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Recent Evolution of the Natural Inlets of a Barrier Island System in Southern Portugal

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ABSTRACT

Four natural inlets, existing in a multi-inlet, barrier island system, were studied for the period between the 1940s and 1996. Inlet width and position of the inlet channel were determined using a series of vertical aerial photos and charts. The objective of the work was to determine the association between inlet migration patterns and different hydrodynamic conditions, major storms and engineering interventions. Results indicate that natural inlet opening and evolution were mainly affected by three factors: (a) existence of sub-embayments (western and eastern) inside the system, (b) exposure to wave energy, and (c) inlet efficiency. Two distinctive eastward migration patterns were found by analysing the correlation coefficient (r) between inlet width evolution and inlet migration and by the comparison of the shape of the curves fitted to the inlet migration behaviour. Typical migration of the high-energy flank (on the west side of the system) is characterised by an initial stage of readjustment, with low migration rates, followed by a stage of high eastwards migration rates, up to a limiting position. Inlet width remains reasonably constant during the entire migration cycle, thus the correlation between inlet width and position is very low. Typical inlets on the low-energy flank (east side of the system) are formed by barrier breaching during major storms and produce initially very wide inlets. Eastward inlet migration on the low-energy flank follows a natural logarithmic curve where channel migration is accompanied by strong constructional processes on the updrift barrier. Due to subsequent inlet width reductions, the correlation between inlet width and position is significant.

ADDITIONALINDEXWORDS: *Tidal inlet, Inlet migration, Morphology, Anthropogenic effects, Ria Formosa, Algarve*

INTRODUCTION

Barrier island systems are dynamic and sensitive areas of the coastal environment. Several authors have focused their attention on the study of these complex systems and, particularly, on tidal inlet evolution and behaviour as one of their most dynamic parts (i.e. NUMMEDAL and FISHER, 1978; FITZGERALD, 1996). Besides their natural and environmental importance, tidal inlets are often important in providing the only access to a harbour or coastal population. Natural and anthropogenic factors such as sea level rise, storm events, dune occupation or coastal engineering actions, often produce changes in tidal inlet conditions. Thus engineering actions like inlet relocation (e.g. KANA and MASON, 1988; VILA *et al*., 1999) or channel dredging (e.g. JOHNSEN *et al*., 1999) are often needed to maintain the efficiency of water exchange and/or navigability of tidal inlets. Background knowledge of tidal inlet behaviour and evolution is therefore needed to understand and predict the consequences of engineering actions or extreme natural events.

The present study is focused on the recent evolution of the natural inlets of the Ria Formosa barrier island system. Objectives of this work are to study inlet migration and inlet width evolution over the last few decades, and to determine and compare inlet migration patterns in relation to different hydrodynamic conditions. The study also intends to contribute to the understanding of tidal inlet behaviour in multi-inlet barrier systems, and to the general knowledge of tidal inlet migration patterns. In the particular case of Ria Formosa, it will provide background knowledge prior to the adoption of any nature conservation or engineering actions.

STUDYAREA

The Ria Formosa is a multi-inlet, barrier island system located in southern Portugal (Figure 1). Its present configuration consists of two peninsulas and five islands that extend over 50 km (PILKEY *et al*., 1989). Connection between the ocean and the backbarrier area is made through six tidal inlets. According to ANDRADE (1990), the backbarrier area consists mainly of salt marsh and small sandy islands covering $8.4x10^7$ m^2 and comprising a complicated pattern of tidal channels and creeks. According to ANDRADE (1990), the average depth of the area is 4 m referred to mean sea level (msl).

Tides in the area are semi-diurnal, average ranges are 2.8 m for spring tides and 1.3 m during neap tides, however, maximum ranges of 3.5 m can be reached. Wave climate in the area is moderate to high (CIAVOLA *et al*., 1997). Incident waves are normally from the W-SW, representing 68% of the total (C.COSTA, 1994), although "Levante" (SE Mediterranean wind) occurs often in the area producing the E-SE waves, that represent 29% of the total (C.COSTA, 1994). Storms have been defined for this area as events where Hs (Significant Wave Height) is greater than 3 m (PESSANHA and PIRES, 1981). M.COSTA (1994) concluded that the highest storm frequency occurs in the period between November and January. PIRES (1998) established the return periods for the main incident wave directions and concluded that for the same return period, SW storms are more energetic than SE storms.

The cuspate shape of the Ria Formosa system produces 2 areas differentiated in terms of exposure to wave action. The west flank is more energetic, being under the direct influence of the dominant wave conditions, while the east flank is only directly exposed to the "Levante" conditions.

The west flank typically has only one tidal inl*et al*though at various times in the past has had up to three tidal inlets (WEINHOLTZ, 1964, ESAGUY, 1986a). Ancão Inlet (Figure 1) is a small migrating inlet that has an average width of 300 m (VILA *et al*., 1999). Several authors have described the behaviour of this inlet as cyclic eastward migration (WEINHOLTZ, 1964; ESAGUY, 1986a; DIAS, 1988; PILKEY *et al*., 1989; VILA *et al*., 1999), although other authors have interpreted its behaviour as erratic movements with no defined directions or cyclic behaviour (ANDRADE, 1990; SALLES, 2001). Ancão Peninsula and Barreta Island are narrow (in the vicinity of Ancão Inlet), consisting of one single dune ridge that can reach heights of 7 m (msl).

The east flank presently has five inlets, although the number of inlets has varied over time. Two of the inlets in this flank, Faro-Olhão Inlet and Tavira Inlet (see Figure 1) were artificially opened and stabilised with jetties in 1929-1955 (ESAGUY, 1984) and 1927-1985 (ESAGUY, 1987), respectively.

