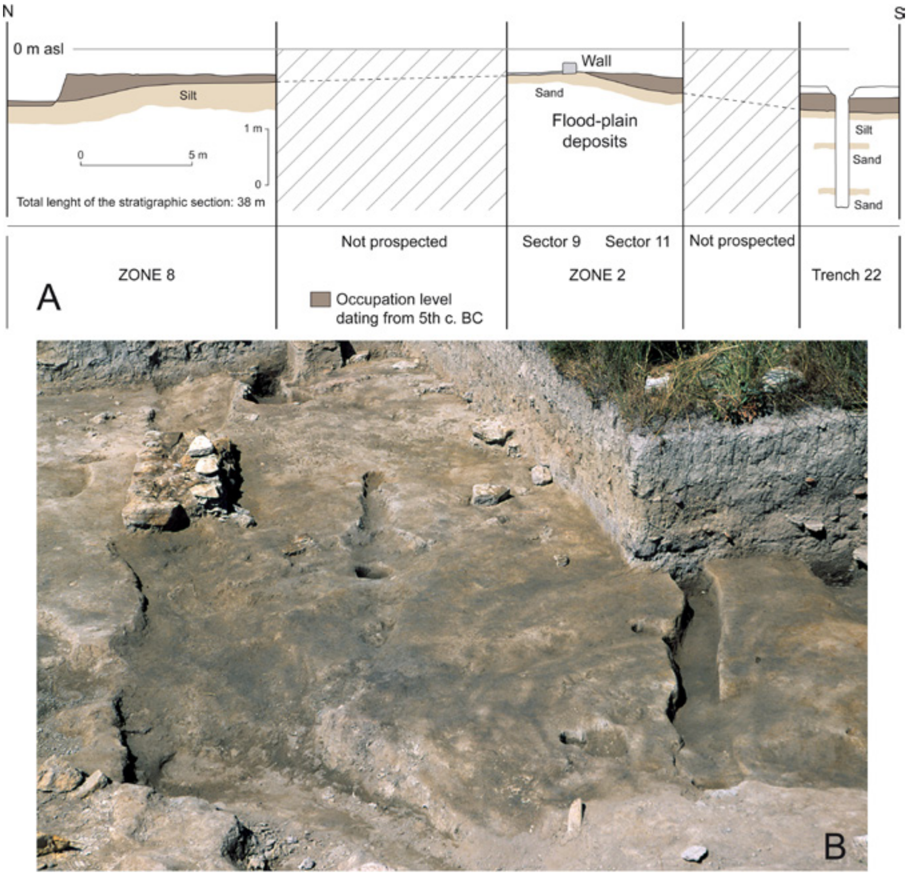


Fig. 7. Characteritics of land use in La Capelière (after Arnaud-Fassetta and Landuré, 2003).
A: Schematic stratigraphic section showing the general topography on which human settlement was installed during the Greek period.
B: Details of occupation levels of the 5th c. BC. (photo: C. Landuré, July 2001). Note the presence of sand deposited soil (in low position) and the tracks of load-bearing posts installed in sandy-silt deposits.

the site was occupied by a swamp situated between -3.1 m and -2.4 m. Then, the creation of a floodplain combined with a rising river bank raised the topographical surface by 2.3 m, up to -0.1 m asl. This increase height of the lands created a better-drained environment more favourable for settlement.

The site of Mornès is also at a height (0.6 m asl) on floodplain deposits capping one of the ancient bars of the river mouth of the palaeo-Rhône of Saint-Ferréol. Like the other sites, the settlement is very close to the Rhône River, present here as a secondary branch. However, despite being situated at an important altitude, which is higher than other contemporary sites, the site was occupied for only a couple of decades in the 1st c. BC, maybe due to the abandonment of the secondary channel.

In the light of these four examples, it seems that the proximity of the river, which was favoured by societies for economic reasons, necessitated construction on the highest sites, which limited the duration and the height of inundation at the sites, and therefore reduced their vulnerability. The most favoured locations were river banks (La Capelière, Les Combettes, Le Carrelet), the higher zones of the flood plain (Cabassole) and secondarily, the fossils bars of the river mouth capped by flood plain deposits (Mornès).

