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GEOMORPHOLOGICAL AND ENVIRONMENTAL CHARACTERIZATION OF THREE ESTUARIES ON THE SPANISH COAST

Memoria presentada por **María Aranda García** para optar al grado de Doctor en Ciencias y Tecnologías Marinas - EMAS

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A mi madre.

Abre la ventana
y deja que el sol alumbre
por todos los rincones de tu casa.
Víctor Jara.

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Summary

The main aim of this PhD thesis is to develop and validate a methodology that allows to understand the integral functioning of the estuaries, and to characterize the estuarine subsystems and their connectivity. To achieve this, three study zones have been selected: (1) San Vicente de la Barquera estuary (N Spain), (2) Guadiana River estuary (SW border between Spain and Portugal) and (3) Ebro River Delta estuary (NE Spain), which cover most of the environmental range and oceanographic conditions that occurs on the Iberian Peninsula coasts.

Different specific objectives have been proposed, and a particular methodology has been developed to achieve each of them. The first one consists in a historical observation and analysis of the state of the three study sites to understand which processes have occurred on them in the last years. To do that, a hierarchical classification representing estuarine eco-geomorphological features relevant to estuarine dynamics and functioning has been proposed to unify and standardize the terms when mapping these types of environments. After that, a 30-year time series of high resolution maps has been developed, analysing the changes in feature surfaces by means of Geographic Information System (GIS). The results explain the changes with time on each of the study sites at a long-term scale. Besides, a common general behaviour to all transitional systems, as well as the relationships among main subsystems (namely shoreline sandy environments, dunes, tidal flats and drainage network) and processes inherent to each one have been described. Through this methodology, it is demonstrated how beaches and dunes serve as protective barriers for the tidal flats, acting as sediment buffer for the entire system. Besides, the subsystems are connected by the drainage network, responsible for the exchange of matter and energy in between them. These results add an important perspective towards a general understanding of the dependence of the main estuarine features on intrinsic and boundary conditions.

Based on results from the previous specific objective, the second specific objective is to evaluate the most relevant natural processes and the anthropogenic influence on their functioning to understand what is happening within the estuary. For that, San Vicente de la Barquera estuary has been selected as test site, due to the quality and amount of available information for this site. Specifically, saltmarshes in San Vicente de la Barquera estuary have been studied in detail as they have been previously identified as the most changed features within the estuary. To achieve this specific objective, saltmarsh evolution has been

studied in a spatial context by means of detailed maps of change in vegetation cover combined with topographic data, to identify patterns of change. The results support the evidences of saltmarsh disappearing in this estuary. Despite no clear pattern of vegetation loss/gain in relation to elevation has been identified over the entire study period, indications of physical stress within the saltmarsh linked to self-organized process are described. In addition, regional and local factors have been studied to identify possible causes of saltmarsh deterioration. With this methodology it is demonstrated the importance of both natural forcing factors and human interventions when describing saltmarshes evolution and future trends.

The last two specific objectives proposed are to define a set of variables to characterize all the above described processes in a simple manner and suitable to other estuarine zones, and to design and validate with them an environmental characterization index for estuaries (*EstuarIndex*). This final part of the PhD thesis pretends to answer the question of what is going to happen in each of the study zones as well as what needs to be done to develop a comprehensive methodology for estuarine management in Spain. For that purpose, different variables have been proposed to evaluate the environmental status of the main estuarine subsystems based on previous index-based studies. Three field campaigns were carried out in each study area to collect information *in situ*, two of them at the end of summer time and one at the end of winter time, to obtain information on seasonal peaks. Besides, an extensive bibliographical review has been made to obtain information about those variables that did not require measurements. The results obtained by means of the index provide a good approach to the environmental status of the estuaries. All of them show medium-high index values. Besides, in the three study cases, results obtained are consistent with what was observed in the field during the field campaigns. For this reason, this index could be considered as a first valid approximation to characterize the main dominant processes within estuaries, which are responsible for their long-term evolution. Despite an "static view" of the system is represented by a unique final value, the developed index provides a final view based on processes with a wide time scale.

These results can be used by coastal managers to make adequate plans regarding estuarine management, as they are simple and reliable tools. Furthermore, the methodology here presented has been designed to be applied to any estuary of mid-latitudes.

Resumen

El principal objetivo de la presente tesis doctoral es desarrollar y validar una metodología que permita entender el funcionamiento de los estuarios desde una perspectiva integral, además de caracterizar los subsistemas que los componen y su interconectividad. Para ello, se han seleccionado tres zonas de estudio: (1) estuario de San Vicente de la Barquera, (2) estuario del río Guadiana y (3) desembocadura del Delta del Ebro. Estas zonas cubren las principales condiciones ambientales y oceanográficas de la costa de la Península Ibérica.

Para alcanzar el objetivo principal, se han propuesto diferentes objetivos específicos, para cada uno de los cuales se ha desarrollado una metodología específica. En primer lugar, realizar un seguimiento histórico y un análisis del estado de las tres zonas de estudio para así entender qué procesos dominantes han tenido lugar en los últimos años en cada una de ellas. Para unificar y estandarizar términos en lo que a cartografía se refiere, en primer lugar, se ha propuesto una clasificación jerárquica que engloba todas las morfologías relevantes respecto a la dinámica y el funcionamiento estuarino. A continuación, se ha elaborado un conjunto de mapas de alta resolución espacial y temporal (30 años) a través de Sistemas de Información Geográfica (SIG), que han permitido analizar los cambios en las superficies ocupadas de cada una de las morfologías cartografiadas. Los resultados obtenidos han permitido explicar cambios a largo plazo de cada uno de los estuarios seleccionados. Esto hace posible la descripción de un comportamiento común a todos los sistemas de transición, de las relaciones entre los principales subsistemas (a saber, ambientes arenosos costeros, dunas, llanuras mareales y red de canales), así como de los procesos inherentes a cada uno de ellos. A su vez, a través de esta metodología se ha demostrado cómo playas y dunas sirven como barrera protectora para las llanuras fangosas, además de actuar como reservorio de sedimento para el sistema completo. Además, estos subsistemas están conectados a través de la red de canales que es la responsable del intercambio de materia y energía en todo el sistema. Estos resultados añaden una perspectiva importante para la comprensión general de cómo las principales morfologías estuarinas dependen de las condiciones internas y externas del estuario.

En base a estos resultados, la evaluación de los procesos naturales más relevantes, así como la influencia antropogénica en su funcionamiento ha sido planteada como segundo objetivo específico de la tesis, para entender qué procesos están funcionando actualmente en el estuario. Para ello, se ha seleccionado el estuario de San Vicente de la Barquera como zona

para testar la metodología planteada, debido a la calidad y cantidad de datos disponible para esta zona de estudio. En concreto, para lograr este objetivo específico, se ha estudiado en detalle la evolución de las marismas de este estuario ya que se trata de las morfologías que más cambios han sufrido en las últimas décadas. En concreto, se han desarrollado mapas de cambio de vegetación de detalle y, posteriormente, se han combinado con datos topográficos para identificar patrones de cambio. Los resultados evidencian la progresiva desaparición de las marismas. Además, a pesar de que no se ha identificado una pauta clara de pérdida/ganancia de vegetación en relación con la elevación del terreno, sí se han descrito indicios de estrés físico en la marisma relacionados con procesos de auto-organización de la misma. Por otro lado, se han estudiado los factores regionales y locales para intentar identificar las posibles causas del deterioro de estas marismas, demostrándose la importancia tanto de los factores naturales como de las intervenciones humanas en el funcionamiento y evolución de estas morfologías.

Por último, se definen dos últimos objetivos específicos. Estos se centran en la definición de un conjunto de variables que permitan caracterizar todos los procesos descritos anteriormente de una manera simple y fácilmente aplicable a otras zonas, así como diseñar y validar con ellas un índice de caracterización ambiental de estuarios (*EstuarIndex*). Esta parte final de la tesis pretende responder a la pregunta de qué va a suceder en cada una de las zonas de estudio en un futuro próximo si las tendencias identificadas continúan, así como qué se necesita para desarrollar una metodología holística para la gestión estuarina en España. Para ello, se han definido un conjunto de variables que permiten evaluar el estado de conservación de los principales subsistemas estuarinos, basado en índices existentes. Se llevaron a cabo tres campañas de campo en cada zona de estudio para recoger información *in situ*, dos de ellas al final del período de verano y otra a final de invierno, para obtener información sobre los picos estacionales. Además, se ha realizado una extensa revisión bibliográfica para obtener información de aquellas variables que no podían ser medidas en el campo. Los resultados obtenidos tras aplicar el índice a las tres zonas de estudio proporcionan un buen enfoque del estado ambiental de estos estuarios. Todos ellos muestran valores medios-altos. Estos resultados concuerdan con lo observado en el campo por lo que el índice propuesto puede considerarse como una buena aproximación a la caracterización de los principales procesos dominantes en los estuarios, responsables de su evolución a largo plazo. A pesar de que con un valor final se otorga una "imagen estática" del estado del estuario, este índice pretende proporcionar una imagen final basada en procesos a gran escala, por lo que constituye una herramienta útil para estudios futuros. Estos resultados pueden ser utilizados por gestores costeros para elaborar planes adecuados de gestión de estuarios, ya que son herramientas sencillas y fiables. Además, la metodología de la presente tesis doctoral se ha diseñado para ser aplicada a cualquier estuario de latitudes medias.

Riassunto

L'obiettivo principale di questa tesi di dottorato è quello di sviluppare e convalidare una metodologia che permetta di comprendere il funzionamento degli estuari da una prospettiva integrata, nonché di caratterizzare i sottosistemi che li compongono e la loro interconnettività. A tal fine sono state selezionate tre aree di studio: i) l'estuario di San Vicente de la Barquera, ii) l'estuario del fiume Guadiana e iii) la foce del delta dell'Ebro; difatti, le condizioni ambientali e oceanografiche di queste regioni sono particolarmente rappresentative della costa della penisola iberica.

Per raggiungere questo scopo sono stati proposti diversi obiettivi specifici, per i quali è stata sviluppata una metodologia peculiare. In primo luogo, effettuare un'analisi storica e delle condizioni delle tre aree di studio per comprenderne l'evoluzione durante ultimi anni. A tal fine è stato preparato un insieme di mappe ad alta risoluzione spaziale e temporale (30 anni) attraverso l'uso dei Sistemi Informativi Geografici, che ha permesso di analizzare le variazioni delle superfici occupate di ciascuna delle morfologie mappate. Al fine di unificare e standardizzare le informazioni da un punto di vista cartografico, è stata inizialmente proposta una classificazione gerarchica che comprendeva le eco-geomorfologie rilevanti per comprenderele dinamiche e il funzionamento degli estuari. I risultati ottenuti hanno messo in evidenza i cambiamenti a lungo termine di ciascuno degli estuari selezionati. Ciò ha permesso di descrivere un comportamento comune a tutti i sistemi di transizione, le relazioni tra i principali sottosistemi (cioè gli ambienti sabbiosi costieri, le dune, le pianure di marea e la rete di canali), così come i processi inerenti a ciascuno di essi. Attraverso questa metodologia è stato dimostrato come le spiagge e le dune fungano da barriera protettiva per le piane tidali, oltre che da serbatoio di sedimenti per l'intero sistema. Inoltre, questi sottosistemi sono collegati attraverso la rete di canali che è responsabile dello scambio di materia ed energia in tutto il sistema. Questi risultati aggiungono una prospettiva importante che conducono ad una comprensione generale dei fattori interni ed esterni, dai quali dipendono le principali morfologie dell'estuario.

Sulla base di questi risultati, la valutazione dei processi naturali più rilevanti, così come l'influenza antropogenica sul loro funzionamento è stata proposta come secondo obiettivo specifico della tesi, al fine di capire l'attuale evoluzione nell'estuario. A questo scopo, l'estuario di San Vicente de la Barquera è stato scelto come area di sperimentazione della metodologia, grazie alla qualità e alla quantità dei dati disponibili per questa zona di studio.

In particolare, per raggiungere questo specifico obiettivo, è stata studiata nei dettagli l'evoluzione delle paludi di questo estuario, in quanto sono state identificate come l'ecosistema che ha subito i maggiori cambiamenti negli ultimi decenni. In particolare, sono state sviluppate mappe dettagliate relative ai cambiamenti della vegetazione e successivamente combinate con dati topografici per identificare dei trend morfologici. I risultati dimostrano che le paludi stanno scomparendo. Inoltre, sebbene non sia stato individuato alcun chiaro andamento positivo o negativo della vegetazione in relazione all'altitudine del terreno durante tutto il periodo di studio, sono state descritte indicazioni di stress fisico nelle paludi legate ai processi di auto-organizzazione della palude. Sono stati studiati anche fattori regionali e locali nel tentativo di individuare le possibili cause del degrado delle paludi. Questa metodologia ha dimostrato quantoi fattori naturali che degli interventi umani influenzano il funzionamento e l'evoluzione di queste particolari morfologie.

Infine, a partire da questi due obiettivi più specifici, è stato possibile definire un insieme di variabili che permettessero di caratterizzare tutti i processi sopra descritti in modo semplice e facilmente applicabile ad altre aree, e di progettare e validare con essi un indice di caratterizzazione ambientale degli estuari (*EstuarIndex*). Questa parte finale della tesi mira a rispondere alla domanda su come ciascuna area di studio evolverà, così come su ciò che è necessario per sviluppare una metodologia olistica per la gestione degli estuari in Spagna. A tal fine è stato definito un insieme di variabili per valutare lo stato di conservazione dei principali sottosistemi dell'estuario, sulla base degli indici esistenti. In ogni area di studio sono state effettuate tre campagne sul campo per raccogliere informazioni in loco, due delle quali alla fine del periodo estivo e un'altra alla fine dell'inverno, per ottenere informazioni sui picchi stagionali. Inoltre, è stata effettuata un'ampia revisione della letteratura per ottenere informazioni su quelle variabili che non potevano essere misurate sul campo. I risultati ottenuti dopo l'applicazione dell'indice alle tre aree di studio hanno fornito un buon approccio allo stato ambientale degli estuari. Tutti hanno mostrato dei buoni valori. Questi risultati sono in linea con quanto osservato sul campo, per cui l'indice proposto può essere considerato come una buona approssimazione alla caratterizzazione dei principali processi dominanti negli estuari, responsabili dell'evoluzione a lungo termine. Sebbene un valore finale dia un "quadro statico" dello stato dell'estuario, questo indice fornisce un quadro finale basato su processi su larga scala.

Questi risultati possono essere utilizzati dai manager costieri per sviluppare dei piani di gestione degli estuari appropriati, in quanto si tratta di strumenti semplici e affidabili. Inoltre, la metodologia di questa tesi di dottorato può essere applicata a qualsiasi estuario di media latitudine.

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Acronyms

AB	Access to the Beach
AC	Access Control
BW	Beach Width
C	Connectivity
CVI	Coastal Vulnerability Index
D	Driftlines
DI	Dune Index
DNI	Drainage Network Index
DoA	Degree of Anthropization
DoF	Degree of Fragmentation
DSAS	Digital Shoreline Analysis System
DTM	Digital Terrain Model
DW	Dune width (m)
EBR	Ebro River delta mouth
EF	Ecological Factors
ER	Exposed Roots
ES	Dune front with presence of Erosive Scarps
ETRS89	European Terrestrial Reference System 1989
EU	European Union
FoV	Frequency of Visitors
FS	Fixed Structures
GIS	Geographical Information System
GUA	Guadiana River estuary
HAT	Highest Astronomical Tide
IAS	Invasive Alien Species
EF	Exposure Frequency in the lower limit of the saltmarsh
IHM	Hydro-geomorphological Index
IP	Information Panels
KDE	Kernel Density Estimation
LiDAR	Light Detection And Ranging
LRR	Linear Regression Rate (m/year)

LTCOS	Long Term Changes in the Occupied Surface
LTCPS	Long Term Changes in the Profile Slope
LTE	Long Term Evolution of the shoreline
LTEWS	Long Term Evolution of the Width of the Saltmarsh
MC	Beach surface affected by Mechanical Cleaning
MH	Modal Height (m)
MHWN	Mean High Water Neap
MHWS	Mean High Water Spring
MMU	Minimum Mapping Unit
MOF	Morphosedimentary and Oceanographic Factors
MPF	Management and Protection Factors
MSL	Mean Sea Level (m)
MSTR	Mean Spring Tidal Range
MSTR	Mean Spring Tidal Range
Nat	Naturalness of the flow regime
NP	Number of patches
PCF	Plant Cover Fragmentation
PCI (LIC)	Place of Community Interest
PD	Patch Density
PionSW	Pioneer Saltmarsh with respect to the total Saltmarsh Width
PMS	Predominant Morphodynamic State
PNOA	Spanish National Plan of Aerial Orthophotography
PoI	Presence of Invertebrates
PoM-C	Presence of Micro-Cliffs
PoR	Presence of Rabbits, and their burrows
PSC	Plant Succession Continuity
RC	Rates of Change
RMSE	Root Mean Square Error
RS	Reference Surface
RSLR	Relative Sea Level Rise
RTK-DGPS	Real Time Kinematic - Differential Global Positioning Systems
RTR	Relative Tidal Range
RZ	Reclaimed Zones

S	Stoniness
SB	San Bars
SC	Sand Collectors
SF	Shell Fishing Pressure
SfM	Structure from Motion
SHDI	Shannon's Diversity Index
SPAB (ZEPA)	Zone of Special Protection for birds
SSEI	Shoreline Sandy Environments Index
SVB	San Vicente de la Barquera estuary
T&P	Vehicle Traffic and Parking
TC	Total Cover
TFI	Tidal Flats Index
Tn	Transect n
UAS	Unmanned Aerial Systems
W	Waste

Nomenclature

p_{ij}	Proportion of area of a mapped feature i
n_{ij}	Number of reference points classified as mapped feature I and reference feature j
n_{i+}	Number of pixels per sample and in the entire map in stratum i
N_{i+}	Number of pixels in the entire map in stratum i
P_c	Overall proportion of pixels correctly classified
P_{Ui}	User's accuracy for feature i
P_{Pi}	Producer's accuracy
κ	Kappa coefficient
p_{k+}	Map sum for feature k
p_{+k}	Reference sum for feature k
K	Smoothed Kernel function
n	Sample size
h	Bin-width
Ω	Dimensionless fall velocity or Dean's number
H_b	Wave height at the break point
w_s	Sediment fall velocity
T	Wave period
g	Gravitational constant
H_0	Significant wave height
D_{50}	Median value of the grain size
$\sum Lc$	Total accumulated length of the channels (km)
S	Total saltmarsh surface (km^2)

1. General Introduction

1.1. Definition and classification of estuaries

Broadly defined, estuaries are transitional systems between fresh water from rivers and salt water from open oceans (Nielsen, 2009). The upper limit of an estuary upstream is usually defined by the limit of the salt water intrusion, or where tidal oscillation is discernible (Ibáñez *et al.*, 1997). These transitional zones comprise a great variety of associated systems such as marshes, dunes and beaches. They represent the culmination of an eustatic cycle, whose sedimentary infilling is carried out from river valleys previously excavated, with continental, marine and native sediments (López, 2015).

The estuaries develop on both low and rocky coasts and are found worldwide independently of energy regime and depositional environment (Perillo, 1995; Figure 1.1). The diversity of estuaries is due to multiple factors, according to the variety of processes and interactions between environments that take place in these areas, and can be grouped in two classes of factors: (1) historical factors inherent to the main geological features of the zone and (2) contemporary factors, derived from the main active processes (tides, waves and river discharges, mainly; Arche, 2010). The diversity of factors is precisely, the main problem in establishing an definition of estuary that is valid for all scientific disciplines in all situations (Brito, 2012; Galván, 2014).

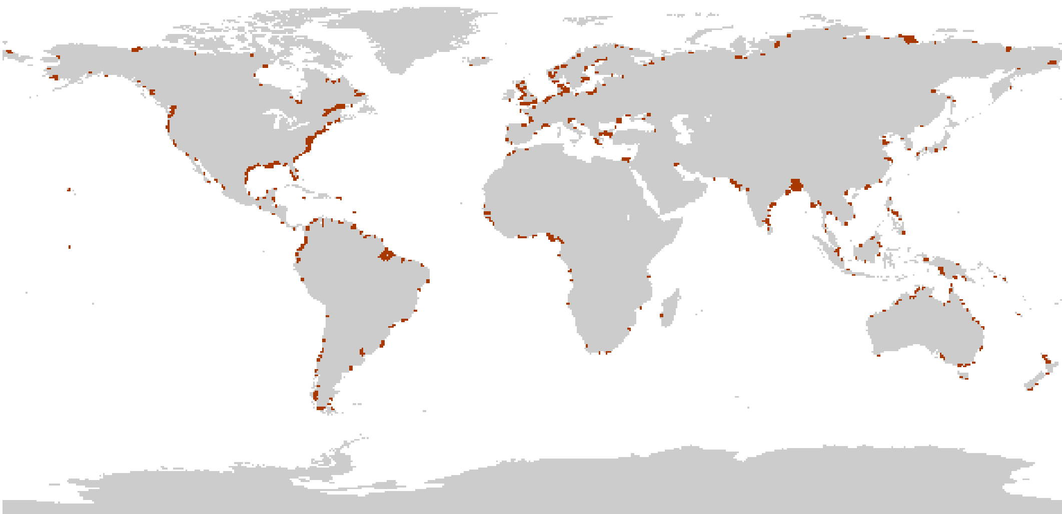


Figure 1.1. Global distribution of over 1,300 estuaries, including some lagoon systems and fjords (modified from "Sea Around Us" project).

The definition of estuaries has been, therefore, a controversial issue over the past years and it is discussed also at present, depending on the field of study, and even more with the trend in recent years to apply multidisciplinary approaches for the management of different environments (Brito, 2012). In an attempt to unify definitions, Perillo (1995b) defined an estuary as a *semi-enclosed coastal body of water that extends to the effective limit of tidal influence, within which sea water entering from one or more free connections with the open sea, or any other saline coastal body of water, is significantly diluted with fresh water derived from land drainage, and can sustain euryhaline biological species from either part or the whole of their life cycle.* This author integrated not only geomorphological and physical characteristics of estuaries, but also biological ones, which seems to be a suitable definition according to the scope of the present thesis. Not only scientist, but also the legislative framework has the need to achieve a multidisciplinary approach when defining estuaries. Indeed, the European Water Framework Directive (Directive 2000/60/CE) defined the concept of transitional waters, which aimed to define the variability that characterizes those systems.

The classification of estuaries has been also widely discussed. The most used classifications follow different criteria, from entrance conditions (Cooper, 2001), stage of development and degree of infilling (Roy, 1984), morphology (Fairbridge, 1980), tidal range (Hayes, 1975), to vertical stratification and salinity structure (Cameron and Pritchard, 1963). One of the most used classification was defined by Dalrymple et al. (1992), who related estuaries with coastal systems (deltas, tidal flats, beaches), according to dynamic agents (river, tides and waves; Figure 1.2) and long-term processes, taking into account sea level variations and sediment inputs.

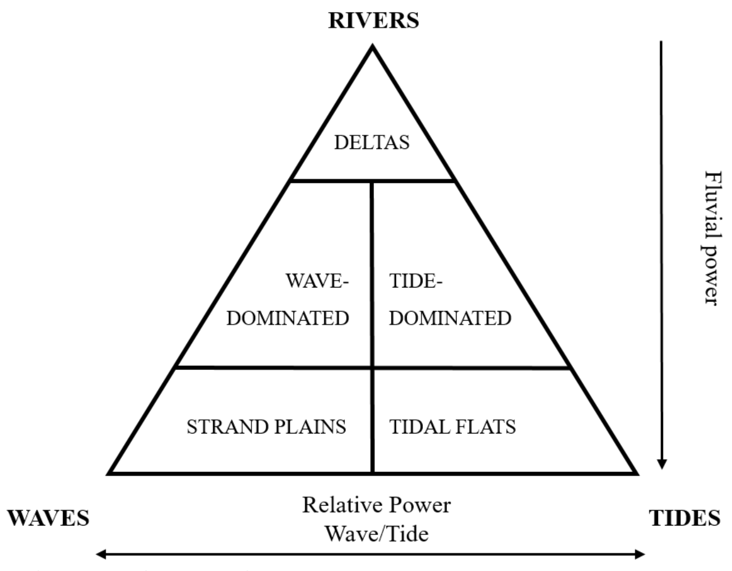


Figure 1.2. Simplified classification of coastal environments associated with estuaries according to Dalrymple et al. (1992), considering river input, wave and tidal processes.

Thus, those authors defined two main types of estuaries based on these concepts: wave-dominated estuaries, where waves are strongly dominant at the mouth, producing littoral transport and, therefore, usually present a confining barrier, and tide-dominated estuaries, where tides are much stronger than both waves and river discharges, generally with a funnel-shape and wide mouths. Apart from these two main types, mixed wave-tide environments (Hayes, 1975) and river-dominated environments (deltas) are also included on most used classifications (Cooper, 1993).

A correct estuarine functioning depends on the connectivity between the dynamic forces and the subsystems within the estuaries. This connectivity can occurs at different scales: between estuaries and other systems but also within the different environments present in an estuary (Kennish, 2016). This complex interaction of factors makes estuaries singular zones also from an ecological point of view, as they are amongst the most productive ecosystems worldwide (Basset *et al.*, 2013). The variety of gradients occurring in these areas supports the development of multitude of habitats. Thus, studying the evolution and behaviour of estuaries is often difficult, due to the challenges to record data in areas of difficult access, the problems of methods and instrumentation in these transitional systems (land-sea interface) and the scales at where different processes occur, among others (Knight and FitzGerald, 2005). With some exceptions, these difficulties translates into database limitations, since data are usually sparse, particularly for long-term scales (Carter and Woodroffe, 1994).

Therefore, the quantification and monitoring of estuarine changes require diverse methods (Ojeda, 2000) to evaluate the great diversity of processes involved, where spatial and temporal scales are intimately linked. Thus, fast processes often take place at small spatial scales, while secular trends often take place at wider spatial scales (Figure 1.3; Carter and Woodroffe, 1994). According to this, the scale of the analysis may determine differences in the coastal trends (Del Río, 2007). The very short-term scale, often defined as *instantaneous* scale, involves changes of hydrodynamic nature, mainly waves, currents and winds. This scale usually affects small areas (order of meters). The short to medium term (from says to years), the *event* scale, is the adequate to study processes of morphodynamic nature (Gracia *et al.*, 2005), affecting territories between a few metres to several kilometres. The medium to long-term (from years to decades) is defined as the *engineering* or the cartographic scale, and allows for the study of the system progressively adapting to changes on a spatial scale of tens of kilometres. Lastly, the geological scale is a long-term scale, from hundreds to thousands of years, in which the coastal changes related to global phenomena affect areas much wider. Thus, it is important to study connection between estuaries and other systems (*engineering* scale), together with *instantaneous* and *event* processes, which allows to determine the current state of the system. Lastly, it is important to combine studies at the short, medium and long terms to identify and describe the behaviour of the system, in order to predict future evolution – certainly the type of information requested by coastal planners.

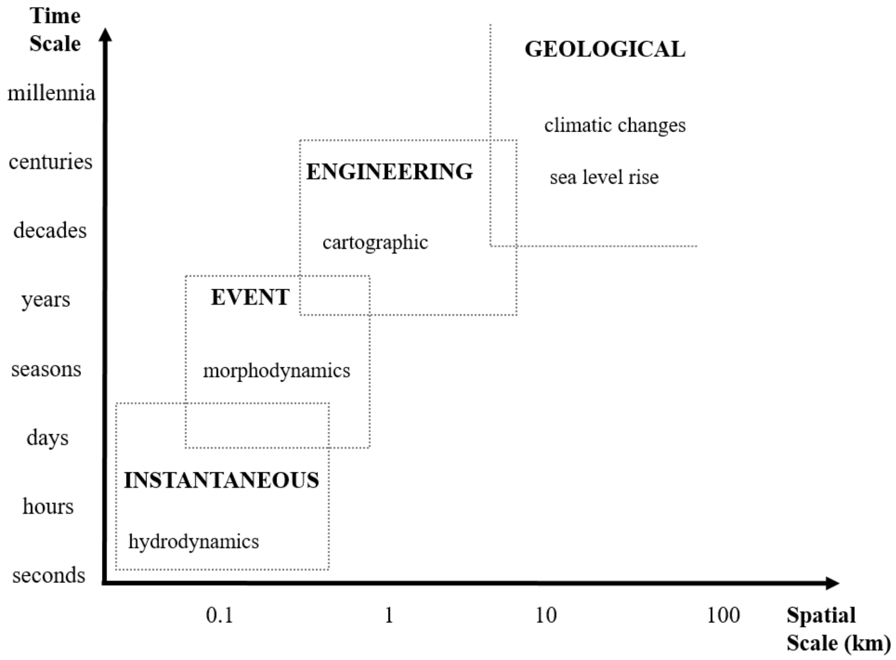


Figure 1.3. Definition of spatial and temporal scales involved in coastal evolution (Modified from Carter and Woodroffe, 1994).

All the aforementioned processes, working at different scales, have been monitored by means of numerous methods in the last years: satellite imagery (Laengner *et al.*, 2019; and references therein), aerial photogrammetry (Schmidt *et al.*, 2004; Del Río, 2007; Ghosh, 2019) or Light Detection and Ranging (LiDAR; Schmid *et al.*, 2011; Doyle and Woodroffe, 2018), as well as video-monitoring systems (Montes *et al.*, 2018; and references therein); combined with ground-based surveying with Real Time Kinematic Differential Global Positioning Systems (RTK-DGPS) or Terrestrial Laser Scanner (TLS; Harley *et al.*, 2011). Lastly, new methods are arising and increasingly used, the Unmanned Aerial Systems (UAS) and Structure from Motion algorithms (SfM; Talavera, 2019), which present a high spatial and temporal resolution, besides low costs. It is important, then, to select the proper methodology by finding a right balance between temporal and spatial resolution, which also depends on the aim of the study.

1.2. Importance of studying estuaries

The abundance of fertile land and natural resources has always been a claim for the settlement of human populations in estuarine areas (Small *et al.*, 2003; Davis and Kidd, 2012; Boerema and Meire, 2017). In fact, the highest proportion of world's population is concentrated on coastal areas and, specifically, in areas close to river mouths (Figure 1.4; Besset *et al.*, 2019). Estuaries provide important ecosystem services as resource supply (extractive fishing, aquaculture or salt and aggregate extraction), culture (tourism and leisure activities) and regulation services (energy and morphosedimentary regulation or biological control; Beaumont *et al.*, 2007). Besides, they play an important role providing physical support and ongoing processes which support these activities, known as 'geomorphic services' (Reed *et al.*, 2009).

Figure 1.4. Estuary of the SE coast of Australia, showing the main associated subsystems (beaches, dunes and saltmarshes) as well as human settelements (Source: El Siglo Coahuila; https://www.elsiglocoahuila.mx/coahuila/noticia/366957.muestra-estudio-la-vulnerabilidad-de-los-estuarios-al-cambio-climatico.html).

For decades, the estuarine management focused mainly on the economic exploitation of the resources offered by these ecosystems. Under this aim, the changes in land use for estuaries worldwide has included artificial channels to improve maritime transport, drying up of some surfaces by dykes construction for agriculture and grazing, land-use change or urbanization (Turner *et al.*, 2000; Atkins *et al.*, 2011; Barbier *et al.*, 2011). Special case is the construction of dams, which, indeed, is probably the strongest pressure on rivers nowadays and, consequently, on estuaries worldwide (Syvitski *et al.*, 2005). These changes include direct impacts as alteration of the hydrological regimes, and loss of areas occupied by the associated systems within the estuaries, but also indirect impacts as eutrophication (Barbier *et al.*, 2011; Grill *et al.*, 2019). All together, these modifications have led to the loss of a large part of the surface occupied by intertidal areas (Hood, 2004), directly affecting the general functioning of the system and, therefore, each associated subsystems and the processes taking place on them.

The short to medium term projections of these changes (increase in global temperature, decrease in precipitation in many temperate areas, and sea level rise, mainly), are expected to affect increasingly the nature and dynamics of the substrate and, therefore, of the vegetation cover. These changes may have consequences on the extension and distribution of the associated systems, increasing the situations of natural risk, as coastal flooding (Sayers *et al.*, 2002). An effective adaptation to all these changes requires integrated management measures, able to take into account the interdependence on functioning of the different coastal systems. This involves the design of new methodologies to improve our capacity to carry out assessments of the integral functionality of coastal systems in general, and of estuaries in particular (Clark *et al.*, 2001).

The term eco-geomorphology has been increasingly used in numerous studies concerning coastal conservation and management. It encompasses the biogeographic approach in the study of interactions between the biosphere and the physical systems (Parker and Bendix, 1996; Doyle and Woodroffe, 2018). As described by Dalrymple *et al*. (1992), it is necessary to study the relationships of estuaries with other adjacent systems, describing the importance of active processes that take place in these areas. The relative balance of waves, tides and river processes exerts a considerable control over morphology, but also over the ecological dynamics of deltas and estuaries (Woodroffe, 2002). These conditions, together with the broad climatic and geographical setting, are the boundary conditions controlling the formation and evolution of the estuarine habitats. Thus, the essence of estuarine eco-geomorphological functioning is the connectivity between subsystems (Basset *et al.*, 2013) and the boundary conditions. *A priori*, this connectivity can be considered obvious and well-described, although the reality is not so simple (Castañeda *et al.*, 2020).

In recent years, numerous studies worldwide have focused on morphological and ecological changes undergone in estuaries due to the above mentioned pressures (Chust *et al.*, 2010; Basset *et al.*, 2013; French *et al.*, 2016; Farris *et al.*, 2019; Ghosh, 2019; Laengner *et al.*, 2019). However, rarely these studies have included the two perspectives (Mury *et al.*, 2020).

Most of these studies had focused on plant-substrate relations (Rajakaruna and Boyd, 2014) and rarely address the landscape scale.

The difficulty of combining these perspectives together with the inherent difficulties of studying complex systems at a whole level requires a significant effort. However, in the context of the coastal conservation, it is necessary to evaluate this connectivity at different temporal and spatial scales to develop multiple zoning and functioning schemes.

1.3. International and national assessment of estuaries

The pressures described in the previous section and the forthcoming changes have led the administrations to develop environmental management policies to evaluate the state of conservation of the coastal habitats. They largely respond to the European Union (EU) mandate through the "Habitat Directive", which states that every EU member state must monitor the conservation status of the habitats on their territories. The interest on coastal habitats has led the EU to include specific aspects of these environments in additional directives (e.g. Water Framework Directive, Marine Strategy Framework Directive, for instance). To maximize the usability of these Directives, it has been developed the INSPIRE Directive (INfrastucture for SPatial InfoRmation in Europe), which aims for the standardization of the environmental databases to meet multiple user needs, and for the development of methodologies that allow each institution to carry out standard gathering of environmental information.

In Spain, the transposition of the Habitat Directive was effective by Law 42/2007 on Natural Heritage and Biodiversity. This law stated that the National and Regional Administrations have to monitor the conservation status of their habitats, paying particular attention on those included in Annex I of the Habitat Directive. In particular, the estuaries in Spain are considered as transitional zones (defined by the Water Framework Directive, 2000/60/CE), not only because their natural characteristics, but also from an administrative point of view. Thus, the management competences for the assessment and use estuarine spaces are met with a mosaic of administrative units that must coexist and coordinate. These units are, mainly, the General Directorate of Coastal Areas (national competences), regional competences, local competences and the Hydrographical Confederations (river basin management state entities), which have competences in the river basin, regardless of regional borders. Unfortunately, this complex map of competences and responsibilities makes it difficult to achieve efficient administrative coordination.

In this sense, a project called “Bases ecológicas preliminares para la conservación de los Tipos de Hábitat de Interés Comunitario en España” (VV.AA., 2009) carried out a first approach to an standardized assessment of the conservation status of habitats of Community Interest in Spain, whose application to estuaries can be found in Ibáñez *et al.* (2009). Despite such initiatives, the development of holistic monitoring methods for complex and extensive systems, such as estuaries, still remains insufficient in Spain. Only few works have included a multidisciplinary approach to the study of estuarine dynamics, and it is needed to apply an integral perspective to estuarine management (Nixon *et al.*, 1986; Mann, 2000; Olsen *et al.*, 2006; Schlesinger and Bernhardt, 2013; Pallero *et al.*, 2018; Wasson *et al.*, 2019). This absence of comprehensive methods for estuarine assessment, together with the lack of high quality time series, often results in inefficient management measures (Scherer *et al.*, 2014).

1.4. Aims of the study

Taking as starting point the above described, the main objective of the present PhD thesis is to characterize estuarine subsystems and their connectivity, as well as to develop and validate a methodology that allows to understand and assess the integral functioning of estuaries.

To achieve this, two hypotheses have been defined (see scheme below), each of them validated through specific objectives. Thus, the thesis is organized in two blocks, each one with two associated specific objectives. The first one responds the requirements of hypothesis I and it is developed in chapters 3, 4 and 5, and the second block responds the requirements of hypothesis II and it is developed in chapter 6.

HYPOTHESIS I: Mid-latitude estuaries present the same types of associated subsystems (i.e. beaches, dunes, tidal flats and the drainage network), interconnected through the water body and whose individual functioning influences the functional status of the whole system.

SPECIFIC OBJECTIVE I: To determine the recent and current evolutionary state of three estuaries located in different biogeographic and oceanographic regions along the Iberian coast.

SPECIFIC OBJECTIVE II: To evaluate the most relevant natural processes and the anthropogenic influence on their functioning.

HYPOTHESIS II: The management of estuarine systems requires the implementation of methods of evaluation, for example the application of indexes that consider the functional integrity of the system, incorporating an ecosystem approach and allowing the diagnosis of the current and future environmental status of the system.

SPECIFIC OBJECTIVE III: To define a set of variables to characterize the natural and anthropogenic processes dominant in estuarine systems.

SPECIFIC OBJECTIVE IV: To design and validate an environmental characterization index of estuaries as well as to develop vulnerability maps of the study zones.

1.5. Thesis outline

The present thesis is organised in 7 chapters. Since there is not a general methodological chapter, each of the chapters contains the specific methodology carried out to achieve the stated objectives, along with the main results obtained to make it easier to read and interpret. Thus, the final structure of the thesis is as follows.

Chapter 1: General Introduction.

The first chapter includes a general background on the main topics covered in this thesis along with the motivation for the thesis. At the end of the chapter, the main hypotheses and objectives are outlined.

Chapter 2: Study Zones

The chapter 2 summarises the main characteristics of the study sites, including their historical evolution, hydrodynamic and climatic aspects, as well as a summary of the main anthropic pressures that affect each site. In addition, the main eco-geomorphological subsystems present at each site are also briefly described.

Chapter 3: Estuarine Mapping and Eco-Geomorphological Characterization

This chapter presents the geomorphological changes suffered in the study zones according to 60-year time series analyses. These analyses allow estimating the evolution and current state of each of them. The chapter includes methods and results of the analyses.

Chapter 4: Tidal flats analysis: The San Vicente de la Barquera study case

According to results obtained in the previous chapter, in chapter 4 a specific methodology to study the evolution of one of the most threatened subsystems (tidal flats) is described. This chapter presents the results of the application of the methodology in the San Vicente de la Barquera estuary as a test site. The study site was selected for the quality and quantity of available data.

Chapter 5: Considerations on the connectivity of the estuarine processes

Chapter 5 discusses the results for the study of the estuarine connectivity presented in chapters 3 and 4, closing the most relevant findings confirming the first hypothesis of the thesis.

Chapter 6: Estuarine Vulnerability Assessment: *EstuarIndex*

Chapter 6 describes an index design and applied for assessing the environmental status of mid-latitude estuaries. The chapter includes the description of the methodology as well as the results and discussion of its application on the study areas. Therefore, the second hypothesis of the thesis is contrasted in this chapter.

Chapter 7: General conclusions

The main conclusions reached in the present thesis are described in this chapter.

Lastly, the list of **References** cited along the thesis are presented at the end of the manuscript together with the **Annexes**.

2. Study Zones

2.1. Location, historical evolution and hydrodynamic forcing

This work focuses on three study sites, namely (1) San Vicente de la Barquera estuary (SVB), (2) Guadiana River estuary (GUA) and (3) Ebro River delta mouth (EBR). These zones are located on different geological and biogeographical regions along the Iberian coast (Figure 2.1.a): (1) North-Atlantic region, (2) South-Atlantic region, and (3) Mediterranean region, which cover most of the environmental range and oceanographic conditions that occurs on the Iberian Peninsula coasts.

The first study site, San Vicente de la Barquera estuary (Figure 2.1.b), is located in the Cantabrian coast (N Spain, Gulf of Biscay). Geologically the estuary is inset on the coastal mountain reliefs of the Cantabrian Range, a continuation to the west of the Pyrenean orogeny. The valley cuts transversely a complex, very tectonized, structure of different units trending E-W with ages ranging between Triassic and Palaeogene. A series of Cretaceous limestones represent the prevailing lithology in contact with the main estuary channels (Ramírez del Pozo *et al.*, 1976).

Geographically, the estuary is made up of two shallow estuarine bodies which converge northward to form the main estuary (basic morphometric characteristics are detailed in Table 2.1, obtained from Flor-Blanco, 2007 and Cantabric Hydrographic Confederation: https://www.chcantabrico.es/las-cuencas-cantabricas/marco-fisico/hidrologia/rios/escudo).
The SVB estuarine complex is linked to short rivers, *Escudo* and *Gandarilla* rivers, with a low hydrological regime (Flor-Blanco *et al.*, 2015). The main one, the Escudo river, has not many pressures and is neither of great magnitude. Nevertheless, several interventions (i.e. canalization of the drainage system as it goes through urban areas) during the 20th century have led to the reduction of fluvial sedimentary inputs to the estuary. On the other hand, the oceanic inputs of sediment are conditioned by the configuration of the coast. Like most of the Cantabrian estuaries, the estuary forms an incised valley, almost completely infilled with sediments (Flor-Blanco and Flor, 2019), and presents a confining sand barrier, artificially channeled by two lateral jetties (constructed in 1944), that change the morphodynamics of the entire estuary (Flor-Blanco *et al.*, 2015). Regarding the hydrodynamic conditions and according to the classification proposed by Dalrymple *et al*. (1992), the SVB is a tide-dominated totally-mixed estuary (Flor-Blanco, 2007), with a semi-diurnal mesotidal regime. The mean spring tidal range (MSTR) is 3.94 m and the Highest Astronomical Tide (HAT) reaches 4.85 m (Figure 2.2; Santander tide gauge, National Port Authority, 2019). Tide is

the most important dynamic factor in this zone, leading to well-developed tidal flats, extending upstream up to 6 km from the river mouth. The predominant waves come from NW (Figure 2.3 .a), with the most frequent significant wave height ranging between 1 and 2 m and peak periods greater than 9 s in most cases (frequency of 65%). In this particular area, the coast orientation favours the refraction of the incident waves and forms a local coastal drift current moving westward. Besides, this region is considered as a high energy area with strong and persistent winds from various directions but mainly from W-NW-NE (Figure 2.3.b; Flor-Blanco *et al.*, 2015). The regional littoral drift in this area, and therefore the coastal sand transport, has an eastward direction.

Climatically the zone is characterized by an oceanic climate, with no dry season. Nevertheless, the climate shows slight variations due to the effect of geographical and thermodynamic factors (mainly the marine influence and atmospheric disturbances typical from these mid-latitudes). Precipitations are abundant in this area, with approx. 850 mm/year, and moderate average temperatures between 12 ºC and 15ºC (López, 2015, Figure 2.4).

The second study site is the Guadiana River estuary (Figure 2.1.c). It is located on the southern border between Spain and Portugal, inset on the low reliefs of the western limits of the Guadalquivir Tertiary basin. The materials surrounding the estuary mainly consist of horizontal, Neogene sands and gravels (Leyva *et al.*, 1983).

Geographically the estuary consists on a single channel (50-700 m wide; Lobo *et al.*, 2004), N-S oriented. It is also a rock-bound estuary (Morales, 1995), as it presents a narrow deep channel. It is the fourth longest river in the Iberian Peninsula, with a mean discharge of 144 m^3/s, although with an inter-annual and seasonal variability (Morales *et al.*, 2006; Morales and Garel, 2019; Table 2.1 specifies the most relevant morphometric data for this work, obtained from Morales, 1995; Morales and Garel, 2019). During the second half of the 20th century, the construction of over 100 dams along its watershed has strongly reduced the sediment supply, due to the regulation of more than 75 % of the drainage area. The *Alqueva* dam (2002), the closest to the Guadiana River mouth, is the most relevant for the reduction in liquid and solid discharges and, therefore, an important pressure for the estuarine dynamics. As a consequence, for the estuary, the riverine contribution is significantly lower than that of littoral transport (Garel and Ferreira, 2011). The Guadiana estuary was developed during the Holocene period through the prograding of sandy barriers and the whole system acquired a wave-dominated delta shape, which is a typical morphology of a mature estuarine system in advanced stage of sediment infilling (Morales, 1997). This thesis focuses on the part of the estuary with marine influence, that is, the part affected by the dynamics of external drivers.

During the second half of the 20^{th} century, the construction of jetties and revetments on the Portuguese margin of the estuary caused a severe rigidization of the shoreline; for this reason, this study only evaluated the most natural margin, the Spanish one.

Regarding the hydrodynamic characteristics and according to the criteria established by Dalrymple et al. (1992), the Guadiana estuary is a wave-dominated system. It has a mesotidal regime, with a MSTR of 3.06 m, and a HAT of 3.87 m (Figure 2.2; Isla Canela tide gauge, National Port Authority, 2019). The mixing of the estuary varies seasonally with river discharges from a well-mixed water column during low discharges periods to partially stratified one during winter (Morales, 1995). Predominant waves come mainly from SW and SE with an average of significant height between 0.5 and 1 m (Figure 2.3.c; Morales *et al.*, 1994; Costa *et al.*, 2001). This, together with the longer action time of the SW waves produces a main littoral drift moving eastward. Regarding the winds, in this region they come from NW and SW mainly (Figure 2.3. d), with an average wind speed of 3 to 4.5 m/s (National Port Authority, 2019).

Climatically this zone is characterized as semi-arid climate, with the exception of summer and winter seasons considered as arid and temperate-humid, respectively. The average rainfall is of around 500 mm/year (Figure 2.4.b) and the average temperatures about 18º C (Morales, 1995).

Table 2.1. Morphometric characteristics of the three studies estuaries (h: depth of the main channel, b: width of the main channel, salt wedge: the upstream limit with influence of salt water, L main channel: total length of the main channel (from the source to the mouth), L estuarine section: length of the estuarine section of the main channel, drainage basin: area drained by the river).

Morphometric characteristic	SVB	GUA	EBR
h	-	< 6 m	6.79 m (mean)
b	197 m (max.)	200-700 m	297.42 m (mean)
Salt wedge	~ 5.8 km	~ 60 km	~ 32 km
L main channel	26.8 km	834 km	911 km
L estuarine section	6.30 km	80 km	42.56 km
Drainage basin	70.842 km^2	67129.38 km^2	85534 km^2

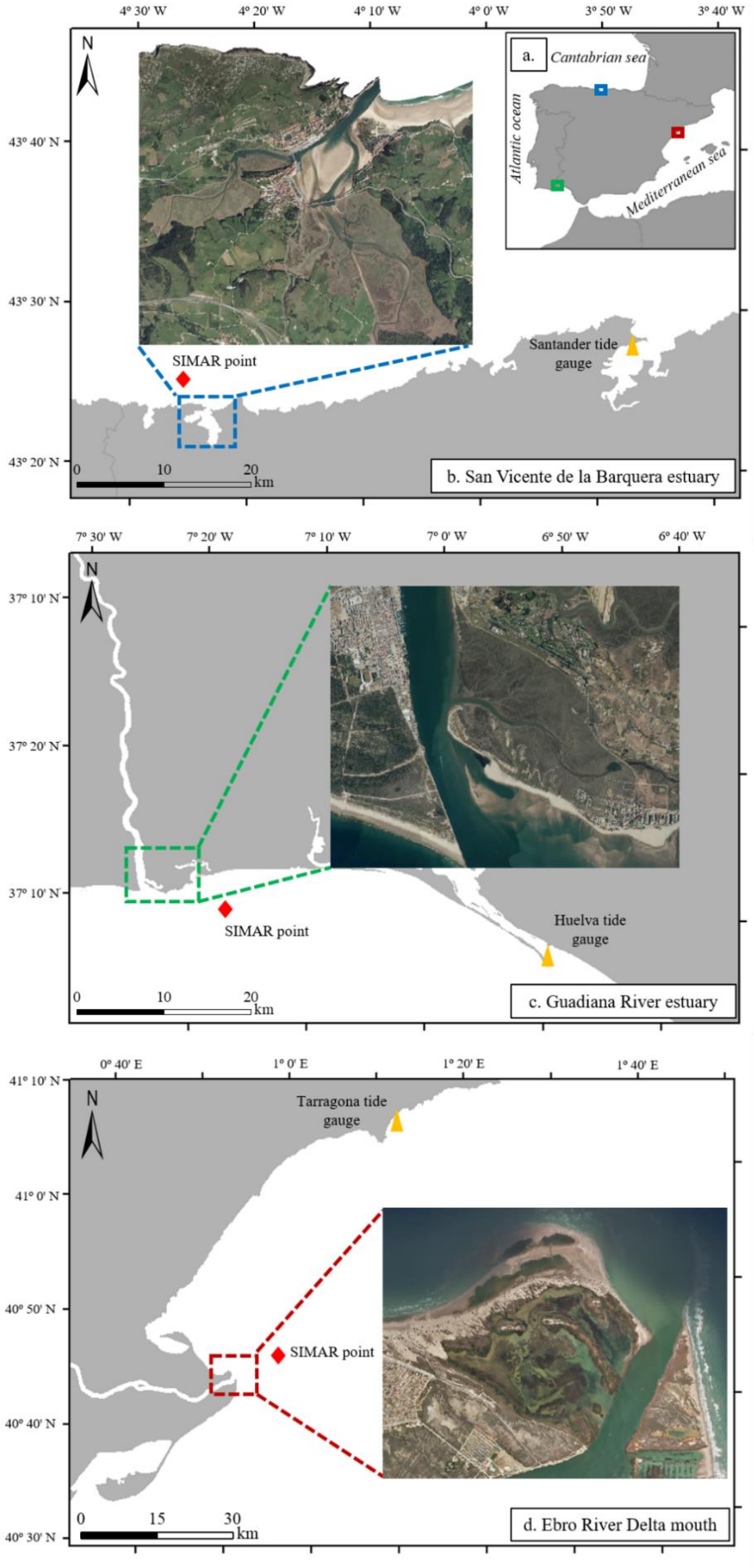


Figure 2.1. (a) Location of the study areas along the Iberian coast (colours on the image match with colours representing the corresponding estuary in the figures of this thesis), with a closer look at the sites: (b) the San Vicente de la Barquera estuary, (c) the Guadiana River estuary and (d) the Ebro River Delta mouth. SIMAR points and tide gauges' positions from which all the hydrodynamic data have been extracted are indicated.

