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River channel changes in the Rhone Delta (France) since the end of the Little Ice Age: geomorphological adjustment to hydroclimatic change and natural resource management

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Abstract

This study provides a representative example of a river affected by artificial width contraction and consequent bed incision in a context of sea-level rise. Geomorphological adjustment in the Rhone catchment since the final stage of the Little Ice Age has been induced by hydroclimatic change and human disturbances. These adjustments are examined to highlight the response of two sand-bed distributary channels of the Rhone Delta. By using methods such as sedimentological evidence, historical sources, planimetric resurvey, repeated longitudinal and cross-profiling and hydraulic data, the geomorphological and hydraulic responses to channel changes are characterised and their consequences assessed. It is shown that the reduction of sediment yield is a combined effect of a decrease of flood frequency, sediment dredging and building of dams on the Rhone River and its tributaries. The combination of decreased catchment sediment yield, artificial width contraction, increased stream power and boundary shear stress is the cause of channel incision of the Rhone River. In the coastal zone, the increase of the Rhone River's stream power has facilitated the transport of sediment down to the subdeltas. Engineering works, designed to stabilise the planform and to limit overbank flooding, caused (1) channel entrenchment, thus (2) the destabilization of infrastructure (e.g. bridges, quays) along the river, (3) the lowering of the phreatic water table in the floodplain, which in turn induced (4) soil salinization (change in salt wedge position); eventually, the channelization led to (5) an increase of the flood hazard and risks because, although more rare, the inundations have become more destructive. However, the contribution of the large flood events is negligible in terms of progressive channel in-filling because of their low frequency. Finally, no relation exists between the vertical adjustment of the Rhone channel through entrenchment and

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relative sea level, which rose at a rate of up to 2 mm year^{-1} during the 20th century. Clearly, natural resource management, in particular engineering activities, were the main cause of the river channel changes that occurred during the last century.

Keywords: Rhone Delta; Hydroclimatic change; Artificial width contraction; Channel bed degradation; Flood flow modifications; Sea-level change

1. Introduction

The Rhone River is a large hydrosystem, the Holocene functioning of which has been controlled by the interplay of numerous factors including climate, structure, energy gradient, influence of sea-level variations in the lowest part of the system and human action. Fluctuations in the ratio between these key parameters has played a decisive role in the adjustment of water discharge, sediment supply and channel changes during both Late Glacial and Holocene periods. In the Rhone Valley, most channel changes have been characterized by channel in-filling which took place when sediment supply exceeded the river transport capacity (Bravard et al., 1997; Provansal et al., 1999). This was notably the case during the Younger Dryas/Preboreal period (11–9 ka BP), Atlantic (5.8–5.4 ka BP), First Iron Age (2.8–2.4 ka BP), Early Roman Antiquity (1st century BC–2nd century AD), Late Antiquity–High Middle Age (AD 5th–8th centuries) and Little Ice Age (AD 14th–19th centuries). Conversely, periods of sediment deficit led to channel incision. In this respect, periods of channel incision have been identified during the Late Glacial (13–12 ka BP), Atlantic (6.8–5.8 ka BP), Second Iron Age (5th–1st centuries BC) and during the Roman Antiquity (AD 2nd–5th centuries). Most of the available literature dealing with the Rhone Valley is chiefly concerned with identifying successive phases of channel incision and channel in-filling: very few works consider possible correlations between channel incision/aggradation and channel widening/narrowing. Two factors can explain this: firstly, the difficulty of obtaining complete and accurate channel cross-sections; secondly, management of the bank system since the Neolithic, one of the impacts of which might have been to reverse the expected effects of hydraulic dynamics on channel morphology.

The historical account of stream evolution of the Rhone River in its delta presented in this paper is aimed at highlighting the relationship between channel incision/aggradation and channel widening/narrowing since the late 19th century. In doing so, it addresses the problem of channel incision as a result of artificial narrowing between 1895 and 1995. This change that took place in the Rhone Delta may be explained by taking into account the specific context of the two last centuries, which features, first, global warming, and hence reduction of runoff and of the occurrence of large flooding events in relation with the end of the Little Ice Age, second, major human disturbances of the Rhone hydrosystem, which caused serious impact on the sediment delivery ratio and third, relative sea-level rise, which has been estimated in the Rhone Delta to be 2 mm year^{-1} during the 20th century (Suanez et al., 1997).

Table 1
Brief review of channel degradation in the world over the last 200 years

Location	River	References
Rhône catchment	Upper Rhône River	Bravard (1986), Klingeman et al. (1994), Petit et al. (1996)
	Rhône River in its delta	Arnaud-Fassetta (1997; this study)
	Giffre River, Menoge River, Arve River	Peiry (1987)
	Fier River, Filière River	Peiry et al. (1994)
	Ain River	Marston et al. (1995)
	Doubs River	Larinier (1980)
	Saône River	Astrade and Bravard (1999)
	Drac River	Blanchet and Brissaud (1968)
	Arc River, Romanche River	Peiry et al. (1994)
	Herbasse River	Landon et al. (1993)
	Isère River	Salvador (1993)
	Drôme River, Ardèche River	Landon and Piégay (1994)
	Buëch River	Gautier (1994)
	Durance River	Miramont and Guilbert (1997), Warner (2000)
	Gard River	Masson and Séguier (1987)
Others French streams	Fecht River	Maire and Wilms (1986)
	Moselle River	Maire and Lasserre (1991)
	Loire River	Charrier (2000), Gautier et al. (2000), Leteinturier et al. (2000)
	Dore River	Cubizolle (1996)
	Allier River	Bazin and Gautier (1996)
	Cher River	Cuinat (1981), Garnier (2000)
	Adour River, Gave de Pau	Beaudelin (1989)
	Garonne River	Décamps et al. (1989), Steiger et al. (1998)
	Tech River, Têt River, Agly River	Mussot and Benech (1995)
	Var River	Prudhomme (1975)
	Golo River	Margat and Roux (1986)
	Fium seccu, Figarella River	Gaillot and Piégay (1999)
European rivers	Ebre River (Spain)	Guillen and Palanques (1992)
	Enza River (Italy)	Tagliavini (1978)
	Arno River (Italy)	Rinaldi and Simon (1998)
	Piave River (Italy)	Surian (1999)
	Rhine River (Germany)	Kuhl (1992)
	Southwest Germany	Kern (1997)
	Vistula River (Poland)	Lajczak (1995)
	Raba River (Poland)	Wyzga (1996)
	Warche River (Belgium)	Assani (1997)
	Lower Rhine River (The Netherlands)	Van Urk and Smit (1989)
	Meuse River (The Netherlands)	Klassan et al. (1998)
	Switzerland	Vischer (1989)
	Schraubach River, Ticino River, Enziwigger River, Moesa River, Upper Reuss River, Emme River (Switzerland)	Jaeggi and Zarn (1999)

(continued on next page)

Table 1 (*continued*)

Location	River	References
	Wooler Water (United Kingdom)	Sear and Archer (1998)
	Edendon Water (United Kingdom)	Ballantyne and Whittington (1999)
	Tay River, Tummel River (United Kingdom)	Winterbottom (2000)
Rest of the world	United States	Galay (1983), Schumm et al. (1984)
	United States	Harvey and Watson (1986), Kondolf (1997)
	Arizona (United States)	Bull and Scott (1974)
	California (United States)	Haltiner (1997)
	Southwestern United States	Elliott et al. (1999)
	North–Central Mississippi (United States)	Thorne (1999)
	Alberta (Canada)	Parker and Andres (1976)
	Australia	Erskine (1988)
	New South Wales Coastal Rivers (Australia)	Warner (1994)
	Ringarooma River, George River (Tasmania)	Knighton (1991)
	Japan	Fujita and Yamamoto (1992)
	Kuchoro River (Japan)	Nakamura et al. (1997)
	Taïwan	Kondolf (1997)

According to recent papers on this topic, incision is widespread. All over the world, many of the rivers flowing through industrialized and urbanized areas possess altered channels, a common phenomenon which has developed during the last 150 years in response to climatic and/or to human-induced changes (Table 1). Along numerous tributaries of the Rhone catchment, it has been demonstrated that recent degradation of fluvial beds can largely be correlated with a severe decrease in runoff since the end of the Little Ice Age, channelization of the Rhone River and the management of the catchment over the 20th century (Bravard, 1991). However, at the catchment scale, degradation in the fluvial system is not synchronous. In the Northern Alps, recent work concluded that channel incision began after 1950 (Peiry et al., 1994). Incision processes may have begun earlier in the Mediterranean part of the Rhone catchment. In the Rhone Delta, the drastic reduction of the sediment load associated with various modifications of the flood flow regime during the 20th century has induced channel degradation and a chronic deficit in the coastal sediment balance (Arnaud-Fassetta, 1997; Suanez and Provansal, 1998).

Although some research has documented vertical changes to the channel bed of the Rhone River and its tributaries, little work exists on bed-level adjustments in the Mediterranean basin caused by recent hydroclimatic change, sea-level variation and human disturbances. The overall aim of this paper, therefore, is to distinguish the respective contributions of these key parameters to driving channel change, and to demonstrate that geomorphological adjustment was largely influenced by human activities during the 20th century, in the context of lower frequency, high discharge events.

2. Regional setting

The Rhone River is one of the most important catchments in western Europe, with a drainage area of ~ 97 800 km^2 (Fig. 1). Before discharging into the Mediterranean Sea, the Rhone River (total length: 812 km) and its tributaries flow across various geological units (Alps, Massif Central, Jura) underlain by plutonic, extrusive, metamorphic and sedimentary rocks.