Armona Inlet (Figure 1) is considered to be the only naturally stable inlet of the system (WEINHOLTZ, 1964; PILKEY *et al*., 1989). It has occupied the same position through recent centuries although its width has varied significantly (WEINHOLTZ, 1964; ANDRADE, 1990; SALLES, 2001). During the last century, its width has narrowed by approximately 2,500 m, from 4,300 m in 1873, to 1,850 m in 1983, according to ESAGUY (1984) and DIAS (1988). The same authors explained that narrowing of the inlet was mostly related to the growth of the eastern tip

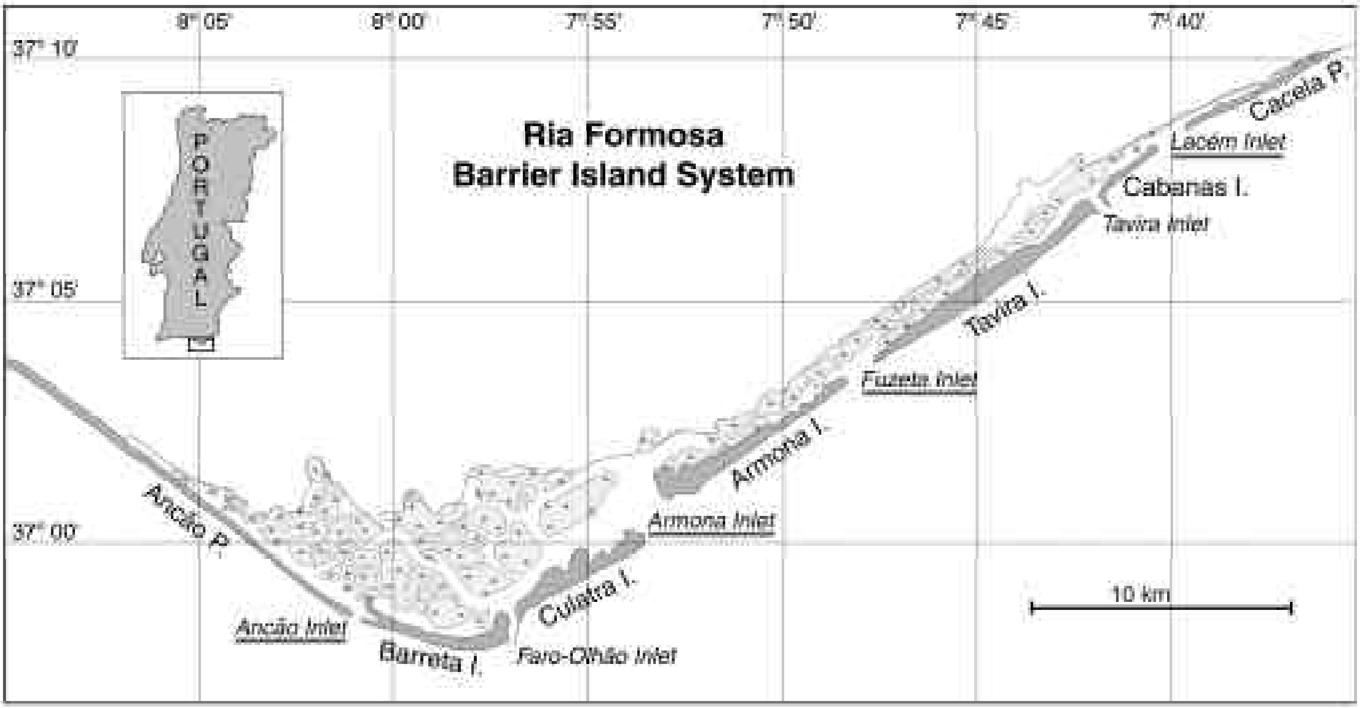

Figure 1. Location of study area. The names of the natural inlets analysed in this study are underlined.

of Culatra Island, since its growth rates were similar to the inlet narrowing rates. As a consequence of the rapid growth, the eastern part of Culatra Island contains low dune areas with high overwash susceptibility (ANDRADE *et al*., 1998) that under high energy conditions could lead to barrier breaching. Due to its width, this inlet has a very complex morphology and often consists of two or more channels.

Fuzeta Inlet (Figure 1) shows a clear pattern of cyclic easterly migration (WEINHOLTZ, 1964; ESAGUY, 1985; DIAS, 1988; PILKEY *et al*., 1989; ANDRADE, 1990; SALLES, 2001). The typical width of this inlet varies from thousands to hundreds of metres, consisting, on occasions, of two channels. Armona and Tavira islands, in the vicinity of the inlet, do not have very high dune ridges thus, overwash susceptibility is quite high (ANDRADE *et al*., 1998), especially at the eastern tip of Armona Island.

Lacém Inlet (Figure 1) typically opens over a wide area during storms because Cabanas Island is easily inundated. Accretion processes on Cabana Island cause inlet eastward migration as well as inlet narrowing (DIAS, 1988; PILKEY *et al*., 1989). Typical widths for this inlet range from thousands to hundreds of metres and a double channel can exist.

METHODS

Inlet width and position were determined for Ancão, Armona, Fuzeta and Lacém inlets for the period between the 1940s and 1996. This period was chosen (a) because it corresponds to the period for which quality information (vertical aerial photos, charts, maps and documents) is available. And (b) because since 1997 the Ria Formosa barrier island system has undergone an extensive engineering programme, including inlet relocation, inner channel dredging and beach and dune renourishment (vide RAMOS and DIAS, 2000; DIAS *et al*., in press).

To determine inlet width, the minimum width at the inlet gorge was measured using as reference the high tide marks, for vertical aerial photos, and the mean sea level isobath, when using charts or maps. Comparison of inlet width measurements using different levels is problematic and can introduce errors related with the slope of the inlet margins. Results of error analysis provided an average error of 40 m for the west flank, and 80 m for the eastern one, when comparing data referred to different isobaths (i.e., charts vs photos). Since the large majority of the computed inlet width changes are in the order of hundreds to thousands metres, the method used here provides good long term estimations, showing the important reductions or increases in inlet width.