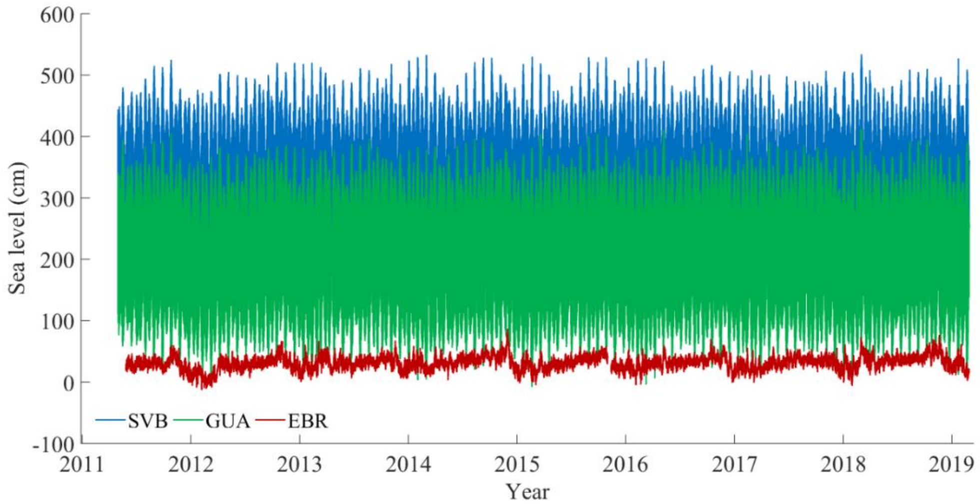


Figure 2.2. Sea level (cm) evolution on each study site. Differences in tidal ranges can be observed. Data obtained from the nearest tide gauges of each study site.

The last one, the Ebro River delta mouth (Figure 2.1.d) is located on the Mediterranean coast of the Iberian Peninsula and is one of the most important deltas in the western Mediterranean (Ibáñez *et al.*, 1997). It is also one of the six great rivers of the Iberian Peninsula and the only one that drains into the Mediterranean Sea. Besides, it presents the largest discharges in Spain (426 m^3/s), with a marked variability between dry and wet years (Genua-Olmedo, 2017; main morphometric characteristics are detailed in Table 2.1, data obtained from Hydrographic Confederation of the Ebro River: http://www.chebro.es/che/memoria2019/, Movellán, 2004; Rodríguez-Santalla *et al.*, 2011). Nevertheless, the river input of sediment has been drastically reduced by the construction of dams (e.g. *Flix* (1948), *Mequinenza* (1966) and *Ribarroja* (1967) dams, particularly; Rodríguez-Santalla and Somoza, 2019). The direct effect of dam constructions in the Ebro Delta is the interruption of the sediment transport, causing morphological changes downstream, as well as in the associated habitats (Kondolf, 1997; Rodríguez-Santalla and Somoza, 2019). The extension of the emerged area is 325 km^2, which represents only a 15 % of the total area of the delta (Rodríguez-Santalla and Somoza, 2019). The elevations do not exceed 5-6 m and approx. 50 % of the total surface lies below 0.5 m above MSL (Genua-Olmedo, 2017). The Ebro Delta began to develop at the end of the sea level post-glacial eustatic rise (Maldonado, 1977, 1986) and its shape is the result of the advance of successive deltaic lobes that have progressed radially (Somoza *et al.*, 1998; Rodríguez-Santalla *et al.*, 2011). The current shape of the mouth is linked to a change on the river flow in 1947 (Figure 2.5). As a consequence, it was created the *Gola Norte* (*Garxal*), which is the area where the present thesis is focused. The two mouths coexisted until 1956, when the *Gola Este,* o *Cap Tortosa*, was naturally closed (Serra *et al.*, 1998). In particular, the study area focuses on the river mouth (Figure 2.1).

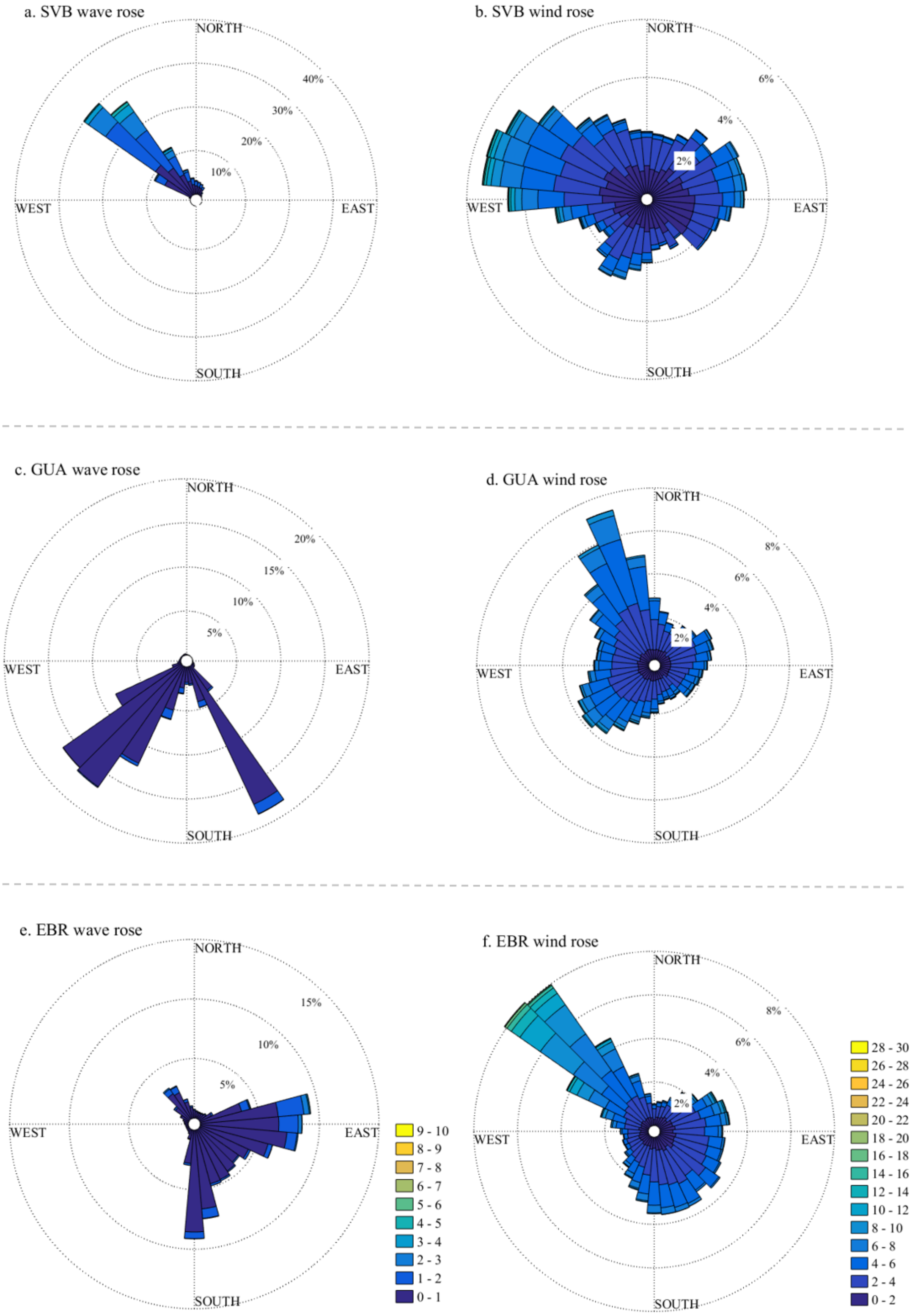


Figure 2.3. Wave (left) and wind (right) roses from each study sites extracted from the SIMAR points: SVB - SIMAR 3122034 (4.42ºW, 43.42ºN), GUA - SIMAR 5026023 (7.33ºW, 37.17ºN) and EBR - SIMAR 2095129 (0.92ºE, 40.75ºN). See Figure 2.1 for visual location of the SIMAR points. Data provided by the National Port Authority (2019).

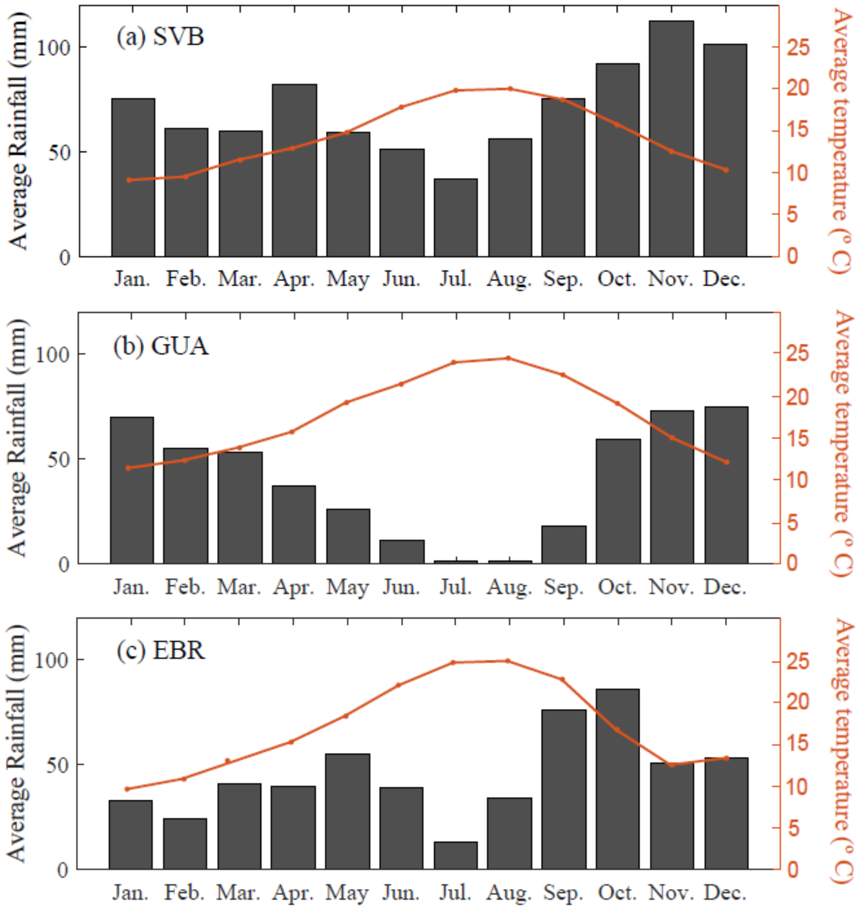


Figure 2.4. Climographs for the three study zones. Data provided by the National Meteorological Agency (Aemet).

The Ebro Delta has a microtidal regime (Figure 2.2), with a MSTR of about 0.20 m (Franquet Bernis *et al.*, 2017), what gives a greater importance to the meteorological tide component (surges). The combined effect of meteorological and storm surges has a strong erosive effect both on the coast and on the dune fields of this area (Sánchez *et al.*, 2011). Originally, the Ebro Delta was dominated by fluvial sediment deposition remodeled by waves (Sánchez-Arcilla and Jiménez, 1997). Currently, it is a wave dominated system (Rodríguez-Santalla and Somoza, 2019) where waves come mainly from three directions: E, S and NW (Figure 2.3.e). East component is the dominant direction due to its frequency and energetic components, and in fact is the responsible for the main transport of sediments in the mouth of the Ebro River delta. Waves and currents in the Ebro delta are strongly controlled by wind dynamics. Thus, the wind is an important component in this area, with strong winds during spring, matching with E wave events (Figure 2.3.e; Cateura et al., 2004). The strongest winds come from NW. This component is associated with the *Mestral* winds, corresponding to wave calm periods (Jiménez *et al.*, 1997). Winds have a double-effect on dune fields: on one hand, the formation of dunes is conditioned by the influence of the predominant winds in this area, from NW (Figure 2.3.f) and, on the other hand, lead to a loss of sediment (Serra, 2007). Lastly, prevailing littoral drift in the N hemidelta, where the study area is located, follows a NW direction.

Additionally, the average subsidence of the delta was estimated in 1 to 3.2 mm/year in recent decades (Ibáñez *et al.*, 1997). The medium-long term effects of this subsidence together with the relative sea level rise (RSLR) estimated for this area (1-2 mm/y), result in an effective RLSR between 3 and 6 mm/y, in the areas close to the mouth (Verdaguer, 1983; Barnolas, 1995; Day *et al.*, 1995; Ibáñez *et al.*, 1995). Nevertheless, Ibáñez *et al*. (2010) described that floods and river overflowing enhance vertical accretion, minimizing the effects of the RSLR in the mouth complex.

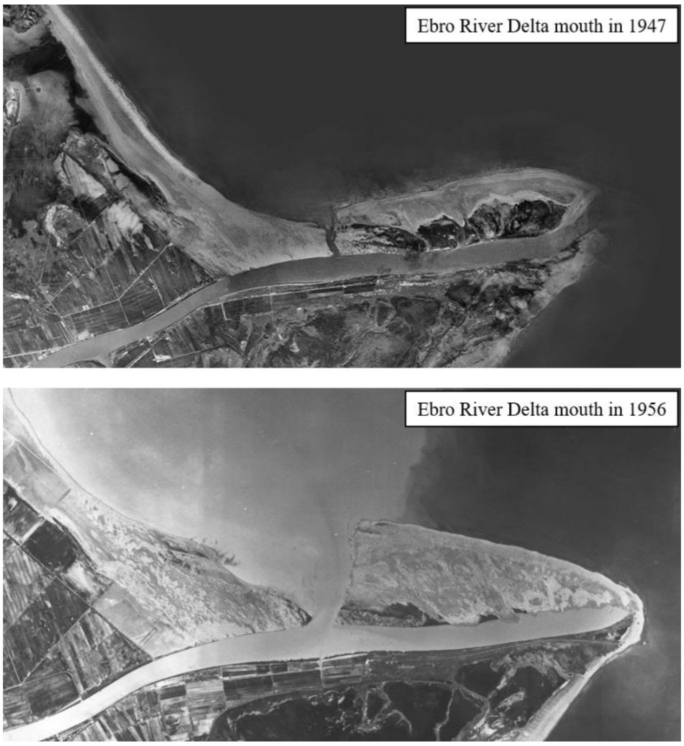


Figure 2.5. Aerial photographs showing the major changes in the mouth of the Ebro River Delta between 1947 and 1956.

Climatically, this zone has a littoral Mediterranean climate, with moderate temperatures during winter and sub-arid weather in summer, as consequence of high temperatures and low precipitations. The thermoregulatory effect of the sea softens the temperatures in the coastal strip throughout the year, with average values between 15.5 ºC and 17ºC, and an average rainfall between 500-600 mm/year (Sánchez-García *et al.*, 2011; Figure 2.4.c).

2.2. Eco-geomorphological settings

This section describes the main subsystems present in each study site, with a brief description of the evolution, functioning and main plant communities associated.

2.2.1. San Vicente de la Barquera estuary (SVB)

The SVB estuary can be longitudinally divided in three sectors according to Flor-Blanco (2007): the mouth complex, the sandy bay and the tidal flats. Each of these sectors presents different morphosedimentary features. As regards the mouth complex, there is an external beach (*Merón* beach) backed by a dune system. It is a wide dissipative semi-natural beach (Figure 2.6.a), where different anthropic pressures can be found, namely crosswalks, a parking directly on the dune system and a camping behind it (Figure 2.6.b). Those pressures have increased in the last 30 years, with the urbanization of the zone. Due to this, the active foredune system is not wide enough to host a 'complete' sequence of habitats, showing mainly a succession of embryo-primary-grey dunes fixed by grasses (approx. 20 m wide), with relative low heights (5-7 m above mean sea level). Behind this foredune ridge, there is a relict dune field fixed mainly by *Pinus pinea* strongly affected by the camping construction on it at the end of the 20th century. The main species present in the dunes are *Ammophila arenaria*, *Euphorbia pharalias* and *Elymus farctus* colonizing the embryo band, followed by *Atriplex prostate*, *Aetheorhiza bulbosa*, *Eryngium maritimum*, *Dittrichia viscosa*, *Linaria supina*, *Cakile maritima*, *Reichardia gaditana* and *Calystegia soldanella*, among many others. There are also two estuarine reflective beaches inside the sandy bay (*Los Vagos* and *Tostadero* beaches), with small dunes at the backshore. The grain size on these estuarine beaches is larger than in the external beach-dune system due to the deposit of dredged material obtained from the navigation channels. The sandy bay presents a great heart-shape flood-tidal delta totally emerged during low tide (Figure 2.1.b).

Similar to other Cantabrian estuaries, the main channel and tidal flats are widely developed in this estuary. In the SVB estuary, the main channel is called *Rubín* (developed by the Escudo River) and situated on the eastern zone. The second one, the *Pombo* system, (Gandarilla River) is located on the left, western side of the valley. The tidal flats present a patched-distribution of vegetation with typical species of these latitudes (Figure 2.6.c and d). The mudflats are stablished in the low-intertidal zone and are colonized by seagrasses (*Zostera noltei*) and macroalgae (mainly *Ulva spp.*). The pioneer saltmarsh vegetation in the SVB estuary consists mainly of perennial common grass (*Spartina maritima*) and the annual glasswort *Salicornia spp.* The medium-upper saltmarsh is colonized by perennial vegetation composed mainly of scrub (*Sarcocornia perennis*, *Arthrocnemum macrostachyum*, *Limonium humile*, *Aster tripolum*). In addition, in some points of the upper saltmarsh, there are also small patches of the exotic invasive species *Spartina densiflora*.

The SVB estuary is protected as part of The Oyambre Natural Park since 1988 and the saltmarshes are included in the Natura 2000 Network and considered PCI area (Place of Community Interest).

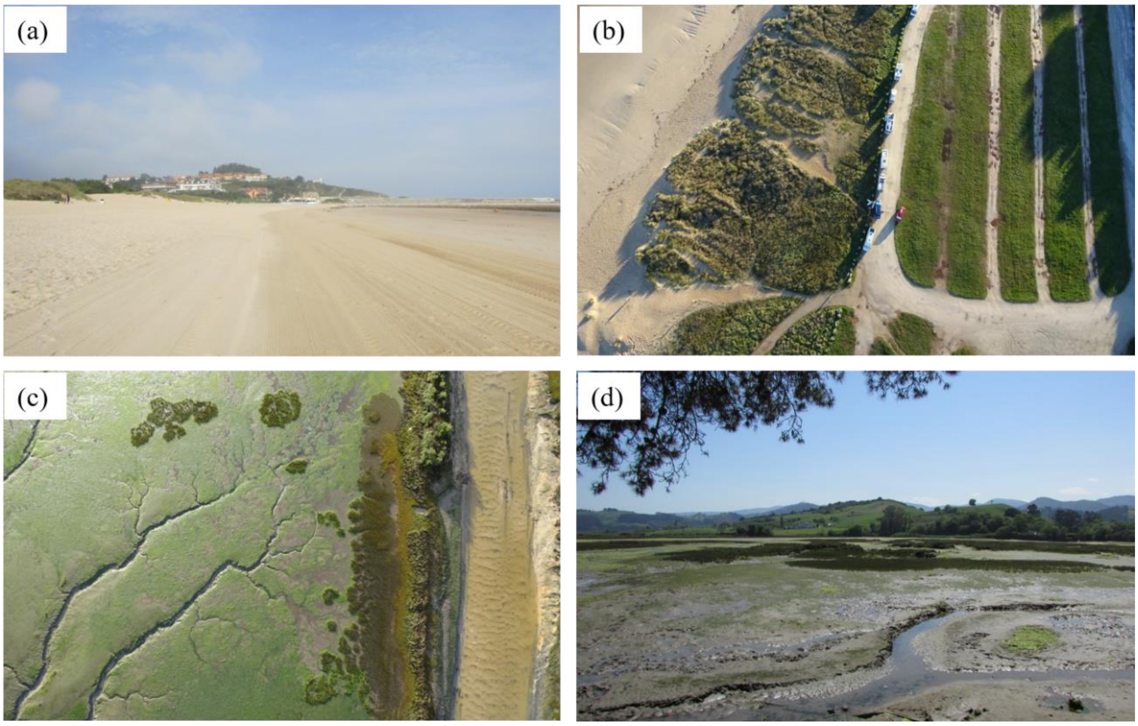


Figure 2.6. Images of the main geomorphological systems in San Vicente de la Barquera estuary: (a) Lateral view of the external beach; (b) Aerial photo of the external dune field, showing the crosswalks and cars on it; (c) Aerial photo showing the patched distribution of the saltmarsh and mudflats colonized by seagrasses and macroalgae; (d) General view of the saltmarsh in the inner part of the tidal flat. The aerial views were obtained from a dron flight in 2018.

2.2.2. Guadiana River estuary (GUA)

According to Morales (1995) and attending to ecological and hydrological characteristics, the Guadiana River estuary can be divided in three sectors attending their ecological and hydrological characteristics: the marine estuary, the central estuary and the upstream. This thesis is focused in the marine part. The GUA estuary presents a typical funnel-shape morphology, with a large amount of sediment deposited in the open area what generates a submerged deltaic zone in its front. The marine estuary is formed by a succession of recurved spits separated by saltmarshes, and an ebb-tidal delta (Figure 2.7). The saltmarshes have an extensive drainage channel network, creating in this sector a subsystem of sedimentary contribution partially independent of the estuary (Morales, 1995).

The intertidal sand deposit or sand shoal in the open area is of great importance for the sediment dynamics of the estuary, since it acts as sediment buffer and sand store (Figure 2.8.a). It is constantly influenced by hydrodynamic agents (i.e. waves and tides) generating shoals that act as swash platforms (Morales and Garel, 2019). The strong dynamics of this zone and the consequent mobility of the sand bars required the construction of jetties (1972-1974) to keep stable the mouth characteristics (Garel and Ferreira, 2015): one emerged jetty was constructed in the Portuguese side and other submerged one in the Spanish side. One of the direct effects these fixed structures was the split of the sandy subtidal shoal merged to the Portuguese side (O'Bril bank), bypassing part of the sediment to the Spanish side (Garel and Ferreira, 2015). After that, a strong erosion of the bank and a landward migration of the sediment has been described (10-100 m/year; Garel et al., 2014), favouring the formation and growth of upstream recurved spits (Figure 2.7).

Figure 2.7. Upstream recurved spits in the Guadiana River estuary. (1) Old recurved spit, (2) New recurved spit. Sectors of the beach are showed by (a) and (b) boxes.

The external beach of the Guadiana River estuary is natural in its westward side, being more influenced by anthropic features eastwards, where Isla Canela urbanisation is located. Its natural part is about 2 km long with a variable width (from 30 to 100 m, approx.), alternating progadational and erosional areas (Figure 2.8.b). It is an intermediate beach very close to a reflective state on its upper (dry) part (Figure 2.7.a), with gentler profiles towards the semi-natural part of Isla Canela, where the beach shows a wider and more dissipative behaviour (Figure 2.7.b). The increase in the beach width in this last sector is due to the presence of a jetty in the mouth of the Carreras mouth (eastward), limiting the longshore transport to the East.

As for the dune system, it also shows a differential behaviour depending on the sector of the beach. The height of the dune system is lower in the natural part (3 – 5 m above mean sea level), reaching almost 8 meters in the easternmost part, the anthropic zone. In the natural part, the profiles are the typical of "well-developed dune systems" and around 100 m wide. Nevertheless, due to the reduced width on the westernmost part of the beach, the dune fronts show an erosive profile, with scarps and absence of embryo dunes. The most recent sandy hook (Figure 2.7) is constituted by primary dunes of limited development, colonized by *Ammophila arenaria* and *Elymus farctus* in the embryo zone (when appearing), followed by species typical of fixed and grey dunes like *Thymus carnosus*, *Crucianella maritima*, *Eryngium maritimum*, *Armeria pungens*, *Echium gaditanum*, *Salsola kali*, *Cakile maritima*, *Pancratium maritimum* and *Polygonum maritimum*, mainly (Figure 2.8.c). The older spit (Figure 2.7) presents well-developed fixed dunes with an increase in plant density and a great density of *Juniperus spp.* and *Retama monosperma* at the back zone.

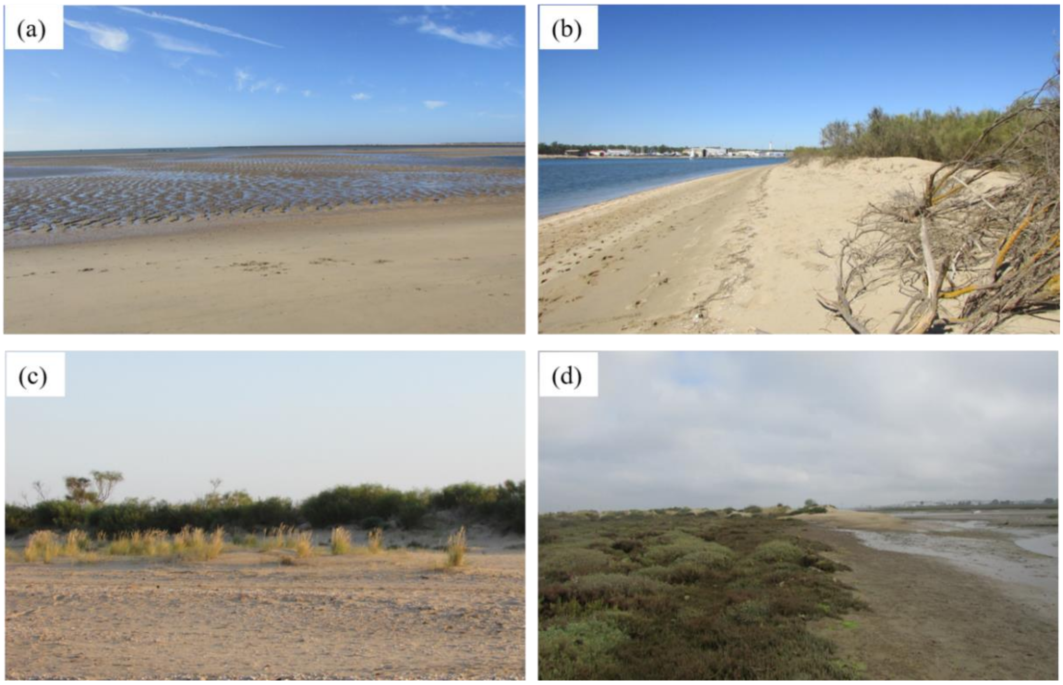


Figure 2.8. Images of the main geomorphological systems described in the Guadiana River estuary: (a) Intertidal sand deposit; (b) External beach in the western sector; (c) Embryo dunes and foredune behind them; (d) Saltmarsh profile showing plant succession.

The tidal flats in the GUA estuary show two well-differentiated zones, separated by the recurved spits (Figure 2.7). The first one is a mature system completely colonized by dense vegetation, with profiles with a very gentle slope. The second one is smaller and formed in the sheltered area between the two recurved spits (Figure 2.8.d). Both zones present the typical plant succession of Atlantic saltmarshes, with a pioneer area colonized by *Spartina maritima* and *Salicornia spp.*, followed by *Sarcocornia spp.*, *Suaeda spp.*, *Halimione portulacoides* and *Arthrocnemum spp.*, mainly. It is also remarkable the great abundance of *Spartina densiflora* at some points of this zone.

The areas described for the GUA estuary are included in the RAMSAR wetland and Natura 2000 Networks, as well as regulated as PCI, Natural Zone and SPAB (Special Protection Area for Birds).

2.2.3. Ebro River Delta mouth (EBR)

The current shape of the Ebro Delta is described as two hemideltas separated by the main river channel (Figure 2.1.d). The front of the delta is composed by the river mouth and two narrow littoral spits: *El Fangar* to the NW and *Los Alfaques* to the SW (Rodríguez-Santalla and Somoza, 2019). The right side of the river mouth (*San Antonio* Island) is the one where the dynamic agents have more impact, matching with the most energetic waves (Figure 2.3.e). In the left side, the study zone, the development of the beach and dune ridges led to the formation of a submerged meadow (*El Garxal*, Figure 2.9.d), sheltered by these sandy features.

Specifically, the study area focuses on the side of the *Riumar* beach and its associated dune system. The north-west section of this beach is a semi-natural beach crossed by a raised walkway with several access points to the beach and a well-developed dune system at the back. Whereas the eastern part of the beach is protected and, therefore, completely natural. The access to the natural part is limited by a fence (Figure 2.9.a), protecting more than 8 km of beach length, with a very gentle slope and intertidal well-developed sand bars. This beach is very dynamic with rapid geomorphological changes that varies seasonally (Guillén, 1992; Valdemoro *et al.*, 2007; Sánchez-Arcilla *et al.*, 2008). In recent years, new recurved spits are formed in the area closest to the river. These spits lead to the formation of coastal lagoons when the final part of the spit reaches the beach, due to its concave shape (Figure 2.9.c).

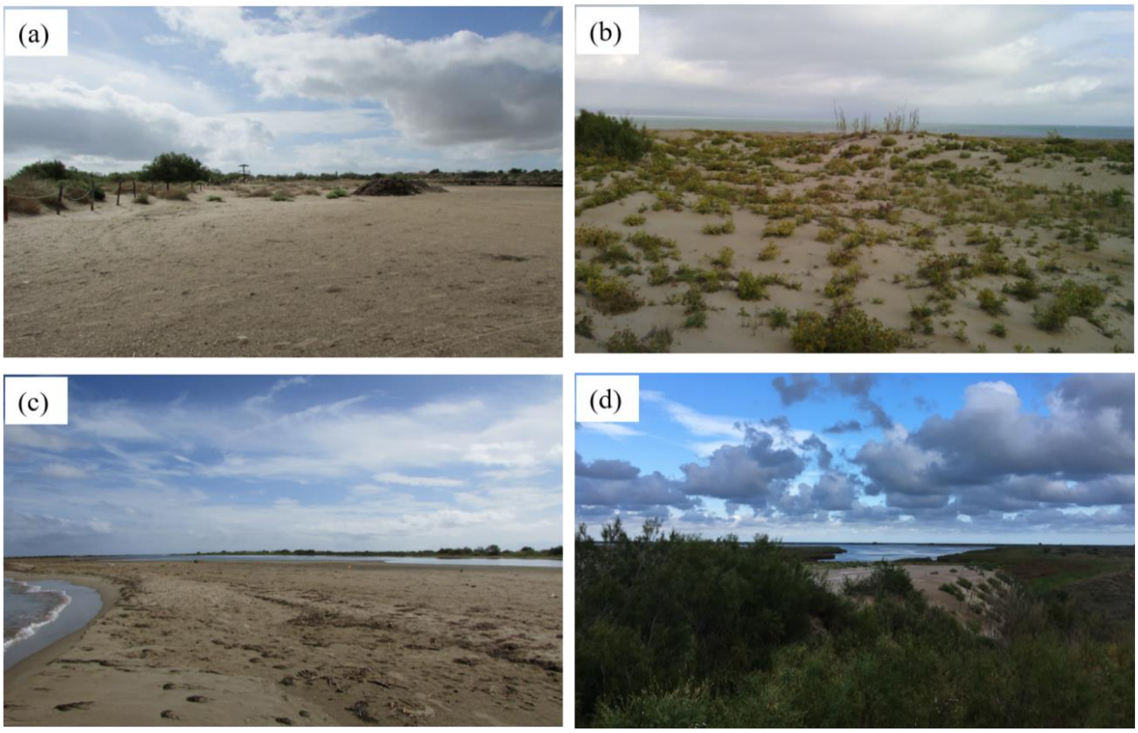


Figure 2.9. Images of the main geomorphological systems described in the Ebro River Delta estuary: (a) Limit between semi-natural and natural beach with the fence marking the boundary in between both of them; (b) Dune system colonized by grasses; (c) Natural beach and coastal lagoon in between the dune field and the beach; (d) Vegetated wetland (El Garxal).

The dune system on the natural part is protected with an enclosure control. The dimensions of the dune system are not homogeneous throughout, being narrower and lower in the southern part, where the erosive agents are stronger. The highest dunes range between 5-6 m above MSL in the northern part and between 2-3 m in the southern part. The dune system is totally vegetated and is well developed. However, in the right part of the river mouth (*San Antonio* Island), the foredune is interrupted by several washover fans, which have increase in number and extension in the recent years and, therefore, have produced a significant erosion of beach and dunes.

The basic sub-environments described in numerous studies of dunes on the Iberian coasts can be distinguished in the Ebro Delta, matching with the main habitat types, according to their associated plant communities. Thus, the typical transect in this zone shows embryo dunes – mobile dunes with *Ammophila arenaria* – fixed dunes – wet dune slacks and stabilized dunes (Figure 2.9.b). Furthermore, in the external part of the southern area, incipient barchan dunes can be observed.

As for the associated habitats in the dune fields, the embryo dunes are colonized by *Cakile maritima*, *Salsola kali* and *Elymus farctus*, mainly, followed by mobile dunes with *Ammophila arenaria*. Furthermore, towards the southern part, it is common to find incipient dunes fixed by *Sarcocornia spp.* and *Arthrocnemum spp*, typical plants of muddy environments (i.e. saltmarsh species). Fixed dunes are colonized by grasses and other species typical from Mediterranean fixed dunes like *Echinophora spinosa*, *Eryngium maritimum*, *Inula crimoides*, *Euphorbia pharalias, Silene spp.*, *Sittrichia viscosa*, *Helichrysum picardii* and *Conyza canadensis*, among others. *Juncus maritimus* and *Scirpus holoschoenus* colonize the wet dune slacks and *Tamarix spp.* is the main species found in the stabilized dunes landward.

The ecological values of the habitat diversity on the EBR estuary (beaches, dunes, wetlands, coastal lagoons, etc.) coexist with an intensive economic activity focus on rice crops. The singularity and relevance of the Ebro delta led to the declaration as Natural Park in 1983 (Real Decrete 357/1983 of 4 August). Besides, some zones are protected as Biosphere Reserve, LIC (PCI) and ZEPA (SPAB) zones due to the great biodiversity of species and ecosystems, as well as Natura 2000 Network area.

3. Estuarine Mapping & Eco-Geomorphological Characterization

The contents of this chapter have been published in:

Aranda, M.; Gracia; F.J. and Peralta, G. 2020. Estuarine mapping and Eco-Geomorphological characterization for Potential Application in Conservation and Management: Three Study Cases along the Iberian Coast. *Applied Sciences*, *10 (13)*, 4429.

3.1. Introduction

Estuaries are complex and dynamic natural systems composed of many interconnected subsystems. They present high levels of structural and functional complexity (Borja *et al.*, 2008). In the outermost zone, a confining sandy complex is usually developed, formed mainly by beaches and dunes (exposed to external agents or purely estuarine). The inner part is made up of different types of vegetated wetlands or saltmarshes, crossed by channels in which plains and sandy features develop. Thus, the geomorphology associated to estuarine environments is complex, and its study from a holistic point of view is difficult, but essential for the complete understanding and management of the system (French *et al.*, 2016).

The reconstruction of the historical evolution of estuaries and the ability to predict future trends in the short to medium term, considering anthropic pressures, highlights the need to develop thematic mapping, to integrate historical and current information and to improve our ability to assess the resilience of the system (Knight and FitzGerald, 2005). The use of aerial imagery and Geographical Information System (GIS) for detecting landscape changes is widely used for this purpose (Schmidt *et al.*, 2004; Ghosh, 2019; White *et al.*, 2019) and, in the case of coastal systems, it can be challenging because of the difficulties derived from imagery quality and atmospheric and oceanographic conditions. Moreover, the older the image, the more difficult it is to analyses due to the storage and scanning qualities. However, the analysis of old images is indispensable for long-term studies.

This chapter aims to assess the changes suffered in three estuaries along the Iberian coast in the last 60 years, in order to understand the mechanisms involved in the estuarine processes at a time-scale of decades. To do so, a general pattern in estuarine systems through high-resolution evolutionary mapping and the local patterns inherent to each system is done.

3.2. Methodology

To cope with the main objective of this chapter, firstly, the main features common to all estuaries were identified designing a hierarchical classification scheme. This scheme was the basis scheme to develop the historical mapping from the last 60 years. Secondly, the historical evolution of every estuary was estimated from a variety of cartographic data and using a Geographic Information System (ArcGIS 10.2). Lastly, an accuracy assessment was carried out to identify the main sources of error for this methodology.

3.2.1. Estuarine mapping and area calculation

Remote sensing imagery is a common resource to create thematic maps (Laengner *et al.*, 2019, and references therein). However, the use of satellite images often requires the definition of specific classifications for single images due to the differences in intrinsic characteristics (e.g. specific external conditions at the moment of the shot and angle and type of sensor, among others). Besides, publicly available remote sensing imagery have lower spatial and temporal resolution than aerial orthophotos (30 m/pixel compared with 0.25 m/pixel in some cases). For these reasons, this study was developed on-screen digitization using visual image interpretation of different elements, i.e. colour, texture and plant association (Arveti *et al.*, 2016).

The three study areas (Figure 2.1) were mapped using historical aerial ortophotographs obtained from the Spanish National Plan of Aerial Orthophotography (PNOA) and Geological and Cartographic Institute of Catalonia (ICGC), for some images of the EBR study site (Table 3.1). The geodetic reference system used was the European Terrestrial Reference System 1989 (ETRS89-H30), according to the guidelines of the Geographic Superior Council, and following the INSPIRE European Directive (2007/2/CE).

Stereoscopic photo-interpretation techniques were carried out for the oldest images (i.e. before 2000s) and then scanned and georeferenced in ArcGIS 10.2, through a second-order polynomial function, using at least 15 well distributed control points on every image. The coordinates of these control points were taken from correctly georeferenced recent orthophotographs. The accuracy of the georeference process was determined by calculating the total Root Mean Square Error (RMSE), less than 0.5 m in all cases. This type of analysis requires ortophotographs taken on low tide conditions and clear days to easily identify and record submerged features. Unfortunately, the number of images fulfilling these requirements is limited and it was necessary to soften the requirements to get enough data for this work. Therefore, some maps have a larger uncertainty than others and, as a consequence, the results must be interpreted with caution.

Table 3.1. Metadata of the aerial orthophotographs used for each study zone. Not found data are showed with "-".

Date	Scale	Pixel size (m)	Colour
San Vicente de la Barquera estuary			
October 1956	1:32000	1	B&W
April 1988	1:5000	0.12	RGB
1997	1:40000	-	RGB
September 2003	1:40000	-	RGB
August 2010	1:20000	0.25	RGB
July 2014	1:20000	0.25	RGB
July 2017	1:20000	0.25	RGB
Guadiana estuary			
July 1956	1:32000	1	B&W
1977	1:8000	0.5	B&W
March 1984	1:30000	1	B&W
August 1998	1:40000	1	RGB
October 2006	1:30000	0.10	RGB
May 2009	1:30000	0.5	RGB
August 2011	1:30000	0.5	RGB
2013	1:30000	0.5	RGB
July 2016	1:20000	0.25	RGB
Ebro delta river mouth			
September 1984	1:30000	-	B&W
1994	-	0.5	B&W
May 2003	1:30000	0.5	RGB
May 2007	1:15000	0.5	RGB
June 2012	1:20000	0.25	RGB
June 2015	1:20000	0.25	RGB
2016	-	0.5	RGB
2017	-	0.25	RGB

Every feature was mapped throughout the study period with the Habitat Digitizer Tool (NCCOS, 2003) extension to ArcGIS (ESRI©). Each feature was recorded with a unique ID, according to a hierarchical classification scheme (Table 3.2), which was based on an extensive literature review. The use of unique IDs allows to the habitat digitizer tool to easily define and assign attributes to polygons (Zharikov *et al.*, 2005). The maps were developed with a minimum scale of 1:2500. This ensures to delineate small features with enough relevance to have a role in the estuarine system. In addition, this tool allows setting a Minimum Mapping Unit (MMU, Stehman and Czaplewski, 1998), i.e. the minimum object identifiable in the image, and areas lower than 100 m^2 were not mapped.

The hierarchical classification scheme was designed following three categories or levels of organization, from general to specific: (a) *category 1*, representing the main subsystems within the estuary, common to every mid-latitude estuarine zone: *Shoreline Sandy Environments, Dunes, Tidal flats/Wetland, Drainage Network* and *Rocky units*. The first two subsystems encompass sandy environments, the third one includes muddy environments (named with two different terms in order to differentiate between micro and macro-mesotidal environments), the fourth one corresponds to the tidal drainage subsystem (which is a mix of sandy and muddy environments) and, lastly, the rocky units which are only present in San Vicente de la Barquera estuary; (b) *category 2*, covering all the features present in each subsystem of the *category 1*, defined mainly by Habitat Directive 92/43/CEE, EUNIS habitat classification and CORINE Land Cover classification; and (c) *category 3*, for those features which needed to be more specific than category 2. Thus, the hierarchical scheme is intended to be a standardized procedure to be applied in every estuarine zone of mid-latitude (Table 3.2). To reduce spatial uncertainties, the features defined in Table 3.2 were firstly verified in the field to improve their definition, and secondly validated with field surveys after mapping.

Table 3.2. Hierarchical classification applied to the study sites with the type of features and brief descriptions of each one. Numbers in between brackets after the name of the feature indicate the level of the category (Category 1: Subsystem, Category 2: Features; Category 3: More specific features).

Feature	**Description, eco-geomorphological role**
Shoreline Sandy Environments (1): Gently sloping sand-covered shorelines affected by waves and currents action, just above normal tide limit (EUNIS classification).	
Beach (2)	Accumulation of shore material formed into distinctive shapes by waves and currents. The beach form is generally seaward-sloping boundary between a water body and mobile sediment, and a flat or landward-sloping surface at the upper limit of the beach (Carter, 1988).
Estuarine beach (2)	Unvegetated or partially vegetated, sand, gravel, or shell intertidal beach in partially enclosed areas (estuaries, bays, lagoons and similar features) connected to the oceans dynamics (Nordstrom, 1992).
Relict littoral ridge (2)	Non-active often wind constructed shore-ridge, generally parallel to the coastline with landward-adjacent similar ridges (Otvos, 2017).
Overwash deposit (2)	The continuation of the uprush over the crest of the most landward (storm) berm. The resulting deposit is not subject to reworking on the active beach by normal wave and tidal action (Leatherman and Williams, 1977).
Sand bar (2)	Intertidal ridge-shaped accumulations of sand with an associated horn landward. It can be bare, without associated vegetation, or presenting seagrasses and algae.
Dunes (1): Sandy accumulations generated by wind dynamics that develop behind beaches with enough sediment availability (Sanjaume and Gracia, 2011)	

Mobile dunes (2)	Primary dunes without vegetation or with only a few species of dune building plants (Sanjaume and Gracia, 2011). They are colonized by pioneer vegetation typical of the first dune ridge (*Ammophila arenaria*, *Elymus farctus*, *Euphorbia paralias*, *Pancratium maritimum*, *Calystegia soldanella*, *Polygonum maritimum*, among others).
Embryo dunes (3)	The most elemental and smaller dunes formations (Sanjaume and Gracia, 2011).
Parabolic dunes (3)	U-shaped dunes convex noses trailed by elongated arms (Sanjaume and Gracia, 2011).
Barchan dunes (3)	A crescent-shaped dune downwind orientated (Sanjaume and Gracia, 2011).
Sand sheets (3)	Areas of aeolian sand where dunes with slip faces are generally absent (Kocurek and Nielson, 1986).
Fixed dunes (2)	Aeolian deposits whose mobility is impeded by a consistent plant cover (shrub or tree nature). Typical species of this band of the dune system are *Crucianella maritima*, *Helicrysum stoechas*, *Sporobolus arenarius* and *Armeria spp*., among others.
Estuarine dunes (2)	Accumulations of sand, gravel, or shell on the back part of estuarine beaches in partially enclosed areas (estuaries, bays, lagoons and similar features) connected to the ocean dynamics (Sanjaume and Gracia, 2011). They present the same species as external dunes and, exceptionally, halophytes typical of tidal environments (e.g. *Sarcocornia spp*. and *Arthrocnemun spp*.)
Relict dune ridges (2)	Non-active dune-ridges formed by aeolian processes usually from fine-to-medium sand by accretion of embryonic backshore/berm dunes behind the high tide zone (Otvos, 2017). The associated vegetation is typical from mature and stablished soils, i.e. tree and shrub vegetation.
Wet dune slacks (2)	Damp or wet hollows left between dunes where the groundwater reaches or approaches the surface of the sand (EC 2007). Rushes and wet grasses are the main plant communities present in these features.

Tidal flats1 (1): Sedimentary plains developed in areas affected by tides, with a predominance of fine sediment transported by water and stabilized by vegetation (Boorman, 2003).

Wetlands2 (1): Shallow aquatic environments, from brackish to hypersaline, isolated or partially connected to the sea in environments with low tidal ranges.

1 Saltmarshes/ *2* Vegetated wetlands (2)	*1* Coastal ecosystem in the upper coastal intertidal zone between land and open saltwater or brackish water which are intermittently flooded by the tides and colonized by halophytes.
	2 Wetlands are ecosystems that depends on constant or recurrent, shallow inundation or saturation at or near the surface of the substrate. Common diagnostic features of wetlands are hydric soils and hydrophytic vegetation (National Research Council, 1995).
1 Mudflats/2 Submerged meadows (2)	1 Muddy platforms common to the intertidal zone of most estuaries (zone below neap high-tide level). The vegetation of these features is poor, mainly seagrasses and pioneer saltmarsh plants (Dame, 2008).
	2 Permanent shallow flooded wetlands by seawater, colonized by salt-tolerant species (Wolanski *et al.*, 2016).
Coastal lagoon (2)	Inland water body, usually oriented parallel to the coast, separated from the ocean by a barrier, connected to the ocean by one or more restricted inlets, and having depths which seldom exceed a couple of meters (Kjerfve, 1994).
Drainage Network (1): Estuarine channel system, including minor forms related to their bottom and margins.	
Channel 1 (2)	Main river channel. It is the estuary in the strict sense, which extends upstream to the edge of the salt wedge (Morales, 1995).
Channel 2 (2)	Distributary channels directly derived from the main channel.
Channel 3 (2)	Distributary channels derived from the secondary distributary channels.
Artificial channel (2)	Non-natural channels within the fluvial network.
Sand flat (2)	Sandy environment located preferentially in the lower intertidal zone. It is an unstable areas characterized by the constant resuspension of sediment by tidal flood and ebb currents (López-Calderón *et al.*, 2016).
Flood tidal delta (2)	Accumulation of sand on the shoreward side of an inlet, initially formed during storm surges and maintained by flood currents (Hayes, 1979).
Ebb tidal delta (2)	Accumulation of sand on the seaward side of an inlet formed by the ebb tidal current (Hayes, 1979).
Rocky units (1): Bedrock, boulders and cobbles which occur in the intertidal zone (EUNIS classification).	
Cliff (2)	Very steep, vertical, or overhanging rock slopes

Rocky platform (2)	Flat (planar) platforms carved into rocks formed by weathering and wave erosive action.

The extensions of the three study areas were selected taking into account the presence of the types of subsystems described in Table 3.2 (*Category 1*). Thus, the mapping was focused on the predominantly marine part of the three estuaries. Thus, the total extension is similar for SVB and EBR sites (circa 5 km^2), and almost double in the case of GUA, due to its natural boundaries.

The main active processes for each study area were also mapped based on reviewed literature. Then, the main ebb and flow directions through the channel networks were identified. These directions are considered responsible for the development of sandy and muddy environments in the estuarine systems. The transport of sediment into the estuary is mainly due to the flood tide and the wave generated currents, responsible for the formation, in some cases, of the flood tidal deltas. On the contrary, the sediment transported seaward, outside the estuary, is a consequence of the ebb discharge and forms ebb tidal deltas, in the outer part of the estuary (Isla, 1995; FitzGerald *et al.*, 2001; Vila Concejo, 2003).

Once defined and mapped every unit together with the main hydrodynamic processes, the changes in the occupied surface over the entire study period were calculated. In addition, the evolution of each subsystem was quantified by setting the surface occupied on the first year as a reference surface. In this way, all subsequent changes were related to the same area. Features with large changes were analysed in more detail (*Categories 2 & 3*).

For the SVB and GUA estuaries, the reference surface, i.e. 100 %, correspond to 1956. However, the EBR site suffered great changes from 1956 to 1984, having large differences in perimeter and, therefore, a different reference surface. As a consequence, although the initial state is described in this chapter in order to better understand the delta evolution, the 1956 image was not included in the quantitative calculations and the reference surface was decided to be that of 1984.

Thus, for each feature, the percentage of occupied surface (OS) with respect to the reference one was calculated following Eq. 3.1:

$$OS = \frac{S^2 year\ i * 100}{S^2 reference\ year} \quad \text{(Eq. 3.1)}$$

In addition, to quantify the rates of change of the features (RC, *Categories 2 & 3*) in the total period, the calculation of the rates was made using the Eq. 3.2:

$$RC = \frac{S^2 \ year\ (i+1) - S^2\ end\ year\ i}{year\ (i+1) - year\ i} \qquad \text{(Eq. 3.2)}$$

3.2.2. Accuracy assessment

Unquestionably, every map is a simplification of reality, so certain errors must be taken into account when interpreting it. Therefore, the error assessment/accuracy of the cartography is an important issue in the development of thematic maps. The term accuracy is usually employed to express the 'correctness' of the map. The level of accuracy is very important not only to provide guidance when using the thematic map, but also when performing map-based analyses. The accuracy assessment is now widely accepted as a fundamental step in the development of thematic maps (Foody, 2002).