2.1. Palaeohydrology and deltaic development

Located on the French Mediterranean coast about 40 km west of Marseilles, the Rhone Delta (43°20′N to 43°35′N, 4°5′E to 4°50′E) corresponds to a sub-aerial surface of ~ 1740 km^2. Similar to many of the deltas worldwide, it is a product of post-glacial eustatic sea-level rise (Pons et al., 1979; L'Homer et al., 1981; Gensous and Tesson, 1997). However, the Rhone River is one of the most important agents in controlling deltaic evolutionary stages because it is one of the main suppliers of water and sediment to the system. Recent work by Arnaud-Fassetta (2000) has identified the precise evolution of water and sediment discharges of the Rhone River in its delta during the late Holocene. One of the last hydrological changes occurred during the Little Ice Age (17th–18th

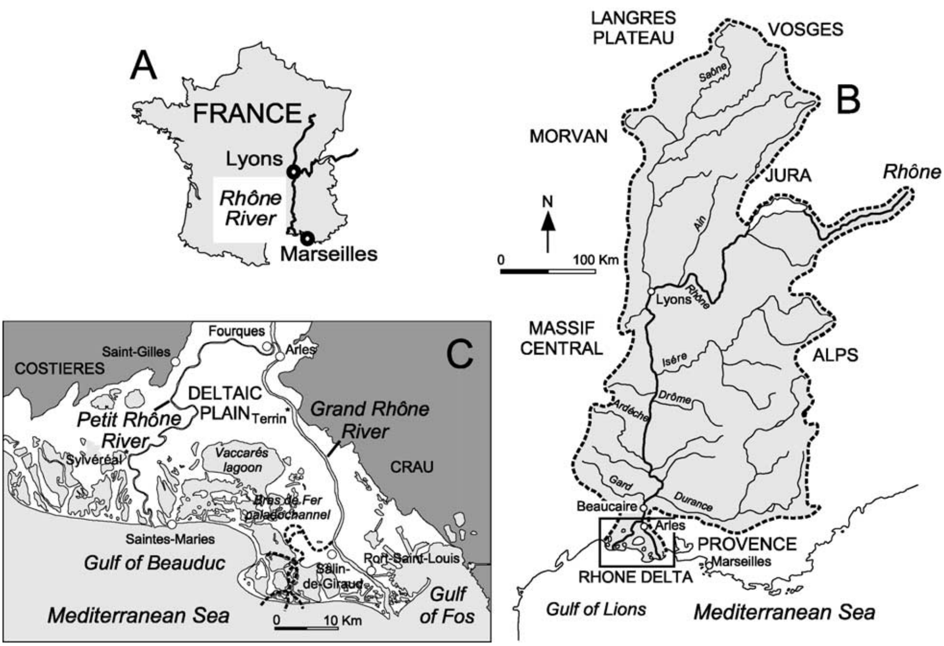


Fig. 1. Location map of the study sites. (A) Location of the Rhone River in France. (B) The Rhone drainage basin. Note the asymmetry of the drainage network; most of the tributaries drain the Alpine units. (C) The Rhone Delta. The present-day discharge ratio between the Grand Rhone River to the East and the Petit Rhone River to the West is approximately 9:1.

centuries). This was characterized by abundant water and sediment discharges which played a decisive role in the delta geomorphology through aggradation of the channel bed, braid development, crevassing and substantial progradation of the coastline.

2.2. Present-day hydrology and hydrography

Upstream of the delta, the Rhone River has the 42nd highest mean annual water discharge in the world. At 60.5 km upstream of the Rhone River-mouth (Beaucaire water-gauge station), the average water discharge was estimated at 1701 $m^3 s^{-1}$ for the period 1961–1996. Discharge is characterized by large variations, ranging from 11 640 $m^3 s^{-1}$ during the 100-year flood of May 1856 and 10 981 $m^3 s^{-1}$ during the 90-year flood of January 1994 to approximately 4200 $m^3 s^{-1}$ during 1-year flooding events and 320 $m^3 s^{-1}$ during periods of severe low water. Despite the huge water discharge from the Rhone River, the hydrological regime in the delta is characterized by intra- and interannual variability because of various influences (glacial, nival, pluvial) in the catchment.

Downstream of Fourques, the Rhone River discharges into the Mediterranean Sea via two distributaries, the Grand Rhone River to the East and the Petit Rhone River to the West. The Grand Rhone River (total lengh = 50 km; mean gradient = 0.00009) drains 85–90% of the discharge in the delta plain area. Its channel is straight [sinuosity (p) = 1.1] with bankfull width varying from 150 m at Arles to 1.1 km near the river-mouth. Bankfull mean channel depth is 9 m, with variations from 4 to 12 m and a maximum value (22 m) upstream of Salin-de-Giraud. The Petit Rhone River (total lengh = 60 km; mean gradient = 0.00005) discharges 10–15% of the river water into the sea. It is sinuous (p = 1.35) in its upstream reach and meandering (p = 1.7) further downstream. Bankfull channel width varies between 85 and 285 m and mean channel depth is 6.5 m, with variations from 4 to 12 m and a maximum value (19 m) downstream of Sylvéreal. Salt wedge intrusion occurs in both channels when the river discharge is lower than ~ 1000 $m^3 s^{-1}$ at Beaucaire. The location of the upstream limit of the salt wedge depends on many other factors including wind direction and strength, wave regime and sea-level variations (Savey et al., 1971).

2.3. Sediment yield

The bed material of the Rhone River in its delta is characterized by four types of sediments (cobble–pebble, sand, compact silt, mouth mud). However, sands are predominant, with a median grain size (D_{50}) of 400–550 μm (Quisserne, 2000; Arnaud-Fassetta et al., submitted for publication). Sand particles move by both saltation and suspension at practically all flows and the bed material is therefore continuously being reworked (Arnaud-Fassetta, 1997). Entrenchment of the channel bed is facilitated by the relatively fine diameter of the bed material. Gravels only occupy the upstream section of the Grand Rhone channel up to the Terrin riffle. Silt–clay deposits comprise the bed in negligible amounts near the river-mouth. However, the silt–clay fractions represent the main part of present-day sediment load [median diameter (D_{50}) of 2.5–10.5 μm)], which has decreased from 35×10^6 to 7.39×10^6 t $year^{-1}$ since the early 19th century (Surrell, 1847; Pont et al., 2002). This marked sediment load decrease may have been influenced by both hydroclimatic change (i.e. the end of the Little Ice Age) and major human disturbances of the Rhone catchment through (1) reforestation and upland sediment retention as a result of agricultural/pastoral abandonment and land management laws of 1860 and 1882, notably the "Restauration des Terrains en Montagne" works, (2) in-channel sediment mining and dredging, (3) dams, reservoirs and flow diversions constructed to irrigate and generate hydroelectric power and (4) urbanisation.

3. Available data and methods

The evolution of the Rhone River in its delta during the 20th century has been analysed on the basis of cross-sections and longitudinal profiles, hydraulic data, historical sources (text and maps), sedimentology of channel deposits and records of human intervention in the fluvial hydrosystem.

3.1. Cross-sections and longitudinal profiles

Temporal trends of bed-level adjustment have been determined from repeated surveys of monitored channel cross-sections. On the Petit Rhone River, cross-sections were surveyed every 200 m (total of 101 cross-sections), in 1895 by the Service Spécial du Rhône (SSR) between 56.8 and 36.8 km above the river-mouth and more recently in 1995 by the Compagnie Nationale du Rhône (CNR) from 56.8 km down to the sea. On the Grand Rhone River, cross-sections were surveyed at each kilometre (total of 39 cross-sections), in 1907 by the SSR between 42.5 and 4.5 km above the river-mouth and more recently in 1999 by the CNR from 42.5 km down to the sea. The method of surveying cross-sections was developed with the use of soundings, with a precision of ± 20 cm. Longitudinal profiles of the Grand Rhone channel bed taken in 1907, 1967 and 1991 between Arles and Port-Saint-Louis (Fig. 1), at 500-m intervals using a total of 85 points. Longitudinal profiles of the Petit Rhone channel bed, corresponding to 101 points separated by 200 m, were established in 1895, 1969 and 1995 between Fourques and Saint-Gilles (Fig. 1).

3.2. Hydraulic data

Selected hydraulic values were calculated from 101 cross-sections of the Petit Rhone River and 39 cross-sections of the Grand Rhone River. Specifically, discharge, channel capacity, specific stream power and boundary shear stress were selected to represent flow conditions. Channel capacity was obtained using the equation:

$$C = Wd \tag{1}$$

where W = channel width (m) and d = mean channel depth (m). Specific stream power (ω), expressed as the rate of potential energy expenditure per unit bed area of channel, was calculated using the equation (Bagnold, 1966; Bull, 1979):

$$\omega = \rho_w g Q S W^{-1} \tag{2}$$

where ρ_w = density of water (1000 kg m^{-3} for sediment-free water), g = acceleration due to gravity (9.81 m s^{-2}), Q = discharge (m^3 s^{-1}) and S = gradient of the water energy surface (m m^{-1}). Discharge (Q) in Eq. (2) was estimated from the relation (Rotnicki, 1991):

$$Q = (0.921\ n^{-1})AR^{0.67}S^{0.5} + 2.362 \tag{3}$$

where n = Manning's resistance coefficient, A = cross-sectional area (m^2) and R = hydraulic radius (m). The Strickler (1923) equation was used to determine an initial value of n in Eq. (3):

$$n = 0.0151\ D_{50}^{0.17} \tag{4}$$

where D_{50} = median bed material grain size (mm). Relationship of specific stream power and bedload transport capacity of the Rhone River was quantified using the Bagnold (1980) stream power function, where the bedload transport rate per unit width (I_b) is given by:

$$I_b = 0.1\{[(\omega - \omega_0)0.5^{-1}]^{1.5}(d\ 0.1^{-1})^{-0.67}(D_{50}\ 0.0011^{-1})^{-0.5}\} \tag{5}$$

where ω_0 = critical stream power (W m^{-2}). Critical stream power ω_0 is defined by:

$$\omega_0 = 290(D_{50})^{1.5}\log(12dD_{50}^{-1}) \tag{6}$$

Boundary shear stress (τ_0), corresponding to the unit tractive force, has been calculated using the relation of Du Boys et al. (1879):

$$\tau_0 = \rho gRS. \tag{7}$$

3.3. Historical sources (text and maps)

A wealth of information on the channel change is available in the form of old river maps and associated archives. Historical data reveal trends within the hydrological regime since 1500 (Pichard, 1995). Detailed channel mapping from the late 19th and 20th centuries led to the identification of fluvial metamorphosis. Maps have permitted the quantification of the evolution of the number of bars and of channel geometry (Volcot, 2001).

