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# NATURAL VERSUS ANTHROPIC CAUSES IN VARIATIONS OF SAND EXPORT FROM RIVER BASINS: AN EXAMPLE FROM THE GUADIANA RIVER MOUTH (SOUTHWESTERN IBERIA)

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**Abstract**. Flood events in many river basins with highly variable discharge values remove accumulated sediments from the riverbed and estuaries. These sediments are exported to the shelf and the adjacent coastlines.

Data for rainfall and river discharge for the Guadiana River basin in southwestern Iberia show a strong link with North Atlantic Oscillation (NAO) index patterns. A negative NAO index usually results in more rainfall, and subsequent flooding in the river basin during winter months.

During the second half of the 20th century, the flow regime of the Guadiana River and its tributaries have been increasingly constrained by the construction of dams. The consequences were a reduction of coarse-grained sediment export from the upper river basin to the estuary, and a reduction in the number and type of floods.

**Key words**: Guadiana River, sediment transport, estuarine sand bodies, floods, NAO, anthropic influence.

## INTRODUCTION

The supply of sand from river basins to coasts and shelves is vital for the stability of coastlines and the maintenance of shelf sand bodies. The consequences of a reduction in sand supply from river basins to the oceans are large-scale coastal erosion and alteration of sedimentation patterns on the shelves, with consequences not only for natural habitats, but also the economy. The export of sediment from river basins is conditioned by a series of factors. Particularly, climatic variations on an inter-annual to multi-decadal scale have an important geomorphological impact (e.g. Maas, Macklin, 2002; Goy *et al*., 2003; Viles, Goudie, 2003). The North Atlantic Oscillation (NAO) is the dominant mode of winter climate variability in the North Atlantic region, ranging from central North America to Europe and much into northern Asia. The NAO is a large-scale seesaw in atmospheric mass between the subtropical high and the polar low. The corresponding index is the difference of sea level pressure normalised for the period 1901–1980 between the northern station situated in Stykkissholmur (Iceland) and a southern station whose location varies according to the authors: Ponta Delgada (e.g. Rogers, 1997), Lisbon (e.g. Hurrell, 1995) or Gibraltar (e.g. Jones *et al.*, 1997). The choice of southern station can make some differences, particularly in seasons other than winter (e.g. Jones *et al*., 1997; Visbeck, 2000). A positive phase of the NAO reflects below-normal pressure in the northern North Atlantic and above-normal pressure over the central North Atlantic, leading to strong westerly winds associated with warm and moist air masses across the northern Europe during winter (e.g. Visbeck, 2000). The negative phase reflects the opposite pattern in circulation and air temperature across Europe. Its vast influence on European river discharge patterns is well documented (e.g. Goodess, Jones, 2002; Rimbu *et al*., 2002).

During the course of the 20th century, anthropic influence in river systems has become an increasing limiting factor of river discharge, and consequently reducing sediment supply to estuaries, adjacent coasts and shelves, as river basins are increasingly dammed and water used for production of electricity, for irrigation, and as a source of drinking water (see Brandt, 2000 for a review on the downstream morphological effects of dam construction). The problem of run-off reduction and related reduction in sediment supply is particularly accentuated in rivers of arid and semi-arid zones, where water supplies show large seasonal variations, with low run-off levels during summer months and flooding during the winter. Prominent examples

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are the Nile River in Egypt (e.g. Summerhayes *et al*., 1978; Frihy, 1988; Stanley *et al*., 1998), the Colorado River in the USA (e.g. Bowen, Inman, 1966; Carriquiry, Sanchez, 1999), or the Yangtze River in China (e.g. Chen X. *et al*., 2001; Chen Z. *et al*., 2001).

The focus of the present study lies on the Guadiana River in southwestern Iberia, which has experienced a similar increase in anthropic influence during the second half of the 20th century (e.g. Brandão, Rodrigues, 2000; Gonzalez *et al*., 2001). Our aim is to relate the alteration in volume of sub- and intertidal sand banks within the Guadiana Estuary and adjacent shelf to both natural and anthropic causes, put the historic evolution of the estuarine mouth into this context, and to discuss the implications of these alterations for the estuary–coast–shelf system.

