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Recent morphological evolution of a Mediterranean lagoon complex: the Palavasian lakes system (France)

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Abstract:
Lagoons of the Gulf of Lion, recognized for their natural heritage, are a key challenge for local economic activities. Their morphological evolution is an important issue in the current context of climate and environmental changes. Analysis of topo-bathymetric data of the Palavasian lakes system has helped to clarify its evolution since the XVIIIth century. Human impacts and contributions from the watershed appear to be the main drivers governing the evolution of the system. Over the past 40 years, the system shows a tendency to slowly fill at an accumulation rate of 1.3 mm/year. Differences between lagoons are highlighted according to local natural and anthropogenic forcings.

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1. Introduction

Lagoons are known to be environments in unstable equilibrium, and from a morphological view, they may tend towards filling or erosion and marine flooding (PHLEGER, 1969; NICHOLS, 1989; BIRD, 1994). These environments are subject to various sediment supplies from land, sea, endogenous production (biological activity) and wind (CASTAINGS, 2008). The diversity of these factors and variability of natural and anthropogenic forcings acting on such systems make their evolution difficult to determine. However, the morphology of the lagoons is a critical issue for the management of natural areas and for the future of human activities associated with them (fishing, shellfish farming, navigation, tourism …). The future of several lagoons was recently studied all over the world: Laguna Madre (MORTON *et al.*, 2000), Arcachon Bay (ALLARD *et al.*, 2009), Venice lagoon (MOLINAROLI *et al.*, 2009). Through the analysis of topographic and bathymetric data, we will try to identify the trends for a lagoon complex whose evolution is still poorly understood: the system of Palavasian's lakes located in the South of France (figure 1a).

2. Study area

The lagoons of the Gulf of Lion were formed during the Holocene period under the influence of local hydrodynamics and sea level changes (RAYNAL *et al.*, 2010). Since that time, they are a trap for sediments that accumulate (MARTIN, 1978; CATALIOTTI-VALDINA, 1978; DUBOUL-RAVAZET & MARTIN, 1981; BARUSSEAU *et al.*, 1992). The Palavasian's lagoon complex, located in the Northern Gulf of Lion, extends for about thirty kilometres (figure 1a). Originally, the system was a single lagoon also connected to the Thau lagoon in the West, as evidenced by the old maps (ANDREOSSY, 1669; CASSINI, 1778). It was fragmented by natural dynamics and human developments. The channelization of the Lez river toward the sea (XVIIth century) and the digging of the Rhone-Sete waterway (XVIIIth to XIXth century), have contributed significantly to this separation. The first part of this channel is visible in the map of Cassini (figure 1b). Today, the lagoon complex is composed of nine major lakes. Sediment supply to the lagoons is irregular and highly dependent on the Mediterranean climate variability. The flow of rivers is low or nonexistent during summer, the sediment transport is concentrated mainly in flash floods (BOURRIN *et al.*, 2006); yet little quantitative data are available on these small watersheds. Sediment supply can also be made by marine sedimentary flooding of the low points of the sand barrier beach during a storm causing the opening of temporary inlets (DEZILEAU *et al.*, 2010) or through artificial inlets that are kept open. The system has undergone significant urbanization over the last century, with the development of the city of Montpellier and the growth of seaside resorts, on the sand barrier during the 1970s (Frontignan-Plage, Palavas-les-Flots, Carnon, La Grande Motte).