3.4. Sedimentology of channel deposits

Grain size variations of channel deposits reveal changes in flow competence of the Rhone River. The grain size analysis for the Little Ice Age period was based on the sedimentology of seven cores (4–12 m in length) taken along the thalweg of the Bras de Fer palaeochannel (Arnaud-Fassetta and Provansal, 1999). The CM diagram of Passega (1957), which defines the maximum grain size (i.e. relative maximum competence) of the graded suspension (C_s), was used to compare the sand-bed deposits of the Little Ice Age (121 samples) with the present-day bed material (72 samples) collected in 1999 in the rivers Grand Rhone and Petit Rhone (Quisserne, 2000; Arnaud-Fassetta et al., submitted for publication).

4. Historical channel changes (1895–1995)

In the Rhone Delta, historical channel changes have affected both the geometry and hydraulics of the channel.

4.1. Change in channel geometry

Change in channel geometry was dominated by two processes: (1) narrowing that was caused by artificial means and (2) resulting deepening (Fig. 2).

Firstly, earth in-filling of either (Fig. 3) or both riverbanks resulted in severe width contraction of Rhone River channel at the end of the 19th century (Fig. 4). On the Petit Rhone River, mean width at bankfull stage narrowed from 181 m in 1995 to 135 m in 1995 (25% reduction). On the Grand Rhone River, mean width at low flows narrowed from 428 m in 1907 to 337 m in 1999 (21% reduction) (Table 2).

Secondly degradation, deduced from the comparison of longitudinal profiles, is chiefly a result of bed contraction of the Rhone River in its delta (Fig. 5). Incision mainly took place near the centreline of the channel (Fig. 6). On the Petit Rhone River, an overall downcutting of the bed by 0.7 m (10 mm year^{-1}) was noted between 1895 and 1969 through comparison of profiles (Fig. 4A). Degradation mainly occurred in the upstream

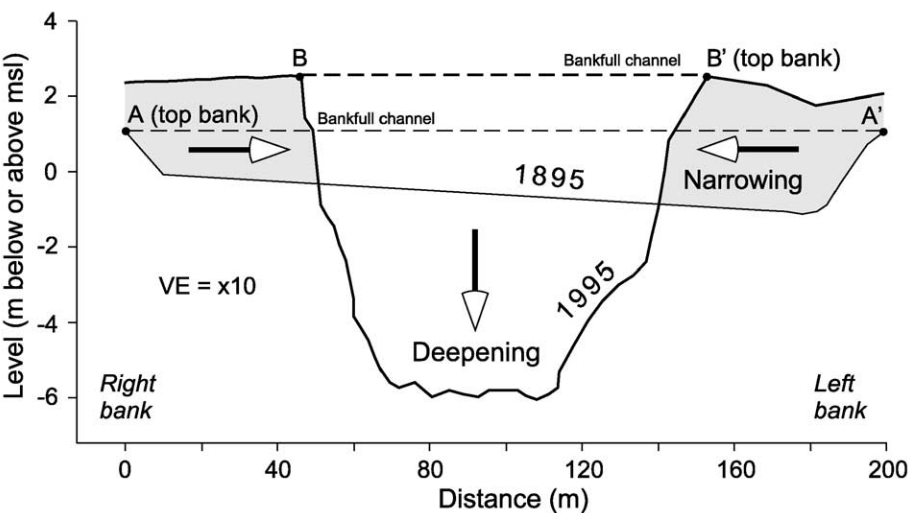


Fig. 2. Cross-section channel changes along the Petit Rhone River, 44 km upstream from the sea. In 1895, the river channel was large and shallow. By contrast, in 1995, the channel is markedly incised, as a consequence of artificial width contraction and reduced sediment yield.

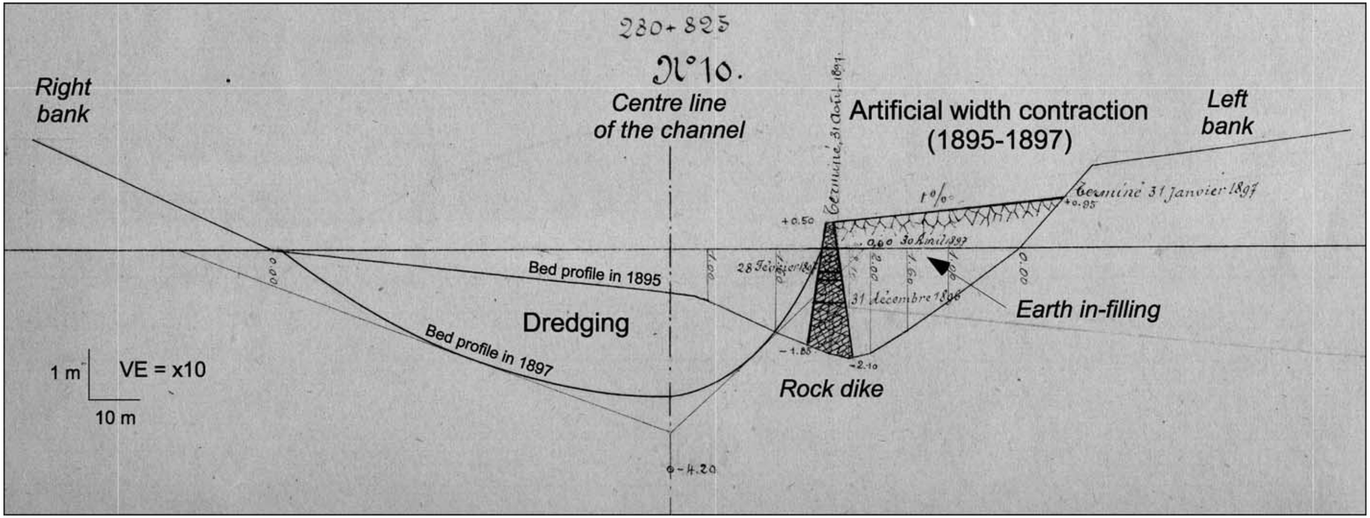


Fig. 3. Artificial width contraction and dredging of the Petit Rhone channel between 1895 and 1897 (from Ponts and Chaussées, 1898). These engineering works explain the combined occurrence of the narrowing of channel width and the incision of the channel depth since the end of the 19th century.

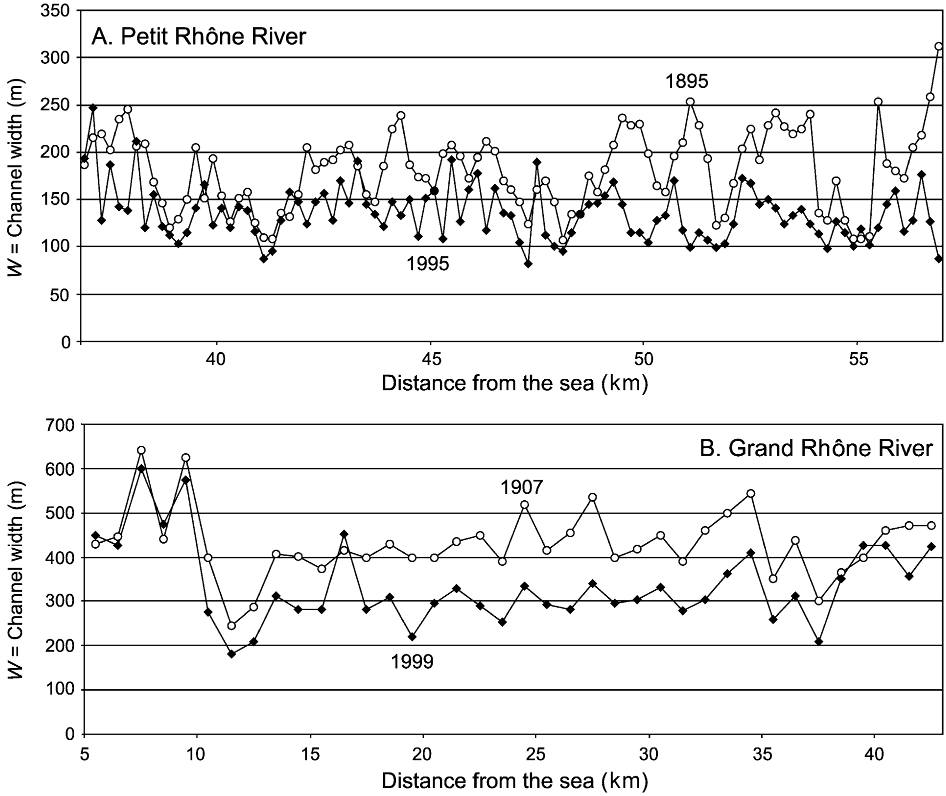


Fig. 4. Changes in channel width of the Petit Rhone River (A) and the Grand Rhone River (B) between 1895 and 1999. Both graphs highlight the channel narrowing of the Rhone River in its delta induced by engineering works (channelization) at the end of the 19th century.

reach, with a maximum value of 5.4 m. Between 1969 and 1995 (Fig. 4B), system-wide reinforcement of the degradation trend produced generalized downcutting of the channel by 1.8 m (70 mm year^{-1}). In contrast to the previous period, the downstream part of the river was more affected by entrenchment, with a maximum value of 6.8 m. Hence, a mean of 2.5 m of river incision, with a local maximum value of 10.4 m, has, therefore, occurred during the 20th century, with rates of channel incision (700% increase) increasing rapidly after 1969 (Fig. 4C). The same trend was observed on the Grand Rhone River. From 1907 to 1967, longitudinal profile comparison evidenced an overall downcutting of the channel by 0.4 m (7 mm year^{-1}) (Fig. 4D). Most of the incision, with a maximum value of 4.7 m, affected the riffles of the channel bed. Degradation accelerated between 1967 and 1991, with a system-wide channel downcutting rate of 0.6 m (26 mm year^{-1}), especially upstream of the delta (Fig. 4E). Thus, degradation of the channel bed of the Grand Rhone River was observed between 1907 and 1991, with downcutting of the channel ranging from 1.1 m to a maximum value of 6.8 m (Fig. 4F). The rates of channel incision (450% increase) rose rapidly after 1967.