## REGIONAL SETTING

### HYDROGRAPHIC AND CLIMATIC CHARACTERISTICS

The Guadiana River basin, with an area of 66,960 $km^2$, and a length of 810 km, is the fourth largest on the Iberian Peninsula (Fig. 1a). The regional climate is classified as semi-arid, with the exception of July and August (arid) and November to January (temperate-humid) (Morales, 1993). As a consequence, the Guadiana run-off volume is subjected to high seasonal and inter-annual variations (e.g. Loureiro *et al*., 1986). For instance, between 1946 and 1989 the minimal annual run-off measured at Pulo do Lobo (Fig. 1b) was of 252 $hm^3$, and the largest one of 13,881 $hm^3$, while the maximum monthly run-off for this period was of 6,649 $hm^3$ (January 1970) and the minimum of 0 $hm^3$ (September to October 1954).

Severe droughts are a recurring problem. During the period 1940/41 to 1994/95, most droughts had the duration of one year (Henriques and Santos, 1999). Based on severity and affected area Henriques and Santos (1999) estimate that the most severe drought of this period occurring in 1943/44 has a return period of 100 years, while droughts observed in 1980/81, 1982/83 and 1994/95 have associated return periods greater than 25 years.

Seasonal run-off fluctuations result in winter floods during years with high precipitation events, with sometimes devastating consequences for the local population. Ortega and Garzón (1997) cite a total of 128 catastrophic floods since the year 680 when reliable Arab sources began to register them (this number must be seen as a minimum, as records during the Middle Ages were less accurate, and possibly failed to record a number of significant events).

