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ORIGINAL PAPER

EstuarIndex: an eco-geomorphological index to assess the conservation state of estuaries

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Abstract

The main objective of this work is to present a novel methodology to assess the environmental, ecological, and conservation status of mid-latitude estuaries by means of an index-based method, *EstuarIndex*. The *EstuarIndex* is an integration of four sub-indexes, assessing the status of the main subsystems present on estuaries: sandy environments, dunes, tidal flats, and the drainage network. Each sub-index includes variables combining three types of factors: morphosedimentary and oceanographic factors, ecological factors, and management and protection factors. The environmental status is finally evaluated in five possible classes: (1) Very low, (2) Low, (3) Medium, (4) High, and (5) Very High, according to EU requirements for classifying the conservation status of habitats. Three pilot zones along the Spanish coast have been chosen for testing the method: San Vicente de la Barquera estuary (N Spain), Guadiana estuary (SW Spain), and Ebro River delta mouth (E Spain). They present different oceanographic and geomorphological conditions. The results obtained have proven that *EstuarIndex* is a suitable methodology for the application to other estuaries. The systematic application of *EstuarIndex* on broad time scales would allow evaluating the system trends, what seems key for implementation of more realistic restoration strategies, and it has a great potential as a tool for environmental management in natural protected areas. Furthermore, it may help in the detection of the most relevant site-specific vulnerabilities for long-term sustainability in response to both natural and artificial drivers.

Keywords Estuaries · Estuarine conservation · Coastal vulnerability · Index-based assessment · Habitat connectivity

Introduction

The capacity to predict coastal changes and assess coastal vulnerability with reasonable reliability is a common goal for decision-makers worldwide (Thieler and Hammar-Klose 1999). To identify areas susceptible to change due to increased coastal pressures, it is necessary to have methodologies to evaluate the corresponding level of vulnerability. An early methodology was the Coastal Vulnerability Index (CVI) (Gornitz 1991; Gornitz et al. 1994). Today, the CVI is probably one of the most widespread index-based methods for estimating coastal vulnerability to sea-level rise (SLR) (Koroglu et al. 2019).

Index-based methods are common procedures for assessing the vulnerability of a given natural system. These types of methods use the combination of variables that allow vulnerability to be expressed as a dimensionless synthetic index (Rizzo 2017). The advantage of using indices is the reduction of several values into a single one which, as they are applied by sectors within the system, allows the identification of the most vulnerable points within the system. This can be also described as a disadvantage, as the extreme simplification of the complex structures and processes typical of coastal areas into a single value, which reduces the complex coastal dynamics into a 'static view' of state of vulnerability of the system, is not always 100% representative of the functioning of the system. Another disadvantage of index-based methods is the subjective nature of their application, since each author tends to modify, or even create a new index, to fit specific objectives that are not well covered in the original design (García-Mora et al. 2001; Ciccarelli et al.

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2017; Peña-Alonso et al. 2017; Rizzo et al. 2018; Defne et al. 2020). Consequently, there is not a universal coastal index facilitating the comparison between coasts of different regions. Instead, there is a great diversity of indexes that improve the scientific knowledge and the amount of information available for each site, making difficult the comparison of sites and, in the case of Spain, hampers the creation of a national homogeneous database evaluating the environmental status of the national coasts.

Trying to narrow this methodological gap, this work aims to design a simple index-based methodology (*EstuarIndex*) with easy and extended applicability. For that, different locations and types of estuaries have been selected to illustrate the index efficiency. *EstuarIndex* evaluates the vulnerability of estuaries to increasing coastal pressures with a subsystem category approach (i.e., beaches, dunes, saltmarshes, and the drainage networks), modifying a previous attempt (Aranda et al. 2019) to extend it to any mid-latitude estuary.

Study zones

To broaden the applicability of the method, three study areas were selected with the aim of including the oceanographic and environmental variability of Spain (Fig. 1). Specifically, the study areas are: (1) San Vicente de la Barquera estuary (N Spain; SVB in Fig. 1a, (2) Guadiana River estuary (SW Spain; GUA in Fig. 1b, and (3) Ebro River Delta mouth (E Spain; EBR in Fig. 1c.

The first one is located on a mesotidal coast where fluvial sediment supply to the coast is rather limited (Flor-Blanco 2007). The Guadiana estuary is located on a low-energy mesotidal coast with important fluvial sedimentary input (Morales and Garel 2019). The Ebro River Delta is located on a microtidal environment with decreasing sediment discharge by the river due to strong artificial regulation of its basin (Aranda et al. 2022).