Inlet position was determined in each case by measuring the distance, along a fixed line, following the orientation of the coast, from an arbitrary reference point to the centre of the main channel of the inlet. Positions were then converted such that they refer to a point located 10 m west of the initial position of the inlet in the 1940s. In case of double channel inlets, a morphologic criteria was applied, that is, measuring both channels (Armona Inlet) or choosing the final remaining channel (Lacém Inlet).

Data sources consisted of a series of vertical aerial photos (see Table 1) and one navigation chart published in 1982 by the Portuguese Instituto Hidrográfico, showing Ancão Inlet conditions in 1979-80 (scale: 1/15,000).

Complementary data, published by other authors, were used when possible to provide a better coverage of the studied period (see Table 2). Data for double channel inlets were only employed if the morphologic criterion was coincident with the one used in this study. Consequently, no additional data were utilised for Armona Inlet and results from SALLES (2001) were not used for Lacém Inlet. ANDRADE’s (1990) data were not employed because his criteria was not explicit, and his values are remarkably different from those obtained for this and other studies, even for the same years. Other authors obtained their data using fixed lines, that (even if they are also alongshore) possibly have a different orientation from the one used here. An error analysis was performed taking into account the angle of orientation of the line (a), as well as the distance to the reference point (d). A function of error was obtained (e=

Table 1. Coverage and scale of vertical aerial photos used for this study.

Year	Ancão Inlet	Armona Inlet	Fuzeta Inlet	Lacém Inlet	Scale (approximate)
~1945*	yes	yes	yes	no	1/20,000
1969	no	yes	yes	no	1/25,000
1972	yes	no	yes	yes	1/7,000
1976	yes	yes	yes	yes	1/25,000
1985	yes	yes	yes	yes	1/15,000
1989	yes	yes	yes	yes	1/10,000
1996	yes	yes	yes	yes	1/8,000

*Exact date for these aerial vertical photos is unknown.

0.0002 dα²), providing an average error of 30 m for differences between 0.5º and 15º and between 50 m and 5000 m, with a maximum value of 170 m. Thus, comparison of data provided by other authors introduces an extra error to data accuracy. However, the main aim of this study is focused on determining long period trends rather than specific or short period changes. Therefore, accuracy of the data used is considered to be sufficient for long term trend determination, since inlet position changes are normally in the order of hundreds to thousands of metres.

Correlation coefficients (Pearson-r, hereafter termed r) between inlet width and channel position were calculated to define possible interdependency between these parameters.

To obtain a better definition of each inlet migration pattern, curve fitting of the inlet evolution over time was undertaken. This involved studying the polynomial or logarithmic relationship between inlet position and time. Comparison of migration patterns between inlets was then made using these curves. However, it should be noted that fitted curves were not calculated with the purpose of predicting future behaviour of the studied inlets, thus they are only of application in between the positions interval given by the data.

Inlet evolution (width and position) results were then analysed by comparison with engineering actions undertaken in the system (i.e. inlet stabilisation) as well as with storm records obtained from bibliographic sources.

RESULTS

Ancão Inlet

Ancão Inlet (Figure 2) evolution in terms of width and position is shown in Figure 3. During the study period, this inlet experienced two eastward migration cycles: Ancão-1 and Ancão-2. The opening date of Ancão-1 inlet is unknown, however, in 1941 a major storm was recorded in the area (WEINHOLTZ, 1964; ESAGUY, 1985, 1986a, 1986b; ANDRADE, 1990) and thus the opening of an inlet at a position close to that recorded for ~1945 could have occurred. Sometime between 1972 and 1976, a new inlet (Ancão-2) opened at a western position, close to the one of ~1945 (Figure 3). There are no certainties about the exact date of the opening of Ancão-2 inlet. However, PITA and CARVALHO (1987) indicated, using hind cast predictions, the occurrence of a very large storm in January 1973. For a short period two inlets co-existed, one at its final stage and the other one at its beginning.

With the exception of the last stage of Ancão-1, where the inlet was almost completely infilled, inlet width did not exhibit strong variations during the study period (Figure 3). Average width, not taking into account the last stage of Ancão-1, was found to be 260 m. Maximum inlet width was 410 m reached by Ancão-2 in 1976.

Migration trends were similar for both cycles (r=0.981, significant with 99% of confidence), with the inlet showing an initial stage of readjustment, characterised by low migration rates, followed by a stage of high eastwards migration rates, until a limiting position about 2,700 m from inlet initial position was reached. The Ancão-2 migration cycle was, however, more rapid than the Ancão-1 cycle. Average migration rates were close to 40 m/yr for Ancão-1 and 100 m/yr for Ancão-2. Maximum migration rates occurred in the last stages of inlet evolution with 210 m/yr for Ancão-2. The temporal length of the migration cycle for Ancão Inlet appears to be in the order of 30-40 years.

There is no significant relationship between inlet migration and inlet width evolution. Correlation coefficient values between these parameters are very low, –0.051 for Ancão-1 and 0.163 for Ancão-2. Thus, channel migration and inlet width evolution appear to be independent processes for this inlet, with the inlet width being reasonably constant at all evolutionary stages.

Curve fit values for both cycles of inlet migration are shown in Table 3. The best fit for both of the Ancão migration patterns was found to be a second order polynomial function.

Armona Inlet

Armona Inlet (Figure 2) had two channels for the entire study period, both of which appear to have had equal hydrodynamic importance. Due to this, both channels were measured in order to study inlet evolution: Armona W and Armona E. The evolution of the position of both channels as well as inlet width evolution is shown in Figure 4.

Inlet width decreased during the study period, with the exception of a small increment of 200 m between 1989 and 1996. Average rates of inlet width decrease were about 30 m/yr for the entire study period, reaching a maximum of

Table 2. Years for which data from other authors were used at specified inlets.

