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7

Geoarchaeology of ancient harbours in lagoonal contexts: an introduction

Christophe Morhange, Nick Marriner, Guénaëlle Bony, Clément Flaux, Mattieu Giaime and Mourad Kouka

Ancient harbours provide insights into landscape changes and the evolution of ancient maritime societies.[1] Sediments transported by rivers, run-off and the sea have been trapped in harbour basins over several millennia, creating rich sedimentary archives. These archives allow ancient palaeo-environments and processes to be reconstructed and provide insights into both millennial-scale changes and high-energy events such as storms and floods.

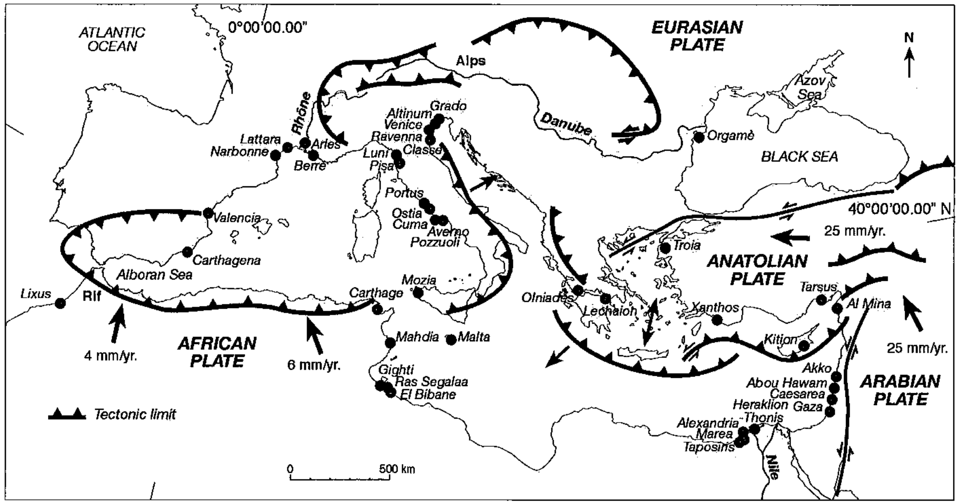
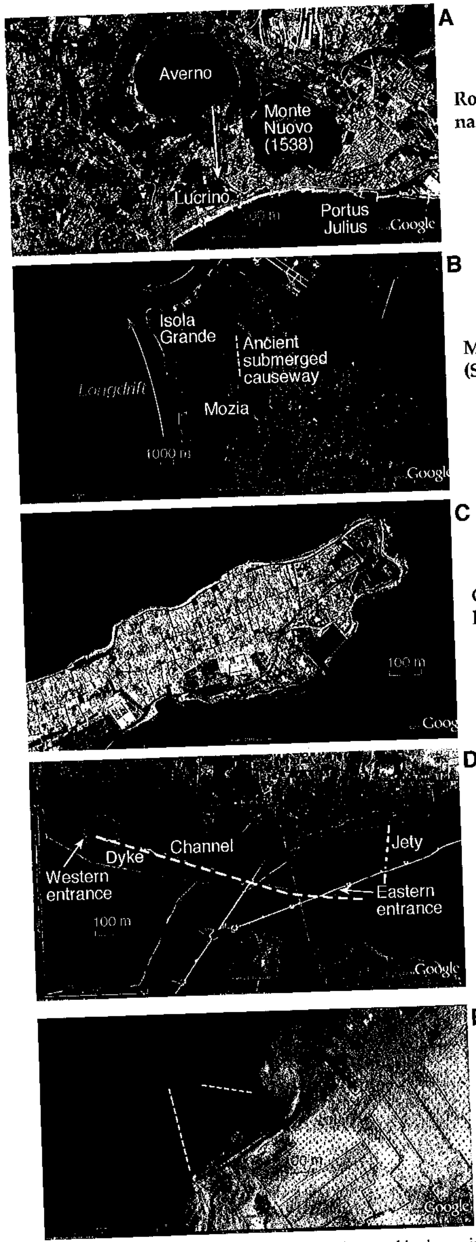


Fig. 1. Lagoonal harbours and lagoons cited in the text (authors).

At millennial timescales, two factors affect shorelines: (a) relative sea-level rise;[2] and (b) progradation driven by the sediment supplied by rivers.[3] Coastal progradation and infilled inlets have caused rapid sedimentation inside harbour basins, particularly in lagoonal contexts, such as the ancient landlocked harbours of the Kuban delta (Taman peninsula, Russia)[4] and the Acheloos delta.[5] Because paralic environments[6] are characterized by unique geomorphological and ecological traits,[7] four main agents have influenced the management and long-lasting sustainability of lagoonal harbours (fig. 1):

1 Marriner and Morhange 2007.
2 It has been decelerating for the last 7000 years at least: Stewart and Morhange 2009.
3 Stanley and Warne 1994.
4 Kelterbaum *et al.* 2011.
5 Greece: Vött *et al.* 2007.
6 Areas of paralic sedimentation (from the Greek *paralia*, meaning seacoast) denote intercalated marine and continental deposits and environments found on the landward side of a coast. These include alluvial, lagoonal and littoral environments.
7 Kjerfve and Magill 1989; Guelorget and Pertuisot 1983.