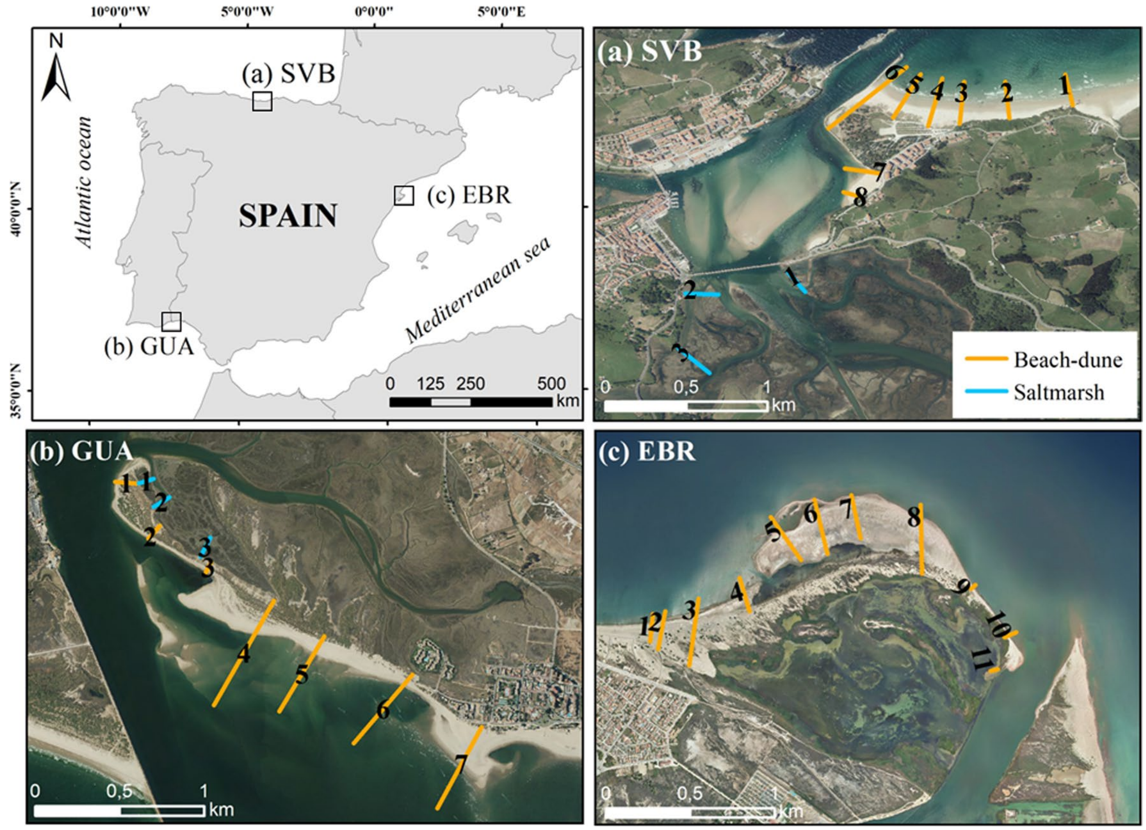

Fig. 1 Location of study cases and transects positions. **a** San Vicente de la Barquera estuary (SVB), **b** Guadiana estuary (GUA), and **c** Ebro River Delta mouth (EBR). Yellow transects correspond to beaches and dunes, and blue ones to tidal flats. Transect number is indicated next to the corresponding transect

Methods

The *Estuarindex* is an integration of four sub-indexes (Fig. 2), which evaluate the environmental conservation status of the typical subsystems of a mid-latitude estuary: *Shoreline Sandy Environments Index* (SSEI), *Dunes Index* (DI), *Tidal Flats Index* (TFI), and *Drainage Network Index* (DNI).

The sub-indexes are designed to include variables from three types of factors: (1) morphosedimentary and oceanographic factors (MOF), (2) ecological factors (EF), and (3) management and protection factors (MPF). All the variables that need further explanation are detailed in the *Supplementary Material* file. The reference value of each variable was set at the first high-quality information available for the system, or in a specific state considered pristine according to the literature of the site, 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 (Pethick and Crooks 2000), i.e., the systems within the estuary are linked and the functioning of each one has an impact on the others. Finally, the environmental status of the whole system is evaluated after the application of the four sub-indexes, resulting in five possible classes: (1) Very low, (2) Low, (3) Medium, (4) High, and (5) Very High, according to EU requirements for classifying the conservation status of habitats.

In situ data collection

In situ data collection was carried out for the data acquisition on each study zone. It included visual inspection of the subsystems, field measurements of selected variables, and topographic surveys. Measurements were designed in transects (Fig. 1; additional details of field measurement can be found in Aranda 2021; and in Supplementary Material file). Each study area was visited three times over a year to include seasonal and interannual fluctuations (Table 1).

Table 1 Sampling dates according to campaigns and study 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

Topographic data were obtained with a differential GPS with real-time kinematic correction (RTK-DGPS, Leica GS18). To have a unique reference system, and to be able to compare the data between study areas, the heights were referred to the Spanish reference datum. All campaigns were carried out during low spring tides.

The number of transects needed to represent each subsystem was variable depending on the study area, according to its specific physical and oceanographic characteristics, extension, or accessibility (Fig. 1). For the mesotidal systems (SVB and GUA), the tidal flat transects were spread out to cover the entire marsh (> 100 m distance, Fig. 1). Vegetation monitoring was structured according to local zonation, using a minimum area of 1 × 1 m randomly distributed in each vegetation horizon along each transect.