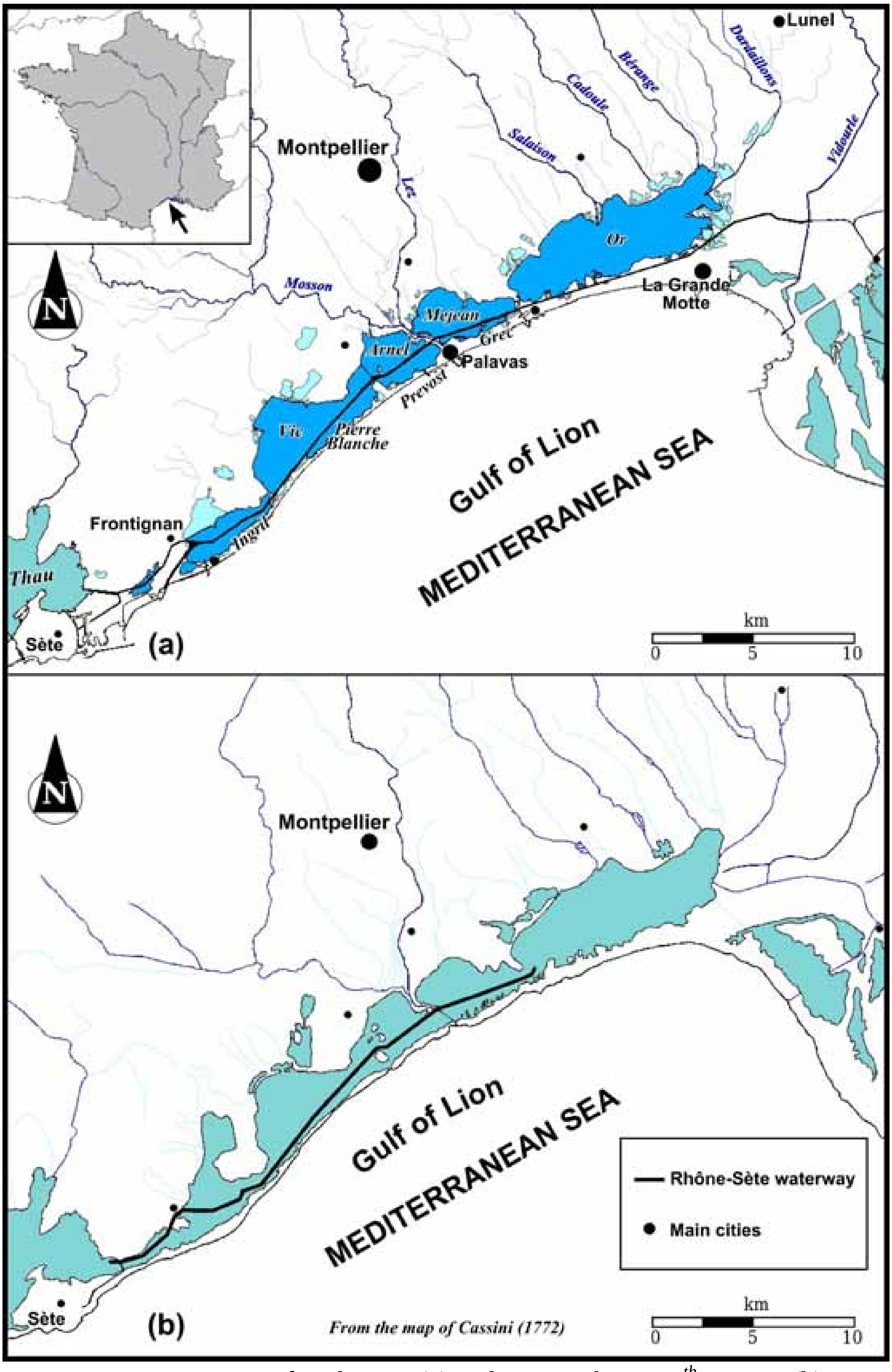

Figure 1. Location of study area (a) and state in the XVIII[th] century (b).

3. Material and methods

3.1 Data used and corrections

Two kinds of data were used for this study, topographic data of the coastline of lagoons and three sets of bathymetric data, as summarized in table 1. Contour line of the lagoons in 1772 was digitized from a Cassini map georeferenced locally on 200 stable points (mainly churches and persistent farmhouses), using QGIS software. The average error generally accepted for Cassini's maps is about 300 metres (EHESS/CNRS & BNF, 2004). This value is consistent with the average error of georeferenced control points, estimated at 284 metres. The outline and bathymetry of the lagoons for 1965 and 1985 datasets were digitized from paper maps of scale 1/10000 and a *GTCO CalComp* digitizing table. For 2005, the coastline used comes from the *BDTOPO* of the French National Geographic Institute (IGN).