At present, from local to regional scales, the accuracy assessment is usually estimated using an error or confusion matrix, which is based on a simple cross-tabulation of the mapped feature labels with those observed in the field. The confusion matrix uses more comprehensive measures to express the accuracy of the map than the basic percentage of correctly assigned cases, such as the kappa coefficient (κ). This procedure helps to identify and characterise which areas of the map give rise to errors, and this allows to focus efforts on them and, thus, to solve them with the use of additional information, improving the final quality of the map (Olofsson *et al.*, 2014). They are widely accepted, although the bias of the test pixels also skews the accuracy of the confusion matrix (White *et al.*, 2019, and references therein).

As the studied system with the largest data availability is the San Vicente de la Barquera estuary, it was used to test the accuracy assessment in the present thesis. As explained above, the accuracy assessment compares the values on test pixels recorded in the field (reference points), with the corresponding pixels in the map. To do that, a field campaign was carried out on dates close to the last available orthophoto to validate the last cartographies. It consisted on the collection of topographic ground control points on the major geomorphological subsystems (beach, dunes and saltmarshes), and helped to delineate the most problematic features. Besides these control points, a flight with an Unmanned Aerial System (UAS) was also performed according to the Spanish regulations for UAS operations (flying height of 120 m above ground level), obtaining an orthomosaic with 0.03 m pixel size. The high resolution of the orthomosaic allowed to used it as an additional source of data to obtain test pixels in areas that could not be accessed on foot due to access difficulties, i.e. some mudflats points.

To minimize the bias of the test pixels, it was considered at least ten test pixels for each feature. The confusion matrix produce several measures of accuracy (Stehman, 1997; Table 3.3). This work uses the overall proportion of pixels correctly classified (Eq. 3.3), the user's (Eq. 3.4) and producer's accuracy (Eq. 3.5) and the kappa coefficient (Eq. 3.6; Zharikov *et al.*, 2005), and they are listed below.

Table 3.3. Confusion matrix for a Land-Cover Scheme of q classes (Stehman and Czaplewski, 1998).

		Reference				
		1	2	…	q	
Map	1	p_{11}	p_{12}	$\cdots$	p_{1q}	p_{1+}
	2	p_{21}	p_{22}	$\cdots$	p_{2q}	p_{2+}
	⋮	⋮	⋮	…	⋮	⋮
	P	p_{q1}	p_{11}	$\cdots$	p_{qq}	p_{q+}
		p_{+1}	p_{+2}	$\cdots$	p_{+q}	

- The overall proportion of pixels correctly classified (P_c) is the sum of the corrected classified pixels, i.e. the sum of the the main diagonal of the confusion matrix, and represents the probability that a random pixel is correctly classified in the map:

$$P_c = \sum_{k=1}^{q} p_{kk} \quad \text{(Eq. 3.3)}$$

- The user's accuracy (P_{Ui}) for feature *i* is the conditional probability of a random point classified as feature *i* by the map is classified as feature *i* by the reference data:

$$P_{Ui} = \frac{p_{ii}}{p_{i+}} \quad \text{(Eq. 3.4)}$$

- The producer's accuracy (P_{Pi}) for feature *i* is the conditional probability of a random point classified as feature *i* by the reference data is classified as feature *i* by the map:

$$P_{Pi} = \frac{p_{ii}}{p_{+i}} \quad \text{(Eq. 3.5)}$$

- The kappa coefficient (κ) indicates, for a stratified random sample of test pixels, the proportionate reduction in classification error, compared with the error of a random assignment of features:

$$\kappa = \frac{P_c - \sum_{k=1}^{q}(p_{k+} * p_{+k})}{1 - \sum_{k=1}^{q}(p_{k+} * p_{+k})} \quad \text{(Eq. 3.6)}$$

where p_{k+} and p_{+k} are the map and reference sums for feature k, respectively. It ranges between -1 to +1, where 1 indicates perfect agreement between reality and the classified image and 0 indicates complete randomness.

3.3. Results

3.3.1. Estuarine mapping and area calculation

The geomorphological features identified in the study sites allow the monitoring of all the subsystems of *Category 1*: *shoreline sandy environments, dunes, tidal flats/wetlands, channel* and *rocky units* (Table 3.2) for almost 60 years. Although only 5 years of evolutionary maps are shown (Figure 3.1, Figure 3.2 and Figure 3.3), the calculation of the areas was carried out in each site on the dates indicated in Table 3.1.

The most evident change on the last 60 years (Figure 3.1) is the reduction in the area of *saltmarshes* and, consequently, the increase in the area of *mudflats*. In line with the rapid expansion of urbanized areas on the Spanish coast in the early 1990s, the *anthropic features* increased markedly at both sides of the estuary. On the eastern side of the estuary, the development of dune fields was directly limited by the increase in *anthropic features*. In this area, the littoral drift heads the east. However, as indicated in chapter 2, there is a local counter-drift due to the morphology of the coast that refracts the waves, making possible the formation of the external *beach* and dune fields. The *beach* remained almost the same thorough the entire study period, with slight variations due to differences on tidal level at the time the orthophotos were taken. The *ebb tidal delta* had little variations on shape, with no relevant effects in the occupied area. Regarding the *sand flats* and the *sand bars*, especially the ones in the channels of the Eastern tidal flat, both increased in area with time, particularly near the main bridge. These processes were, very probably, facilitated by the main flow directions of the ebb and flood currents (see arrows in Figure 3.1).

From the three estuaries, the GUA estuary (Figure 3.2) is the most stable one, without notorious natural changes during the study period, but with a remarkable variation in the area occupied by the *anthropic features* around the *saltmarsh* due to touristic pressures. The urbanization of Isla Canela led to a partial loss of the *saltmarsh* surface, which was transformed into an urban area, crops or grasslands (*Transformed saltmarsh* in Figure 3.2). Moreover, the area of sandy environments increased, with the formation of new *dunes* and the growth of the width of the *beach*. The evolution of the recurved spits upstream reveals the large availability of sediment in this area. With time, the initial hook was consolidated as a *relict dune ridge*, and a new active *dune ridge* was established with the development of a recent *saltmarsh* in between both dune ridges. Additionally, a new hook developed at the end of the external *beach* in recent years (early 2000's to present), with an associated sheltered area (*mudflats** in Figure 3.2). Very relevant for this system is the presence of a huge sediment bank formed in the outer part of the estuary and mapped as a group of *sand bars* to unify terms. This sand bank fluctuates over time, making it difficult to map. The *drainage network* became more developed and dense over the years, partly due to an increase in the quality of the orthophotos, but also due to the natural evolution of the *saltmarsh*. Regarding the main active processes, the littoral drift in this zone moves eastward although waves and tides have a crucial role in the development of morphologies in the lower part of the estuary, as indicated by the evolution of the main sandy structures (see black arrows in Figure 3.2).

The EBR estuary suffered great changes between 1956 and 1984 (Figure 3.3 and Figure 3.4). The first available aerial photo of the zone (1947, top image in Figure 2.5) shows the old mouth of the river, presently located in the Southern part of the *San Antonio* island (*Abandoned channel* in Figure 3.3), and the current active mouth derives from the breakage of the old channel on its left side, as a consequence of a river flooding in 1937 (Rodríguez-Santalla *et al.*, 2010). In 1956, the original mouth was already closed and the active mouth opened very widely (Figure 3.4), initiating the change to shift toward the present shape. Huge sand sheets covered *San Antonio* island in 1956, which could be considered as a complex sandy system, i.e. *shoreline sandy environments* and *dunes*, with virtual absence of *muddy* features, except for the proper deltaic plain. This area did not suffer remarkable increase in *anthropic features* due to its protection as a Natural Park in 1989 and to its difficult access. However, it underwent important eco-geomorphological changes during the last 30 years (Figure 3.3). The most evident one was the development of the *beach* and *dune ridges* in *El Garxal* (a *submerged meadow* in the left side of the *main channel*). These sandy features protect and make possible the formation of a wide *wetland*, which opens to the *main* *channel*. During the study period, the main littoral drift transport supplied important inputs of sediment into *El Garxal* (main changes between 1984 and 1994), enabling the formation of new recurved spits (see left black dotted arrow in Figure 3.3). These spits have been slowly connected to land with the consequent formation of a new *coastal lagoon* between 2012 and 2017 (dark blue feature in Figure 3.3).

Besides, on the western side of the wetland, the *parabolic dunes* increased in area, even burying part of the *vegetated wetland*. On the eastern side of the channel (*San Antonio* island), an erosive trend has been maintained in the last years. Despite the main littoral drift flowing to the south, prevailing winds and waves come from the east, being the latter responsible for the main sediment transport and shoreline morphology in this area (black dashed arrows in Figure 3.3).

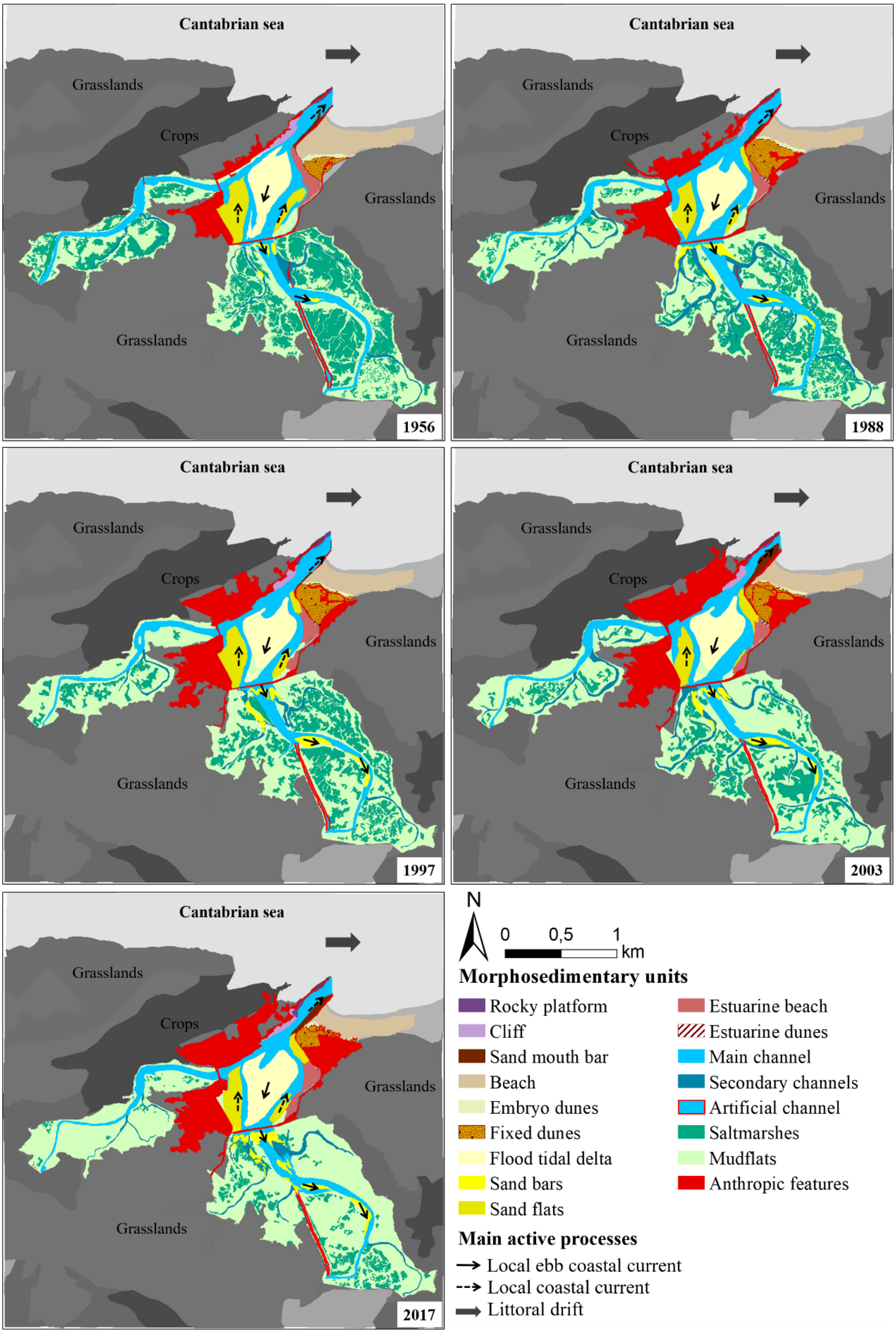


Figure 3.1. Historical evolution of the eco-geomorphological features identified in San Vicente de la Barquera estuary (1956 - 2017).

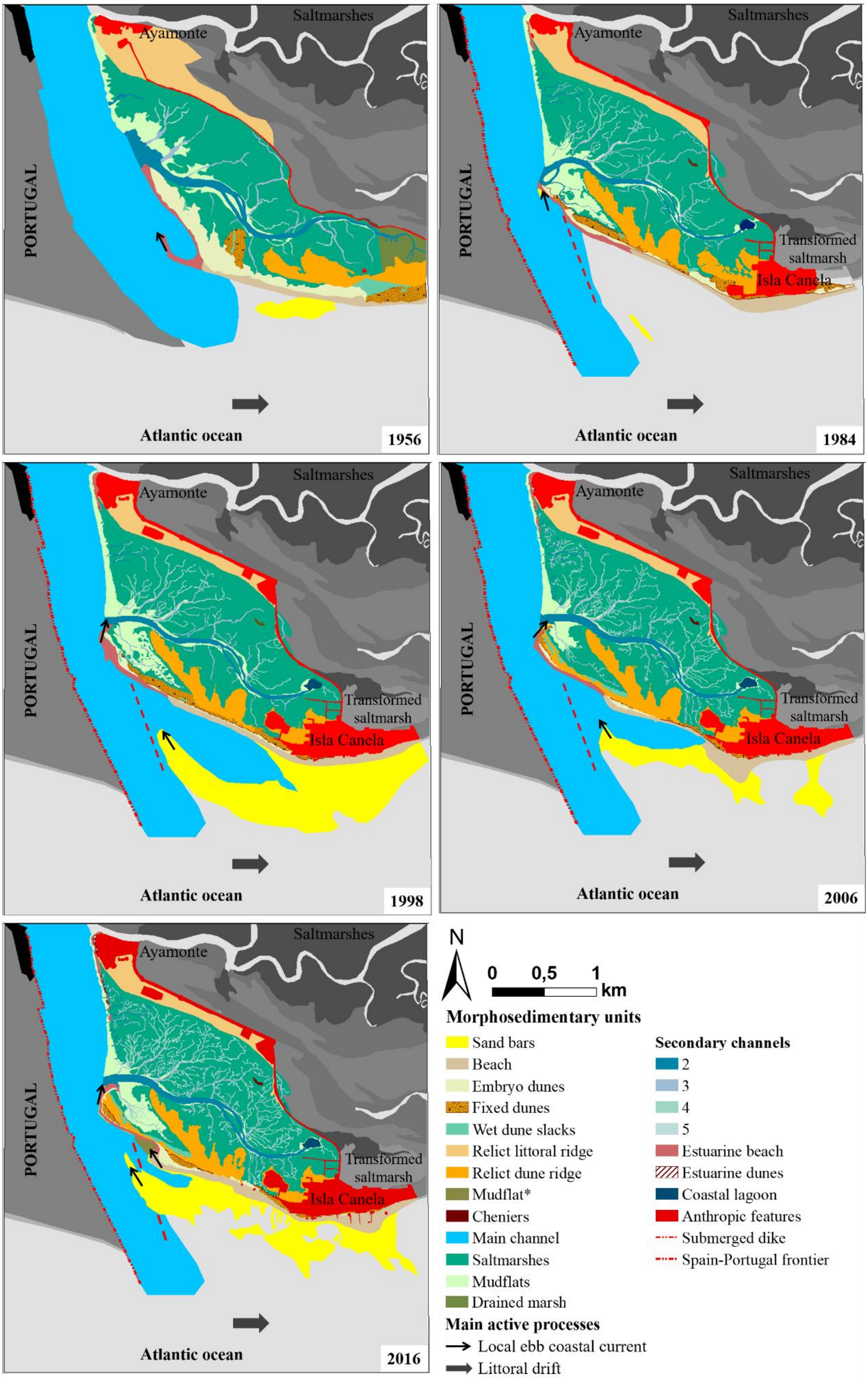


Figure 3.2. Historical evolution of the eco-geomorphological features identified in Guadiana River estuary (1956 – 2016). The symbol * after a feature name indicates that such feature is still developing.

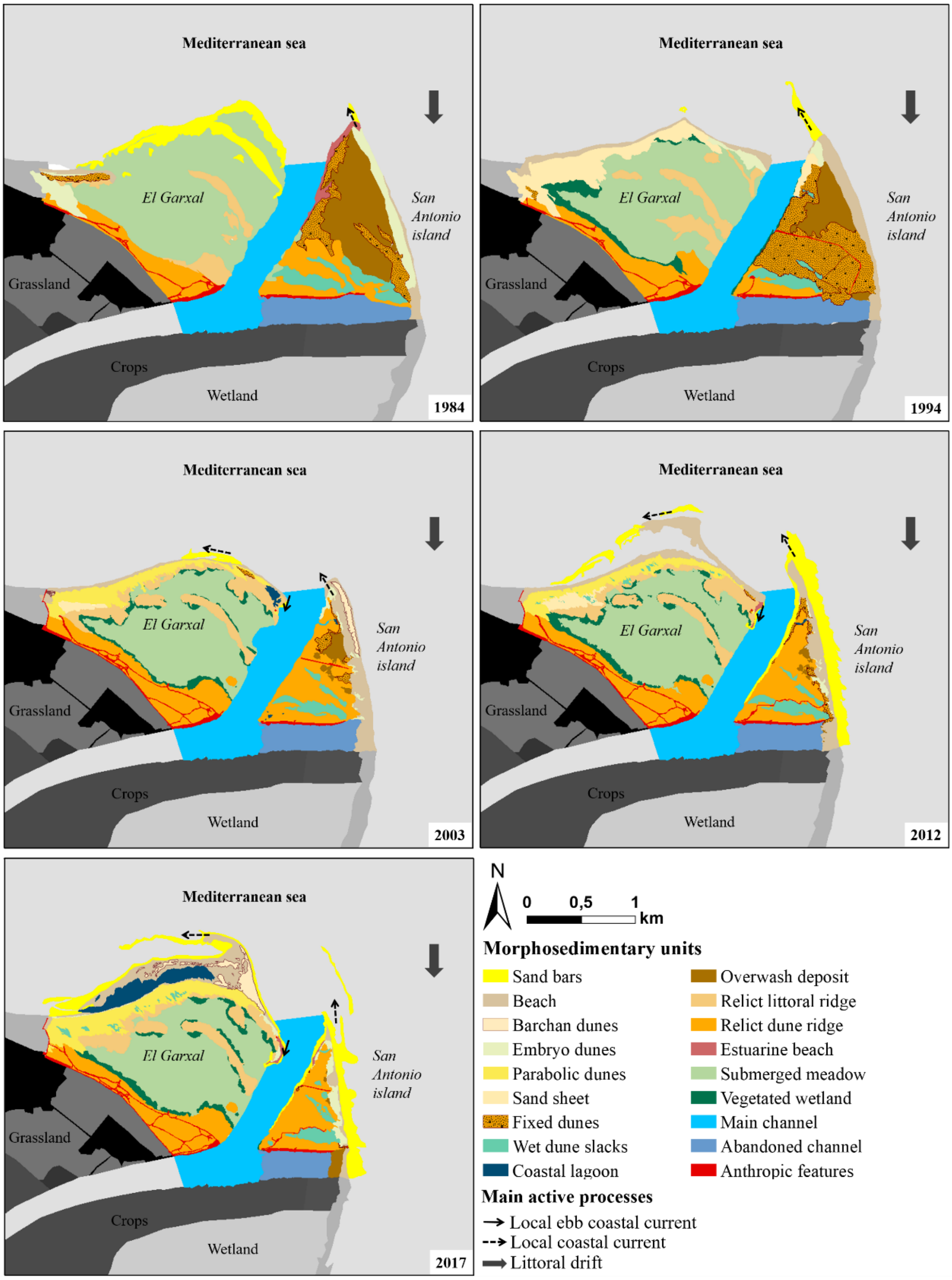


Figure 3.3. Historical evolution of the eco-geomorphological features identified in Ebro delta River mouth (1984 - 2017).

The total areas on the GUA (Figure 3.2) and EBR (Figure 3.3) estuaries are dependent on the state of the sublittoral *sand bars* attached to the coast and, in the case of GUA, also on the tide level at the time the orthophoto was taken. Seasonality is also relevant to the degree of the feature development; however, it is difficult to include this variable in the general calculation of areas.

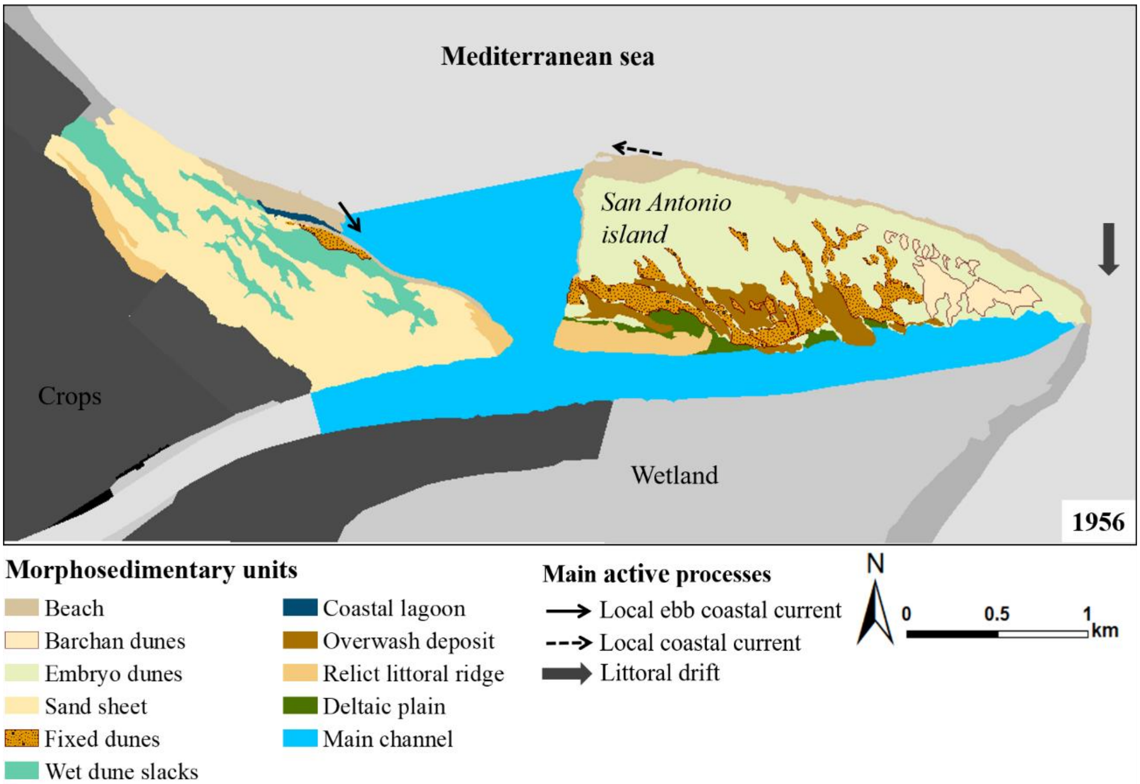


Figure 3.4. Eco-geomorphological map of the Ebro delta mouth in 1956.

3.3.1.1. *Changes in occupied surface*

Changes in the perimeter of occupied surfaces can be used as a proxy for fluctuations in net size over time (Figure 3.5). This reveals that the SVB estuary increased in total occupied area compared to 1956 (Figure 3.5). This was mainly due to the increase in *anthropic features*, which had grown until the 2000s and later stabilized afterwards. As expected due to their geographical constraints (see the section on study sites), the rest of the SVB subsystems mostly maintained their surfaces, since the possibilities of changing their perimeter are limited. Although it appears to be a fluctuating system, the GUA estuary, was the most stable case, showing a similar surface at the initial and final years (Figure 3.5). The changes were related to variations in *sand bars* in the intertidal zone, which are very dynamic features, and whose emergence depends on the tidal and seasonal conditions. Lastly, the Ebro River delta seems to be the most vulnerable one, showing a 10 % decrease in the total occupied surface in the last 30 years. This trend has been fuelled by the strong changes associated to the erosion process of *San Antonio* Island, which is counterbalanced by the growth on the left side of the estuary.

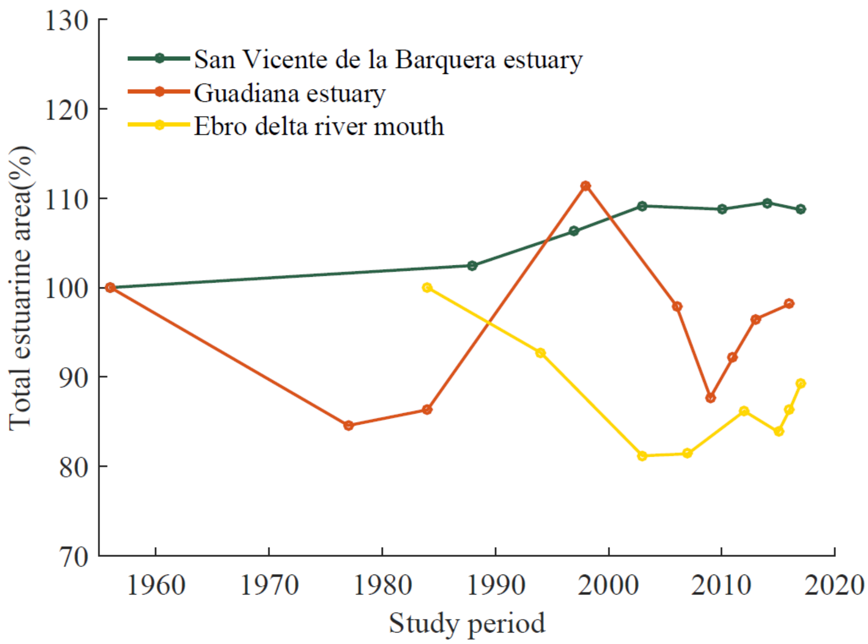


Figure 3.5. Temporal changes in total occupied surface of the three study zones, referred to the considered reference surface. Note difference on reference time for the Ebro case.

When analysing more specifically by *Category 1* (Table 3.1), the percentage of changes makes it possible to identify the most dynamic subsystems (Figure 3.6). To facilitate this identification, the *tidal flat/wetland* category was divided into the *Category 2* units (*saltmarshes/vegetated wetland* and *mudflats/submerged meadows*). The analysis revealed that, in the SVB estuary, the main changes affected the *muddy* environments, with a decrease in the extension of the *saltmarshes* higher than 20 % (corresponding to approximately 85 ha) that gradually became *mudflats* (Figure 3.6). For the GUA and the EBR estuaries, the changes mostly affected the *sandy* environments. In particular, the GUA estuary showed rather stable *saltmarshes* and *mudflats*, the former with a slight increase over time due to the protective role of the recurved spits. In the natural part of the estuary, new sandy features, especially *dunes*, increased. However, this effect was masked by the anthropogenic loss associated with the constructions on the *Isla Canela* side (Figure 3.6).

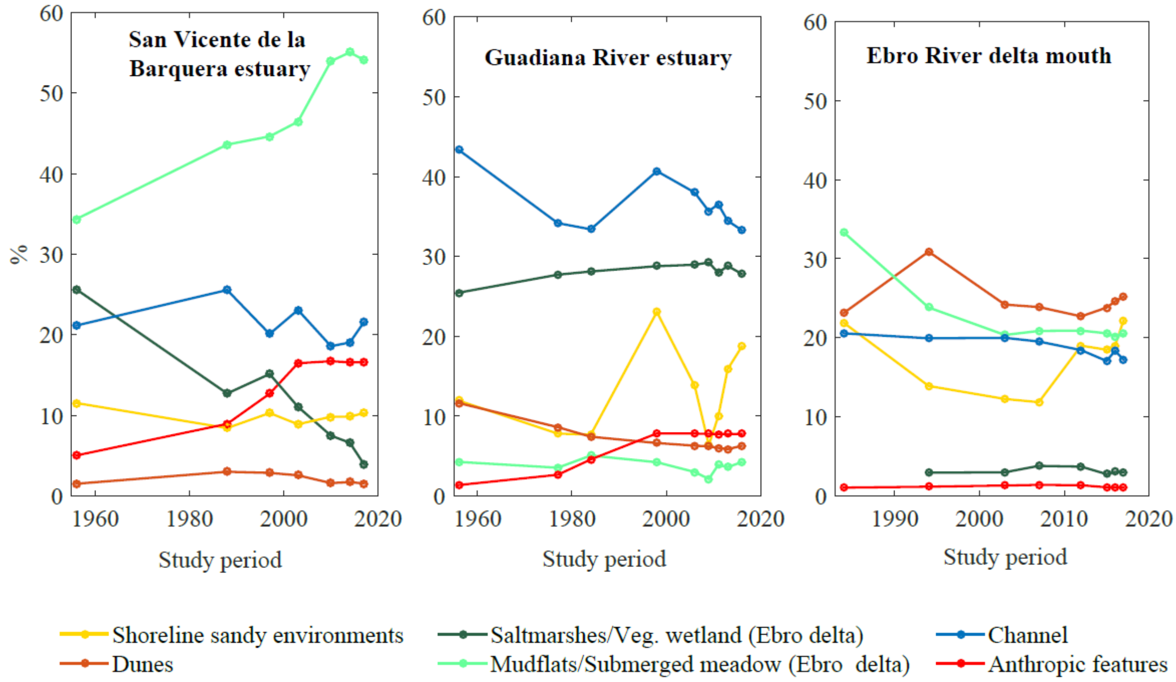


Figure 3.6. Temporal changes in the surface occupied by the main subsystems (Category 1) for the three study sites (% referred to the reference surface for each study site). Note the temporal scale changes on the x-axis.

The *shoreline sandy environments* in the GUA estuary includes large areas of *beach* and *sand bars* (*Category 2*). These features experienced huge variations, what explains the corresponding temporal curve in the general trend of the system (Figure 3.5). On the case of the EBR estuary, the sandy subsystems (*shoreline sandy environments* and *dunes*) increased in the last few years by almost 3 % (Figure 3.6). As described for the GUA estuary, this gain was partially masked and counterbalanced by the strong erosion suffered on the east side of the estuarine system. Despite this, the *sandy* environments increased between 10 - 20 ha during the last 5 years.

The *channels* are also very dynamic features in the mesotidal estuarine systems (Figure 3.6). However, these variations could be mainly due to the effect of the tidal level at the moment the orthophoto was taken.

3.3.2. Accuracy assessment

The assessment of the maps accuracy of the SVB maps is shown in Table 3.4. This table compares field data with the corresponding test pixels in the map of 2017 for all defined features (Table 3.2). The value of the overall accuracy of the SVB cartography in 2017 is high (0.87), and the κ coefficient is 0.95. An overall accuracy of 0.87 means that a randomly selected area has an 87% chance of being correctly classified.

Table 3.4. Confusion matrix resulting from classifying training pixels in San Vicente de la Barquera estuary for the map of the year 2017. Shaded cells indicate areas with larger confusion coefficients in between defined features. Column numbers matches with row numbers.

Map/Reference	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	P_{Ui}
Anthropic Features (1)	**10.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**100.0**
Beach (2)	0.0	**13.0**	6.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**68.4**
Embryo Dunes (3)	0.0	0.0	**4.0**	0.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0	**66.7**
Estuarine Beaches (4)	0.0	0.0	0.0	**10.0**	2.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
Estuarine Dunes (5)	0.0	0.0	0.0	1.0	**5.0**	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
Fixed Dunes (6)	0.0	0.0	0.0	0.0	0.0	**8.0**	0.0	0.0	0.0	0.0	0.0	**0.0**
Flood Tidal Delta (7)	0.0	0.0	0.0	0.0	0.0	0.0	**10.0**	0.0	0.0	0.0	0.0	**0.0**
Mudflats (8)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**23.0**	4.0	0.0	0.0	**0.0**
Saltmarshes (9)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**13.0**	0.0	0.0	**0.0**
Sand Bars (10)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0	**6.0**	0.0	**0.0**
San Flats (11)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**10.0**	**0.0**
P_{Pi}	**100.0**	**100.0**	**40.0**	**90.9**	**71.4**	**80.0**	**100.0**	**92.0**	**76.5**	**100.0**	**100.0**	

The largest uncertainties are the limits between *beach* and *embryo dunes* features, and also between *saltmarshes* and *mudflats* (shaded cells in Table 3.4). The subtle differences in elevation between these features and the difficulties in identifying the type of vegetation associated to them from aerial photography often makes it difficult to define these boundaries when there is an absence of accurate topographic data. Otherwise, the methodology made a correct identification for the rest of the features.

4. Tidal flats analysis: The San Vicente de la Barquera study case

The contents of this chapter have been published in:

Aranda, M.; Gracia; F.J., Peralta, G. and Flor-Blanco, G. 2020. Towards a Comprehensive Functionality Assessment of Estuaries: First Approaches in San Vicente de la Barquera Estuary (Cantabria, Spain). In: *Estuaries and Coastal Zones in Times of Global Change. Proceedings of ICEC-2018*. Eds.: Nguyen, K.D., Guillou, S., Gourbesville, P. and Thiébot, J. Springer Singapore.

Aranda, M.; Gracia; F.J., Peralta, G. and Flor-Blanco, G. 2020. The Application of High-Resolution Mapping for the Analysis of Recent Eco-Geomorphological Changes in the Saltmarshes of San Vicente de la Barquera Estuary (North Spain). *Journal of Coastal Research*, 95, 341-345.

4.1. Introduction

Saltmarshes are low-land systems strongly connected to coastal and river dynamics, and depending on vegetation for stabilization (Donatelli *et al.*, 2018). These highly complex systems are of great importance for their strong ecological value and their abundant ecosystem services, being specially relevant the role as natural coastal defence (Kirwan and Megonigal, 2013; Arkema *et al.*, 2017; Ganju, 2019) since, over the last few decades, population is mainly concentrated in coastal areas and this is expected to continue in the future (Bouma *et al.*, 2014). Because of this, it is important to quantify long-term changes to understand the processes and timescales driving the evolution of the saltmarshes (Sturdivant *et al.*, 2017) in order to recover or to maintain the ecosystem services they provide. Besides natural processes, the changes derived from anthropic actions play a crucial role in the evolution of these systems, needing also monitoring, since the combination of both, natural and anthropogenic, may be responsible for saltmarsh deterioration and disappearance (Mcowen *et al.*, 2017). Recently, saltmarsh conservation and restoration are part of the philosophy of “nature based solution” for coastal management, as these systems play an important role in reducing the impact of increasing coastal pressures (Temmerman *et al.*, 2013; Ganju, 2019). However, the provision of their important ecosystems services (e.g. buffer against energetic events, nurseries for consumers, or carbon and sediment storage on a geological time scale; Costanza *et al.*, 1997), depends on the health and correct functioning of the saltmarsh.

Despite their highly described importance, saltmarshes worldwide have suffered major losses in their extent and associated ecosystem services. Thus, the threat of saltmarshes is widely outlined. Numerous studies had focus on the quantification of changes over time (Laengner *et al.*, 2019; and references therein), and associated causes, e.g. saltmarsh drowning by SLR effect (Bartholdy *et al.*, 2004; Kirwan and Temmerman, 2009; Kirwan *et al.*, 2010; Bouma *et al.*, 2016) together with the sediment input deficit (Ganju *et al.*, 2017). Thus, its study is important to assess the persistence of the system at a landscape level since edge erosion seems to be the main cause of saltmarshes disappearance worldwide (Van de Koppel *et al.*, 2005; Mariotti and Fagherazzi, 2010).

Our capacity to manage the threats for saltmarshes will depend on our knowledge on the mechanisms and processes that drive the formation and evolution on these complex systems. Taking this into account, and based on results for San Vicente de la Barquera estuary obtained in the previous chapter, the present chapter carries out, in this estuary as a test site, a study of the origin of the changes and disappearance of saltmarshes, since they have been identified as the most changing features within this estuary.

4.2. Methodology

To meet the objective, data from the 60-years geomorphological diachronic maps developed in the previous chapter were used, limiting the study area to the tidal flats (i.e. saltmarshes and mudflats). In addition, a sea level data series from 1993 to 2018 from the Santander tide gauge (Figure 2.1.b), belonging to the Spanish Institute of Oceanography, and a Digital Terrain Model (DTM) of the zone (Figure 4.1) were also used. The DTM was obtained from a UAS flight conducted in this area in 2018 and has a maximum vertical error of 0.18 m. the data from the drone flight were calibrated with *in situ* topographic measurements performed with a RTK-DGPS in the same date, together with data of vegetation in the area (species and distribution). All the data were expressed relative to the MSL in Alicante (the Spanish reference datum).

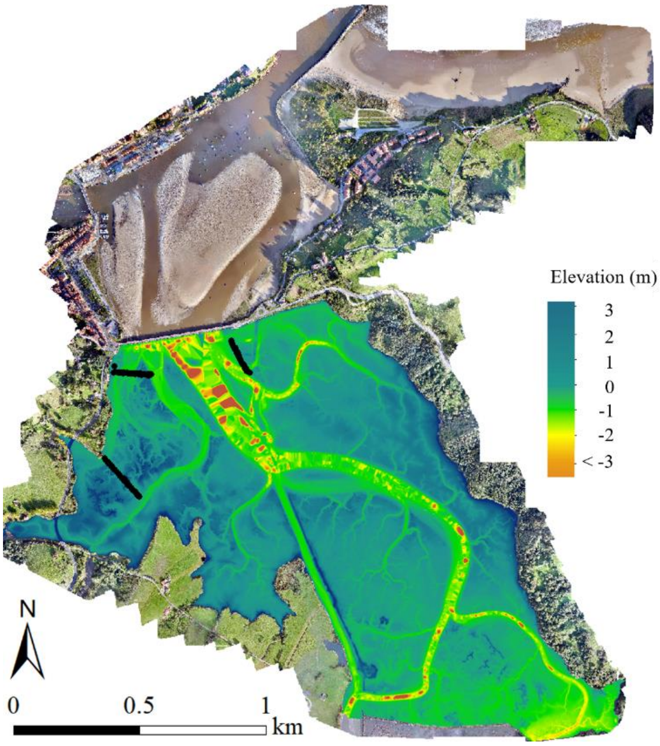


Figure 4.1. Projection of the DTM of the SVB tidal flats on the mosaic of the estuary. The DTM as obtained from a drone flight in 2018. Data below -2 meters correspond to water (main channel) and are not included in the analysis. Data above 3 meters correspond to the upper limits of the tidal flat area, so they are not included either. The black lines correspond to the field transects.

The analyses carried out with the above-described data sources can be divided into two main blocks: (1) analysis of the changes in the tidal flats over the last 60 years and (2) identification of the causes of these changes.

4.2.1. Changes in tidal flats over the last 60 years

Based on the date of the available orthophotos (Table 3.1), six change maps were developed corresponding to the time intervals between two consecutive orthophotos for the entire study period (1956-2017).

The geomorphological maps were converted into binary rasters by using Map Algebra tool in ArcGIS (Figure 4.2.1). Once converted into raster format, the corresponding change maps were obtained by overlapping the geomorphological maps. The change maps include 4 defined classes (Figure 4.2.2): (1) stable vegetation areas (*No Change*; green), (2) vegetation *gain* areas (yellow), (3) vegetation *loss* areas (red) and, (4) *mudflats* (grey). This analysis enables qualitative and quantitative outputs, highlighting the changes and calculating the total extent of the changes that occur in different time periods for each defined class.

To identify the existence of vegetation change patterns associated with elevation changes, the change maps were combined with the digital terrain model (DTM). As no previous elevation data are available for this area, the elevation of the DTM was assumed constant throughout the study period. The areas below -2 and above 3 m MSL were discarded, as these values can be considered the lowest and highest limits of the saltmarsh, respectively, according to the field data. The combination of the DTM with the change maps provides an elevation for each pixel on the change maps (Figure 4.2.3). The final output is a data base for each time interval (i.e. the period between two consecutive orthophotos), where rows are the pixels and columns are the class and elevation, respectively.

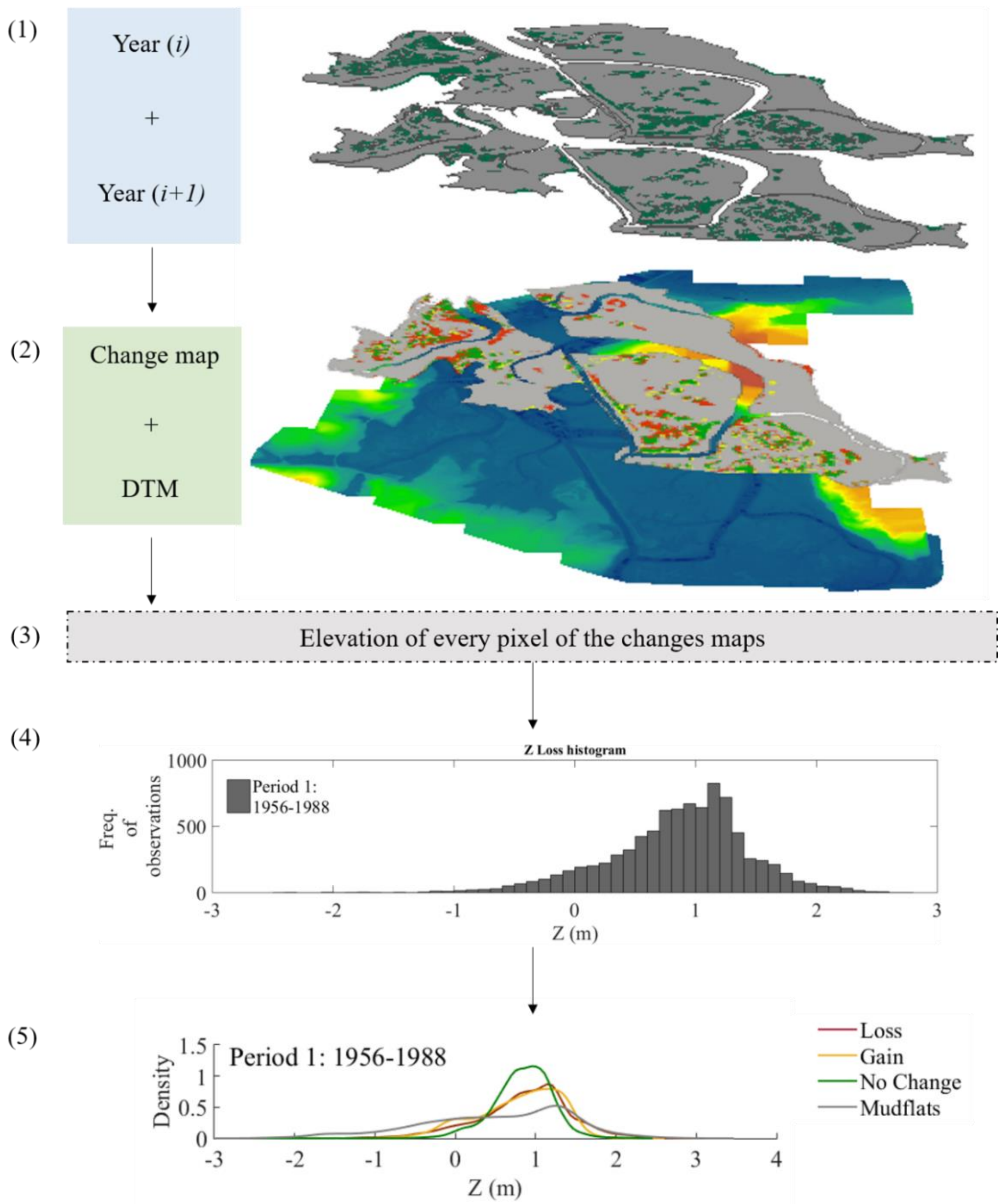


Figure 4.2. Implemented workflow to obtain the change maps with elevation per pixel. (1) Combination of geomorphological maps of the tidal flat in two consecutive time intervals to obtain the change maps (saltmarshes: green; mudflats: grey); (2) Combination of the change map, from the previous step, with the DTM; (3) Results: data base with the class and elevation of every pixel; (4) Example of the histogram for period 1 for the Loss class from data from step (3); (5) Example of the density curves for period 1 from data from step (4) for each defined class.

For each class on every defined time interval, the probability density function of the elevations was calculated. This is expected to characterize the elevation of each class and the evolution throughout the study period. First, the histograms of each class were calculated at each time interval (the bin-width was fixed for every interval in 0.1 m; Figure 4.2.4, as an example). Second, from the histograms the frequency count of observations was obtained and the probability density was estimated according to the Kernel Density Estimation (KDE, Eq. 4. 1). The KDE is a nonparametric method of estimating the probability density function (pdf). It estimates the probability density based in the Kernel normal function and evaluates equally spaced points, creating a smooth curve given a set of data (Baxter *et al.*, 1997), more representative of landscape gradients.

$$\hat{f}(x) = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{x - X_i}{h}\right) \qquad \text{(Eq. 4. 1)}$$

Where $x_1, x_2, \ldots, x_n$ are the samples in the distribution, *n* is the sample size, *K* is the smoothed Kernel function and *h* is the bin-width, which is analogous to the bin-width of the histogram, affecting the smoothness of the resulting curve. The final result was the frequency curves of each class with respect to elevation (Z(m); Figure 4.2.5, as an example). The median of these curves were used as a proxy to quantify the variations in elevation for each class throughout the study period.

4.2.1.1. Landscape metrics analysis

Even though the role of saltmarsh vegetation in retaining sediment, favouring the vertical accretion, has been repeatedly studied (Dijkema *et al.*, 1990; Morris *et al.*, 2002; Fagherazzi *et al.*, 2004; Feagin *et al.*, 2009, 2015; Raposa *et al.*, 2016), some authors describe that vegetation is not crucial for lateral erosion of saltmarshes (horizontal development), being the sediment characteristics the main factor controlling erosion (Feagin *et al.*, 2009). More recently, Bouma *et al.* (2016) described that saltmarshes are controlled by two-way processes, namely biological (vegetation growth) and physical (sediment transport), being known as the biogeomorphic feedback. The study of the biogeomorphic feedback helps to define both vertical and horizontal saltmarsh evolution and, therefore, the trend of the system. The biogeomorphic feedback leads to complex spatial self-organized systems with different responses to environmental forcing (Van de Koppel *et al.*, 2005; Marani *et al.*, 2010; Balke *et al.*, 2014). Rietkerk and van de Koppel (2008) defined the spatial self-organization as “the process where large-scale ordered spatial patterns emerge from disordered initial conditions through local interactions”. Based on this concept, numerous ecological studies describe that spatial self-organized patterns may be an indicative of stress in the system (van Der Heide *et al.*, 2010).

To improve the understanding of the processes related with the SVB saltmarshes degradation, the principles of the biogeomorphic feedback were applied via the study of the evolution of the four classes using landscape metrics. Landscape metrics are defined as quantitative measurements of a landscape which shows a heterogeneity on its distribution. They use as the minimum spatial unit the *patch*, which is defined as a homogeneous area (polygon in GIS) that differs from its surroundings (Forman, 1995), and the basis for this analysis is a thematic map (for this study, the six change maps obtained in the previous section). Landscape metrics have proven to be one of the most important variables of global change affecting ecological systems, and a highly valued source of information to identify relations between the processes within the system (Cushman *et al.*, 2008; Modica *et al.*, 2012). They have gained importance in recent years due to their utility as tools for quantifying structure and patterns in thematic maps, at natural ecosystem level (O'Neill *et al.*, 1988; Gustafson, 1998; Hargis *et al.*, 1998), but also for supporting urban planning and management (Herold *et al.*, 2005).

The behaviour of the landscape metrics of the SVB tidal flats and the dynamics at landscape and class levels were analysed in each change map using FRAGSTATS v.4.0 (McGarigal, 2015). This program requires to unify the format of the maps to perform synoptic analyses over the past 60 years (1956-2017). Therefore, the change maps (raster format) were converted to a grid with the same pixel size (7.5 x 7.5 m). The changes in the landscape structure were evaluated by using independent metrics (Cushman *et al.*, 2008), which included *Number of patches* (NP, equal to the number of patches in the landscape), *Patch Density* (PD), that is the number of patches of the corresponding patch type divided by the total landscape area, in m^2, and *Shannon's Diversity Index* (SHDI, Eq. 4.2), which describes the landscape diversity, i.e., the heterogeneity from the diversity of patches through the years; (McGarigal, 2015).

$$SHDI = -\sum_{i=1}^{m} (P_i * ln\, P_i) \qquad \text{(Eq. 4. 2)}$$

where P_i is the proportion of the landscape occupied by patch type (class) i. SHDI = 0 when the landscape contains only 1 patch (i.e., no diversity). SHDI increases as the number of different patch types increases and/or the proportional distribution of area among patch types becomes more equitable.

After the analysis of the landscape shapes, the size-frequency distribution of patch-sizes was used to provide information on the spatial structure of the vegetation and to identify signature of processes in the evolution of the patch size and, therefore, in the degradation of the saltmarshes. To detect the presence of scale-invariant patterns, it was tested if the pattern of the patch size distribution could be explained by a power law (Taramelli *et al.*, 2018; Zhao *et al.*, 2019)This pattern can be interpreted as a sign of self-organization and stress (Rietkerk and van de Koppel, 2008). The fit to the power law was performed by applying the 'logfit' function (MATLAB©; Lansey, 2020), using the best fit to estimate the size-frequency distribution of each patch in the initial and final periods. The data were tested through the potential axis scaling (log-log, log-linear, linear-log, linear-linear), choosing the one with the smallest error.

4.2.2. Causes of changes

Studying variations in plant communities and external drivers is a useful approach to link the degradation to possible regional causes (e.g. SLR), or to local causes in the area (i.e. anthropogenic effects in the estuary). Therefore, the regional and local factors of the area were evaluated to identify the possible causes associated with the changes observed in this subsystem.

4.2.2.1. Regional factors

As a consequence of the low sediment input into the estuary, the vertical accretion in the SVB saltmarshes is limited, which points the SLR as one of the main factors involved in the fragmentation of the saltmarsh. This would lead to progressive drowning of the saltmarsh (sediment accretion rates < rates of SLR; Mariotti and Fagherazzi, 2010; Kirwan and Megonigal, 2013), which would become bare mudflats or partially vegetated by seagrasses and macroalgae.