Index design: variables and estimation methods

This section describes variables and equations to calculate the four sub-indexes of the *EstuarIndex* (Fig. 2). For each

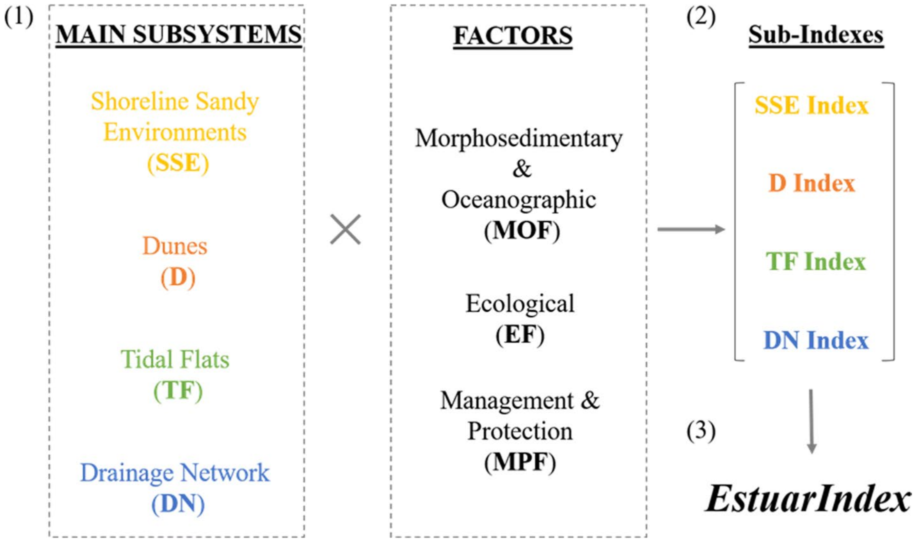

Fig. 2 Flowchart showing the *EstuarIndex* structure. (1) Calculation of MOF, EF, and MPF for every main subsystem, (2) Calculation of sub-indexes (SSEI, DI, TFI, and DNI), and (3) calculation of *EstuarIndex* based on the integration of the sub-indexes

subsystem, variables are proposed according to the factor considered (MOF, EF, and MPF).

1. Shoreline Sandy Environments Index (SSEI):

The aim is to provide a tool flexible enough to assess any mid-latitude beach. Range of values of proposed variables are defined in Table 2.

- 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 (Table 2). The MOF include: (1) beach width (m, BW) between the dune foot and the wet line. This variable is classified according to the range proposed by Aranda et al. (2019); (2) long-term evolution of the shoreline (m/year, LTE), considering a time span of more than 30 years (Rizzo 2017). The values are assigned following the classification proposed by Gornitz et al. (1997). This variable was defined using only the Linear Regression Rate (LRR; m/year); (3) predominant morphodynamic state (PMS); (4) presence of sand bars (SB); and (5) stoniness of the beach (S), considered as the proportion of coarse elements (clasts, medium-to-large shells, etc.) covering the surface of the beach (Hodgson 1974).
- Ecological factors (EF): These factors measure the ecological state of the system. For this subsystem, only the (1) presence/absence of drift lines (D) was considered. Drift lines are deposition material (often marine organic waste) that usually accumulate on the lowest level of the supralittoral zone, just above the wet line. The have been considered as they play 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 (Vacchi et al. 2017; Boudouresque et al. 2016) Haga clic o pulse aquí

Table 2 Shoreline Sandy Environments Index (SSEI)

Shoreline Sandy Environments	1	2	3	4	5
MOF					
BW (m, Atlantic region)[1]	< 25	> 25	> 40	> 50	> 60
BW (m, Mediterranean reg.)[1]	<15	>15	>20	>30	>50
LTE (m/year)[2]	<-2	<-1	0	>1	>2
PMS[3]	Reflective	Reflective high tide	Intermediate	Dissipative	Ultra-dissipative
SB[4]	Absent	-	1	-	>1
S (%)[1]	>50	>40	>30	>15	<15
EF					
D[1]	Absent	Rare	Occasional	Frequent	Permanent
MPF					
W[5]	Unclean	Moderately unclean	-	Moderately clean	Clean
DoA[1]	Urban	-	Seminatural	-	Natural
FoV[1]	Frequently	-	Seasonally	-	Rarely
AB[1]	Any mode of transport, public transport	-	Private transport	-	Not mechanical transport
MC (%)[1]	>75	<75	<50	<25	0
F[1] (specify)	Fixed structures such as jetties, promenades, breakwaters, ports, etc.	-	Small structures	-	Absence

Range of values of variables proposed for the morphosedimentary factors (MOF), ecological factors (EF), and management and protection factors (MPF) of the Shoreline Sandy Environments. *BW* beach width, *LTE* long-term evolution of the shoreline, *PMS* predominant morphodynamic state, *SB* presence of sand bars, *S* stoniness of the beach, *D* presence/absence of driftlines, *W* waste, *DoA* degree of anthropization, *FoV* frequency of visitors, *AB* access to the beach, *MC* mechanical cleaning, *F* fixed structures. Superscript numbers next to variables indicate the references from which they have been modified with 1: Aranda et al. (2019), 2: Gornitz et al. (1997), 3: Gornitz (1991); Rizzo (2017), 4: Gracia et al. (2009), 5: García-Mora et al. (2001)

Table 3 Dunes Index (DI): range of values of variables proposed for the morphosedimentary factors (MOF), ecological factors (EF), and management and protection factors (MPF) of the Dune environment