Bathymetric data from 1965 consist of profiles of sounding points globally oriented north-south, and spaced 100 to 500 meters, depending on the lake sizes. The precision of the acquisition method used at that time is not known. The 1980s dataset includes only the lagoons of Pierre-Blanche (1980), Grec (1986), Or (1989) and Prevost (1991), their vertical accuracy is ±10 cm. The 2005 dataset consists of sounding profiles oriented perpendicularly to the axis of the Rhone-Sete waterway, spaced 100 to 200 metres, and closer data near the passes between the lagoons and the canal. These data were measured using a differential GPS device coupled to a single-beam sonar, with a vertical precision of ±4 cm (SMNLR, 2006).

Table 1. Topo-bathymetric data used

Date	***Source***	***Contour line***	***Bathymetry***
1772	*Cassini's map parts n°57 and 92 measured from 1770 to 1774*	*Whole area*	*Non available*
1965	*CNABRL Seashore development mission measured from 1964 to 1966*	*Whole area*	*Whole area*
1985	*SMNLR - measured from 1980 to 1991*	*Partial area*	*Partial area*
2005	*SMNLR - measured from 2004 to 2006*	*Whole area*	*Whole area*

All data were converted to the Lambert93 geographic coordinate system. The official IGN69 system is used as altimetric reference, 1965 dataset was converted from the old Lallemand datum. Moreover, to avoid the effects due to changes in sea level on the water level basis, data were corrected. The sea level rise during the last century is estimated between 1 and 4 mm/year (IPCC, 2007; CABANES *et al.*, 2001). The level in the Mediterranean sea appears to increase more slowly than in oceans (CALAFAT & GOMIS, 2009). However, it has spatial disparities with greater increase in the Gulf of

Lion than in the Provence coast (CAZENAVE *et al.*, 2002). In view of these studies, we have chosen to apply a correction based on an average sea level rise of 2 mm/year for old bathymetric data. The correction was calculated separately for each lagoon, based on the specific dates of the bathymetric charts.

3.2 <u>Evolution of lagoon area</u>

Coast lines of each lagoon were separated and were the subject of a surface calculation for dates 1772, 1965 and 2005. The areas were then compared to assess their evolution. Only the nine major lakes were considered in this study, salt marshes and minor water bodies (less than 100 ha) representing about 10% of the surface were not taken into account. They are in fact disconnected from the overall system, and field observations show that they are usually dry during summer. The uncertainty on the lagoon area was calculated from the precision of the original data for 2005 and from the georeferencing errors for 1772 and 1965 maps. In addition, for the 1772 dataset on areas with few control points, the surface of marshes bordering the lagoon was taken into account to increase the uncertainty value.

3.3 <u>Evolution of lagoon depth</u>

Bathymetric data were processed using the *ArcGIS* software and *Spatial Analyst* module. The sounding points were interpolated separately for each lagoon on a grid with a 50 × 50 metres resolution. This calculation is based on an inverse distance weighted algorithm (IDW), whose parameters were adjusted according to the density of data available for each date. The resulting raster files were compared. For this, the *Raster Calculator* tool was used by performing algebraic operations [2005-1965], [2005–1985] and [1985-1965]. The results allowed to differentiate areas of accumulation, stability and erosion. In order to take into account the high uncertainty of historical data, we chose a conservative approach (VAN DER WAL & PYE, 2003) representing as stable bathymetric variations less than ±25 cm.

4. Results and discussion

4.1 <u>Main evolution of the system</u>

The results on the evolution of lagoon areas (table 2 and figure 2) show a general trend towards the reduction of lagoon space. However, it is possible to distinguish two groups of lakes. Grec, Ingril, Pierre-Blanche and Prevost present a clear reduction of their water body surface. Or, Vic, Arnel and Mejean are more stable. The loss of area is faster in the recent period, with an average loss of 8.2 ha/year since 1965, against 4.8 ha/year over the previous period. The bathymetric changes (figures 3 and 4) show a general tendency to fill the system with a large proportion of stable areas related to the conservative approach adopted.

