CHAPTER 369

ALTERNATIVES TO BEACH STABILIZATION: CAMBRILS COAST CASE STUDY (SPAIN)

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ABSTRACT

A study of alternatives including a shoreline evolution numerical modelization has been carried out in order to both diagnose the erosion problem at the beaches located between Cambrils Harbour and Pixerota delta (Tarragona, Spain) and select nourishment alternatives.

INTRODUCTION

Cambrils and Montroig are two villages located in a zone of big tourism growth in the Tarragona coast (northeast of Spain) 35 km from Tarragona and 125 km from Barcelona, very well communicated by road, motorway and railway (see figure 1).

Due to the importance of this tourist zone the Spanish Ministery planned a beach nourishment project for the area, including six beaches (6,000 meter long): Verge del Camí, Llosa, Torrent d'en Gené, Ardiaca, Riudecanyes and Pixerota.

The Cambrils Harbour construction in the thirties with a breakwater reaching the active depth, acting as a sediment transport barrier, strongly modified the littoral dynamics on beaches located southwest, suffering a severe regression only partially controlled by stabilization works carried out, which consisted basically in the construction of detached breakwaters and sand contribution. The efficiency of those works wasn't completely satisfactory, and the coastal zone between Cambrils Harbour and Pixerota delta presents nowadays a clear lack of stability with a general trend to regression.

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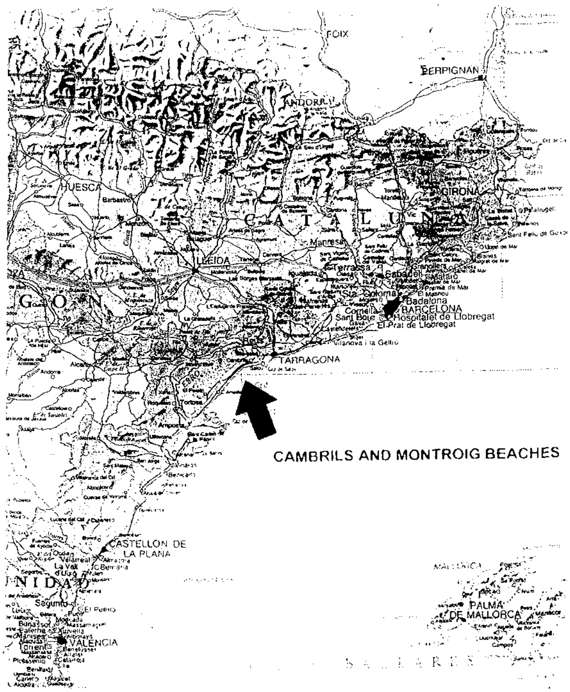


Figure 1: Location plan

MARITIME CLIMATE

The wave data used were:

- Cap Tortosa directional buoy, belonging to the General Directorate of Ports and Coasts of the Catalonia Autonomous Government during the interval 90/6 to 93/6, located at 0°58'6'' E, 40°44'6'' N coordinates in a depth of 45 m.
- Visual data registered at Casablanca oil platform during the interval 1983-1988, located at 1°21'30'' E, 40°43'3'' N coordinates in a depth of 170 m.
- Visual data registered by ships in the zone 0°-2°20'E, 40°-41°30'N and treated by the National Oceanic and Atmospheric Administration in Asheville.

The three data are valid though each of them presents some inconvenients:

- The Cap Tortosa buoy data have great reliability for being instrumental registers, but encompass a period of only three years.
- The ship visual data present a longer temporal interval, enough to represent the average zonal climate, but they have lesser reliability because of their origin.
- The Casablanca visual data present an intermediate reliability compared to other data.

NATIVE SAND GRANULOMETRIC ANALYSIS

A complete topographic and bathymetric survey of the studied zone was made including from dry beach to depth -13, deeper than active depth. At the same time a native seabed sand sampling campaign was performed: sixty sand samples in twelve profiles at five depths (+2.5, ±0.0, -3.0, -5.0 and -8.0) were analyzed obtaining the results shown in table 1.