Dunes	1	2	3	4	5
MOF					
DW (m)[1]	<50	≥50	>250	>500	>1000
MH (m)[1]	<1	≥1	>2	>3	>6
DoF (%)[2]	≥50	-	25-50	-	None
ES (%)[1]	>75	≤75	<50	<25	0
EF					
PSC[2]	None	-	Discontinue	-	Complete
PoR[2]	High	-	Sporadic	-	None
PoI[2]	None	-	Sporadic	-	High
ER (%)[2]	>50	>25	>15	>5	≤5
MPF					
T&P[1]	None	-	Seasonal	-	Permanent
SC[1]	None	-	Sporadic	-	Permanent
AC[1]	None	-	Moderate	-	Total
IP (nº per 1000 m)[1]	0	1	2	3-4	≥5
W (%)[2]	≥50	<50	<25	<5	0

DW Dune width, *MH* modal height of the active dune system, *DoF* degree of fragmentation, *ES* Dune front with presence of erosive scarps, *PSC* plant succession continuity, *PoR* rabbits, or their burrows, *PoI* invertebrates, reptiles and bird nests, *ER* exposed roots, *T&P* vehicle traffic and parking, *AC* access control, enclosure of the dune system, *SC* installation of sand collectors, *IP* information panels, *W* percentage of the dune front affected by solid waste. Superscript numbers next to variables indicate the references from which they have been modified with 1: Gracia et al. (2009), 2: García-Mora et al. (2001)

para escribir texto., and providing sediment to adjacent dune systems (Beltran et al. 2020).

- Management and protection factors (MPF): The evaluation of anthropic pressures in the beach subsystem was evaluated according to: (1) waste (W), classified in four qualitative categories (García-Mora et al. 2001); (2) degree of anthropization (DoA), without considering rigid structures but rather the urbanization of the beach; (3) frequency of visitors (FoV), related to carrying capacity of the beach (Rodella et al. 2017); (4) access to the beach (AB); (5) mechanical cleaning (%; MC), a practice that often involves the destruction of marine debris, pioneer plants, and invertebrate communities living on the beach (Roig-Munar et al. 2012; Beltran et al. 2020); and (6) fixed structures (F).
- *Shoreline Sandy Environments Index quantification*

The value of each factor results from

$$\mathrm{SSE_{MOF}} = \frac{(\mathrm{BW} + \mathrm{LTE} + \mathrm{PMS} + \mathrm{SB} + \mathrm{S})}{25}, \tag{1}$$

$$\mathrm{SSE_{EF}} = \frac{\mathrm{D}}{5}, \tag{2}$$

$$\mathrm{SSE_{MPF}} = \frac{(\mathrm{W} + \mathrm{DoA} + \mathrm{FoV} + \mathrm{AB} + \mathrm{MC} + \mathrm{FS})}{30}, \tag{3}$$

where $\mathrm{SSE_{MOF}}$, $\mathrm{SSE_{EF}}$, and $\mathrm{SSE_{MPF}}$ 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 three factors (Eq. 4)

$$\mathrm{SSEI} = \frac{(\mathrm{SSE_{MOF}} + \mathrm{SSE_{EF}} + \mathrm{SSE_{MPF}})}{3}. \tag{4}$$

2. Dune Index (DI)

The conservation of dunes depends on the balance between sedimentary and ecological factors and is often linked to the natural succession of plants, since this is one of the most representative indicators of the environmental health of dune systems. Range of values for each variable proposed are indicated in Table 3.

- Morphosedimentary and Oceanographic factors (MOF): The proposed variables are: (1) dune width (m; DW) and (2) modal height of the active dune system (m; MH). Together, these two variables provide information on the resilience of the dune system (Gracia et al. 2009); (3) degree of fragmentation (%; DoF) with respect to the total occupied surface; and (4) dune front with presence of erosive scarps (%; ES).

Table 4 Tidal Flats Index (TFI): range of values of variables proposed for the morphosedimentary factors (MF), ecological factors (EF), and management and protection factors (MPF) of tidal flat environments

Tidal Flats	1	2	3
MOF			
LTEWS (m)^1	Erosion (>50%)	Erosion (<50%)	Accretion
PoM-C	All along the profile	Local	None
LTCPS	Remarkable changes	Slight variations	No changes
EF			
LTCOS^2	Loss	No change	Gain
PionSW (%)	< 20%	20 – 40 %	>40 %
ExpF^3	Remarkable changes	Slight variations	No changes
TC (%)^4	< 30%	30-70 %	>70%
PCF4	Total	Discontinue	None
IAS5	Expansion	No expansion*	None
MPF			
WR	> 40%	<10%	No
SF	Continuous	Seasonal	None
W (transect %)^6	>50%	<50%	0

LTEWS long-term evolution of the width of the saltmarsh, *PoM-C* presence of micro-cliffs, *LTCPS* long-term changes in profile slope, *LTCOS* long-term changes in occupied surface, *PionSW* proportion of the pioneer zone, *EF* exposure frequency in the pioneer zone, *TC* total plant cover, *PCF* plant cover fragmentation, *IAS* negative indicator species, *WR* wetland reclamation, *SF* shell fishing pressure, *W* presence of waste. Superscript numbers next to variables indicate the references from which they have been modified with 1: Defne et al. (2020), 2: Aranda et al. (2019), 3: Balke et al. (2016), 4: de Vries et al. (2018), 5: Committee (2004), 6: García-Mora et al. (2001)

