CONTRIBUTION TO THE STUDY OF COASTAL RIVERS AND ASSOCIATED PRODELTA'S TO SEDIMENT SUPPLY IN GULF OF LIONS (NW MEDITERRANEAN SEA)

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INTRODUCTION

On continental margins, in front of each river as well as lagoon mouths appears a preferential area of sediment accumulation under the wave storm base (Aloïsi & Monaco 1975, Monaco 1971, 1987, Pauc 2005). These deposition areas, commonly named prodeltas, are the subaquaeous extension of aerial deltas in the inner-shelf around 30 m water depth. They are composed of fine-grained sediments and concentrate organic material, as well as pollutants, pathogens and heavy metals of human origin (Roussiez et al. 2005). Prodeltas play an important role in the land-to-sea transfer of particulate matter, as secondary sources of particulate matter to the shelf. Thus, their evolution must be relevant for the management of coastal zones because they are good indicators of the quality of littoral environments.

In the Gulf of Lions, a river dominated continental shelf incised by canyons, sediment supplies are largely influenced by inputs from the Rhone River at the northeast, and by several mountainous coastal rivers with a torrential regime along the Languedoc-Roussillon coast (Fig. 1). The dispersal of riverborne sediments, mostly discharged during extreme flood events, is constrained in the littoral zone by the wind-driven coastal circulation, and form several prodeltas in the inner-shelf of the Gulf of Lions (Aloïsi & Monaco 1975). The remaining part of suspended sediments not trapped in prodeltas, as well as sediments resuspended during storm events are advected cyclonically along the shelf (Guillen et al. 2006, Ulset al. 2005).

Sedimentation on the Rhone prodelta has been intensively investigated (Miralles et al. 2005, Radakovitch et al. 1999). It has been shown that the Rhone prodelta is an important sink for sediment and particle-reactive elements and pollutants: a large amount of sediment which enters the coastal area is retained in the prodelta; the remaining part is resuspended by waves and advected seaward by currents (Lansard 2004). Occasionally, complete seasonal sedimentary sequences can be preserved in the prodelta area, revealing high variability of the sedimentary inputs throughout a year (Beaudouin et al. 2005). In contrast, the function of coastal rivers and their prodeltas along the Languedoc-Roussillon coast is poorly understood, particularly their capacity to trap riverborne sediments and associated pollutants. This study addresses several key questions regarding such systems: How much sediment are inputs by the small coastal rivers of the Languedoc-Roussillon? What are the sedimentological characteristics of the main prodeltas (Aude and Tet)? What are the sediment budgets of these prodeltas?

MATERIALS AND METHODS

Long-term river discharge time-series: The liquid discharge of the different rivers of the Gulf of Lions was compared using data from the French national data bank (HYDRO) for the last 30 years for the rivers of the Languedoc-Roussillon area (Tech, Têt, Agly, Aude, Orb, Herault, Lez and Vidourle). Their fluvial regime was compared with that of the Rhone River, estimated from the “Compagnie Nationale du Rhône” (CNR) databank.
Solid suspended fluxes for each river were estimated by using rating curves linking coupled data of instantaneous river discharge and corresponding suspended sediment concentration. Rating curves for the Agly, and Herault Rivers were taken from published works. Rating curves for the Tet and Rhone Rivers were updated with our measurements. New rating curves were derived for the Tech, Aude, Orb, Lez & Vidourle rivers using data collected by the “Réseau de bassin Rhône-Méditerranée et Corse” (RMC) databank and ourself (Table I). Equations were determined, with relatively good correlation coefficients. The significance of the Fisher test for linear relations, and the large number of measurements to estimate non-linear relations, allow

**Table I.** Rating curves between instantaneous river discharge ($Q_i$ [m$^3$s$^{-1}$]) or mean daily river discharge ($Q_{dm}$ [m$^3$s$^{-1}$]) and the concentration of suspended solids in suspension ($C$ [mg L$^{-1}$]) or mean daily suspended solid discharge ($Q_s$ [t day$^{-1}$]), obtained from a compilation of data extracted from various references and the data from this study. Determination coefficient ($r^2$), the number of measurements ($n$) and $p$-values associated to the Fisher test (confidence interval = 0.95) for linear relations are also shown.