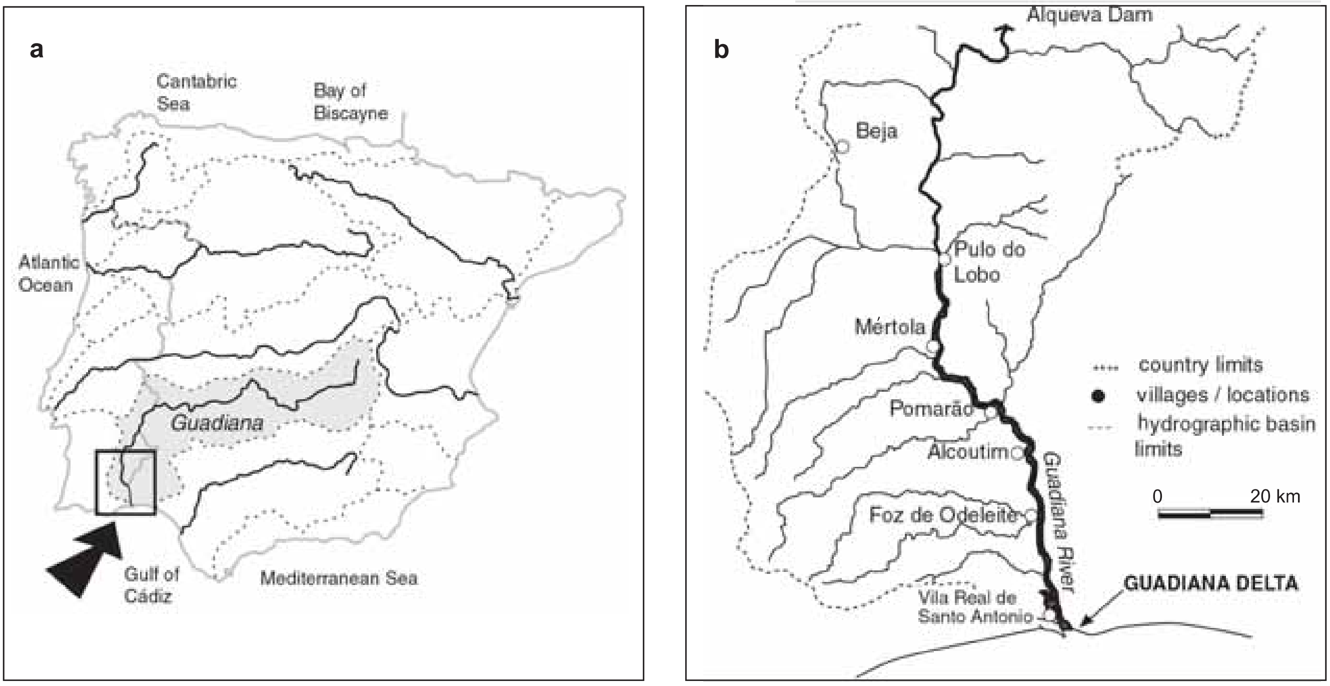


**Fig. 1. Location of the Guadiana River basin (a). The Guadiana Estuary and the location of the Alqueva Dam (b)**

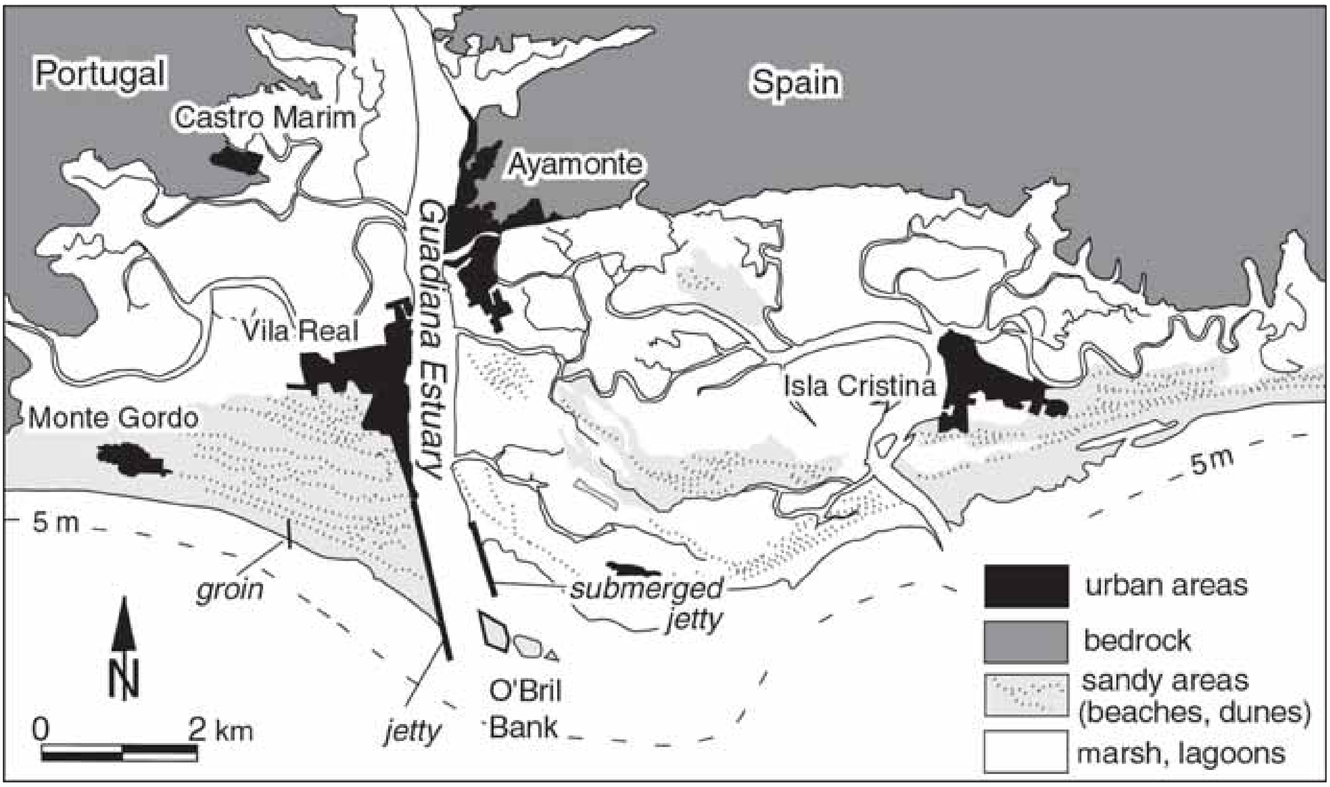


**Fig. 2. Main geomorphological elements of the present day Guadiana Estuary and Delta system**

The lower Guadiana River is separated from the upper river basin by the Pulo do Lobo, a near vertical 13.5 m high waterfall. The estuary begins 15 km down river from this location, at Mértola, the furthest upriver location reached by salt water at spring high tide before the construction of dams (Fig. 1b). The turbidity maximum is found, depending on the tides, between 20–35 km up river from the mouth, more or less between Foz de Odeleite and Alcoutim (e.g. Dias, Ferreira, 2001; Fig. 1b). The Guadiana Estuary is a freshwater-dominated estuary during flood periods, being *de facto* transformed into a river during these periods (Plaza *et al*., 2003), while between spring and autumn the salinity distribution is controlled by tides, with strong vertical mixing occurring during spring tides, and salt-wedge formation during neap tides (Rocha *et al*., 2002).