*Less than 10% expansion in the last 10 years

- Ecological Factors (EF): 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 include (1) plant succession continuity (PSC), and presence of typical faunistic communities; (2) rabbits, or their burrows (PoR); and (3) invertebrates, reptiles, and bird nests (PoI), which sometimes negatively influence the stabilization of dunes (Williams et al. 2001). The erosion due to wind exposure can be directly expressed by the (4) exposed roots (ER).
- Management and Protection Factors (MPF): (1) vehicle traffic and parking (T&P); (2) control access or isolation of the dune system (AC). Numerous techniques allow the recovery of the dune front, including such direct protection measures, or stabilization by (3) installation of sand collectors, SC). Additionally, (4) information panels (IP) provide information to visitors about the actions carried out and the importance for the conservation of the dunes (Gómez-Pina et al. 2002; Ley Vega et al. 2007; Almeida 2017). Finally, the list ends with the (5) percentage of the dune front affected by solid waste (W), with a visual estimation in the field of the amount of solid waste covering the dune area. As for the shoreline sandy environments, the sampling frequency here proposed is biannual.
- Dune Index quantification

The value of each factor results from

$$D_{\mathrm{MOF}} = \frac{(\mathrm{DW} + \mathrm{MH} + \mathrm{DoF} + \mathrm{ES})}{20}, \tag{5}$$

$$D_{\mathrm{EF}} = \frac{(\mathrm{PSC} + \mathrm{PoR} + \mathrm{RoI} + \mathrm{ER})}{20}, \tag{6}$$

$$D_{\mathrm{MPF}} = \frac{(\mathrm{T\&P} + \mathrm{SC} + \mathrm{AC} + \mathrm{IP} + \mathrm{W})}{25}, \tag{7}$$

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 unweighted average of the three factors (Eq. 8)

$$\mathrm{DI} = \frac{(D_{\mathrm{MOF}} + D_{\mathrm{EF}} + D_{\mathrm{MPF}})}{3}. \tag{8}$$

3. Tidal Flat Index (TFI)

The evaluation of tidal flats, understood as systems including vegetated saltmarshes and bare mudflats, is particularly complex (Defne et al. 2020). The scarcity of vulnerability indexes to evaluate the state of conservation of saltmarshes at national and international levels justifies that the reference values here presented include only the results obtained in the field, and only for two of the study

Table 5 Drainage Network Index (DNI)

Drainage Network	1	2	3	4	5
MOF					
$C^{*,1}$	Decrease	-	Remaining constant	-	Increasing
Nat^2	Marked alterations in the amount and seasonal patterns of circulating flow.	Marked variations in the amount of circulating flow but not major changes in the seasonal regime.	Moderated variations in the amount of circulating flow but well characterised seasonal regime.	Minor changes in the amount and seasonal patterns of circulating flow	Amount and temporal distribution of circulating flow according to natural dynamics

Values assigned to the different variables. *C* Connectivity, *Nat* Naturalness of the flow regime. Superscript numbers next to variables indicate the references from which they have been modified with 1: Horton (1945), 2: Ojeda et al. (2007)

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

areas (since Ebro Delta, a microtidal environment, does not include tidal saltmarshes), as the natural value of salt marshes increases with the tidal range, and including a microtidal area will give a low or negative value within the TFI, without actually being a poorly maintained system. A set of variables has been proposed through a combination of results of previous works such as Mccorry and Ryle (2009), Committee (2004) or Defne et al. (2020). Ecology, geomorphology, and physical factors are difficult to separate in saltmarshes. Nevertheless, as in previous subsystems, the variables have been grouped in morphosedimentary and oceanographic (MOF), ecological (EF), and management and protection (MPF) factors, but ranging their values between 1 and 3, being 1 the lowest conservation status and 3 the highest one (Table 4).

- Morphosedimentary and oceanographic factors (MOF): (1) long-term evolution of the width of the saltmarsh (LTEWS). 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; (2) presence of micro-cliffs (erosion edges; PoM-C); (3) long-term changes in profile slope (LTCPS), since variations in the slope of the transects provide information about the spatial extent of the tidal inundation (Leonardi et al. 2016).
- Ecological factors (EF): (1) long-term changes in occupied surface (LTCOS), and (2) proportion of the pioneer band with respect to the total saltmarsh width (%; PionSW), as the pioneer band of the saltmarsh plays a fundamental role in slowing down the incident flow, favoring in most cases the deposition of sediment (Peralta et al. 2008). The extent of the pioneer saltmarsh has been stablished considering *Spartina maritima* and *Salicornia spp.* as pioneer species, both globally distributed along saltmarshes in temperate zones; Other variables include (3) exposure frequency in the pioneer zone (ExpF), defined in Aranda et al. (2022); (4) total plant cover (%; TC), estimated by visual inspection of the percentage of plant cover in a minimum area (1 m^2) per vegetation horizon; (5) plant cover fragmentation (PCF); and (6) presence of negative indicator species (IAS), quantifying the area occupied by the IAS and monitoring its evolution to identify any sign of expansion (Committee 2004).
- 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. They include landfills or (1) wetland reclamation (WR): land-use changes including landfills or reworking of the drainage system, (2) shell fishing pressure (SF), and (3) presence of waste (%; W). At any case, information on local anthropogenic actions should be gathered with revision of the scientific literature and technical reports made in the zone.
- Tidal Flat Index quantification