<table>
<thead>
<tr>
<th>Rivers</th>
<th>Rating curve</th>
<th>References</th>
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<tbody>
<tr>
<td>Tech</td>
<td>$C = 1.2485Q_i + 6.0628$ ($r^2 = 0.61, n = 250, p &lt; 0.0001$)</td>
<td>RMC data bank</td>
</tr>
<tr>
<td>Tet</td>
<td>$\log C = 0.3866 \log Q_i^2 - 0.0846 \log Q_i + 1.011$ ($r^2 = 0.60, n = 1805$)</td>
<td>Serrat et al. (2001) + RMC data bank and POEM station measurements</td>
</tr>
<tr>
<td>Agly</td>
<td>$Q_s = 13.27Q_{dm}^{0.833}$ for $Q_{dm} &gt; 50$ m$^3$/s and $Q_s = 0.541Q_{dm}^{1.029}$ for $Q_{dm} &lt; 50$ m$^3$/s ($r^2 = 0.81, n = 195$)</td>
<td>Serrat (1999)</td>
</tr>
<tr>
<td>Aude</td>
<td>$\log C = 0.1666 \log Q_i^2 - 0.0872 \log Q_i + 1.42041$ ($r^2 = 0.30, n = 80$)</td>
<td>RMC data bank + unpublished data</td>
</tr>
<tr>
<td>Orb</td>
<td>$C = 0.0018Q_i^2 - 0.0228Q_i + 15.92$ ($r^2 = 0.50, n = 242$)</td>
<td>RMC data bank + unpublished data</td>
</tr>
<tr>
<td>Herault</td>
<td>$\log C = 1.9247 \log Q_i^2 - 4.3949 \log Q_i + 2.7407$ ($r^2 = 0.70, n = 38$)</td>
<td>ORME data bank (Ludwig, 2003)</td>
</tr>
<tr>
<td>Lez</td>
<td>$C = 1.9177Q_i + 8.0411$ ($r^2 = 0.41, n = 241, p &lt; 0.0001$)</td>
<td>RMC data bank</td>
</tr>
<tr>
<td>Vidourle</td>
<td>$\log C = 0.2443 \log Q_i^2 + 0.1827 \log Q_i + 0.6983$ ($r^2 = 0.57, n = 27$)</td>
<td>RMC data bank</td>
</tr>
<tr>
<td>Rhone</td>
<td>$\log C = 1.5006 \log Q_i^2 - 8.1858 \log Q_i + 12.416$ ($r^2 = 0.75, n = 521$)</td>
<td>Pont (1997) + RMC data bank</td>
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the use of these rating curves to approximate the annual export of total solids in suspension from all the rivers to the Gulf of Lions.

We grouped the different rivers by their geographical location from the south to the north of the gulf, and by hydrological regimes: the western rivers along the Roussillon coast (Tech, Tet, Agly) have catchment areas in the Pyrenees; the central rivers along the Languedoc coast (Aude, Orb, Hérault) have catchment areas between the Pyrenees and the Massif Central; the northern rivers (Léz & Vidourle) have catchment area between the Massif Central and the Alps.

**Sedimentological and radiochemical analysis:** Two 20 cm long sediment cores were collected at 28 m water depth with 4 cm of diameter perspex tube on the Tet and Aude prodeltas. The Tet prodelta core was sampled by scuba divers in July 28, 2004 at the POEM station. The Aude prodelta subcore was sampled in a box-core sampled in October 20, 2002 at MT28 site at 43°12’13”N / 03°16’48”E (Fig. 1). Subsamples of these cores at 1 cm intervals were used for grain size and radiochemical analyses. A Malvern-Mastersizer 2000 was used for the granulometric analysis. The radioculnide \(^{210}\)Pb (\(T_{1/2} = 22.3 \) years) was used to estimate secular sedimentation rates and quantify sediment budget on prodeltas (Sommerfield & Nittouer 1999). \(^{210}\)Pb activities were determined by counting the alpha emission of the granddaughter radionuclide \(^{210}\)Po extracted from sediment samples by complete acid digestion, according to the procedure described in Radakovich (1995). Activities of \(^{210}\)Pb measured and corrected are assumed to be equal to the activity of \(^{210}\)Pb. Excess \(^{210}\)Pb (\(^{210}\)Pb\(_e\)) activity was determined by subtracting a mean value of supported \(^{210}\)Pb from the total activity. The supported \(^{210}\)Pb activity was determined at the base of the down-core profile of \(^{210}\)Pb data. \(^{210}\)Pb geochronologies were developed using the Constant Rate of Supply model of Goldberg (1963). Sediment mass-accumulation rates (g cm\(^{-2}\) yr\(^{-1}\)) were calculated by least squares linear regression of the log for \(^{210}\)Pb\(_e\) activity \textit{versus} cumulative mass, which takes into account down-core variations in sediment density. Sediment accumulation rates (cm/yr) were determined also by normalizing the sediment profile to the density measured for each sediment sample.