Roman harbour of Averno volcano, naturally protected basin (Italy).

Marsala lagoon (Sicily, Italy).

Cothon of Mahdia (Tunisia), harbour basin carved in substratum.

Mariut lagoon (Egypt), ancient harbour of Taposiris Magna, dredging channel and artificial dyke.

Roman harbour of Ras Segala (Bou Ghrara, Tunisia), elongated moles.

Fig. 2, A-E. Geomorphological diversity of lagoonal harbours in the Mediterranean (images from Google Earth).

1. The geological context

This relates to the difference between lagoons on clastic coasts[8] and lagoons on rocky coasts. Lagoons are a typical feature of deltaic environments, where hydro-sedimentary processes and fluvial and marine dynamics generate natural coves. Rivers build lateral embankments that create marshy depressions, whereas littoral drift leads to the accretion of sand spits and barriers that shelter lagoons on their leeward side. Sediment transfer plays a key rôle in the evolution of the coastline and coastal inlets. Lagoons in delta environments protected by sand spits are unstable coastal systems. By contrast, rocky lagoons are far more stable, such as the lagoon formed in the Averno caldera (Italy), on the volcanic substratum of the Phlegraean Fields.[9] There are also mixed lagoons, situated around both rocky and clastic coastal features, such as the Maryut lagoon on the NW margin of the Nile delta; the morphology of this lagoon is affected by Pleistocene aeolianites on its W side, while its E side is affected by the Canopic branch of the Nile (fig. 3).[10]

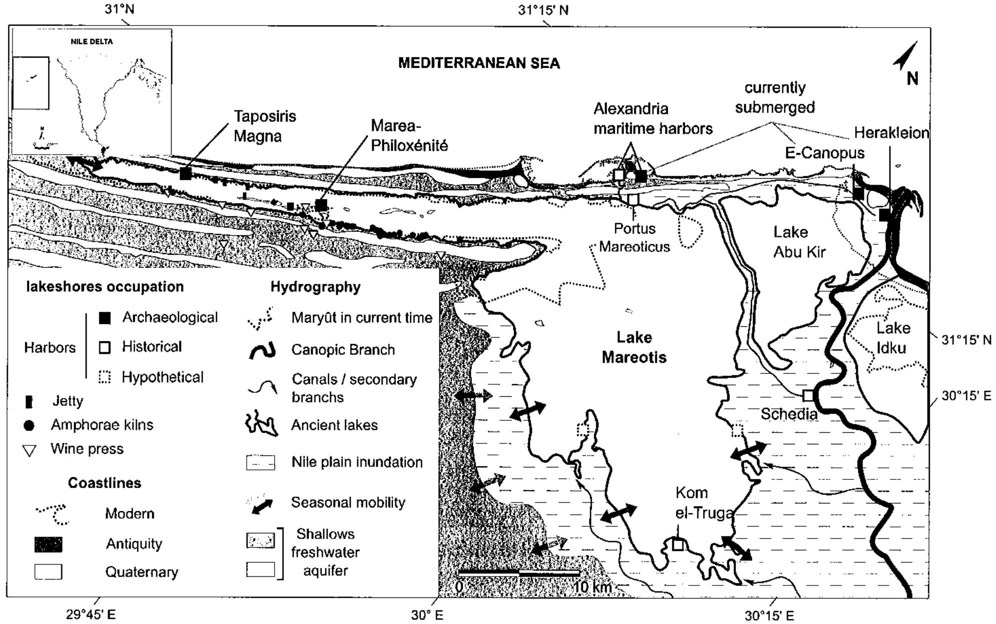


Fig. 3. Hydro-geomorphological map of the NW Nile delta during antiquity. The wind rose is the result of measurements undertaken between 2000 and 2008 (after Flaux *et al.* 2012).

Different geomorphological contexts have created lagoons of various sizes, volumes and depths, characteristics that determine the importance of the associated harbour city. A harbour city's potential to develop and survive was determined by the initial volume of the basin (e.g., the accommodation space) and the sediment budget causing the lagoon to be infilled over time. The ratio between the watershed area and the lagoon's volume explains the geomorphological

8 That is, displaying the accumulation of transported sediment (such as mud, silt, sand or pebbles).
9 This lagoon served as a Roman military harbour (fig. 2, A).
10 Flaux *et al.* 2012.