The other preventive measures for minimising the societal vulnerability: Boulder armouring on the riverbanks and drainage ditches in the flood plain

Other measures were taken for protection against floods, or at least, to minimise their destructive consequences. The most common were the erection of boulder armouring on the river banks and the digging of drainage ditches on the floodplain:

- Boulder armouring was probably discontinuous in this period, and made up of decametric sized, unattached blocks of stone, positioned on the inner face of the river banks so as to limit erosion during high river flows. We detail here one discovered at Le Carrelet (Martin, 2004). On this site, a survey with a mechanical shovel revealed the (concave) left riverbank of the palaeo-Rhône of Saint-Ferréol, exposing a boulder armouring made of blocks whose size varied from 0.3 m to 0.6 m (Fig. 8 A to C). Visible for a length of 6 m, it had a width of 2.5 m for a height of 1.5 m, and its top reached the spot height of -0.6 m asl. It seals the upper part of the river bank, radiocarbon dated between 30 BC and AD 110 (Lyon-360). This hydraulic installation, probably constructed between the FDR2a and the FDR2b (see above), had two functions: the obvious one, which was protecting the concave river bank from the phenomenon of sapping, and the more hypothetical function of protecting zones of settlement (which we have, however, not managed to locate).

- Drainage ditches were dug at the periphery of the settlements. Most of the time they lowered the water table height making the high zones of the floodplain drier. Some examples of these ditches have been revealed in the excavated sites. At Cabassole, a ditch (FO 2011) was revealed over a length of 5 m. It was 3.5 m wide and 0.5 m deep, with oblique inner walls and a flat bottom. Its infilling, dating from the 8th and 10th c. AD, was silt mixed with tiles, scoria and animal bones. These mixed characteristics did not enable the identification of its precise function of the ditch. During the same period, another ditch (FO 2077), similar to the previous one, was filled. It was 3.5 m wide and 0.6 m deep, its basal sediments were composed of layers of ashes that came from the emptying of nearby ovens. This level was sealed by a 0.5 m thick fill, which showed an alternation of sandy units (eight out of all) and carbonate-rich clayey-layers, which indicated a hydraulic functioning and show that the ditch was regularly filled with water. The phases with water and of rapid flow are reflected by sandy layers, whereas the carbonate-rich clayey-layers are associated with phases of flood settling (decantation) and evaporation. This ditch, orientated N-5, was probably used for evacuating the water of the palaeo-Rhône of Saint-Ferréol (to the north) towards the Vaccarès lagoon (to the south). The grain size of the sedimentary infill shows how powerful the flood water of the Rhône River was capable of moving sands from the inhabited floodplain. The importance of the deposit and the number of sandy units are demonstrated by the repetition of this phenomenon.

At La Capelière, a ditch (FO 7026) demarcates the settlement of the 1st c. BC (Fig. 8D). Orientated N-45, it extends towards the west (*i.e.*, in the swampy depressions situated at -1 m bsl) it allows the evacuation of the water of the palaeo-Rhône of Ulmet situated to the east of the site. The ditch was 1.7 m wide at the top, 1 m deep and U-shaped. It was infilled with homogeneous, massive alluvia, which can be interpreted as a very rapid infilling, probably following a phase of flooding.

The evolution of fluvial risk in the Rhône delta (600 BC-AD 1000)

Most of the time, the sites were occupied regardless of the rhythm of the floods

In general, the variability of the flood rhythm in the Rhône floodplain did not have a direct impact on the duration of the settlements.

For example, the settlement in Cabassole, located in the floodplain of the palaeo-Rhône of Saint-Ferréol, was exposed to more or less frequent floods at any time during the occupation (5th-4th c. BC, 1st c. BC-1st c. AD, 4th-5th c. AD, 5th-6th c. AD, 8th-10th c. AD). Relative variable sedimentation rates show that floods are irregular: high rates during the FDR 2 (2-4 mm yr^{-1}) and FDR 3 (1.3-2.5 mm yr^{-1}), low rates during the IFDR 1 (0.6-1.2 mm yr^{-1}), the IFDR 2 (0.8-1 mm yr^{-1}) and the IFDR 3 (0.5 mm yr^{-1}). On the whole, we cannot establish any relationship between the flood record and the length in time of human occupation. During the 5th-4th c. BC, the 4th-5th c. AD and the 8th-10th c. AD, human occupation of the site might have been favoured by the rarity of the floods (LWDR 1, IFDR 2, IFDR 3). During the 5th-4th c. BC and the 1st c. BC-1st c. AD, the occupation phases remained diffuse and/or temporary although the hydrological context was completely different – a FDR context for the first period and a LWDR context for the second period. Finally, no trace of human occupation was identified during FDR 2 (1st c. BC-1st c. AD) although occupation levels of the 5th-6th c. AD are well preserved during FDR 3.

