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Composition and Transport Dynamics of Suspended Particulate Matter in the Bay of Cadiz and the Adjacent Continental Shelf (SW - Spain)

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Additional information is available at the end of the chapter

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1. Introduction and objective

The quantification of suspended particulate matter (SPM) and the investigation of its dynamics are of major importance to understand sediment transport dynamics and many land-shelf-ocean interaction processes [1, 2, 3, 4, 5, 6]. The analysis of SPM transport processes in the marine environment requires a simultaneous study of water masses dynamic and movement, the direction and intensity of the currents as well as the characteristics of the suspended matter and the characteristics of the bottom sediments [7, 8, 9]. The application of remote sensing techniques to the study of suspended matter dynamics allows model for marine and coastal water circulation, based on the use of "turbidity patterns" as natural tracers; relating parameters of water quality to satellite images [10, 11, 12]. The utility of satellite images lies in the high frequency with which data can be taken on a point of the earth. This allows a large volume of information for various meteorological situations, that would be very difficult to obtain using conventional sampling methods. However, images must be calibrated and evaluated using "in situ" data [13].

Studies on the behaviour of suspended particulate matter have been made by many oceanographers and sedimentologists [14, 15, 16]. Several authors have studied the mineralogy of suspended matter, in order to investigate the influence of tides in estuarine systems and the relationship between the minerals in suspension and those deposited [17, 18]. Others studies have been focused on the possibility of using clay minerals in suspension as tracers, allowing to follow the progression of the river flows path in marine environment [19, 20, 21]. In the Gulf of Cadiz, Several works have been realized with the objective of determining the suspended matter content and their influence on the recent marine sedimentation [8, 22, 23].

Studies about the dynamics of fine sediments and clay minerals in the bay of Cadiz and the adjacent marine deeper zones have been approached [24, 25, 26]. The paths by which fine sediment are transported from different source areas to the marine environment have been deduced, using clay minerals as dynamic tracers [27, 28]. Others studies have been focused on the sedimentary exchange dynamics between inner area of Cadiz bay and the continental shelf [29, 30, 31]. The main objective was the determination of the nature and origin of the suspended particulate matter in the bay of Cadiz, as well as the hydrodynamic behaviour of turbidity plumes and the dispersal of SPM and its effects on the inner continental shelf. The proposed chapter is based on data of suspended particulate matter concentration, mineralogical compositions, degrees of turbidity, Landsat images analysis and complemented by grain sizes and hydrodynamic data. The combined study of dispersal of suspended sediment and degrees of turbidity by analyzing Landsat images, allows to recognize the transport paths followed by the fine sediments in the surface marine waters from the inner areas of Cadiz bay to the external zones and the adjacent continental shelf.

2. Area description

The study area is located at the Southwest of the Iberian Peninsula, between the mouth of the Guadalquivir River and the Trafalgar Cape (Fig.1).

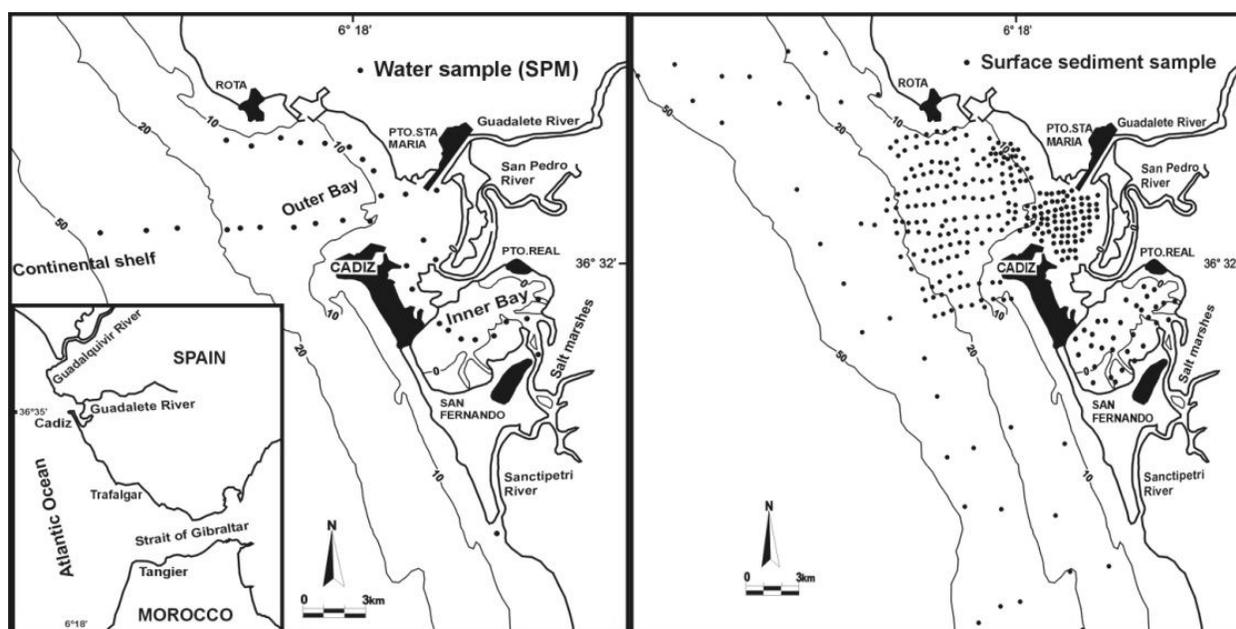


Figure 1. Geographical setting and location of surface sediment and water samples in the study area.

The Bay of Cadiz is about 28.5 km long and 13.5 km wide. Three sedimentary environments are distinguished: The outer bay (surface of about 118km²), located to the north, is divided into two zones, a western and an eastern one, with presence of rocky outcrops in the North (Rota) and south (Cádiz), resulting slopes of 2°. The outer bay, is well connected to the conti-

mental shelf, and is very affected by the waves, currents and storms. The inner bay (Surface $\approx 40 \text{ km}^2$) or Lagoon system located to the South and protected from waves and storms of the West and Southwest. Characterized by shallow water ($<5 \text{ m}$ depth and slope of 0.15°), except in the navigation channel connecting the inner and outer bay (12 m depth and slope of 2.2°). The salt marshes and tidal flat (Surface $\approx 227 \text{ km}^2$), occupy the most internal and sheltered areas, drained by a complex system of tidal creeks and channels of great importance in the hydrodynamic. This wide marshes zone occupied by halophyte vegetation is isolated from the open sea by sandy beach ridges and littoral spits.