**Mapping of prodeltas:** Smectite, a specific clay contained in fine sediments, was used to delimit the prodeltas expanse. Smectite content > 20% and > 40% were respectively used to delimit the Aude and Tet prodeltas. Maps of smectite content in surficial sediment of the Tet prodelta (Monaco 1975) and the Aude prodelta (Aloisì & Monaco 1975) were integrated and referenced geographically in a GIS software.

**Hydrodynamics:** Currents were measured with an Acoustic Doppler Profiler (ADCP 600kHz, RD Instruments) through the whole water column at 28 m depth at the station named POEM (“Plateforme d’Observation de l’Environnement Méditer-

<table>
<thead>
<tr>
<th>Rivers</th>
<th>Average, (min-max) daily water discharge (m(^3)/s)</th>
<th>Average annual water discharge (10(^6) m(^3)/yr)</th>
<th>Mean annual suspended solid flux (10(^6) t/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tech</td>
<td>9.55 (&lt; 1 - 625)</td>
<td>301.47</td>
<td>0.032 ± 0.006</td>
</tr>
<tr>
<td>Tet</td>
<td>10.82 (&lt; 1 - 471)</td>
<td>341.54</td>
<td>0.061 ± 0.018</td>
</tr>
<tr>
<td>Agly</td>
<td>6.13 (&lt; 1 - 1020)</td>
<td>193.44</td>
<td>0.098 ± 0.030</td>
</tr>
<tr>
<td>Aude</td>
<td>37.95 (&lt; 1 - 1300)</td>
<td>1197.61</td>
<td>0.194 ± 0.157</td>
</tr>
<tr>
<td>Orb</td>
<td>26.67 (1.05 - 1430)</td>
<td>841.64</td>
<td>0.110 ± 0.044</td>
</tr>
<tr>
<td>Hérault</td>
<td>40.61 (&lt; 1 - 1320)</td>
<td>1281.58</td>
<td>0.089 ± 0.028</td>
</tr>
<tr>
<td>Léz</td>
<td>2.17 (&lt; 1 - 239)</td>
<td>68.65</td>
<td>0.003 ± 0.001</td>
</tr>
<tr>
<td>Vidourle</td>
<td>6.83 (&lt; 1 - 783)</td>
<td>215.44</td>
<td>0.051 ± 0.016</td>
</tr>
<tr>
<td>Rhône</td>
<td>1768.59 (322 - 10861)</td>
<td>55812.43</td>
<td>10.147 ± 3.360</td>
</tr>
</tbody>
</table>

**Table II.** – Top, Statistics of the water and suspended sediment discharges of the rivers of the Gulf of Lions over the 1977-2004 period. Uncertainties on the solid discharge estimates were calculated from Ferguson 1987. The average annual water discharge of the coastal rivers is 4441 x 10\(^6\) m\(^3\)/yr and represents 8% of the average annual water discharge of the Rhône. The average annual suspended solid discharge of the coastal rivers is 0.637 x 10\(^6\) t/yr and represents about 6.3% of the average annual suspended discharge of the Rhône River. Bottom, Comparison of suspended sediment supply from some rivers and accumulation rates in the associated prodelta.

**RESULTS**

**The different regimes of the Gulf of Lions rivers**

Mean annual discharges of the Rhône River, averaged over the 1977-2004 period, give estimates of 5.38 x 10\(^10\) m\(^3\)/yr of water (compared to 5.39 x 10\(^10\) m\(^3\)/yr from Antonelli et al. (2004) over the period 1961-1996), and 10.14 x 10\(^6\) t/yr of fine-grained sediment (compared to 7.4 x10\(^6\) t/yr from Pont et al. (2002) over the period 1961-1996). The Rhône River discharge exceeds the mean annual discharge of freshwater and suspended sediment by all the coastal rivers by one order of magnitude (Table II top). Looking at the inter-annual variability of the mean annual water discharge, the Rhône River discharge varies by a factor of 3, while the discharge of the coastal rivers vary by a factor up to 10 (Fig. 2 top).