Inlet	Salles (2001)	Esaguy (1985)	Esaguy (1986a)	Esaguy (1986b)
Ancão	1951, 1964	--	1950, 1965, 1978, 1979	--
Fuzeta	1951, 1964	1944, 1955, 1962, 1982, 1984	--	--
Lacém	--	--	--	1950, 1962

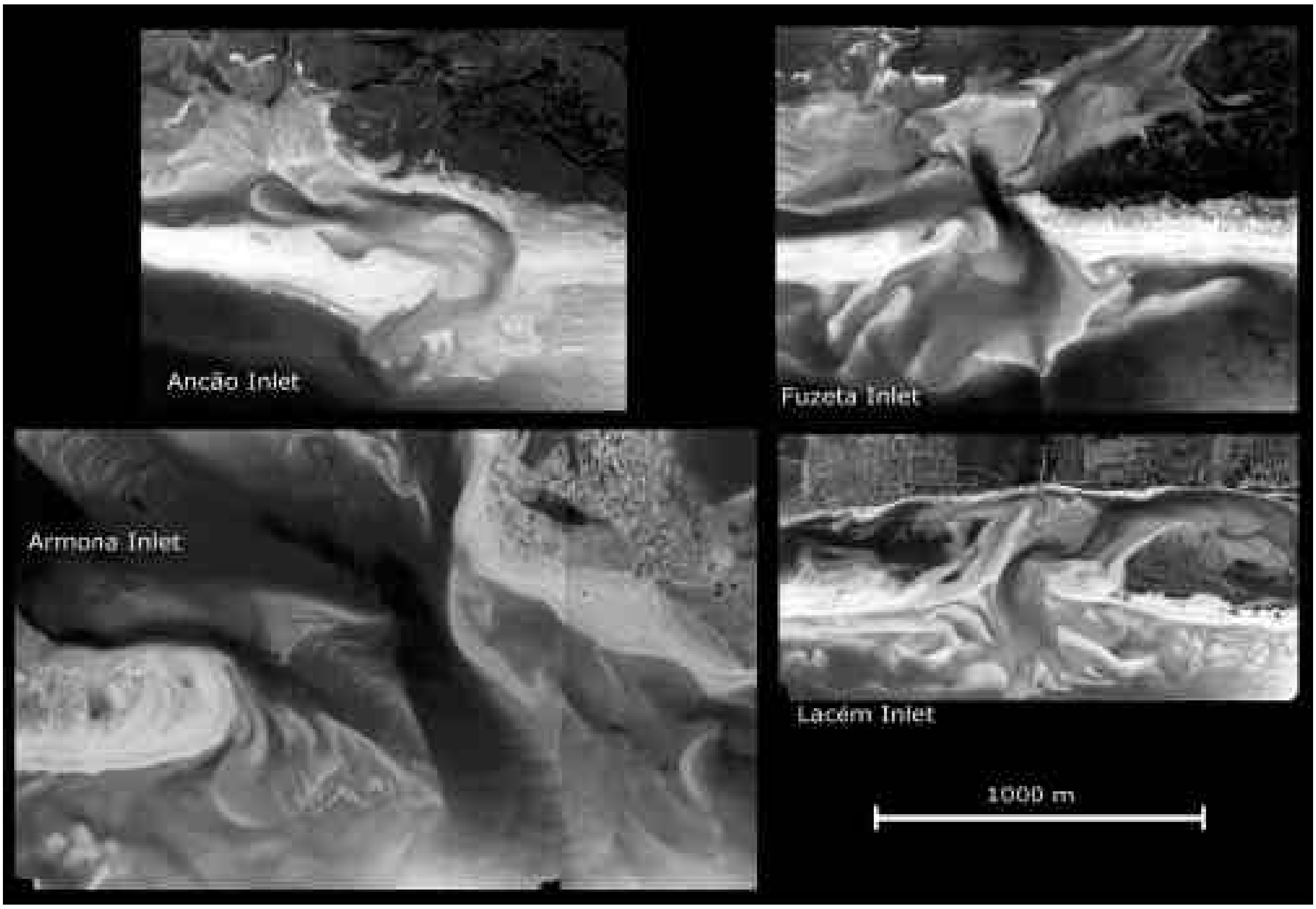

Figure 2. Aerial view of the natural inlets of the Ria Formosa barrier island system in 1996.

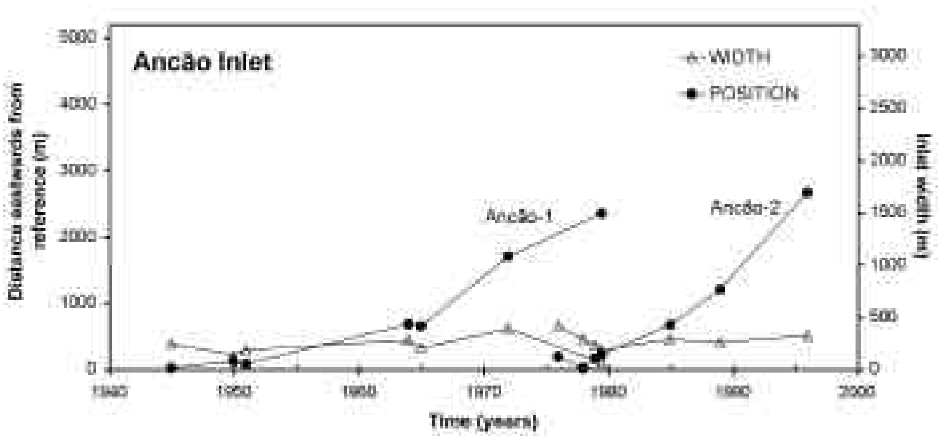

Figure 3. Inlet width and displacement evolution of Ancão Inlet.

Table 3. Details of curve fits obtained for the inlet migration patterns. A second order polynomial fit is used for all inlets, except for Fuzeta-b and Lacém, to express inlet position (P, in metres) in terms of time (t, in years), i.e. P= at2 + bt + c. For Fuzeta-b and Lacém inlets a natural logarithmic curve is used, i.e. P= a ln(t) + b. Determination coefficients (R^2) indicate the percentage of behaviour defined by the curve fit.