Furthermore, the settlement of Les Combettes, located on a steep river bank, must have been faced with the floods of the palaeo-Rhône of Saint-Ferréol during the whole period of its occupation (6th-10th c. AD). However, the study of ceramic materials from the archaeological levels sandwiched between flood deposits from -0.1 m bsl to 0.6 m asl shows that floods did not interrupt human occupation. As in Cabassole, the site was abandoned when aggradation of the floodplain slowed down due to the decrease in hydraulic activity of the palaeo-Rhône of Saint-Ferréol.

In conclusion, environmental determinism seems to be relatively weak and subtle. When the hazard is only represented by Rhône's floods, whatever its frequency, it does not hinder long-term human occupation in the floodplain. On the contrary, when the hazard involves floods with crevasse splays and avulsions, it can cause sites to be abandoned or unoccupied for several decades.

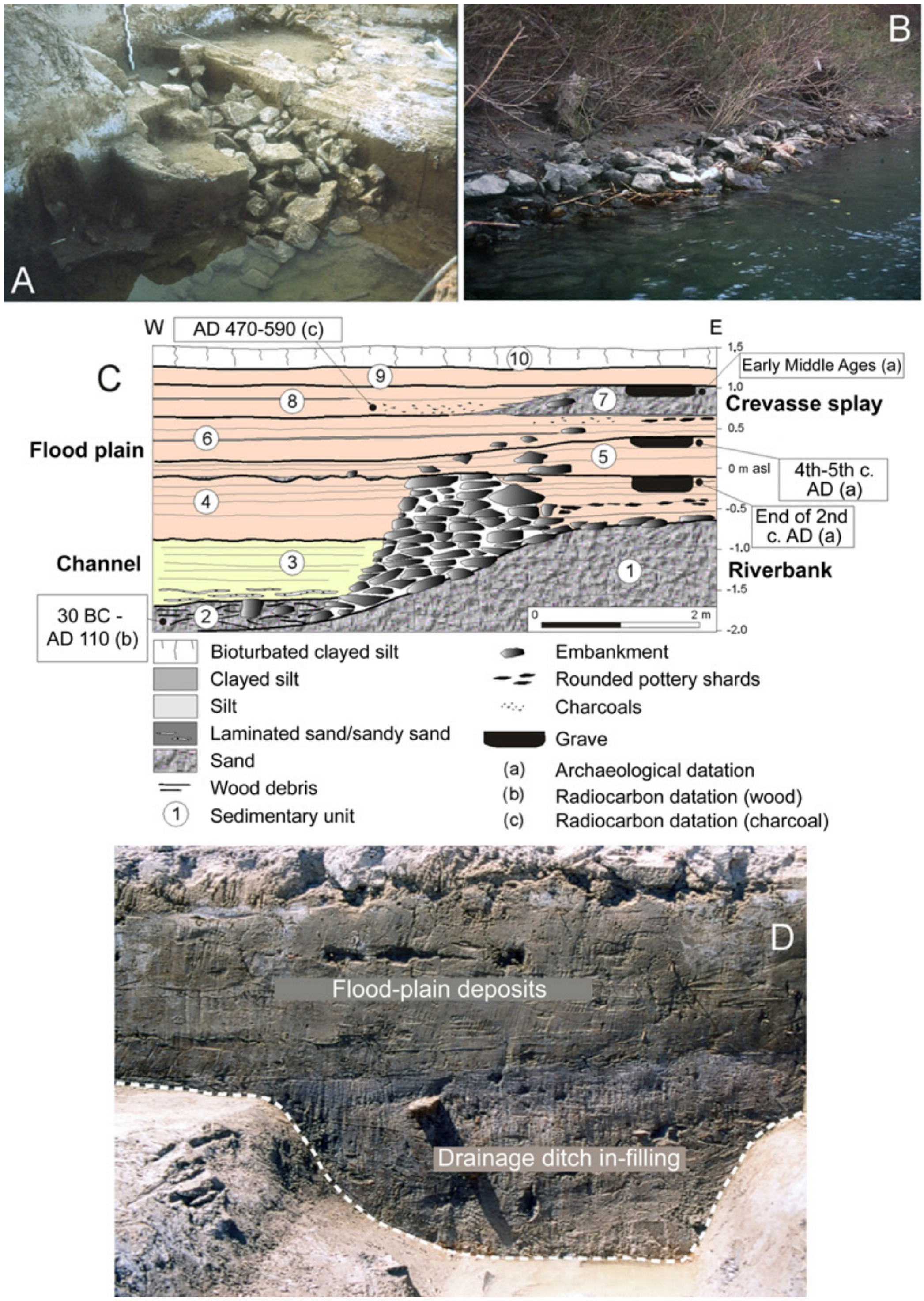


Fig. 8. Ancient and modern hydraulic structures in the Rhône delta (after Arnaud-Fassetta 1998, completed). A : View of boulder armouring (30 BC-AD 110) discovered in Le Carrelet (photo: G. Arnaud-Fassetta, August 1995). B: View of present-day boulder armouring on the riverbank of the Petit Rhône River showing some similarities with the one of Le Carrelet (photo: G. Arnaud-Fassetta, November 1995). C: Stratigraphic section in Le Carrelet showing the succession of four fluvial palaeoenvironments: a riverbank supporting a boulder armouring dated 30 BC-AD 110; the channel of the palaeo-Rhône of Saint-Ferréol, which was infilled (on the cross section) before the end of the 2nd c. AD; a flood plain occupied from the end of the 2nd c. AD and the early Middle Ages; and a crevasse splay dated from AD 470-590. D: View of a drainage ditch (1st c. BC) discovered in La Capelière (photo: C. Landuré, July 2001).

Some examples of abandoned or unoccupied sites during the FDRs

FDR periods were locally characterised by violent floods, followed by crevasse splays and avulsions and the complete or partial abandonment of the settlements, as illustrated by the sites of La Capelière and Le Carrelet.