2.1. Oceanographic setting

The zone is affected by a mesotidal regime, where the mean tidal range is 2.39 m . In spring tides the highest range reaches 3.71 m and in neap tides the lowest range is 0.65 m [32]. In the Bay of Cadiz, the bottom morphology influences the behaviour of the tidal wave, causing a time delay of 12 minutes between the outer and the inner bay. The speed of the tidal current is highly variable, with the highest values reached inside the Bay of Cadiz, where the highest speeds have been determined along the Strait of Puntales [33], reaching values over 1.5 m/s during spring tide ebbs. The input and output flows, are controlled by the tidal regime. The tidal currents oriented SW-NE are directed into the bay, while the ebbs (NW-SE) outwards [34, 35]. They are responsible of fine sediment transport from inner zones toward the external bay and continental shelf [36]. Wind and waves action are also essential factor in the sedimentary dynamics. Waves present seasonal character and the storm average frequency is of 20 days/year. The strongest storms occur in the fall-winter season and the calm periods during the summer. The prevailing swell is from the west. The data from the point WANA 1054046 in the WANA network, show that the waves from the W and SW represent 70% of the time for the period 2006- 2012 (Fig. 2). Storm waves are related to southwest Atlantic storms [37]. Mean significant wave height ($H_{1/3}$) is 0.85 m and represent 45%. The most common periods range from 3 to 4 seconds. The maximum values of $H_{1/3}$ reached during storms are 4 m . with periods of 6.24 s [38].

The main littoral-drifts spreads towards the southeast, generating transport in the same direction because of the coastal orientation, facing westerly and SW winter storms. Easterly winds also generate littoral-drifts towards the North and NW. In the continental shelf, the hydrodynamic regime is controlled by the North Atlantic Surface Water (NASW) moving towards the southeast, and is responsible for the dispersal of fine sediments from the Guadalquivir and Guadiana Rivers (annual flux of 9200 km^3 and 5500 km^3 respectively) [39,40, 27, 28]. The Mediterranean Outflow Water (MOW) moving west to deeper water [41, 42] and do not have an influence on the present day sedimentation in our study area.

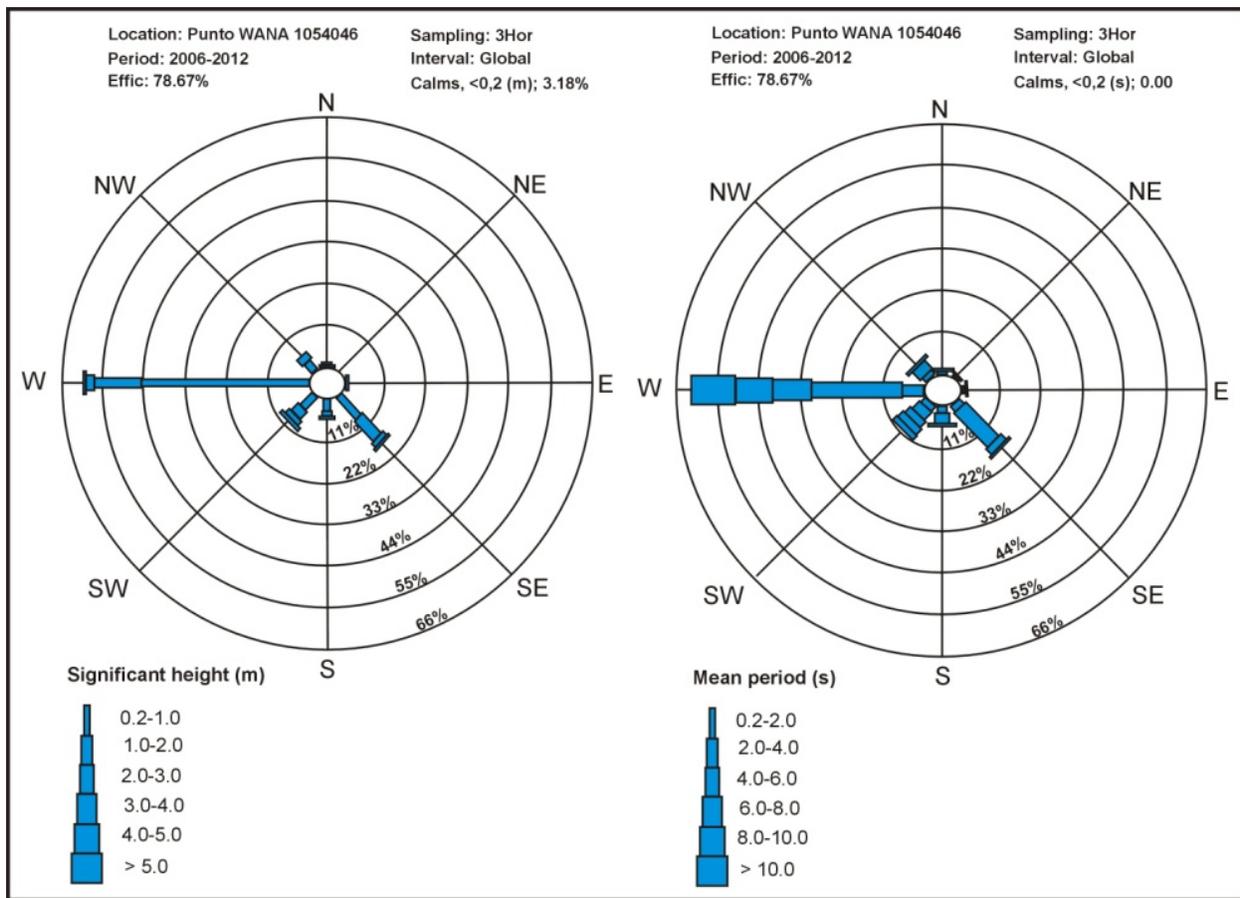


Figure 2. Significant height and peak period rose in the study area (Wana point 1054046).

2.2. Physiographic and Geologic framework

The coastline physiography is oriented NNW-SSE, with some sectors facing E-W that give the coast a stepped outline, strongly controlled by tectonic fractures [43]. The influence of tectonic structures and coastal morphology constitute an essential factor in the hydrodynamic control of the sedimentation and distribution of facies in the bay of Cadiz and the continental shelf [44, 45]. An Early Quaternary compressive tectonic episode has been deduced from reverse faults observed in marine sediments of the continental margin [46]. The continental shelf has a gentle slope and a slight inclination toward the west, with an average width of 40 km and is oriented from NNW-SSE with NNE-SSW sectors. The physiography of the sea-bottom shows a close concordance with the shoreline, the isobaths generally running parallel to the coast. The slope break occurs at 150-200 m water depth and shows significant variation north to south in cross section [26, 47]. The most important geological formations present in the surrounding areas of Cadiz bay are mainly pre-orogenic units from the Betic Mountain Range. Other units outcropping are Post-orogenic formation from the Neogene Guadalquivir basin. Upon all those materials, appear Quaternary deposits constituted by muddy marshes, beach sands and continental deposits [48, 49, 50, 51, 52, 53, 54].