Table 2. Present surface of the lagoons and relative changes since 1772.

Lagoon	*Actual area (ha)*	*Evolution 1772-1965*	*Evolution 1965-2005*
Ingril	*534*	*-38 ± 12 %*	*-11 ± 3 %*
Vic	*1337*	*-5 ± 10 %*	*-1 ± 0,5 %*
Pierre-Blanche	*270*	*-17 ± 11 %*	*-11 ± 4 %*
Arnel	*445*	*-10 ± 10 %*	*+1 ± 0,5 %*
Prevost	*245*	*-8 ± 10 %*	*-9 ± 4 %*
Mejean	*727*	*-3 ± 10 %*	*0 ± 0,5 %*
Grec	*117*	*-39 ± 12 %*	*-33 ± 9 %*
Or	*3039*	*-6 ± 10 %*	*-4 ± 2 %*

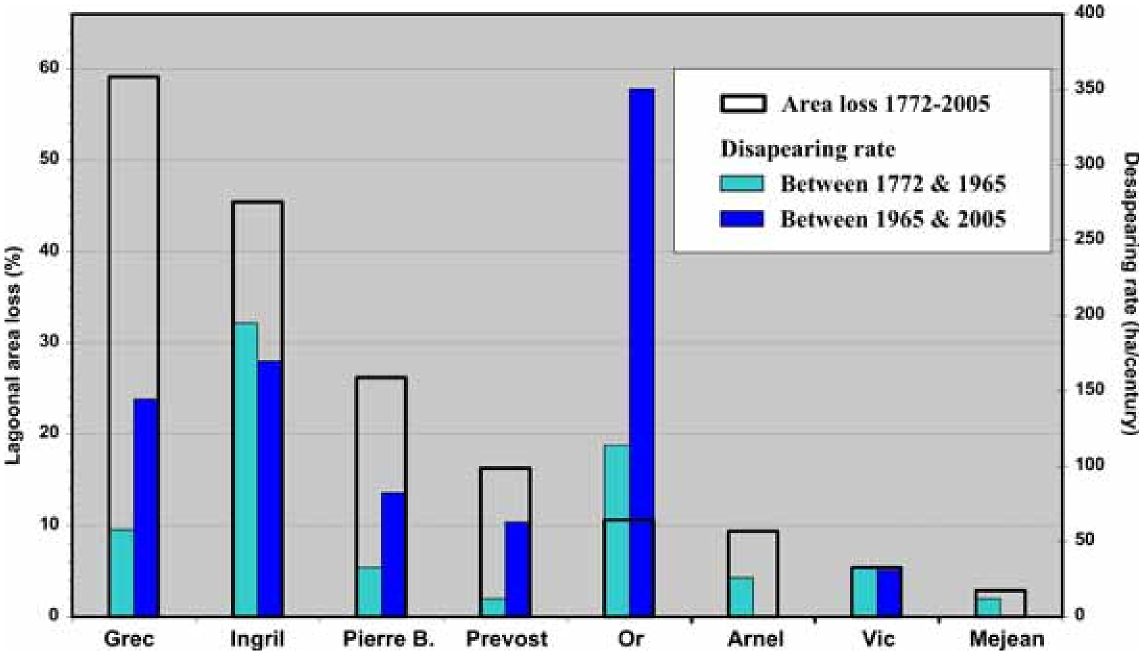

Figure 2. Area loss of Palavasian lagoons.