Table 2
Changes in sediment yield, bank height, channel geometry and channel hydraulics on (A) the Petit Rhone River at bankfull stage between 1895 and 1995 and (B) the Grand Rhone River at low flows between 1907 and 1999

A. Petit Rhône River

Variable	Symbol	1895			1995			Mean variation 1895–1995
		Minimum	Mean	Maximum	Minimum	Mean	Maximum	
Bank height (m above msl)	H_m	1.0	3.6	6.5	1.8	4.7	6.8	30% increase
Channel width (m)	W_b	107	181	312	82	135	247	25% decrease
Mean channel depth (m)	d_b	1.2	2.7	4.4	3.5	6.8	12.8	150% increase
Maximum channel depth (m)	$d_{max\ (b)}$	1.8	4.6	7.8	6.3	9.3	17.6	100% increase
Channel capacity (m^2)	C_b	194	492	929	500	895	1285	80% increase
Specific stream power ($W\ m^{-2}$)	ω_b	0.1	0.6	1.2	1.3	3.8	9.4	535% increase
Boundary shear stress ($N\ m^{-2}$)	$\tau_{0\ (b)}$	0.5	1.0	1.8	2.0	3.7	6.3	270% increase
Discharge ($m^3\ s^{-1}$)	Q_b	90	249	461	333	832	1205	235% increase
Sediment load ($\times 10^6$ t $year^{-1}$)	Q_s	–	7[a]	–	0.15	0.7[b]	2	78% decrease

B. Grand Rhône River

Variable	Symbol	1907			1999			Mean variation 1907–1999
		Minimum	Mean	Maximum	Minimum	Mean	Maximum	
Bank height (m above msl)	H_m	–	–	–	2.0	3.5	6.4	–
Channel width (m)	W_{lf}	–	428	–	183	337	600	21% decrease
Mean channel depth (m)	d_{lf}	2.1	4.5	9.6	2.3	6.4	11.0	40% increase
Maximum channel depth (m)	$d_{max\ (lf)}$	2.9	7.5	16.1	4.0	8.0	14.9	7% decrease
Channel capacity (m^2)	C_{lf}	1105	1881	2356	820	2096	3767	11% increase
Specific stream power ($W\ m^{-2}$)	ω_{lf}	0.04	0.3	1.2	0.1	2.9	15.8	865% increase
Boundary shear stress ($N\ m^{-2}$)	$\tau_{0\ (lf)}$	0.1	0.5	1.9	0.1	1.7	16.5	240% increase
Discharge ($m^3\ s^{-1}$)	Q_{lf}	388	776	1397	759	899	925	15% increase
Sediment load ($\times 10^6$ t $year^{-1}$)	Q_s	–	28[a]	–	1.05	6.7[b]	17.7	78% decrease

Note the narrowing of mean channel width and sediment yield and the increase of mean channel depth, channel capacity, specific stream power, boundary shear stress and discharge both channels of the Rhone Delta.
[a] Surrell (1847).
[b] Pont et al. (2002).

Accelerating degradation, more marked on the Petit Rhone River, has increased both the bankfull mean and maximum channel depths as well as the mean bank height. The morphological impacts of channel incision included gradual destruction of the channel bars, thus the increasing stream power. Chutes and side channels were

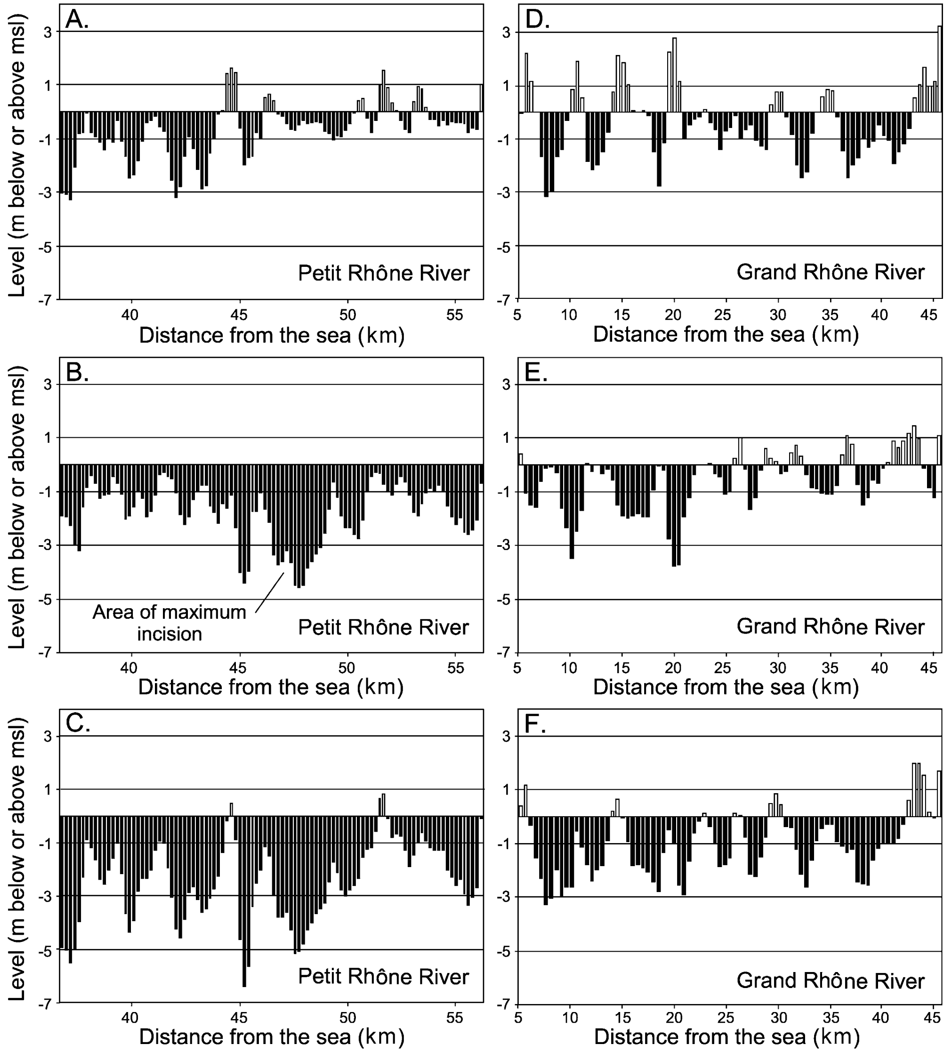


Fig. 5. Changes in longitudinal profile on the Petit Rhone River (A) between 1895 and 1969, (B) between 1969 and 1995 and (C) between 1895 and 1995; changes in longitudinal profile on the Grand Rhone River (D) between 1907 and 1967, (E) between 1967 and 1991 and (F) between 1907 and 1991. Channel incision, which affected both distributaries of the Rhone Delta, was more important along the Petit Rhone River.

progressively in-filled and disconnected from the main channel because of decreasing mean water levels. In the Rhone Delta, decreasing bed material volume led to the exposure of ancient deposits in many places of the channel bottom. Even today, it is not uncommon to find older paludal floodplain deposits outcropping on the Rhone alluvial bed (Fig. 7A).

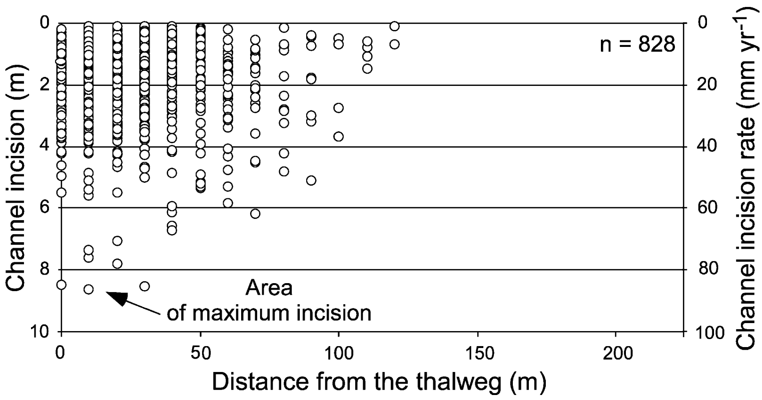


Fig. 6. Channel incision versus distance from the thalweg of the Petit Rhone channel between 1895 and 1995. The area of maximum incision is located near the thalweg of the channel. Dots correspond to channel incision values measured along 101 cross-sections, every 10 m from the thalweg of the channel towards both banks.