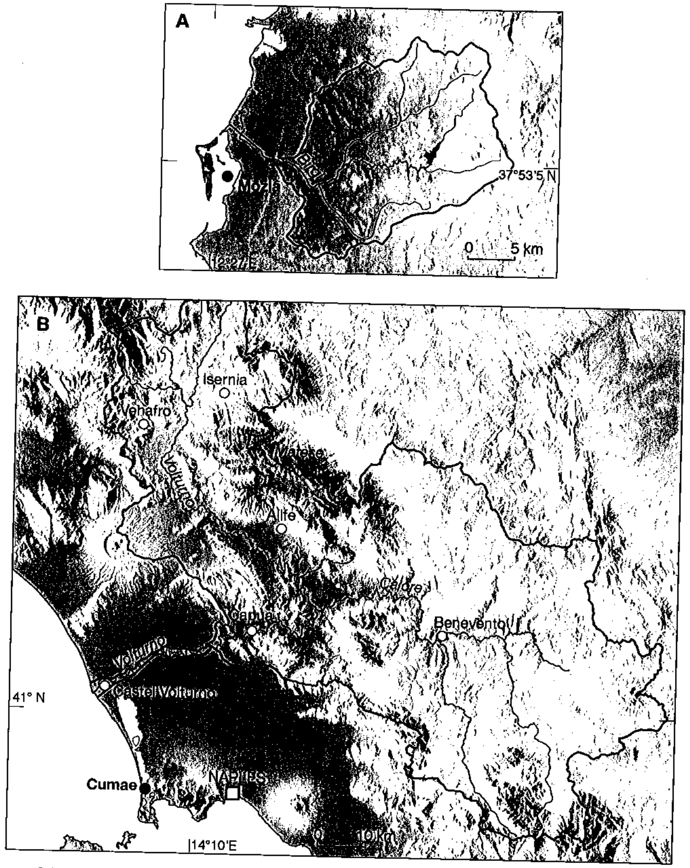


Fig. 4. Areas of the catchments of the Birgi (A) and Volturno (B) rivers, with the locations of the lagoonal harbours of Mozia and Cumes.

evolution of harbours. For instance, the harbour of Cumes-Licola on the downdrift side of the Volturno had a watershed of *c.*5560 km^2 and silted up rapidly. By contrast, the very large lagoon of Marsala (still an active lagoon system) surrounds the islet of Mozia, being located downdrift from the Birgi river, and has a much smaller watershed with a surface area of just *c.*350 km^2 (figs. 4, A-B). It was advantageous for ancient societies to settle around large lagoons, such as the Phoenician colony of Mozia, founded during the 8th c. B.C. inside a lagoon system protected by the coastal spit of Isola Grande that acted as a natural breakwater (fig. 2, B).[11]

2. Proximity to river outlets and sediment budgets

Lagoons act as sediment sinks for the surrounding watersheds during floods. The closer the sediment source (i.e., the river outlet), the faster the rate of silting. Conversely, river flow flushes

11 Basso *et al.* 2008.

lagoon systems and, in combination with the daily tidal cycle, keeps the inlets open and navigable. Three types of lagoonal harbour morphology can be identified:

(a) Distal lagoonal harbours, situated far from the river outlet, such as Mozia and Cumes (figs. 4, A-B).

(b) Artificial harbours in proximity to a fluvial outlet, such as the basin and channels of Portus which necessitated the development of massive infrastructure, particularly dredging for the port's foundations, and costly maintenance, all set in the context of the Roman empire and its desire to master the environment.[12]

(c) Estuarine lagoons that are exposed to both marine and fluvial hazards, such as at Ostia,[13] Carthago Nova,[14] Narbonne,[15] or along the Israeli coast (where A. Raban has hypothesized the use of estuarine and lagoonal environments as natural harbours during the Bronze Age).[16]

3. Meteo-marine dynamics and high-energy events

Meteo-marine dynamics are linked to the maritime conditions (waves, tides) and winds. Tidal influence is more pronounced where inlets are numerous and wide, for they reach a maximum speed inside inlets before they are attenuated by a lagoon's transport pathways. Tides drive a considerable exchange of water between a lagoon and the sea. The wind acts in an antithetical manner; when it blows with sufficient speed towards the land, it transports sand from the shoreline, supplying additional sediments that infill the basins. In regions of weak tide, such as the Mediterranean, the wind plays a major rôle in the movement of surface water.

Although lagoons constitute naturally protected environments, they are affected by high-energy events such as storms and tsunamis. Recent research has elucidated sediment facies and forms associated with extreme events, such as the onshore movement of sand tracts and the development of wash-over fans. Spits can migrate inland or be broken into several distinct structures, concomitant with the formation of new inlets or the widening of pre-existing ones. For lagoons, the effects of storms are normally restricted to the sea front.

Tsunami impacts have attracted considerable interest from some geo-archaeologists, particularly following the coastal disasters of Sumatra (2005) and Fukushima (2011).[17] Ancient harbour basins are sometimes considered to be good records for these past events, such as Caesarea Maritima (Israel)[18] or Lechaion (Greece).[19] Notwithstanding the geo-morphological impact of these high-energy events, these palaeo-catastrophes need to be set within wider geoarchaeological and palaeo-environmental contexts.