Sample	D_{16} (mm)	D_{50} (mm)	D_{84} (mm)
+2.5	1.568	0.549	0.290
±0.0	1.684	0.553	0.296
-3.0	0.453	0.299	0.180
-5.0	0.439	0.312	0.221
-8.0	0.439	0.311	0.212
Total	0.859	0.390	0.232

Table 1: Native sand granulometry

BORROW SAND GRANULOMETRIC ANALYSIS

Studies performed in the last years verified the existence of submarine sand banks close to the project area, capable of being used for beach nourishment (as in the L'Hospitalet de l'Infant beach regeneration).

Another possible source for borrow sand was the material originated by the granite meteorization, locally known as "sauló". There existed four quarries near the project area that had been already used by the Ministery with satisfactory results.

The representative mixture granulometric characteristics for the two borrow sand types are shown in the table 2

	D_{16} (mm)	D_{50} (mm)	D_{84} (mm)
"Sauló"	1.568	0.549	0.290
Seabed sand	1.684	0.553	0.296

Table 2: Borrow sand granulometry

REGENERATION CHARACTERISTICS

There isn't a general rule that relates submerged beach slope with sand granulometry. However it's known that the slope proportionaly increases with the average sand grain size.

R. Silvester in his classical publication "Coastal Engineering" showed relationships between the beach slope and the sand size for three types of beaches: protected, semi-exposed and exposed.

For the different native sand samples the relation between beach slope and grain size was analyzed, obtaining figure 2, in which the three theoretical curves before mentioned were drawn, too. The values measured in Cambrils and Montroig beaches were located on the curves, representing exposed beaches. The borrow sand average size (0.42 or 0.92 mm) was located in the upper zone of the figure, where an additional dotted line representing Cambrils and Montroig beaches was drawn.

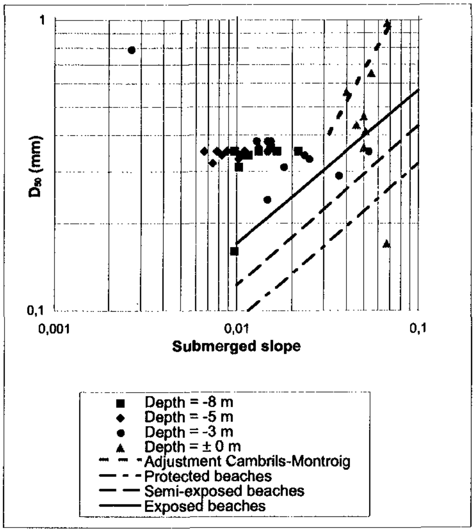


Figure 2: Submerged beach slope vs. Average grain size

In 1984 Garau and Friedman suggested a beach profile model for the case of sand classified by littoral processes for open beaches in the Mediterranian. The beach slope could be calculated using the average diameter D_{50} by means of the expression

$$m = 0.075 + 0.035 \cdot \ln D_{50}$$

Finally, from eroded profiles analysis Vellinga (1984) got a relationship between beach slope (with a certain granulometry) and slope (with another grain size):

$$m_1 = m_2 \left(\frac{w_1}{w_2} \right)^{0,56}$$

where w is the grain fall velocity. Once known the Cambrils and Montroig beaches grain sizes (D_{50} = 0.39 mm) and slopes (between 1V:30H and 1V:57H) and borrow sand sizes (D_{50} = 0.42 or 0.92 mm) the design beach slope could be calculated. The Ministery finally chose the seabed sand option with 1V:50H as submerged slope.

The estimation of longshore sediment transport rate induced by breaking wave actionwas used to obtain the zero transport direction, that is the shoreline orientation for which the average sand movement is zero.

A first estimation using the Komar's formulation was made in the assumption of straight uniform beach. The calculations were made for different shoreline orientations between 10°N and 115°N and for the three wave data (see figure 3). It can be noticed that the differences between the ship and Casablanca visual data curves are relatively little whereas the Tortosa buoy data curve differs much more (this is probably due to that the differences between the ship and Casablanca visual data curves are relatively little whereas the Tortosa buoy data curve differs much more (this is probably due to the shorter time interval which could be not completely representative of average local climate). It can be observed too, that for the real shoreline orientation (around 60° N) the transport direction is NE-SW, as it could be deduced from sand accumulation north of Cambrils Harbour (that acts as total barrier to sediment transport). A further analysis indicated that sediment transport values estimated with the ship visual data seemed to be overestimated, specially gross transport, so the most representative data appeared to be those obtained from the Casablanca data. In this case the zero transport orientation was approximately 38°N.