  In contrast to previous subsystems, for the tidal flat, the variables have different weight in the calculation of the sub-index of the factors (Eqs. 9, 10 and 11). The assigned weight is an initial proposal to give less weight to short-term variables, which may be ephemeral

$$TF_{MOF} = \frac{(0.4 * LTESW) + (0.4 * PoM - C) + (0.2 * LTCPS)}{3}, \quad (9)$$

$$\mathrm{TF}_{\mathrm{EF}} = \frac{(0.2 \ast \mathrm{LTCOS}) + (0.2 \ast \mathrm{PionSW}) + (0.2 \ast \mathrm{ExpF}) + (0.13 \ast \mathrm{TC}) + (0.13 \ast \mathrm{PCF}) + (0.13 \ast \mathrm{IAS})}{3}, \tag{10}$$

$$\mathrm{TF}_{\mathrm{MPF}} = \frac{(0.5 \ast \mathrm{RZ}) + (0.3 \ast \mathrm{SF}) + (0.2 \ast W)}{3}. \tag{11}$$

The TFI is finally obtained from the average of the values of the three factors (Eq. 12)

$$\mathrm{TFI} = \frac{(\mathrm{TF}_{\mathrm{MOF}} + \mathrm{TF}_{\mathrm{EF}} + \mathrm{TF}_{\mathrm{MPF}})}{3}. \tag{12}$$

4 Drainage Network Index (DNI)

Table 6 Estuarine vulnerability index (*EstuarIndex*) ranges

EstuarIndex: Conservation status				
Very low	Low	Medium	High	Very high
1	2	3	4	5
0 ≤ 0.20	0.21 - 0.40	0.41 - 0.60	0.61 - 0.80	> 0.80 - 1

– River dynamics is key for the functioning and ecological quality of the estuarine environment and should be considered a key aspect when evaluating the ecological status of estuaries, since the drainage network acts as a "conveyor belt" for matter and energy, linking the dynamics of the subsystems (Ojeda et al. 2007). This work proposes a channel index (Table 5) adapted from the hydro-geomorphological index (IHM) proposed by Ojeda et al. (2007). The information required for the evaluation was obtained through an extensive review of the available literature for each study zone. Neither ecological nor anthropogenic aspects have been proposed, since the river drainage network is not included in this work approach. Morphosedimentary and oceanographic factors (MOF): The (1) connectivity (C) between subsystems directly relies on the drainage network: the greater the network, the better the state of estuary conservation. In this case, connectivity is considered as the total sum of linear meters of channels