This inter-annual variability is even higher if the mean annual suspended solid discharge is considered. The
mean annual suspended solid flux of the Rhone River varies by a factor of 50, whilst the suspended solid flux of the northern rivers varies by a factor of 300, and up to 500 for the western rivers (Fig. 2 bottom). Such variability both in the liquid and the suspended solid discharge of the coastal rivers comes from the fact that these rivers are characterised by extreme flash-flood events during which the major part of the total annual amount of suspended sediment is introduced to the coastal area. For example, about 78% of the solid flux of the Tet River over the period 1978-1999 occurred in only 50 days (Serrat et al. 2001).

**Trapping of continental inputs to prodeltas**

The surface of the prodeltas of the Tet and the Aude rivers are well defined in the inner-shelf by accumulation of specific clay species issued from the drainage of their catchments. The Tet prodelta is defined by high content of smectite (> 40%), and its surface estimated to 11.9 km² is located slightly southward from the river mouth (Fig. 3). In the case of the Aude, the prodelta area (smectite content > 20%) was evaluated to 121.5 km² (Fig. 4). The surface of the Aude prodelta is larger than the Tet prodelta because it concentrates the inputs of the Aude, Orb and

Fig. 2. – Top, Variability of the annual liquid discharge of the rivers of the Gulf of Lions from 1977 to 2004. The western rivers include the Tech, Tet and Agly Rivers. The central rivers include the Aude, Orb and Hérault Rivers. The northern rivers include the Lez and Vidourle Rivers. Bottom, Variability of the annual suspended solid discharge of the rivers of the Gulf of Lions from 1977 to 2004.
Herault rivers.

The sedimentary logs and down-core profile of grain-size parameters and $^{210}\text{Pb}_\text{ex}$ activity of the cores sampled on the Aude and the Tet prodelta are shown on Fig. 5 and represent their sedimentary record in a secular time-scale. The top layer of both sediment cores was overlaid by a thin layer (~1 cm) of fluid mud composed of aggregates enriched in organic matter. Under this layer, the top 10 cm of both cores are composed of fine sands characterised by a constant level of $^{210}\text{Pb}_\text{ex}$ activity (20 - 25 Bq/kg for the Tet prodelta, and 30 - 35 Bq/kg for the Aude prodelta). Below this layer, an intermediate layer formed of silts is observed where $^{210}\text{Pb}_\text{ex}$ activity decreases down supported $^{210}\text{Pb}$ activity is reached at around 14 cm depth for the Tet prodelta (Fig. 5a), and below 20 cm depth for the Aude prodelta (Fig. 5b); the supported $^{210}\text{Pb}$ activity corresponding to the remnant $^{210}\text{Pb}$ activity in the sediment. The level at which the supported $^{210}\text{Pb}$ activity is reached defines the modern (secular age) sedimentary signal of the prodelta. In both cores, the bottom layer is composed of fine silts and clays and is characterised by low values of $^{210}\text{Pb}_\text{ex}$ activity (~0 Bq/kg). We thus observe coarsening-up modern sedimentary sequence both in the case of the Tet and Aude prodeltas.

Sedimentation rates estimated from down-core profiles of $^{210}\text{Pb}_\text{ex}$ activity for the Aude and Tet prodeltas give respective values of 0.12 and 0.07 cm/yr (respective mass accumulation rates of 0.15 and 0.10 g cm$^{-2}$ yr$^{-1}$).