At La Capelière, human occupation was discontinuous from the 5th c. BC to the 7th c. AD. A small rural settlement was built on the bumpy sandy-silt flood deposits right from the beginning (see above). As regards its geographical situation – to the west of the main channel of the palaeo-Rhône of Ulmet and down to the confluence between the two of its secondary distributaries, the site can easily suffer from floods and crevasse splays (Fig. 9). That is why human occupation levels of the 1st c. BC are completely covered by sandy-silt deposits, which are 0.1 m thick at the centre of the habitation site and 0.4 m thick on its borders. These floodplain deposits are connected to sands (crevasse splays) to the north of the site and have covered a site, interpreted as a warehouse in which two amphoras were found (Fig. 9D). After these catastrophic floods, which probably appear in the second half of the 1st c. BC (~40 BC), the settlement is abandoned and only reoccupied by a farm a few decades later (mid-1st c. AD).

At Le Carrelet, sandy silts (flood deposits), whose thickness reaches 0.8 m, buried boulder armouring laid on a steep river bank, which was constructed between 30 BC and AD 110. No traces of a settlement have been revealed during this FDR 2 period (see above), although a settlement was probably there at the same time as the boulder armouring. Only a tomb dating from the end of the 2nd c. AD was discovered at the top of the flood deposit (Martin, 2004). In fact, the main phase of human occupation was the 4th c. AD, *i.e.* during the IFDR 2 (see above): during this period, flood events and crevasse splays were rare. The 4th c. AD was marked by the implantation of a settlement, interpreted as an important *vicus*, with a ground area of 1-2 ha (Martin, 2004). From the 5th c. AD, the channel of the Rhône was characterised by infilling because of numerous floods and high sediment yield (FDR 3, see above). This hydrogeomorphological context is favourable for increased overbank flooding and the formation of crevasse splays. Constructions from the 4th c. AD are buried under 1 m of sandy-silts (flood deposits) and silty-sands (crevasse splays; Fig. 9C). At the end of the FDR 3 (*ca*. 7th-8th c. AD), no houses existed on the site and the only remains found were two graves, which probably only reflect a sporadic human presence.