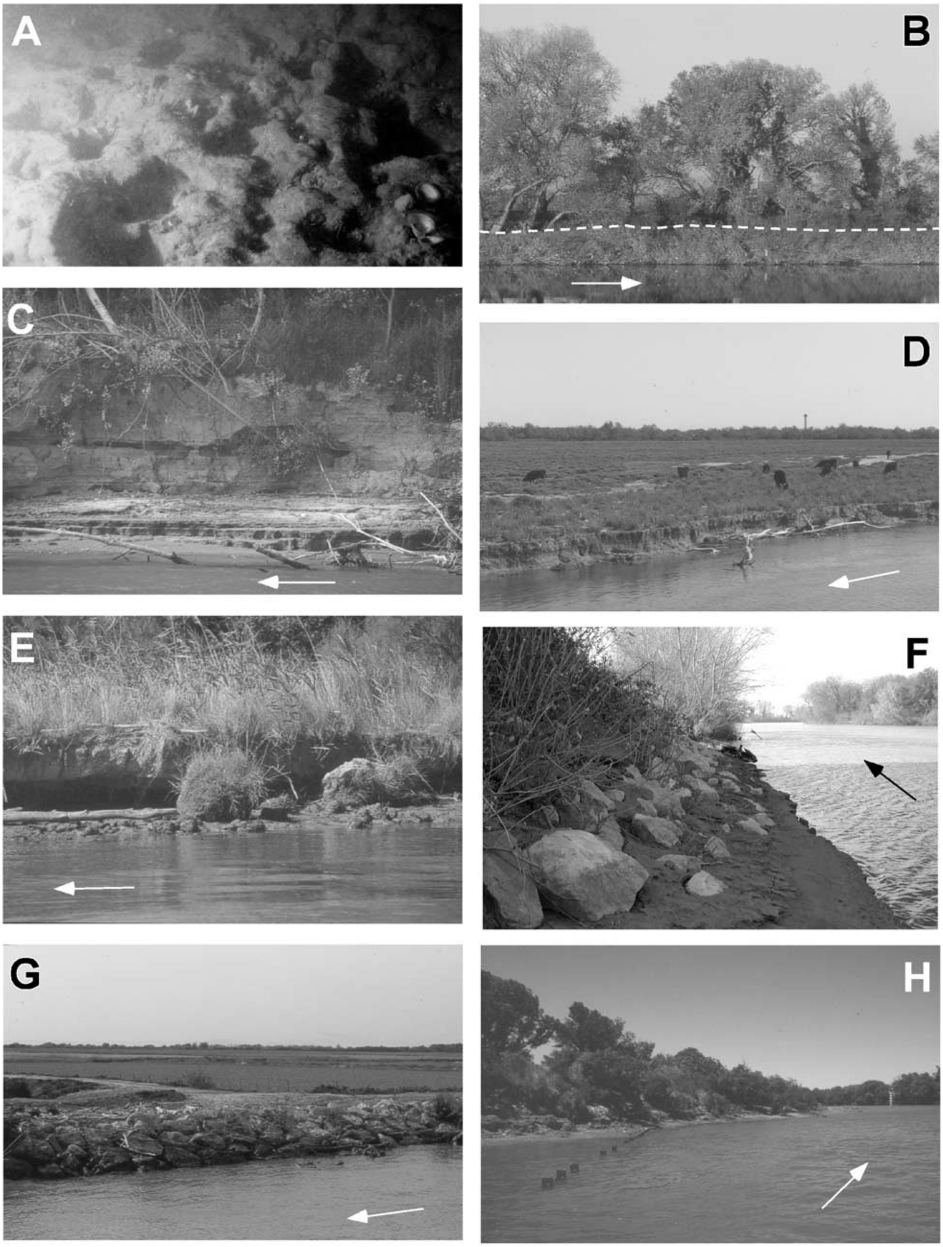
4.2. Change in channel hydraulics

Severe degradation of the channel bed along the thalweg of the Rhone River in its delta markedly increased bankfull and low flow discharges, channel capacity, specific stream power and boundary shear stress (Table 2). Increases in specific stream power and boundary shear stress resulted in reinforcement of both flow competence and bed material transport capacity. Comparison of CM diagrams (Passega, 1957) of the channel deposits of the Little Ice Age (AD 1586–1725) with those of the contemporary channel suggests that the present-day Rhone River has a higher competence (Fig. 8).

However, the competence inferred from sedimentological data represents only the minimum competence of the river rather than its real competence, which can far exceed the grain size of the sediments deposited in the channel. To test this assumption, I therefore calculated the critical stream power needed to entrain the sediments (Table 3). The results

Fig. 7. Photographs showing the channel and the banks of the Rhone River. (A) Scouring of alluvial floor, Petit Rhone River. The channel is incised into Holocene floodplain deposits; the cohesion of the silty material (25–35 kPa) allows erosion of small sub-circular depressions (∅ 30–70 cm, depth 10–20 cm) due to cavitation processes (negative by M. Guillemard, November 1995). (B) Vegetated bank of the Upper Petit Rhone River. Note the significant bank height (~ 5 m) and the line below the riparian forest, which corresponds to the maximum elevation of the November 1994 flooding event (negative by G. Arnaud-Fassetta, November 1994). (C) Eroded layered bank (height ~ 3.5 m) of the Grand Rhone River, upstream of Arles city (negative by G. Arnaud-Fassetta, July 2000). (D) Eroded cohesive bank of the Petit Rhone River near to the river-mouth. Note that the bank height (~ 1 m) is lower than in the upstream sections (in B) of the river (negative by G. Arnaud-Fassetta, May 1998). (E) Undercut and cantilever failure affecting the layered bank (height ~ 0.8 m) of the Grand Rhone River near the river-mouth (negative by G. Arnaud-Fassetta, July 2000). (F) Boulder armouring of the vegetated bank of the Upper Petit Rhone River (negative by G. Arnaud-Fassetta, February 2001). (G) Block armouring built after the 1993–1994 flooding events on the Petit Rhone River upstream of the river-mouth (negative by G. Arnaud-Fassetta, May 1998). (H) Hydraulic deflector used to divert the water flows towards the Petit Rhone channel (negative by G. Arnaud-Fassetta, July 1999).

obtained suggest that the bankfull specific stream power of the Upper Petit Rhone River was able to transport material up to 6.39 mm in diameter in 1895. In 1995, the strong increase of stream power allowed the initiation of motion of particles up to 23.82 mm in diameter. Similarly, unit sediment transport at bankfull stage was limited in 1895 for the



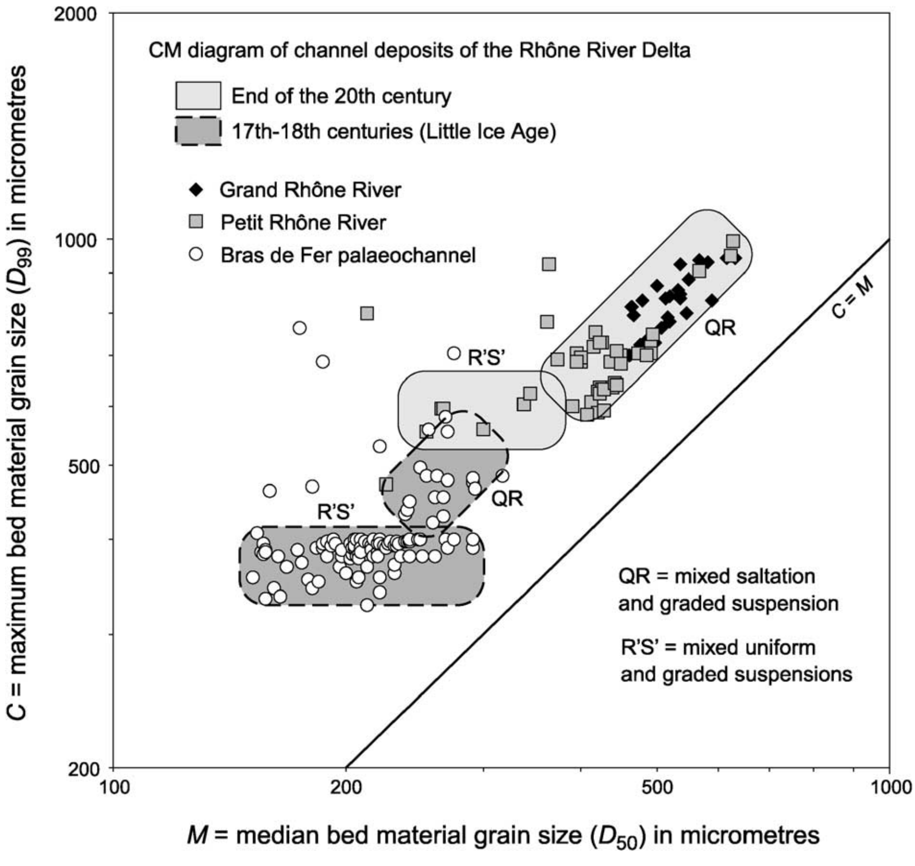


Fig. 8. Increasing flow competence of the Rhone River in its delta since the Little Ice Age, as displayed by the CM diagram (Passega, 1957) of channel deposits. Sedimentological data ($n=121$) of the Bras de Fer (17th–18th centuries) were obtained by coring. The sedimentological data of present-day Rhone channels (Grand Rhone, $n=27$; Petit Rhone, $n=46$) were sampled by scuba diving surveys.

representative sand fraction (0.3–0.5 mm in diameter) of the Rhone River in its delta to 0.024 to 0.018 kg m^{-1} s^{-1}. In 1995, the transport capacity was much higher for the sand fraction being 0.234 to 0.181 kg m^{-1} s^{-1}.

The increase of channel depth has furthermore generated residual pockets of salt wedge near the channel bottom. On the other hand, the increase of the specific stream power and bed shear stress during the 20th century has reduced the incursion of the salt wedge upstream of the Rhone River.

5. Causes of channel changes

Any understanding of changed river channels in the Rhone Delta must rest on the identification of the causes of river change, natural and/or societal. The main causes seem

Table 3
Critical stream powers (ω_0) and estimated bedload transport rates (I_b) of the Petit Rhone River at bankfull discharge in 1895 (A) and 1995 (B)

ω (W m^{-2})	d (m)	D_{50} (mm)	ω_0 (W m^{-2})	I_b (kg m^{-1} s^{-1})
A. 1895				
0.55	2.70	0.30	0.01	0.024
0.55	2.70	0.40	0.01	0.020
0.55	2.70	0.50	0.02	0.018
0.55	2.70	6.39	0.55	0.000
B. 1995				
3.77	6.80	0.30	0.01	0.234
3.77	6.80	0.40	0.01	0.202
3.77	6.80	0.50	0.02	0.181
3.77	6.80	23.82	3.77	0.000

See the text for the equations.

to be (1) significant reduction of water flows and sediment fluxes since the end of the Little Ice Age and (2) major human disturbances of deltaic plain area and Rhone catchment. In contrast, base-level control at the medium-term time scale (10–100 years) seems to have played a minor role in driving channel change.

5.1. Reduction of high flooding events and sediment fluxes since the end of the Little Ice Age

Climatic change since the end of the Little Ice Age is the first cause of the reduction of runoff, with impacts on the flood frequencies and the mass of sediment load.