INLET	COEFFICIENTS			R^2
	a	B	c	
Ancão-1	2.16	-26.68	103.70	0.983
Ancão-2	5.54	-12.25	-0.29	0.998
Armona W	0.10	-15.44	-86.65	0.974
Armona E	0.15	-15.35	2173.00	0.825
Fuzeta-a	6.57	-111.40	442.78	0.942
Fuzeta-b	1820.6	-3901.2	--	0.960
Lacém	3141.0	-7161.0	--	0.988

about 50 m/yr for the periods 1945- 1976 and 1985-1989.

Migration rates were calculated separately for both channels, Armona W and Armona E. Eastwards migration occurred for Armona W with an average eastern migration rate of 22 m/yr, and a maximum of 43 m/yr between 1969 and 1976. Armona E showed a first stage of westerly migration with an average migration rate of 19 m/yr. Since 1976, the position of the eastern channel of Armona Inlet has shown little variation. Therefore, and essentially due to the eastward displacement of Armona W, the separation between the channels decreased during the study period. The comparison of the evolution of both channels showed an inverse r of –0.866 that is significant with a 95% of confidence.

The correlation between channel position and inlet width was calculated for both channels. It was observed that the decrease of inlet width was inversely related to the migration of Armona W (r=-0.923, significant with 99% confidence) and positively related to the westward displacement of Armona E (r=0.912, significant with 95% confidence).

The best curve fit for both channels was found to be a second order polynomial function, shown in Table 3.

Fuzeta Inlet

Fuzeta Inlet (Figure 2) width evolution and channel positions through the study period are shown in Figure 5. The date of the opening of Fuzeta Inlet is not known, although its western position in 1944, suggests it may have formed during the major storm of 1941.

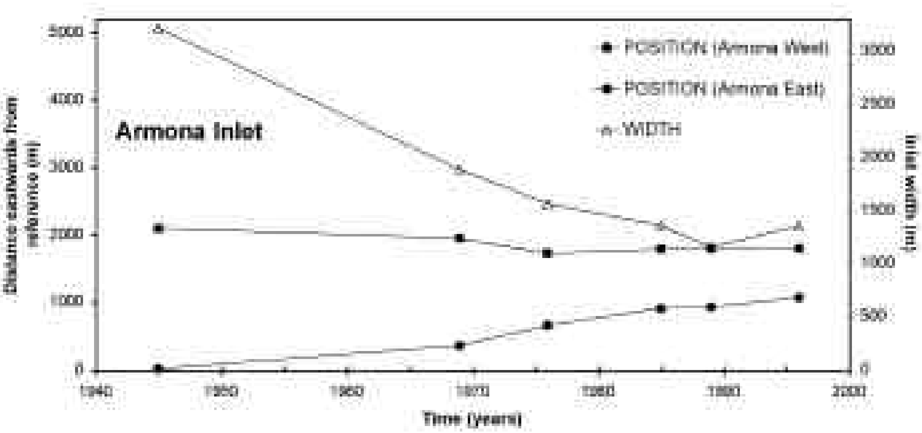

Figure 4. Inlet width and displacement evolution of Armona Inlet.

Inlet width showed strong variation during the study period, with an average width for the entire period of approximately 600 m. However, 3 stages can be distinguished: (a) between 1944 and 1951 inlet width decreased from 750 m to 130 m; (b) between 1951 and 1964 width increased dramatically to a maximum of 2050 m; and (c) between 1964 and 1996 inlet width decreased to 240 m in 1996. The most important inlet width change occurred between 1962 and 1969 with an initial increase rate of 550 m/yr, followed by a decrease of 260 m/yr. During this period, inlet morphology became more complex, with the existence of two channels. SALLES (2001) interpreted maximum inlet width in 1964 as the result of the opening of an inlet west of Fuzeta during a major storm in March 1961 (WEINHOLTZ, 1964; ESAGUY, 1986b), and the merging of both inlets in the period between 1962 and 1964 due to natural processes.

Inlet position (Figure 5) showed an eastward migration for the entire study period. Three migration stages can also be distinguished: (a) between 1944 and 1955 migration rates were low (average migration rate was 19 m/yr); (b) between 1955 and 1964 they were high, with an average of 259 m/yr; and (c) a period of moderate eastward migration at an average rate of 63 m/yr. The average migration rate for the entire study period was 82 m/yr. The maximum migration rate between 1962 and 1964 (410 m/yr) was possibly associated with the merging of the two inlets.

Correlation between inlet width and channel position was calculated for two periods, before and after the width peak of 1964. Between 1944 and 1964 there was a positive correlation (r=0.892, significant at the 95% confidence level) and between 1969 and 1996 there was an inverse r of –0.924 (significant at the 99% confidence level).

Two different curve fits for the migrating behaviour were calculated for the periods before and after the maximum width. For the period between 1944 and 1964 (Fuzeta-a) the best fit was given by a second order polynomial function (see Table 3), while the second period (Fuzeta-b) showed a logarithmic behaviour (Table 3). Several authors (ESAGUY, 1985; ANDRADE, 1990; SALLES, 2001) found 3,500 m to be the maximum distance migrated by Fuzeta Inlet. Therefore, in 1996, Fuzeta Inlet was near its eastern limit position.

Lacém Inlet

Lacém Inlet (Figure 2) was opened by the 1941 major storm (ESAGUY, 1986b). Data on inlet width evolution and channel migration is shown in Figure 6. The inlet channel showed an eastward migration for the entire study period. Inlet width showed some strong variations, with a generally decreasing trend.

The average width of Lacém Inlet was approximately 1,240 m for the entire study period, with a maximum recorded for 1962 (2,800 m), probably due to the major storm described by WEINHOLTZ (1964) and ESAGUY (1986b) that affected the study area in early 1961. A second high inlet width value was observed in 1976 (2,230 m), probably caused by the same storm that opened Ancão-2 inlet. Until 1976 Lacém Inlet showed 2 channels; merging of the channels caused a strong decrease in inlet width between 1976 and 1985. Lacém Inlet width was still decreasing between 1985 and 1996, however, at much lower rates.

