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Holocene fluvial dynamics in the Rhône Delta
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The author tells the paleohydrological change of the Rhône Delta during the last 3000 years of its history. The Ph.D. is a multi-disciplinary research dealing with the nature of the delta by geographers, paleoecologists, historians and archeologists and the constraints imposed by civilization in the Camargue.

The first part of the Ph.D. deals with recent fluvial dynamics in the Rhône Delta. The available data (geomorphology, sedimentology, hydrology) constitutes a useful reference for the Holocene fluvial paleoenvironmental analysis. Processes induced by the hydroclimatic change and the human disturbances of the Rhodanian watershed after the final phase of the Little Ice Age are examined to illustrate the impact on both the sand-bed channels of the Rhône River in the deltaic plain area.

Remarkable channel changes occurred in the Rhône Delta. The Rhône River has undergone a reduction along the axis of the channel since the end of the 19th century, following the changes in water and mineral discharges in the watershed. On the Petit Rhône River, 2.5 m of channel incision with local value of 10.4 m occurred since 1895, with the rates of reduction (700% decrease) rising rapidly after 1969. On the Grand Rhône River, degradation of the alluvial floor was observed between 1907 and 1991, with a downcutting of the channel by 1.1 m and maximum value of 6.8 m. The rates of channel incision (450% increase) rise rapidly after 1967. This evolution was a response to the decreasing frequency of floods during the drought-dominated era of the late 19th and 20th centuries, combined with channelization and generalized watershed management. The same trend is observed for the solid discharge of the Rhône River. Prior to emplacement of barrages on the Rhône River and its tributaries, the average annual sediment load, primarily fine sand, silt and clay carried in suspension, was estimated to 21 x 10^6 t/a during the first part of the 19th century. In the early 21th century, it was estimated at 6 x 10^6 t/a (a 70% decrease). The same hydrological change affects the Mediterranean streams of the watershed, the Durance, the Ardèche and the Drôme in particular. But the incision phenomenon is later (post AD 1950) in the northern Alps (Arve, Isère, Drac). Entrenchment of the Rhône River in the delta is not related to the relative sea level rise estimated to 2 mm/a during the present century. Climatic and anthropogenic factors in the watershed are decisive in the morphological control of the fluvial channels in the Rhône Delta.

The AD 1990-2000 decade represents a period of “flood-dominated regime”, with the large floods of AD 1993/94. Sedimentary balance was different on the riverbanks, the floodplain and the channel of the Petit Rhône River. On the riverbanks and the floodplain, the sedimentary balance was 0,43 Mm^3 to 0,92 Mm^3. Grain size and transport capacity are proportional to the liquid discharge. In the axis of the channel, the sedimentary balance between AD 1989 and AD 1995 showed a deficit of 42000 m^3/a. The morphosedimentary processes changed with the power, the origin and the chronological succession of the floods. Large floods contribute to channel aggradation but the phenomenon is very short and disturbed since the last 50 years by important human activities, such as commercial exploitation of sand and gravel from riverbeds, construction of dams on the main channel and embankments.

The second part of the Ph.D. analyzes the fluvial functioning in the Rhône Delta during the late Holocene times. Several cross-sections were investigated on many archeological sites, in collaboration with local archeologists. The analysis of fluvial dynamics was completed by several cores taken along the axis of the paleochannels. Chronostratigraphy of the channels is based on radiocarbon dating, archeological remains and historical data. The

sediment grain-size and the CM pattern were used to reconstruct the depositional environments. By combining malacology, palynology and anthracology, this study gives evidence for an ecological change in the floodplain. Based on these criteria, three types of hydrological regime and hydrological change were identified.