Changes in the hydrological regime of the Rhone River were studied by Pichard (1995), who compiled the height of all floods greater than 5.25 m above msl at the Arles gauging station for the period 1500–1995. Note that the height of floods greater than 5.25 m at Arles corresponds to a discharge of over 7000 m^3 s^{-1} (i.e. 10-year flood) at the present time. Fig. 9 shows several decades (1651–1720, 1751–1860) of flood-dominated regime (FDR), which correspond historically to aggradation in the palaeochannel of the Bras de Fer and rapid progradation of its mouth, particularly between 1680 and 1712. These periods of FDR alternated with periods of low flood frequency (1721–1750, 1861–1995) which correspond to a drought-dominated regime (DDR) and a reduction of coastline progradation (Arnaud-Fassetta and Provansal, 1999). Despite the fact that the Lower Rhone catchment has been subjected to several large floods (1886, 1897, 1910, 1935, 1951, 1955, 1993, 1994) since the end of the Little Ice Age (~ 1860), the flood frequency has decreased considerably: eight to nine floods of over 7000 m^3 s^{-1} per decade (1850–1900), four to five per decade (1900–1950) and two to three per decade (1950–2000) (Pichard, 1995).

Since the end of the Little Ice Age, the rare flooding events have played a modest role in terms of long-term channel in-filling. This statement is supported by evidence from the flood events of 1993–1994, which were studied to assess the geomorphological role of

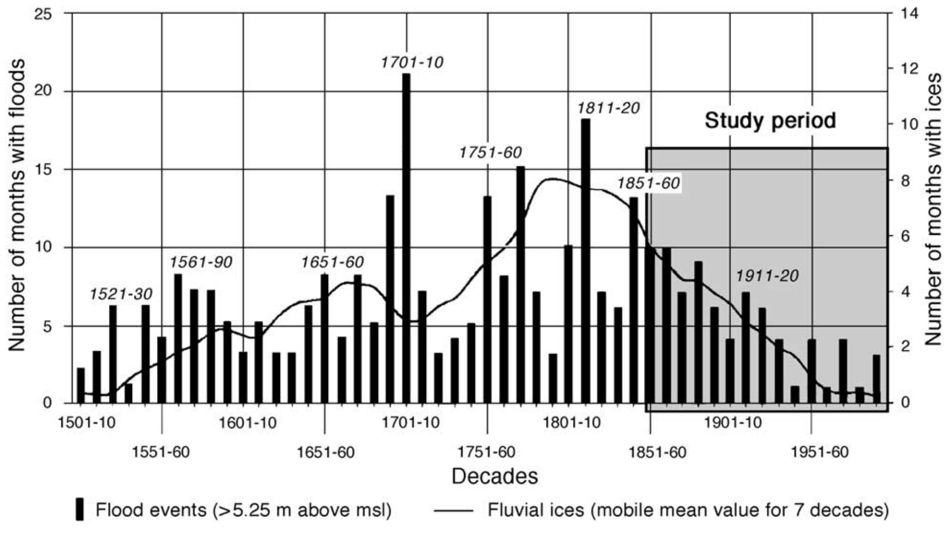


Fig. 9. Histogram showing the frequency of flooding episodes that have affected the Grand Rhone River at Arles since 1500 (from Pichard, 1995). Frequency is expressed by the number of months per decade with floods >5.25 m above msl. The figure clearly shows that flood frequency, which was very high during the Little Ice Age (maximum 22 months/decade), has noticeably and gradually decreased during the 20th century (maximum 10 months per decade).

rare, large floods on the sediment balance of the channel (Fig. 10). During this 14-month period, the Rhone River was affected by three large floods. The instantaneous peak discharges were 9800 m^3 s^{-1} (October 1993), 10 981 m^3 s^{-1} (January 1994) and 9757 m^3 s^{-1} (November 1994), which correspond to return periods of 32, 90 and 30 years, respectively. Nevertheless, the specific impacts of the three flooding events were strikingly different. In October 1993, the bed of the Rhone River responded to the flood through major aggradation (0.68×10^6 t km^{-2}). In January 1994, aggradation of the channel bed was limited to less than 0.01×10^6 t km^{-2}. In November 1994, the large flood event generated erosion of the channel bed, with value of -0.03×10^6 t km^{-2}. Therefore, the geomorphological impact of these rare floods was only significant in the short term, generating only temporary changes to sediment storage in the bed. At the medium and long terms, large floods did not restore the channel bed, which experienced a net sediment deficit of 0.18×10^6 t km^{-2} between 1989 and 1995. The volume of sediment entering storage during the 1993–1994 FDR was largely eroded during the next DDR period. On this basis, it may be concluded that the large flooding events of the 20th century played a modest role in terms of the long-term sediment balance. This may certainly be attributed to their low frequency.

Prior to the building of dams on the Rhone River and its tributaries, the mean annual sediment load supplied to the delta (primarily sand, silt and clay carried both as suspended and wash load) was estimated to be 21×10^6 m^3 $year^{-1}$ [or 35.7×10^6 t $year^{-1}$ with submerged density of sediment (ρ_s) = 1.7] during the first part of the 19th century (Surrell, 1847). After the end of the Little Ice Age, the load decreased and it was estimated to be

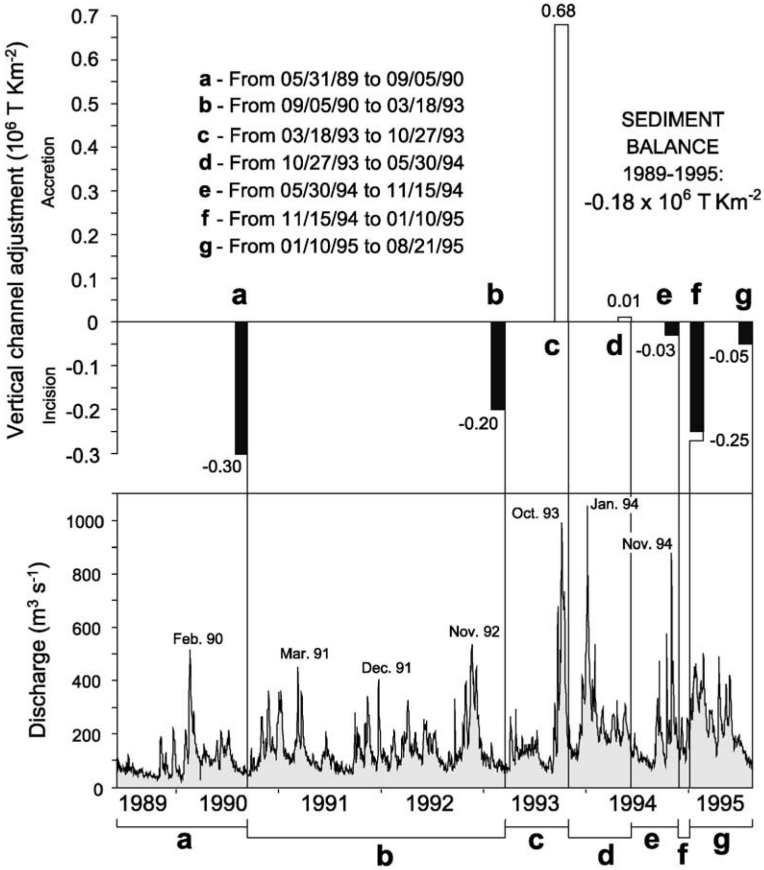


Fig. 10. Evolution of the channel bed of the Petit Rhone River between 1989 and 1995 (from Arnaud-Fassetta, 1997). Note the temporary channel aggradation caused by the large flooding events of 1993–1994, in contrast with the long-term trend characterized by channel incision.

30×10^6 t year^{-1} at the beginning to the 20th century (Pardé, 1925). In the post-dam era, there has been a massive reduction in sediment load and Savey and Déleglise (1967), Pauc (1976) then El Habr and Golterman (1987) estimated that the sediment yield of the Rhone River was only 5.0×10^6 t year^{-1} during the 1960s, 2.2×10^6 t year^{-1} during the 1970s and 2.6×10^6 t year^{-1} during the 1980s, respectively. At the end of the 20th century, the mass of sediment carried by the Rhone River at Arles was estimated at an average of 7.39×10^6 t year^{-1}, with annual variation between 1.2×10^6 and 19.7×10^6 t year^{-1} (Pont et al., 2002). Therefore, the sediment yield has decreased to only $\sim$ 22% of its pre-Little Ice Age value.

To sum up, the trends identified from historical literature indicate a significant combination of decreasing sediment yield, hydroclimatic change (reduction of high flooding events) and increasing human management of the catchment. These changes are the cause of channel degradation. The impacts of these changes on the fluvial system and its morphology are discussed below.

5.2. Major human disturbances of the Rhone catchment and deltaic plain

In the Rhone catchment, the responses of flow processes and channel forms to engineering and river regulation have been widely studied (Bravard et al., 1999). Human disturbances of the Rhone catchment over the last 150 years can be grouped into five categories:

(1) Reforestation of up-valley slopes, which began in the late 19th century and was particularly widespread during the first decades of the 20th century. Agricultural retreat and the implementation of a series of land management laws led to reforestation and decreased erosion of large areas of the uplands, resulting in a major reduction in catchment sediment yield to the fluvial system (Peiry, 1987; Bravard, 1994). Runoff, mass wasting and soil erosion are drastically decreased following reforestation (ONF, 1994). However, reforestation of catchments has mainly induced a decrease in the yield of finer sediments (silt and clay) which are not representative of the sandy bed material of the Rhone River in its delta (Quisserne, 2000). Therefore, reforestation cannot be directly responsible for channel incision in the Rhone Delta during the 20th century.

(2) River water pumped out the Rhone Delta for irrigation is estimated to be 380–405 $\times 10^6$ m^3 $year^{-1}$ for the period 1994–1996 (Gindre et al., 1999). After use, a small volume of the water (50×10^6 m^3) flows towards the Vaccarès lagoon while most of the water (155–220 $\times 10^6$ m^3) is pumped back to the Rhone River. Irrigation and drainage water increased the quantities of finer sediment ($\sim 30 \times 10^3$ t $year^{-1}$ of silt and clay) trapped by decantation in the deltaic plain, reducing the alluvial sediment supply toward the river-mouths (Pont, 1993). This quantity is negligible ($< 0.5\%$) with respect to the annual yield (7.39×10^6 t $year^{-1}$) carried by the Rhone River to the sea.