The eastward migration rate of Lacém Inlet had an average value of 97 m/yr. However, migration rates were much higher between 1950 and 1976, with a maximum of

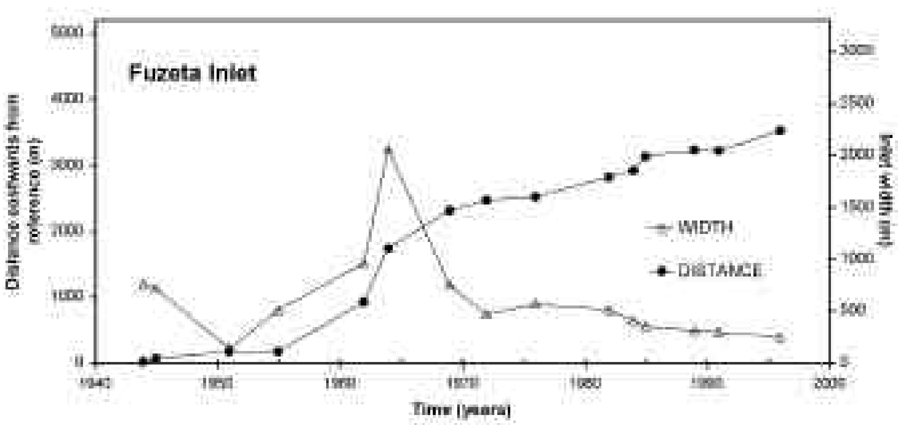

Figure 5. Inlet width and displacement evolution of Fuzeta Inlet.

204 m/yr between 1950 and 1962. The minimum migration rate occurred between 1985 and 1989.

Due to the existence of initial inlet width variations, the correlation between inlet width and channel migration was not calculated for the entire study period. Between 1950 and 1972 a correlation coefficient was not calculated due to the existence of only 3 data points with strong changes. However, between 1976 and 1996 there was a significant inverse correlation (r=–0.983 at 95% confidence level) that shows interdependence between inlet width evolution and channel migration.

The best curve fit for Lacém Inlet migration was found to be a natural logarithmic curve, whose function is shown in Table 3. This function describes reasonably well the behaviour of the inlet channel during the study period. The limit location that defines the end of Lacém Inlet eastward migration on Cacela Peninsula is unknown.

DISCUSSION

Natural versus stabilised inlets

Hydrodynamic studies carried out by SALLES (2001) indicate a division of the Ria Formosa barrier island system into 3 hydrodynamically quasi-independent sub-embayments: (a) the western sub-embayment, including Ancão, Faro-Olhão and Armona inlets; (b) the central sub-embayment, including Fuzeta and Tavira inlets; and (c) the eastern sub-embayment, only including Lacém Inlet. However, ANDRADE (1990) found that Tavira and Lacém inlets were part of the same sub-embayment. It is possible that at the beginning of the study period this could have been the case, however, with the migration of Lacém Inlet this connection would have become less obvious. Given the study period presented here, Lacém is considered to be included in the same sub-embayment as Fuzeta and Tavira inlets. Thus, a western (with Ancão, Faro-Olhão and Armona inlets) and an eastern sub-embayment (with Fuzeta, Tavira and Lacém inlets) are considered. This hydrodynamic division has important implications for the explanation of the effects caused by the artificial opening and stabilisation of both Faro-Olhão and Tavira inlets. Following this division, the artificial opening of Faro-Olhão Inlet (1929-1955) could have had significant consequences for Ancão and Armona inlets, whilst the opening and stabilisation of Tavira Inlet (1927-1985) could have had significant consequences for Fuzeta and Lacém inlets.

Stabilisation of the Faro-Olhão Inlet was completed in 1955 (ESAGUY, 1984). In Figure 3 it is seen that Ancão Inlet did not experience any significant changes during the first stages of the study period. ANDRADE (1990) found that Ancão Inlet is only connected with the rest of the system during late flooding or early ebbing stages of the tide. This hydrodynamic semi-independence of Ancão Inlet could have minimised the consequences of the opening and stabilisation of Faro-Olhão Inlet.

The effects of Faro-Olhão Inlet on Armona Inlet have been studied by ESAGUY (1984). According to this author, Armona Inlet decreased its width between 1873 and 1983 at an average rate of 20 m/yr and a maximum of 50 m/yr for the period between 1950 and 1977, with this maximum being related with the stabilisation of Faro-Olhão Inlet. Data presented here (see Figure 4), show that average decrease rates were about 30 m/yr for the entire study period reaching two maxima of 50 m/yr for the periods ~1945-1976, which can be directly related to the stabilisation of Faro-Olhão Inlet, and 1985-1989, whose relationship with these engineering actions is not clear. The works at Faro-Olhão Inlet enhanced an ongoing process, i.e. the reduction of Armona's Inlet width, a process ongoing since the end of the 19th century but which was highly accelerated. Another factor to be taken into account is that Faro-Olhão Inlet was dredged at a location where another inlet had existed before (ESAGUY, 1986b). The former inlet (Bispo Inlet), opened in 1861, was almost completely infilled when the construction of Faro-Olhão Inlet begun (SALLES, 2001). This may have minimised the consequences of the engineering works.

Tavira Inlet (Figure 1) was artificially opened for the first time in 1927, and closed soon after the opening (ESAGUY, 1987). In 1936 it was artificially re-opened and stabilised but it closed again by 1950 (ESAGUY, 1987). It was re-opened again in 1961 (after the March storm) and in 1985 it was finally dredged and stabilised (ESAGUY, 1987). Consequences of the 1961 re-opening of Tavira Inlet in Fuzeta and Lacém inlet evolution are not obvious in Figures 5 and 6, however, the spacing of the data does not allow differentiation between the consequences of the re-opening and those caused by the 1961 storm. The 1985 stabilisation does not seem to have had important consequences for Fuzeta or for Lacém inlet evolution. It is unrealistic to assume that Tavira Inlet opening and stabilisation in a multi-inlet system did not produce any strong consequences in the neighbouring inlets. However, it is important to note that the hydrodynamic efficiency of Tavira Inlet is very low, representing a very low percentage (about 4%) of the total tidal prism of the system (ANDRADE, 1990). Thus, its opening did not cause a strong influence on the hydrodynamics of the neighbouring inlets.