The river crosses an open coastal plain only in its last 7 km (Fig. 2). This coastal plain is part of an old deltaic plain, dominated by marsh systems formed by the river (Morales, 1997). The mouth of the estuary is a highly dynamic area, with considerable movement of sediments and associated morphological changes. The coastline reached a position close to the present only once about 200 years ago (*op. cit.*). The western margin of the estuary mouth prograded about 900 m since the beginning of the 20th century, 25% of which occurred after the construction of two jetties at the estuary mouth in 1974 (Gonzalez *et al*., 2001). During the same period, the barrier island spit marking the eastern margin prograded about 500 m into the main estuarine channel. This westward progradation was accompanied by coastal erosion at a rate of about 3 m/year since the construction of the jetties (*op. cit.*).

Tides on the coast adjacent to the estuary are semidiurnal mesotidal, with average tidal amplitudes of around 2 m, reaching 3.88 m at spring tides. Tidal currents at the river mouth are about 0.6 m/s during peak flood tide, and 1.2 m/s during peak ebb tide (Institúto Hidrográfico, 1998).

The offshore coastal wave regime is primarily dominated by waves from W and SW (approximately 50% of occurrences). The southeastern waves also have a significant influence with *ca*. 25% of occurrences. The average offshore significant wave height is about 0.9 m, with an average period of 4.6 s, with peak average periods of about 8 s (Costa, 1994). The net annual littoral drift is from W to E. The wave regime results in a net eastward littoral drift, estimated to be, by various authors, in the order of 150,000–300,000 $m^3$/year in the area of the Guadiana estuary mouth (CEEPYC, 1979; Cuena, 1991; Gonzalez *et al*., 2001; Boski *et al*., 2002).

## ESTUARINE MOUTH SAND BODIES

Because of its relatively moderate river outflow levels during summer months compared to tidal currents, the lowermost Guadiana Estuary accumulates sand in its bed and in the vicinity of its mouth during this part of the year, in areas where the current energy decreases below the threshold of movement. These sand banks can grow to a size where they hinder the traffic of vessels, as channels and sand banks can quickly change their location. The O'Bril sand bank at the mouth of the Guadiana River is a good example of this processes (Fig. 2), and will be used in this paper as a proxy for the behaviour of all sand banks within the lowermost Guadiana Estuary.

The existence of the O'Bril Bank can be reliably traced back to at least 1648, as it appears on a map of the Algarve of this date. It shows a cyclic behaviour, as described by Weinholtz de Bivar (1978) and Morales (1997). The bank grows over the course of a few decades on the western margin of the Guadiana Estuary, rotating east to the distal part of the bank, thus partially blocking the mouth of the estuary. Subsequently, a new river channel usually forms close to the western margin splitting the bank into two (or more) segments. This new channel widens in time, initiating a migration of the bank towards the eastern estuary margin. Eventually, the sand bank will attach itself onto the eastern, Spanish shoreline. From here, the remnants of the sandbank slowly erode. The sand is either transported downdrift eastwards, or amalgamated to the coastline. This cycle has occurred several times over the past few hundred years.

## KEY POINTS OF ANTHROPIC PRESSURE

The Guadiana River basin has been under growing pressure from anthropic activity. Since Roman times, and particularly the late 19th century, the region has been exploited by mining activities (e.g. Gonçalves, 1988; García, 1996), with lasting impact on vegetation, as large amounts of wood were used for the calcination of ores (García, 1996). Another key anthropic factor responsible for the deterioration of vegetation cover in the river basin was the so-called *campanha do trigo* (= wheat campaign), an isolationist attempt for self-support of the country in the thirties. During this "wheat campaign", huge areas in the interior of the Iberian Peninsula were deforested and used for agricultural purposes. The result was a large increase in soil erosion, resulting in an increase in sedimentation near the estuary mouth between 1938 and ca. 1945 (Gonzalez *et al*., 2001).

From the 1950s onwards, the river and its tributaries have been increasingly affected by the construction of dams (Fig. 3). Furthermore, large amounts of water have been used for irrigation (Fig. 3). Until 1992 about 9,000 hm$^3$ of water per year were stored in dam lakes, while water used for irrigation reached volumes of around 1,100 hm$^3$/year (CHG, 1994). The inauguration of the Alqueva barrage complex in February 2001, covering an area of *ca*. 250 km$^2$, and retaining a maximum capacity of 4,150 x 10$^6$ m$^3$ (expected normal volumes are of 3,150 x 10$^6$ m$^3$), has created the largest artificial lake in western Europe. With the inauguration of this dam, the volume of water that can be retained in dam lakes in the river basin has increased to about 13,000 hm$^3$/year (Fig. 3).