4. Human agency

Human agency can create lagoons dug into bedrock, such as the basin of Mahdia (Tunisia) (fig. 2, C);[20] in loose sediments as at the cothon harbour of Carthage,[21] or at Lechaion during the Iron Age,[22] and during the Roman period in vast artificial basins such as those of Claudius and Trajan at Portus.

Research has underestimated the systematic dredging of basins at the time of their construction, sometimes as early as the first millennium B.C.[23] The history of human occupation of watershed

12 Keay *et al.* 2005; Goiran *et al.* 2010; Salomon *et al.* 2014.
13 Goiran *et al.* 2014.
14 Martínez Andreu 2004.
15 Sanchez *et al.* 2014.
16 Raban 1987.
17 Marriner *et al.* 2010; Marriner and Morhange 2013; Morhange *et al.* 2013.
18 Reinhardt *et al.* 2006; Goodman-Tchernov *et al.* 2009.
19 Hadler *et al.* 2013.
20 Carayon 2005.
21 Gifford *et al.* 1992.
22 Morhange *et al.* 2012; Mourtzas *et al.* 2013.
23 Marriner and Morhange 2006; Morhange and Marriner 2010.

areas can also explain modifications in sediment loads. V. Maselli and F. Trincardi, for instance, have researched the relationships between the progradation of Mediterranean deltaic lobes and human settlement on the Ebro, Rhône, Po and Danube during the Roman period.[24]

Having listed forcing agents, we underline 5 different types of lagoonal harbour contexts during antiquity and discuss both their capabilities and constraints. The geo-morphological evolution of lagoons has invariably resulted in their disappearance due to silting or submersion.

Type 1: Artificial basins

In simple terms, one can differentiate basins dug into bedrock from those excavated by dredging loose coastal sediments. The term 'cothon' is used to describe an artificially protected basin, although this name is associated only with the Punic harbour of Carthage.[25] Archaeologists define a cothon as an artificially dug basin with access to the open sea via a channel. The harbour basin of Carthage was built on a clastic coast that has been prograding for thousands of years; it was mainly composed of two internal basins dug into a natural lagoon.[26] The rectangular ("merchant") harbour is dated to the end of the 4th to 3rd c. B.C.,[27] while the circular ("military"} harbour was developed at the end of the 2nd c. B.C. At Mahdia (fig. 2, C), the harbour basin comprises a rectangular basin, cut into calcareous sandstone and linked to the sea by two channels. The structure has been dated to the Fatimid period (10th c. B.C.).[28] Fishermen still anchor their boats inside the basin. At Taposiris Magna (Maryut lagoon), the Roman harbour included a dam and an artificially dug access channel that was 1.7 km long (fig. 2, D).[29]

These examples illustrate that maintaining the water column (i.e., the draught depth) and accessibility of a harbour system were the two prerequisites to its longevity, which cannot be ensured without difficulty. The costs involved in building and maintaining such harbours explains why they are rare compared to the majority of other harbour systems that employed the natural potentialities of lagoons.

Type 2: Silted lagoonal harbours on deltaic margins

This is the most frequently encountered and best-described type of harbour because the geomorphological evolution of lagoons led in most instances to their silting up (due to sea-level stabilization and a significant supply of sediment at base level) during the historical period.[30] For examples see the Aegean coasts[31] and the harbours of Lattara (Languedoc),[32] Luni on the Magra delta,[33] Xanthos,[34] and Tell Akko.[35] In every case, archaeological analyses have elucidated a regressive sediment sequence revealing the transition from a marine bay to a confined paralic swamp.

Type 3: Lagoonal deltaic harbours that are still in existence today

Some lagoonal harbours still exist today and are sailable, such as the ancient harbour of Orgame (Romania), connected to the largest lagoonal system in the Danube delta,[36] generated by the

24 Maselli and Trincardi 2013.
25 Carayon 2008.
26 Hurst, Paskoff and Rakob 1985.
27 Stager 1992.
28 Valérian 2006.
29 Boussac and El-Amouri 2010.
30 Anthony 2009.
31 Kraft *et al.* 1977 and 1980.
32 Bagan *et al.* 2010.
33 Bini *et al.* 2012.
34 Écochard *et al.* 2009.
35 Zviely *et al.* 2006.
36 Bony *et al.* 2013.