Migration trends

According to the results presented here, two main types of migration patterns can be distinguished inside the Ria Formosa barrier island system. Ancão Inlet represents migration where the updrift margin of the inlet is built approximately at the same rate as the downdrift margin is eroded (Figure 7a). Both the ebb and the flood deltas

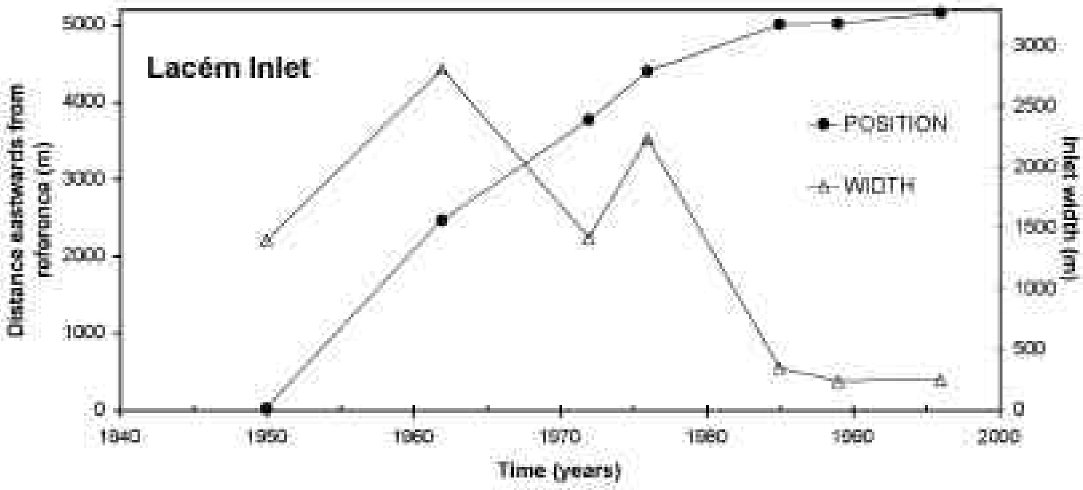

Figure 6. Inlet width and displacement evolution of Lacém Inlet.

migrate at approximately the same rate as the inlet channel (PILKEY *et al*., 1989), and inlet width is almost constant and therefore independent of inlet migration, except during the last stages of inlet closure (Figure 3). Migration patterns for Ancão Inlet showed an initial stage of readjustment, with low migration rates, followed by a stage of high eastwards migration rates, until it reached a limit position (about 2,700 m from inlet initial position). Lacém Inlet represents the second type of migration, where channel migration is accompanied by strong constructional processes on the updrift barrier, and consequently, by inlet width reductions (Figure 7b). This particular form of migration was first described by PILKEY *et al.* (1989) and exists at wide inlets formed by large storms that completely eroded portions of the updrift barrier. Inlet position with time at Lacém Inlet followed a natural logarithmic migration pattern accompanied by inlet width reduction, with the exception of the occurrence of large storm, when inlet width increased (Figure 6).

Differences between these two migration patterns are due to several reasons: (a) incident wave energy is much greater on the west flank and decreases towards the east, Cacela Peninsula being the least energetic area of the system (ANDRADE, 1990); (b) barriers located updrift from the inlets in the east flank have lower dune areas that present a high degree of overwash susceptibility (ANDRADE *et al*., 1998) and thus, destruction of large portions of these barriers is more likely to occur on the east flank of the Ria Formosa. However, these factors do not completely explain the different migration patterns obtained in this study.

Fuzeta Inlet is a mixed case where the inlet started with a pattern similar to the one observed for Ancão (see Figure 7a), however, as consequence of a major storm event, a large portion of Armona Island was eroded and Fuzeta Inlet became very wide. Since that time, the migration pattern observed for this inlet has been logarithmic and therefore, similar to that observed for Lacém Inlet (see Figure 7b). It appears that the destruction of the easternmost tip of Armona Island after the 1961 storm caused the change in the migration pattern. PILKEY *et al*. (1989) explained Fuzeta Inlet migration as occurring in a series of "jumps", as a new inlet would open during a storm at a short distance east of the former position. Data presented here do not show evidence of the migration occurring by "jumps", nevertheless, some "jumps" may have occurred without effecting the long term migration patterns of the inlet. An inlet "jump" would help to explain the very high migration rates found for the period 1962-1964. Consequences of the 1973 storm, that possibly opened Ancão-2 and caused a peak in Lacém Inlet width, on Fuzeta Inlet are not obvious in Figure 5. Overwash susceptibility in the vicinity of Fuzeta Inlet is not as high as around Lacém Inlet, and the maximum width of Lacém Inlet after the 1961 storm was much greater than the one recorded for Fuzeta Inlet. Thus, the energy required to erode Fuzeta Inlet margins and increase its width is greater than that needed to erode Lacém Inlet margins.