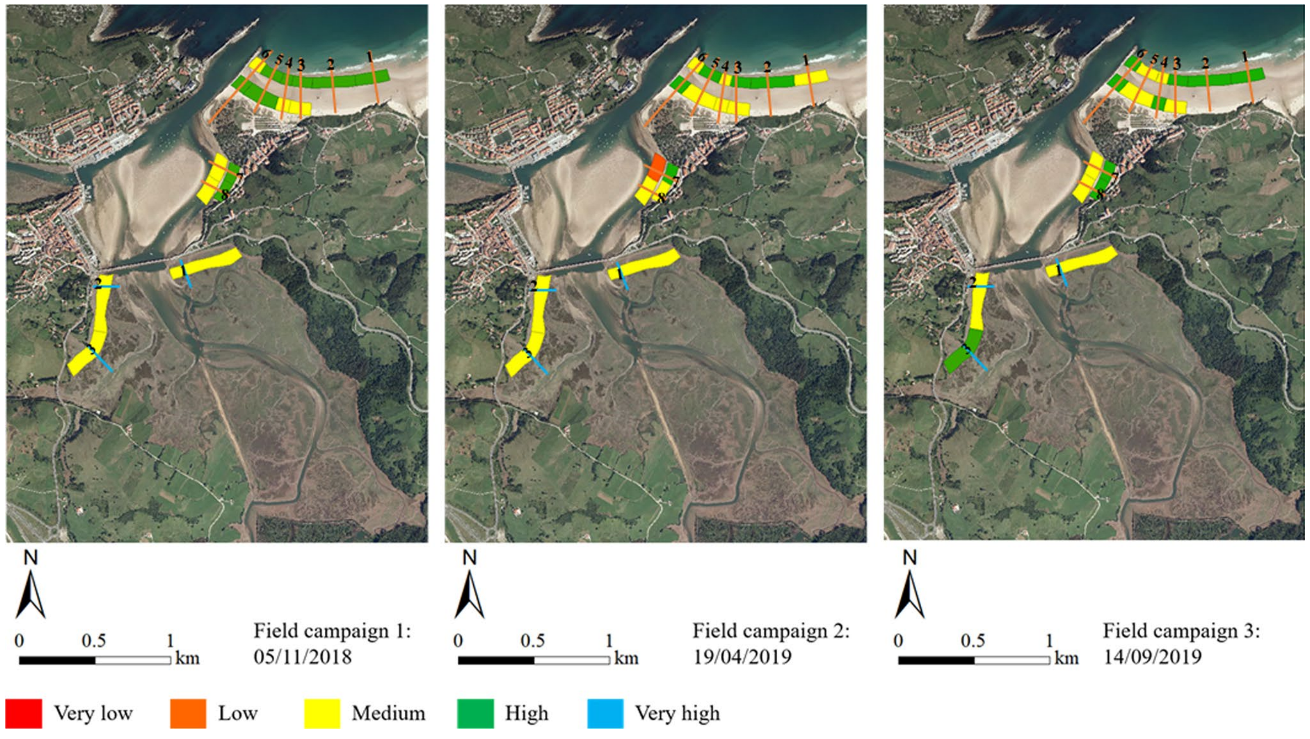

Fig. 3 Graphical outputs of the vulnerability assessment of the San Vicente de la Barquera estuary for successive campaigns (left to right). The values of the subindices are highlighted as colored stripes. Transects locations are also indicated, matching with each stripe. SSEI stripe is the one on the external side of the beach, DI tripe is the one on the inner part of the beach, and the saltmarsh stripes are located on each transect in the inner part of the estuary. Transects legend correspond to Fig. 1

divided by the total area of the saltmarsh (Horton 1945; Eq. 13)

$$C = \frac{\sum Lc}{S}, \tag{13}$$

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).

The (2) naturalness of the flow regime (Nat) assesses if the amount of water that carries the drainage network has been modified by any anthropic pressure.

- Drainage Network Index quantification

  In absence of EF nor MPF, the Drainage Network Index (*DNI*) is only estimated according to MOF (Eq. 14)

Table 7 Results of applying *EstuarIndex* in San Vicente de la Barquera estuary for the three 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

$$\mathrm{DNI} = \mathrm{DN}_{\mathrm{MOF}} = \frac{(C + \mathrm{Nat})}{10}. \tag{14}$$

Integration of sub-indexes: *EstuarIndex*

The estuarine conservation index (*EstuarIndex*, Eq. 15) was computed as the un-weighted average of the values for the four partial indexes (SSEI, DI, TFI, DNI). Thus, *EstuarIndex* ranges between 0 and 1, being 0 the lowest conservation status of the system

$$EstuarIndex = \frac{(\mathrm{SSEI} + \mathrm{DI} + \mathrm{TFI} + \mathrm{DNI})}{4}. \tag{15}$$

Considering the EU requirements for classifying the conservation status of habitats (European Commission 2015),

Table 8 Results of applying *EstuarIndex* in Guadiana estuary for the three 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

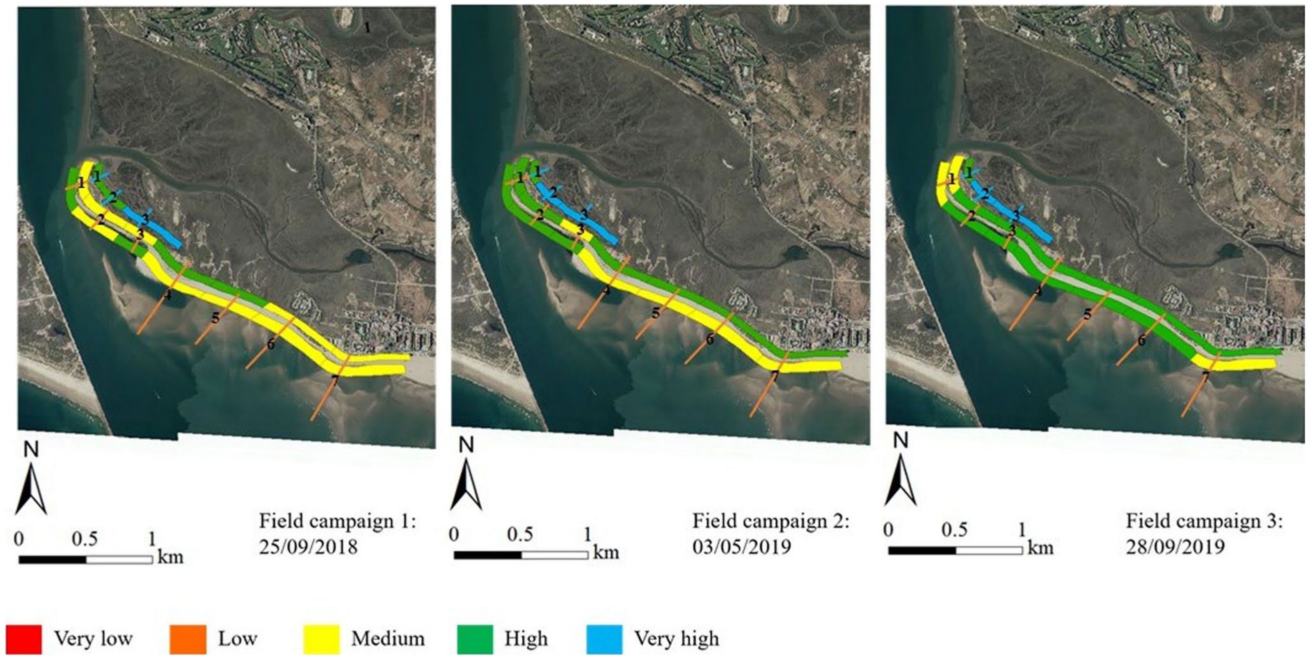

Fig. 4 Graphical outputs of the vulnerability assessment of the Guadiana River estuary for successive campaigns (left to right). Transects locations are also indicated, matching with each stripe. SSEI stripe is the one on the external side of the beach, DI tripe is the one on the inner part of the beach, and the saltmarsh stripes are located on each transect in the inner part of the estuary. Transects legend corresponds to Fig. 1