3. Materials and methods

The study of concentration of suspended particulate matter (SPM) was based on the analysis of 36 water samples obtained in different zones of the study area (tidal creeks and channels, river mouths, lagoon, etc). The study of surface sediments was carried out on 250 samples collected from different sectors of the bay of Cadiz and the adjacent continental shelf (Fig.1). The sample position was determined by Differential Global Position System (DGPS) and errors made in the horizontal DGPS positioning were verified as being less than 2m. The extraction of surface sediments was performed by means of *Van Veen* dredge and gravity cores. The water samples were taken 3hours after high tide, wind from the north and north-east, average speed of 55km/hr and mean wave height of 0.6 and maximum of 1.5m. The extraction of samples was executed to specific depths with oceanographic bottles, simultaneously with the passage of the Landsat satellite over the study zone. The purpose of this operation is to obtain a synoptic picture of the turbid flumes, by comparing the data obtained from direct methods (water samples) and those of indirect methods (satellite images). The separation of SPM has been achieved following the method of [55], which consists to the filtration of a volume of five liters of water through pre-weighed filters by MILLIPORE (0.45 microns). Filters were washed with distilled water, dried at about 60°C and weighed. The $<2\mu\text{m}$ fraction was separated by a standard sedimentation method [56, 57]. The use of satellite images in this study is based on the utilization of inorganic SPM as a natural tracer. Satellite images of the Bay of Cadiz have been recorded by the satellite TM Landsat, using bands 2 and 5, and a spatial resolution of 30x30 m. Landsat images has been analysed to obtain extent and direction of turbidity plumes in several hydrodynamic situation in Cadiz bay and inner shelf waters. The process of the images has been carried out according to the methodology described by [58].

Systematic granulometric and mineralogical analyses were carried out to establish facies distribution and mineralogical composition. The collected samples (approximately 250 g of surface sediments) were placed in plastic bags sealed and identified. The Grain size of coarse fraction was determined by dry sieving sediments, using sieve column ranging from 4 Phi (0.063 mm) to -2 Phi (4mm). The fine fraction analysis was made by use of laser diffraction analyser (AMD). Grain size data were processed by GRADIST software (version 4.0). The characteristic statistic indexes and parameters were calculated using standard method [59, 60]. The mineralogical analysis of suspended particulate matter (SPM) and surface sediment was made through X-ray Diffraction techniques (XRD) using a Philips PW-1710 diffractometer, equipped by Cu-K α radiation, automatic silt and graphite monochromator. Quantification of different mineralogical phases was calculated by the classic method of area measurement of peaks, considering the different reflection capacities of the minerals [61, 62]. Factor Analysis (Principal Components Analysis, PCA) was used to determine the mineral assemblages and to establish possible sediment transport paths from the bay toward the continental shelf.

4. Results

4.1. Surface Sediment Characteristics

Grain size analysis of modern sediments of Cadiz bay bottoms show that samples are mainly composed of sand and mud, and subordinate amounts of gravel. The grain size distribution shows the predominance of the coarser fractions in the outer bay, more exposed to wave action and currents. The finer fractions appear in more sheltered zones of the bay.

Taking into account the textural characteristics of the marine deposits and the sedimentary environments, we can differentiate various types of sediment (Fig. 3).

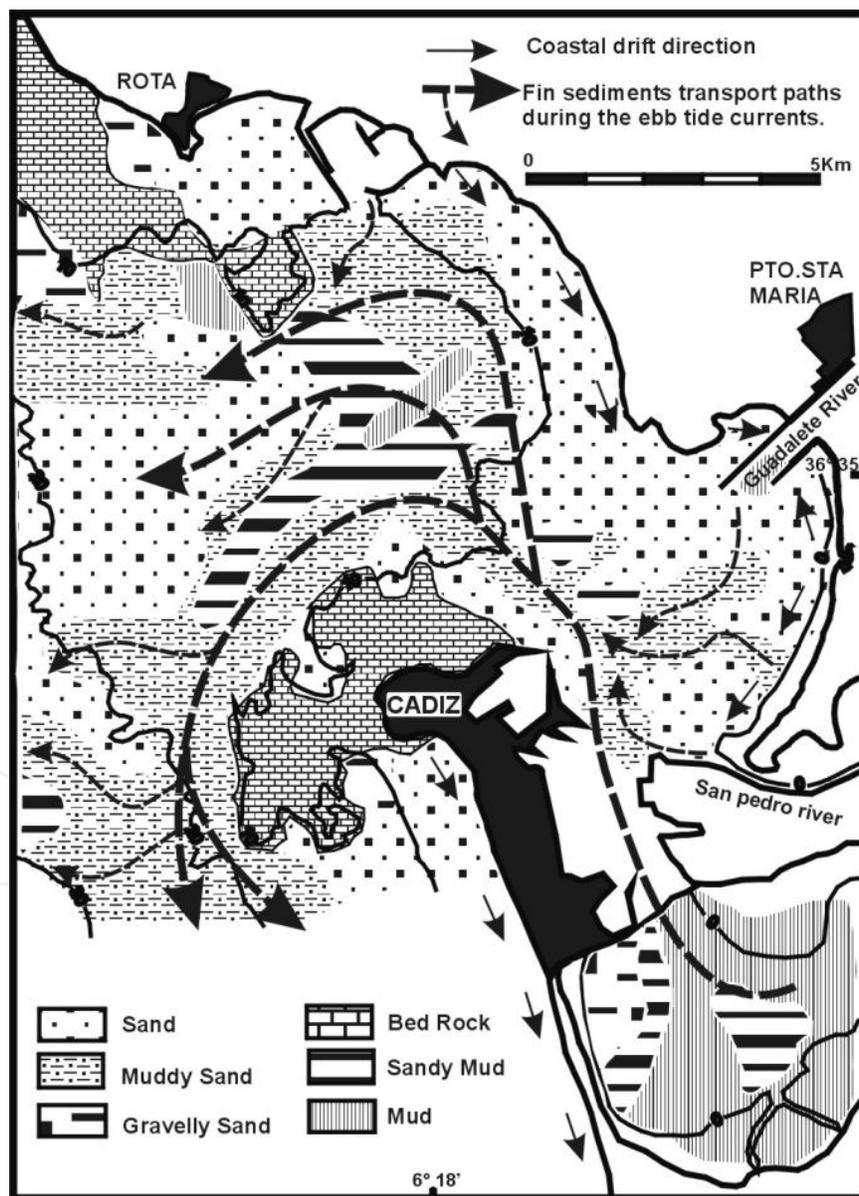


Figure 3. Surface sediments distribution on the Bay of Cadiz and transport paths of fine particules.