The average incident wave direction was also estimated according to

$$D_{av} = \frac{\sum_i D_i \cdot p_i}{\sum_i p_i}$$

where p_i is the presentation probability, obtaining a value D_{av} = 135,1°N, very close to the zero net transport direction. Therefore this was considered as the average wave direction, value very similar to the perpendicular to the shoreline orientation north of Cambrils Harbour, were there is no sand movement.

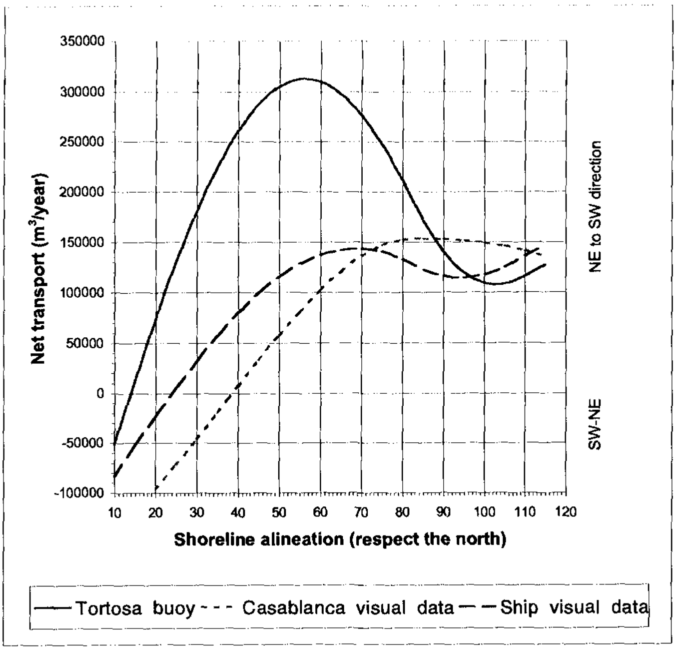


Figure 3: Net sediment transport

HISTORICAL EVOLUTION

A previous step to alternatives study was the shoreline historical evolution analysis in order to know the situation in the area between Cambrils Harbour and Pixerota delta, and how the existing beaches were formed. Five aerial photographs restitutions corresponding to 1947 (February), 1957 (June), 1965 (August), 1973 (June) and 1977 (March), two aerial photopraghs (not restituted, for qualitative estimation, June of 1983 and May of 1990) and May 1994 bathymetry were used for the analysis.

Historically the Cambrils and Montroig coast presented a continuous beach nourished by the sand transported by littoral drift in NE-SW direction. The Cambrils Harbour, built in the late thirties, became the main artificial barrier to sediment transport.

The main local sedimentary sources are the existing streams (Alforja, Verge del Camí, Torrent d'en Gené, Riudecanyes and Pixerota) characterized by a discontinuous flow, only important during storms periods. Some of them have created small deltaic formations with coarser material (gravels).

The correspondence between the beaches located south of the harbour and its distance or kilometric point (KP) is

Verge del Camí (**V**)	100 to 900	L'Ardiaca (**A**)	2300 to 2800
Llosa (**L**)	900 to 1800	Riudecanyes (**R**)	2800 to 3400
Torrent d'en Gené (**T**)	1800 to 2300	Pixerota (**P**)	3400 to 5400

The 1947 shoreline included the Cambrils Harbour presence and became the comparison base for the study. In the period 1947-1957 the **V**, **L**, **T** and **A** beaches eroded in average 2.7, 2.8, 1.8 and 2.1 meters/year respectively, although the first 200 meters of **V** beach advanced 0.8 m/year. The first 400 meters of **R** beach eroded 1 m/year whereas its last 200 meters advanced 0.4 m/year. **P** beach eroded an average of 0.9 m/year. The cause of this behaviour was the interruption of sediment transport by Cambrils Harbour that in the zone had the NE-SW direction: therefore beaches located SW of the port became the main nourish source for the littoral current, so its erosion process started.

Between 1957 and 1965 the generalized erosion process continued with an absolute lower value in the northern half. The average regressions were 0.7, 1.4, 1.1, 1.1 and 1.1 m/year respectively, though the first 350 meters of **V** beach advanced 1.5 m/year. The first 200 meters of **P** beach advanced 0.4 m/year whereas the rest eroded in average 1.1 m/year.