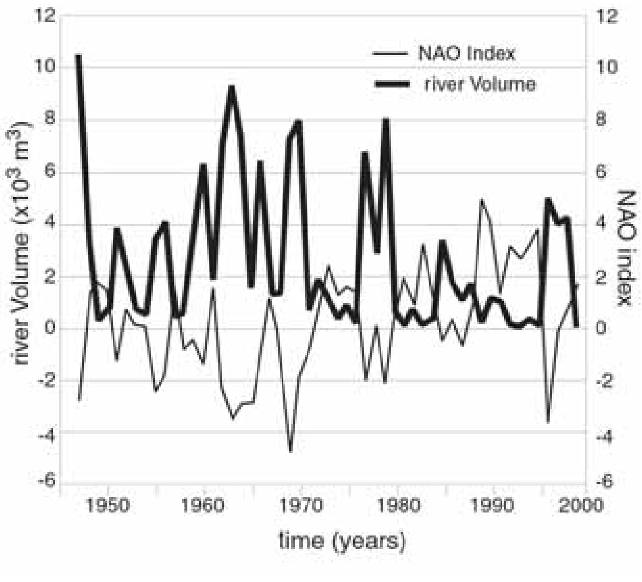


**Fig. 3. Volume of water stored in dams in the Guadiana River Basin and amount of water used for irrigation (no data after 1992 available) (after Loureiro *et al.*, 1986; CHG, 1994)**

The estuary mouth morphology itself has been heavily influenced by the construction of two large jetties in 1974, the western one with a length of 2,090 m, and the eastern submerged jetty with a length of 900 m (see location on Fig. 2) (Gonzalez *et al*., 2001). The construction of this set of jetties, and others along the southern coast of Portugal has probably led to significant inhibition of the westward littoral drift (e.g. Dias, 1988; Gonzalez *et al*., 2001), thus reducing this source of sand, and/or altering its rhythm of supply.

## MATERIAL AND METHODS

The Guadiana River discharge levels are for the periods between 1946 and 2000 at Pulo do Lobo (see location on Fig. 1), as available from the INAG (Instituto Nacional da Água — Portuguese National Institute for Water) web site (http://snirh.inag.pt/). For the correlation with the North Atlantic Oscillation (NAO), the Winter version of the NAO index computed with pressure data from Lisbon was used; the data was extracted from www.cgd.ucar.edu:80/cas/climind/nao_winter.html.

The extension of the O'Bril Bank was based on the area enclosed by the Portuguese hydrographic zero (2 m below mean sea level), as seen on bathymetric map reproductions published in Weinholtz de Bivar (1978). The maps were georeferenced by ERMapper 6.0 using a series of geographic tiepoints. The projection used is UTM (Datum Lisbon, Castelo de São Jorge).

# RESULTS

## CORRELATION OF THE RIVER VOLUME WITH THE NAO

A plot comparing the NAO Winter Index with the Guadiana River winter run-off volume between 1946 and 1999 is shown on Figure 4. The data show a strong negative correlation (r = –0.76) between the negative NAO Winter Index and winter flooding events in the Guadiana River basin. Equally, several periods with successive positive NAO indices, particularly 1972–1975, 1980–1983, and 1988–1994 correspond to periods of low river run-off, and in the case of the years 1980/81, 1982/83 and 1994/95, with extreme droughts.

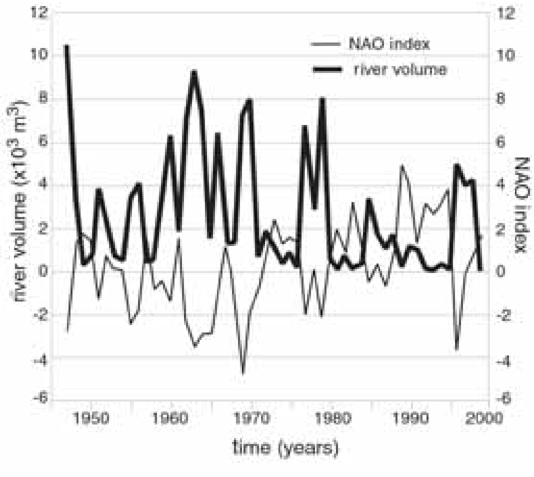


**Fig. 4. Comparison of the NAO Index and the Guadiana River volume for the second half of the 20th century**

## ANTHROPIC ALTERATION OF FLOOD STYLE AND FREQUENCY

Until about 1955, the Guadiana River basin was virtually unhindered by dam structures, with the exception of some very minor constructions in the upper river basin, two of which dates back to Roman times. At present, the high level of river damming, regulating about 81% of the Guadiana River catchment area after the inauguration of the Alqueva dam in February 2001 (Rocha *et al*., 2002), has a large influence not only on frequency but also on style of floods in the river basin.