Armona Inlet represents a peculiar case. As explained previously, narrowing of the inlet has been an ongoing process since at least 1873 (ESAGUY, 1984). As shown in Figure 4, the two Armona channels are converging. ESAGUY (1984) stated that once both of the channels have merged, the remaining channel would get deeper and start an eastward migration similar to that described for Ancão Inlet. Data presented in this study do not show any evidence

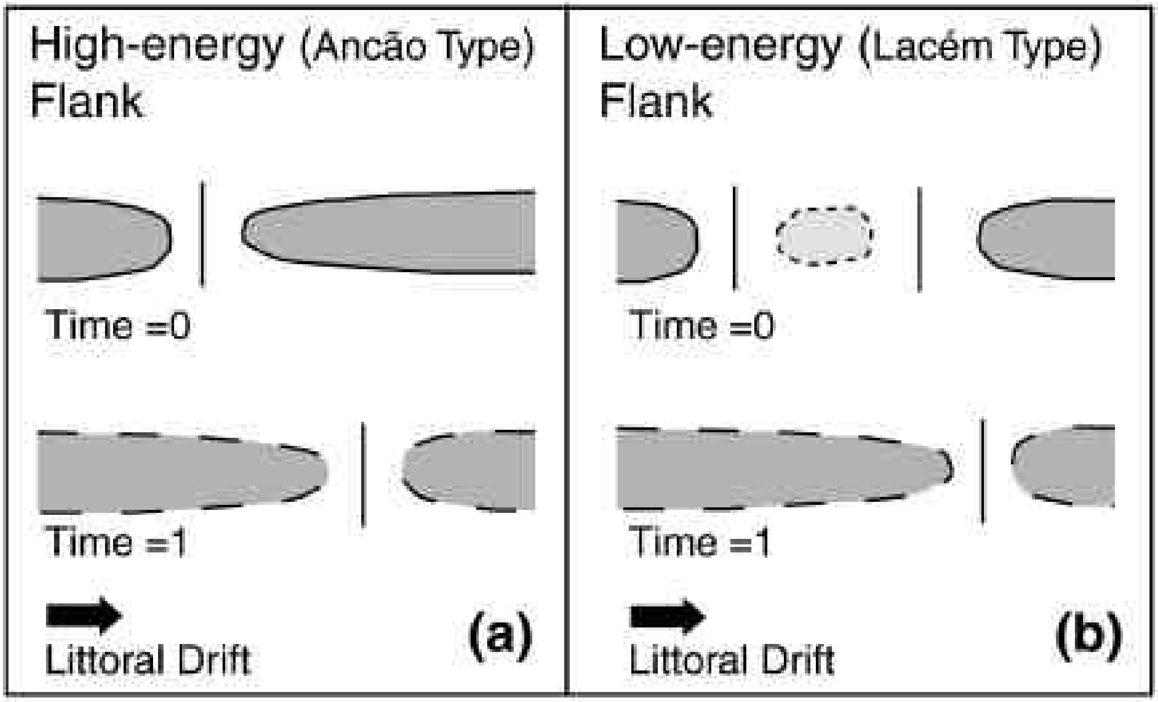

Figure 7. Typical inlet migration patterns determined for the natural inlets at the Ria Formosa barrier island system. (a) Represents the Ancão type of migration, typical for the high-energy flank. (b) Shows the Lacém type of migration, typical for the low-energy flank.

to supporting this theory, which can only be verified in the future, after the merging of the channels. However, it seems to be possible that Armona Inlet, like the other natural inlets located on the east flank, was formed during a major storm (perhaps in the last century) that eroded most of Culatra Island. Inlet migration (Armona W) due to updrift barrier re-construction, such as occurs at Lacém Inlet (see Figure 7b), is an ongoing process, showing slower rates that the other inlets with this type of migration pattern, i.e. Lacém Inlet and the second phase of Fuzeta Inlet.

CONCLUSIONS

A study of the evolution of the four natural inlets of a multi-inlet barrier island system is presented here. Both natural variations of the hydrodynamic forcing factors, and variations caused by engineering interventions, namely the artificial opening and stabilisation of two inlets on the east flank of the system, were taken into account.

The consequences of the artificial opening and stabilisation of an inlet are mainly related to three factors: (a) the existence of sub-embayments inside the system that constraints the number of natural inlets that will be under the influence of the engineering interventions; (b) the exposure to wave energy that affects inlet behaviour; and (c) the location of the artificial inlet within the system that determines its hydrodynamic efficiency.

Two sub-embayments were defined within the Ria Formosa barrier island system, the western including Ancão, Faro-Olhão and Armona inlets, and the eastern one, including Fuzeta, Tavira and Lacém inlets. Data presented in this paper showed that Ancão Inlet, due to its quasi-independency within the western sub-embayment, did not show any observable variations in its behaviour after the opening and stabilisation of Faro-Olhão Inlet. However, the width of Armona Inlet, which had been decreasing since the end of the 19th century, started to decrease at much higher rates, thus losing some of its hydrodynamic efficiency. It is believed that the consequences of the opening and stabilisation of Faro-Olhão Inlet were not greater because it was performed in a former inlet position. Due to the low hydrodynamic efficiency of Tavira Inlet, analyses performed for Fuzeta and Lacém inlet showed no directly related variations in their behaviour after the opening and stabilisation of Tavira Inlet.

Results presented in this study showed that long term inlet migration patterns are eastward for the whole system. Two very well differentiated migration patterns were found for this system: one for the high-energy (west), and one for the low-energy (east) flanks of the system. Migration patterns were found by analysing the relationships between inlet width evolution and inlet migration as well as by comparison of the shape of the curve fits. Typical migration for the high-energy flank is characterised by an initial stage of readjustment, with low migration rates, followed by a stage of high eastwards migration rates, until reaching a limit position. Inlet width stays reasonably constant during the entire migration cycle, thus r between inlet width and position is very low. Typical low-energy flank inlets are formed by barrier breaking during a storm, giving large values of inlet width during the initial stage. Migration patterns for the low-energy flank follow the trend of a natural logarithmic curve, where strong construction processes of the updrift barrier accompany channel migration. As a consequence, inlet width generally decreases with the migration, and values of r between inlet width and inlet migration are generally significant. Due to the high overwash susceptibility of inlet margins on this flank, inlet width could increase during large storms.

Forcing factors taken into account in this study were wave climate on each flank (including major storms) and coastal engineering interventions. However, there are other factors such as ebb/flood dominance that can affect inlet migration patterns, which are beyond the scope of this study. The study of these factors in the future would help the understanding of inlet migrating patterns.

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