The sand is the dominant fraction of the outer bay sediments, with an average of 75% especially in the littoral zone. In some areas, this fraction changes laterally to muddy sand facies; due to the recent action of transport processes taking place in this area of the Cadiz bay. This facies extend into the 20-30 m deep inner shelf, being configured in two bands, one by the north margin of the bay and another one more to the South, bordering the city of Cadiz. The silt appears in low proportions (10%), giving the highest values in some sectors of the outer bay and the adjacent continental shelf. Its distribution is of great importance to understand the modern sediment dynamics in the Bay of Cadiz, especially the sediment exchange between the inner and outer bay. The Clays are an important sedimentary fraction, especially in low-energy sedimentary environments where concentrations reach 90% such as inner bay and the tidal channels that drain the salt marshes. In the outer bay, the contents are very low (<5%). The gravels (less than 5%), are mainly composed of bioclasts and rock fragments, derived from erosion of rocky shoals and coastal cliffs.

Deposit environment	Bay of Cadiz and inner shelf	Salt marshes and tidal creeks
Clay minerals	Factor 1 (99% of the variance)	Factor 1 (100% of the variance)
Illite	2.15	2.16
Smectite	0.31	0.25
Interstratified I-S	0.28	0.19
Chlorite	0.29	0.38
Kaolinite	0.29	0.28
Mineral assemblage	I ¹ /S ¹ /Sm ¹ /Cl ¹ /K ¹ /I-S ¹	I ¹ /S ¹ /Cl ¹ /K ¹ /Sm ¹ /I-S ¹

Table 1. Factor scores of the clay minerals in the bay of Cadiz-inner shelf and the salt marshes- tidal creeks, Q-mode factor analysis.

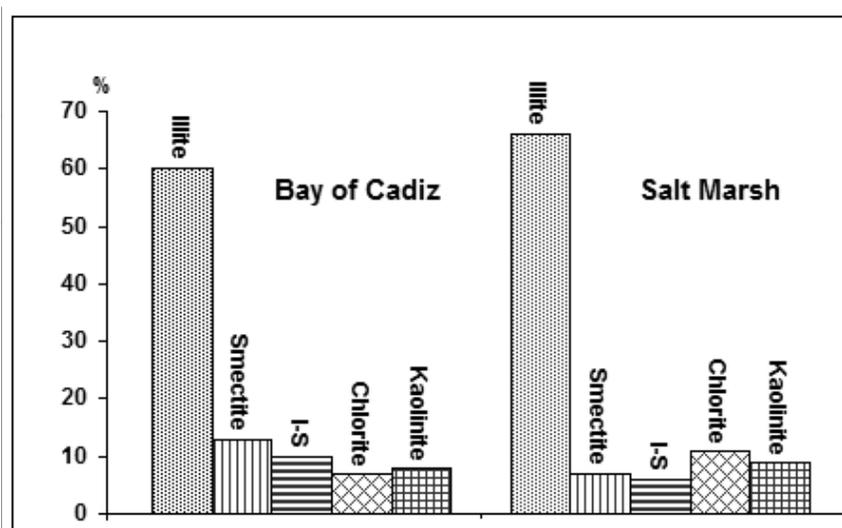


Figure 4. Clay mineralogy of surface sediments in the bay of Cadiz and the salt marsh.

In what concerns the mineralogical composition, the main minerals in terrigenous sediments of the bay of Cadiz are quartz (55%), calcite (20%) and plagioclases (5-10%). The mineralogical analysis of clay fraction indicate the predominance of Illite (60%), followed by Smectite (13%), interstratified Illite-smectite (10%), kaolinite (8%) and Chlorite (7%) (Fig. 4). In the salt marshes, the most abundant clay mineral is Illite (66%). Other clay minerals found in lesser quantities are Kaolinite (9%) and chlorite (10%) especially in the high tidal zone, and smectite (7%) in tidal creeks and tidal channels bottoms. Factor analysis was used to establish the relationships between different clay minerals and their associations. The Q-mode factor analysis results are summarized in Table 1.

4.2. Suspended sediment concentration

In the study area, significant concentrations of suspended matter are frequently observed, due to the existence of different sources of fine sediments (river mouths, e.g. Guadalquivir and Guadalete rivers, tidal channels, etc.), and the action of the hydrodynamic regime (Winds, waves and tidal currents). The concentration of suspended particulate matter under the hydrodynamic conditions at the sampling time (winds of N and NE, average speed of 55km/hr) shows an average dry weight content of 6.5 mg/l (Fig.5). The highest values were found in the outer bay, especially in the oriental sector, near the Guadalete and San Pedro river mouths (16 and 25 mg/l respectively) and to the south in Sanctipetri tidal creek (13mg/l). The concentrations of SPM are also relatively high in the central part of the bay, particularly north of the city of Cadiz (14mg/l) and in the navigation channel (12.87 mg / l) connecting the inner and the outer bay of Cadiz. The higher concentrations of SPM are consistent with the pattern of tidal currents and the distribution of fine facies on the sea bottom. The lowest values (1.5-5 mg/l) appear in the adjacent continental shelf waters characterized by low sediment input, as well as in parts of the inner bay less affected by tidal currents.

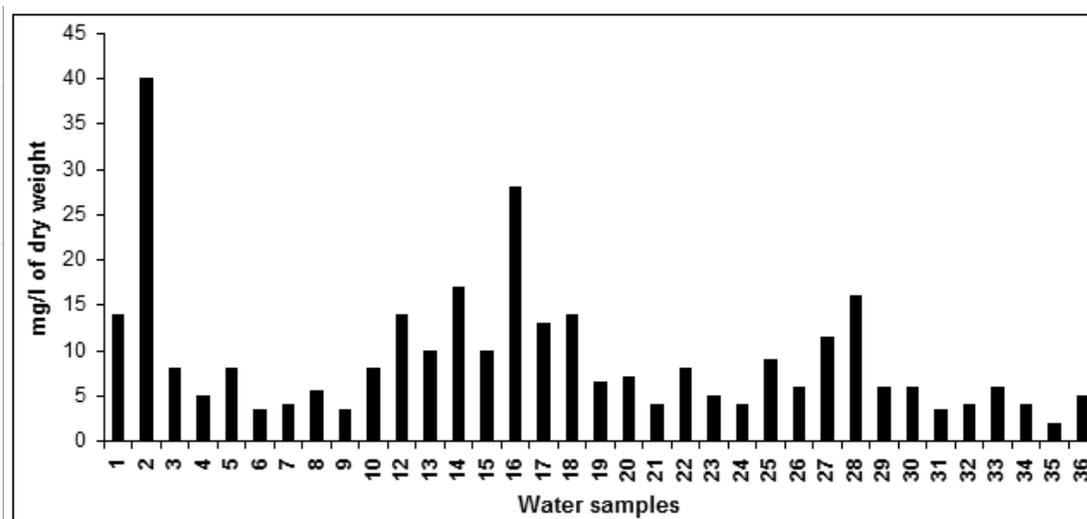


Figure 5. Distribution of suspended sediment concentration (in mg/l of dry weight) in the surface waters of the study area (see Fig. 6 for location of water samples).