DISCUSSION

Today sedimentation in prodeltas in the Gulf of Lions

Down-core profiles of grain-size parameters and $^{210}\text{Pb}_\text{ex}$ activity on the Tet and the Aude prodeltas reveal evidence of low but recent sedimentation. First, the fluffy layer observed at the top of the two cores is considered as a freshly deposited material as evidenced by the texture of the material composed of aggregates. Its formation could be due to the flocculation of riverborne suspended material located in the benthic nepheloid layer as observed on the continental shelf in the Gulf of Lions (Aloïsi et al. 1979, Durrieu de Madron & Panouse 1996), or it could correspond to a relict flood layer deposited during high river discharge. Indeed, the residence time of flood layer
is highly dependent upon near-bed current conditions, and is estimated to be less than 2 months on the Tet inner-shelf in relation with the recurrence of strong bottom currents induced during storm events (Courp & Monaco 1990). Then, constant $^{210}$Pb$_{xs}$ activities are observed in the top 10 cm sediment layer of both cores. The homogeneity of these values indicates that this layer has certainly been reworked by physical processes during storm events and/or bioturbation. Altimetric data on the Tet prodelta shows that erosion and deposition sequences of several centimeters during severe storm events promote the reworking of the top sediment layer (Guillèn et al. 2006). Grain-size parameters and constant values of $^{210}$Pb$_{xs}$ activity in the top 10 cm seem to indicate low sedimentation in these prodeltas, and $^{210}$Pb geochronology could then give more information concerning their capacity to trap sediment.

**Preliminary sediment budgets in prodeltas**

Fine-grained sediment supplies amount to $61 \times 10^6$ kg/yr for the Tet River and $402 \times 10^6$ kg/yr for the group composed of the Aude, Orb and Herault Rivers (Table II bottom). The annual sediment trapping rate $T$ (kg/yr) in prodelta was determined following the relation $T = S \times m$ where $S$ is the surface of the prodelta ($\text{km}^2$) and $m$ the maximum mass-accumulation rate (g cm$^{-2}$ /yr).

Fig. 4. – Detailed sedimentary map of the Aude prodelta redrawn from Aloisi & Monaco (1975). The Aude prodelta, common to the Aude, Orb and Herault Rivers, is delimited by smectite content > 20%. The black square represents the location of the core MT 28. Nearby prodeltas are linked with the ponds of Sigean and Ayrrole in the south and with the Thau lagoon in the north.

Fig. 5. – Sedimentary logs of cores sampled on the Tet and the Aude prodeltas and down-core profiles of grain-size parameters (% of particles > 63 µm) and $^{210}$Pb$_{xs}$ activity. Sedimentation rates in cm/yr are also shown. The limit of the reworked layer, with homogeneous $^{210}$Pb$_{xs}$ activities, corresponds to the sediment thickness that could be reworked by bottom currents.
Conclusions

The Rhone River is the main input of freshwater and sediment to the Gulf of Lions, but small coastal rivers along the Languedoc-Roussillon coast, characterised by a strong inter-annual variability, can discharge large amounts of sedimentary material to the inner-shelf in a few days. The liquid and suspended solid discharges of all the coastal rivers to the Gulf of Lions are 4441 x 10^6 m³/yr and 0.637 x 10^7 t/yr respectively and represent about 8 and 6.3% of the liquid and suspended solid discharges of the Rhone River.

The sedimentation rates on the Tet and the Aude prodeltas, representative of Roussillon (western) and Languedocian (central) rivers of the Gulf of Lions, are small: 0.07 and 0.12 cm/yr respectively, compared to the Rhone prodelta (~20 cm/yr). Sediment budgets suggest that: (i) 20% of the Tet River suspended solid discharge is trapped permanently in the Tet prodelta; and (ii) 45% of the suspended solid discharges of the Aude, Orb and Herault rivers are trapped permanently in the Aude prodelta. Most of the sediment introduced by coastal rivers in the inner-shelf of the Gulf of Lions mainly during flash-flood events thus bypasses the prodeltas and is advected southward.

Further studies are necessary to improve the estimation of the sediment supply of the coastal rivers to the Gulf of Lions. In particularly, estimation of sediment fluxes by the Aude River, the second larger river of the gulf in terms of sediment yield, could be improved, e.g. by increasing the

![Wind all seasons](Image)

Fig. 6. – (a) Rose diagrams of dominant winds measured at the weather station of Torrelles over the 2003-2005 period; and (b) Depth-averaged current direction at the POEM station measured over the 2003-2005 period. The units are frequency (0.25 = 25%).
measurements of SSCs during flood events. More sediment analysis (both grain-size and geochronological analysis) have to be realised on prodeltas of the Gulf of Lions in order to improve the estimation of sediment trapped and thus pollutants and pathogens in those areas as well as in front of lagoon mouths.

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REFERENCES


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