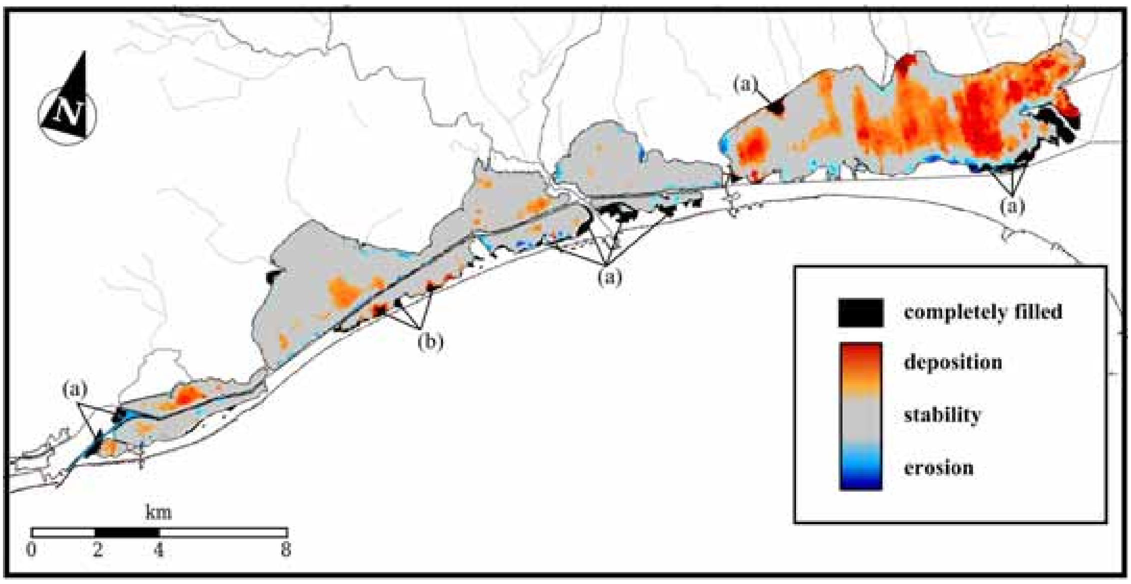

Figure 3. Evolution of Palavasian lagoons between 1965 and 2005
Completely filled areas come from anthropic impact (a) and natural process (b).

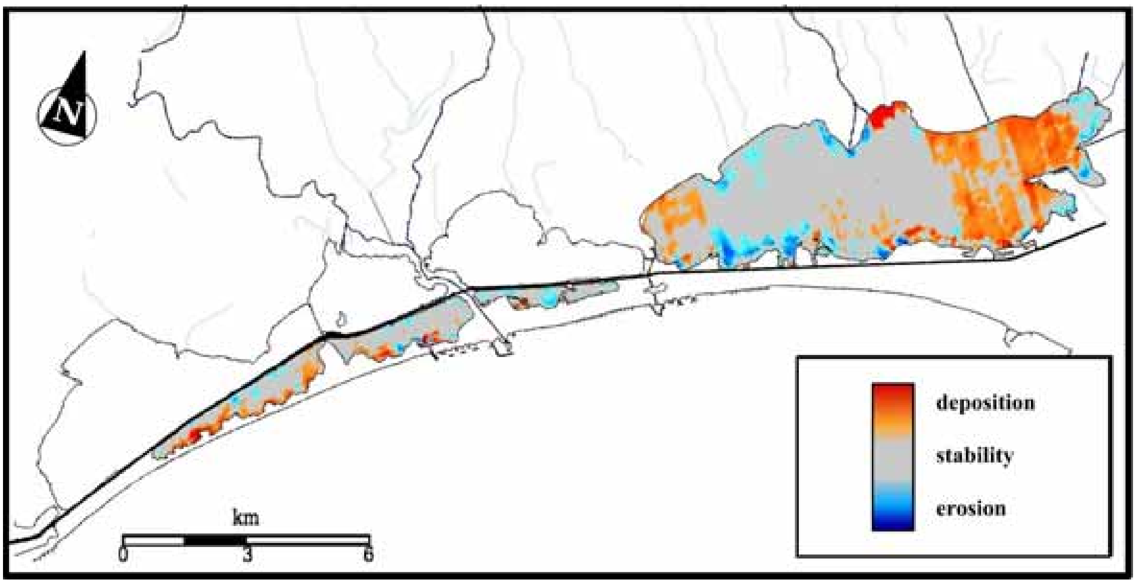

Figure 4. Bathymetric evolution of Palavasian lagoons between 1985 and 2005.