(3) In-channel sediment mining and dredging were very intensive in the catchment during the 20th century (Bravard, 1994; Gautier, 1994; Landon and Piégay, 1994). Sediment removal by mining was estimated to be 0.75×10^6 t $year^{-1}$ between 1949 and 1968 in the Isère basin (Goncelin–Domène section) and 0.52×10^6 t $year^{-1}$ between 1950 and 1972 in the Drac River (floodplain of Grenoble) (Peiry et al., 1994). In the Arve River, sediment mining was estimated by Blanc et al. (1989) to be as high as 0.69×10^6 t $year^{-1}$ between 1950 and 1985. In the Rhone Delta, dredging of riffles has been very important since the late 19th century. In the Grand Rhone River, the CNR has removed 0.032×10^6 t $year^{-1}$ since 1988. Since the sediment deficit induced by channel sediment mining and dredging affects chiefly the coarse sedimentary fraction that is representative of the bed material, it certainly can be considered as one of the main cause of present-day channel incision in the Rhone Delta.

(4) The construction of 77 dams (19 on the Rhone River), reservoirs and flow diversions severely reduced the sediment load downstream (Salvador, 1993; Peiry et al., 1994; Petit et al., 1996). In 1952, the Donzère dam was the first dam erected on the Rhone River. On the Durance River, which represents the last major left-bank tributary (order 9, according to the stream ordering method of Strahler, 1952) of the Rhone River (order 10), only about 1–2% of the former mean discharge (about 200–300 m^3 s^{-1}; Pardé, 1937)

now reaches the Rhone River at Avignon since the construction by Electricité de France (EDF) of the Serre–Ponçon dam in the early 1960s and the diversion of river flows into the concrete canal of Provence. Combined with the effect of the end of the Little Ice Age, this regulation was an important factor in the reduction of catchment sediment yield (Juramy and Monfort, 1986). In the 1950s, the fine (i.e. silt and clay) sediment yield (627.5 t km^{-2} $year^{-1}$) has decreased to 42% of the former value estimated at the end of the Little Ice Age (1868–1869) at 1090 t km^{-2} $year^{-1}$. In the 1960s (i.e. following the regulation), fine sediment yield has decreased to 91% of the former value. About the coarse sediment yield, it was estimated to be 87.5 t km^{-2} $year^{-1}$ in the 1950s; after the regulation, it has dropped to 42 t km^{-2} $year^{-1}$ (52% decrease) in the 1960s.

In conclusion, the fact that catchment sediment yield has decreased does not prove that this is the cause of incision of the Rhone River in its delta. In fact, channel incision occurs when available transport capacity is greater than the load supplied from upstream (Schumm, 1977; Starkel, 1983). Thus, to test the relation between transport capacity and channel incision, I used the available transport capacity values estimated in 4.2 (cf. supra) at bankfull discharge. Values show that in 1895, the Rhone River in its delta had the capacity to transport all the fine sediment yield coming from the catchment. During the 20th century, reinforcement of stream power and boundary shear stress increased the transport capacity of the Rhone River again. Therefore, the combination of decreased catchment sediment yield, increased stream power and boundary shear stress is the cause of channel incision of the Rhone River.

(5) Engineering works, such as catchment bank revetments, groynes, hydraulic deflectors and flood protection levees, were designed to stabilise the planform and to limit the extent of overbank flooding (Fig. 11). Between the 17th and the 19th centuries, most of the length of the Rhone River was confined within levees causing incision of the channel bed; thus, reducing the area of the floods has accelerated sedimentation rates on the proximal floodplain (i.e. inter-embankment floodplain zone). Since the completion of the levees at the end of the 19th century in the Rhone Delta, accretion of 1–3 m has been observed within the inter-embankment floodplain, increasing the local relief and unevenness between the inter-embankment floodplain and the surface outside the levees. Combined with channel incision and growth of the inter-embankment floodplain surface, reduced overbank flooding extent and greater concentration of flow within the channel zone by hydraulic deflectors and flood protection levees have increased the channel capacity, the specific stream power as well as the boundary shear stress to such an extent that flood waves have become progressively more powerful.

Therefore, instead of minimizing the flood hazard, the channelization led to an increase of the flood hazard and risks because, although rarer, the inundations have became more destructive to property (erosion of agricultural areas by floodplain stripping and crevassing, destroyed houses and alluvial forest, undermining of bridge piles and quays).

Additionally, the floodplain has become drier with the lowering of phreatic water table connected to the mean water level to the channel. Lowering of the phreatic water table has in turn favoured the salinization of the floodplain soils, reinforced by the rising of saline waters in connection with the salt wedge position gradually moving upstream the deltaic

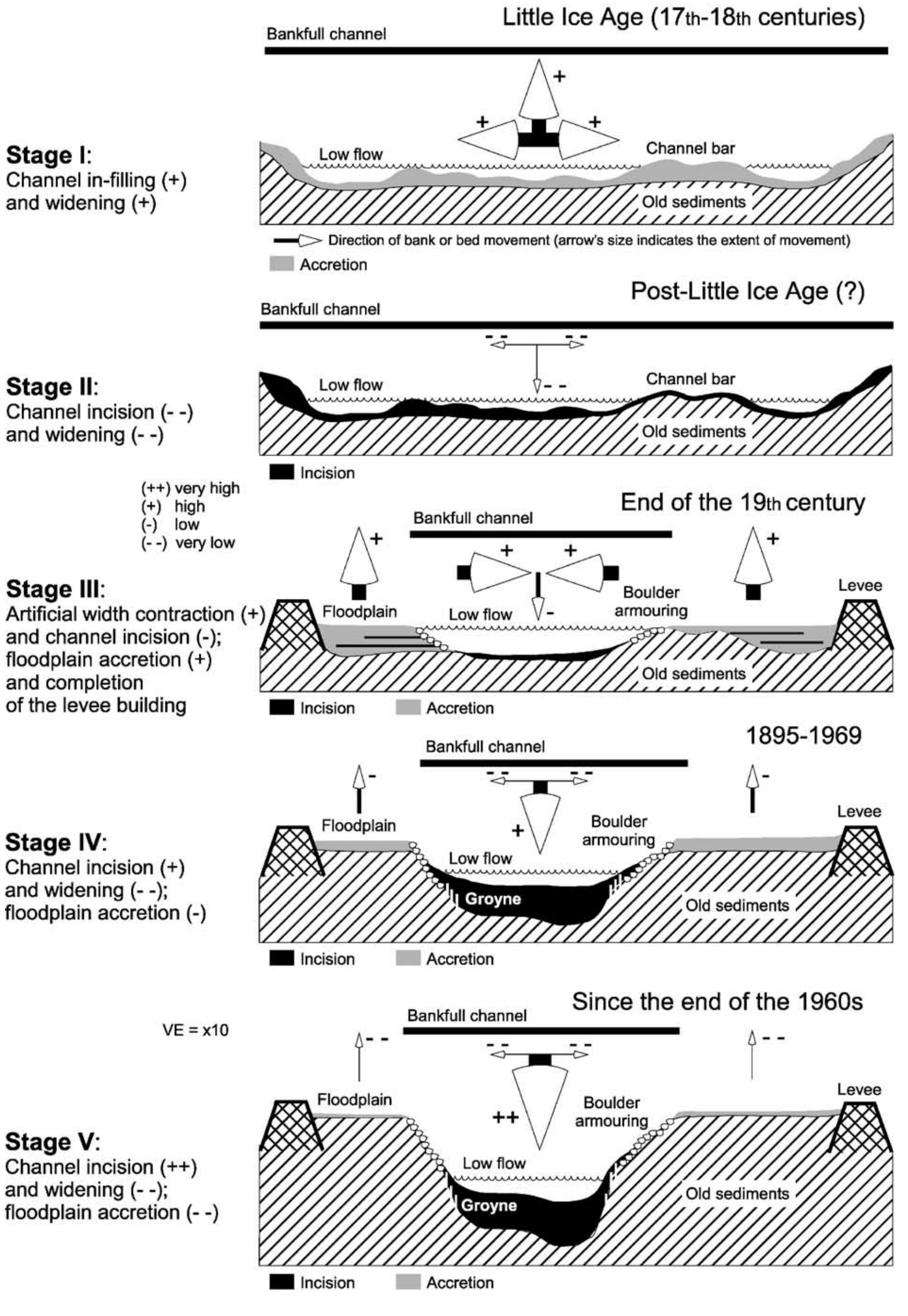


Fig. 11. Sequential changes of the Rhone channels in the delta since the Little Ice Age (17th–18th centuries). Artificial width contraction since the end of the 19th century induced major channel change, i.e. incision and floodplain accretion, which in turn created, by positive feedback, new conditions for severe flood hazards.

plain. Nowadays, the concentration of salt in surface waters represents a serious phreatic hazard in agricultural areas.

Moreover, most of the cross-section profiles of the channels were "re-designed" at the end of the 19th century. Re-design involved channel straightening that was completed at the beginning of the 20th century. Fig. 3 gives an idea of the engineering techniques used to channelize the Rhone River in its delta. Channel margins were artificially in-filled (1895–1897) and the thalweg of the new channel was generally dredged to fix the stream and to maintain a sufficient channel capacity.

To conclude, the three last groups of factors (i.e. construction of dams, reservoirs and flow diversions; in-channel sediment mining and dredging; engineering works), in contrast to the two first ones (i.e. reforestation of up-valley slopes; river water pumped out the delta for irrigation), should be considered as the main causes of channel incision in the Rhone Delta.

6. Discussion

In the context of decreasing flood frequency since the end of the Little Ice Age, human interventions largely influenced the channel changes which occurred during the 20th century in the Rhone Delta. Thus, although the flood frequency has decreased, it was interesting to evaluate the role played by the large flood events in terms of channel sediment balance; their role appeared modest in terms of long-term channel in-filling. More specifically, reduced sediment yields and increased stream powers have generated a morphological adjustment through incision of riverbeds that it is important to detail. Moreover, possible relation between the vertical adjustment of the Rhone channel and the sea-level change is discussed.