4.3. Clay minerals composition of SPM

In the present study, clay minerals have been used as tracers, due to their small size making them the only particles susceptible of being transported away from the bay, out towards the continental shelf; and can be useful in the determination of the pathways of fine sediments and the suspended matter. Analysis of the mineralogical composition of suspended matter shows that the most abundant clay mineral consists mainly of illite (41%) followed by smectite (38%), chlorite (11%), interstratified Illite-smectite (7%) and kaolinite (6%) (Fig.6 & table.2).

Clay minerals	Outer bay	Inner bay	Tidal creeks	Continental shelf
Illite	37	43	43	38
Smectite	36	40	35	40
Interstratified I-S	6	9	5	10
Chlorite	12	15	14	9
Kaolinite	7	5	6	7

Table 2. Means values in percentage of clay minerals in SPM of different deposit environments.

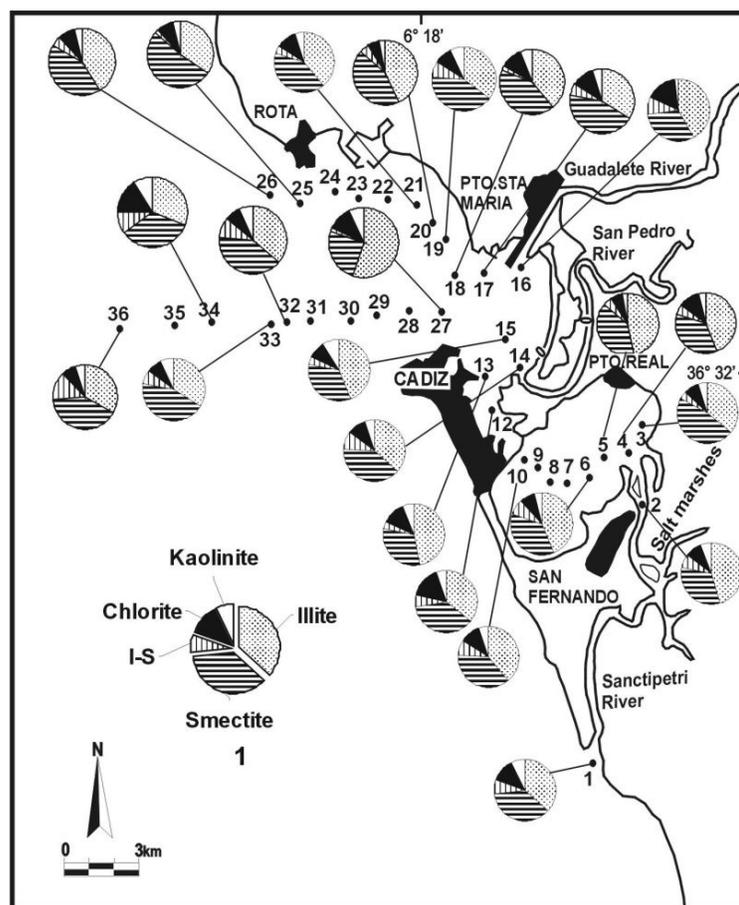


Figure 6. Distribution of principal clay minerals of suspended particulate matter in the study area.

The relations between the clay minerals were established by Q-mode factor analysis. The main clay minerals assemblage obtained in suspended matter is I>S>Cl>I-S>K (Fig. 7). The clay minerals distribution indicates high concentration of illite in the inner and protected part of Cadiz bay, while in the adjacent marine zones predominates the smectite.

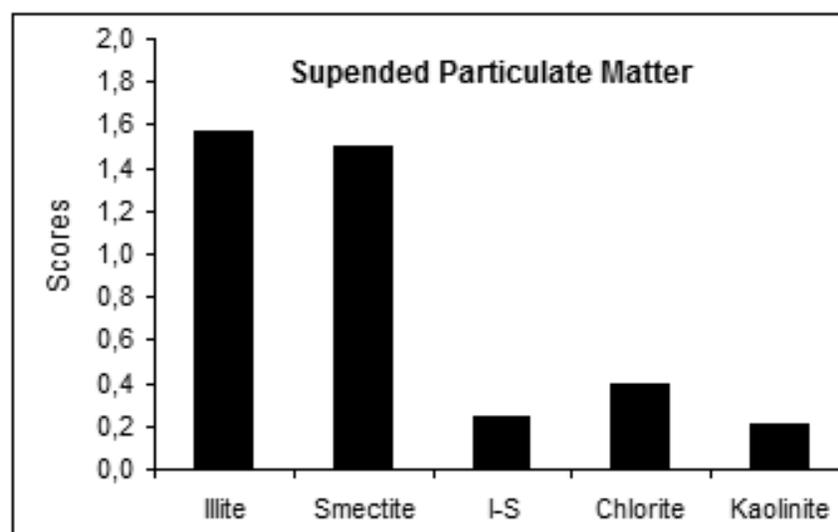


Figure 7. Factor scores (factor1: 99% of the variance) of the clay minerals in SPM obtained by Q- mode factor analysis.

The R-mode factor analysis results provide three factors explaining the 100% of the total variance. Factor 1 (52%) groups exclusively smectite (negative loading: -0.95), is well represented on all bottoms of the bay of Cadiz. Factor 2 (28%) associates interstratified IS (positive loading:0.89) to kaolinite (0.4). This factor scores better in the western sector of the inner bay and central part of the external as well as in front of the river mouths of the Guadalete and San Pedro. Factor 3 (20%) with only the mineral chlorite (0.95), dominates next to the mouths of the Sancti Petri tidal creek and the San Pedro and Guadalete Rivers.

4.4. Landsat images analysis

The use of satellite images in studies of transport dynamics of sediment in suspension is of great interest. The usefulness of this technique is based on the monitoring of turbidity plumes, consisting mainly of suspended inorganic particles. Geologists, geographers and oceanographers, also applied this technique, for coastal processes study [10].

Landsat TM images used in this study are property of the Spain Ministry of Environment (Junta de Andalucía). The analyses of these images for different hydrodynamic and meteorological situations illustrate the existence of water masses of different degrees of turbidity, oriented from the inner zone towards the outer bay extending to the continental shelf (Fig. 8). The highest turbidity is observed in the coastal areas of the bay, as well as in front of the mouths of the Sancti Petri tidal creek and the San Pedro and Guadalete Rivers.