4.2 <u>Interpretation of surface changes</u>

A look at present land use identifies anthropogenic causes as the source of most of the completely filled areas during the recent period (Figure 3). On the Ingril lagoon, changes are old and began centuries ago with the separation of the Frontignan salt pans. The filling has continued with the development of Sete harbour and linked industries in the early XXth century, the construction of a tourist resort (1970s) and the digging of a new channel for the Rhone-Sete waterway (1980s).

Prevost and Grec lagoons were directly affected by urban development and tourism in the coastal area throughout the XXth century, and especially since the 1970s.

The Pierre-Blanche lagoon also has had a faster filling over the recent period. However, it is likely due to natural sedimentary fans associated with marine dynamics during extreme climatic events. This process is probably enhanced by various factors: the weakening of sand dunes due to high summer use, the fact that there is no beach protection in contrast to adjacent areas, and the sea level rise.

Given its large size, the Or lagoon has a relatively limited area loss. However, its evolution is one of the fastest (figure 2). It was initially filled by the sedimentary progradation of rivers. During the last half century, the filling has accelerated due to human actions, including expansion of the Montpellier-Frejorgues airport in the northern part and the development of hydraulic connections with the Rhone-Sete waterway in the south.

The area for the lagoons of Vic, Arnel and Mejean changed little over the period considered. The channelization of the Lez river towards the sea (XVIIth century) has certainly slowed the filling by diverting sediment supply.

4.3 Interpretation of bathymetric changes

Within the lagoons, the main deposit area is located in the eastern part of the Or lagoon. This part focuses many inputs from rivers (Cadoule, Berange, Dardaillons, various canals including connections with the Vidourle). Other areas of large deposits are located in the lagoons of Arnel, Vic, Pierre-Blanche and Ingril. For Arnel lake, the deposits are probably related to the flood inputs from the Mosson and Lez rivers. In the Vic lagoon, deposits are concentrated in the deepest areas in the centre of the lagoon. This preferential accumulation can be explained by a lower reworking of sediment by waves. In the case of the Pierre-Blanche lagoon, sediment accumulations are located mainly in the continuity of areas completely filled by storm wash-over fans. Those deposits are a factor of filling also recognized in earlier times for this lagoon (SABATIER, 2009). For the Ingril lagoon, the large number of communications with the Rhone-Sete canal (six passes compared with one to three for other lakes of the system) could be a source for the deposits observed. Prevost lagoon shows reduced accumulation areas located next to the external inputs: connections with Rhone-Sete waterway, small canal of Palavas and the inlet. Accumulation for this lagoon is surely underestimated because dredgings were performed to pull off sand in the inlet and its surroundings. Finally, the Grec and Mejean lagoons show almost no deposition areas.

Eroding areas are located on the edges of the lakes. The low water depth allows here a greater resuspension of sediment during strong winds events. Dredging may also have contributed to this evolution. Over the study period, dredging has been performed to keep functional passes between lagoons and the Rhone-Sete canal, into inlets and in the Prevost lagoon.

A noticeable point is the named "Pointe du Salaison" located in the Or lagoon (figure 5). As a result of the construction of a new drainage channel for floods, the former river bed is now experiencing erosion and an accumulation area appeared at the mouth of the new channel.