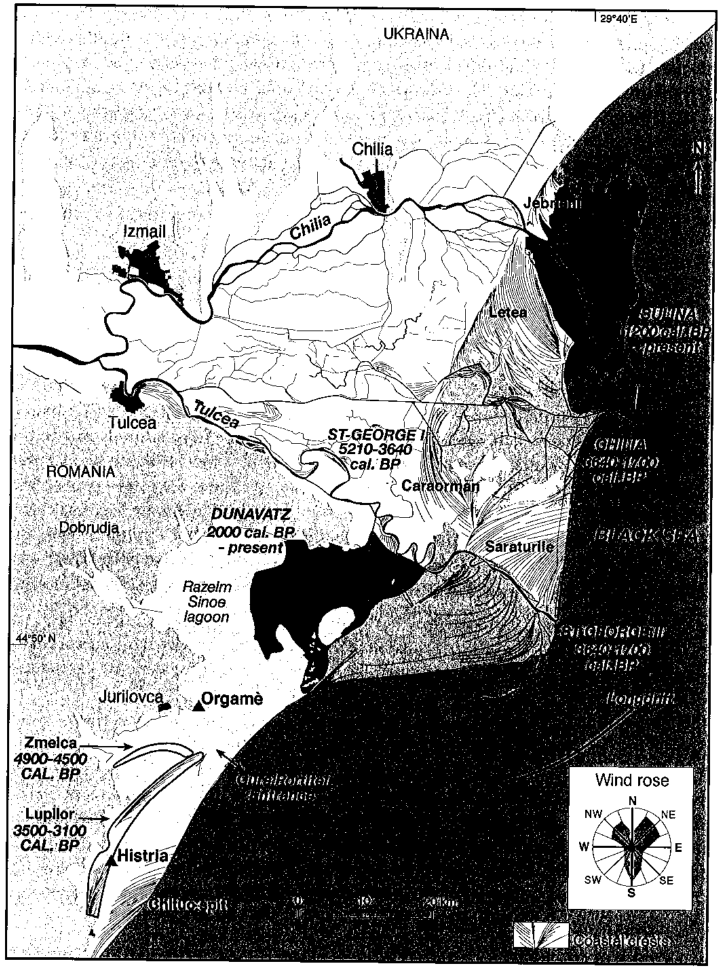


Fig. 5. Geomorphological map of the southern margin of the Danube delta and the lagoonal harbour of Orgame (Romania).

progradation of the St. George lobe (fig. 5).[37] Bio-sedimentological data provide a comprehensive picture of the transition from a marine bay to a lagoonal environment around 2000 B.C. From then onwards, this environment was characterised by fine-grained sedimentation and the development of lagoonal fauna resulting from the protection afforded by two successive sandspits. From 300 B.C. onwards, sediment supply from the Danube became more important as the endo-lagoonal lobe of the Dunavatz branch developed, transforming the mesohaline[38] environment into an oligohaline

37 Panin 2003.
38 Water whose salinity is between 3‰ and 18‰ (i.e., brackish). Such concentrations are typical of estuarine areas, where freshwater from fluvial systems mixes with seawater.

lagoon.[39] The Orgame coastline is characteristic of coastal environments on the distal margin of a delta. Its foundation is linked to the formation of long sandspits that provided coastal protection. This natural protection had developed long before the establishment of ancient harbours; it explains the foundation of many harbour systems that could be accessed via lagoonal inlets. At Orgame, the absence of artificial protection structures, such as breakwaters, attests to the natural low-energy context of the environment. The vastness and the relatively important depth of the lagoonal system, together with the stability of the inlet, explain the harbour's longevity. This was also the case with the harbour of Narbonne.[40]

Type 4: River-outlet harbours

From early antiquity onwards, estuaries provided seemingly good coastal shelters against storms, but over the centuries, scientists have realized that these environments were not as well protected as initially thought because they were exposed to other hazards. Estuarine harbours present three specific problems:

(a) River floods

These can cause considerable destruction, as at Pisa San Rossore. One of its ancient harbours was located in proximity to a palaeo-meander of the Arno river (the Serchio branch) 3 km from the coast.[41] Excavations unearthed 16 ancient vessels which appear to have sunk during high-energy floods. At Narbonne, the mapping of recent catastrophic floods shows that the flood limits of the river Aude closely mirror the banks of the Holocene lagoon and that they have probably affected harbour activities.[42] Renovations of the dykes at the mouth of the Aude were regularly carried out during the High Empire, revealing difficulties in channelizing the river's course.[43] This raises the question of the impact of palaeo-floods on harbour organisation and urban networks.[44]

(b) Coastal progradation and the closure of estuaries by coastal sandspits

Some research has suggested that estuarine harbours may have long lives despite a high supply of sediment. Examples include the tells of Wadi Gaza[45] and Troy,[46] the rocky harbours of Malta,[47] and some Ionian harbours.[48] All of these harbours are located in deep Holocene rias sometimes over tens of kilometres long.

At Ravenna, fluvial sediments have formed a shoreline characterized by series of sub-parallel dune systems (fig. 6 in colour on p. 107). Communication routes and habitats were established in the Roman lagoon, and it was possible to navigate on it. In the first part of the first millennium A.D., navigation was probably possible on the whole lagoon via tidal inlet channels, as is attested by Procopius of Caesarea in the 6th c. A.D. During the last 2000 years, a series of successive coastal dunes formed and enclosed the Roman and Byzantine harbours, making it very difficult to locate the ancient harbours where sediment supply was particularly high. One issue concerns the stabilization of inlets that were transformed into artificial access channels as early as the Roman period.

(3) Coastal erosion and deltaic subsidence

These two processes are closely related to relative sea-level rise, regardless of its cause. They result in a rapid regression of clastic shorelines, eroded by wave action.