Lateral saltmarsh development is not as well documented as the vertical one, but its study is of general ecological importance as it determines the ratio of vegetated and bare intertidal area within the intertidal zone (Balke *et al.*, 2016), and its change can be a good indicator of the evolution of the saltmarsh. The position and dynamic of pioneer zone, i.e. limit between saltmarsh and mudflat, is a good indicator of the evolution of the saltmarsh as it can provide insight about erosion/accretion processes within the system. The zone of the establishment of this lowest limit requires events of exposure within the tidal cycle, i.e., event on which this elevation "skip" the tides, which is known as inundation frequency (1/d). The more frequently these events occurs, the greater the probability that this area will be occupied by the pioneer saltmarsh (see Balke *et al.*, 2016 for more details about the global model for the establishment of the saltmarsh-mudflat limit). In the present work, as the term inundation frequency may lead to confusion on some occasions, it has been replaced by *exposure frequency*.

Based on this concept, maps of inundation duration (%) and exposure frequency (%) were developed for SVB estuary. These maps were based on time series of the water level of the nearest tide gauge (Santander's gauge; Figure 2.1.b), and the DTM of the area (Figure 4.1). With a vertical spatial resolution of 1 cm, it was calculated how many times every pixel was flooded during a period, and normalized by the number of tidal cycles in that period. This analysis allows identifying local variations in the duration and frequency of inundations in recent years, which could explain the evolution of the saltmarsh and relate it with regional causes.

4.2.2.2. Local factors

The SLR is not expected to be the sole cause of the decline in the saltmarsh. Therefore, the previous data were complemented with the data from the topographic surveys (11/2018, 04/2019 and 09/2019). This allows for *in situ* evaluation of vegetation patches and evaluation of the micro-topographic configuration of the saltmarsh. The *in situ* evaluation was based on three profiles perpendicular to the landward zone, measured with a DGPS-RTK (vertical errors < 0.04 m, see black lines in Figure 4.1). Depending on the topography, the points of the profiles were separated approx. 1 m. The coverage and presence of plant species were also recorded at each point.

As anthropogenic impacts may also have contributed to the negative trend of the SVB saltmarshes (e.g. pollutant discharges, deepening of shipping channels, river margins fixing, landfills or wetland reclaim; Boorman, 2003; Balke *et al.*, 2016), to gather information on local anthropogenic actions in recent decades, the scientific literature and technical reports of interventions made in the SVB estuary were reviewed.

4.3. Results

4.3.1. Changes in the tidal flats over the last 60 years

The spatio-temporal analysis of the changes in SVB saltmarshes (Figure 4.3) reveals that the saltmarsh is switching into mudflats. The greatest change occurred at the beginning of the study period, when a large area of loss of vegetation is observed (Figure 4.3, red patches). Nevertheless, during these early periods, large areas of *No Change* (Figure 4.3, green patches) and *Gain* (Figure 4.3, yellow patches) classes were also observed (Periods 2 and 3). Another major change was observed in between periods 4 and 5, when most of the saltmarsh turned into *Mudflat* (grey patches), being extremely low the abundance of areas of the G*ain* class during the period 5.

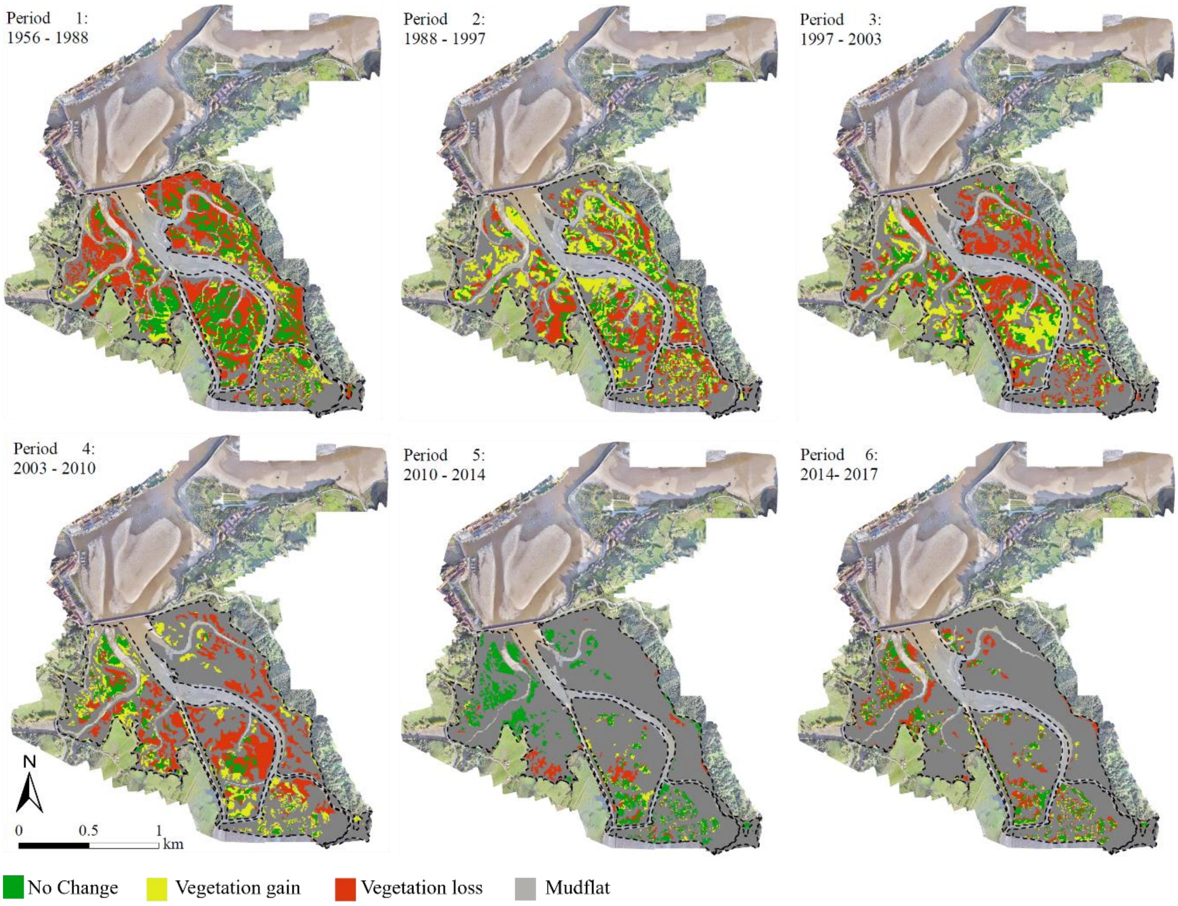


Figure 4.3. Change maps for the San Vicente de la Barquera tidal flats in each time interval studied. Dotted lines delimit the boundaries of the study area.

When combining the change maps with the DTM, the analysis of the median values of the obtained density curves (Figure 4.4) reveals the topographic sequence of the pattern observed in Figure 4.3. First, more vegetation was lost at lower elevations (red line in Figure 4.4), moving upwards through the study period, but showing a sharp decrease in the affected elevation between the last 2 periods (2010-2014 and 2014-2017). The distribution of vegetation *Gain* and *No Change* patches (yellow and green lines in Figure 4.4, respectively) showed a similar temporal pattern, increasing the elevations at where they occur with time. On the contrary, the elevation of the mudflats showed a quite constant median over time, taking place at lower elevations through the study period (according to mean values in Figure 4.4). Although the loss of vegetation appears to be the dominant process over time (Figure

4.3), it is not until period 4 (2003-2010) that the median elevation of vegetation *Loss* exceeds the median elevations of G*ain* and N*o Change*. Therefore, as of period 4, vegetation was lost at higher elevations than gained or maintained. Contrary to expectations, in periods 4 and 5 (2003-201 and 2010-2014, respectively), the elevations patterns in *Loss*, *Gain* and *No Change* of vegetation patches did not match with the other periods, when the losses concentrated at the lowest elevations. In periods 4 and 5, the *Loss* of vegetation patches occurred at higher elevation than *Gain* or *No Change*. *Mudflats* patches increased in density and occupied lower elevations (Figure 4.3 and Figure 4.4). In the last period (2014-2017), the loss of vegetation occurred at its lowest elevation (Figure 4.4), even lower than the areas occupied by mudflats, denoting that the vegetation disappear at low elevations again.

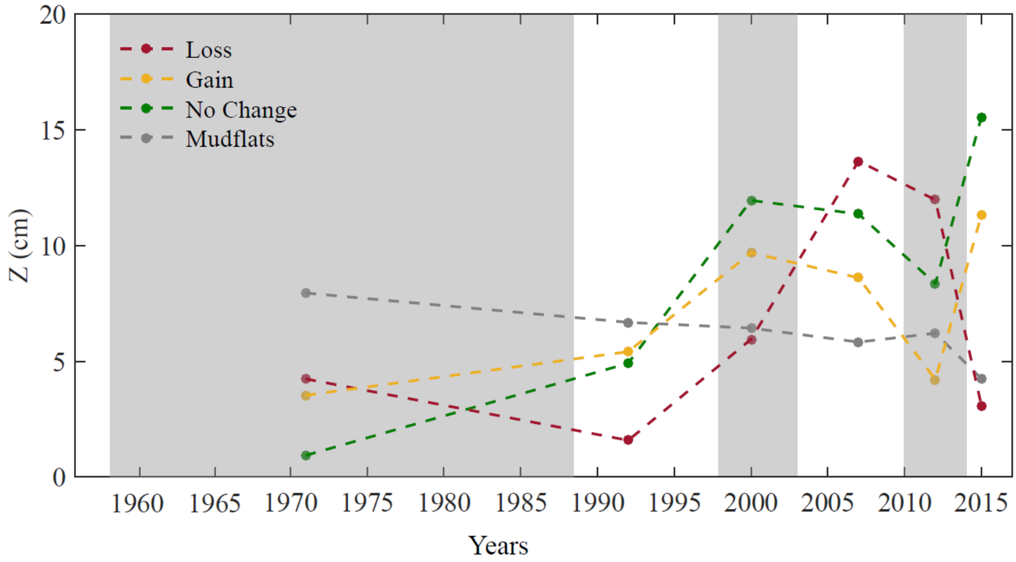


Figure 4.4. Median values of the density curves for each defined class obtained from the change maps. The study periods are indicated by alternating shaded areas. Study periods: 1 (1956-1988), 2 (1988-1997), 3 (1997-2003), 4 (2003-2010), 5 (2010-2014) and 6 (2014-2017). Z data are refered to MSL in Alicante, the Spanish Reference Datum

4.3.1.1. Metrics analysis at landscape and class levels

The landscape metrics also captured the ongoing fragmentation process of the SVB tidal flats (Table 4.1). At the landscape level and throughout the studied periods, there is a constant decrease in the number of patches (NP), although an upturn was observed in the final interval. The reduction in NP seems associated with the large increase on the mudflats' surface over the years (Figure 4.5), which produced large patches of this feature (Figure 4.3). This trend is also noted in the patch density (PD), which decreases from 855 to 647 patches/ha (Table 4.1). However, the metric that best captured the trend observed in the SVB estuary was the Shannon's Diversity Index (SHDI). This index decreased sequentially from

1.28 to 0.57 values over the time intervals, as a consequence of a decrease in patch heterogeneity over the years, i.e. larger patches of mudflats, and fewer and smaller patches of the other three classes.

Table 4.1. Values of landscape metrics for all time intervals under investigation. NP: number of patches; PD: Patch Density; SHDI: Shannon's Diversity Index.

	Period 1 1956-1988	**Period 2** 1988-1997	**Period 3** 1997-2003	**Period 4** 2003-2010	**Period 5** 2010-2014	**Period 6** 2014-2017
NP	1291	1236	814	602	551	1031
PD	854.92	828.78	524.01	375.81	318.38	647.09
SHDI	1.28	1.24	1.16	0.97	0.57	0.63

When focusing the analysis on the evolution and fragmentation of the surface at the class level (left graph on Figure 4.5), it can be observed that the saltmarsh loss percentage was highest in the first interval (1956 – 1988, the longest time interval) and decreased with time and total available area, from 32.1 % to 8% of the surface. Regarding the number of patches (NP; right graph on Figure 4.5), a generalized decrease is observed along the studied period, except for the last one, in which a remarkable increase in NP was estimated.

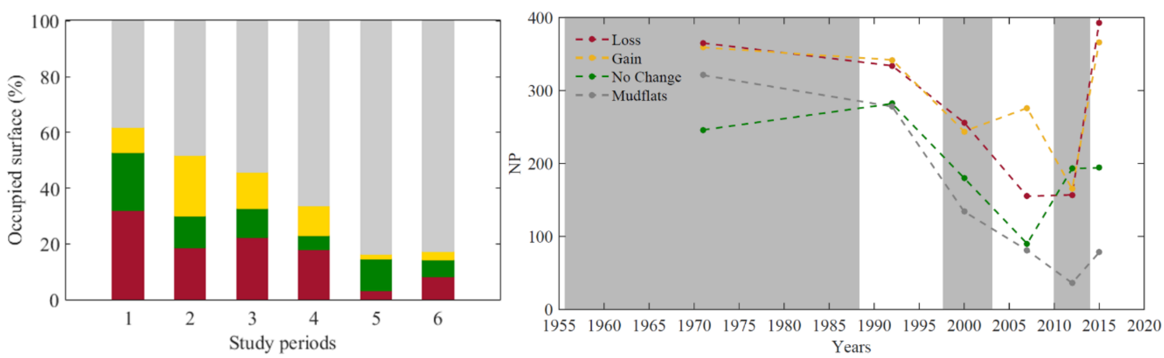


Figure 4.5. Landscape composition of the study area by class throughout the study periods. Left graph: evolution of the occupied surface of each class in [%] with respect to the total surface of the tidal flat; Right graph: evolution of number of patches (NP) by class during the study periods. Study periods are indicated by alternating shaded areas: 1 (1956-1988), 2 (1988-1997), 3 (1997-2003), 4 (2003-2010), 5 (2010-2014) and 6 (2014-2017).

This final increase in NP was especially high for the *Loss* and *Gain* classes (red and yellow, respectively), reaching almost the initial values, but occupying a smaller surface in total, i.e. the same number of patches but considerably smaller. Finally, the M*udflats* class increased in surface (38.14 % to 82.84 %) but decrease in NP, since the contrary effect occurs: the patches are less fragmented with time and, consequently, larger.

4.3.1.2. *Patch size distribution*

For all defined classes, the best fit was the power law relationship (log-log scale). In general, when comparing initial and final periods, the results show that the frequency of occurrence decreases with patch-size for *Loss*, *Gain* and *No Change* classes (Figure 4.6). However, in period 6 the fit is generally rotated clockwise relative to the fit in period 1 and the quality increases (see values of R^2 in Figure 4.6). Contrary to this pattern, the frequency of large mudflats patches increased over time, justifying the right displacement of the fit from period 1 to period 6 (Figure 4.6).

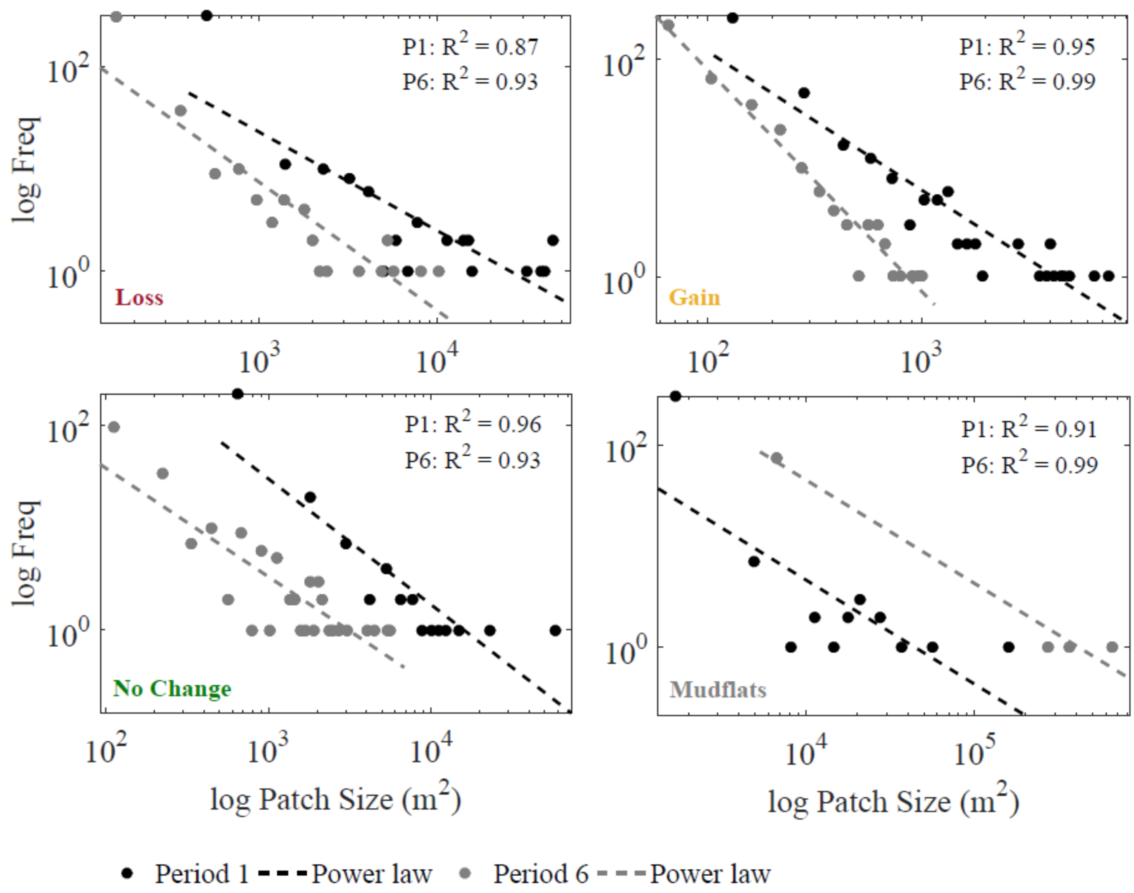


Figure 4.6. Patch size distribution by class in the first and last time intervals. The axes are log-log scale. The points correspond to the observed data and the lines to the power law fit. P1 = 1956-1988, P6 = 2014-2017.

4.3.2. Causes of changes

The duration of the inundation and the exposure frequency in the SVB estuary showed small changes over time. The projection of the curves over time reveals a slight oscillation throughout the studied period (1993-2018; Figure 4.7). Only when the initial and final curves were plotted showed a clear difference (Figure 4.8).

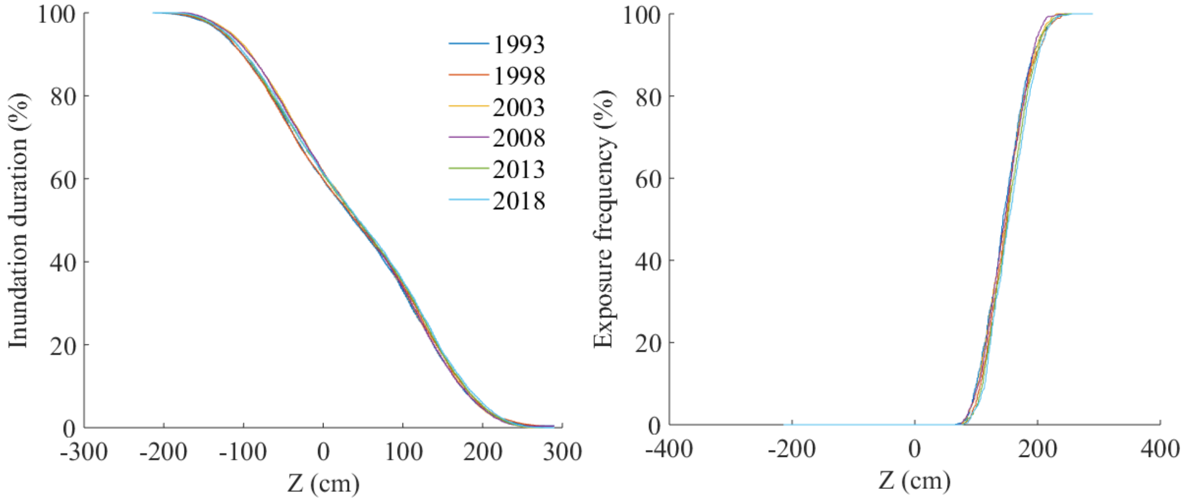


Figure 4.7. (a) Inundation duration and (b) exposure frequency curves every five years obtained from data of the Santander tide gauge (1993-2018).

The differences in inundation duration and exposure frequency over 25 years reveals a net displacement to the right of the curves, slightly larger for the second ones. This difference affects the elevation to which the pioneer vegetation could settle up, indicating that this elevation is circa 10 cm higher after 25 years (right panel in Figure 4.8).

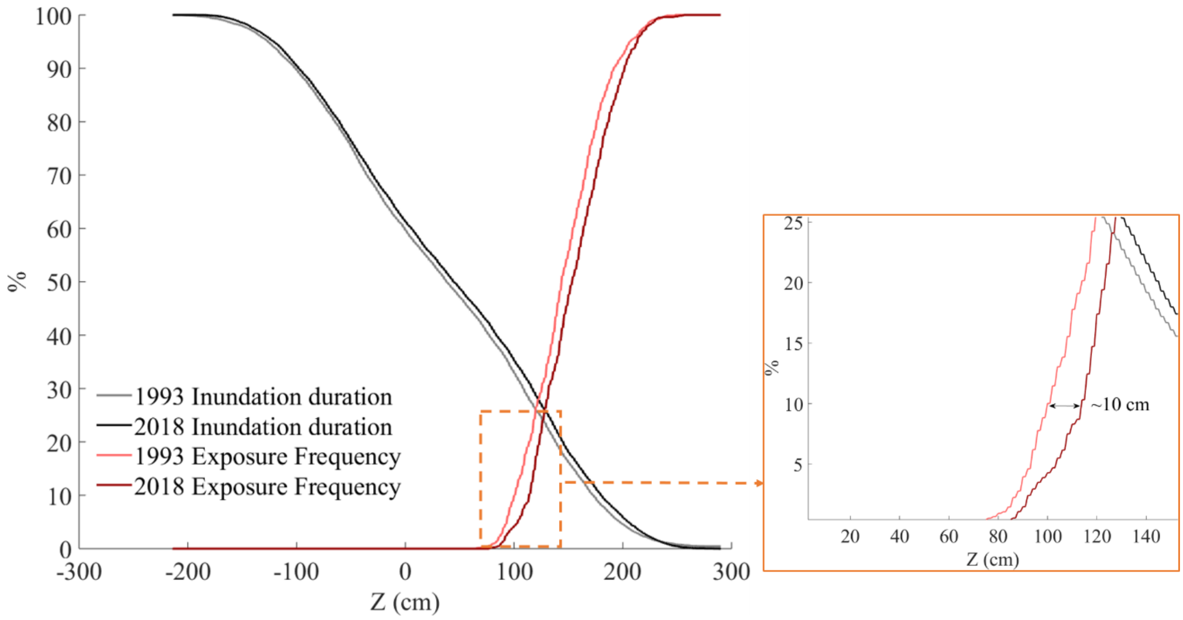


Figure 4.8. Inundation duration (black lines) and exposure frequency (red lines) for the initial and final years of the time series of Santander tide gauge.

The combination of inundation duration and exposure frequency results with the DTM allows to transform Figure 4.8 into maps of inundation duration and exposure frequency (Figure 4.9) for the study area in the year 2018. These maps show the zones where the saltmarsh vegetation can settle up (over 30% in Figure 4.9.b), confirming observations made during the field campaigns. The exposure frequency map (Figure 4.9.b) can be used as a proxy for saltmarsh expansion probability, although the edges must be interpreted carefully since the errors in the DTM are larger in these areas. In the field, the lowest limit vegetation presence, i.e. the pioneer zone, was measured about 1 m above MSL. At this elevation, the inundation duration is around 40% and the exposure frequency is around 30 %. For the upper marsh, the limit is not so clear, with remarkable differences across the *in situ* profiles (Figure 4.10).

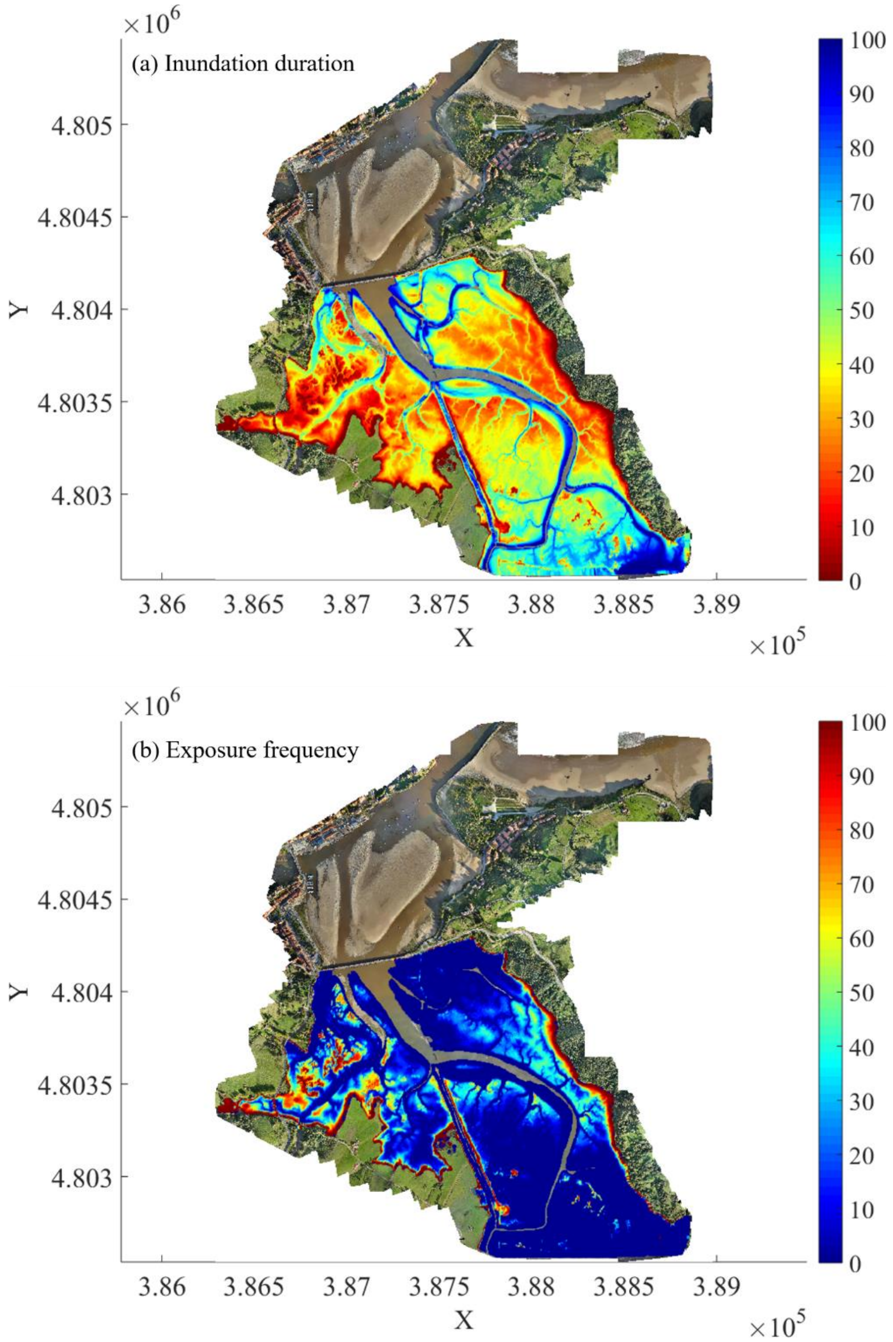


Figure 4.9. (a) Inundation duration (%) and (b) exposure frequency (%) maps obtained from the combination of results from figure 4.8 with the DTM of the tidal flats.

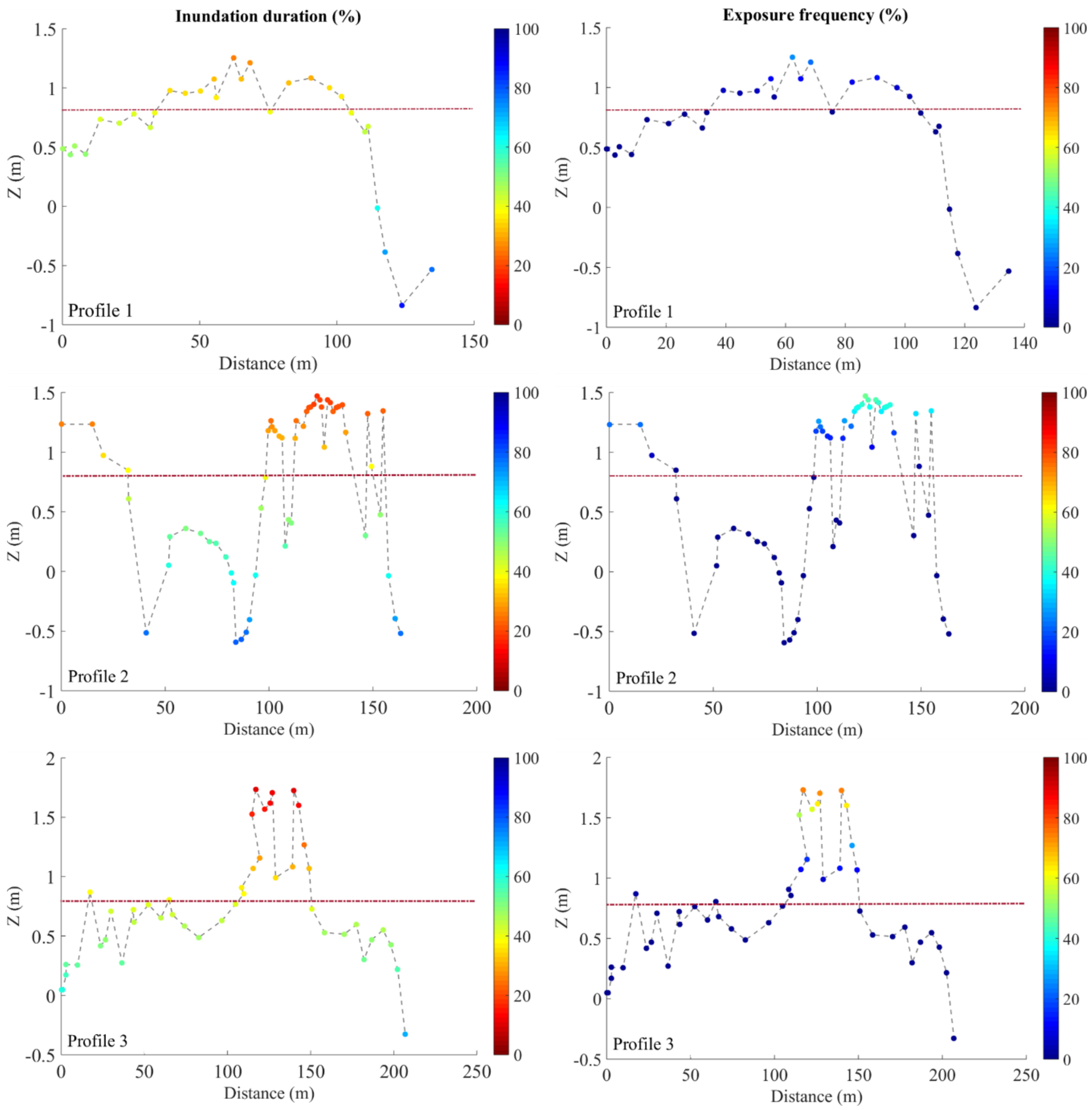


Figure 4.10. Relation between the topographic profiles measured in the field with DGPS-RTK and the inundation duration and exposure frequency percentajes. Dotted red line indicates the MHWN in San Vicente de la Barquera estuary (0.747 m above MSL in Alicante, Spanish Reference Datum). The beginning of the profile (0 m in the x-axis) correspond to the landward zone.

In fact, the combination of the obtained plant zonation measured in the field with the corresponding exposure frequency reveals that the pioneer zone and the upper saltmarsh may occur in the same elevation range (Figure 4.11). However, the lowest limit of the pioneer zone extends circa 10 cm lower than the lowest limit of the upper saltmarsh.

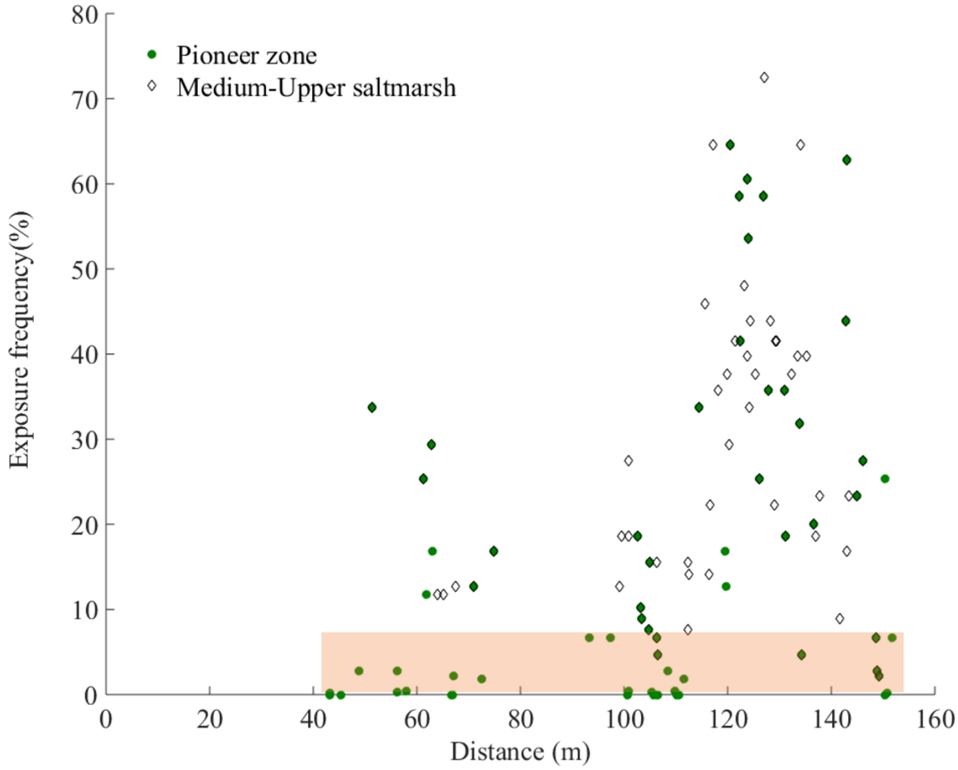


Figure 4.11. Exposure frequency of the vegetation horizons identified in San Vicente de la Barquera estuary (SVB), from topographic field data recorded with RTK-DGPS. The beginning of the profile (0 m in the x-axis) correspond to the landward zone. The area shadded in orange corresponds to the pioneer zone identified in the field.

Keeping in mind that the SVB saltmarsh has a 'patchy nature' (Figure 4.3), with wide tidal flats but also with areas with a strong micro-topography defined by micro-cliffs and channels, and eroded saltmarsh edges, this configuration hinders the establishment for both pioneer and upper-zone plants over the above described limit. Within the vegetation patches, the differences in elevation between the pioneer areas and medium-upper saltmarsh are very subtle.

5. Considerations on the connectivity of the estuarine processes

This chapter presents a joint discussion of the main results obtained in chapters 3 and 4for the validation of the first hypothesis raised in this thesis. These chapters focused in the study of historical and current evolutionary states of the three study zones and in a preliminary evaluation of the most relevant processes controlling the SVB estuary, together with the anthropogenic influence on its functioning, respectively. In chapter 3, not only the estuarine changes, but also the processes and relationships between the main estuarine features were explained, adding the contribution of dependency to the relevance of boundary conditions.

5.1. Considerations on the eco-geomorphological characterization of the three study zones

A classification of estuarine environments has been firstly proposed based on the European Union guidelines on the monitoring of habitats of Community Interest (Habitat Directive 92/43/CEE, Water Framework Directive 2000/60/EC, INSPIRE Directive 2007/2/EC, and Marine Strategy Framework Directive 2008/56/EC, mainly), and the Spanish legislation (e.g. Spanish Strategic Plan for Natural Heritage and Biodiversity). The remarkable point is the combination of previous information from other classifications, usually developed at a very specific level (habitat type; e.g. EUNIS Habitat Classification, CORINE Land Cover Classification), to develop a new one but at the level of estuarine subsystems and associated features (Table 3.2). This classification has been developed in response to the lack of estuarine management proposals, particularly in Spain, and it considers not only the water body but the entire system. The hierarchical classification has given the criteria for the eco-geomorphological maps to be unified, allowing the comparison of mapped features, which is necessary to assess changes in occupied surface.

Thus, the evolutionary trends in spatio-temporal variations and eco-geomorphological processes have been described for three Iberian estuaries under contrasting oceanographic conditions. The quantification of areas and the mapping of the main subsystems throughout the study period (Figure 3.5 and Figure 3.6) have proved to be efficient methods for identifying vulnerabilities, possible drivers and potential consequences for the entire system.

At the level of the entire system (Figure 3.5), the results illustrate that estuaries with strong physical constrictions, as the SVB, may modify the occupied area mainly by changing some features on detriment of the others. In other estuaries that lack such physical constrains, as GUA and EBR, temporal changes are more evident. However, the changes associated with intertidal sandy subsystems have to be analysed with caution as they can be strongly affected by tidal (in the case of GUA estuary) and seasonal conditions. The GUA and EBR estuaries show that boundary conditions may generate contrasting processes (erosion vs sedimentation) that may mask the magnitude of the dynamic processes. Therefore, revealing these processes requires the choice of an appropriated temporal scale. At any of these cases, a smaller spatial scale analysis will help to evaluate the processes involved in the dynamics of the whole system.

In this sense, the identification of the most vulnerable features and their associated habitats may requires the analysis of the features at the levels of *Categories 2 and 3* (Table 3.2), in which case a more detail cartography is necessary (Figure 3.1, Figure 3.2 and Figure 3.3). A detailed cartography reveals that the main changes in the San Vicente de la Barquera estuary (Figure 3.1) were related to changes in the *muddy* environments (Figure 5.1; i.e. saltmarshes and tidal flats). The smooth change in the total occupied area was due to the growth of the *mudflat*s to the detriment of the *saltmarshes*. In fact, the *saltmarshes* in the SVB estuary suffered a strong negative trend, approx. 1.4 ha/year loss (Figure 5.1), which implies a surface loss of around 20 % with respect to its initial surface in 1956 (see Annex 1 for more detailed about changes in occupied surface). The persistence of this negative trend may lead to the disappearance of the *saltmarsh* and its ecosystem services, with the risk of transforming the system in a vast muddy intertidal plain covered, in the best of cases, by seagrasses and macroalgae. The loss of the *saltmarsh*, and their associated communities, will reduce the capacity of the system to retain sediment (van der Wal *et al.*, 2008).

Previous studies have shown that the sediment balance of these systems, both internally and externally, may enable the adjustment of the bed elevation to the sea level rise (SLR) (Winterwerp *et al.*, 2013). Nevertheless, if the source of sediment is reduced and the system is unable to this adjustment, there will cause the migration of the vegetation to higher elevation areas, only if there is an available accommodation area (Fagherazzi *et al.*, 2020). The effect of SLR together with the impossibility of landward migration due to the orography of the SVB zone, may promote the squeeze of the *saltmarsh*, reducing the probability for plant survival (Bouma *et al.*, 2016). Based on literature, the persistence over time of the *saltmarsh* depends on a balance between the supply of sediment and plant growth (Best *et al.*, 2018), and the external energetic forcing, including wave energy, storm surges and tidal flooding (Van de Koppel *et al.*, 2005; Fagherazzi *et al.*, 2012; Nicoletta Leonardi *et al.*, 2016; Ganju *et al.*, 2017).

Doing a similar analysis for the GUA estuary (Figure 5.1), it can be concluded that the *saltmarsh* has an equilibrated balance between sediment supplies and hydrodynamic processes. The interaction of external and internal drivers favours sediment remobilization (Morales and Garel, 2019), resulting in an increment of surface of approx. 0.3 ha/year (Figure 5.1) in the last 60 years. An equilibrated balance of sediment inputs allows the tidal subsystem to prograde (horizontally) and aggrade (vertically), following a natural behaviour (Wasson *et al.*, 2019). The large availability of sandy sediments in this system comes from the river itself, which erodes deeply weathered granites in its basin, and by the erosion of westward sandy cliffs, transported to the estuary by the prevailing eastward littoral drift. (Garel *et al.*, 2014; Morales and Garel, 2019). Thus, the sediment supply, the coastal circulation system, the areas of wave refraction and the resulting shore currents are crucial to achieve a coastal equilibrium and to maintain the balance of the Guadiana River estuary (Ghosh, 2019; Morales and Garel, 2019).

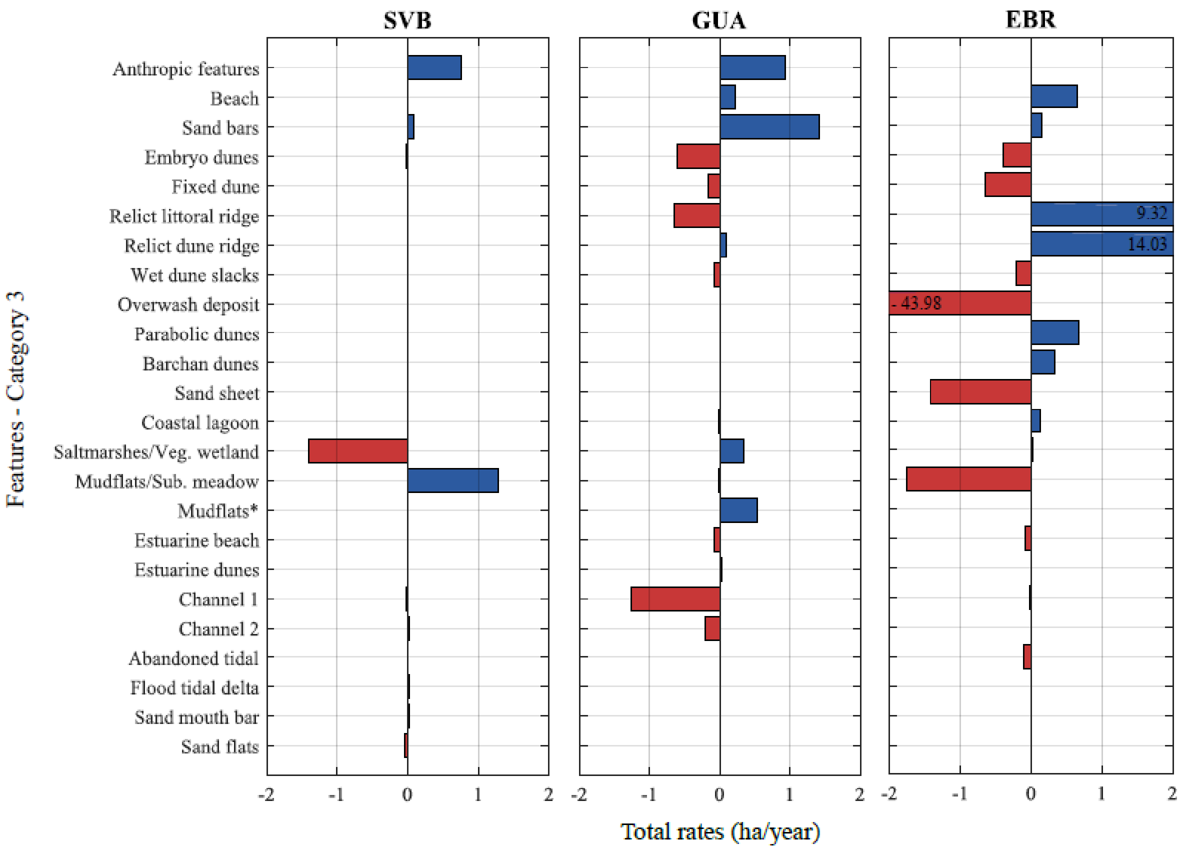


Figure 5.1. Total rates of change (ha/year) per feature (*Category 2 & 3*) in the three study sites. To maintain the same x-scale for the three study sites, the total rates of change in Relict littoral ridge, Relict dune ridge and Overwash deposit in EBR, which showed rates of change greater than ± 2 ha, were indicated numerically on each bar.

The relationship between sandy and muddy environments is clearly illustrated in the SVB and the GUA estuaries. In the last one, the progradation of the sandy spits reduces the input of wave energy, and leads to the generation of new sheltered muddy environments (indicated as *mudflat** in Figure 3.2). This also occurred in *El Garxal* in the EBR estuary (Figure 3.3). The oldest information available for the EBR estuary (Figure 2.5) allows dating the formation of *El Garxal* between 1956 and 1984 (no orthophotographs are available between those years), sheltered by the sandy environments, which includes *sand bars* and the *San Antonio Island* on the right side of the river mouth. Together with the action of waves and winds, this island/hemi-delta, mainly formed by sandy features, facilitated the formation of *littoral/dune ridges* on the other side of the channel, where they were controlled by wave and wind action (Rodríguez-Santalla *et al.*, 2010). This process has eroded gradually this island through decades by wave action, but also due to the reduction of river sediment input, as the discharges of this river have been intensively regulated since the beginning of the 20th century (Guillén and Palanques, 1992; Rodríguez-Santalla and Somoza, 2019). As a consequence, the *San Antonio Island* is presently recording a heavy erosion (Figure 3.3; Rodríguez-Santalla and Somoza, 2019), causing the strong negative rates in *overwash deposit*s detailed in Figure 5.1 (more than – 40 ha/year), only recorded in the *San Antonio island*.

The relationships in between the sandy/muddy environments have been also described in other estuarine systems (Basset *et al.*, 2013), and it is widely described that the weakening of a protective dune system after external impacts, natural or artificial, has consequences on the local active saltmarshes backward located (Wong *et al.*, 2014; Talavera *et al.*, 2020). Building and urbanizing on the upper zones of *shoreline sandy environments* and *dunes*, interrupt their dynamics. This pressure, in addition to the effects of sea-level rise (Church and Clark, 2013), and other effects of climate change on the coasts (Ciscar *et al.*, 2011), makes these features prone to disappear (Cendrero *et al.*, 2005; Vousdoukas *et al.*, 2020).

To summarize, understanding the processes connecting the estuarine subsystems is important to enhance current schemes in ecosystem connectivity (Figure 5.2), as this is key to the long term functioning of ecosystems (Bouma et al., 2016, and references therein). Complex system transitions, self-organization and connectivity are crucial concepts to understand the dynamics and the adaptation of coastal habitats to future scenarios (Basset *et al.*, 2013; Wolanski and Elliott, 2015a; Wolanski, 2017).

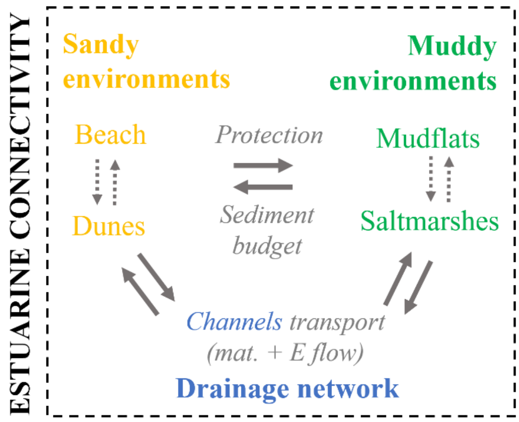


Figure 5.2. Processes connecting the estuarine main subsystems.

With limitations, this study analyses the behaviour of the estuary as a whole over a period long enough to identify feedbacks between geomorphological and ecological systems.

It is showed how small-scale features have effects on the functioning of the estuary as a whole (Wolanski and Elliott, 2015b), and that mapping is the best tool for its monitoring. Thus, the detailed maps that have been presented, in addition to the adaptation to European and national classifications and regulations, improve the understanding of the functioning of estuarine systems, in a framework compatible with other available tools (French *et al.*, 2016). Reducing the scale of working features provides to the stakeholders the basis for drawing up management plans adapted to their specific systems. This work demonstrates that the reduction of the spatial resolution helps to understand the causes of change and facilitates the identification of pressures in the short, medium and long terms, and therefore may improve the success of estuarine management practices (Talavera, 2019).

5.1.1. Methodological considerations

For the current situation, the increasing availability of high-quality image datasets combined with automatic classifications, i.e. pixel by pixel basis, are the main resources used to analyse changes on different landscapes (van der Wal *et al.*, 2008; Sturdivant *et al.*, 2017; Laengner *et al.*, 2019). However, for retrospective studies it is necessary the use of aerial orthophotographs libraries. The quality of the aerial orthophotos is an important issue as it may limit the accuracy on the identification of feature limits (Table 3.4). A comparison between orthophotos and UAS images (Figure 5.3) illustrates well this issue. It is evident that a higher spatial resolution (UAS images) facilitates the visual distinction of these limits (Figure 5.3, left panes). However, for features with microtopography, as saltmarsh plant versus seagrass areas (Figure 5.3, right panes), the definition of boundaries requires accurate digital elevation models, along with field topographic data, to improve the quality of future analyses.

In previous studies, the main sources of error when processing orthophotos have been related to the quality of the image and the bias of the analyst (Olofsson *et al.*, 2014). Thus is, the error sources may differ between cartographies. Therefore, the accuracy assessment should be specific for each cartography and the ground truthing campaigns should be performed the same year of the orthophoto to make conditions comparable.