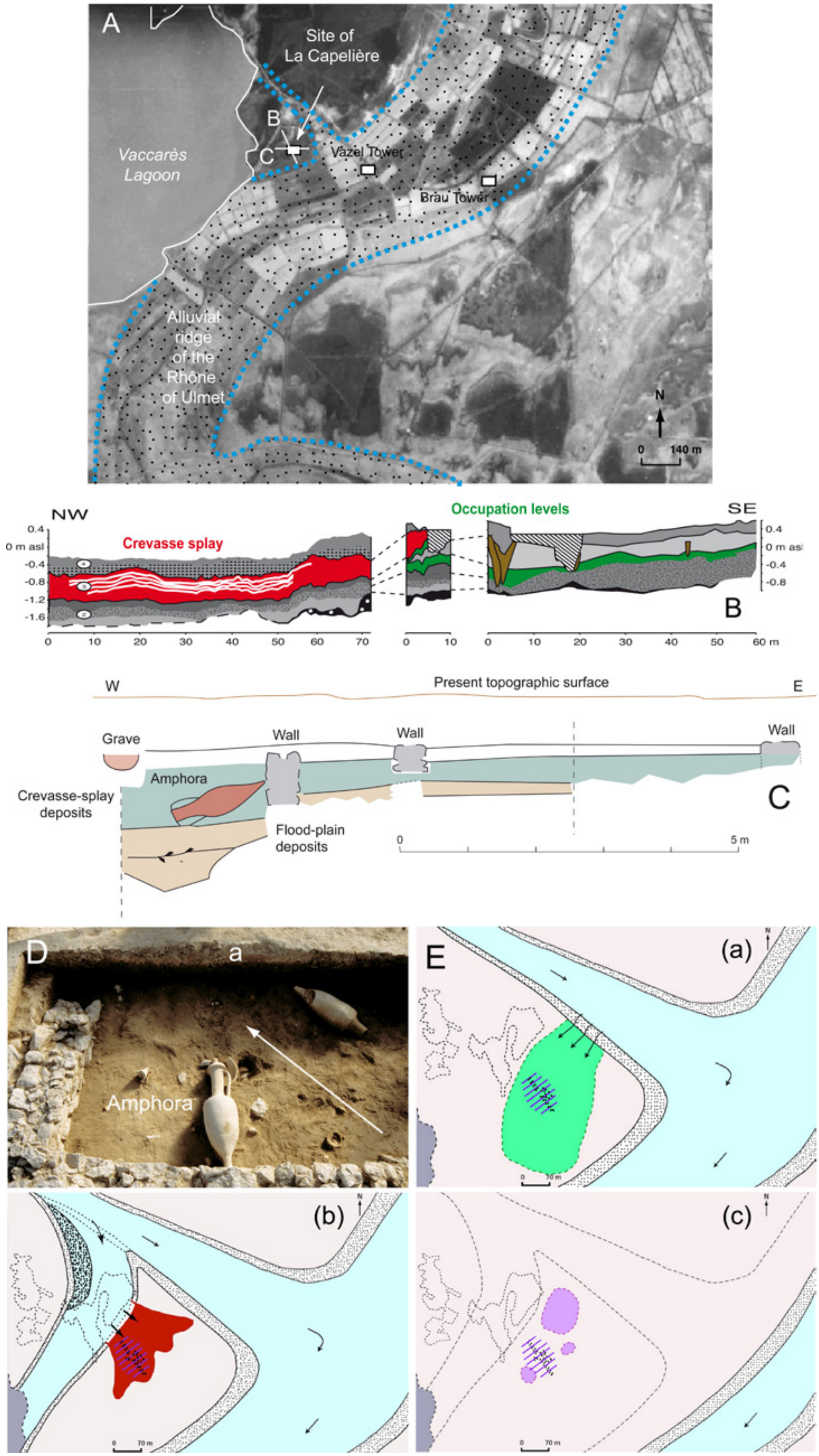
Discussing the fluvial risk

The afore-mentioned examples show a very complex situation. Sometimes, Rhône floods hindered continuous rural settlement as was the case at the site of La Capelière, where a crevasse splay was followed by the abandonment of the settlement over a few decades, from the end of the 1st c. BC to AD 30. At Le Carrelet, numerous overbank flows buried the ancient settlement by 1 m of sandy silts. But floods did not always have the same impact on the whole delta. For example, on the sites of Les Combettes and Cabassole, the habitation site developed and grew in FDR periods; frequent overflows occurred but without major consequences on the continuity of settlement.