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39 Water whose salinity is between 0.5‰ and 3‰.
40 Sanchez *et al.* 2014.
41 Benvenuti *et al.* 2006; Sarti *et al.* 2010.
42 Ambert 2000 and 2011.
43 Sanchez *et al.* 2014.
44 Allinne 2007; Arnaud-Fassetta *et al.* 2010; Leveau 2012.
45 Morhange *et al.* 2005.
46 Kraft *et al.* 1980 and 2003.
47 Marriner *et al.* 2012.
48 Brückner *et al.* 2005 and 2006; Kraft *et al.* 2007; Stock *et al.* 2014.

The outlet of the Canopic branch of the Nile has attracted research interest (including submarine surveys). The ancient harbour structures of Heraklion-Thonis[49] are now positioned 6 m below present sea level. J. D. Stanley *et al.* have ascribed this to earthquakes, tsunamis, and exceptional Nile floods.[50] These processes were associated with the subsidence of the deltaic sediments. In its final stage, the Canopic branch dried up, leading to the erosion of its outlet in a context of a reduced supply of sediment.

The outer harbour of Arles, located at the outlet of a former branch of the Rhône, near St. Ferreol, seems to have undergone a similar transformation. Structures lying at a depth of 6 to 9 m have been attributed to boathouses or warehouses. The outer harbour, dated to the 1st c. A.D., was situated on a deltaic lobe affording natural protection that was ideal for an anchorage.[51]

Type 5: Mixed harbour systems in inland seas: the examples of the Maryut (Egypt) and Bou Ghrara (Tunisia)

Lake Maryut (*Mareotis*), which lies behind Alexandria on the W margin of the Nile delta (fig. 3), contains a great diversity of harbour structures. At Taposiris Magna, the Roman harbour appears to have been associated with customs activities; access was restricted by a funnel-shaped entrance and exit channels, linked by a 1.7-km-long channel (fig. 2d).[52]

By contrast, at Marea-Philoxenia the harbour can be easily accessed; it consists of a 2-km-long pier divided by several quays constructed at right angles to the shoreline to form separate basins. The docking zone, active between the 5th and 7th c. A.D., had two functions: to disembark Copt pilgrims, and to load regional agricultural produce and handcrafted objects. The considerable length of the quays ensured that docking was always possible despite seasonal differences in the water level (up to 1.5 m) driven by Nile floods. E. Khalil has compared the navigability of the NW harbour basin and the S harbour basin in order to determine the environment's geomorphological potentiality.[53] The S basin is oriented parallel to the dominant winds that blow from the northwest, helping boats navigate to Alexandria. Minor branches of the Nile flowing into the harbour bring a significant supply of sediment. Because of the harbour's relatively flat bottom, its spatial dimensions are sensitive to the annual Nile floods, which makes the banks very mobile. The presence of many islets also makes the basin a swampy environment. Conversely, the NW branch lies perpendicular to the dominant winds and is surrounded by rocky coasts where the majority of the identified harbour structures are concentrated. Here, the narrowness of the basin is easier to control. Maryut's harbour system thus constitutes a mixed fluvial and lagoonal harbour with two distinct geographical and commercial areas.

In a similar vein, the Gulf of Bou Ghrara (S Tunisia) contains a wealth of archaeological remains.[54] The small inland sea, separated from the Mediterranean by the island of Jerba, is relatively well protected from the open swell. With a surface area of 430 km^2, an average depth of 5 m and tides of 1 m, the lagoon is conducive to navigation. Its coast is composed of two well-defined geomorphological units (fig. 7 in colour): 'active' cliffs on the W and E shores; and a clastic coastline fed by the alluvial cones of the surrounding wadis. The location of the ancient harbour of Gigthis, close to a large wadi, raises questions about the initial choice concerning the foundation of this harbour. Fluvial sediment supply may partially explain both the length of the jetties (*c.*150 m), pointing to the shallow draught that already existed during the Roman period and their necessity for purposes of docking, as at Ras Segala (fig. 2e); it may also explain the decline of harbour activities due to high sediment supply in the 6th and 7th c. A.D.

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49 Goddio 2007.
50 Stanley *et al.* 2004 and 2007.
51 Long 2009.
52 Boussac and El-Amouri 2010.
53 Khalil 2010a and 2010b.
54 Slim *et al.* 2004.

Conclusion

Our preliminary typology stresses the importance of geo-morphological contexts. We have underlined the major rôles of the accommodation space (defined on the bottom of p. 97) of lagoons and supply of sediment over the medium to long term. The proximity to a river outlet, sediment supply, the accommodation space, and the direction and intensity of longshore drift are the four main natural constraints that determine the longevity of harbour activities. Sea-level rise during the last 7,000 years has only had a minor impact on sedimentation processes and the maintenance of harbour activities, with the exception of thick deltaic sequences that have undergone compaction. Natural processes generally are more influential than human operations.