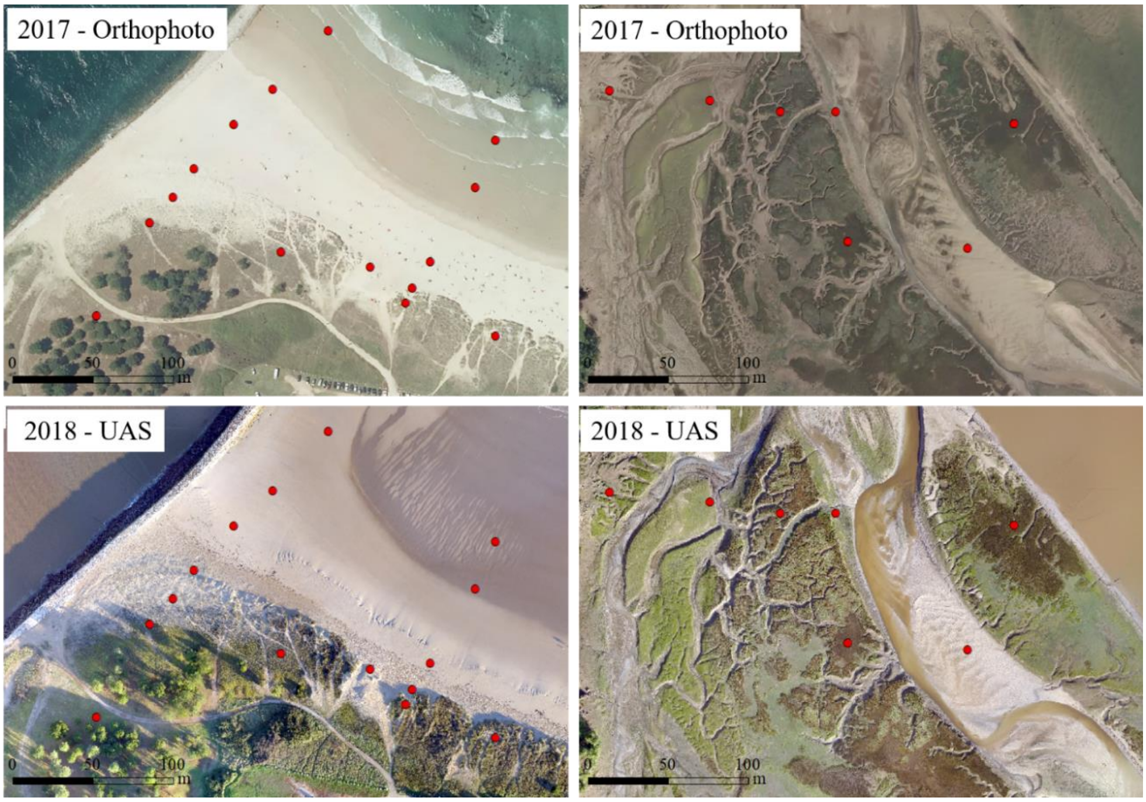


Figure 5.3. Examples of limitations for feature classification raised on the accuracy assessment for SVB estuary. The images show the differences between acquisition methods. Left images show the limit between beach and embryo dune habitats; Right images show the limit between saltmarsh (darkest green) and mudflat (covered by macro-algae and seagrasses) features. Red dots indicate test points in the field.

5.2. Considerations on the specific analysis of the most threatened subsystem in the SVB estuary: tidal flats analysis

With the recent evolution of an estuarine system quantified and described, it is possible to identify the most unstable features within the system to apply specific methodologies that help to understand the drivers of change in each of them, and thus be able to design management measures focused on those "weak" points. This was the aim of chapter 4, where the saltmarshes of San Vicente de la Barquera estuary have been studied in detail. The change maps and the metric analysis of the landscape (Figure 4.3 and Figure 4.4) revealed that the process of vegetation loss is affecting the lowest parts of the saltmarsh, as was expected, but also the highest elevations. At any case, the median elevation of saltmarsh vegetation loss has increased over time, although in recent years the trend appears to be reversing (Periods 5 and 6 in Figure 4.4). A similar temporal pattern has been observed for plant colonization (Figure 4.4, *Gain class*) also with increasing elevation over time. The pattern of plant colonization could be related to increasing flood elevation (Figure 4.8). According to the results, the threshold between the saltmarsh and mudflats for SVB is 1 m above MSL. This together with the map of the exposure frequency, rather than the inundation duration, can be used to define the limit of establishment of the pioneer vegetation, according to Balke *et al.* (2016). With these boundary conditions, can be suggested that only a small area of the entire intertidal surface seems suitable for saltmarsh plant colonization (yellow tones in the west area of Figure 4.9.b). In that area (near the main bridge), the elevation of the floor has increased in recent years. This increase has fed by sand deposited as a consequence of increased energy from coastal storms, but also due to the remobilization from dredging works (Flor-Blanco *et al.*, 2015). This is also noted in the topographic profiles (Figure 5.4) where a slight increase in the higher areas can be observed for the three of them, especially for profiles 1 and 2 (Figure 4.1). Therefore, it is clear that the processes at small temporal scales also affect the behaviour of the system within the defined time intervals (Figure 4.3). Small time scale processes also include seasonality, so the conclusions may be conditioned by the date when the data were taken (orthophotos and *in situ* data), i.e. before or after the growing season.

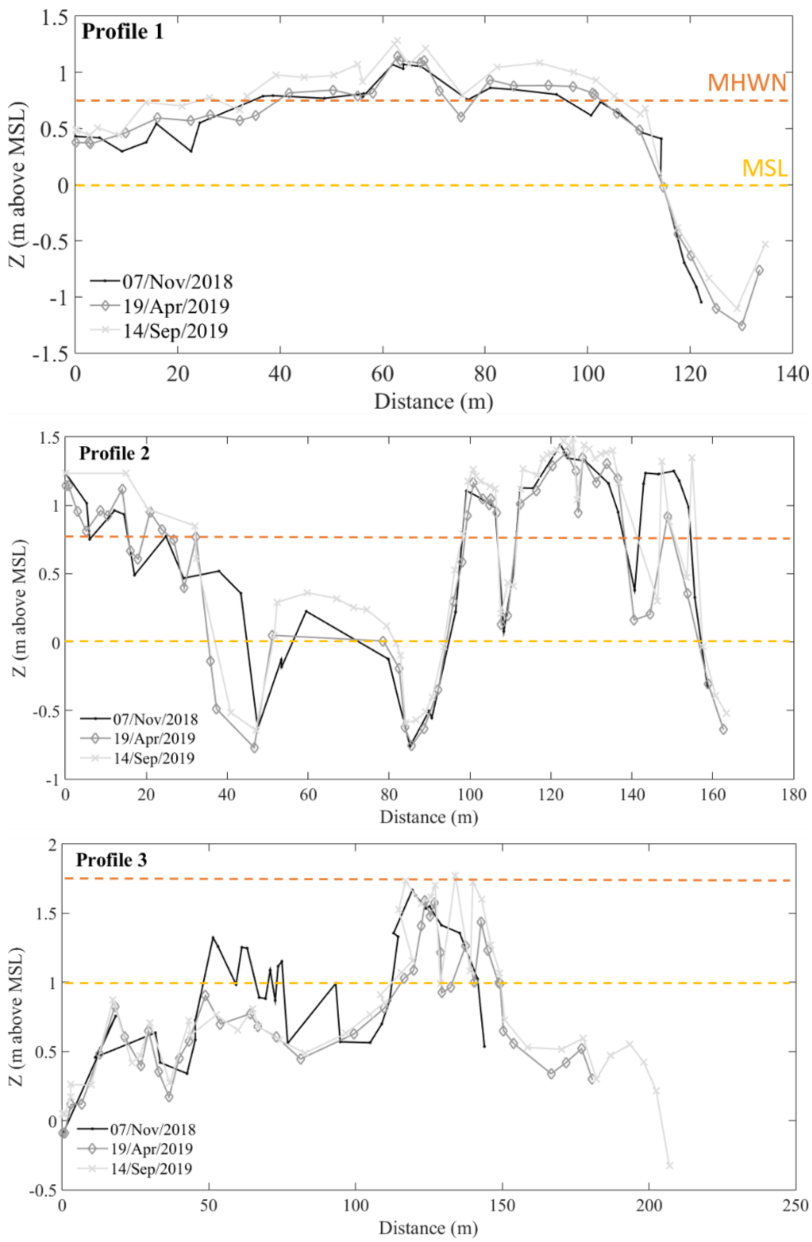


Figure 5.4. Evolution of the microtopography distribution in the three profiles measured in SVB satlmarshes. MHWN = 0.747 m; MSL = 0 m (Data are referred to MSL in Alicante, Spanish reference datum). The beginning of the profile (0 m in the x-axis) correspond to the landward zone. Location of the profiles is showed in Figure 4.1.

A healthy functioning of an ecosystem is highly depending on the landscape connectivity (Taylor *et al.*, 1993). The characterization of landscape changes must take into account the differences between structural and functional connectedness. The structural connectedness refers to the physical continuity of the patches within the landscape (i.e. large patches instead of small ones), whereas the functional connectedness comprises the connectivity of the processes of the biogeomorphic systems (Bouma *et al.*, 2016). In this sense, the SVB saltmarshes show a clear decline on the structural connectedness (Table 4.1 and Figure 4.5), while there are some indications of stress for the functional one, as there exist some indications of self-organized processes in the long-term (Figure 4.6). Thus, the functional connectedness of the SVB estuary could be evaluated by the behaviour of the patch-size distribution over time (van Wesenbeeck *et al.*, 2008). The fit of the evolution of the SVB saltmarsh patches to a power law pattern (Figure 4.6), suggests the existence of self-organized processes controlled by scale-dependent feedback mechanisms (Rietkerk and van de Koppel, 2008; Taramelli *et al.*, 2018), which could explain the increasing patchy distribution of the SVB saltmarshes. According to Van de Koppel *et al.*, (2005), self-organize processes improves the functioning of the saltmarshes at short time scales, but increase the physical stress on the edge on the vegetation at greater timescales, favouring habitat change and fragmentation.

5.2.1. Causes of change

The origin of the saltmarsh decline in the SVB estuary cannot be attributed to a single cause. Although the combination of regional and local factors may have contributed to this degradation, in this particular case, the local factors seem more relevant, with anthropogenic pressures sustained for so long that they have reduced the resilience of the saltmarsh. Since the middle 20th century, the SVB estuary has been subjected to drying processes, which modified the internal hydrodynamic pattern, even isolated, almost a century ago, some parts of the intertidal area with the construction of more than 2500 m of retaining walls (Hoyos Cordero, 2018). Fortunately, in 1988, the SVB saltmarshes became part of the Natura 2000 Network and the *Oyambre* Natural Park. This led to the implementation of several actions to recover their 'naturality'. The last one, in 2016, consisted on recovering the dried surface and re-naturalize part of the estuary (Figure 5.5). Both, the drying process almost a century ago and the recent re-naturalization lead to strong changes in the configuration of the saltmarsh, with adaptation processes driven by the hydrodynamic conditions. Similar actions have been carried out in other estuaries of the Cantabrian coast since the 1950s, e.g. Santoña (Cantabria), Plentzia and Urdaibai (Vasque Country; García-Artola *et al.*, 2017). However, in those cases, the saltmarshes regenerated after tidal re-inundation in less than 10 years (Cearreta *et al.*, 2013), probably due to the biogeomorphic feedbacks supported by the supply of enough sediment that translated in very high sedimentations rates (average 15 mm yr^{-1}), and increase of colonization opportunity areas. Thus, future studies in the San Vicente de la Barquera estuary should focus on the fluxes of sediment and the quantification of sedimentation rates within the estuary, to better understand the processes and evolution of the estuarine subsystems and to identify main drivers of change for a better management of the estuary.

Figure 5.5. Remains of the retaining walls built in the 20th century to dry the inner part of San Vicente de la Barquera saltmarsh. The orange arrow indicates the position of the levee, recently removed at some points to allow the re-inundation of the zone.

The anthropogenic impacts in the SVB saltmarsh, not only include land reclamation, but also repeated dredging in the main channel of the estuary to adapt it for navigation. The first dredging documented was in 1933, with a dredged volume of 218.702 m^3 of sand, 85.779 m^3 of gravel and 1.542 m^3 of rock (Gobierno de Cantabria, 2018). The following dredging works repeated the dumping works of the dredged material in the reclaimed saltmarsh areas, with exception of those of 1988 and 1995 (biggest sandy dredging works), when the materials were dumped on *El Tostadero* beach (one of the estuarine beaches of San Vicente de la Barquera estuary, in the Eastern part of the ebb tidal delta; Figure 3.1) and *El Rosal* (the external beach). Since 1933, almost 30 dredging works were carried out in the SVB estuary (Figure 5.6), affecting the dynamics of the estuary and the tide propagation along the system. According to Flor-Blanco (2007), the main effects of these changes are the increase of the tidal wave height in the estuary due to a resonance effect after the depth reduction, but also by the effects of the main bridge that crosses the estuary. According to the results observed in Figure 4.4 and Figure 4.5, and despite the general negative trend, the decrease in dredging since 1990s may have contributed to the partial recovery of the saltmarsh. However, the sand input does not go into the inner part of the estuary, as this area does not show the same aggradation trends than the observed in the area near the bridge by means of topographic profiles (see Figure 5.4 where certain aggradation can be noted in profiles 1 and 2, both located near the bridge). It would be desirable, therefore, the study of this inner part in detail in a broader time scale to better reflect its evolution and possible recovery.

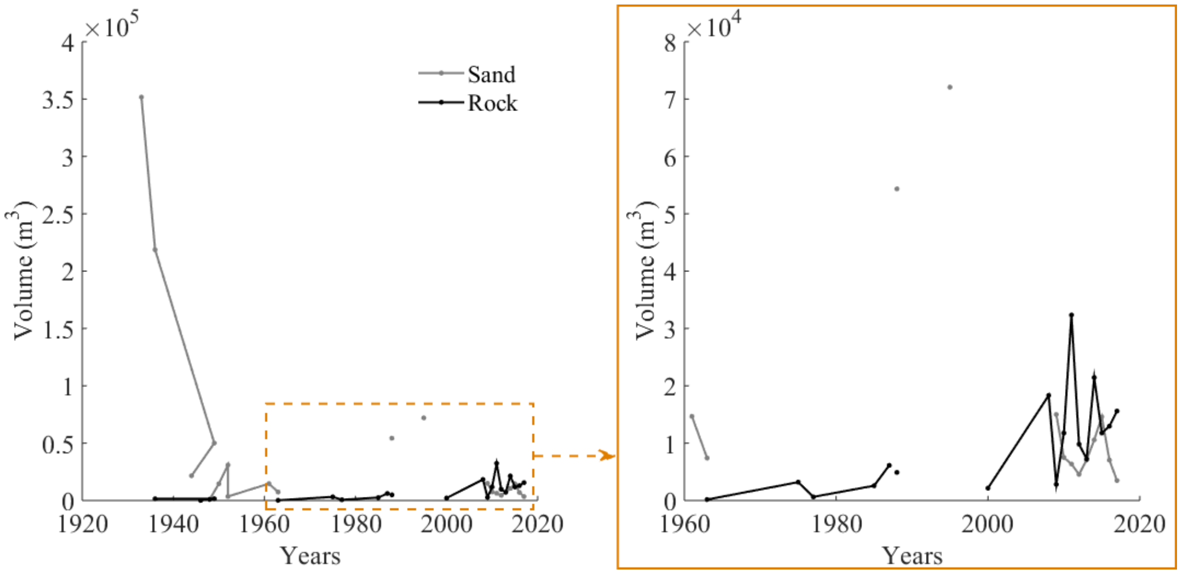


Figure 5.6. Volume of dredging's works carried out in SVB estuary in the last century. Data from Gobierno de Cantabria (2018).

The negative consequences for saltmarshes of deepening channels to facilitate the maritime transport have been described in other estuaries worldwide (e.g. Westerschelde and Scheldt estuaries in the Netherlands and the Elbe estuary in Germany, among others; Meire *et al.*, 2005; Kerner, 2007). Despite their spatial scales differ from the SVB estuary, these works provide empirical data to demonstrate the major effects that local actions may have on the estuarine functioning, in the intrinsic dynamics and in the processes of the estuaries. Besides dredging, another anthropogenic impact in the SVB estuary was the canalization of the *Escudo* River, limited to the urban areas. The canalization affected the amount of sediment reaching the estuary, which is now retained upstream. The *Escudo* River is small, suffers not many pressures and neither of great magnitude. However, as it does not run through any mountain or any abrupt or irregular area, its surrounding relief favours the occupation of the alluvial plain with the consequent pressure on the environment (Hoyos Cordero, 2018). In summary, the combination of anthropogenic pressures suffered over the years has altered the local hydrodynamics of the system and the saltmarsh has gradually eroded.

The acceleration of the saltmarsh disappearing is a process previously described for both North America and Europe (Kirwan *et al.*, 2008). Based on the study of saltmarshes along the US coast, Ganju *et al.* (2015) described how saltmarshes with an integral functionality tend to retain sediment, while degraded ones export it. Thus, the decrease in plant biomass leads to a decrease in ground elevation, due to the lower contribution as plant growth and sediment retention to the local balance of sediment processes (van der Wal *et al.*, 2008; Belliard *et al.*, 2017; Donatelli *et al.*, 2020). It seems clear that saltmarshes will persist only if they can grow vertically or migrate upland at enough rate to adjust to the local SLR rates (Morris *et al.*, 2002; Day *et al.*, 2008; Kirwan and Megonigal, 2013). In SVB, the presence of rigid structures and the geological constrain make impossible the upland migration of the saltmarsh, creating the conditions for coastal squeeze (Bouma *et al.*, 2016). Specifically, the SLR rates described for the area of SVB are 2.08 ± 0.33 mm yr^{-1} from 1943 to 2004 and 2.67 ± 3.24 mm yr^{-1} from 1993 to 2004, showing an accelerated rate at the end of the analysed period (Chust *et al.*, 2010). Merging these trends on SLR with the results showed in the present work and the anthropic pressures above-described, the loss of the saltmarsh could be expected to accelerate in the near future, with a virtual total disappearance of vegetation in 15-20 years if the present trend continues, and a contrary behaviour on mudflats (Figure 5.7). This would lead to the loss of this ecosystem and the corresponding ecosystem services.

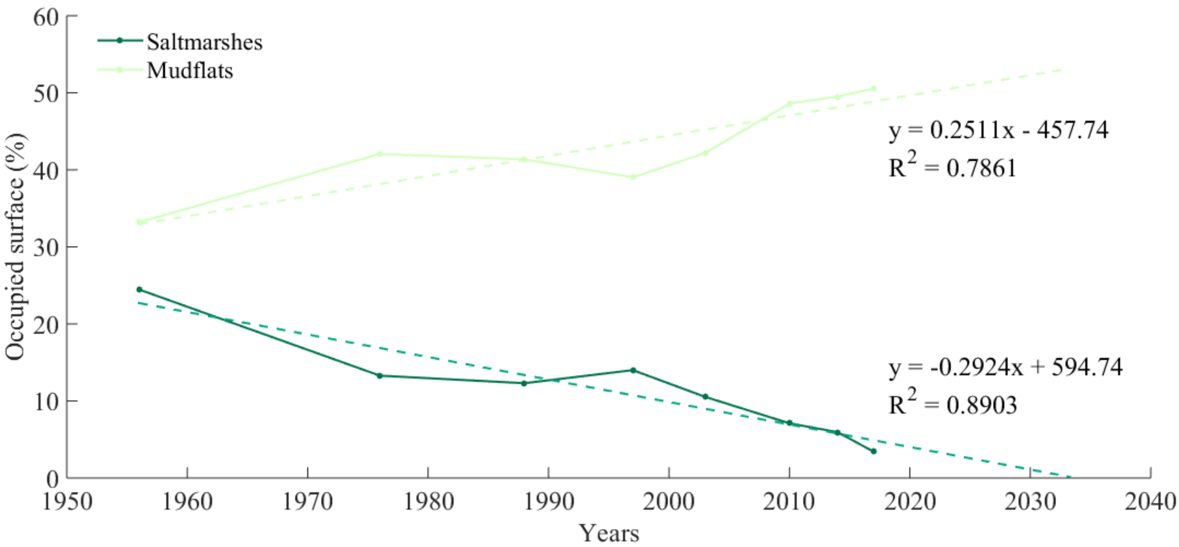


Figure 5.7. Evolution of the occupied surface (%) by saltmarshes and mudflats in the San Vicente de la Barquera estuary during the studied period (1956-2017) and their extrapolated trend showing a surface 0% by the year 2034 for saltmarshes and around 55% for mudflats, according to the equations obtained from the graph.

Understanding the marsh edge dynamics is crucial to estimate the vulnerability of the saltmarsh in response to the SLR (Marani *et al.*, 2011). Nowadays, there is an extensive literature describing the loss of wetlands around the world (Boorman, 2003; Farris *et al.*, 2019; Laengner *et al.*, 2019; Wasson *et al.*, 2019; Donatelli *et al.*, 2020; among others). However, most of these works agree on the uncertainty of the SLR effects because of the lack of knowledge on the interaction between the hydrodynamic conditions and eco-geomorphological processes over time (Rodríguez *et al.*, 2017). In short, it is still necessary a deep study on processes favouring/inhibiting the lateral expansion of tidal saltmarshes (Bouma *et al.*, 2016).

6. Estuarine vulnerability assessment: *EstuarIndex*

6.1. Introduction

The capacity to predict coastal changes and assess the vulnerability with a certain degree of reliability is a common goal on decision-makers worldwide (Thieler and Hammar-Klose, 1999). To determine which areas are susceptible to change due to increasing coastal pressures, it is necessary the use of methodologies to evaluate the corresponding level of vulnerability. One of the first methodologies developed to evaluate the coastal vulnerability was proposed by Gornitz (1991) and Gornitz *et al.*, (1994): the Coastal Vulnerability Index (CVI). The CVI is one of the most commonly index-based methods used to assess coastal vulnerability to SLR and has been widely applied on worldwide coasts (Koroglu *et al.*, 2019; and references therein).

Index-based methods are common procedures used to assess the vulnerability of a given natural system. These methods are based on the combination of several variables that allow the vulnerability to be expressed as a dimensionless synthetic index (Rizzo, 2017). The advantage of this approach is the reduction of information to a single value. When the index is applied by sectors, this method allows to highlight the most vulnerable areas. Nevertheless, this methodology also has disadvantages as they simplify the large number of complex structures and processes that interact in coastal areas into a single value, which frequently results in a 'static view' of the state of vulnerability status of the system. Besides, the application of index-based methods is often subjective, as each author tends to modify or even creates a new index to fit specific objectives not well covered in the original design (García-Mora *et al.*, 2001; Ciccarelli *et al.*, 2017; Peña-Alonso *et al.*, 2017; Rizzo *et al.*, 2018; Defne *et al.*, 2020; among many others). Consequently, there is not a universal index accepted worldwide. Instead, there is a great diversity of indexes that improves the scientific knowledge and the amount of information available for each site, but that makes difficult the comparison of sites and, in the particular case of Spain, disables to have a homogeneous national database.

Taking the above mentioned into account, this thesis develops an index-based methodology (*EstuarIndex*) to assess the vulnerability of estuaries to increasing coastal pressures described along the present thesis, based on the previous studies on coastal areas. Like most initiatives for the assessment of natural systems, this index is subject to constraints such as the available information for a given zone, the criteria of the assessors, the difficulty of finding reference models, etc. (Rizzo, 2017). Aware that the physical and oceanographic conditions of each zone determine its evolution, the variables considered have been adapted, when possible, both for Atlantic coasts (San Vicente de la Barquera and Guadiana estuaries) and for the Mediterranean ones (Ebro Delta river mouth), to enable its application to any estuarine environment in the Iberian Peninsula and even to any temperate coast of mid-latitudes.

EstuarIndex is based on a proposal from the Ministry for the Ecological Transition and the Demographic Challenge, necessary to respond to the demands/working methods of the European Union to monitor of the conservation status of the habitats of the Natura 2000 Network every six years (Art. 17 of Council Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora). However, the index here presented is not designed for habitat type rather for subsystems categories, following the Table 3.2. In any case, it is an adaptation of the proposal by Aranda *et al.*, (2019). Hence, the aim is to design a simple methodology easy to apply and suitable for any estuary.

6.2. Methodology

This chapter proposes a new methodology for an index-based method. The final index is based on the definition of 4 sub-indexes, corresponding with the main subsystems described in the chapter 3 (Table 3.2): *Shoreline Sandy Environments Index* (SSEI), *Dunes Index* (DI), *Tidal Flats Index* (TFI) and *Drainage Network Index* (DNI). The four sub-indexes are based on information already available (or easy to obtain in the field).

The method is a linear combination of variables ranked between 1 – 5 (1-3 for tidal flats), being 1 very low conservation status and 5 very high conservation status, based on indexes previously described in the literature. The variables are grouped according to three sets of factors: (1) morphosedimentary and oceanographic factors (MOF), (2) ecological factors (EF) and (3) management and protection factors (MPF). The variables grouped by factors are all integrated in a unique index, *EstuarIndex* (Figure 6.1), which allows defining the environmental status of the whole system based in 5 classes: (1) Very low, (2) Low, (3) Medium, (4) High and (5) Very High.

The establishment of the reference values for each subsystem is an important requirement. The reference value can be set as the first high quality information available for the system, or as a specific state considered pristine according to the literature, i.e. the system's dynamics is not interrupted or altered by any external factor, as well as being connected to the other systems in the estuarine environment.

On this basis, this chapter is structured in two sections: (1) the methodology used to collect *in situ* information on each study area, and (2) the description of the variables proposed for each estuarine subsystem and the estimation methods.

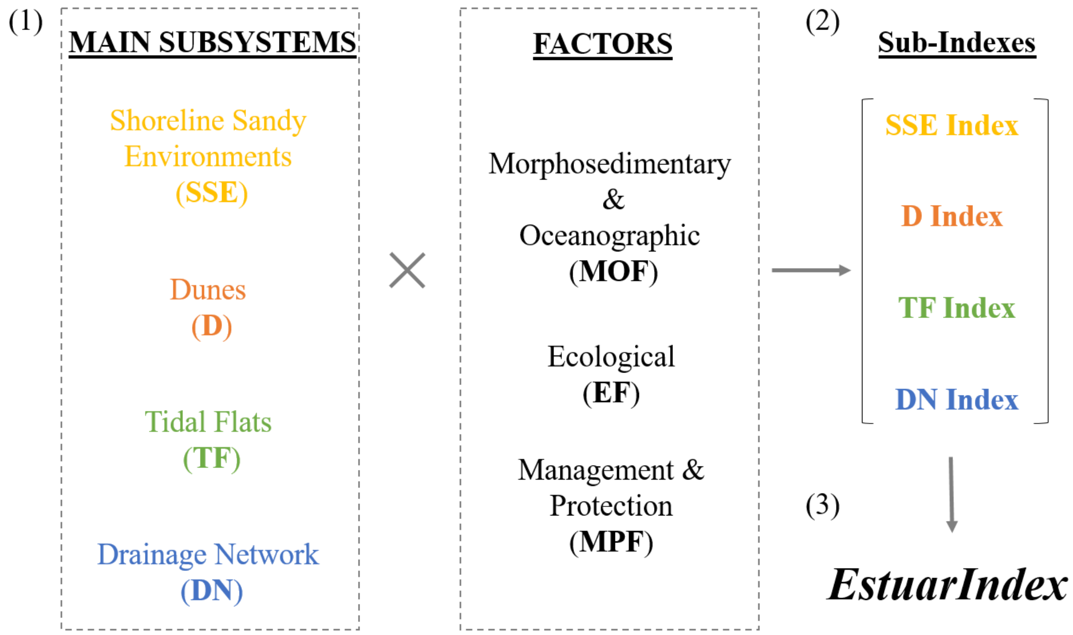


Figure 6.1. Flowchart showing *EstuarIndex* structure. (1) Calculation of MOF, EF and MPF for every main subsystem, (2) Calculation of sub-indexes (SSEI, DI, TFI, DNI) and (3) calculation of *EstuarIndex* based on resuls obtained for each of the sub-indexes.

6.2.1. Field campaigns

The methodology for field work is the same in the 3 study zones including visual inspection of the subsystems (shoreline sandy environments, dunes and tidal flats), *in situ* measurements of selected variables (see field campaign templates in Annex 2) and topographic surveys. *In situ* measurements were structured in transects along which the variables were measured or sampled (Figure 6.2).

The monitoring period took place between 2018 and 2019 (Table 6.1), including two samplings in early autumn (2018 and 2019) and one sampling in early spring (2019). The temporal design aimed to obtain information on seasonal peaks, as well as a point estimate for interannual fluctuations.

Table 6.1. Dates of field campaigns in the corresponding studied estuaries. SVB: San Vicente de la Barquera, GUA: Guadiana, EBR: Ebro delta.

	SVB	GUA	EBR
Field campaign 1	05/11/2018	25/09/2018	18/09/2018
Field campaign 2	19/04/2019	03/05/2019	02/04/2019
Field campaign 3	14/09/2019	28/09/2019	12/10/2019

The topographic data were obtained with a differential GPS with real-time kinematic correction (RTK-DGPS, Leica GS18). On beach and dunes systems, the topographic data were recorded in continuous mode. On saltmarshes, this was not feasible and the topographic data were recorded in static mode to minimize errors (Figure 6.3.a). The topographic surveys provide *x*, *y* coordinates and the ellipsoidal height of each point. In order to have all the heights referred to the same reference system and, thus, be able to compare the data between each of the sites, all the heights were referred to the mean sea level in Alicante, which is the Spanish reference datum.

To ensure the correct orientation and replication, each transect was created on a geographic information system (ArcGIS 10), exported as .dxf format and imported into the RTK-DGPS. The transects were perpendicular to the coastline, in beaches and dunes, and perpendicular to the main channel, in saltmarshes. To maximize the length of the transects close to hydrographic zero, all the campaigns were performed during spring low tides. A variable number of transects was selected for each study area to represent each subsystem (Figure 6.2). The total number of transects collected in SVB was 6 for the external beach and dunes, 2 for the estuarine beach and dunes and 3 for the tidal flats (Figure 6.2.a); for the GUA system were 7 for the external beach and dunes, and 3 for the tidal flats (Figure 6.2.b); and for the EBR system were 10 for the external beach and dunes and 1 for the estuarine beach (Figure 6.2.c).

Specifically, for tidal flats of the mesotidal systems (SVB and GUA), the profiles were spaced more than 100 m apart so that they were sufficiently representative of the entire marsh (Figure 6.2.a and b). Contrary to beach-dune systems, the access and displacement in saltmarshes is difficult, and transect planning requires a previous visual field inspection to identify access points and suitable areas. Because of this, the transect selection was done directly in the field during the first field campaign. The sampling points along transects were marked with wooden stakes and the exact positions were measured with the RTK-DGPS, to repeat the same points in the following campaigns (Figure 6.3. a and b). The monitoring of the vegetation was structured in zonation bands along the marked transect, measuring the biological variables by using 1x1 m minimum area randomly distributed in each band (Figure 6.3.c and d).

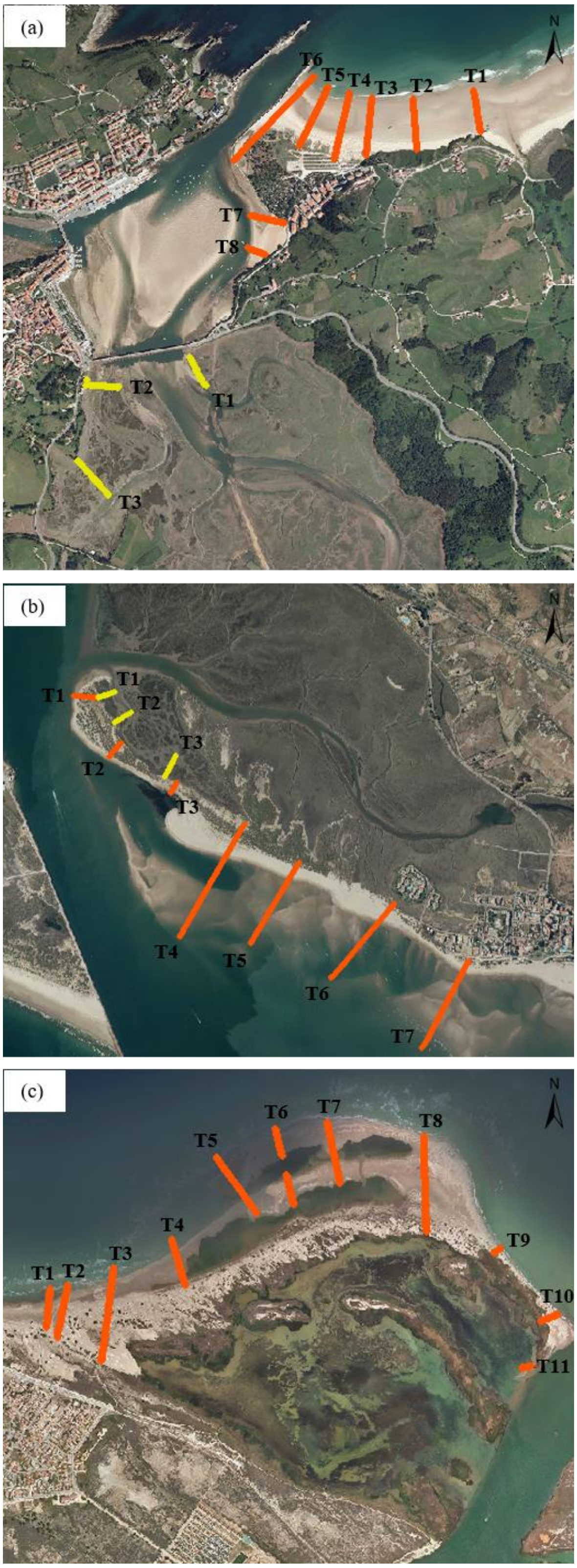


Figure 6.2. Location of the field measurement transects (*Tn*) on each study site. (a) San Vicente de la Barquera estuary, (b) Guadiana estuary, (c) Ebro River Delta mouth. Orange transects correspond to beaches and dunes, yellow ones to tidal flats.

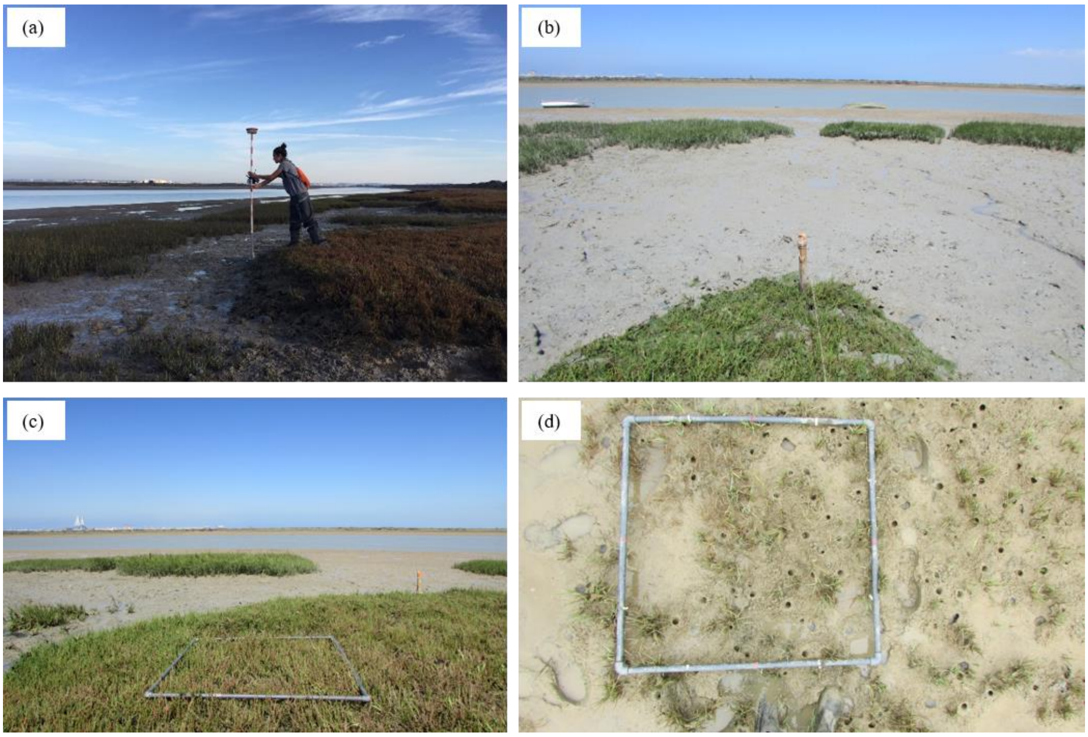


Figure 6.3 (a) Static points recording with the DGPS, (b) image of the wooden stake used in the first field campaigns to select accessible saltmarshes points, (c) minimum area placed in the field, and (d) minimum area on top of the pioneer band of the saltmarsh.

6.2.2. Index design

This section describes in detail the methodology to estimate the sub-indexes (Figure 6.1.2), describing the variables and the necessary information, and the equations to calculate the vulnerability values of the *EstuarIndex*.

6.2.2.1. Shoreline Sandy Environments Index (SSEI):

The great diversity of factors that play an important role in the development of beaches makes it difficult to choose variables for the characterization and monitoring these systems, namely geomorphology of the beach, grain composition (biogenic or non-biogenic), tidal range, degree of anthropization, wave regime, among others. This also affects to the establishment of the reference values, which must be considered adequate or optimal for each enclave. Thus, the reference values may present a strong variability between different regions, not only on a large scale, but also in relation to local factors, which may determine the singularities of each system. Despite the many challenges, the aim of this index is to provide a flexible enough tool for evaluating any mid-latitude beach.

- Morphosedimentary and Oceanographic factors (MOF):

The MOF evaluate the physical state of the beach, gathering information on the main morphological and dynamic characteristics of the beach. The MOF for shoreline sandy environments include the following variables:

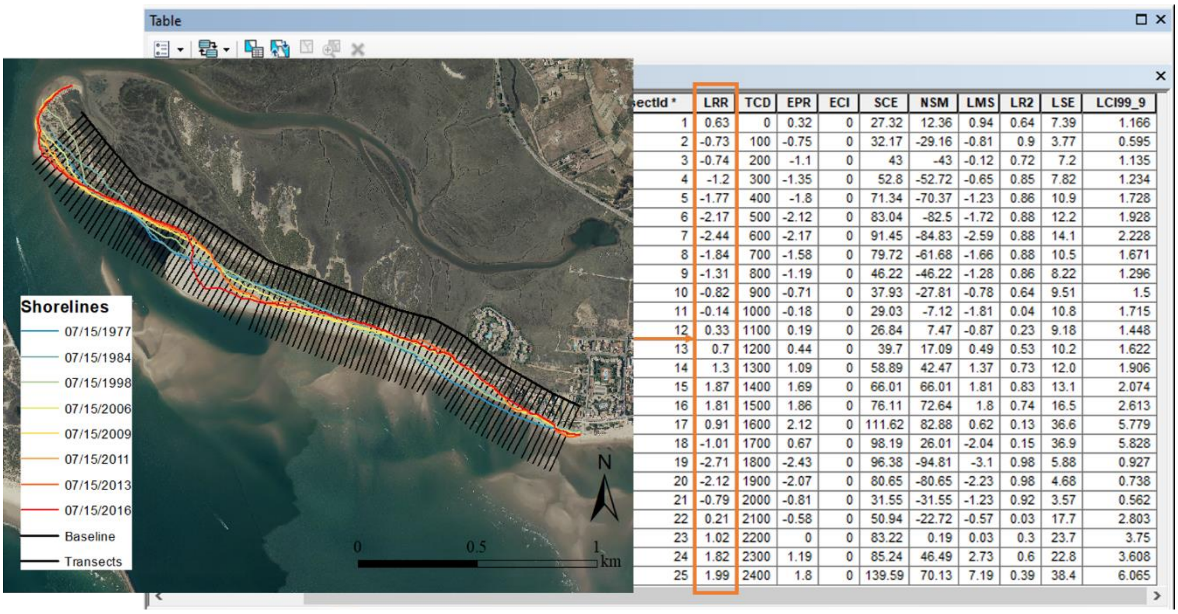
1. **Beach width (m; BW)**

This variable is evaluated considering the distance between the dune foot and the wet line in the beach and it is classified according to the range proposed by Aranda *et al.*, (2019). The best way to measure the beach width is *in situ* with a DGPS-RTK. In absence of field surveys, it is possible to estimate the width of the beach on aerial photography by measuring the distance between the wet line and the dune foot (or the promenade in the case of urban beaches). The wet line (i.e. the high tide line) is a common proxy for determining shoreline variations, despite some limitations are described (Byrnes and Anders, 1991; Pajak and Leatherman, 2002). Nevertheless, it is considered a good proxy of the lower limit of the beach because (1) it is available in all the orthophotographs, because (2) it has a relatively low variability in general and, finally, because (3) it is easily identifiable in both current and old photographs (Puig, 2016).

2. **Long term evolution of the shoreline (m/year; LTE)**

This term includes the temporal variations of the shoreline considering a time span of more than 30 years (Rizzo, 2017). The values are assigned following the classification proposed by Gornitz *et al.* (1997).

The evolution of the shoreline was quantified by analysing the orthophotographs available for the study zones. The dune foot was selected as the proxy for the identification of the shoreline. This proxy is the most used in the literature, since it is not affected by seasonality (Puig, 2016). In the present work, and depending on the orthophotograph characteristics, the identification of the dune foot was based on slope differences, changes in the colour of the image and the onset of vegetation in embryo dunes (Ojeda, 2000; Del Río, 2007). The dune foot was identified and digitized with the ArcMap software and stored as shapefiles. Once extracted the shorelines, the quantification of change rates was performed with the ArcGis extension Digital Shoreline Analysis System (DSAS 4.3; Thierler *et al.*, 2009). The process consists of defining a baseline, as parallel as possible to the digitized dune foot and as straight as possible so as not to generate irregularities. Both the dune foot lines and the baseline were used as input data in the DSAS extension. Then, the statistical output was represented in transects projected perpendicular to the baseline and evenly spaced (Figure 6.4). The distance between transects was set at 50 m for GUA, 100 m for EBR, and 25 m for SVB due to the small extension on the last site. The long-term evolution of the shoreline was defined using only the Linear Regression Rate (LRR; m/year; Figure 6.4).



ectId *	LRR	TCD	EPR	ECI	SCE	NSM	LMS	LR2	LSE	LCI99_9
1	0.63	0	0.32	0	27.32	12.36	0.94	0.64	7.39	1.166
2	-0.73	100	-0.75	0	32.17	-29.16	-0.81	0.9	3.77	0.595
3	-0.74	200	-1.1	0	43	-43	-0.12	0.72	7.2	1.135
4	-1.2	300	-1.35	0	52.8	-52.72	-0.65	0.85	7.82	1.234
5	-1.77	400	-1.8	0	71.34	-70.37	-1.23	0.86	10.9	1.728
6	-2.17	500	-2.12	0	83.04	-82.5	-1.72	0.88	12.2	1.928
7	-2.44	600	-2.17	0	91.45	-84.83	-2.59	0.88	14.1	2.228
8	-1.84	700	-1.58	0	79.72	-61.68	-1.66	0.88	10.5	1.671
9	-1.31	800	-1.19	0	46.22	-46.22	-1.28	0.86	8.22	1.296
10	-0.82	900	-0.71	0	37.93	-27.81	-0.78	0.64	9.51	1.5
11	-0.14	1000	-0.18	0	29.03	-7.12	-1.81	0.04	10.8	1.715
12	0.33	1100	0.19	0	26.84	7.47	-0.87	0.23	9.18	1.448
13	0.7	1200	0.44	0	39.7	17.09	0.49	0.53	10.2	1.622
14	1.3	1300	1.09	0	58.89	42.47	1.37	0.73	12.0	1.906
15	1.87	1400	1.69	0	66.01	66.01	1.81	0.83	13.1	2.074
16	1.81	1500	1.86	0	76.11	72.64	1.8	0.74	16.5	2.613
17	0.91	1600	2.12	0	111.62	82.88	0.62	0.13	36.6	5.779
18	-1.01	1700	0.67	0	98.19	26.01	-2.04	0.15	36.9	5.828
19	-2.71	1800	-2.43	0	96.38	-94.81	-3.1	0.98	5.88	0.927
20	-2.12	1900	-2.07	0	80.65	-80.65	-2.23	0.98	4.68	0.738
21	-0.79	2000	-0.81	0	31.55	-31.55	-1.23	0.92	3.57	0.562
22	0.21	2100	-0.58	0	50.94	-22.72	-0.57	0.03	17.7	2.803
23	1.02	2200	0	0	83.22	0.19	0.03	0.3	23.7	3.75
24	1.82	2300	1.19	0	85.24	46.49	2.73	0.6	22.8	3.608
25	1.99	2400	1.8	0	139.59	70.13	7.19	0.39	38.4	6.065

Figure 6.4. Example of the transects, baseline and shapefile containing all the digitalized dune foots for the GUA beach.

3. **Predominant Morphodynamic State (PMS)**

The morphodynamics of a beach is conditioned by the marine dynamics (sea level variations, waves and currents, mainly), morphological variations, grain size, etc. Masselink and Short (1993) also added tide as a modulating agent and introduced it into the morphodynamic classifications of beaches (Figure 6.5). The classification proposed by these authors is profusely used in the literature. It takes into account the dimensionless fall velocity or Dean's number (Ω; Eq. 6.1). This parameter was proposed by Gourlay (1968) and Dean (1973), and depends on wave conditions (Eq. 6.2), grain size (Eq. 6.3), and the Relative Tidal Range (RTR; Eq. 6.4), which is the Mean Spring Tidal Range (MSTR) divided by the wave height at the break point (H_b).

$$\Omega = \frac{H_b}{w_s.T} \qquad \text{(Eq. 6.1)}$$

where H_b is the wave height at the break point, w_s is the sediment fall velocity and T the wave period.

$$H_b = 0.39\,.\,g^{0.2}.\,(T.\,H_0^2)^{0.4} \qquad \text{(Eq. 6.2)}$$

where g is the gravitational constant, T is the wave period and H_0 is the significant wave height. Both parameters were obtained from the SIMAR wave time series of each site, provided by the Spanish National Port Authority. The SIMAR points are located at an offshore distance and the data they provide are obtained from numerical modelling.

$$w_s = 273 \, . D_{50}{}^{1.1} \quad \text{(Eq. 6.3)}$$

where D_{50} is the median value of the grain size.

$$RTR = \frac{MSTR}{H_b} \quad \text{(Eq. 6.4)}$$

The sediment samples to calculate D_{50} were collected during the first field campaigns. In general, the number of samples collected along the selected profiles on each beach was four, with the exception of EBR, where 5 samples were collected due to the large extension of the selected profile (*c.a.* 400 m). The characterization of the sediment was done with a sieve analysis column including 0.063, 0.090, 0.125, 0.212, 0.250, 0.500 and 1 mm mesh sieves. Previously dried in an oven for 48 h at 80ºC, the samples were sieved for 10 minutes. The weight of the sediment retained on each sieve was used to estimate the D_{50} with the GRADISTAT software (Blott and Pye, 2001).

The MSTR values used for SVB, GUA and EBR were 3.93 m, 3.06 m and 0.20 m, respectively. For the San Vicente de la Barquera and Guadiana study zones, these values were calculated from the vertical references of the nearest tide gauges (Figure 2.1; Instituto Hidrográfico de la Marina, 2020). Whereas for the Ebro study site, it is a bibliography value (Franquet Bernis *et al.*, 2017), since the microtidal zones are not included in the Tide Table. Regarding H_b, it was obtained from SIMAR wave time series of each site. The used value corresponds to the mean value from the data series. Once estimated the parameters, the morphological state of the beach is established according to Figure 6.5.

The establishment of the predominant morphological state of a beach requires a wide data series to avoid interannual fluctuations. Thus, the seasonality of this variable was estimated with data of at least 2 consecutive years. This makes it possible to quantify the variations associated with seasonal energy conditions and establish an annual average permanence of each morphodynamic state. The predominant morphological state is set in values that appears more than 50% of the times this variable is measured.

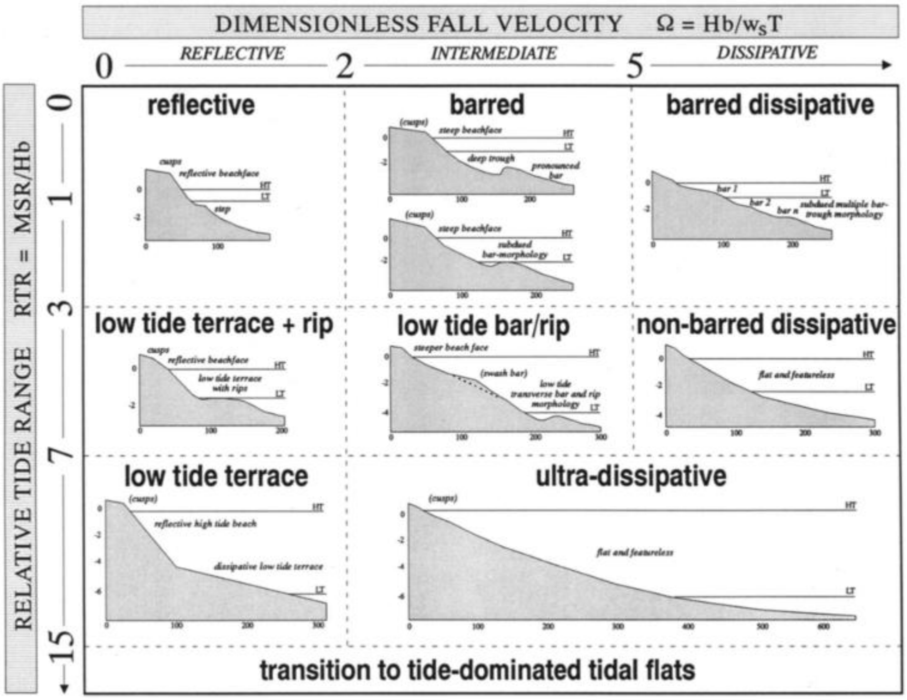


Figure 6.5. Morphodynamic classification of beaches (Obtained from Masselink and Short, 1993).

4. Sand Bars (SB)

Sand bars are intertidal ridge-shaped accumulations of sand. They can be bare, without associated vegetation, or with presence of seagrasses and algae. Sand bars dissipate wave energy and supply sand to the beach. This variable was classified according to Gracia *et al*. (2009). Sand bars can be identified *in situ*, with topographic profiles (Figure 6.2) or by analysis of ortophotographs. In the present work, the presence of intertidal sand bars was identified *in situ* with topographic profiles and visual inspection. This variable is quantified according to the number of present sand bars. The corresponding values for the *Shoreline Sandy Environments Index* are presented in Table 6.2.

5. Stoniness (S)

This variable estimates the proportion of coarse elements (clasts, medium to large shells, etc.) in the sand of a beach. Generally, beaches prone to erosion tend to lose sand, maintaining the amount of coarse elements. Over time, this type of beaches become increasingly stony. The level of stoniness conditions colonisation by flora and fauna, with different species being present on beaches with different degrees of stoniness. The temporal tendency of this variable is an interesting proxy for the beach's capacity to host different flora and fauna (Speybroeck *et al.*, 2005). Stoniness was visually estimated as the percentage of coarse elements covering the surface of the beach, according to Hodgson's method (1974; Figure 6.6).