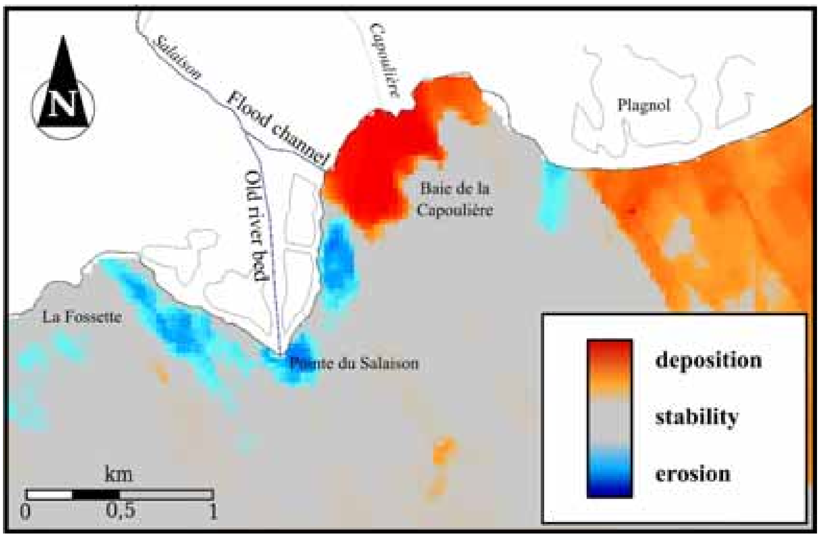

Figure 5. Recent evolution at the "pointe du Salaison" (Or lagoon).

4.4 Quantitative aspects

Although uncertainties on old bathymetric charts are important, the quantitative examination of changes can be useful to give an idea of the evolutionary speed into the lagoon system. Average rates of depth change and annual accumulated volumes were estimated excluding artificially filled areas. The results for each lagoon are presented in table 3. Lagoons of Ingril, Pierre-Blanche, Arnel, Mejean and Or have a slow filling trend. Lagoons of Vic and Prevost are globally stable over the study period which is short in relation to the processes involved. The Grec lagoon is the only one showing a tendency to erosion. It is also the most impacted by land reclamation (figures 2 et 3). This erosion trend may be explained by the materials removed to be used in filled areas.

Where intermediate data are available, a good agreement is observed in sedimentation rates except for the Or lagoon. A much higher sedimentation rate is estimated in the ancient period. Considering the important difference with the other lagoons, it is likely that an error in the acquisition of the data for this lake is at the origin of the phenomenon. For Pierre-Blanche lagoon, the results are consistent with the geochronological data available, 2.7 ± 0.2 mm/year (SABATIER *et al.*, 2010). There is no data for other lagoons in the system.

The average trend for the whole Palavasian lagoon complex gives a sedimentation rate of 1.3 ± 4 mm/year, equivalent of a net accumulation of about 93,000 m^3/year. Based on the average depth of the lagoon system, and assuming the stability of present forcings, we can suppose there would be a total filling of Palavasian lagoon in about 500 years.

Table 3. Sedimentary evolution of Palavasian lagoon (negative erosion).

Lagoon	***1965-1985 (mm/yr)***	***1985-2005 (mm/yr)***	***1965-2005 (mm/yr)***	***volume (m^3/yr)***
Ingril	-	-	*1,9 ± 5*	*9587*
Vic	-	-	*0,2 ± 5*	*11912*
Pierre-Bl.	*3,3 ± 6*	*2,8 ± 2*	*2,8 ± 5*	*7760*
Arnel	-	-	*2,0 ± 5*	*7065*
Prevost	*0,6 ± 6*	*-0,5 ± 2*	*0,0 ± 5*	*365*
Mejean	-	-	*1,1 ± 5*	*3289*
Grec	*0,0 ± 6*	*-2,5 ± 2*	*-1 ± 5*	*-913*
Or	*10 ± 6*	*1,8 ± 2*	*7,2 ± 5*	*54255*

5. Conclusions

This analysis of topographic and bathymetric data has enabled an assessment of the recent evolution of the Palavasian lagoon system. A general trend towards a reduction of the lagoon area is observed. The global bathymetric evolution is slow and includes distinct patterns according to the different lakes.

Human's actions appear as an important factor of this evolution; it is responsible for more than 2/3 of the completely filled areas during the past 40 years. This can occur directly by land reclamation. It can also be indirectly impacts changing the system dynamics like river channelization and beach protection. The distribution of deposition areas suggests a significant contribution of inputs from the watershed in the filling process. An active marine dynamics is also involved in the filling of Pierre-Blanche lagoon, a sector where the coast is not artificialized unlike the rest of the lagoon complex. The high uncertainty in the old bathymetric data and the one concerning sea level rise prevents making a reliable estimation of the future evolution of the system from these results. A more accurate monitoring of the lagoon dynamics and external inputs (watershed and sea) is necessary to go further.

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