The periods of hydrological crisis (*i.e.*, periods of flood-dominated regime; FDR) reflect a high-energy fluvial dynamics. In the floodplain, the sediments are characterized by homogeneous coarse grains, indicating a consistently higher transport of the Rhône River. The sedimentation rates are important, indicating frequent overflowing of the banks, facilitated by a channel undergoing rapid changes in its banks with a high transport capacity. The crisis phases imply high hydrological levels in the channel. They are associated with the rising of the ground water levels in the flood plain. The fluvial pattern corresponds to a "delta braiding" (*i.e.*, wandering pattern) associated with a multiplication of the delta branches caused by the rupture of the levee (avulsion). The deposition of thick alluvial units, the increase of water discharge and sediment rates, morphological changes of river banks and the raising of ground-water levels produced over time significant hydromorphological changes in the delta. The most important change took place at the turn of the 17th-18th century. Other important hydromorphological changes occurred from late antiquity to the high Middle Age (5th-8th centuries) and at the beginning of Roman antiquity (1st century BC-AD 1st century).
The phases of hydrologic calm (*i.e.*, periods of drought-dominated regime; DDR) are characterized by a regular hydrological regime with rare exceptional flood events. In the flood plain, fine deposits are dominant which implies a low water power. The low sedimentation rates are in phase with less frequent flood events, an incised channel, and/or a reduced transport capacity. The low sedimentation rates explain the development of biosoils in the flood plain. In the channel, fine sands with a high proportion of carbonates of biological origin are dominant. The flood levels often reached only the lowest parts of the banks, due to the channel incision which induces a low level of the ground water and the drainage of the flood plain. The period from the end of the 1st century to the beginning of the 2nd century and the period 1960-75 correspond to periods of DDR, which are characterized by the absence of large flood events. The river change corresponds to the substitution of wandering channel for a single meandering channel.

The periods of hydrological irregularity (*i.e.*, periods of irregular flood-dominated regime; IFDR) are placed between periods of FDR and DDR. They correspond to a regular hydrological regime with only some exceptional flood events. In the flood plain, the interannual sedimentation is characterized by a high grain-size variability. The riverbanks are constituted by a succession of sand units (periods of flood events) alternating with clayed, carbonated units (hydrological calm). Rare flood events do not prevent channel incision. The permanent low level of the ground water favoured the drainage of the flood plain. These periods of IFDR occurred between the 3rd and the 4th centuries and at the end of the 16th century. They were comparable to the period at the end of the 20th century (1990-95), when several exceptional floods interrupted a period of DDR.

A synthesis of the activity of the Rhône River in its delta plain during the last 3000 years and its relation to the human and climatic history of the watershed is approached in the third part of the Ph.D.

The role of soil movements in the delta plain and the relative height of the sea level are discussed. The Rhône Delta is not affected by large rates of subsidence. On one hand, this phenomenon had only a secondary effect on the geography of the Rhône paleochannels, and did not prevent the channel incision during a period of DDR. On the other hand, the low rates of negative soil movements are in phase with the low accretion rates in the delta plain during the late Holocene, which tended to favor the progradation of the coastline.

The hydrosedimantary fluctuations and the fluvial metamorphoses of the Rhône River did not play a determining role in the land use. In relation to river and crafts activities and,

very early (Bronze Age), with the cultivation of cereals in the flood plain, habitats were confined to the higher parts of the riverbanks. The population density was important from the end of the antiquity to the 17th-18th centuries, even if agricultural production suffered from the rise of the ground-water levels.

Alluvium origins and paleogeographical history of the watershed functioning were deduced from the analysis of mineralogical tracers (heavy minerals). Correlation between the fluvial activity in the delta and the human-climatic history of the Rhône valley reveals very disparate situations and raises some fundamental questions. The delta plain received water and sediment fluxes from the whole watershed between the end of antiquity and the early Middle Age, which corresponds to a climatic change (*i.e.*, cooler and more humid conditions, in a context of unequal land use). But in most cases, only a part of the Rhône watershed had an impact on the Rhône Delta. The Southern Alps and the Provence area played a main role only during the Subboreal. The Rhône River rather appears in phase with the Northern Alps (4th-2nd century BC), the Massif Central (end of the AD 17th century), and both the Northern Alps and Massif Central (from the 1st century BC to the AD 1st century, then at the beginning of the AD 5th century). These observations allow us to outline a climatic paleogeography which could distinguish, during certain periods, the South-East (Provence, southern Alps) from the rest of the Rhône watershed. Indeed, the exceptional situation at the beginning of the Christian era contrasts with the decrease of torrential activity in the Provence and the South Alps during the same period. The Rhône River thus becomes an allogenic element in the Provence. Furthermore, the short period of DDR between the end of the AD 1st century and the beginning of the 2nd century corresponds to a drier climate in the watershed.

To conclude, the hydrological changes of the Rhône River seem to have taken place earlier in the delta (end of the 17th century) than in the Northern Alps and the upper part of the Rhône valley (end of the 18th century), suggesting that the sediments originating from the Alps played a less significant role than those which came from the southeast part of the Massif Central.