6.1. Channel incision, bank instability and destabilization of engineering structures

Fig. 12 illustrates how degradation of the channel bed increased bank heights along the Rhone River in its delta immediately after the artificial channel narrowing. In 1895 (i.e. just before channel narrowing), the mean bank height was 3.6 m in the upstream section of Petit Rhone River, whereas it was 4.7 m in 1995.

We can contrast the upstream section with the downstream section of the Rhone River in its delta in terms of bank response versus the channel incision. In the upstream section, the bank height is higher (2–7 m above low water) (Fig. 7B and C). Bank instability resulting from bed lowering is very common because the bank height exceeds critical bank height for mass failure in most cases. Bank revetments and roots of alluvial forest, made up of *Populus alba*, *Alnus glutinosa*, *Salix alba*, *Ulmus campestris*, *Quercus pubescens* and *Betula* sp., play an important role in reducing bank instability and erodibility. In the downstream section, incision of the channel bed has not provided a decrease of the water level, which is controlled by the Mediterranean base level. The bank height is lower (0.2–2 m above low water), and the density of woody riparian vegetation is lower as well because of the presence of the salt wedge in the floodplain (Fig. 7D and E). Halophytes, particularly *Tamarix*, become predominant. In conclusion,

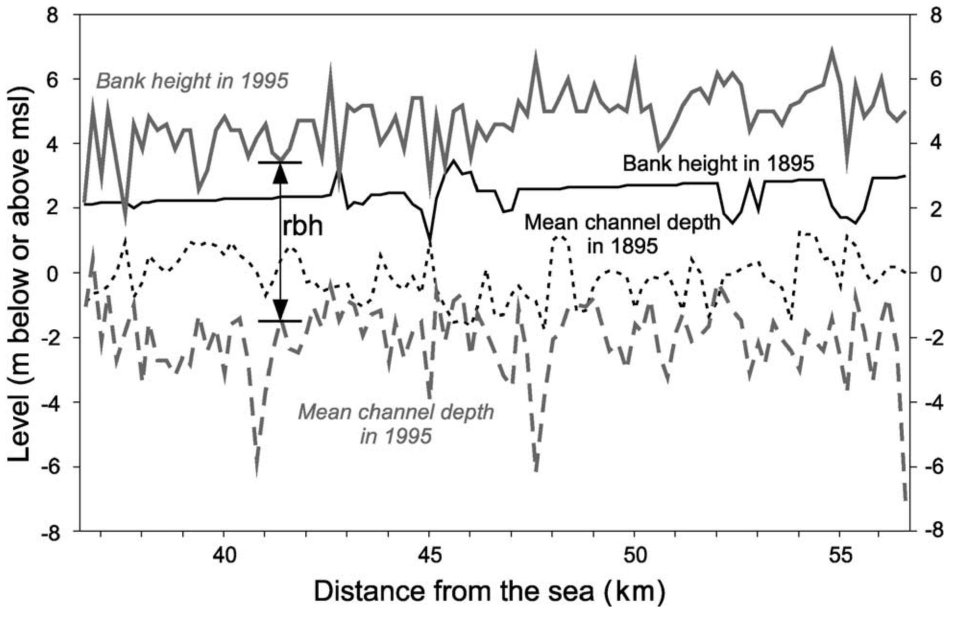


Fig. 12. Evolution of bank heights and mean channel depths of the Petit Rhone River between 1895 and 1995. Note that the relative bank height (rbh) increase in elevation is due to the joint effect of both bank accretion (partially artificial) and channel incision.

bank instability resulting from bed lowering is very common in the meanders near the river-mouth.

Engineering works were used to reduce bank instability and rapid widening in the Rhone Delta just after channel narrowing (Fig. 7F, G and H). Various types of protection (flood wall, boulder armouring) have been particularly useful to protect the existing riverbanks from erosion and in particular to limit fluvial hazards, for example, near to the several quays (Arles, Port-Saint-Louis, Saintes-Maries) and bridges (Arles, Fourques, Augery, Saint-Gilles, Sylvéréal).

6.2. Increasing stream power, channel incision and subdeltas growth

During the 20th century, sediment transport to the coastal system was facilitated by the Rhone's channelization from upstream to the mouth. Increasing specific stream power and sediment yield coming from incised river channels in the Lower Rhone Valley, downstream of the last dams in particular, could have maintained substantial sediment supply for the Rhone subdeltas. Evidence of both lateral and vertical extents of the modern subdeltas has been collected by combining sounding, seismic-reflexion profiles and sedimentological data (SOGREAH, 1984; PNOC, 1993). During the present century, the Grand Rhone subdelta was rapidly prograding (8–25 m year^{-1} since 1934) and aggrading (30–50 cm year^{-1} since 1895). Thus, an increase in specific stream power resulted in most of the sediment eroded downstream of the dams making its way down to the subdelta front (no-mobility zone), thus increasing a sedimentary deficit in the coastline.

6.3. Minor control of channel incision by the sea-level change in the medium term (10–100 years)

Schumm (1993) argued that the question of the impact of sea-level change on the fluvial system does not have a ready answer. Fisk (1944) and Lane (1955) concluded that the effect of sea-level change can be very significant on the vertical position of the riverbed. In contrast to these authors, Leopold and Bull (1979), Saucier (1981) and Blum (1992) suggested that sea-level changes affect the vertical position of the channel bed only locally and to a minor extent. In fact, the adjustability of the riverbed depends not only on sea-level controls but also upon several other variables grouped as geological and geomorphological controls (Schumm, 1993).

In the Rhone Delta, incision of the riverbeds was synchronous with the relative Mediterranean level rise, estimated by Suanez et al. (1997) at 2 mm year^{-1} during the 20th century. I hypothesize that the relative sea-level rise has not been followed by alluvial in-filling in the Rhone Delta because:

(1) The magnitude and rate of base-level change to the 20th century scale were low and many adjustments of the fluvial system have occurred to render the impact of the base-level rise null and void.

(2) Anthropogenic factors, such as sediment yield reduction due to construction of 77 dams in the catchment, dredging and channelization of the Rhone River up to the mouth negated the impact of the base-level rise to generate a severe entrenchment in the thalweg of the Rhone channel. Rising base level was not responsible for lateral accretion which in the Rhone channel had predominantly a human cause.

Therefore, even if the impact of sea-level change cannot be ruled out, the change in channel pattern since the end of the Little Ice Age was mainly of climato-anthropogenic origin and did not require any rise in base level to force the river metamorphosis.

7. Conclusion

The recent history of the Rhone River in its delta provides a clear example of how hydroclimatic change combined with river engineering can induce channel narrowing and incision through changes to the flood flow regime, sediment supply and channel geometry. The geomorphological behaviour of the Rhone River in its delta has been strongly altered since the end of the Little Ice Age. The evolution of the channel can be summarized as follows.

(1) The shifting pattern of the Rhone River in its delta can be explained by different hydroclimatic and anthropogenic factors overlapping one another, but the human disturbances appear as responsible for major channel changes during the 20th century (Fig. 11). Analysis of cross-sections and longitudinal profiles has revealed, after artificial channel narrowing, a dramatic increase in channel incision, bankfull discharge, channel capacity, flow competence, specific stream power, boundary shear stress and transport

capacity. Incision of the channel bed, which affects both channels of the Rhone Delta, occurred in response to river management in the delta and the catchment, in association with the hydroclimatic change following the Little Ice Age. Degradation of the Rhone channel is concentrated along the thalweg of the channel. Vertical adjustments of the channel bed began in 1895. The rate of channel incision has increased since 1967–1969 due to engineering and management of the catchment and, in particular, construction of large dams. The sediment yield of the Rhone River in its delta was estimated to be 35×10^6 t year^{-1} during the first part of the 19th century. By the end of the 20th century, sediment load carried by the Rhone River at Arles has declined by a factor 4.7 to a value of 7.39×10^6 t year^{-1} (~ 78% decrease).

(2) Incision of the Rhone River in its delta is synchronous with that of the other streams in the catchment and, in particular, the Durance, Ardèche and Drôme (Landon and Piégay, 1994; Warner, 2000). This Mediterranean channel incision at the turn of the 20th century contrasts with the Northern Alps channel incision (Arve, Isère, Drac) which occurred later (post-1950).

(3) Incision of the Rhone channel is contrary with the relative sea-level rise which has increased by 2 mm year^{-1} during the 20th century. In the context of anthropogenically affected river systems, and to the medium term (10–100 year), the base-level position does not play any role in terms of channel vertical adjustment.

(4) The regional coastal fringe of the Rhone Delta has exhibited a chronic sedimentary deficit over several decades, in response to the decrease of Rhone sediment yield. In addition, the marked increase in specific stream power of the Rhone River during the 20th century has further exacerbated the coastal sediment deficit by exporting most of the fluvial sediment supply to the front delta of the Grand Rhone River (in particular) and to the offshore zone.

8. List of symbols

The following symbols are used in this paper

d	mean channel depth
d_b	bankfull mean channel depth
d_{lf}	mean channel depth at low flow
$d_{max\ (b)}$	bankfull maximum channel depth
$d_{max\ (lf)}$	maximum channel depth at low flow
n	Manning's resistance coefficient
p	channel sinuosity
A	cross-sectional area
C	channel capacity
C_b	bankfull channel capacity
C_{lf}	channel capacity at low flow
C_s	maximum grain size of the graded suspension
D_{50}	median bed material grain size (M)
D_{99}	maximum bed material grain size (C)
H_m	bank height

I_b	bedload transport rate per unit width
Q	discharge
Q_b	bankfull discharge
Q_{lf}	discharge at low flow
Q_s	sediment load
QR	mixed saltation and graded suspension
R	hydraulic radius
$R'S'$	mixed graded and uniform suspensions
S	gradient of the water energy surface
W	channel width
W_b	bankfull channel width
W_{lf}	channel width at low flow
g	acceleration due to gravity
ρ_s	density of sediment
ρ_w	density of water
$\tau_{0\ (b)}$	bankfull boundary shear stress
$\tau_{0\ (lf)}$	boundary shear stress at low flow
τ_0	boundary shear stress
ω	specific stream power
ω_b	bankfull specific stream power
ω_{lf}	specific stream power at low flow
ω_0	critical stream power

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