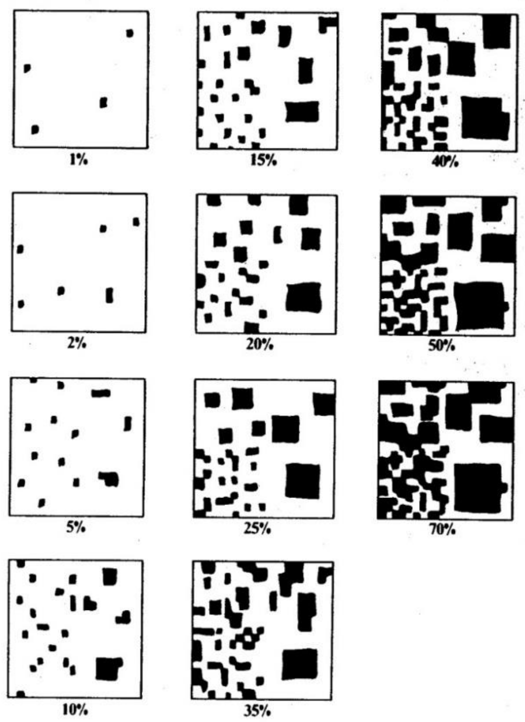


Figure 6.6. Template for estimating the stoniness percentage (Hodgson, 1974).

- Ecological Factors (EF):

These factors measure the ecological state of the system. For the beach subsystem, only was considered the presence/absence of driftlines.

6. **Presence/absence of driftlines (D)**

As other drift material, the marine organic waste usually accumulates on the lowest level of the supralittoral zone, just above the wet line. The organic deposition is usually composed by algae and seagrasses (Davies *et al.*, 2004). This accumulation plays a crucial role on coastal protection and food webs, retaining sediment and creating sheltered areas for a wide variety of invertebrates, which in turn constitute food for many coastal birds (Servera *et al.*, 2002; Roig-Munar *et al.*, 2006).

The identification of these ephemeral features requires sometimes the combination of field inspection and aerial orthophotograph analysis, since its identification is possible with the last. In this work, this variable was estimated *in situ* during field work, recording presence/absence of these features, as well as thickness and continuity along the shoreline when present. Depending on the behaviour and exposure of the beach, the frequency of occurrence of this features is variable. Thus, the proposed values for its evaluation (Table 6.2) refer to these factors, being classified as rare, occasional, frequent or permanent.

- Management and Protection Factors (MPF):

Human interventions strongly condition the evolution of coastal systems. The evaluation of anthropic pressures in the beach subsystem was evaluated according to the next variables.

7. Waste (W)

Solid waste affects specially to urban or semi-natural beaches. However, these types of beaches usually have regular cleaning works that ensure waste control. On the contrary, in natural beaches, with much less human pressure, but without cleaning-works, large amounts of solid waste tend to accumulate, mainly due to deposition of waste from the transport of wave and currents (Figure 6.7). Waste on the beach was evaluated qualitatively on every field campaign by visual inspection. According to García-Mora *et al.* (2001), the waste estate was classify in four categories, based on the amount of litter found in every transect. The corresponding values are expressed in Table 6.2.

Figure 6.7. Examples of waste in the driftlines on the natural parts of GUA beach (left) and EBR beach (right).

8. **Degree of anthropization (DoA)**

The degree of anthropization/artificialisation of a beach does not take into account rigid structures such as walkways, breakwaters, dikes, etc., but rather the urbanisation of the beach. This variable classify beaches according to three categories, natural, semi-natural or anthropic beach (Roig-Munar *et al.*, 2012; Table 6.2).

9. **Frequency of visitors (FoV)**

This variable is estimated as the range of touristic occupation related to the carrying capacity of the beach (Rodella *et al.*, 2017). It is usually considered as an indicator of the pressure suffered during the summer period. Higher occupation implies an increase in risks, such as trampling, which have negative consequences on flora and fauna, sediment contamination, etc.

The range of occupation of a beach can be estimated in situ by counting the number of people per unit area of the beach, or with a visual estimation from high points. Sometimes, this information can be also obtained from town council or stakeholder reports, which often collect information on beach occupation. This variable has a strong seasonal component that has to be considered when collecting the information.

In this work, the frequency of visitors was estimated visually during the field campaigns, which temporal design covered the seasonal variation (Table 6.1). According to Aranda *et al.* (2019), this variable was qualitatively evaluated dividing the beaches in 3 categories (Table 6.2).

10. Access to the beach (AB)

Beach accesses are often very much related to the degree of anthropization. Thus, an urban beach, with the presence of a promenade at the back of the beach, often presents walkways for an easy and comfortable access. Semi-natural beaches are also usually provided with these structures, in a more integrated way with the environment, meeting the dune ridges with elevated walkways, but often with access roads at the back or park place which modify the structure of the dune system (e.g. Figure 2.6. b in San Vicente de la Barquera estuary).

On the contrary, natural beaches do not have any of these rigid structures.

The estimation of this variable was made by visual inspection in the field, by counting beach walkways, as well as the possibility of access to the beach (by walk, in your own vehicle or in any other type of transport).

11. Beach surface affected by mechanical cleaning (%; MC)

The removal of organic driftlines involves the removal of a habitat expressly listed in the Habitats Directive: 1210, *Annual vegetation on marine litter*. In addition, it often involves the destruction and disposal of marine debris, pioneer plants and invertebrate communities living on the beach (Roig-Munar *et al.*, 2012; Figure 6.6). To quantify if the beach surface is affected by mechanic cleaning it is necessary to ask for technical reports on the relevant authorities, as this variable is not easy to be quantified in the field. As far as possible, it is recommended to obtain updates of the actions carried out on the beach with the same frequency as the field campaigns, or at least annually.

Figure 6.8. Driftlines accumulation by mechanic cleaning in the EBR back-beach.

12. Fixed structures (FS)

The presence of rigid structures implies artificialisation of the beach. These structures modify the dynamic of the beach and its natural capacity for change and transport sediment, what limits the expansion of the habitats present on it.

This variable is quantified by visual inspection in the field or by recording information from competent environmental authorities. They can also be distinguished by aerial photography in case it is not possible to collect the information through the methodologies mentioned above. In the present thesis, the sampling frequency was the frequency of the field campaigns (i.e. six-monthly). The variable was valuated qualitatively and grouped in three categories. The proposed ranks are detailed in Table 6.2.

- *Shoreline Sandy Environments Index quantification*

To calculate the value of each factor, the values of the corresponding variables are sum and divided by the maximum value that can be reached (Eqs. 6.5, 6.6 and 6.7):

$$SSE_{MOF} = \frac{(BW+LTE+PMS+SB+S)}{25} \quad \text{(Eq. 6.5)}$$

$$SSE_{EF} = \frac{D}{5} \quad \text{(Eq. 6.6)}$$

$$SSE_{MPF} = \frac{(W+DoA+FoV+AB+MC+FS)}{30} \quad \text{(Eq. 6.7)}$$

where SSE_{MOF}, SSE_{EF} and SSE_{MPF} are the values obtained for the Morphosedimentary and Oceanographic Factors (MOF), Ecological Factors (EF) and Management and Protection Factors (MPF), respectively.

The final value for the Shoreline Sandy Environments Index (*SSEI)* is obtained from the un-weighted average of the 3 factors (Eq. 6.8):

$$SSEI = \frac{(SSE_{MOF}+SSE_{EF}+SSE_{MPF})}{3} \quad \text{(Eq. 6.8)}$$

Table 6.2. **Shoreline Sandy Environments Index (SSEI)**. Values assigned to the different variables proposed for the morphosedimentary factors (**MOF**), ecological factors (**EF**) and management and protection factors (**MPF**).

MOF	1	2	3	4	5	References
Beach width (m)						Modified from Aranda *et al.* (2019)
Atlantic region	<25	>25	>40	>50	>60	
Mediterranean region	<15	>15	>20	>30	>50	
Long term evolution of the shoreline (m/year)	<-2	<-1	0	>1	>2	Modified from Gornitz *et al.* (1997)
Predominant Morphological State	Reflective	Reflective high tide	Intermediate	Dissipative	Ultra-dissipative	Modified from Gornitz, (1991) and Rizzo (2017)
Intertidal sandy bars	Absent	-	1	-	>1	Modified from Gracia *et al.* (2009)
Stoniness (%)*	>50	>40	>30	>15	<15	Aranda *et al.* (2019)
EF						
Organic accumulations of marine origin (driftlines, accumulated marine waste)	Absent	Rare	Occasional	Frequent	Permanent	Modified from Aranda *et al.* (2019)
MPF						
Waste	Unclean	Moderately unclean	-	Moderately clean	Clean	Modified from García-Mora *et al.* (2001)
Degree of anthropization	Urban	-	Seminatural	-	Natural	Modified from Aranda *et al.* (2019)
Frequency of visitors	Frequently	-	Seasonally	-	Rarely	
Access to the beach	Any mode of transport, public transport	-	Private transport	-	Not mechanical transport	
Beach surface affected by mechanical cleaning (%)	>75	<75	<50	<25	0	
Fixed structures (specify)	Fixed structures such as jetties, promenades, breakwaters, ports, etc.	-	Small structures	-	Absence	

6.2.2.2. Dunes Index (DI)

The conservation status of a dune system depends on the balance between sedimentary and ecological factors. A dune system is considered equilibrate when it is not disturbed by any pressure or threat that may modify its natural structure and functions (Sanjaume and Gracia, 2011). That is, a constant sedimentary balance, is that not strongly modified by natural or artificial causes, and with a pattern of plant succession not interrupted by passage of vehicles and users, or by pollution or waste of any kind. In this sense, the conservation of dunes is highly aimed at supporting the natural succession of plants, since this is one of the most representative indicators of the environmental health of dune systems.

Dune systems play an important role in coastal resources. Their conservation has natural and social implications beyond the maintenance of landscapes or the conservation of plant and animal species. In nature, all elements are connected or linked, either by trophic or geodynamic relationships. Therefore, it is not surprising that the degradation of a dune ecosystem may cause the erosion of the beach or the decline of the saltmarsh that is sheltered behind it.

Not all types of dunes have the same relevance to facilitate the development of the dune complex. Specifically, the embryo dunes favour generation of other dunes and ensure the preservation of the system, what enables the development of a mature ecological succession. Therefore, they are considered the most vulnerable and important for the conservation of the system (van Puijenbroek, 2017). An important variable in the morphological classification of dunes is height. The dunes of a growing system are usually characterized for ridges vegetated with *Ammophila arenaria* with heights of no less than 0.5 m and preferably greater than 1 m.

With this description of the favourable reference area for dune systems, a key indicator will be the resilience. This variable can be estimated as the ability to not significantly decrease in surface or the capacity to easily recover after a loss of surface. According to this, and based on previous studies, several variables are proposed for the environmental assessment of the dune system (Lithgow *et al.*, 2014).

- <u>Morphosedimentary and Oceanographic factors (MOF):</u>

This group of variables gather the main morphological and dynamic characteristics of the dune to evaluate its physical state.

1. Dune width (m; DW) and modal height of the active dune system (m; MH)

Together, these two variables provide information on the resilience of the dune system, as they are related with the resistance of the system against the action of coastal storms (Gracia *et al.*, 2009). The width of the active dune system can be estimated using aerial photography, allowing the quantification of changes over time. In the case of the height, although regional and national web viewers provide altimetric information, the accuracy and update frequency are usually insufficient. In the present work, the measurement of both variables was carried out with a DGPS-RTK on the selected profiles (Figure 6.9.a).

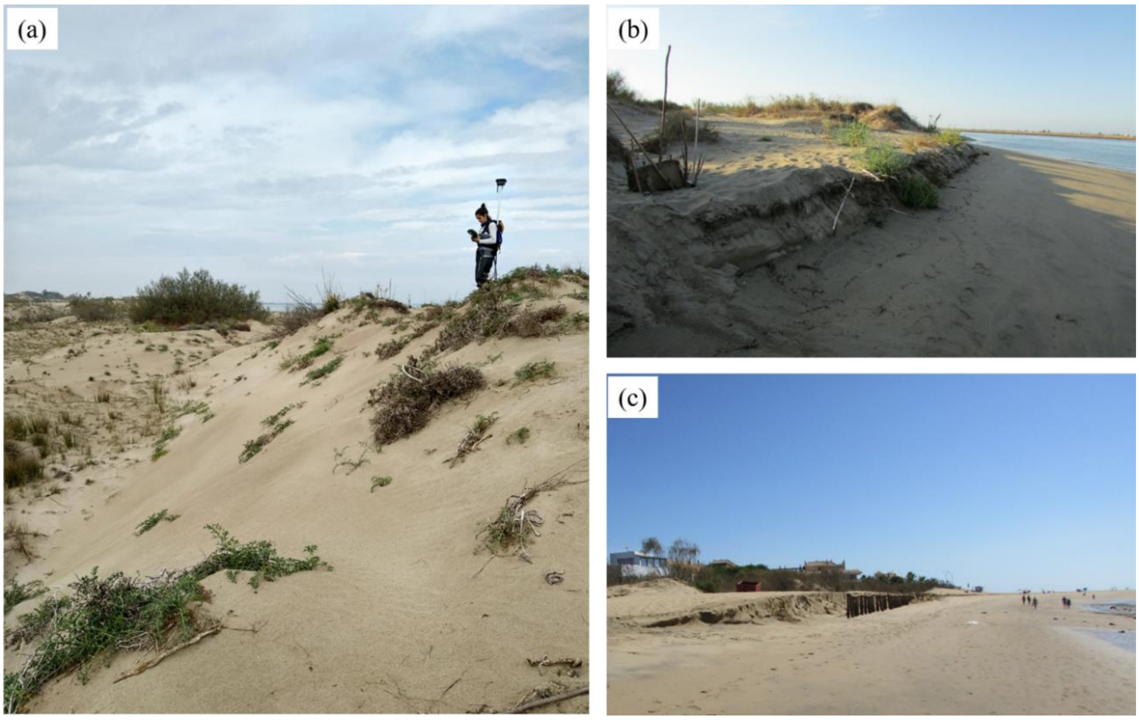


Figure 6.9. (a) Height measurement of the dune system in the Ebro delta and examples of dune erosive scarps in the (b) natural part of the GUA dune system and (c) the semi-natural part of the GUA dune system, with installation of a wooden fence for sand trapping.

2. Degree of fragmentation (%; DoF)

The degree of dune system fragmentation over time (García-Mora *et al.*, 2001) is an essential indicator for conservation and a key parameter to evaluate the lateral connectivity of the dune system, which is related to the resilience of the system. This variable is related to the occupied surface and is expressed as percentage (%) with respect to the total occupied surface. In this work, the level of fragmentation has been determined during the field campaigns and classified in three categories. The corresponding values are defined in Table 6.3.

3. Dune front with presence of erosive scarps (%; ES)

This variable is considered as a direct indicator of erosion and a symptom of sediment supply deficiency in the medium-long term (Figure 6.9.b and c). This variable has to be evaluated in the field, since the vertical scarps are difficult to recognize by remote sensing techniques. The results are expressed as a percentage of the considered transect (Table 6.3).

- Ecological Factors (EF):

Vegetation plays a fundamental role in the formation and development of dune systems. The interaction between wind and vegetation is key for the development of a dune system (García-Mora *et al.*, 2001; Sanjaume and Gracia, 2011). Important indicators in the evaluation of the conservation status of dunes includes, **plant succession continuity (PSC)**, and presence of typical faunistic communities (**rabbits, or their burrows** –**PoR**- and invertebrates, reptiles and bird nests -**PoI**), which sometimes influence negatively the stabilisation of the dune system (Williams *et al.*, 2001). In the case of vegetation not only diversity, but also erosion is considered very relevant. The erosion due to wind exposure can be indirectly expressed by the **exposed roots (ER)**. This last variable is directly related to erosive scarps, and it constitute a proxy for vegetation vulnerability as may be related with increases in plant mortality and decreases in the resilience of the dunes to erosive agents.

- Management and Protection Factors (MPF):

It is important to take into account that human activity influences natural processes in many ways, and that they can change the sedimentary balance, and even shape or destroy the morphology of the dunes. In short, they directly or indirectly influence natural processes and the dune response (Almeida, 2017). Thus, the role of human interventions cannot be ignored (Nordstrom, 1994; Nordstrom and Arens, 1998).

The **vehicle traffic and parking (T&P)** causes compaction and remobilization of sediment, as well as the destruction of the present plants, with the consequent difficulty of revegetation. Tourism, and in general leisure activities on the beach, often means the degradation of the dune vegetation (and consequently the degradation of the food chain). Therefore, in addition to traffic and parking control, it is also important **to control access or isolate the dune**

system (AC) from trampling by pedestrians. These pressures affect directly to the vegetation communities, reducing not only their populations but also their regrowth capacity.

Numerous techniques allow the recovery of the dune front, including direct protection (Access control, enclosure of the dune system), stabilization (**installation of sand collectors, SC**) and/or reinforcement by the use of the aforementioned measures. Additionally, **information panels (IP)** provide to visitors information about the actions being carried out and the importance for the conservation of the dunes (Gómez-Pina *et al.*, 2002; Ley Vega *et al.*, 2007; Almeida, 2017).

Solid waste accumulation is also an important variable to consider in the state of the dune complex. The **percentage of the dune front affected by solid waste (W)** and rubbish depends on the local characteristics, as well as on the 'Waste' variable on the beach index. In urban beaches, the input of waste can be large, but cleaning is regulated, while natural beaches lack mechanized cleaning but the pressure by waste is not strong. Thus, a visual estimate should be made in the field of the amount of solid waste that covers the dune area.

As for the shoreline sandy environments, the sampling frequency here proposed is biannual. Ranked values of each variable are detailed in Table 6.3.

- *Dunes Index quantification*

Each factor is calculated as the sum of the points of each variable divided by the sum of the maximum value that this factor can reach (Eqs. 6.9, 6.10 and 6.11):

$$D_{MOF} = \frac{(DW+MH+DoF+ES)}{20} \quad \text{(Eq. 6.9)}$$

$$D_{EF} = \frac{(PSC+PoR+RoI+ER)}{20} \quad \text{(Eq. 6.10)}$$

$$D_{MPF} = \frac{(T\&P+SC+AC+IP+W)}{25} \quad \text{(Eq. 6.11)}$$

where D_{MOF}, D_{EF} and D_{MPF} are the values obtained for the Morphosedimentary and Oceanographic Factors, Ecological Factors and Management and Protection Factors, respectively.

The final value for the *DI* is obtained from the un-weighted average of the 3 factors (Eq. 6.12):

$$DI = \frac{(D_{MOF}+D_{EF}+D_{MPF})}{3} \quad \text{(Eq. 6.12)}$$

Table 6.3. **Dunes Index (DI)**: Values assigned to the different variables proposed for the morphosedimentary factors (**MOF**), ecological factors (**EF**) and management and protection factors (**MPF**).

MOF	1	2	3	4	5	References
Width of the active dune system (m)	<50	≥50	>250	>500	>1000	Modified from Gracia *et al.* (2009)
Modal height (m)	<1	≥1	>2	>3	>6	
Degree of fragmentation (%)	≥50	-	25-50	-	None	Modified from García-Mora *et al.* (2001)
Dune front with presence of erosive scarps (%)	>75	≤75	<50	<25	0	Modified from Gracia *et al.* (2009)
EF						
Plant succession continuity	None	-	Discontinue	-	Complete	Modified from García-Mora *et al.* (2001)
Presence of rabbits (burrows)	High	-	Sporadic	-	None	
Presence of invertebrates, reptiles and bird nests in the dune system	None	-	Sporadic	-	High	
Plants with exposed roots (%)	>50	>25	>15	>5	≤5	
MPF						
Vehicles traffic and parking	None	-	Seasonal	-	Permanent	Modified from Gracia *et al.* (2009)
Presence of sand collectors	None	-	Sporadic	-	Permanent	
Access control, enclosure of the dune system	None	-	Moderate	-	Total	
Information panels (nº per 1000 m)	0	1	2	3-4	≥5	
Waste (% of surface affected in the dune system)	≥50	<50	<25	<5	0	Modified from García-Mora *et al.* (2001)

6.2.2.3. Tidal Flats Index (TFI)

The evaluation of saltmarshes is particularly complex. Currently, there is a virtual absence of indexes to evaluate the state of the saltmarshes from an eco-geomorphological point of view. Previous studies have focused on methods to assess ecological status according to the guidelines of the Water Framework Directive, i.e. assessment of the environmental status of aquatic habitat types. The scarcity of vulnerability indexes to evaluate the state of conservation of saltmarshes at national and international levels justify that the reference values here presented include only the results obtained in the field for two of the study areas (since Ebro Delta, a microtidal environment, does not have tidal saltmarshes). Therefore, this is an initial proposal, and further data at a longer time scale is needed to obtain a more solid and robust vulnerability index for tidal flat environments.

The permanent or seasonal nature of the water component is highly relevant to the ecological dynamics of wetlands. These transition zones (both from hydrological and sedimentological points of view) present a truly complex diversity. Links between ground elevation, inundation duration and plant zonation are strong (Adam, 1990). Thus, the assessment of the saltmarshes requires the monitoring of changes in plant zonation (towards expansion or retraction), as well as the changes in physical dynamics and sedimentology of the zone.

Understanding that saltmarsh evaluation is more complex than the evaluation of the previous subsystems, it is proposed a set of variables following the same structure of the other subsystems, but taking into account the results of previous works such as *Saltmarsh Monitoring Project 2007-2008* (Mccorry and Ryle, 2009), Common Standards Monitoring Guidance for Saltmarsh Habitats (Joint Nature Conservation Committee, 2004), and Defne *et al.* (2020). According to this, the evaluation of the conservation status of an estuarine saltmarsh has been structured with the same groups of factors, morphosedimentary (MOF), ecological (EF) and management and protection (MPF) factors, but ranging the values of the variables between 1 and 3, being 1 the lowest conservation status and 3 the highest one. Since it is not based on existing indices but on data obtained along the present thesis, some of the variables are an adaptation of previous studies and others are newly defined. Therefore, it is an initial proposal where values are still under validation process.

- <u>Morphosedimentary factors (MF):</u>

The morphosedimentary factors allow evaluating the physical state and evolution of the saltmarsh subsystem from morphological and dynamic characteristics of the tidal flat.

1. Long term evolution of the width of the saltmarsh (LTEWS)

The width of the saltmarsh provides information on the resilience of the system and its ability to buffer against coastal erosion. The width of the saltmarsh has been directly related to its capacity to attenuate waves (Willemsen *et al.*, 2020) and, therefore, with the resilience of the system to coastal erosion. Assigning a reliable value to this variable requires long-time series, to capture the dynamics of natural change in the system. Otherwise, the estimation may be biased by interannual variations. In this study, the reference value was fixed by the first available aerial photograph and, from there on, it has been calculated whether transects have experienced erosion or accretion. The percentages defined in Table 6.4 are calculated with respect to the reference value, which is considered the 100%.

2. Presence of micro-cliffs (erosion edges; PoM-C)

Erosion/accretion processes may affect variables as width of the saltmarshes (Figure 6.10). The presence of erosion can be identified in the field with presence of micro-cliffs along the transects (Mariotti and Fagherazzi, 2010; Marani *et al.*, 2011), whereas the occurrence of erosion/accretion events along saltmarsh boundaries can be determined through the analysis of the shoreline evolution. In this work, this last analysis was performed with aerial photographs dated between 1956 and 2016, using the vegetation boundary as a proxy for the identification of the saltmarsh-line evolution (Fernandez-Nunez *et al.*, 2019).

Figure 6.10. Example of micro-cliff in the SVB saltmarsh.

3. Long term changes in profile slope (LTCPS)

Variations in the slope of the transects provide information about the spatial extent of the tidal inundation (Leonardi *et al.*, 2016). This variable also affects the length of the transects, since a gentle slope tend to have wider profiles and, therefore a well-developed saltmarsh is expected. Changes to a steeper slope may be symptom of erosion and is usually associated to a decrease in the area occupied by saltmarsh vegetation. In any case, since saltmarshes generally have very flat slopes (Figure 6.11), the evaluation of the profile slope should be combined with the analysis of the micro-topography, thus providing more accurate information on local changes.

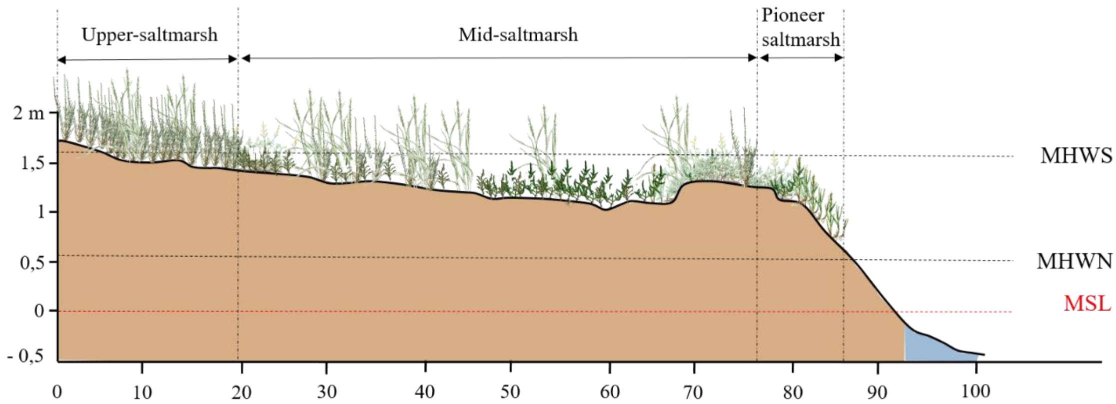


Figure 6.11. Example of a typical perpendicular profile of a saltmarsh (GUA estuary). The values of mean high water spring (MHWS) and mean high water neap (MHWN) correspond to the Guadiana estuary, 1.565 m and 0.573 m, respectively.

- Ecological factors (EF):

In tidal flat environments, there is a strong relationship between plant communities, geomorphology and physical factors making difficult to differentiate between morphological and ecological factors. Therefore, ecological factors proposed below are strongly linked to the factors previously described, but focuses on the plant communities along the saltmarsh transect.

4. Long term changes in occupied surface (LTCOS)

The quantification of changes in the occupied surface in the medium-long term (time span of more than 30 years) allows to establish the trend of the system and to filter interannual fluctuations (Espinar, 2009), as shown in chapter 3. Changes in surface is one of the variables most used to quantify the conservation status of habitats, since habitat modification, fragmentation and loss are the most important responses to stress (Airoldi and Beck, 2007; and references therein). In the particular case of tidal flats, specifically for saltmarshes, it is often difficult to distinguish between the horizons of saltmarsh zonation (Figure 6.11) and whenever data and methodology allow it, the total area occupied should be quantified by distinguishing between pioneer-low and mid-high zones, as changes in the pioneer-low band are close related to changes in the evolution of the saltmarsh (Bouma *et al.*, 2016).

5. Proportion of the pioneer band with respect to the total saltmarsh width (%; PionSW)

The pioneer band of the saltmarsh plays a fundamental role in slowing down the incident flow, favouring in most cases the deposition of sediment (Peralta *et al.*, 2008). This process allows the young saltmarsh to accumulate sediment, favouring accretion processes and facilitating the process of ecological succession (Castellanos *et al.*, 1994). The width and the lower limit of the pioneer saltmarsh can be also considered as good indicators of the state of conservation of a saltmarsh, since a decrease in width or the displacement of the low limit landward may be related to erosive processes or other pressures that restrict the development of this horizon. Therefore, to evaluate expansion vs retreat states it has been considered relevant to evaluate the extent of the pioneer saltmarsh with respect to the transect length. Assuming as symptom of health not to decrease in extent from the established baseline.

The extent of the pioneer saltmarsh has been established considering *Spartina maritima* and *Salicornia spp.* as pioneer species, both globally distributed along saltmarshes in temperate zones. Key for this variable is detailed in Table 6.4.

6. Exposure frequency in the lower limit of the saltmarsh (pioneer zone; EF)

The lowest limit of establishment of the pioneer zone is highly relevant for the study of the saltmarsh evolution (Balke *et al.*, 2016, and references therein), as it has been described in chapter 4. The exposure frequency is considered the best variable to define this limit (Balke *et al.*, 2016), which is expected to change according to changes in the exposure frequency. The evaluation of these changes also requires a long-term evaluation (> 50 years; Table 6.4), as no remarkable changes are expected to occur in the short term.

7. Total cover (%; TC)

In many ecological studies, plant abundance is measured by plant cover. In this work, this variable was estimated in the field through visual inspection of the minimum area (Figure 6.3.d) at regular intervals along the transects. When total cover and elevation had a significant relationship, total cover was evaluated by vegetation horizons. Otherwise, total cover was estimated as the average for the entire profile.

8. **Plant cover fragmentation (PCF)**

The zonation is a characteristic spatial pattern in the distribution of organisms that is especially evident in the distribution of saltmarsh plant species as bands parallel to the waterline (Figure 6.11). Changes in this pattern are usually a symptom of habitat change. For example, during processes of coastal squeeze, the upland migration may produce reversed spatial pattern when the pioneer species (particularly *Salicornia* spp.) recolonise the former elevation of the high marsh.

The zonation pattern in the saltmarsh usually includes the pioneer-low horizon (area of distribution of *Spartina maritima* and *Salicornia* spp.), the mid-marsh horizon (continuous horizon with *Atriplex* spp., *Sarcocornia* spp., *Suaeda* spp., *Halimione portulacoides*, often dominant), and the upper-marsh horizon (with *Limonium* spp. and *Arthrocnemum* spp. often dominant).

In this work, the level of cover fragmentation was estimated in the field, together with total cover, through visual inspection of the minimum area (Figure 6.3.d), following the patterns described in Figure 6.12.

9. Negative indicator species (IAS)

Worldwide, invasive alien species (IAS) are the second cause of loss of biodiversity (even the first one in islands; Pyšek *et al.*, 2012). Particularly, transition habitats, as tidal flats, are prone to be colonized by invasive alien species as they act as ‘landscape sinks’ of material from both terrestrial and marine environments (Garbutt and Wolters, 2008). Thus, the presence of these species should be determined in the field as they may impact negatively on mudflats, pioneer and mid-marsh communities (Daehler and Strong, 1996).

The main objective of this variable is to warn about the establishment or propagation of IAS. The evaluation of this variable requires field survey. Any identified IAS needs a quantification of the propagation state, that is to quantify the area occupied by the IAS and monitor its evolution to identify any sign of expansion. Once the presence of IAS is identified and the occupied surface quantified, the variable value is assigned ensuring growth of no more than 10 % in a period of 10 years with respect to the initial measured surface (Joint Nature Conservation Committee, 2004).

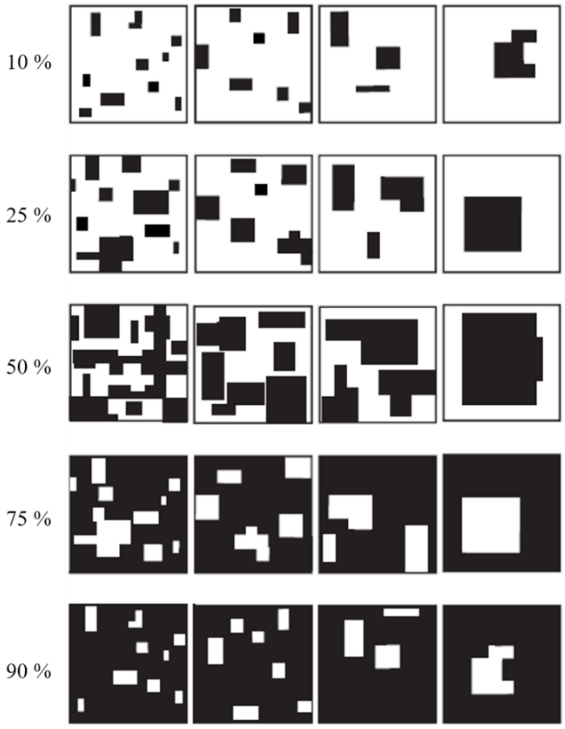


Figure 6.12. Chart to aid with visual assessment of vegetation cover. Source: https://vvpcmn.files.wordpress.com/2010/03/weed-cover-percentages.pdf

- Management and Protection Factors (MPF):

As for any other natural subsystem, the anthropogenic pressures are considered as main drivers in the negative trends of saltmarsh systems. Specifically, for saltmarshes, land use changes -landfills or wetland reclamation-, reworking of the drainage system and shell fishing pressure have been selected as variables to quantify the management and protection factors of these systems. Additionally, the presence of waste along the saltmarsh transect (%) was also considered important to evaluate the conservation status of a saltmarsh. At any case, the information on local anthropogenic actions should be gathered with revision of the scientific literature and technical reports of interventions made in the zone.

10. Reclaimed zones (RZ)

Historically, saltmarshes have been subject to large-scale land claim for agriculture, which in many cases has limited or destroyed the natural transitions to terrestrial communities. The evaluation of this variable requires search for information on actions carried out in the saltmarsh in the past years. Once the reclaimed zones have been identified, this variable is expressed as the percentage of reclaimed zone with respect to the maximum extent of the saltmarsh.

11. Shell fishing pressure (SF)

Human pressures continue to grow in coastal zones. In particular, shell fishing is an issue for the nature conservation of the saltmarsh system. Shell fishing can damage severely the sediment dynamic on the pioneer area, what would decrease the chances of colonization (Bouma *et al.*, 2016). This pressure is usually largest in the pioneer-low-intertidal band, where the trampling of the zone may lead to fragmentation of the system, emerging bare areas with vegetation die-back, and to reduce the success of seedling establishment. This variable can be evaluated with aerial images by quantifying the extent of these bare areas and their expansion.

12. Waste (% along the transect, W)

Lastly, the presence of waste along the saltmarsh is closely related to the arrival of waste transported by the tidal currents rather than direct discharge, as these are areas are no so prone to tourist. Even so, it is important the evaluation of this pressure during the field campaigns to recommend future management plans if necessary. The ranked values of this variable is detailed in Table 6.4.

- *Tidal Flat Index quantification*

In contrast to the indexes of the previous subsystems, for the tidal flat, the variables have different weight in the calculation of the sub-index of the factors (Eqs. 6.13, 6.14 and 6.15):

$$TF_{MOF} = \frac{(0.4*\mathrm{LTESW})+(0.4*\mathrm{PoM-C})+(0.2*LTCPS)}{3} \quad \text{(Eq. 6.13)}$$

$$TF_{EF} = \frac{(0.2*LTCOS)+(0.2*PionSW)+(0.2*IF)+(0.13*TC)+(0.13*PCF)+(0.13*IAS)}{3} \quad \text{(Eq. 6.14)}$$

$$TF_{MPF} = \frac{(0.5*RZ)+(0.3*SF)+(0.2*W)}{3} \quad \text{(Eq. 6.15)}$$

where TF_{MOF}, TF_{EF} and TF_{MPF} are the values for the Morphosedimentary Factors, Ecological Factors and Management and Protection Factors, respectively.

The corresponding weighting of variables is an initial proposal. The aim is to give more weight to long-term variables to the detriment of short-term ones, which can be ephemeral (e.g. waste).

The final value for the *TFI* is obtained from the average of the values of the three factors (Eq. 6.16):

$$TFI = \frac{(TF_{MOF} + TF_{EF} + TF_{MPF})}{3} \qquad \text{(Eq. 6.16)}$$

Table 6.4. **Tidal Flats Index (TFI)**: Values assigned to the different variables proposed for the morphosedimentary factors (**MOF**), ecological factors (**EF**) and management and protection factors (**MPF**).

MOF	1	2	3	References
Long term evolution of the width of the saltmarsh (m)	Erosion (>50%)	Erosion (<50%)	Accretion	Modified from Defne *et al.* (2020)
Presence of micro-cliffs (erosion edges)	All along the profile	Local	None	-
Long term changes in profile slope	Remarkable changes	Slight variations	No changes	-
EF				
Long term changes in the occupied surface	Loss	No change	Gain	Modified from Aranda *et al.* (2019)
Pioneer saltmarsh with respect to the total saltmarsh width (%)	< 20%	20 – 40 %	>40 %	-
Exposure frequency in the lower limit of the saltmarsh (pioneer zone)	Remarkable changes	Slight variations	No changes	Modified from Balke *et al.* (2016)
Total plant cover (%)	< 30%	30-70 %	>70%	Modified from de Vries *et al.* (2018)
Plant cover fragmentation	Total	Discontinue	None	Modified from de Vries *et al.* (2018)
Negative indicator species	Expansion	No expansion (less than 10% expansion in the last 10 years)	None	JNCC, 2004
MPF				
Reclaimed zones	> 40%	<10%	No	-
Shell fishing pressure	Continuous	Seasonal	None	-
Waste (% along the transect)	>50%	<50%	0	Modified from García-Mora *et al.* (2001)

6.2.2.4. Drainage Network Index (DNI)

River dynamics is key not only for the functioning, but also for the ecological value of the estuarine environment. The conservation of the hydro-geomorphological dynamics guarantees the connectivity and the relationship between the elements of the system (Ojeda *et al.*, 2007). Rivers are natural systems of maximum dynamics and complexity, in permanent adjustment due to fluctuations of solid and liquid flows (Werrity, 1997). The underestimation of the importance of fluvial dynamics has notable negative environmental consequences. The reestablishment of the water flow in a claimed area reactivates in short time the ecological dynamics, increasing the biodiversity and the quality of the ecosystems associated with the fluvial channel (Ojeda *et al.*, 2007). Something similar has also been reported after recovering the tidal flow on reclaimed saltmarshes (García-Artola *et al.*, 2017). Thus, the hydro-geomorphological dynamics should be protected and considered a key aspect when evaluating the ecological status of the river in general, and the estuarine zone in our particular case. According to Ojeda *et al.* (2007), every impact over the fluvial system has a response in the hydrological and geomorphological functioning of the entire system, as well as in the associated subsystems. In the estuarine system, the drainage neetwork acts as a "conveyor belt" for matter and energy, linking the dynamics of the subsystems.

This work proposes a channel index adapted from the hydro-geomorphological index (IHM) proposed by Ojeda *et al.* (2007).

The information required for the evaluation of the drainage network was obtained through an extensive review of the available literature for each study zone.

- Morphosedimentary factors (MF):

For the drainage system only morphosedimentary factors have been proposed since the river drainage network is not included in the thesis approach. Therefore, ecological and anthropogenic aspects upstream will not be evaluated. The direct effect of the morphosedimentary factors on the river dynamics is the modification of the caudal reaching the coast. Therefore, this is the unique variable proposed in the form of naturalness of the water flow. The other variable, connectivity, refers to the saltmarsh and not to the drainage network of the river.

1. Connectivity (C)

The drainage network (i.e. the combination of the saltmarsh creeks with the main channel) constitutes the transport vector for matter and energy into the system. Therefore, the connectivity between subsystems rely on the drainage network, and the greater the network, the better the state of conservation. In the case of estuaries, connectivity**,** or channel density, is understood as the total sum of linear meters of channels divided by the total area of the saltmarsh (Horton, 1945; Eq. 6.17).

$$C = \frac{\sum Lc}{S} \qquad \text{(Eq. 6.17)}$$

where C is the connectivity/channel density (km/km^2), $\sum$ Lc is the total accumulated length of all the channels (km) and S is the total saltmarsh surface (km^2).

This variable allows a better understanding of the complexity and efficiency of the drainage network. The higher the density of channels, the more structured the network. Since this variable was originally defined to quantify river channel density and not for tidal flats, where the density of channels is higher, the range of values for the latter has been adapted to high channel densities. Thus, this variable has been evaluated in relative terms with respect to the initial value (oldest known) for each zone, i.e. decrease, increase or constant (Table 6.5).

This variable was estimated following two methodologies, in function of the availability of data. For the SVB case, it was available the data from the drone flight carried out in 2018. This made possible to obtain the system's channel network (up to order 5) through ArcMap's Hydrology tool by means of the DTM. In the GUA case, with no high resolution DTM available, the channel identification was done manually using the latest orthophotograph (2016). It would be desirable to obtain information from the past years to establish a trend but, in the case of the present thesis, these are the initial and unique points, and the database need to be continued in the next years.

The channel order was defined according to the criteria of Strahler (1957). According to this, any channel without a tributary is considered of order 1 and the order increases when channels of the same order are joined. Therefore, the join of two channels of order *n* results in a channel of order *n + 1*, while, the join of two channels of different order maintains the order of the channel with a higher order. Thus, the highest order corresponds to the main channel (Figure 6.13).

The channel density must be quantified in the long term, as no major changes are expected on an annual time scale. This work provides only a preliminary analysis, given the scarcity of available information, since the quality of the historical aerial images is not adequate to extract a sufficiently reliable channel density. Similarly to previously described long-term variables, the correct definition of this variable requires a large database, considering a time span of more than 30 years, and preferably with high spatial resolution data such as mosaics or DTM obtained by means of UAS.

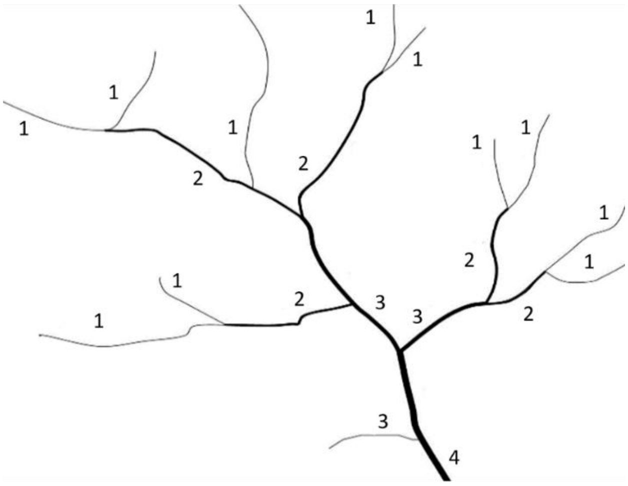


Figure 6.13. Channel ordering method according to Strahler (1957).

2. Naturalness of the flow regime (Nat)

Naturalness assesses if the amount of water that carries the drainage network is modified by any anthropic pressure and it is estimated based on the modification of water discharge into the estuary. To do so, potential causes of upstream modifications of the hydrological functioning (reservoirs, diversion to irrigation channels, etc.) were qualitatively analysed. The data were obtained from the gauging station closest to the mouth. In the absence of stations available, the data were obtained from the databases of the official basin organizations (Hydrographic Confederations).

The flow of suspended particles belongs to the geomorphological cycle and it has a key role in the formation and development of estuarine subsystems. Therefore, its evaluation acquires an important weight within the channel index. In this respect, it was assessed any indication of sediment displacement difficulties, such as armouring. According to Ojeda *et al.* (2007), the degree of naturalness of the basin was estimated qualitatively based on the existing maps and available information.

- *Drainage Network Index quantification*

Neither EF nor MOF have been defined for the drainage network subsystem. Therefore, the Drainage Network Index (*DNI*) is estimated only according to MOF factors (Eq. 6.18).

$$DNI = DN_{MOF} = \frac{(C+Nat)}{10} \quad \text{(Eq. 6.18)}$$

where DN_{MOF} is the value obtained for the calculation of the Morphosedimentary Factors.

Table 6.5. **Drainage Network Index (DNI)**: Values assigned to the different variables proposed.

MOF	1	2	3	4	5	References
Connectivity/ Channel density*	Decrease	-	Remaining constant	-	Increasing	Adapted from Horton (1945)
Naturalness of the flow regime	Marked alterations in the amount of circulating flow, which leads to investments in the seasonal flow regime	Variations in the amount of circulating flow but the changes in the seasonal regime are not very marked	Some variations in the amount of circulating flow but the seasonal flow regime remains well characterised	Slight changes in the amount of circulating flow	Both the amount of flow circulating and its temporal distributio n and processes respond to the natural dynamics	Ojeda *et al.* (2007)

*Connectivity should be measured in a time span of at least 30 years.

6.2.2.5. *Integration of sub-indices: EstuarIndex*

The estuarine conservation index (*EstuarIndex*, Eq. 6.19) was computed as the unweighted average of the values for the four partial indices (*SSEI, DI, TFI, DNI*). Thus, *EstuarIndex* ranges between 0 and 1, being 0 the lowest conservation status of the system.

$$EstuarIndex = \frac{(SSEI+DI+TFI+DNI)}{4} \quad \text{(Eq. 6.19)}$$

Taking into account the EU requirements for classifying the conservation status of habitats (European Comission, 2015), the ranges established to assess the conservation status of a mid-latitude estuary are described in Table 6.6.

Table 6.6. Estuarine vulnerability index (EstuarIndex) ranges.

Conservation status				
Very low	Low	Medium	High	Very high
1	2	3	4	5
≤ 0.20	0.21 - 0.40	0.41 - 0.60	0.61 - 0.80	> 0.80

6.3. Results

To facilitate the description of the results, the results of the sub-indices (*SSEI*, *DI*, *TFI* and *DNI*) will be presented first and, after that, the corresponding values of *EstuarIndex* for each study site. The results of the DNI are not shown graphically since there is only one value for the entire drainage network and there are no transects as in the other subsystems.

6.3.1. San Vicente de la Barquera estuary (SVB)

All transects presented a medium-high conservation status (3-4, yellow and green, respectively; Figure 6.14), except in T7 during the second field campaign (19/04/2019), which will be detailed in the next section.

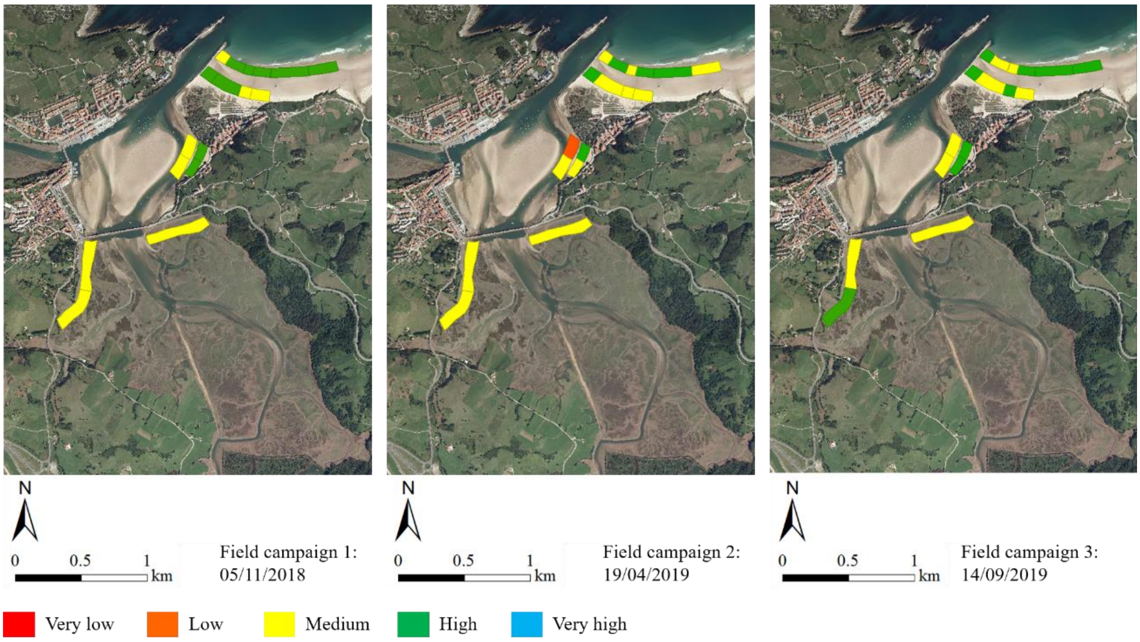


Figure 6.14. Graphical outputs of the SSEI, DI and TFI in the San Vicente de la Barquera estuary for the three field campaigns. The SSEI and DI results are shown as parallel bands, with SSEI in the external and DI in the internal ones. The values for the TFI are showed in the inner part of the estuary. The location of the coloured segments correponds to the location of the transects measured in the field (Figure 6.2). The detailed results for each variable are summarised in Annex 3.

- *Shoreline Sandy Environment Index (SSEI)*

The variables proposed for the *SSEI* assessment revealed some spatial and temporal variability. Firstly, the width of the beach showed values greater than 50 m for all transects, except for T7 (the estuarine beach) which was less than 25 m wide. In terms of long-term evolution (LTE), the beach of SVB is quite stable, with values of 0 m/year for T1, T2 and T4 ("medium" according to Table 6.2), >1 m/year for T3 and T5 ("high"), and >2 m/year for T6 ("very high"). The first two transects have a cliff at their back, so there is no coastal retreat. However, the transects with a dune system landward, are more dynamic in terms of erosion/accretion. The last one is the transect nearest to the dike, where sediment accumulates coming from the east. Regarding the morphodynamic state, the external beach presents typical dissipative values (Ω= 6.81 and RTR=2.02), while the estuarine beach, with slightly steeper slopes was classified as an intermediate beach. No tidal bars have been recorded, neither in the topographic profiles nor the historical analysis of aerial photographs. Nevertheless, according to the classification of Masselink and Short (1993), this beach is on the limit between barred-dissipative and non-barred dissipative (Figure 6.5). Stoniness was high for the low part of the estuarine beach (Figure 6.15.a; T7 and T8) where dredge material accumulates, and very low for the exterior area (D_{50}: 0.24 mm), being classified as medium well sorted sand.

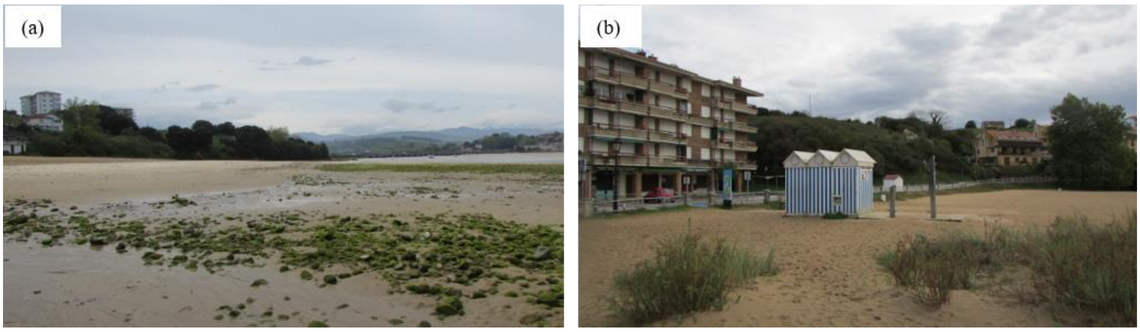


Figure 6.15. (a) Example of the stoniness and (b) anthropic structures in the estuarine beach of San Vicente de la Barquera estuary .