The dam construction began to have a significant influence on natural flood patterns from the mid-sixties onwards. This can easiest be seen if the correlation of NAO Winter Indices with the run-off regime is compared before and after dam construction. The negative correlation of negative NAO with flood frequency is r = –0.81 for the period from 1946 to 1964, and is reduced to r = –0.72 for the period from 1964 to 1998.

Figure 5 shows two typical, comparable flood events measured at Pulo do Lobo. During both floods the river volume peaked between 3,600 and 3,800 $m^3$/s. The event from March 1951 is characteristic for pre-dam building floods. The flood lasted 13 days (the cut-off point being a drop of the river volume below 500 $m^3$/s). The build-up was stepped, lasting 5 days, as tributaries fill up after rain falls and flood levels increase as their water reaches the main river channel (Fig. 5a).

The flood of February 2001 shows a typical flood after dam building (Fig. 5b). (note that at this point the Alqueva Dam was not yet inaugurated). The flood lasted 10 days. Water level increased virtually over night, from the 6th to the 7th of February, as dam floodgates were opened when water levels in dam lakes reached critical levels.

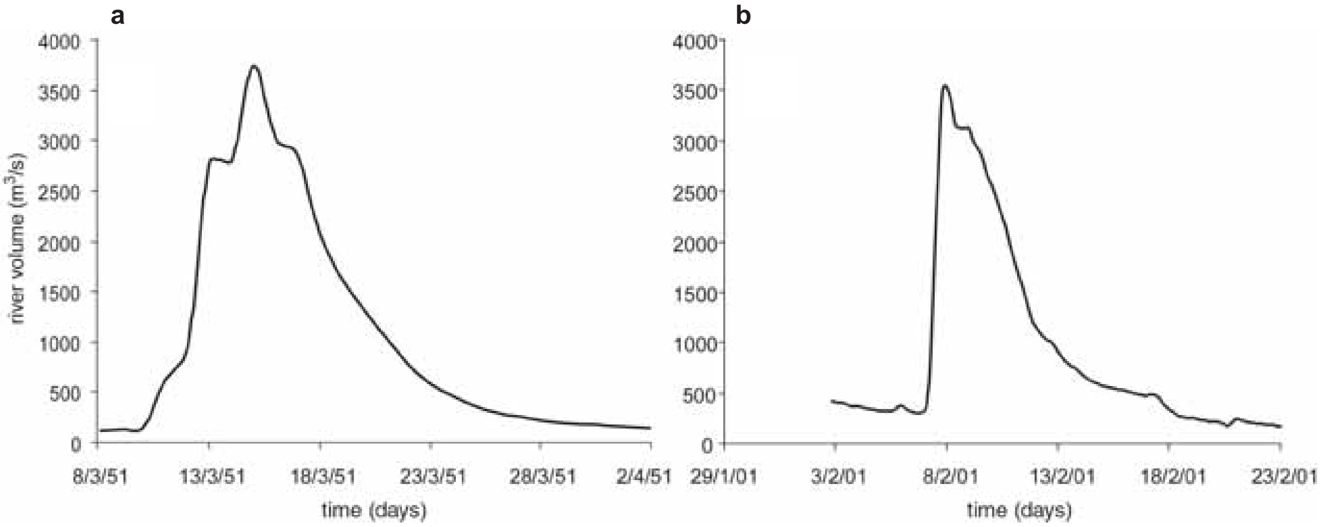
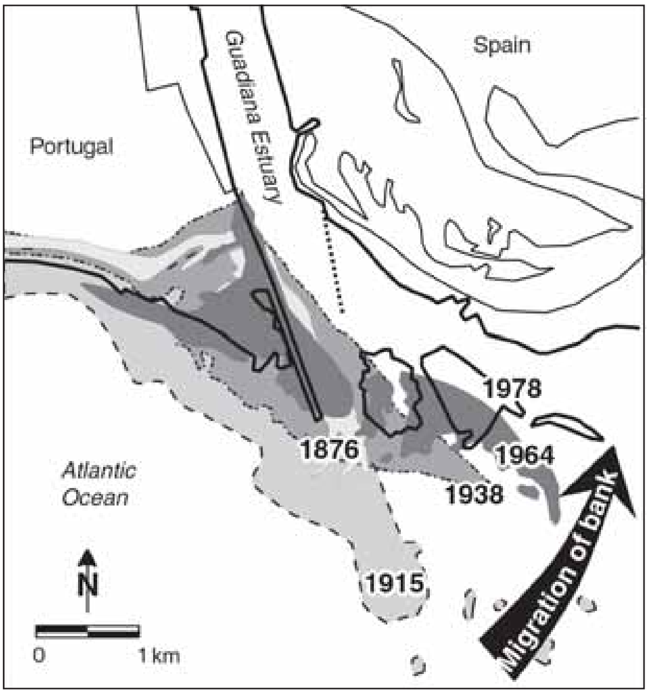