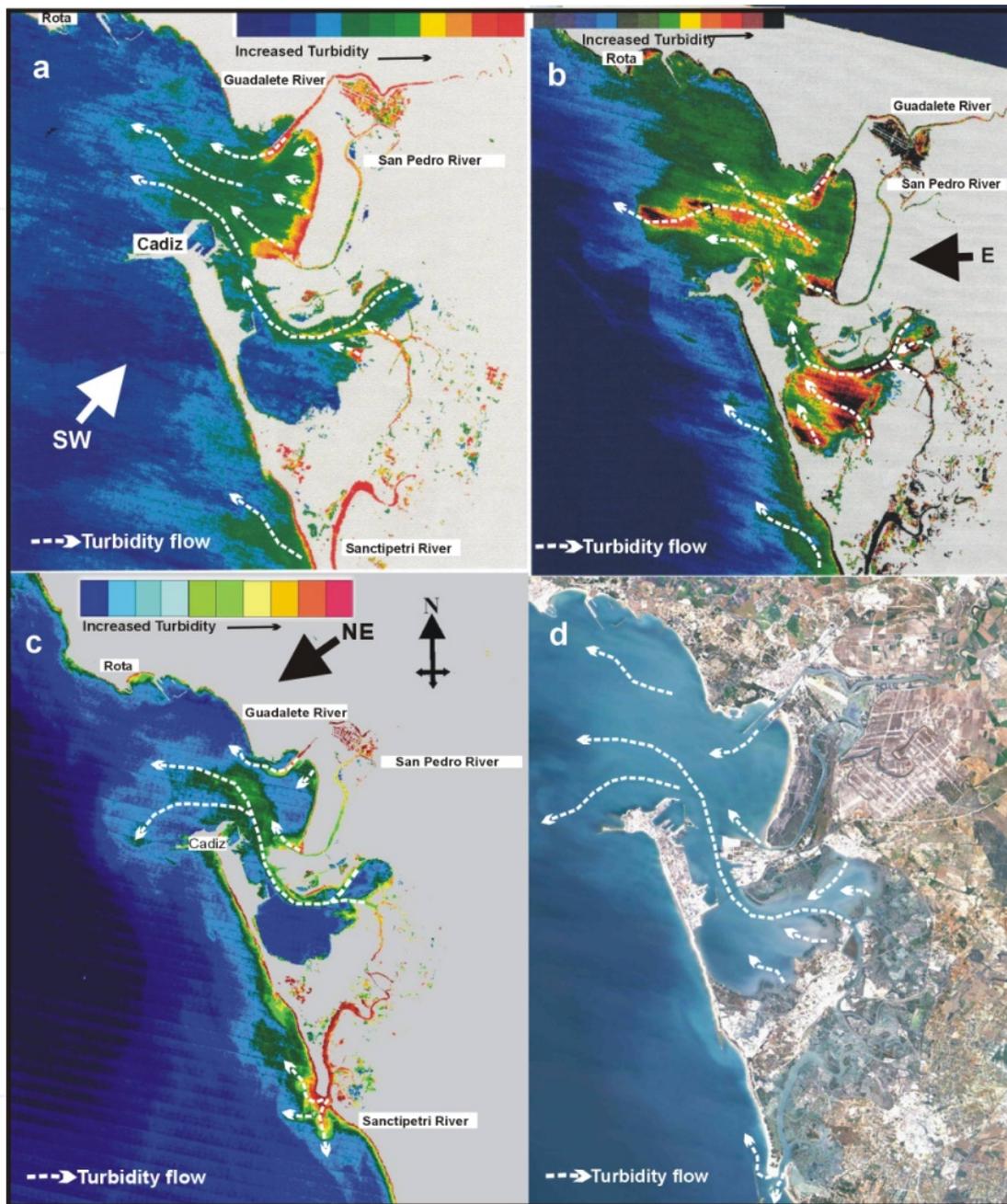


Figure 8. Turbidity plume trayectories in several hydrodynamic situations from the analysis of Landsat TM images of Cadiz bay. 8a: date: 22-05-1996, Wind: Western-WWS, Speed: 39km/h, Hs: 0.6m, Tidal coef: 0.55 ; 8b: date: 13-08-1991, Wind: East, Speed: 37km/h, Hs: 0.54m, Tidal coef: 0.78; 8c: date: 07-06-1996, Wind: North-East, Speed: 55km/h, Hs: 0.6m, Tidal coef: 0.64; 8d: recent satellite image during ebb tide.

In situation of strong Easterly winds (Fig. 8a), suspended matter derived from resuspension of the inner bay bottoms are subsequently transported by ebb tidal currents, with an average speed of 1.02 m / s, which is reduced to 0.77 m / s in the outer bay. These turbid flumes (SPM flows) appear as branch oriented northwards along the eastern edge of the bay and then turn west, influenced by coastline and bottom morphology. Part of the suspended matter tends to leave the bay being deposited in the inner continental shelf. In the continental

shelf, the North Atlantic Surface water current transport a large volume of fine sediments from the Guadalquivir rivers toward the SE. Part of this current can transport fine particles in suspension toward the bay of Cadiz. Satellite image obtained in situation of Northeast winds, shows the existence of several turbidity flows that appear to move from the innermost zones of the bay to the outer one (Fig 8b). These flows are configured in three bands: one oriented towards the NNW following the north margin of the bay. Other band oriented towards the West and the third one goes towards the SSW bordering the Cadiz city. To the south of the bay, turbidity plumes are also observed and coming from the Sanctipetri tidal creek mouth that head towards the inner continental shelf.

On the other hand, during Western (SSW) Wind Conditions, turbidity in open coastal areas adheres to breaking waves zone, being highly concentrated within 20 meters near the beach and at depths less than 2 meters. outcrops rock located to the NW of the city cause, the existence of turbidity plumes in this area (Fig. 8c).

The observation of recent satellite image during ebb tide shows that turbid flumes extend from the inner bay out to the continental shelf, following the coastline and sea bottom morphology (Fig. 8d).

5. Discussion

5.1. Sedimentary processes

The distribution and transport of sediments on the marine environment is function of the wave-current and grain size interactions [63, 64]. They can also reflect the direction of water mass movement [65, 66]. In Cadiz bay bottoms, the grain size distribution, shows the predominance of fine fractions, (silt and clay), toward the more sheltered and internal zones of the bay. While the coarse fractions (sand and gravel), appear in external zones, more opened to the sea and exposed to waves and currents action. Grain size parameters show the prevalence of unimodale distribution (fine and very fine sand), however bimodal and polymodal distributions are present. The mode values increase in coastal areas and near rocky shoals, decreasing towards the central zone of the outer bay and in the inner bay. The general trend and the variability of different grain-size parameters, reflect the control that physiographic and hydrodynamic factors exert on different types of sediment [31].