In the period 1965-1973 the **V**, **L**, **T**, **A** and **R** beaches eroded an average of 1.4, 1.9, 1.9, 1.3 and 0.2 m/year respectively, although the first 300 meters of **R** beach advanced 0.3 m/year. The first 200 meters of **P** beach advanced 0.5 m/year whereas the rest eroded 1.0 m/year.

This means that in 1973 the average shoreline erosion for the sector was between 20 and 55 meters in comparision to 1947 (with extreme values of 70 meters). So in 1976 the first stabilization project was performed, consisting in the construction of four detached breakwaters, the enlargement of an existing breakwater and the nourishment of sand to generate tombolos behind the detached breakwaters that stabiliced the **V**, **L**, and **T** beaches. Nevertheless the lack of sediment proceeding from the three first beaches which in the past had nourished partially the littoral current accelerated the erosion process in the rest of beaches: the **A**, **R** and **P** beaches eroded in average 1.7, 3.6 and 1.9 m/year.

Thus, in 1985 a second stabilization project was carried out, with the construction of two additional detached breakwaters to protect the **A** and **R** beaches and six artificial islands between the detached breakwaters and the coastline to optimize its behaviour that had caused important erosions at the center of the protected beaches. Since then the northern beaches shoreline position hasn't varied substantially, indicating its stability, while the Riudecanyes delta and **P** beach have continued to erode with an average of 0.6 and 1.6 meters/year.

All this values are summarised in table 3 whereas all the shoreline evolution is represented in figure 4.

Beach	Verge del Camí		Llosa	Torrent d'en Gené	L'Ardiaca	Riudecanyes		Pixerota	
1947-57	+0.8	-2.7	-2.8	-1.8	-2.1	-1.0	+0.4	-0.9	
1957-65	1.5	-0.7	-1.4	-1.1	-1.1	-1.1		+0.4	-1.1
1965-73	-1.4		-1.9	-1.9	-1.3	+0.3	-0.2	+0.5	-1.0
1973-77	Tombolos generation		Tombolos generation	Tombolos generation	-1.7	-3.6		-1.9	
1977-94	Tombolos generation		Tombolos generation	Tombolos generation	Tombolos generation	Tomb. gen.	-0.6	-1.6	

Table 3: Average annual accretion and erosion summary

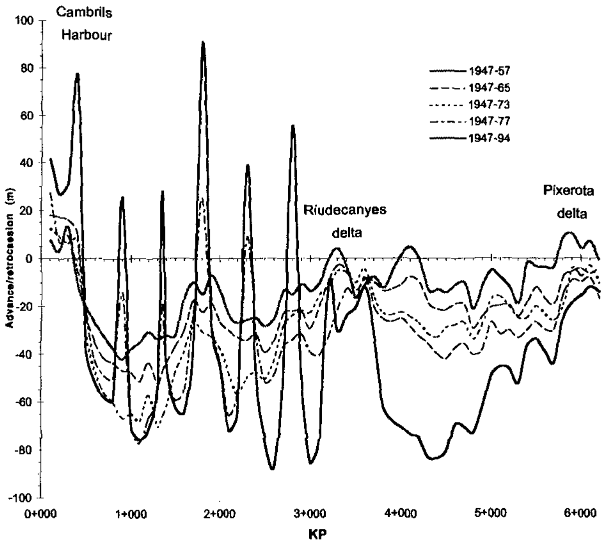


Figure 4: Shoreline evolution between Cambrils Harbour and Pixerota delta

From shoreline variations the volume of sand mobilized by wave action between Cambrils Harbour and Pixerota delta was estimated in 35,000 m^3/year with a direction NE-SW.

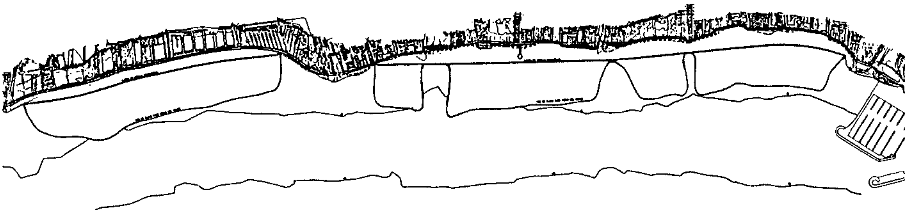
ALTERNATIVES STUDY

In the study carried out nine stabilization alternatives were analysed, taking into account flexible solutions (just sand nourishment) and rigid ones (new breakwaters). All of them included the demolition of the existing detached groins until the depth -2.0 and considered a minimum dry beach width of 60 meters (see figure 5). The quarry and sand volumes required and budgets for each alternative are presented in table 4.