**Fig. 5. Two flood events of comparable magnitude, measured at Pulo do Lobo**

The ratio between build up and decay time of the 1951 flood is 0.625, i.e. the decay lasted approximately twice as long as the build up. In comparison, the same ratio is about 0.05 for the 2001 flood, if half a day for its build up is considered.

## EVOLUTION OF THE O'BRIL BANK DURING THE PAST 150 YEARS

Figure 6 shows the evolution of the O'Bril Bank in the past 140 years. It subsequently grew in size again, reaching a maximum extension around 1915. Ever since this period, it has seen a steady reduction in area, its mid-river portion at present having a smaller extension than after the flood of 1876 (Fig. 6).



**Evolution of the O'Bril Bank at the Guadiana Estuary mouth since 1876**

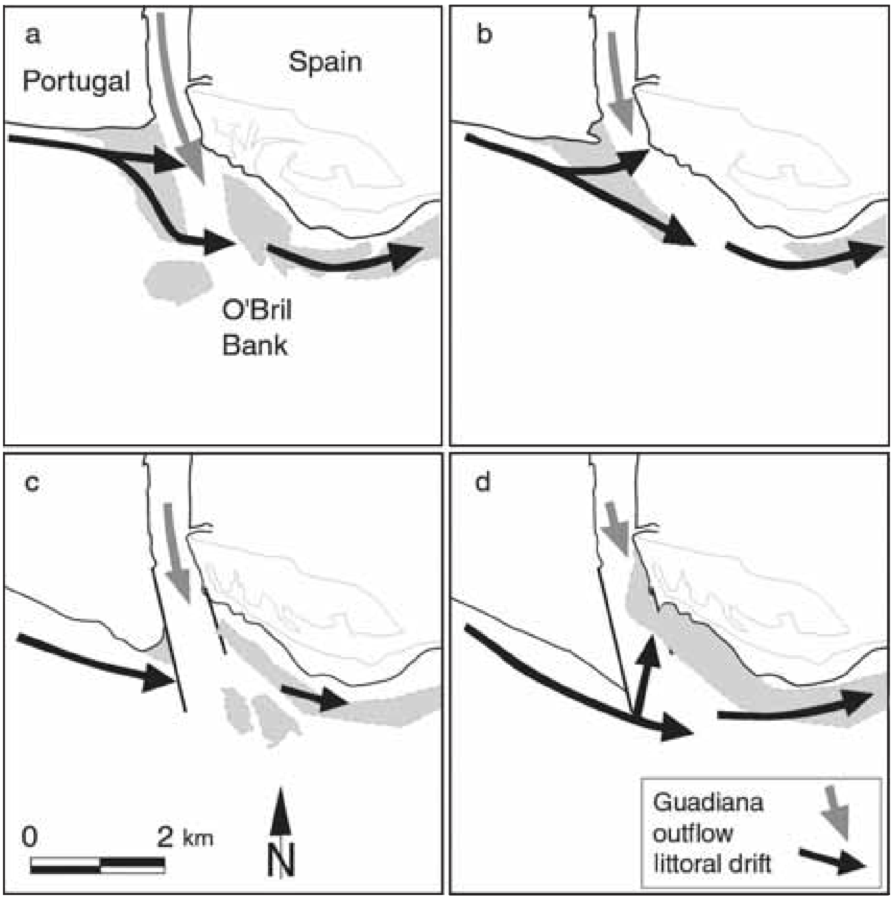


**Fig. 7. Simplified model for the evolution of morphological elements of the Guadiana Estuary mouth during the past century**

The arrows indicate the quantitative direction and amount of sand transported by the Guadiana outflow and the littoral drift; additional important factors (not represented on the image) are tidal currents and wave regime; these do, however, not supply sand themselves, but remobilise it and have a dominant influence on the medium term shape of sand bodies

The O'Bril Bank reached a minimum extension after the catastrophic flood of January 1876 (the largest in historic times), when river levels rose to about 50 m above low-tide level in Pomarão (Fig. 1). During the flood the sand bank was almost completely flushed out onto the shelf (Fig. 6). The bank was left with a subtidal area of approximately 0.8 km$^2$ on the Portuguese side, and a total of 2.7 km$^2$ including the sand bars on the Spanish side.