The abundance and the progressive deposition of fine materials in the inner bay and the salt marshes is related to the existence of sedimentary environment of very low hydrodynamic energy. Their hydrodynamic regime is dominated by tidal currents, especially ebb tides and wind of the East sector [30, 36]. These fine sediments are also found in the outer bay, occupying the central and eastern sectors, covering sandy bottoms. They derive from resuspension of fine-grained materials in the marshlands of the bay and from fine materials supplied by the Guadalete River during periods of rainfall and floods. The presence of mud and sandy mud facies covering sandy bottoms, possibly will indicates actual processes of deposit and transport of fine sediments from the inner bay toward the exter-

nal zone reaching the inner continental shelf (Fig.3). Muddy facies are also present in the continental shelf as a prodeltaic muddy zone situated to the north and deposited in low energy environment. These fine-grained sediments are related to supplies coming from the Guadalquivir River [26, 28, 67].

The grain size distribution allowed the differentiation of particles transport modes, according to its size and the hydrodynamic conditions. The suspended transport predominates in the inner part of the Bay (including tidal channels and marshland areas) and to the north of the continental shelf characterized by mud-clay bottoms deposited in low energy conditions. In general, this type of transport predominates on many marine environments including continental shelves [68]. In the outer bay, especially the western sector that coincide with sandy-mud and mud facies bottoms, the saltation-suspension transport mode predominates and may possibly indicate the transport paths of fine sediments and suspended matter in the study area. The distributions of these different grain size classes reflect the energy level of each depositional environment and the processes of sediment transport; as well as the action of hydrodynamic agents, which control recent sedimentary dynamics between different sedimentary environments of the bay of Cadiz and the continental shelf [33, 44,69].

5.2. Suspended matter dynamics

On coastal marine environments, rivers are the major sources of supplies of suspended particulate matter. Most of great rivers discharge important quantities of SPM, carried by long-shore currents parallel to the coast, forming permanent turbidity plume. The spatial distribution of suspended sediments is a consequence of hydrodynamic forcing acting on the unconsolidated sediments of the shelf and the coastline [70, 71]. In general, waves are more important for resuspension in shallow water (< 10 m) and currents become more important in deeper water (> 10 m) [72, 73, 74].

The measures of concentration of suspended matter obtained in the Bay of Cadiz and the continental shelf waters, show values varying from one area to another. The highest values of concentration of suspended matter are given in the outer bay, due to the influence of Guadalete and San Pedro River mouths. These higher concentrations are consistent with the pattern of tidal currents and the distribution of fine facies on the sea bottom. In the inner bay, the concentrations of suspended matter have lower values, due to increased settling of particles in sheltered environments from waves. In the continental shelf, are given the lowest values found in the study area, corresponding to the lower turbidity of these waters. Numerous studies about the mineralogy of the clay fraction present in surface sediment and suspended matter, show the existence of a strict relationship between clay minerals transported by rivers and those in the sediments of the drainage basin [75, 76]. In our case, comparing the clay mineral composition of SPM and in surface sediment, a significant change is observed in the particulate matter with an important increase of smectite content from 13% in surface sediment to 38% in SPM and decrease of illite content (from 60% to 41%). This effect can be explained by the tendency of illite to focus on the sea bottoms, while smectites tend to stay longer in suspension. The remaining minerals like chlorite, Kaolinite and I-

S has low contents, between 5 and 10%. The main clay mineral association established in SPM is I>S>>Cl>I-S>K, which basically coincides with that obtained for the bay and the continental shelf and differs significantly from that found only in the bay of Cadiz [28]. There is a greater importance of illite in samples of internal areas of the bay and tidal creeks. This mineral, decrease in open water and the continental shelf, favoring the increase of smectite contents. Those differences can be explained considering processes such as settling and selective transport of clay minerals in marine environments [77], in relation with hydrodynamics regime, and the location of the main sources of sediment supply that control the mineralogical composition and concentration of suspended matter.

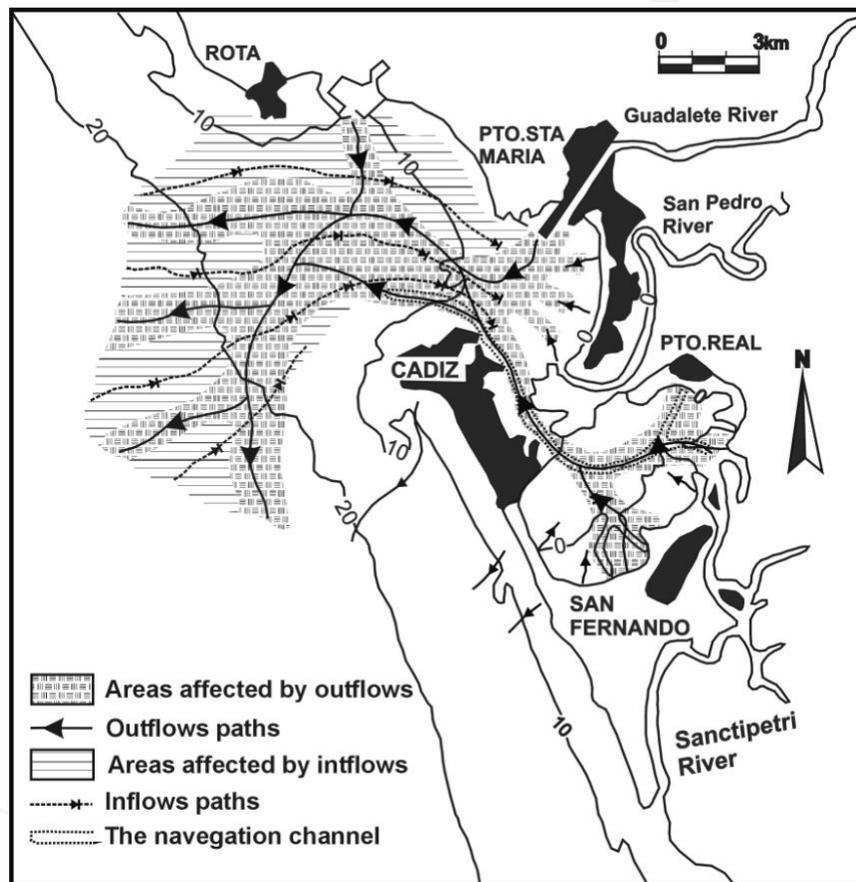


Figure 9. Transport dynamics model of fine sediments and suspended matter between the inner and the outer bay of Cadiz and the adjoining continental shelf.