According to the field work dates, driftlines are not common on this beach (Table 6.1), and in most occasions, they were almost negligible. However, the organic accumulation of marine origin (EF) is a variable of ephemeral character and the results must be interpreted with caution.

The management and protection factors (MPF) of SVB revealed a high conservation level, with beaches generally very clean, with low presence of litter. The degree of anthropization depend on the transect. The first 3 ones are classified as natural beach, backed by a cliff. The rest of the transects of the external beach (T4 to T6) are classified as semi-natural, with artificial structures such as walkaways, access roads and a parking directly on the dune system. Finally, the estuarine beach is classified as semi-artificial and backed by a road and some buildings (Figure 6.15.b). The external beach was classified as seasonal, with larger amount of visitors during summer in comparison with the other seasons. The access to the beach is not regulated, except for the natural part, that is only accessible by foot. The percentage of beach surface affected by mechanical cleaning was in general under 25%. It was remarkable the presence of fixed structures in T6, T7 and T8, although the rest of transects hardly showed this type of structures.

- *Dune Index (DI)*

This subsystem was only present, and therefore evaluated, in T3 to T8. Similar to the beach, the dune subsystem presented values of medium to high conservation status, agreeing with the observations in the field. The effects of energetic events during winter generated some variability, with lower values in the second field campaign. However, the system recovered after summer, presenting values in the last field campaign similar to the first ones.

The dune system presents a width of less than 50 m for T3, T7 and T8, greater than 50 m for T4 and T5, and greater than 250 m for T6 (Figure 6.16), where sand accumulates due to the effects of the dike.

Contrary to expectations, the T6 presented the lowest modal height (around 2 m), due to the low elevations recorded at the back. Nevertheless, the highest elevation in this transect was almost 5 m. For the rest of the transects, all of them had modal heights above 3 m and a certain degree of fragmentation (except the estuarine ones). The degree of fragmentation on the external dune system was elevated (25 - 50%), because of the crossing pathways (Figure 6.17.a) and the parking lot placed directly on it. Regarding the erosive scarps, they were more abundant in T3, T4 and T5 (Figure 6.17.b), with no temporal variability during this study. These transects also presented plants with exposed roots (< 5% of the surface). Related to the fauna, burrows in the dune field were not recorded and the presence of invertebrates, reptiles and bird nests was sporadic.

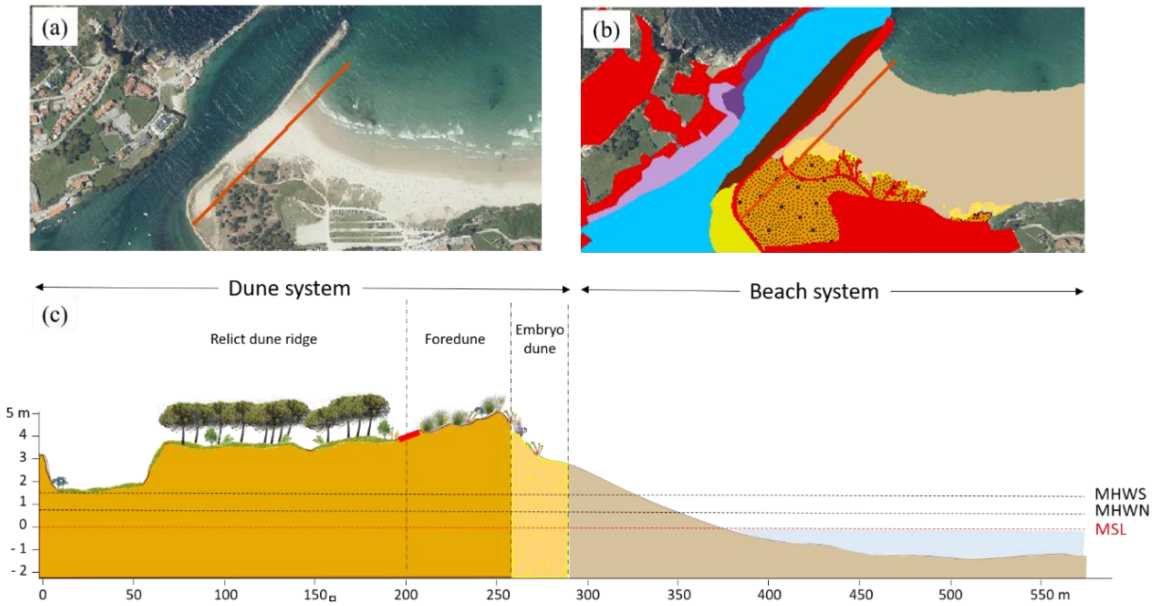


Figure 6.16. T6 of the beach-dune system in San Vicente de la Barquera estuary. (a) Aerial orthophotograph of the transect, (b) geomorphological features identified in T6 (according to Figure 3.1), and (c) topographic profile obtained with the DGPS-RTK and associated plant communities. Colours in (c) match with geomorphological features identified in (b). MHWS=1.959 m, MHWN=0.747 m.

Lastly, the analysis of the MPF indicated a low conservation level for the three field campaigns due to the absence of traffic and parking control, the presence of sand collectors and the lack of access control. The number of information panels was also low, with only one panel on the external beach (T4), and another on the estuarine one (T8). Finally, less than 5% of the dune surface was affected by solid waste, which is a good indicator.

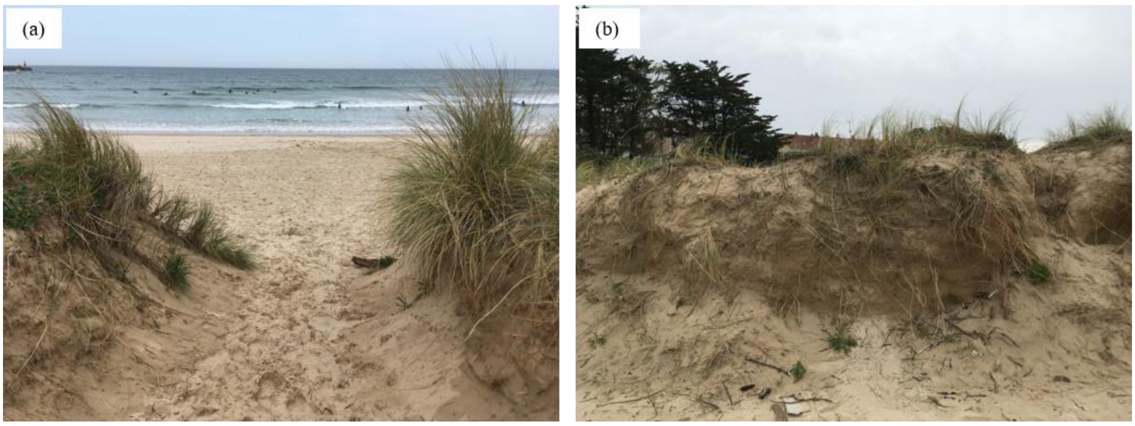


Figure 6.17. (a) Dune fragmentation by trampling and (b) erosive scarps with exposed roots on the front of the dune system.

- *Tidal Flats Index (TFI)*

The tidal flat subsystem presented values of medium conservation status, except for T3 in the last field campaign, when it presented a high conservation status.

The long-term evolution of the saltmarsh width showed symptoms of erosion for the three transects. T1 presented more than 50 % erosion with respect to the original profile, while T2 and T3 less than 50 %. Nevertheless, T3 reaches rates of -1.12 m/year (Figure 6.18). The presence of micro-cliffs is frequent in this saltmarsh, producing usually profiles with irregular patterns (Figure 6.19).

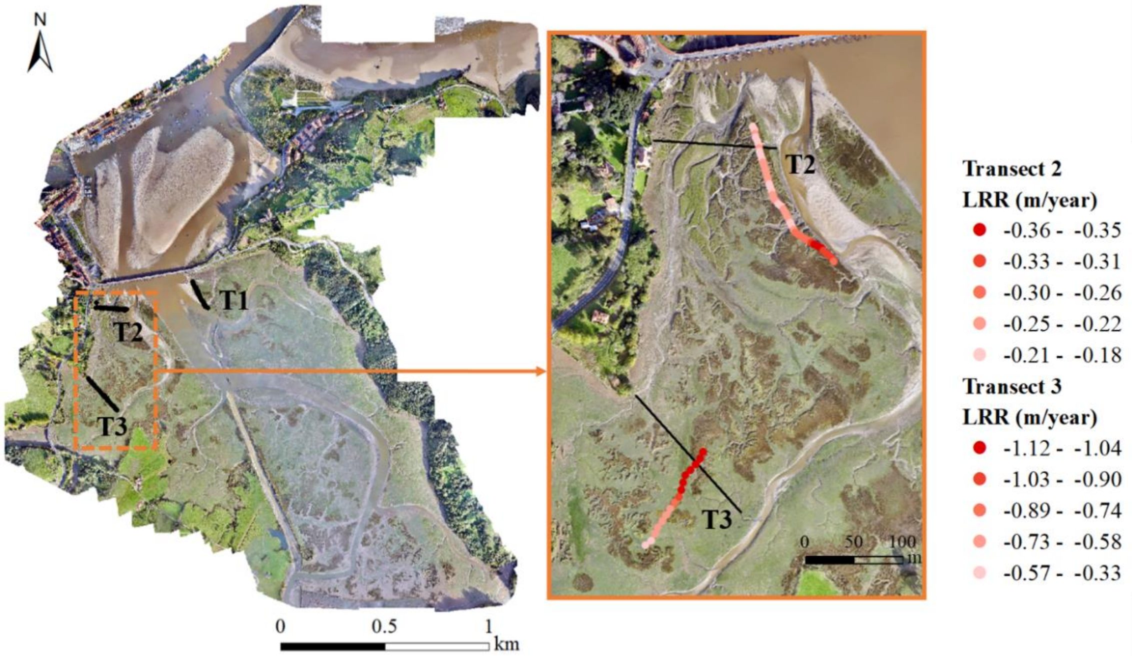


Figure 6.18. Long term evolution of the width of the saltmarsh (LTEWS) based on the Linear Regression Rate (LRR) calculated through historical aerial images for the T2 and T3 in saltmarshes of San Vicente de la Barquera estuary. The results show the erosion of the vegetation border in the last years.

The most remarkable change in the ecological factors (EF) of the SVB saltmarsh was the large loss of the occupied surface (see chapter 3, Figure 3.6). The percentage of pioneer saltmarsh with respect to the total transect length reveals that T1 and T2 have less than 20% of pioneer saltmarsh, while T3 is over 20 %, reaching more than 40 % on field campaigns 2 and 3. This variability may be related with seasonal effects. On the contrary, no changes in the exposure frequency were detected for the lower limit of the studied period. To conclude the ecological factors, the variables *total cover*, *plant cover fragmentation* and *negative indicator species* did not show any temporal variability. The percentages of total coverage are less than 30% for T1, and in between 30 and 70% for T2 and T3. The plant cover in T1 showed symptoms of fragmentation, while in the other two transects the vegetation seems somewhat continuous, with a typical plant zonation. Lastly, no negative indicator species were identified in T1 and T2, but T3 was partly occupied by patches of *Spartina densiflora*, with no signs of expansion throughout the field campaigns.

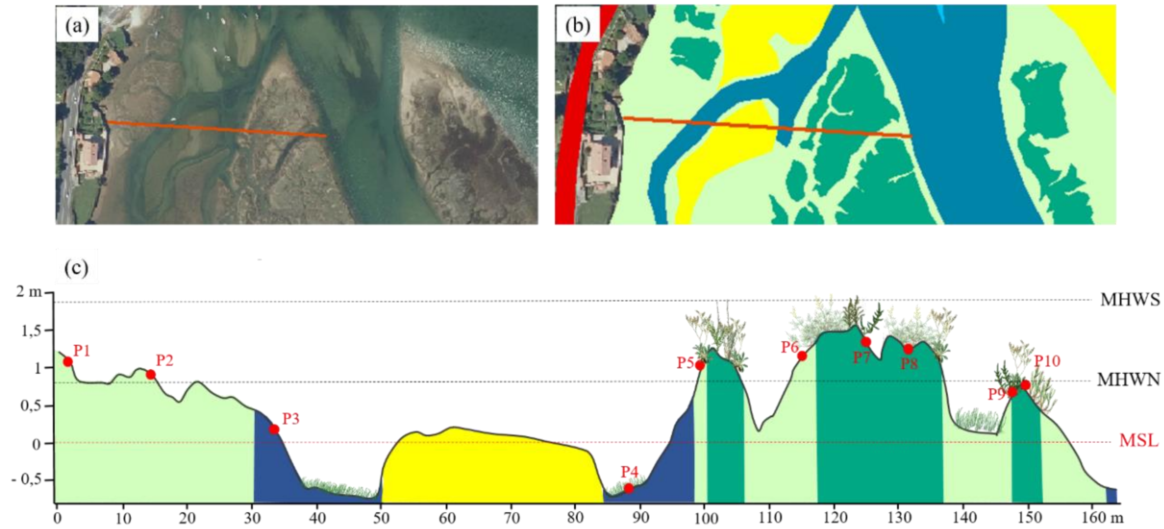


Figure 6.19. T2 of the saltmarsh system in San Vicente de la Barquera estuary. (a) Aerial orthophotograph of the transect, (b) geomorphological features identified in T2 (according to Figure 3.1), and (c) topographic profile obtained with the DGPS-RTK and associated plant communities. Colours in (c) match with geomorphological features identified in Figure 3.1. MHWS=1.959 m, MHWN=0.747 m. Red dots correspond to locations for measurement of variables in the field.

Regarding the MPF, as detailed in chapter 4, the reclaimed zones in the inner part of the SVB estuary modified in some way the hydrodynamics of the area. This affected to the values in the 3 transects as the presence of reclaimed areas influences the saltmarsh as a whole. Similarly, shell fishing pressure affected seasonally to all the transects. Finally, the presence of solid waste was below 50% on T2 and T3, and 0% on T1, making this last area classified as moderately clean.

- *Drainage Network Index (DNI)*

The evaluation of this subsystem is based on the connectivity and naturalness of the drainage system. Due to the scarcity of data with a wide time scale and high spatial resolution, only an initial value of connectivity has been estimated. Therefore, this variable has not been included in the calculation of the index, which would need at least a 30-year time span. In any case, the initial value of the connectivity of the SVB was 18.55 km/km^2. Regarding the naturalness of the drainage system, and based on the consulted bibliography (Flor-Blanco, 2007), it seems to have suffered some variations in the volume of circulating flow but the seasonal flow regime remains well characterised.

- *EstuarIndex*

Based on the results for the SSEI, DI, TFI and DNI (detailed in Annex 3), the *EstuarIndex* had values between 0.58 and 0.60, showing that the San Vicente de la Barquera estuary presented during the study period a constant conservation status of “Medium” (Table 6.7).

Table 6.7. Results of applying EstuarIndex in San Vicente de la Barquera estuary for the 3 field campaigns.

Field campaign	EstuarIndex value	Conservation status
05/11/2018	0.59	Medium
19/04/2019	0.58	Medium
14/09/2019	0.60	Medium

6.3.2. Guadiana river estuary (GUA)

The Guadiana river estuary presented a medium – high conservation status for every transect (3 – 4, yellow and green, respectively; Figure 6.20) and the status of conservation showed a general improvement over time throughout the study period.

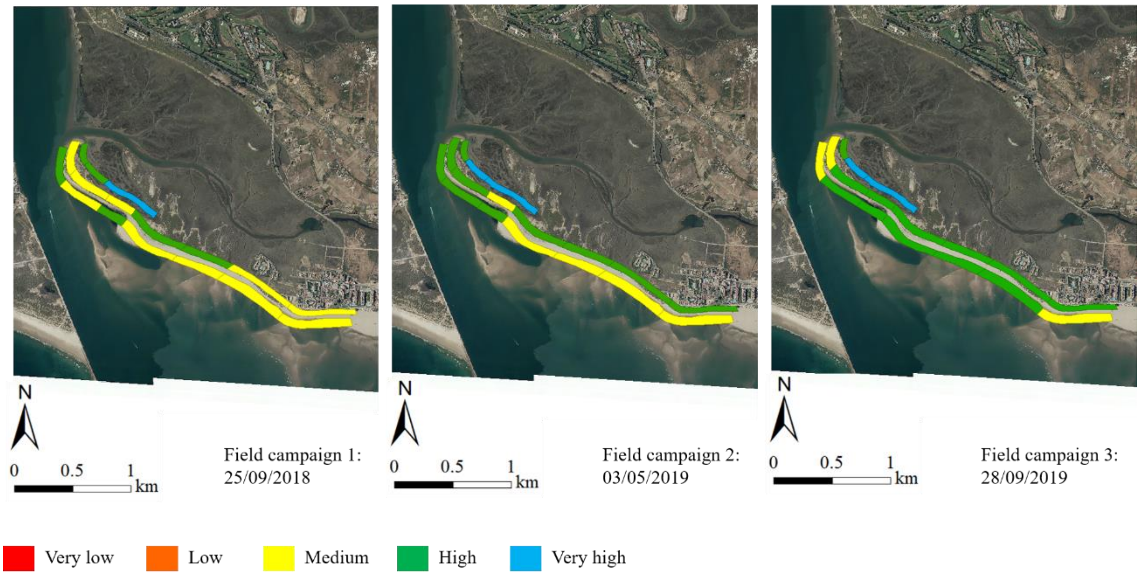


Figure 6.20. Graphical representation of the SSEI, DI and TFI in the Guadiana river estuary for the study period. The results for the SSEI are shown in the external band, the ones for the DI in the middle band and the results for the TFI in the inner one. The location of the coloured segments corresponds to the location of the transects measured in the field (Figure 6.2). The detailed results for each variable are summarised in Annex 3.

- *Shoreline Sandy Environments Index (SSEI)*

In Guadiana estuary, there was greater variability between the proposed transects. Following the order proposed in Table 6.2, the beach was wider in the central sector (> 25 m in most cases, reaching even more than 60 m for T6 in the first field campaign), what is in line with the long-term evolution. Nevertheless, there is some temporal variability, with T5 and T6 having a decrease in beach width after the first field campaign. The central area of the study site is the one with the best conservation status. This area is the prograding section of the beach (Figure 6.21), with values between 1 and 2 m of accretion during the studied period. Considering the entire subsystem, predominantly, the morphodynamic state of the beach is reflective (low tide terrace + rip, according to Figure 6.5, with values of Ω=1.40 and

RTR=6.08). Most of the transects had tidal bars, except for the T1 to T3. However, their quantification was difficult, since the sandy features in this area are very dynamic. Stoniness did not present a clear pattern. Some transects increased in stoniness during the study period (T1, from <15% to >50%), others presented high values the entire study period (T2 and T3, >40%) whereas others had a low stoniness (central zone, T6 and T7, approx. 15%). Thus, although this is a fine sand beach, there is a larger presence of shells during the typical energetic events of winter.

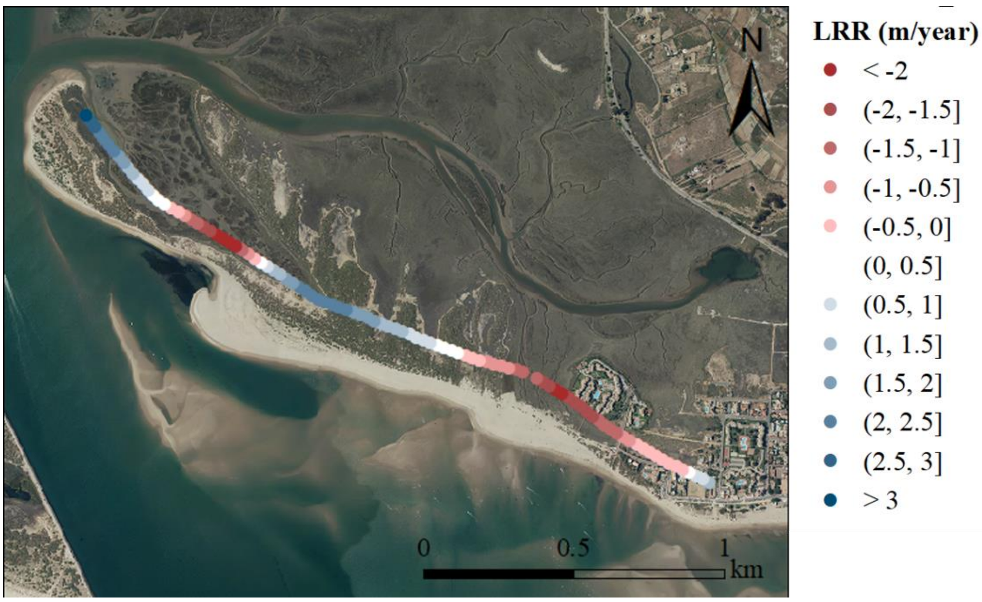


Figure 6.21. Long term evolution (LTE) based on the Lineal Regression Rate (LRR) of the shoreline in Guadiana estuary from 1977 to 2016.

The organic accumulation of marine debris in this zone (EF) was also variable among the zones of the beach although non-clear pattern. This could be related with the high dynamism of this area. In any case, it is frequent to find driftlines in the beach, near to the dune foot. This is especially evident on T3, placed in a sheltered area where there is not withdrawal by dynamic agents.

According to the MPF, this beach has been classified as moderately clean, with some exceptions for T1. The cleanest area corresponded to T6 and T7, which are the closest to the urban zone. The lack of anthropic features made most of the transects considered natural except for T6, considered Seminatural, and T7, considered urban. The presence of visitors is rare in the natural part, with a reduction in frequency with distance from the urban part. However, the presence of visitors is frequent for the urban and seminatural areas. This pattern is maintained throughout the year, due to the general practises of water sports such as windsurfing and kitesurfing. The access to the natural part of the beach is only by walking, but the access is not regulated for any transport in T6 and T7, the seminatural and urban ones. The mechanical cleaning of the beach is frequent in the urban part and absent in the natural one. Lastly, the presence of fixed structures is high in T6 and T7 and absent in the rest. However, in front of T2 and T3 there is a submerged dike.

- *Dune Index (DI)*

The dune system also presented a general increase in the conservation status with time (Figure 6.20, central band). The sector with the best conservation status was again the central one, with no temporal variations. The high values corresponded mainly to high values in MOF and EF, but not in MPF.

The width of the active dune system was more than 50 m for most of the transects, except for the T3 (the narrowest point) and T7 (the urban area with a road directly on the dune field). The longest transect was T4, where the first and second recurved spits merge (Figure 2.7). The modal height for the entire systems was over 1 m, being T5 and T7 the highest transects (> 3 m of modal height). The degree of fragmentation of the dune system was null for most of the transects, except for T7, partially fragmented due to human pressures and T6, partially fragmented as consequence of a parking lot on the back of the dune field and an access path crossing the dunes and saltmarsh to access to the buildings (Figure 6.22.a). Erosive scarps were only detected in T1 and T2 during the first and third field campaign.

The EF were also high for the dune system. The continuity of the plant succession was nearly total in T1 to T5 (except for T1 in the third field campaign) and discontinue for T6 and T7, the most impacted by anthropic actions (trampling mostly). The presence of burrows was limited, and difficult to detect, with some observations in T1, T4, T5 and T7 for the second field campaign, and in T4 and T5 for the last one. The presence of invertebrates, reptiles and bird nests was sporadic in most transects. Finally, it was hard to detect any exposed root in the front of the dune system (<5 %), except for T2 (>15%) and T1 (>5%) during the first field campaign.

Regarding the MPF, there is no control of traffic or parking of vehicles in this zone, although T1 to T4 are only accessible by foot. Sand collectors are permanent on T5 and T6 (Figure 6.22.c and d), but absent in the rest of the dune system. Any measurement of access control to the dune system is missing. Only T6 has information panels (Figure 6.22.b), matching with the windsurfing and kitesurfing areas. Finally, the percentage of waste along the transects is variable, with T1-T5 apparently cleaner than T6 and T7, despite the last ones have mechanical cleaning.

Figure 6.22. (a) Access path to holiday buildings, (b) information panel situated on T6, (c and d) sand collectors in Guadiana estuary.

- *Tidal Flat Index (TFI)*

The highest conservation status in the Guadiana River estuary is that of the saltmarshes. This area has a recent development and the accretion rates recorded for the three transects during this study suggest that it is still growing (Figure 3.2). The saltmarshes show the typical flat profile of expanding marsh absent of micro-cliffs (Figure 6.23), except for T1, where was detected a micro-cliff associated to a secondary channel. Regarding the long-term changes in the profile slope, most of the transects had no changes and only T1 experienced slight changes over time.

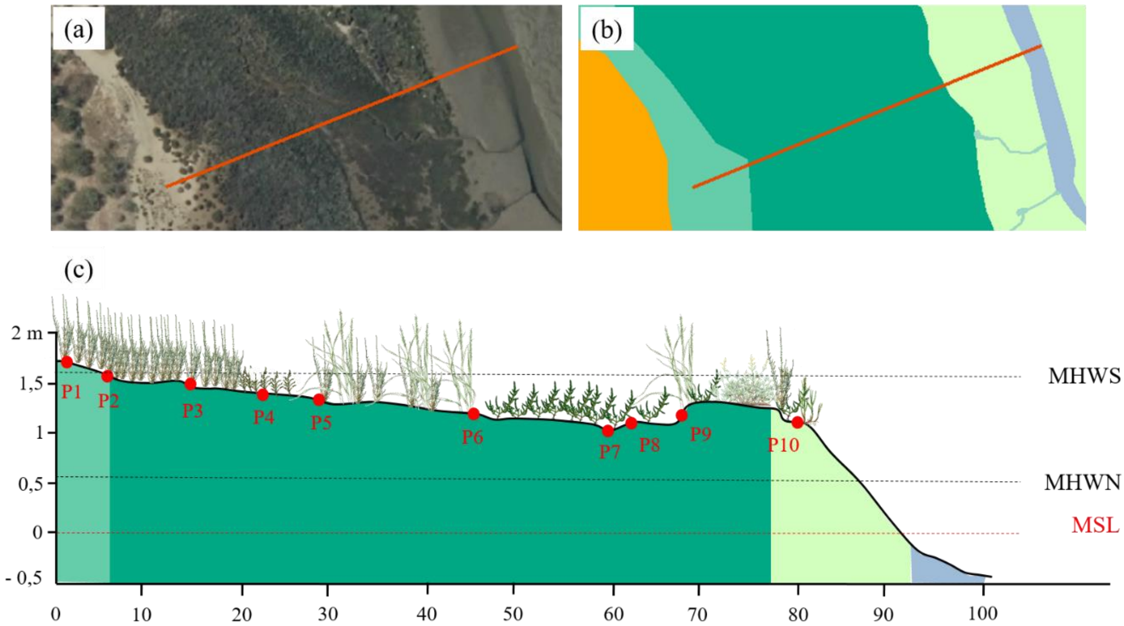


Figure 6.23. T1 of the saltmarsh system in San Vicente de la Barquera estuary. (a) Aerial orthophotograph of the transect, (b) geomorphological features identified in T1 (according to Figure 3.2), and (c) topographic profile obtained with the DGPS-RTK and associated plant communities. Colours in (c) match with geomorphological features identified in Figure 3.2. MHWS=1.565 m, MHWN=0.573 m. Red dots correspond to locations where variables were measured in the field.

Long-term changes in the occupied surface reveal the gain of vegetation cover in the three transects (further details in chapter 3, Figure 3.6). The percentage of pioneer saltmarsh with respect to the total length of the transect is variable among the three transects. With absence of a pioneer zone in the T1 for the first and third campaigns, whereas T2 presented a 37.36 % of pioneer zone (*Spartina maritima* and *Salicornia spp.*). These divergences in pioneer areas could be related with methodological errors, being necessary additional measurements of this variable to obtain reliable results in a wider temporal scale. T2 also presented large variations in the percentage of pioneer zone with time, having a 12.35 % on the first field campaign, 38.41 % in the second one and 0.57 % in the last one. The transect in the oldest area (T3) presented the most stable pioneer zone, with percentages of 56.98 %, 68.2 % and 68.35 % for the three field campaigns, respectively. These results seem more reliable than the previous ones. The exposure frequency in the lowest limit did not show any change. With respect to the total cover, T1 had percentages close to 70 %, while T2 and T3 larger than 70 %. Plant cover only exhibited symptoms of fragmentation in T1. Lastly, the IAS *Spartina densiflora* was discontinuously present in the middle-upper part, but no expansion was observed during the study period (Figure 6.24.a).

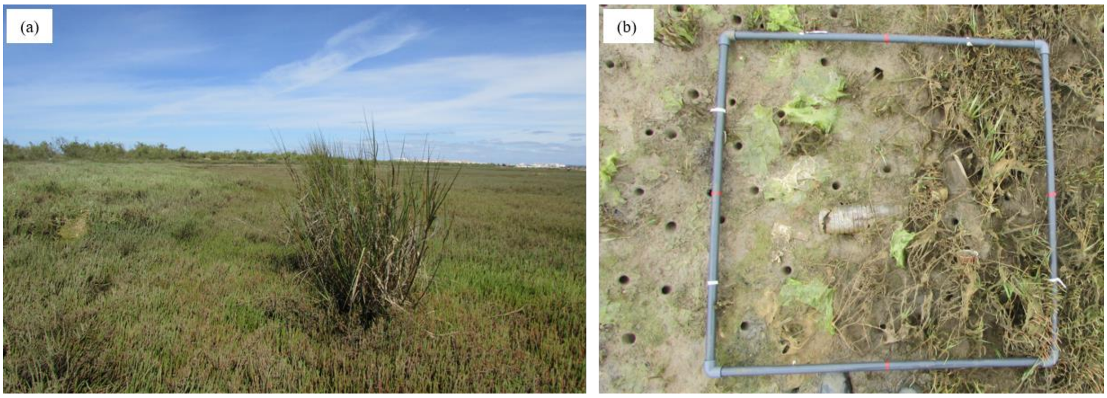


Figure 6.24. (a) *Spartina alterniflora* and (b) example of solid waste in one of the points measured in the Guadiana estuary saltmarsh.

Finally, the variables from MPF show the same values for the three transects. Some historical reclaimed zones in this area devaluate the conservation status for this variable to medium level. In this estuary, shell fishing is intense during the whole year. Fishing is legal in the main river channel, but no in the saltmarsh and tidal creeks. However, illegal shrimp and bivalve fishing occurs almost in the entire estuary. The solid waste for the three profiles was always less than 50 %, and mostly transported by tides (Figure 6.24.b).

- *Drainage Network Index (DNI)*

Similar to the SVB drainage network, the connectivity of the GUA had values of 18.2 km/km^2 that remained stable throughout the study period. Again, it was not included in the calculation of the DNI as long-term measurements are needed. The naturalness of the drainage system was evaluated according to the existing bibliography (Garel and Ferreira, 2011). The results suggest variations in the magnitude of the circulating flow due to relatively recent human interventions, but especially due to the construction of the *Alqueva* dam in 2002, that regulates the magnitude and frequency of the floods. The intra- and inter-annual variability can be strong due to prolonged periods of drought, alternating with episodic floods in winter and spring (Morales *et al.*, 2006; Garel, 2017; Morales and Garel, 2019).

- *EstuarIndex*

According to the results presented for the SSEI, DI, TFI and DNI sub-indexes (detailed in Annex 3), the final values of the *EstuarIndex* for Guadiana river estuary are high for the entire period of study (Table 6.8).

Table 6.8. Results of applying EstuarIndex in Guadiana estuary for the 3 field campaigns.

Field campaign	EstuarIndex value	Conservation status
25/09/2018	0.65	High
03/05/2019	0.66	High
28/09/2019	0.67	High

6.3.3. Ebro river estuary (EBR)

The *EstuarIndex* evaluates the conservation status in the Ebro River Delta mouth as high and very high, in general (Figure 6.25). These values were supported mainly by high values of accretion rates (between 1 and 11 m in the last 30 years), together with high values for the rest of the variables, which are explained in detail the next sections.

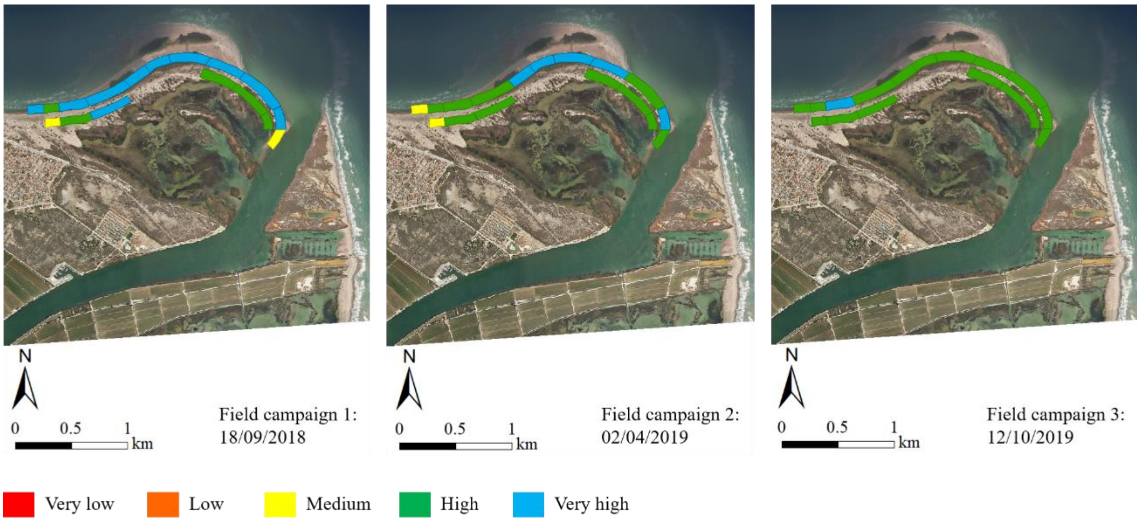


Figure 6.25. Graphical outputs of the SSEI, DI and TFI results in the Ebro River Delta mouth for the three field campaigns. The SSEI results are shown in the external band and the DI ones in the inner band. The location of the coloured segments corresponds to the location of the transects measured in the field (Figure 6.2). The detailed results for each variable are summarised in Annex 3.

- *Shoreline Sandy Environments Index (SSEI)*

When the status is analysed by subsystems and specific variables, it reveals a remarkable variability between transects and field campaigns. The width of the beach was > 50 m for most transects (1, 3, 4, 5, 7, 8, 10). The rest of transects fluctuated around values < 30 m. The transect with the smallest width was T11 (the estuarine beach) with values < 15 m. The

LTE of the beach reveals accretion rates in the central part of the study zone (Figure 6.26), reaching rates of up to 11 m/year in T8. The exception was T9, which seems stable, and T10, eroded at rates of -1m/year, approximately. In this case, due to the strong changes in coast configuration, the LRR have been calculated for two periods: long term (1983-2019), covering the entire study period, and short-term (2009-2019), to see if the trend of the system is accelerated in these last ten years.

Figure 6.26. Long term evolution (LTE) based on Linear Regression Rate (LRR) of the shoreline in Ebro River Delta mouth from 1983 to 2019, and transects used for this calculation. Grey boxes differentiate the anthropic zone (1) from the natural one (2).

The accretion rates were clearly related to the formation of recurved spits westward of the river mouth, with clear differences between long and short term evolution (Figure 6.27). In both Figure 6.26 and Figure 6.27, it can be seen how the beach pivots with respect to a fixed point at the beginning of the natural area (beginning of the box 2 in Figure 6.26, white tones), having a slight erosive behaviour towards the anthropic zone (left) and an accretionary one in the natural area (right). This seems to be strongly influenced by the interaction between the supply of sediment from the river, littoral drift and sediments transported from *San Antonio* island by eastern storms.

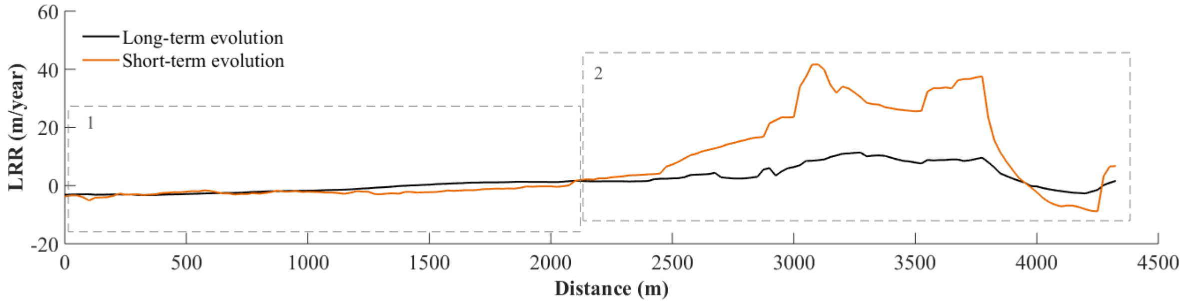


Figure 6.27. Erosion rates as a function of the alongshore coordinate. black line corresponds to long-term evolution of LRR (1983-2019) and the orange line correspond short-term evolution of LRR (2009-2019). Grey boxes differentiate the anthropic zone (1) from the natural one (2). The alongshore coordinate follows the pattern in Figure 6.26, being 0 the western side.

The predominant morphodynamic state of this beach is dissipative (intermediate with bars according to Figure 6.5) with values of Ω =4.72 and RTR=0.27. Nevertheless, T8 can be classified as ultra-dissipative, due to the huge extension of the beach in this zone, and T9 as intermediate, since it is steeper slope and narrower. Intertidal sandy bars are permanent in T4 to T7 (central sector of the study zone where the recurved spits develop), occasional in T1 to T3 (west sector) and rare or absent in T8 to T11 (near the river mouth). The stoniness was in general low, with some punctual exceptions.

Organic accumulation of marine origin is frequent in most transects (Figure 6.28.a) and sometimes favour the formation of embryo dunes (Figure 6.28.b). The accumulation of organic debris is seasonal and clearly dependent on the energy that reaches the coast.

Regarding the MPF in the Ebro River Delta, with exception of the T1, the study zone is in a Natural Park and the corresponding values of conservation are, generally, high. According to the degree of anthropization, the system is considered semi-natural in T1 and T2, and natural for the rest of transects. Attending to the accumulation of waste, the beach is moderately clean with regular mechanised cleaning only in the semi-natural transects (Figure 6.8). In the Natural Park, the solid waste transported by the sea accumulates on the seashore over long time periods, explaining the category of moderately unclean in some of the transects. The frequency of visitors is seasonal, and rare for the farthest transects in the Natural Park, although water sports are practiced throughout the year. The access to the beach is not specifically regulated for T1 and T2 and only allowed on foot for the rest. Finally, the presence of fixed structures is absent, except for T1 with an elevated wooden walkway at the back.

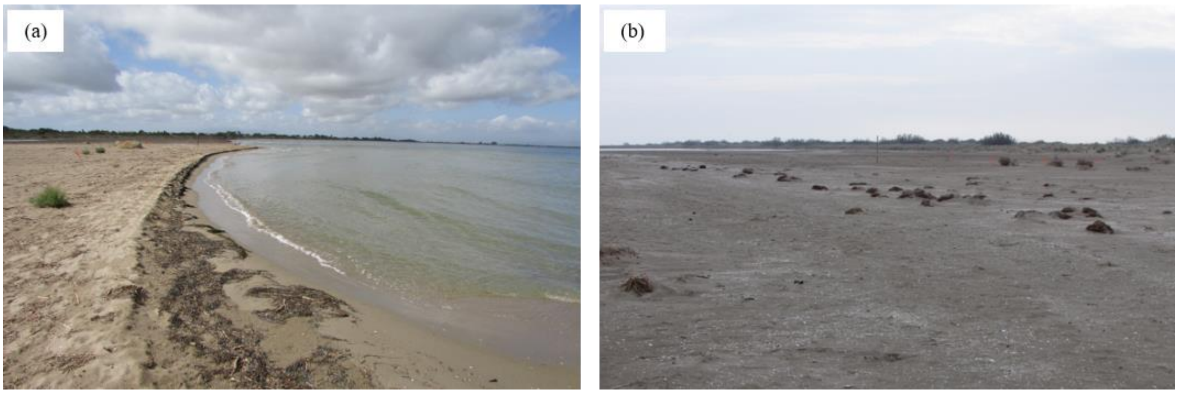


Figure 6.28. (a) Driftlines on the central sector of the beach and (b) embryo dunes fixed by organic accumulations of marine origin, in the Ebro River Delta mouth.

- *Dune Index (DI)*

The dune system has a predominant conservation status of high, with some transects presenting medium values, as T1 in field campaigns 1 and 2. This subsystem has high values of MOF, EF and MPF (see Annex 3), matching with the observations in the field.

The EBR dune system is well developed with a wide beach in front of it, which serves as a barrier against erosive agents. On the contrary, the east side of the mouth, *San Antonio Island*, shows high erosion rates (up to 20 m/year) weakening the dune system in this area. Unfortunately, the access to the *San Antonio Island* was not feasible, therefore, this area has not been included in the calculation of the sub-indexes. Nevertheless, the evolution of this area will be taken into account as it is affecting the evolution of the entire system.

Following with the proposed variables, the width of the dune system was variable in space, but not in time along the study zone. The T2, T4 and T8 were > 50 m wide, and T9 and T10 < 50m wide. Special case is T3, with more than 250 m, probably the wider part of the dune system. The modal height of the dune system was constant throughout the field campaigns, with T2, T4 and T10 having modal heights < 1 m and the rest (T3, T8 and T9) > 3 m, with maximum heights of circa 6 m, 4 m and 5 m, respectively. The protection measures appear efficient enough to maintain a low degree of fragmentation. Nevertheless, T2 was affected by trampling and walkaways probably due to its proximity to the non-protected zone. Lastly, the presence of erosive scarps in the dune fronts was unusual, with some punctual exceptions in the transects located near the river mouth, which is a very dynamic zone and more exposed to erosive agents.

Since the dune system is quite isolated, the EF showed values of high conservation status. Regarding the continuity of plant succession, it is total, or almost total, from T3 to T10, excluding T2 and T9, which shows some discontinuities. Only T3 had burrows. Whereas the presence of invertebrates, reptiles and bird nests was more sporadic, depending on the season. On the other hand, < 5% of the dune front presented exposed roots, what directly matches with the absence of erosive scarps.

Finally, for MPF, the traffic and parking of vehicles is limited to the urban part, behind the dunes, minimizing the influence on the system. There are no sand collectors, in any transect, and access control is total for the dune system (except for T2). In any case, the access to the dune field is difficult having to cross a large coastal lagoon to access to it (Figure 6.29), which was formed after the closure of an old coastal ridge. Information panels are more frequent than in the other two estuaries, especially at the beginning of the protected area. To finish, it was not frequent to find litter on the dune system, < 5 % of the time for almost all transects.

- *Drainage Network Index (DNI)*

Due to the absence of tides, and the corresponding tidal drainage network, only the naturalness of the drainage network has been evaluated. The natural hydrology of the area is strongly modified by the supply of water for intensive agriculture (mostly rice crops) and the construction of dams upstream. These pressures modify the hydrological cycle, forcing a dry period from November to April when the irrigation network is closed after the rice harvest, and a wet period from May to October when the irrigation network opens again to supply the crops (Franquet Bernis *et al.*, 2017). Thus, not only the volume but also the seasonality of the hydrological cycle is modified.

Figure 6.29. Images of the coastal lagoon situated between the dune system and the beach, in the natural protected part of the EBR site. Note the development of new embryo dunes fixed by *Ammophila arenaria* and *Arthrocnemum spp*. in the external part of the coastal lagoon (right image).

- *EstuarIndex*

Based in the results for the SSEI, DI and TFI (detailed in Annex 3), the *EstuarIndex* for the EBR system had values in between 0.61 and 0.66, showing that the Ebro River Delta mouth presented during the study period a conservation status of High (Table 6.9).

Table 6.9. *EstuarIndex* values and corresponding state of conservation of the Ebro river mouth for the 3 field campaigns.

Field campaign	EstuarIndex value	Conservation status
1	0.66	High
2	0.61	High
3	0.61	High

6.4. Discussion

The *EstuarIndex* is an index design to respond to the need for an integrated assessment of mid-latitude estuaries based on the conservation status of their sub-systems. The application of the *EstuarIndex* has proven to be adequate for the evaluation of estuaries of the Iberian coasts. The study zones selected in this thesis have clear differences in physiography, geomorphology, marine conditions, and the land use characteristics. This diversity of conditions has allowed testing this methodological approach for the evaluation of the conservation status under different driving factors controlling the evolution of the estuaries through an index-based methodology. The *EstuarIndex*, evaluates the general conservation status of the estuaries from the lineal combination of 4 sub-indexes that evaluates partially the status of the main subsystems commonly present in an estuary: (1) Shoreline Sandy Environments Index (SSEI), (2) Dune Index (DI), (3) Tidal Flats Index (TFI) and (4) Drainage Network Index (DNI). Each sub-index is estimated according to a limited set of variables easy to measure or estimate. The thresholds and assessment criteria for each variable are also proposed.

6.4.1. Conservation status according to the *EstuarIndex* in contrasting Iberian estuaries

The three estuaries selected in the present thesis are representative of the different geographic regions of Iberian coastal systems. Based on the results of the *EstuarIndex*, the small estuary of the SVB, representative from the Cantabric coasts, seems able to adapt to increasing pressures. The overall functioning of this estuary seems adequate and stable, although the tidal flats have a declining evolution (described in detail in chapter 4). This result suggests a low connectivity among subsystems, since sandy and muddy environments seem to evolve independently. The lack of connectivity may be explained by the morphology of the estuary, incised in a rock valley with a morphology very conditioned by physical constrictions. However, these results must be considered with caution, since the TFI for this system was expected to have medium-low conservation status, according to the level of fragmentation of the saltmarshes (see chapters 3 and 4) and instead the TFI sub-index reached a level of medium. Although the conservation status estimated was not high, the value of the *Estuarindex* could still be considered overestimated, highlighting the need for a revision, or at least a tuning of the variable weighting to reinforce the most relevant variables for the functioning of the system.

For the case of the Guadiana estuary, the conservation status according to the *EstuarIndex* is high. This value agrees with the good functioning of its subsystems (described in chapter 3). This estuary has some similarities with the San Vicente de la Barquera one, such as the classification as a rock-bound estuary, and having two jetties to stabilize the mouth. However, the morphology and evolution of this estuary is quite different from the estuary in the north of the Iberian Peninsula. The conservation status of the Guadiana estuary seems to depend on the accretion rates fed by the remains of the sand shoal attached to the coast (Figure 6.21, blue zones). This accretion proceeds from the evolution of the ebb tidal delta after the construction of the jetties in 1972-1974, when the submerged shoal system (O'Brill bank) was artificially broken (Garel *et al.*, 2014, 2019). These jetties explain the clear differences in behaviour between the coastline of the study site (the Guadiana River mouth) and the Carreras inlet situated downdrift (see Garel *et al.*, 2014, for more details about morphodynamical response of the ebb-tidal delta). These changes, considered positive in terms of the increase in the occupied surface, are driven by major engineering interventions, what should be considered negative according to the proposed index, since they anthropize the functioning of the system.

The sand shoal is expected to maintain the supply of sediment in the coming years. However, this supply is limited and so is limited the time for accretion. The reduction in the supply of river sediment (Figure 6.30), together with the drift currents, has generated strong modifications in this sandy feature in recent years, leading previous authors to conclude that the sediment source that is reaching the coast is limited and that the corresponding effect will be noticeable in the coming years. Thus, although the current status of the estuary is high and it is prograding, there is enough information to expect a decrease in the state of conservation in the medium-long term.

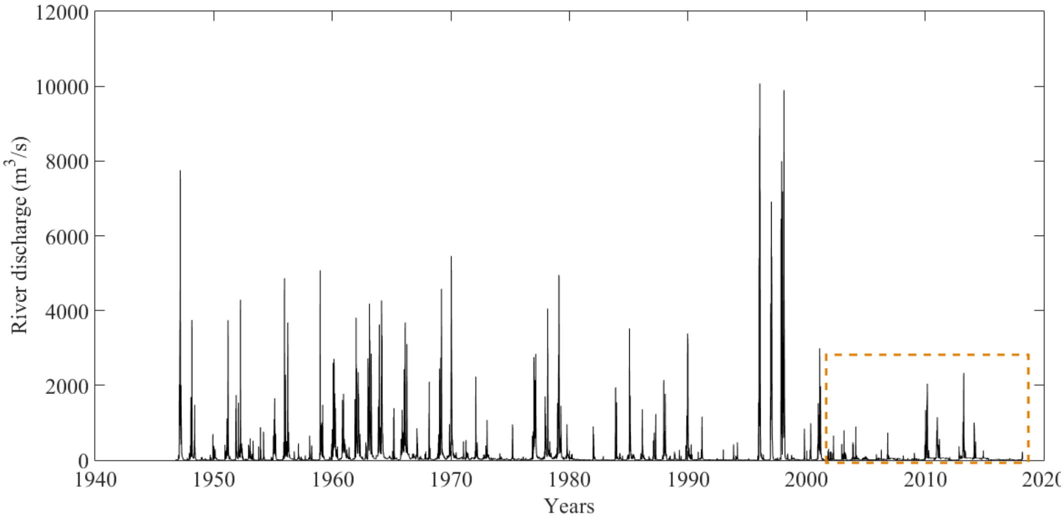


Figure 6.30. Daily averaged river discharge into the Guadiana estuary between 1947 and 2018. The orange box highlights the reduction in river discharges after the construction of Alqueva dam in 2002 (Modified from Moura et al., 2017).

Therefore, appropriate management measures to ensure the current evolution of the system are necessary, since the medium-term evolution of this system is well-known. This study also shows the connectivity of the estuary with the submerged ebb tidal delta, which together with human interventions in recent decades, directly influence the evolution of the estuary. Furthermore, the evolution of the sandy and muddy environments of this estuary is strongly related to the evolution of the shoal and to the erosional / accretional trend of the coastline towards the south. Future works should continue to focus on connectivity within the estuary, but also on connectivity with adjacent systems, i.e. broader spatial scale studies.