In short, three factors affect the environmental evolution of lagoonal harbours:
(a) Their *accessibility* via inlets. Semi-enclosed lagoons result in the main problems: they show the considerable impact of sediment supply at base level and the rôle of coastal drift that tends to infill the inlets, making access routes difficult to maintain; inlets become rapidly blocked, which accelerates the infilling of the lagoon.
(b) Their *navigability*. Marine currents and winds play an increasingly important rôle when the draught depth is reduced on account of sedimentation on the lagoon bottom. Protective structures such as jetties or quays are generally absent due to the natural low-energy environment.
(c) *Seasonal changes in the water level* of the lagoon can lead to significant lateral variations in the position of the shoreline. For instance, in the Maryut lagoon seasonal variations can lead to changes in the water level of up to 1 m.
To protect the maritime interface from natural hazards, the ancients favoured lagoonal environments for their harbour settlements. The protection afforded by these types of environment, however, led to their long-term infilling by sediments and their eventual demise.

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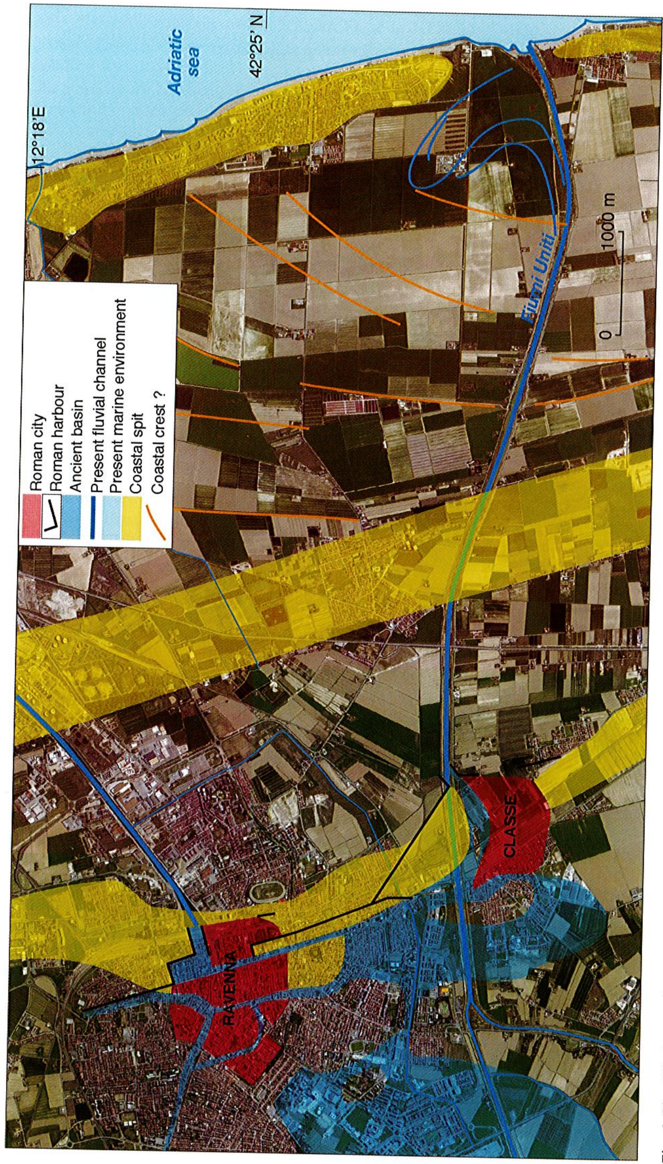
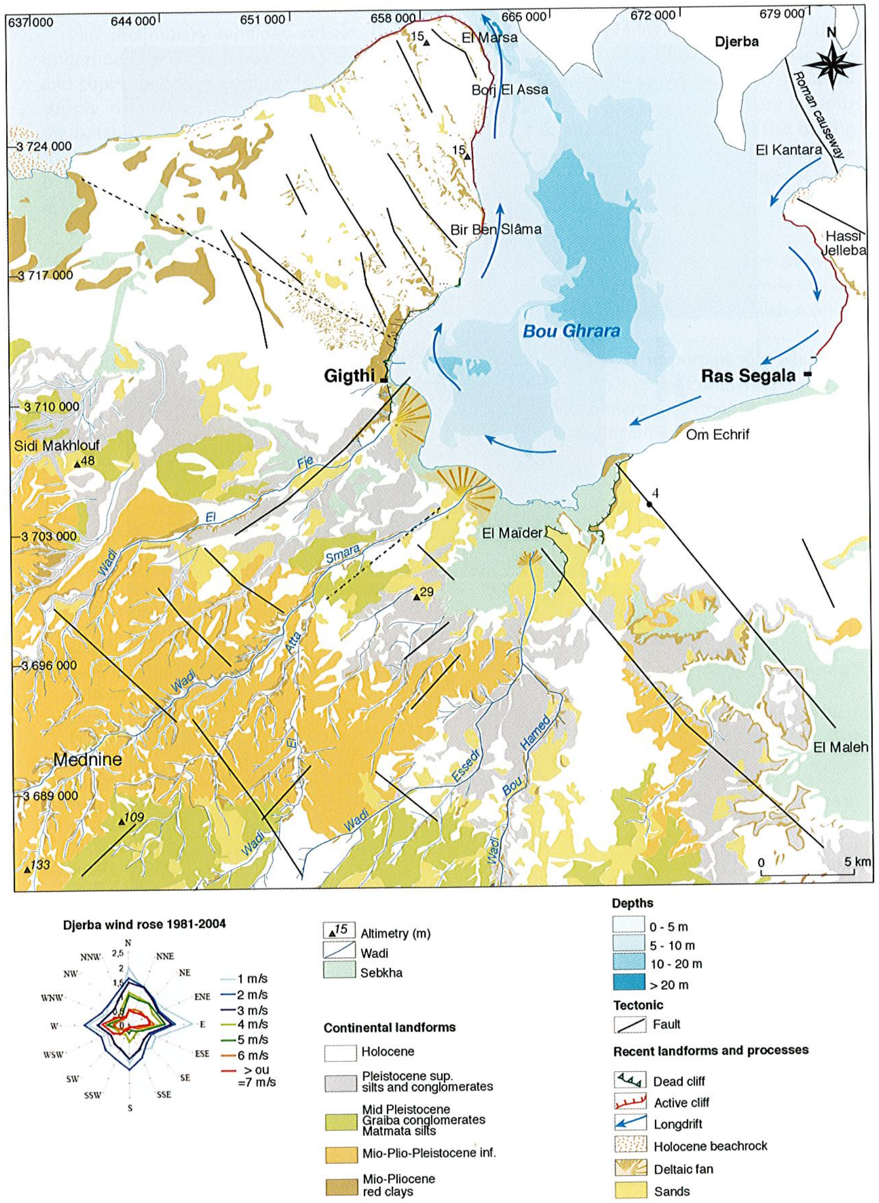