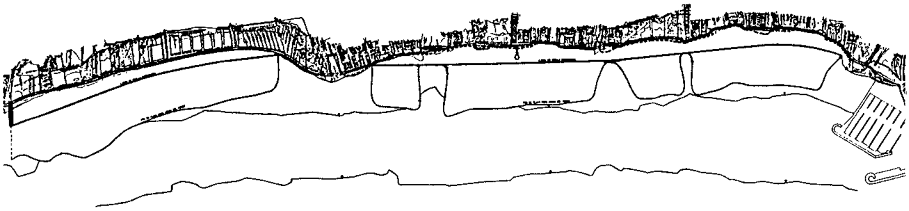
- *Alternative 0:* It consisted exclusively in sand contribution between Cambrils Harbour and Pixerota delta. From the historical shoreline evolution study it was estimated that 8 years after nourishment the erosion in the northern beach would be important enough (about 20 m) to consider a periodical sand contribution south of the harbour at a rate of 35,000 m^3/year.
- *Alternative 1:* Compared to alternative 0 it included a 142 m long groin at the Pixerota delta to ensure a beach support. The groin was designed short enough to let the sediment pass (and nourish southern beaches as Rifà and Porquerola), so the same periodical contributions that in alternative 0 were necessary.
- *Alternatives 1a, 2, 2a:* Compared to option 1, they incorporated one, two and three groins respectively with the same purpose, being also permeables to sand movement.
- *Alternative 2b:* In this case the groins position was very similar to alternative 2a, but they were much longer and included submerged toes in order to stabilize completely the new three northern beaches (untill Riudecanyes delta), as littoral transport was completely interrupted. The southern groin (at Pixerota delta) was the same than in alternatives 0 to 2a. From historical shoreline evolution study it was estimated that 17,500 sand m^3/year would be mobilized in direction NE-SW between Riudecanyes and Pixerota deltas and would cross the last groin to nourish partially the southern beaches (Rifà, Porquerola...). Therefore there would exist in those beaches an insufficiency of 17,500 m^3/year that should be added periodically south of Pixerota delta to avoid its erosion. Moreover, the sand mobilized along the new Pixerota beach would produce important erosions in the northern part, so it was estimated that 8 years after the regeneration periodical sand contributions (17,500 m^3/year) south of Riudecanyes delta would be necessary.

Alternative	**0**	**1**	**1a**	**2**	**2a**	**2b**	**3**	**4**	**5**
KTn of demolished quarry	183	183	183	183	183	183	183	183	183
KTn of quarry for new groins	0	15	37	53	76	352	379	350	291
Km^3 of sand for initial nourishm.	1,695	1,930	2,613	2,684	2,742	3,954	2,841	2,691	2,699
Km^3 of sand for periodical contributions	770	770	770	770	770	787.5	787.5	787.5	787.5
Budget (M$)	13.3	14.3	17.0	17.3	17.6	24.3	20.4	19.5	19.0

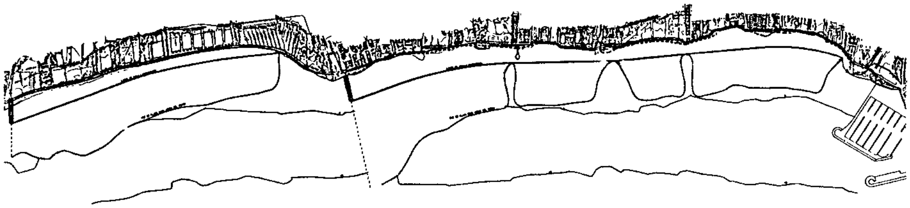
Table 4: Quarry and sand volumes required and budgets