In fact, the continuity of the rural settlements depends mainly on the types of hazard in the floodplain. The phenomenon of flood inundation in the alluvial plain can be considered as a secondary factor in the abandonment of sites or changes in the relevant economic activities, even if the hazard occurs very frequently as it did during the FDRs or IFDRs. Four mains physical factors appear to be involve the abandonment of a site:

(i) Hydroclimatic hazard, especially when it combines overbank flows, crevasse splays and avulsions during a FDR period. The frequency of huge floods is crucial for the infilling of fluvial channels

Fig. 9. Results of geoarchaeological surveys in La Capelière (after Arnaud-Fassetta and Landuré, 2003). They illustrate how the convergence of several hydro- and morpho-dynamic factors has led, at the turn of our era, to the temporary abandonment (several years) a inhabited area near an active channel of the palaeo-Rhône River. A: Location of the archaeological site on the alluvial ridge of the palaeo-Rhône of Ulmet (photo: US Air Force, 1944). B: General stratigraphic section showing the palaeoenvironnemental sequence [paludal, fluviatile (flood plain, crevasse splay)]. C: Detail view of the stratigraphic section B showing archaeological structures (end of 1st c. BC) recovered by crevasse-splay deposits. D: Photograph of two amphoras (end of the 1st c. BC) and walls (end of the 1st c. BC) covered by (a) alluvial deposits (flood plain, crevasse splay; photo: Landuré C., July 1999). The arrow indicates the direction of flood palaeoflux. The presence of an intact amphora closed by a cap is a sign that the site has been rapidly abandoned, probably after the large flood event of the end of the 1st c. BC. E: Map showing the palaeohydrographical evolution around the archaeological site. a: 5th-1st c. BC; b: end of the 1st c. BC; c: 5th c. AD. Note the presence of a crevasse splay whose silty-sand deposits completely recovered the archaeological site at the end of the 1st c. BC. This catastrophic event involved the abandonment of settlement until the mid-1st c. AD.


A
Site of La Capelière
B
C
Vaccarès Lagoon
Vazel Tower
Brau Tower
Alluvial ridge of the Rhône of Ulmet
N
0 140 m
NW
Crevasse splay
Occupation levels
SE
B
0.4
0 m asl
-0.4
-0.8
-1.2
-1.6
60 m
W
Present topographic surface
E
Grave
Wall
Wall
Wall
Amphora
Crevasse-splay deposits
Flood-plain deposits
C
0
5 m
D
a
Amphora
E
(a)
(b)
(c)

(which can be very rapid – from a few decades to two hundred years) and the development of crevasse splays and avulsions. In this context, the hazard involves high energy, which is very dangerous for human life, and can destroy land use patterns that predominated before the flood event.

(ii) Hydromorphy of the floodplain. It is a constraint as important as the fluvial constraint, as explained below.

(iii) A watertable at the ground surface, or even above (artesian conditions) negates the viability of a settlement and the possibility of most economically viable floodplain land-uses. For example, Arnaud-Fassetta *et al.* (2000) have shown that cereal agriculture in Le Pont Noir stopped just after the extension of the hydromorphic zone in the flood plain of the palaeo-Rhône of Ulmet around the 1st c. BC. In another study, Arnaud-Fassetta (2000) argues that human occupation on at sites of Cabassole, La Capelière and Le Pont Noir followed the change of environment from hydromorphous environments (swamp) to well-drained floodplain environments.

(iv) Hydraulic action and channel morphology. In the delta, economic activities were partly supported by the fluvial network. As regards navigation, deep and wide channels, low stream power or the practical of navigatation on secondary channels were very important. However, we do not know how the concept of risk was taken into account. The abandonment of sites could occur in different and contrasting hydrological contexts, either when the channel hydraulic activity was too low (Les Combettes, Cabassole) or high, with the development of crevasse splays (La Capelière) and/or channel infilling, which encouraged the construction and maintenance of secondary channels (for example, the excavation of the Marius canal).