Fig. 6. Simplified map of the ancient harbours of Ravenna and Classe (after Manzelli 2000).



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8

Rivers, wadis and climate in North Africa: torrents and drought

Andrew Wilson

Introduction: rainfall and climate

Sallust (*Jugurtha* 17.5) described Africa as a land where there was *caelo terraque penuria aquarum*, ('a shortage of water from sky and land'), and this has characterised many views of N Africa since. Although this is true for much of *Africa Vetus* and Tripolitania, it is not always the case for *Numidia* and the two *Mauretaniae*, especially the coastal or mountainous zones. N Africa's climate, perhaps the region's most important geographical factor, is characterised by sporadic outpourings of adequate to scarce rainfall; this characteristic is fundamental in determining the nature and behaviour of the region's river systems. Relief also has an important influence on the climate and water resources. The map of rainfall isohyets echoes the map of relief (figs. 2-3 overleaf) and shows the considerable difference between even the better-watered areas of N Africa and most of Europe. The mountains not only precipitate rain (and sometimes snow in winter) and send their runoff to the surrounding plains; the limestone massifs and plateaux also act as subterranean reservoirs feeding large springs.

N Africa's rainfall is characterised principally by extreme seasonal (fig. 1) and yearly irregularity. The maximum and minimum annual rainfall figures regularly display seven- or eight-fold differences, sometimes even more than ten-fold. Annual averages bear little relationship to reality in any given year: at Garian in the Tripolitanian pre-desert, rainfall was within 10% of the theoretical average in only one year between 1927 and 1947.[1]

More important than the annual figure, for agriculture and for urban water-supply but also for the characteristics of the rivers, is the seasonal distribution of rains, with drought and flooding both being frequent. While 300 mm of rainfall evenly distributed throughout the agricultural year (September to August) could ensure a good grain harvest, 400 or 500 mm poorly distributed might yield only mediocre returns. For

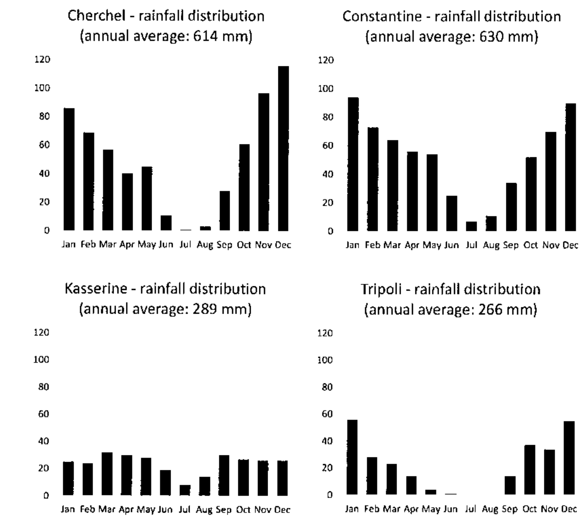

Fig. 1. Modern monthly rainfall data (1982-2012) for Cherchel (*Iol Caesarea*) Constantine (*Cirta*), Kasserine (*Cillium*) and Tripoli (*Oea*) (http://en.climate-data.org/ viewed Jan. 31, 2015).

1 Mattingly 1995, 11.