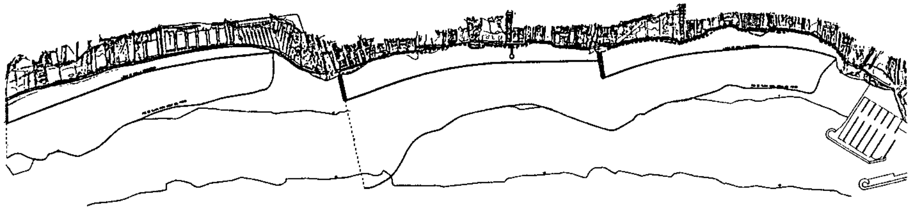
Alternative 0



Alternative 1



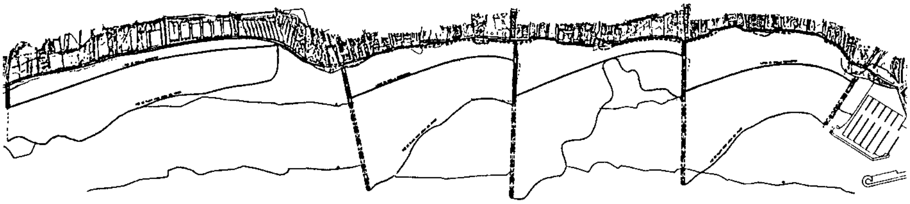
Alternative 1a



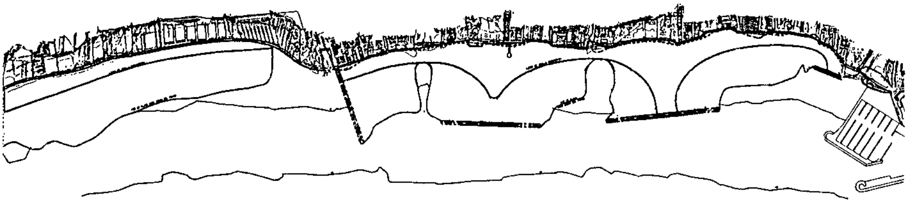
Alternative 2

Alternative 2a

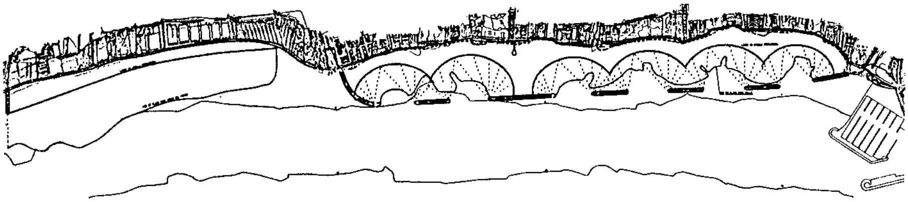
Figure 5a: Suggested regeneration alternatives



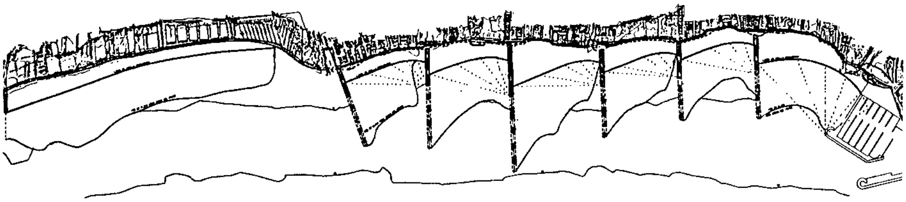
Alternative 2b



Alternative 3



Alternative 4



Alternative 5

Figure 5b: Suggested regeneration alternatives

- *Alternatives 3, 4 and 5:* They had the same purpose than the previous alternative but the complete stabilization of the northern beaches was obtained respectively by means of: *a)* two long detached groins and one transversal groin with a submerged toe, *b)* seven detached groins and *c)* six transversal groins between 157 and 214 meters long with submerged toes respectively. In the Pixerota delta the same groin than in alternative 2b was designed.

SHORELINE EVOLUTION NUMERICAL MODELIZATION

After having presented the nourishment alternatives, the shoreline evolution numerical modelization for three of them (1, 1a and 5) was carried out with the GENESIS v 3.0 program.