Lastly, the *EstuarIndex* also values the EBR system with a high conservation status. The two analysed subsystems of the EBR, beach and dune, reach maximum values in some areas. However, in this case, it would have been important to consider a larger spatial scale, and no just the left side of the river mouth. In this case, the high conservation status can be partly attributed to the protection of the area, but partly is also consequence of the accretion associated to the sediment bypass form the *San Antonio Island* to the external part of *El Garxal*. The *San Antonio island* shows a remarkable negative evolution (Figure 6.31), with more than 40 ha being reduced annually (Figure 5.1), and with erosion rates as high as 20 m/year (even more) according to Figure 6.31.

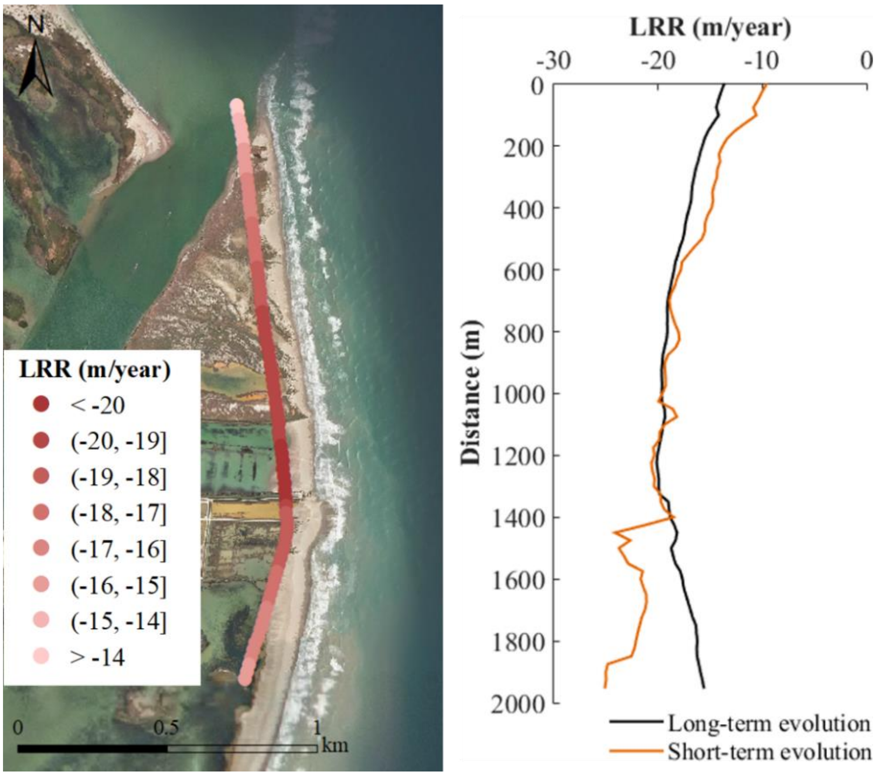


Figure 6.31. Long term evolution (LTE) based on the Linear Regression Rate (LRR) of the shoreline in the San Antonio Island (Ebro River Delta mouth) from 1983 to 2019 on the left, and a comparison of the LRR as a function of the alongshore coordinate for two different time periods: black line corresponds to long-term evolution of LRR (1983-2019) and the orange line correspond short-term evolution of LRR (2009-2019).

Moreover, this erosive trend is increasing in recent years, which is clearly noted in the short-term evolution, with constant erosion in the northern part that becomes more different from the long-term towards the south, where the old mouth was located. As the result, the change rate is increasing in both zones, as accretion at *El Garxal* and as erosion at *San Antonio Island*. If this trend continues, the *San Antonio* island is expected to disappear in the coming years. In such a case, *El Garxal* will be exposed to energetic waves from the East, which will most likely cause its disappearance and that of the associated features. As consequence, the current hemi-deltas of the river mouth complex will disappear.

The deterioration of the Ebro Delta has been associated to the increase in frequency and intensity of storms coming from the East (the most energetic ones in this area), together with the sea level rise (which is aggravated in this zone due to subsidence). However, it is also a consequence of the lack of social and political awareness about the importance and vulnerability of coastal systems (Romagosa and Pons, 2017). An example of this vulnerability was the effects of the storm *Gloria*, which flooded a large part of the delta in January 2020 and washed away large coastal features (Figure 6.32).

Figure 6.32. (a) Latest orthophotography (2020) of the Ebro delta and (b) the same zone in 24-27 January 2020, after the passing of storm Gloria. Images obtained from Cartographic Institute of Cataluña (https://visors.icgc.cat/costa/#13/40.7222/0.8439). Note the sediment plume at the river mouth, the breaching on the beach in the southtern part of San Antonio island and the inundated zones in the inner part of the delta.

Gloria storm was not extreme, but intense (Alonso *et al.*, 2020). Under this scenario, the dune field was almost emerged (Figure 6.32), proving its protective role against such erosive event and supporting the *EstuarIndex* valuation for this zone. Nevertheless, to increase the reliability of the predictions it is needed future studies combining hydrodynamic models with the application of indexes to define the system status, such as *EstuarIndex*,.

Despite the application of the *EstuarIndex* to very different estuaries seem satisfactory, it is still necessary to validate the methodology. This requires future studies in different estuaries, preferably with different size and conservation status. The application of the *EstuarIndex* in other temperate estuarine areas would determine the adequacy of the variables proposed. The development of a comprehensive database (in number of test sites and time scale) would allow comparison between systems to deepen knowledge on estuarine connectivity.

The results here presented illustrates the inefficiency of independently evaluation of estuarine subsystems and support that understanding estuaries as a whole requires a mosaic perspective of interconnected subsystems (Bárcena *et al.*, 2017).

6.4.2. Methodological considerations

The methodology presented in this thesis has demonstrated to be suitable for evaluating the state of conservation of estuarine areas, since the main results match with field observations.

Given the growing awareness of ecosystem services and the relevance in the shaping of coastal processes, the ecosystem functioning must be included in the planning of adaptation strategies at different scales, both temporal and spatial (Silva *et al.*, 2019). On this basis, this index aims to create a dynamic view of the estuary. Therefore, there is still further work to do, applying the methodology in wider spatial and temporal databases and adjusting the variables to this objective. To prevent interannual fluctuations masking long-term trends, a broad temporal scale is required. The design of the *EstuarIndex* has sought to avoid these variabilities. At the moment, there is only enough information on variables with historical data, while the others still need a longer monitoring. Therefore, equalising the information level of all variables should be the first task to take into account in future works.

The value of the *Estuarindex* is not merely a category of “Very Low – Low – Medium – High -Very High” environmental status. These categories allow a quick visual evaluation of the current field conditions (Figure 6.14, Figure 6.20 and Figure 6.25). However, management strategies should not be determined only according to these categories, but also considering the analysis of the variables used for the calculation (Williams *et al.*, 2001), and the results of the study required for their estimations (as chapter 3 and 4). Furthermore, the repeated application of this procedure would generate a dynamic data base, that would allow the detection of temporal discontinuities. Collecting a long-term data base is very important for the management of these dynamic systems. This does not imply increasing frequency, since no variability has been recorded in this work, but regular continuity. Any punctual change will be immediately apparent in this type of systems – for example, the effect of an energetic event on beach and dunes. However, the identification of subtle changes (trends), which could undermine the long-term survival of the system, is a significant challenge (Williams *et al.*, 2001).

For that purpose, the *EstuarIndex* is a good tool, simple to apply and with a reduced number of variables, carefully selected to avoid redundancies with complementary index-based methods (Cooper and McLaughlin, 1998; Williams and Davies, 2001; Villa and McLeod, 2002; Ciccarelli *et al.*, 2017; Rizzo, 2017). Furthermore, the *EstuarIndex* represents a new perspective on the management of the estuaries, with added values on (1) the combination of variables to evaluate sandy and muddy subsystems, and the influence of the drainage network on them, and (2) the integration of geomorphological, sedimentological and hydrodynamic factors with ecological (conditions of the associated vegetation) and anthropogenic ones.

Some of the variables of the *EstuarIndex* are not designed to evaluate by transects, but to evaluate the entire subsystem (e.g. Permanent Morphological State for beaches or Exposure Frequency for tidal flats, among others). These variables accumulate the effects of processes that act on a wide temporal scale and, therefore, require a long time scale to detect changes. Nevertheless, this approach is flexible enough to allow the evaluation of individual subsystems when it is not possible to collect information from the others (due to available data or time).

As every methodology, the *EstuarIndex* has limitations that can be grouped in two types. On the one hand, this methodology needs very specific information to estimate some variables sometimes not easy to find, including detailed topographic data, wave long time series or historical aerial information. The other type of limitations is related with the aim of the design, since the requirement of being a method applicable not only by scientist, but also by environmental technicians of the corresponding administrations, has required a balance between scientific rigor and easy applicability that has limited the variables possible to measure, and therefore, the complexity of this evaluation.

Additionally, while the inclusion of multiple variables is important, this does not exclude that some metrics contribute more to the resilience of an estuary than others (Raposa *et al.*, 2016). For this initial assessment, most metrics have not been weighted differentially to avoid arbitrary weight assignments (except for tidal flats, where an initial proposal had already been made). However, further improvements should include a scientifically reasoned weighting of the variables, firstly by factors and, secondly, by variables within the factors. That is, MOF and EF should have more weight than MPF, since the last have less influence on the estuarine functioning. Regarding the variables, those evaluating processes at larger time scales (as the long term evolution of the shoreline for beaches; the width of the active dune system for dunes; or the exposure frequency for tidal flats) should have more weight, since they are more reliable than more ephemeral variables (e.g. stoniness or driftlines for beaches; dune front with presence of erosive scarps, or exposed roots for dunes; or total cover and plant cover fragmentation for tidal flats, for instance). Special attention must be paid to the weight of variables such as the occupied surface, since, in some cases, the functioning of the system may be able to adapt to past and present pressures, even though its physical structure is decreasing.

In summary, considering that the conclusions on the state of conservation of a natural system may change depending on the type of the applied index, it seems reasonable that evaluating the resilience of estuaries should include multiple indices. There is no a single universal index for the estuarine assessment, and the best assessment comes from the integration of multiple indexes that evaluate the subsystems and their connectivity (Pinto *et al.*, 2009). Thus, *EstuarIndex* seems to adapt to the basic requirements necessary to evaluate those complex systems and can be considered a good starting point for a correct assessment of the Spanish estuaries.

7. General Conclusions

In the present PhD thesis, it has been carried out an assessment of the conservation state of three estuaries along the Iberian coast. Every estuary was analysed as a whole, as well as their main associated subsystems, namely beaches, dunes, saltmarshes and the drainage network. The conclusions drawn from this work are set out below, together with the knowledge gaps still existing and a set of recommendations for future research.

In the first place, considering previous European classifications like the one included in Habitat Directive 92/43/CEE, EUNIS habitat classification and CORINE Land Cover classification, it was developed a hierarchical classification that allows a common procedure for the assessment of estuaries. This procedure lays the foundations for the development of standardized estuarine eco-geomorphological maps.

The development of sequential standardized estuarine eco-geomorphological maps from historical images has been proved to be a useful tool to assess the resilience of estuarine systems under present and future pressures, complying with the first specific objective of this thesis. In future works, the combination of aerial orthophotos, which provide the historical data for the study of landscapes, with other methods, as hyperspectral information from airborne and satellite sensors, will facilitate the reconstruction and monitoring of estuarine changes at landscape level, reducing time and efforts.

The application of this methodology in three Iberian estuaries of contrasting conditions revealed temporal trends and drivers of change. In the North coast of Spain, the San Vicente de la Barquera estuary has showed a strong and gradual decrease in the surface occupied by saltmarshes, possibly as consequence of combination of regional and local factors. In the Gulf of Cadiz, over the past decades, the Guadiana River estuary has suffered variations in shape due to the strong dynamics of external and intertidal sand features and the support of an almost constant sediment input which allowed the development of new morphosedimentary units and the progradation of previously existing ones. Lastly, in the Mediterranean coast, the Ebro River delta mouth is exhibiting a strong positive trend on sandy environments for the left side of the main channel but a negative trend on the right side. If this last trend continues, the dynamic of the entire system may change drastically in the near future.

The interdependence in between subsystems composing an estuary have been proved and described. The results show that the processes shaping the subsystems are common, supporting the establishment of general relationships in between them, and highlighting the influence each one has on the others. The *drainage network* acts as the main connection vector for the entire system, driven by fluvial and tidal currents and the local oceanographic conditions, which promotes the exchange of sediment, organic matter and energy in the entire system. The *Sandy environments* provide a sediment budget to the estuarine system via the *drainage network*. Additionally, the *sandy* features serve as protection to the *muddy* ones, where the sandy spits promote the development of *saltmarshes* and *wetlands*. The results suggest that the degradation of one of the subsystems may influence the functioning of the others, harming the ecosystem services provided by the whole system. These findings confirm hypothesis 1 described in the present PhD thesis, namely “Mid-latitude estuaries present the same types of associated subsystems, interconnected through the water body and whose individual functioning influences the functional status of the whole system”.

The weaknesses of the proposed methodology are mainly related to the establishment of some of the subsystem boundaries. The accuracy assessment done in San Vicente de la Barquera estuary has identified spatial resolution and accuracy of elevation data as main source of error to define accurately the edge of the subsystems when mapping estuarine environments. Therefore, the proposed methodology can improve with the access to high-resolution imagery and elevation data series to monitor estuarine changes.

More precisely, the combination of the analysis of sequential 2D information with high resolution topographic data has allowed to quantify the evolution of the saltmarsh and its fragmentation in San Vicente de la Barquera estuary. Symptoms of self-organization processes in the saltmarsh have been detected on a large spatial-scale, allowing to detect stressing factors supporting the conditions for saltmarsh deterioration. Thus, the study of the interaction between ecological and geomorphological processes on these systems has demonstrated to be crucial when describing changes in a long temporal scale.

The results obtained in San Vicente de la Barquera define the most relevant natural processes in the estuary and the anthropogenic influence on its functioning. The most direct causes of change in these saltmarshes are local, including the reduction of the river sedimentary input within the estuary, the reclamation of tidal flat surface and the dredging of the main channel for navigation. These local changes have modified the estuarine dynamics, diminishing the resilience of the system to predicted future changes, e.g. SLR. The anthropogenic impacts have led to a patched configuration of the saltmarsh, which favours erosive processes, confirmed by the presence of micro-cliffs on the edges, which in turn contribute to the decline of this subsystem. Thus, although the results do not provide a definitive solution to the fragmentation and erosion, they suggest that the future management efforts should focus in those local factors. Besides, future works should also clarify the patterns of erosion/accretion processes within the estuary in a larger temporal scale, by using more high-resolution data. The results obtained meet the second specific objective, which was to evaluate the most relevant natural processes in the estuary and the anthropogenic influence on its functioning, and also permit to confirm the first hypothesis of the present thesis.

The design of the *EstuarIndex* has included a selection of variables to characterize the natural and anthropogenic processes dominant in estuarine systems, whereas its application to the three study zones has calibrated the method for its applicability to Iberian estuaries. The conservation status of the estuaries has been evaluated according to the state of a set of geomorphological, ecological and management conditions, and adjusted to be suitable for the application to other estuaries, both at national and international scales.

For San Vicente de la Barquera estuary, the E*stuarIndex* concludes a "medium" conservation status, suggesting that, despite the fragmentation of the saltmarsh, the system as a whole still can keeps an integral functioning.

In the case of Guadiana River estuary, the *EstuarIndex* estimated a "high" functioning and conservation status. However, the present status of this estuary is conditioned by anthropogenic pressures (mainly the dam construction and the artificialisation of the river mouth and the surrounded coast). Considering the long-term trend of this coast, it seems feasible that this conservation status could change drastically in the upcoming years, highlighting the importance of evaluating the conservation status in a broad temporal scale.

Lastly, the *EstuarIndex* estimated a "high" conservation status for the Ebro River delta mouth. This value was estimated when considering only the left side of the delta. However, the right side has been under a dramatic erosion in the last years, condition that could strongly influence on the overall performance of the index. Therefore, the application of the *EstuarIndex* to this site reinforces the importance of the adequate spatial scale when determining current and future status, taking into account the whole system and subsystems.

Although it has proven to be a suitable methodology, there are still some challenges to face for the wide application of the *EstuarIndex*. Firstly, the calculation of some variables requires specific information, sometimes not easy to find. Secondly, it is necessary the tuning of the weighting of the factors and variables proposed, which will require the application in more study cases. Finally, the validation of the goodness of the method still requires the application to additional estuaries with differences in both size and conservation status.

Estuarine systems provide very valuable ecosystem services and the future provision of these services will depend on the correct management of these complex systems. This management will require the evaluation not only for the effects of punctual pressures but also for the overall balance of the system. The systematic application of *EstuarIndex* on broad time scales would allow the system trends to be evaluated, what seems key for implementation of restoration strategies.

After the study of three estuaries along the Iberian coast and the application of the *EstuarIndex*, it can be concluded that the most relevant pressures for changes in the structure and functioning of estuaries are: (1) decrease in sediment input both from the river and the coast, (2) threats from climate change, mainly SLR and (3) anthropic pressures acting directly on the coast (e.g. urbanization, dredging of channels for navigation, overfishing, among many others). Monitoring each estuary by applying systematic methodologies like the historical eco-geomorphological evolutionary maps and the *EstuarIndex* may help in the detection of the most relevant site-specific pressures involved in the deterioration at different spatial and temporal scales.

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Annexes

Annex 1. Year-by-year changes of every feature in each study zone.

Table A.1.1. Historical changes in features identified in SVB.

SVB	*Occupied surface (ha)*						
	1956	**1988**	**1997**	**2003**	**2010**	**2014**	**2017**
Shoreline Sandy Environments	45.77	33.42	40.84	35.30	39.00	39.07	40.78
Beach	23.50	15.38	16.90	15.75	15.62	15.56	15.88
Estuarine beach	4.95	3.29	4.63	3.72	3.90	4.46	4.80
Sand bars	2.24	4.68	6.22	5.81	6.01	6.01	7.57
Dunes	6.04	11.94	11.38	10.19	6.37	6.85	6.17
Embryo dunes	1.57	1.52	1.08	1.35	0.60	0.57	0.87
Fixed dunes	4.47	10.13	10.13	8.53	5.53	6.05	5.09
Estuarine dunes	-	0.29	0.17	0.31	0.24	0.22	0.22
Tidal flats	237.86	223.29	236.86	228.00	243.55	244.43	230.03
Saltmarshes	101.70	50.44	60.01	43.90	29.68	26.22	15.62
Mudflats	136.16	172.85	176.85	184.10	213.87	218.21	214.41
Drainage Network	83.84	101.31	79.70	91.52	73.69	75.51	85.57
Channel 1	51.30	62.80	51.20	51.55	43.96	44.75	50.44
Channel 2	7.82	16.69	6.07	15.15	3.56	4.18	8.68
Artificial channel	2.70	2.17	1.94	1.61	1.63	1.63	1.63
Sand flats	15.08	10.07	13.09	10.02	13.47	13.04	12.53
Flood tidal delta	20.76	18.97	20.21	20.26	23.13	22.85	22.72

Table A.1.2. Historical changes in features identified in GUA.

GUA	Occupied surface (ha)								
	1956	**1977**	**1984**	**1998**	**2006**	**2009**	**2011**	**2013**	**2016**
Shoreline Sandy Environments	104.23	68.14	67.14	200.92	120.58	55.71	86.76	138.4	163.22
Beach	13.65	16.04	20.96	22.67	26.38	22.61	24.26	31.26	27.15
Estuarine beach	10.11	9.39	5.27	8.10	5.60	3.87	2.78	3.99	5.22
Relict littoral ridge	65.84	40.33	37.44	29.23	29.23	29.23	26.83	26.83	26.83
Coastal lagoon	-	2.39	1.66	-	2.06	-	2.11	2.37	2.11
Sand bars	14.63		1.81	140.92	57.31	-	30.72	73.37	99.66
Mudflats*	-	-	-	-	-	-	-	0.67	2.26
Dunes	101.55	75.21	64.75	57.85	55.00	54.23	52.54	51.17	54.80
Embryo dunes	41.59	7.48	10.03	5.32	2.99	4.04	6.19	5.68	5.80
Fixed dunes	16.49	19.73	13.36	12.70	5.22	6.16	4.42	2.98	6.85
Estuarine dunes	-	-	-	-	0.13	0.02	0.22	-	0.46
Relict dune ridge	36.79	48.00	40.86	39.45	43.59	41.11	38.74	39.49	39.14
Wet dune slacks	6.68	-	0.50	0.38	3.07	2.90	2.97	3.03	2.55
Tidal flats	276.31	272.8	289.6	289.93	279.02	275.8	277.9	283.1	279.67
Saltmarshes	222.03	241.6	245.1	250.96	252.53	255.0	243.7	251.2	242.49
Mudflats	37.25	30.90	44.22	36.89	26.25	18.68	34.00	31.70	36.94
Drainage Network	377.90	297.9	291.2	354.75	331.41	310.9	318.6	300.6	290.18
Channel 1	341.35	276.8	272.3	335.63	308.74	287.0	292.4	276.0	265.78
Channel 2	27.20	15.47	12.48	12.46	15.25	15.46	16.46	15.46	15.54
Channel 3	7.71	3.81	4.18	4.36	4.43	4.88	5.49	4.48	4.47

Table A.1.3. Historical changes in features identified in EBR.

EBR	Occupied surface (ha)							
	1984	**1994**	**2003**	**2007**	**2012**	**2015**	**2016**	**2017**
Shoreline Sandy Environments	99.30	63.12	55.66	53.81	86.21	83.88	86.21	100.72
Beach	5.83	22.35	21.77	20.59	29.16	24.36	27.18	27.27
Estuarine beach	4.36	-	-	0.18	0.61	0.76	0.32	1.40
Relict littoral ridge	15.49	18.95	25.44	25.69	23.63	27.95	26.33	24.81
Overwash deposit	46.89	18.16	4.77	4.75	1.69	4.24	2.32	2.91
Coastal lagoon	-	0.08	1.23	1.54	0.17	0.11	-	12.50
Sand bars	26.73	3.58	2.44	1.07	30.94	26.46	30.05	31.83
Dunes	104.99	140.11	109.7	108.3	103.0	108.0	111.5	114.3
Mobile dunes	19.83	39.80	28.56	23.85	25.33	31.88	33.10	43.58
Embryo dunes	19.83	5.04	2.94	0.43	1.75	0.27	4.24	6.79
Parabolic dunes	-	-	19.92	22.32	18.80	23.24	26.10	29.16
Barchan dunes	-	-	3.07	1.10	-	3.43	2.77	7.63
Sand sheet	-	34.75	2.64	-	4.79	4.93	-	-
Fixed dunes	21.90	55.97	3.71	11.19	4.18	2.74	-	0.19
Relict dune ridge	49.34	37.77	71.27	67.37	65.36	65.38	69.37	63.37
Wet dune slacks	13.91	6.58	6.22	5.94	8.13	8.04	9.10	7.18
Wetlands	151.12	121.46	105.9	111.9	111.7	105.8	105.3	106.7
Vegetated wetland	-	13.36	13.63	17.29	16.86	12.56	13.85	13.70
Submerged meadow	151.12	108.10	92.34	94.65	94.85	93.29	91.50	93.09
Drainage Network	93.28	90.43	90.70	88.59	83.65	77.44	83.26	78.20
Channel 1	64.30	64.43	69.77	67.79	65.57	59.79	65.77	63.70
Abandoned channel	28.98	26.00	20.93	20.80	18.08	17.65	17.48	14.51

Annex 2. Field campaigns templates.

SHORELINE SANDY ENVIRONMENTS					
Date:	Transect number:			Site:	
GEOMORPHOLOGICAL AND ECOLOGICAL FACTORS	5	4	3	2	1
1. Erosive scarps/berms					
3. Stoniness (CHART)					
4. Grain size (field guide) – Take samples and write transect and point					
5. Driftlines (Presence/Absence) 5.1. Thickness (m) 5.2. Lateral continuity (%) 100% - 50% - 0					
6. Embryo dunes (presence/absence)					
MANAGEMENT AND PROTECTION FACTORS					
7. Waste (take photo)	Clean	Moderately clean	-	Dirty	Very dirty
8. Degree of anthropization (NATURAL / SEMINATURAL / URBAN) (take photo)					
9. Frequency of visitors (Seasonal - - - Continuous)					
10. Beach access	On foot	-	Private transport	-	Any transport
11. Mechanic cleaning (%)	0	< 25 %	< 50 %	< 75 %	>75 %
12. Fixed structures (Specify)	None				Abundant

Comments:

DUNES					
Date:	Transect number:			Site:	
1. Species (abundance)	5	4	3	2	1

PLANT ZONATION ALONG THE TRANSECT (draw transect with an approximate location of the species):

ECOLOGICAL FACTORS	5	4	3	2	1
2. Exposed roots (%)	□≤ 5%	□> 5 %	□> 15 %	□> 25 %	□> 50 %
3. Plant continuity (tick √)	□ Total	-	□ Partial	□	□ No continuity
4.Rabbits (burrows) (tick √)	□ None	-	□ Sporadic	□	□ High presence
5. Presence of invertebrates, reptiles and bird nests in the dune system (tick √)	□ Frequent	-	□ Sporadic	-	□ None
6. Degree of fragmentation (%) (tick √)	□ None	-	□ 25 - 50 %	-	□ ≥ 50%
7. Erosive scarps (%) (tick √)	□ 0 %	□ < 25%	□ < 50%	□ <75 %	□> 75 %
MANAGEMENT AND PROTECTION FACTORS	5	4	3	2	1
8. Control of traffic and parking of vehicles	□ Permanent	-	□ Seasonal	-	□ None
9. Sand collectors	□ Frequent	-	□ Sporadic	-	□ None
10. Access control, enclosure of the dune system	□ Total	-	□ Moderate	-	□ None
11. Information panels (nº per 1000 m)	≥ 5	3 - 4	2	1	0
12. Waste (%)	0	< 5 %	< 25 %	< 50%	≥ 50 %

Comments:

SALTMARSHES									
Date:		Transect number:				Site:			
Point number	**Species (enumerate)**	**Cover (%)**	**Spp. cover (%)**	**Patch.**	**Spp. patchiness**	**Height (cm)**	**Nº Photo**	**GPS point**	**Comments**
									:

Annex 3. Detailed results of all the variables applied for the *EstuarIndex* calculation. Results are expressed for every transect measured in the field according to Figure 6.2.

Table A.3.1. Results obtained of applying **SSEI** variables in **San Vicente de la Barquera estuary** (T*n* refers to transect number according to Figure 6.2.a). FC: Field campaign

MOF	FC	1	2	3	4	5
1. Beach width (m)	1	T7			T5	T1 – T4, T6, T8
	2	T7			T5, T8	T1 – T4, T6
	3	T7		T5	T8	T1 – T4, T6
2. Long term evolution of the shoreline (m/year)	1			T1, T2, T4	T3, T5	T6
	2			T1, T2, T4	T3, T5	T6
	3			T1, T2, T4	T3, T5	T6
3. Predominant Morphological State	1			T7, T8	T1 – T6	
	2			T7, T8	T1 – T6	
	3			T7, T8	T1 – T6	
4. Intertidal sandy bars	1	T1 – T8				
	2	T1 – T8				
	3	T1 – T8				
5. Stoniness (%)*	1				T7	T1 – T6, T8
	2	T7		T8		T1 – T6
	3		T7, T8			T1 – T6
EF	**Field campaign**	**1**	**2**	**3**	**4**	**5**
6. Organic accumulations of marine origin (driftlines, accumulated marine waste)	1	T1	T2 – T8			
	2	T1	T4 – T8	T2, T3		
	3		T1 – T5	T6 – T8		
MPF	**FC**	**1**	**2**	**3**	**4**	**5**
7. Waste	1					T1 – T8
	2				T1	T2 – T8
	3					T1 – T8
8. Degree of anthropization	1	T7, T8		T4, T6	T5	T1 – T3
	2	T7, T8		T4, T6	T5	T1 – T3
	3	T7, T8		T4, T6	T5	T1 – T3
9. Frequency of visitors	1			T1 – T8		
	2			T1 – T8		
	3			T1 – T8		
10. Access to the beach	1	T3 – T8				T1, T2
	2	T3 – T8				T1, T2
	3	T3 – T8				T1, T2
11. Beach surface affected by mechanical cleaning (%)	1			T7, T8		T1 – T6
	2				T1 – T5, T7, T8	T6
	3			T1 – T3	T4 – T8	
12. Fixed structures (specify)	1	T6 – T8			T4	T1 – T3,T5
	2	T6 – T8			T3, T4	T1, T2, T5
	3	T6 – T8			T4	T1 – T3,T5

Table A.3. 2. Results obtained of applying **DI** variables in **San Vicente de la Barquera estuary** (T*n* refers to transect number according to Figure 6.2.a). FC: Field campaign

MOF	FC	1	2	3	4	5
1. Width of the active dune system (m)	1	T3, T7, T8	T4, T5	T6		
	2	T3, T4, T7, T8	T5	T6		
	3	T3, T7, T8	T4, T5	T6		
2. Modal height (m)	1			T6	T3 – T5, T8	T7
	2			T6	T3 – T5, T8	T7
	3			T6	T3, T5, T8	T4, T7
3. Degree of fragmentation (%)	1			T4	T3, T5, T6	T7, T8
	2		T4	T3	T5 – T8	
	3			T3 – T6		T7, T8
4. Dune front with presence of erosive scarps (%)	1				T3 – T7	T8
	2			T3	T4 – T6	T7, T8
	3				T3 – T5	T6 – T8
EF	**FC**	**1**	**2**	**3**	**4**	**5**
5. Plant succession continuity	1			T4	T3, T5 – T8	
	2			T4, T5	T3, T6 – T8	
	3			T4, T5, T7	T8	T3, T6
6. Presence of rabbits (burrows)	1					T3 – T8
	2					T3 – T8
	3					T3 – T8
7. Presence of invertebrates, reptiles and bird nests in the dune system	1			T3 – T5, T7, T8	T6	
	2	T7, T8		T3 – T6		
	3			T3 – T5, T8		T6, T7
8. Plants with exposed roots (%)	1			T3, T4	T7	T5, T6, T8
	2			T3	T5	T4, T6-T8
	3		T3		T5	T4, T6 – T8
MPF	**FC**	**1**	**2**	**3**	**4**	**5**
9. Control of traffic and parking of vehicles	1	T3 – T8				
	2	T3 – T8				
	3	T3 – T8				
10. Presence of sand collectors	1	T3 – T8				
	2	T3 – T8				
	3	T3 – T8				
11. Access control, enclosure of the dune system	1	T3 – T8				
	2	T4 – T8		T3		
	3	T4 – T8		T3		
12. Information panels (nº per 1000 m)	1	T3, T6 – T8	T4, T5			
	2	T3 – T8				
	3	T3 – T6	T8			T7
13. Waste (% of surface affected in the dune system)	1				T3, T5 – T8	T4
	2				T3 – T6	T7, T8
	3				T4, T5, T8	T3, T6, T7

Table A.3. 3. Results obtained of applying **TFI** variables in **San Vicente de la Barquera estuary** (T*n* refers to transect number according to Figure 6.2.a). FC: Field campaign

MOF	FC	1	2	3
1. Long term evolution of the width (m)	1	T1	T2, T3	
	2	T1	T2, T3	
	3	T1	T2, T3	
2. Presence of micro-cliffs	1	T2, T3	T1	
	2	T2, T3	T1	
	3	T2, T3	T1	
3. Long term changes in profile slope	1		T1 – T3	
	2		T1 – T3	
	3		T1 – T3	
EF	FC	1	2	3
4. Long term changes in the occupied surface	1	T1 – T3		
	2	T1 – T3		
	3	T1 – T3		
5. Pioneer saltmarsh with the respect to the total saltmarsh width	1	T1, T2	T3	
	2	T1, T2		T3
	3	T1, T2		T3
6. Exposure Frequency in the lower limit	1			T1 – T3
	2			T1 – T3
	3			T1 – T3
7. Total cover	1	T1	T2, T3	
	2	T1	T2, T3	
	3	T1	T2, T3	
8. Plant cover fragmentation	1	T1	T2, T3	
	2	T1	T2, T3	
	3	T1	T2, T3	
9. Negative indicator species	1		T3	T1, T2
	2		T3	T1, T2
	3		T3	T1, T2
MPF	FC	1	2	3
10. Reclaimed zones	1	T1, T2, T3		
	2	T1, T2, T3		
	3	T1, T2, T3		
11. Shell fishing pressure	1		T1, T2, T3	
	2		T1, T2, T3	
	3		T1, T2, T3	
12. Waste	1		T2, T3	T1
	2		T2, T3	T1
	3		T2, T3	T1

Table A.3. 4. Results obtained of applying **SSEI** variables in **Guadiana estuary** (T*n* refers to transect number according to Figure 6.2.b). FC: Field campaign

MOF	FC	1	2	3	4	5
1. Beach width (m)	1	T1 – T3, T7	T4		T5	T6
	2	T1 – T3	T4, T6, T7			T5
	3	T1 – T3	T4 – T7			
2. Long term evolution of the shoreline (m/year)	1	T3, T6		T5, T7	T2, T4	T1
	2	T3, T6		T5, T7	T2, T4	T1
	3	T3, T6		T5, T7	T2, T4	T1
3. Predominant Morphological State	1		T1 – T7			
	2		T1 – T7			
	3		T1 – T7			
4. Intertidal sandy bars	1	T1 – T3		T4 – T6		T7
	2	T1 – T3		T4	T5 – T7	
	3	T1 – T3		T4	T5 – T7	
5. Stoniness (%)	1		T2, T3		T4	T1, T5 – T7
	2	T3, T4	T2, T5			T1, T6, T7
	3	T1 – T3	T5		T4	T6, T7
EF	FC	1	2	3	4	5
6. Organic accumulations of marine origin (driftlines, accumulated marine waste)	1	T4, T5, T7	T1, T2, T6			T3
	2	T4 – T7			T1 – T3	
	3		T1	T2, T7	T3 – T6	
MPF	FC	1	2	3	4	5
7. Waste	1			T3	T2, T4 – T6	T1, T7
	2		T1	T5	T2 – T4	T6, T7
	3			T2	T1, T3 – T5	T6, T7
8. Degree of anthropization	1	T7			T6	T1 – T5
	2	T7		T6		T1 – T5
	3	T7			T6	T1 – T5
9. Frequency of visitors	1		T7	T2 – T5	T6	T1
	2	T7	T6		T5	T1 – T4
	3	T7	T6		T4	T1 - T3, T5
10. Access to the beach	1	T7			T6	T1 – T5
	2	T7				T1 – T6
	3	T7				T1 – T6
11. Beach surface affected by mechanical cleaning (%)	1	T7				T1 – T6
	2		T6, T7		T5	T1 – T4
	3				T7	T1 – T6
12. Fixed structures (specify)	1		T7		T6	T1 – T5
	2	T6	T7			T1 – T5
	3		T7		T6	T1 – T5

Table A.3. 5. Results obtained of applying **DI** variables in **Guadiana estuary** (T*n* refers to transect number according to Figure 6.2.b). FC: Field campaign

MOF	FC	1	2	3	4	5
1. Width of the active dune system (m)	1	T3, T7	T1, T2, T4 – T6			
	2	T3	T1, T2, T4 – T7			
	3	T3	T1, T2, T5 – T7	T4		
2. Modal height (m)	1		T1 – T3, T6	T4	T5, T7	
	2		T1 – T4	T6	T5, T7	
	3		T1, T3, T4	T2, T6	T5, T7	
3. Degree of fragmentation (%)	1			T7	T1, T2, T5, T6	T3, T4
	2				T3, T6	T1, T2, T4, T5, T7
	3				T1, T2	T3 – T7
4. Dune front with presence of erosive scarps (%)	1				T1, T2	T3 – T7
	2					T1 – T7
	3				T1	T2 – T7
EF	FC	1	2	3	4	5
5. Plant succession continuity	1			T7	T1 – T3, T6	T4, T5
	2			T6	T3	T1, T2, T4, T5, T7
	3			T1	T2, T3, T7	T4 – T6
6. Presence of rabbits (burrows)	1					T1 – T7
	2			T1, T4, T5, T7		T2, T3, T6
	3			T4, T5		T1 – T3, T6, T7
7. Presence of invertebrates, reptiles and bird nests in the dune system	1	T7		T1 – T3, T5, T6	T4	
	2			T3 – T7	T1, T2	
	3			T1 – T6	T7	
8. Plants with exposed roots (%)	1			T2	T1	T3 – T7
	2					T1 – T7
	3				T1, T2, T5	T3, T4, T6, T7
MPF	FC	1	2	3	4	5
9. Control traffic and parking of vehicles	1	T1 – T7				
	2	T1 – T7				
	3	T1 – T7				
10. Presence of sand collectors	1	T1 – T4, T7				T5, T6
	2	T1 – T4, T7				T5, T6
	3	T1 – T4, T7				T5, T6
11. Access control, enclosure of the dune system	1	T1 – T7				
	2	T1 – T7				
	3	T1 – T7				
12. Information panels (nº per 1000 m)	1	T1 – T7				
	2	T1 – T5, T7	T6			
	3	T1 – T5, T7	T6			
13. Waste (% of surface affected in the dune system)	1	T3	T7	T2, T6	T1, T4, T5	
	2			T1, T2	T3 – T5, T7	T6
	3		T7	T5	T1 – T4, T6	

Table A.3. 6. Results obtained of applying **TFI** variables in **Guadiana estuary** (T*n* refers to transect number according to Figure 6.2.b). FC: Field campaign

MOF	FC	1	2	3
1. Long term evolution of the width (m)	1			T1 – T3
	2			T1 – T3
	3			T1 – T3
2. Presence of micro-cliffs	1		T1	T2, T3
	2		T1	T2, T3
	3		T1	T2, T3
3. Long term changes in profile slope	1		T1	T2, T3
	2		T1	T2, T3
	3		T1	T2, T3
EF	FC	1	2	3
4. Long term changes in the occupied surface	1			T1 – T3
	2			T1 – T3
	3			T1 – T3
5. Pioneer saltmarsh with the respect to the total saltmarsh width	1	T1, T2		T3
	2		T1, T2	T3
	3	T1, T2		T3
6. Exposure Frequency in the lower limit	1			T1 – T3
	2			T1 – T3
	3			T1 – T3
7. Total cover	1			T1 – T3
	2		T1	T2, T3
	3		T1	T2, T3
8. Plant cover fragmentation	1		T1	T2, T3
	2			T1 – T3
	3		T1	T2, T3
9. Negative indicator species	1		T1 – T3	
	2		T1 – T3	
	3		T1 – T3	
MPF	FC	1	2	3
10. Reclaimed zones	1		T1 – T3	
	2		T1 – T3	
	3		T1 – T3	
11. Shell fishing pressure	1	T1 – T3		
	2	T1 – T3		
	3	T1 – T3		
12. Waste	1		T1 – T3	
	2		T1 – T3	
	3		T1 – T3	

Table A.3. 7. Results obtained of applying **SSEI** variables in **Ebro estuary** (T*n* refers to transect number according to Figure 6.2.c). FC: Field campaign

MOF	FC	1	2	3	4	5
1. Beach width (m)	1			T2, T11	T6, T9	T1, T3 – T5, T7, T8, T10
	2	T2, T11	T9			T1, T3 – T8, T10
	3	T9, T11			T2, T10	T1, T3 – T8
2. Long term evolution of the shoreline (m/year)	1		T10	T9	T1 – T3	T4 – T8
	2		T10	T9	T1 – T3	T4 – T8
	3		T10	T9	T1 – T3	T4 – T8
3. Predominant Morphological State	1			T9	T1 – T7, T10, T11	T8
	2			T9	T1 – T7, T10, T11	T8
	3			T9	T1 – T7, T10, T11	T8
4. Intertidal sandy bars	1	T8 – T11		T1 – T3		T4 – T7
	2	T9 – T11	T8	T1 – T3		T4 – T7
	3	T9 – T11	T8	T1 – T3	T4 – T7	
5. Stoniness (%)*	1	T2			T3, T4	T1, T5 – T11
	2					T1 – T11
	3			T2		T1, T3 – T11
EF	FC	1	2	3	4	5
6. Organic accumulations of marine origin (driftlines, accumulated marine waste)	1	T11		T4		T1 – T3, T5 – T9
	2	T1, T3, T4		T2	T5 – T11	
	3		T4 – T8, T11	T1, T9, T10	T2, T3	
MPF	FC	1	2	3	4	5
7. Waste	1		T8	T2, T5, T11	T1, T3, T4, T6, T7, T10	T9
	2			T2	T1, T3 – T6, T8 – T10	T7, T11
	3				T1 – T7, T9, T10	T8, T11
8. Degree of anthropization	1			T1, T2		T3 – T11
	2			T1, T2		T3 – T11
	3			T1, T2		T3 – T11
9. Frequency of visitors	1			T5 – T10	T3, T4	T1, T2, T11
	2			T2, T4	T1, T7	T3, T5, T6, T8 – T11
	3		T5 – T10	T2, T4	T1, T3	T11
10. Access to the beach	1	T1, T2				T3 – T11
	2	T1, T2				T3 – T11
	3	T1, T2				T3 – T11
11. Beach surface affected by mechanical cleaning (%)	1		T2	T1		T3 – T11
	2			T1	T2 – T4	T5 – T11
	3		T1, T2		T4	T3, T5 – T11
12. Fixed structures (specify)	1			T1, T2		T3 – T11
	2			T1	T2, T5, T6, T9	T3, T4, T7, T8, T10, T11
	3				T1, T2	T3 – T11

Table A.3. 8. Results obtained of applying **DI** variables in **Ebro estuary** (T*n* refers to transect number according to Figure 6.2.c). FC: Field campaign

MOF	FC	1	2	3	4	5
1. Width of the active dune system (m)	1	T9, T10	T2, T4, T8	T3		
	2	T9, T10	T2, T4, T8	T3		
	3	T9, T10	T2, T4, T8	T3		
2. Modal height (m)	1	T2	T4, T10		T3, T8, T9	
	2		T2, T4, T10		T3, T9, T9	
	3		T2, T4, T10		T3, T8, T9	
3. Degree of fragmentation (%)	1				T2	T3, T4, T8, T9, T10
	2		T2		T4, T8	T3, T9, T10
	3				T2, T9	T3, T4, T8, T10
4. Dune front with presence of erosive scarps (%)	1					T2, T3, T4, T8, T9, T10
	2			T2, T3	T4	T8, T9, T10
	3			T9	T8	T2, T3, T4, T10
EF	**FC**	**1**	**2**	**3**	**4**	**5**
5. Plant succession continuity	1			T2, T9	T3, T10	T4, T8
	2			T8	T2, T3, T4	T9, T10
	3			T2	T10	T3, T4, T8, T9
6. Presence of rabbits (burrows)	1				T3, T8	T2, T4, T9, T10
	2		T3			T2, T4, T8, T9, T10
	3					T2, T3, T4, T8, T9, T10
7. Presence of invertebrates, reptiles and bird nests in the dune system	1			T2	T3, T9, T10	T4, T8
	2	T2, T10		T3, T4, T8, T9		
	3			T2, T4, T8, T9	T10	T3
8. Plants with exposed roots (%)	1					T2, T3, T4, T8, T9, T10
	2		T2	T3, T8		T4, T9, T10
	3				T2	T3, T4, T8, T9, T10
MPF	**FC**	**1**	**2**	**3**	**4**	**5**
9. Control of traffic and parking of vehicles	1			T2		T3, T4, T8, T9, T10
	2					T2, T3, T4, T8, T9, T10
	3			T2		T3, T4, T8, T9, T10
10. Presence of sand collectors	1	T2, T3, T4, T8, T9, T10				
	2	T2, T3, T4, T8, T9, T10				
	3	T2, T3, T4, T8, T9, T10				
11. Access control,	1	T2		T8, T9, T10		T3, T4

enclosure of the dune system	2	T2				T3, T4, T8, T9, T10
	3	T2				T3, T4, T8, T9, T10
12. Information panels (nº per 1000 m)	1	T2, T8, T9, T10		T3, T4		
	2	T4, T10	T2, T3, T8, T9			
	3	T3, T4, T8, T9, T10	T2			
13. Waste (% of surface affected in the dune system)	1			T3	T2, T4, T8, T10	T9
	2		T8	T3, T9	T2, T4, T10	
	3			T3, T4, T8	T2, T9, T10	

Annex 4. Summary of Scientific Activities

International Conferences

Aranda, M., Gracia, F.J., Peralta, G. & Flor-Blanco, G. 2018. Towards a comprehensive functionality assessment of estuaries: first approaches in San Vicente de la Barquera estuary (Cantabria, Spain). VI International Conference on Estuaries and Coasts (ICEC-2018), Caen, France (*Oral Presentation*).

Publications in International Journals

Aranda, M., Gracia, F. J. & Peralta, G. (2020). Estuarine Mapping and Eco-Geomorphological Characterization for Potential Application in Conservation and Management: Three Study Cases along the Iberian Coast. *Applied Sciences*, 10, SI 13, 4429; doi: 10.3390/app10134429

Aranda, M., Gracia, F. J., Peralta, G., & Flor-Blanco, G. (2020). The Application of High-Resolution Mapping for the Analysis of Recent Eco-Geomorphological Changes in the Saltmarshes of San Vicente de la Barquera Estuary (North Spain). *Journal of Coastal Research*, SI, 95.

Book Chapters

Aranda, M.; Gracia; F.J., Peralta, G. and Flor-Blanco, G. 2020. Towards a Comprehensive Functionality Assessment of Estuaries: First Approaches in San Vicente de la Barquera Estuary (Cantabria, Spain). In: *Estuaries and Coastal Zones in Times of Global Change. Proceedings of ICEC-2018*. Eds.: Nguyen, K.D., Guillou, S., Gourbesville, P. and Thiébot, J. Springer Singapore.

Del Río, L., Benavente, J., Gracia, F. J., Anfuso, G., Aranda, M., Montes, J. B., Puig, M., Talavera, L. & Plomaritis, T. (2019). Beaches of Cádiz. In Morales, J. A, (Ed.), *The Spanish Coastal Systems. Dynamic Processes, Sediments and Management*, pp 311-334, Springer. ISBN 978-3-319-93168-5

Gracia, F. J., Del Río, L., Aranda, M., Anfuso, G., Talavera, L., Montes, J. B. & Benavente, J. (2019). Dunes in the Gibraltar Strait Realm. In Morales, J. A, (Ed.), *The Spanish Coastal Systems. Dynamic Processes, Sediments and Management*, pp 661-680, Springer. ISBN 978-3-319-93168-5

Reports

Aranda, M., Gracia, F. J. & Pérez-Alberti, A. (coords.). (2019). Selección y descripción de variables que permitan diagnosticar el estado de conservación de la 'Estructura y función' de los diferentes tipos de hábitat costeros. Serie "Metodologías para el seguimiento del estado de conservación de los tipos de hábitat". Ministerio para la Transición Ecológica, Madrid. 132 pp.

Gracia, F. J., Aranda, M. & Pérez-Alberti, A. (2019). Descripción de métodos para estimar las tasas de cambio del parámetro 'Superficie ocupada' por los diferentes tipos de hábitat costeros. Serie "Metodologías para el seguimiento del estado de conservación de los tipos de hábitat". Ministerio para la Transición Ecológica, Madrid. 87 pp.

Gracia, F. J., Aranda, M. & Pérez-Alberti, A. (2019). Descripción de procedimientos para estimar las presiones y amenazas que afectan al estado de conservación de cada tipo de hábitat costero. Serie "Metodologías para el seguimiento del estado de conservación de los tipos de hábitat". Ministerio para la Transición Ecológica, Madrid. 35 pp.

Gracia, F. J., Aranda, M. & Pérez-Alberti, A. (2019). Establecimiento y aplicación de criterios de representatividad para identificar zonas de seguimiento para los diferentes tipos de hábitat costeros. Serie "Metodologías para el seguimiento del estado de conservación de los tipos de hábitat". Ministerio para la Transición Ecológica, Madrid. 42 pp.

Pérez-Alberti, A., Gracia, F. J. & Aranda, M. (2019). Identificación y descripción de los diferentes tipos de costa en el conjunto del litoral español. Serie "Metodologías para el seguimiento del estado de conservación de los tipos de hábitat". Ministerio para la Transición Ecológica, Madrid. 87 pp.

Publications in Preparation

Aranda, M., Montes, J., Peralta, G., Gracia, F.J., van der Wal, D. & Bouma, T.J. (202?). On the possible origin of spatial patterns of change in saltmarshes in San Vicente de la Barquera estuary (N Spain) (*forthcoming submission to the journal Estuarine, Coastal and Shelf Science*).

International Stays Abroad

The author did a research stay in the Royal Netherlands Institute for Sea Research (NIOZ), in the department of Estuarine & Delta Systems (EDS) from November 1st 2019 to February 16th 2020, under supervision of Prof. Dr. Daphne van der Wal and Prof. Dr. Tjeerd J. Bouma. The activities carried out were a collaborative research on large-scale and long-term estuarine system dynamics.

Scientific courses and activities

2017. Sistemas de posicionamiento GNSS. From 20/11/2017 to 01/12/2017 (40 hours). University of Cádiz

2018. Coastal morphodynamic modelling using XBeach. From 16/01/2018 to 23/01/2018 (40 hours). University of Cádiz

2018. Graphical design for researches. From 29/01/2018 to 31/01/2018 (15 hours). University of Cádiz

2018. Identificación y gestión de riesgos e impactos ambientales en costas de interés turístico. From 19/03/2018 to 23/03/2018 (25 hours). University of Cádiz

2018. Teledetección Aplicada al Medio Ambiente. From 08/10/2018 to 19/11/2018 (50 hours). IngeoExpert (https://ingeoexpert.com/nosotros/?v=04c19fa1e772).

2019. Matlab oriented to Sea Research. From 09/09/2019 to 13/09/2019 (20 hours). University of Cádiz

2019. Oceanography and object-oriented programming with Python. From 28/10/2019 to 30/10/2019 (20 hours). University of Cádiz

2020. RODIN, UCA Institutional Repository and Open Access information resources. From 04/05/2020 to 18/05/2020 (15 hours). University of Cádiz

2020. English Course, level C1.1. From 05/03/2020 to 02/06/2020 (90 hours). Centro Superior de Lenguas Modernas. University of Cádiz.

2020. Climate change and Agenda 2030. From 04/05/2020 to 26/06/2020 (40 hours). University of Cádiz.

2020. Attendance to the Brunings Lecture in the Univesity of Utrech, 14 January 2020, about the advances in the last 6 years on estuarine dynamics in the University of Utrecht.