Therefore, this study highlights a paradoxical situation: when fluvial risk was high, the communities established settlements on the alluvial ridges of the palaeo-Rhône River (Saint-Ferréol, Ulmet), which were then very vulnerable to floods (Fig. 10). The abandonment of sites and decreased economic activities could occur suddenly when crevasse splays and avulsions occurred but were typicaly short-lived, or the process could occur gradually, but over a long time, when the water table rose. On the contrary, when the risk was low, moribund palaeochannels with silting of channels favoured a retreat in occupation and the abandonment of sites, although the strength of the hazard and the risk were greatly reduced.

At this point, it is important to introduce the concepts of threshold, vulnerability and resilience in the societal and environmental systems. The threshold concept is linked to the evolution of natural constraints (climate, hydrology) and their environmental expressions (channel hydraulics, crevasse splays, avulsions and water table dynamics. The impact of these constraints can be overcome by societies if their resilience is high, *i.e.* if social groups are able to return to their initial situation immediately after the event. If fluvial constraints are greater than the resilience capacity of societies (which includes societies vulnerability), an irreversible threshold is attained, and societies must find a new equilibrium. At the site of La Capelière, the hydrological hazard represented a large constraint on goods and probably on humans only when the hazard exceeded a certain limit (*i.e.*, when it combined frequent overbank flows, crevasse splays, and avulsions). Environmental pressure and risk became so unbearable for the local population that the site was abandoned and re-occupied a few decades later. In this case, the threshold was reached very suddenly and the vulnerability of the population was high. Moreover, the resilience of the societal system might have been weak and so it took several decades to restore re-inhabit the site, whereas it only took days to a couple of years, for the social system to react to the recent Rhône floods of 1993-94 or 2003 (Arnaud-Fassetta, 2013).

In other cases, the resilience of the societal system might have been stronger, increasing the threshold required to tipp the environmental system from acceptable to unacceptable risk. For example, we showed that the hydraulic conditions of the palaeo-Rhône of Saint-Ferréol decreased, which involved channel infilling from the 8th c. AD. However, its river banks were occupied at least until the 10th c. AD. That means that for two centuries, local populations were confronted with different problems: (i) the discontinuity of the fluvial network and difficulties in navigating in this part of the delta (and the necessary maintenance it implied), (ii) still water [unpleasant smell, diseases, etc. (see Rossiaud, 1994)], and (iii) the rise of salt water levels and the reduction in fresh water supplies, due to an insufficient supply of fresh river water.

Conclusions

The palaeo-Rhône River appears is a major natural element that has structured the development of human settlements in the delta. The vulnerability of societies was great because 79% of the settlement sites were situated along the Rhône channels, in the zone of the alluvial plain liable to flooding. However, vulnerability was lessened by (i) settling on the highest points of the floodplain, (ii) construction of drainage ditches in the floodplain, and (iii) the use

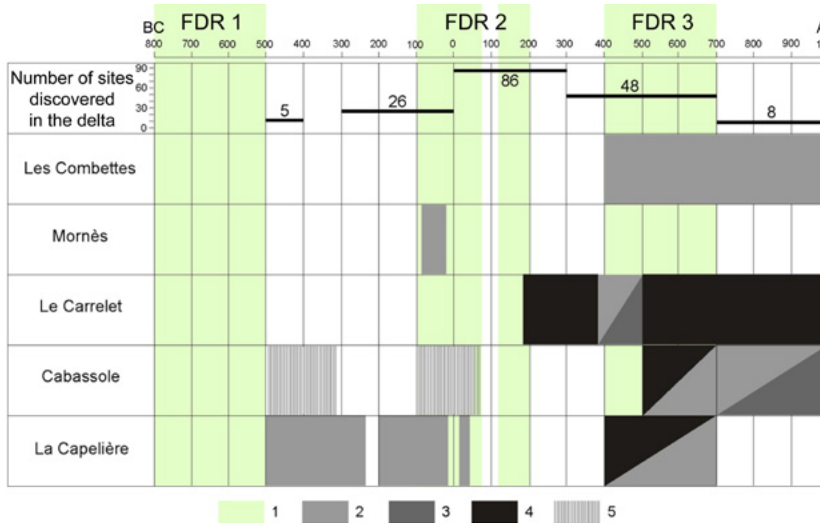


Fig. 10. Correlations between the Rhône's hydrological regime and land use in the deltaic plain from 800 BC to AD 1000 (after Arnaud-Fassetta and Landuré, 2003). 1: "flood-dominated regime" (FDR); 2: settlement; 3: handicraft; 4: necropolis; 5: unknown function. Note the absence of correlations between the hydrological variability of the Rhône River and the number of sites.

of boulder armouring for minimising the effects of fluvial erosion.