Clay minerals and assemblages have been used as dynamic tracers to deduce transport path and the process of sedimentation of fine sediment and SPM [27, 28, 77, 78, 79, 80,]. Others studies indicate that clay minerals can be transported large distance by rivers, wind and currents, indicating the dominant trajectories of fine sediments and the suspended matter [22, 25, 42]. Data from the distribution of SPM concentration in the bay of Cadiz and clay minerals contents and assemblages have been used to establish the transport paths model of SPM in different area of the study zone, through the trace that different minerals have left in ma-

rine bottom surface. Two flows paths have been differentiated (Fig.8): i) The inflows coming from external marine areas located to the north, in particular the Guadalquivir river mouth and other sources. These flows can transport suspended matter and fine sediments to the Cadiz bay bottoms by the action of marine currents, specially the littoral and the Atlantic Surface water currents of SE direction. ii) The outflows coming from Cadiz bay and littoral zones; can reach the continental shelf by mean of ebb tide currents. Two possible transport paths can be deduced; the first one runs preferably by the northern margin of the bay of Cadiz and reaches the Rota city. Another flow oriented towards the west, bordering the city of Cadiz, eventually extending to the continental shelf. These bands might correspond to sea floor marks generated by flows between the bay and the continental shelf; agreement with the tidal flow pattern established by [33] in the Cadiz bay.

5.3. Turbidity flow patterns

The analysis of satellite images can provide information about size and direction of the turbidity plumes and the effect of winds and tidal currents in their distribution; and estimate the concentration of particles in water column, [81, 82, 83]. The turbidity caused by suspended particles is detectable by the reflective bands of Landsat satellite [84, 85]. Based on Landsat images, [34] and [86] show that In the Bay of Cadiz, depending to hydrodynamic conditions, Turbidity plumes follow different directions and can cross the bay area. They reach the inner shelf by the action of tidal ebb, depositing part of its SPM. Once in the open sea, SPM are moved by currents and interact with the general hydrodynamic system affecting coastal areas and the Gulf of Cadiz [27, 28]. According to information obtained from the analysis of Landsat-TM images and the concentration of suspended matter, four levels of turbidity has been differentiated in the sea area between the town of Rota (northwestern boundary of the Bay), and the mouth of Sanctipetri tidal creek (southeastern boundary of the bay) (Fig. 8):

- i. High and very high turbidity Waters appears in the eastern part of the outer bay, near the Guadalete and San Pedro river mouths, whose turbidity plumes are oriented toward the West and NW. Very high turbidity can be observed in the inner bay and the central part of the outer bay, when the spring tide and the southeast wind coincide. South of the bay, the Sanctipetri tidal creek shows also very high turbidity that is oriented toward the SSW.
- ii. Medium turbidity waters are found along the coast and occupy a variable band between 0.5 and 2 km. They are specially represented in the eastern part of the outer bay, configured in a large band following the morphology of the coast and the sea bottom. In situation of Easterly winds, these waters can exceed the environment of the bay of Cadiz and reach the inner shelf by the action of ebb tidal currents.
- iii. Low turbidity are observed in the western sector of the inner bay (except at moments of spring tide and east winds). The degree of turbidity was found to be related to a confined environment, less affected by the action of tidal currents leading to precipitation of suspended matter. The turbidity level in this area may be due to

their muddy bottoms occupied by algae, whose roots and leaves act to retain the sediment and preventing their resuspension. Low turbidity can be observed in the outer bay, under certain conditions, in this case, suspended particulate matter coming from the inner bay, do not reach the outer bay, characterized by profound bottoms making difficult the process of resuspension of fine particles.

- iv. Very low turbidity waters, correspond to Atlantic waters, characterized by little influence of coastline and located at several kilometers from the coast. Under certain conditions, these water, can be mixed with other more turbid found near shore, because of the presence of suspended matter flows generated by the tides.

Taking into account the above data, three geographical sectors have been identified:

- a. Proximal sector. Is a shallow area of high and very high turbidity. Is affected by the physiography of the coast and the sea bottoms. The variation of degree of turbidity in this area are related to continental supply and sedimentary nature of the bottoms (muddy or sandy); as well as the direct action of waves and tidal currents.
- b. Middle Sector. Corresponds to the maritime area limited between the proximal and distal sectors. This is an area of high variability and is affected in its inner part by the action of tidal flows, which alter their limits and water quality up to 4 times daily. The outer boundary of this sector consists of less turbid water, flowing through this area of the Gulf of Cadiz.
- c. External sector. is the maritime zone located about 5 km away from the virtual line between the Rota and Cadiz cities, and characterized by low and very low turbidity. The internal limit is still somewhat affected by coastal dynamics, but less than in the middle and proximal sectors. The degree of turbidity present little change, except during periods of flood (especially in Autumn and Winter) in which the rivers pouring into this part of the Gulf of Cadiz, transport lots of suspended matter, giving way to large turbidity plumes. water turbidity may be episodically affected by the action of tidal flows during spring tides, favored by Southeast winds.

6. Conclusion

- i. The high concentrations of suspended matter present in Cadiz bay waters are linked to major sources of contributions, like rivers and tidal creeks. Fine sediments coming from the remobilization of the inner bay bottoms and the marshlands by the effect of waves and winds, can supply large quantity of suspended material depending on the season. This material is then transported by the effect of tidal ebb currents to the external areas of the bay, and even continental shelf. The use of clay minerals as natural tracers has allowed the determination of suspended matter flows paths taking place in different sectors of the study area.
- ii. The general transport pattern of suspended particulate matter (SPM) is affected by local processes, which take place in littoral zones, in particular in Cadiz bay

and the Guadalquivir estuary. Part of the Atlantic waters rich in SPM coming from the Guadalquivir Rivers reaches the bay of Cadiz and can be deposited in lagoons and salt marshes. The resuspension of fine-grained material in the inner zone of the bay during southeast wind and ebb tidal current generate suspended matter outflows towards the outer bay. Considerable quantity of this SPM is injected in the Atlantic waters.

- iii. Landsat images show that the turbidity pattern coincides generally with the area of the muddiest facies present on the outer bay bottoms and with the geographical locations of the sampling stations providing the highest contents of suspended solids. The combined study of suspended matter concentration and Landsat images analyses, allows recognize the transport paths followed by the sediments in the surface marine waters. these images show that turbidity plumes extend from the inner bay out to the continental shelf by action of the tidal ebb currents, following the coastline and sea bed physiography.
- iv. The transport dynamics of fine sediment and SPM from the inner bay toward the external zone and the inner continental shelf was found to be related to the location and diversity of supply sources, to the coastal and sea bottoms morphology; as well as to the influence of the hydrodynamic system, fundamentally ebb tide currents. Other transport agents are the currents generated by waves. In situation of easterly storm, currents are generated towards the West, which combined with the tidal ebb, give rise to large flumes of turbidity, which are directed offshore. In contrast, the wind and westerly waves are opposed to ebb tide currents favouring the inflow.

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