In 1915, the bank had reconstituted itself, with an area of 3.7 km$^2$ on the Portuguese side and 5.9 km$^2$ as a whole (Fig. 6). Subsequently, the size of the O'Bril Bank showed a continuous decrease, losing approximately 48 m$^2$/year in area. Simultaneously, it began rotating northwards (Fig. 6). This process was accelerated after the construction of the jetties in 1972–1974. On the map of 1978, the O'Bril Bank is smaller than after the great flood of 1876, with a size of 0.6 km$^2$ on the Portuguese side, respectively 1.3 km$^2$ including the Spanish side (Fig. 6). The speed of northward rotation of the bank was found to be irregular. It was quickest between 1915 and 1938 with 65 m/year, slowed down to 19 m/year between 1938 and 1964, and increased slightly to 22 m/year between 1964 and 1978. Figure 7 summarises the main acting forces at the estuary mouth and their change in the past 140 years (after Gonzalez *et al*., 1999). Figure 7a shows the estuary mouth at the beginning of the 20th century. Sand was supplied by littoral drift and river. The interaction of river flow, tides, and waves led to the above described accumulation of sand and migration patterns. With the reduction in sand supply by river outflow since the mid-fifties (Fig. 7b), the main sand supplier for the sand body became the littoral drift. As the power of floods flushing sand onto the inner shelf was reduced, the sand body saw a strong growth and eastward rotation. The western margin of the Guadiana prograded significantly and saw the growth of an extensive dune field (Gonzalez *et al*., 2001). To alter sand migration paths across the main estuarine channel and to inhibit the obstruction of (international) shipping ways, two jetties were built in 1972–1974, leading to a strong reduction in the size of the sand bank (Fig. 7c). However, as a consequence of the infilling of the area to the west of the western jetty, and an even more drastic reduction in river outflow and flood frequency, the river mouth is experiencing at present a beginning of sand carried by the littoral drift bypassing the jetty, and a strong accumulation of sand on the eastern estuarine margin (Fig. 7d).

## DISCUSSION AND CONCLUSIONS

As Viles and Goudie (2003) state, geomorphologists have long argued whether it is possible to untangle the various internal and external forcing factors that cause geomorphic response. This problem is exacerbated by the interconnection of factors such as anthropic behaviour and climatic forcing, where large-scale human activity can be triggered by decadal climatic trends.

Over the past century, human activity has seen a large shift, completely altering its influence into sedimentation patterns in the river basin. While the late 19th and early 20th, as well as the 1930s, were dominated by large-scale deforestation, thus dramatically increasing sediment yield in the river basin (cf. Gonzalez *et al*., 2001), the second half of the 20th century saw a large-scale shutdown of sediment transport by damming in of about 81% of the river basin.

While the large flood of 1876 does not seem to be directly connected to a particularly strong negative NAO index, the subsequent unusually large build up of the O'Bril Bank until 1915 is probably linked to the long positive NAO period from 1904–1915: Between 1903 and 1914, the NAO Winter Index was positive, only turning negative in 1915 with a value of –0.20. The average NAO Winter Index during this period was of 1.54, varying between 0.00 and 3.89. The period between approximately 1950 until 1969 saw then a steady decrease in the index, with pronounced flooding occurring in the river basin throughout the 1960s. Between 1958 and 1971, there were only two years with a positive NAO winter index (1961 and 1967). The average NAO Winter Index during this time was –1.57, with a variation between 1.8 (1961) and –4.89 (1969). This period coincided with a steady decrease of the O'Bril Bank. Simultaneously, the western margin of the Guadiana River mouth, which can be considered the root of the bank, saw a steady increase and progradation (Gonzalez *et al*., 2001).

During the 1980s and 90s, a long series of increasing positive NAO winter indices, resulting in a low number of floods has coincided with the most far-reaching damming in the river basin (it is no coincidence that 3 exceptional drought periods with a statistical return period of 25 years occurred during this period). Between 1980 and 1995, there were only two years with a negative index (1985 and 1987). The average index for these years was 1.84 (varying between –0.75 and 5.08). Between 1989 and 1995, when there were large scale droughts in the southern central portion of Iberia, the index was always positive, averaging 3.29.

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