A thorough calibration process was done in order to obtain transport coefficients for the area, necessary for long term coastal evolution predictions of the alternatives selected. For calibration the 1947 and 1957 shorelines were used. Different simulations were made by varying the formulation parameters until obtaining a proper adjustment between the numerical values of the longitudinal transport and shoreline evolution in comparision with measured values. This adjustment was obtained for $K_1 = 0.40$ and $K_2 = 0.20$

Long term simulations (10 years) were made in order to estimate the beach evolutive trend for the three alternatives. In figure 6 results for the alternative 1 modelization are presented. It can be noticed the main problem is that the shoreline erodes half of the beach amplitude (won with the nourishment) five years after the regeneration at certain points. Therefore a second prediction including periodical sand contributions was made (figure 7). After some tests it was estimated that a 38,000 m^3/year contribution stabilized the beach. This value was very similar to that estimated in the alternatives study. At Riudecanyes and Pixerota deltas the maximum erosion was limitated due to its granulometric characteristics (gravels and boulders). This methodology was repeated for the 1a and 5 alternatives.

CONCLUSIONS

The alternative 1a was selected by the Ministery and a construction detailed design was developed in order to prepare the tendency of the works. Main quantities and budget for the project are:

Tn of quarry demolished from existing groins:	193,000
Tn of quarry for new groins:	81,000
m^3 of sand for initial beach nourishment:	2,616,000
Total budget (M$):	15.6
Length of beach stabilized:	5.2 km

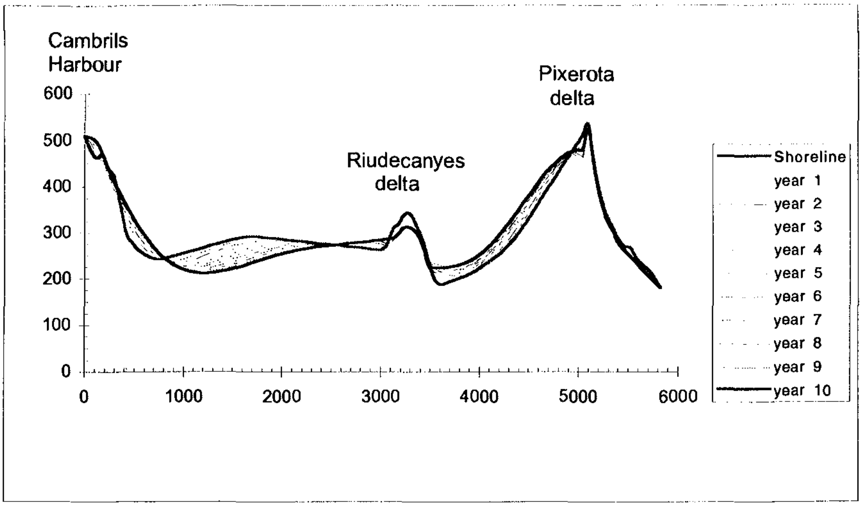


Figure 6: Alternative 1 shoreline evolution prediction without periodical sand contributions

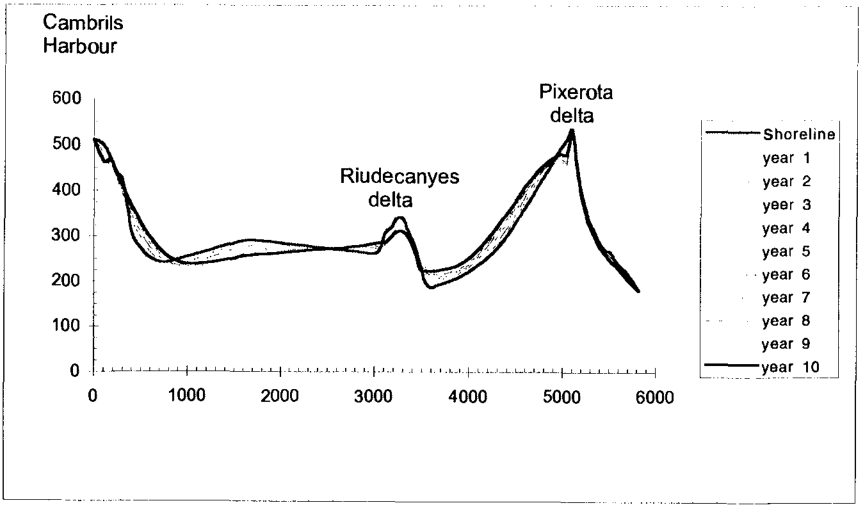


Figure 7: Alternative 1 shoreline evolution prediction with periodical sand contributions