The longevity of occupation of a site depends on the longevity of Rhône channels and palaeochannels. Sites occupied over several centuries were situated near the Rhône palaeochannels, whose life-time extended from several centuries to millennia. However, the site of Mornès, constructed along an avulsed channel that flowed very temporarily, was occupied for only a few decades in the late 1st c. BC.

The permanence of the habitatation sites appears less conditioned by flooding *sensu stricto* than (i) the abrupt events like crevasse splays or avulsions, (ii) the height of water table and hydromorphy in the floodplain, and (iii) the channel morphology and channel hydraulic conditions. Nevertheless, too low or too strong hydraulic conditions can produce the same effects and can force the abandonment of the site.

The fluvially forced risk was high when:

- from the hydroclimatic hazard perspective, (i) there were repetitive flood events, in the context of a FDR, (ii) channel infilling and crevasse splays/avulsions development was high, and (iii) the increase of mean discharges forced the general elevation of water table levels and increased hydromorphy of the floodplain.

- from the societal vulnerability perspective, (i) settlements were installed near the Rhône River or in the zones of possible chute cut-offs and (ii) preventive measures against floodplain inundation or fluvial erosion were ineffective.

Conversely the fluvially forced risk was low when:

- from the hydroclimatic hazard perspective, (i) the incised channels has sufficient capacity to contain most of the flood flows, reducing crevasse splays/avulsions development in a context of LWDR or IFDR, (ii) the hydraulic power of the channel is too low, and (iii) low mean discharges of the river drove the lowering of the water table, enough to allow the good draining of the deltaic plain, but not too much, to limit the soil fertility through salinisation.

- from the societal vulnerability perspective, settlements were (i) rare near the Rhône River or (ii) present but in a context where the preventive measures against floodplain inundation or fluvial erosion were effective, and (iii) the socio-political context was (supposed) favourable.

This study has allowed use to evaluate the status of the fluvial risk, which over time could have been:

- Relatively slight. In certain cases, the fluvial risk could have been completely managed by the social groups living near the Rhône River. In fact, the role of environmental determinism seems to be relatively weak and henceforth we can rule out a simple or uni-causal relationship between cause and effect between the development or abandonment of the settlements and the hydrological regime of the Rhône River. The diversity of fluvial-deltaic environments has probably given human society important choices in the establishment of the settlements and allowed some geographical adjustments when faced with flood events. Moreover, except in the contexts of abrupt flood events (crevasse splay, avulsion), the slow rise in the Rhône's overbank flows probably gave social groups time to react when faced with flood events in the delta.

- Suffered. Even if the fluvial risk was real, in fact very few preventive measures were taken for minimising the vulnerability of the sites. Only some sporadic boulder armouring was found, yet no remain of hydraulic installations really efficient against floods, like artificial levees (or bunds), were discovered.

Furthermore, we must lay stress on the absence of a consistent flood management system along the whole fluvial system. The only preventive measures against floods focused on the excavation of drainage ditches and the piece-meal protection of the river banks by boulder armouring. With the ditches the protection against floods was relatively slight, and with the boulder armouring , the erosion of the riverbanks was reduced but did not prevent the Rhône River of overflowing. Therefore the sites remained vulnerable still faced with floodplain inundation, despite the undeniable will to reduce its effects.

- Accepted. The question still remains, insofar as economic interest can be considered, what were the main drivers for the establishment of settlements in the alluvial plain of the Rhône River. This prompts us to ask three further questions: How did these societies appreciate the fluvial risk? Did they view the flood risk objectively and did they have sufficient technological means or social organisation to analyse the risk in order to have choices other than to accept it? Similarly, has the management of fluvial risk in the rural areas really been a priority (and if yes, on what scale) over the two millenia studied? Over the next few years, the completion of the ACI Young Researchers programme should enable us to investigate these issues and assess their degree of transferabilityto other societies and environments in the late Middle Ages.

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