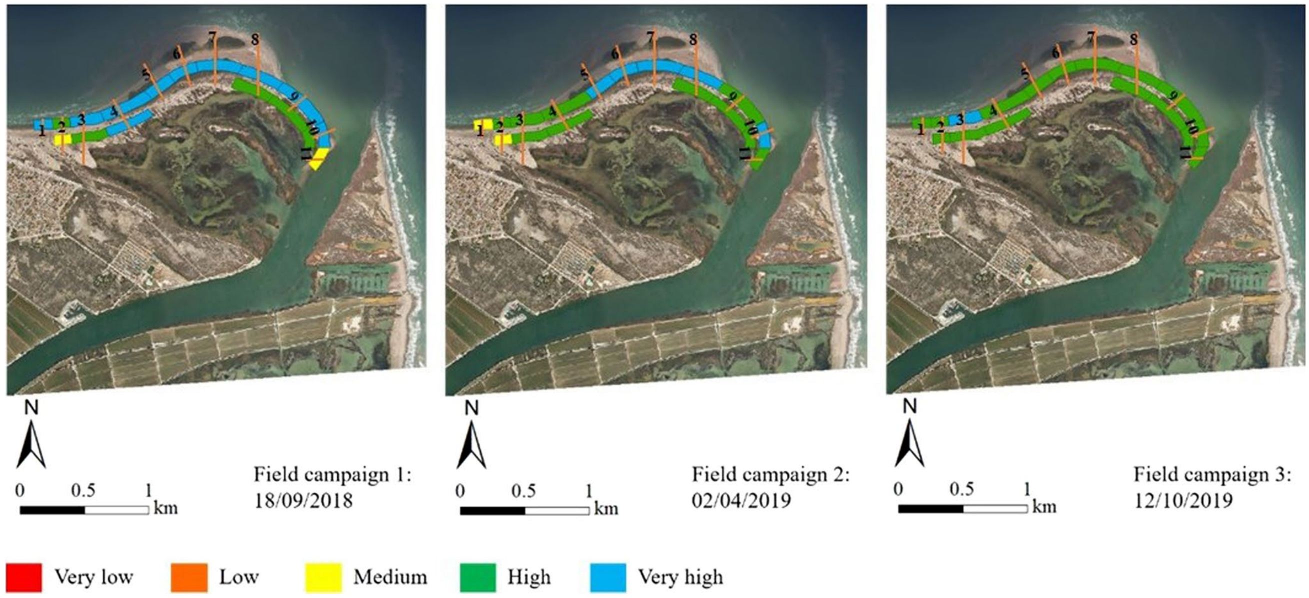

Fig. 5 Graphical outputs of the SSEI, DI and TFI results in the Ebro River Delta mouth for the three field campaigns. The SSEI results are shown in the external stripe and the DI ones in the inner stripe. Transects locations are also indicated, matching with each stripe. Transects legend correspond to Fig. 1

Table 9 *EstuarIndex* values and corresponding state of conservation of the Ebro River mouth for the three field campaigns

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

the ranges established to assess the conservation status of mid-latitude estuary are described in Table 6.

Results

Results of application of the index-based method on each study zone are here presented (specific results of each transect on each study zone is detailed in Online resource 1). To facilitate the description, the results of the four sub-indexes (*SSEI*, *DI*, *TFI*, and *DNI*) will be graphically presented first and, after that, the corresponding values of *EstuarIndex* for each study site will be described. The results of DNI are not shown graphically, since there is only one preliminary value for the entire drainage network on each case, which remains constant.

San Vicente de la Barquera estuary (SVB)

Results are graphically presented in Fig. 3 for SSEI, DI, and TFI. As for the DNI, 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 characterized.

Based on the results for the SSEI, DI, TFI, and DNI, the *EstuarIndex* had values between 0.58 and 0.60, showing that, during the study period, the San Vicente de la Barquera estuary presents a constant conservation status qualified as “Medium” (Table 7).

Guadiana river estuary (GUA)

Results are graphically presented in Fig. 4 for SSEI, DI, and TFI.

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 interannual 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).

According to the results presented for the SSEI, DI, and TFI sub-indexes, the final values of the *EstuarIndex* for Guadiana River estuary are "High" for the entire study period (Table 8).

Ebro river estuary (EBR)

Results are graphically presented in Fig. 5 for SSEI, DI, and TFI.

Based in the results for the SSEI, DI, and TFI, the *EstuarIndex* for the EBR system had values between 0.61 and 0.66, showing that the Ebro River Delta mouth presented during the study period a conservation status of "High" (Table 9).

Discussion

The *EstuarIndex* is designed to respond to the need for an integrated assessment of mid-latitude estuaries based on the conservation status of their subsystems. The application of the *EstuarIndex* seems to be adequate for the evaluation of the conservation status of estuaries of the Iberian coasts under different driving factors controlling their evolution through an index-based methodology. 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. Now, there is only enough information on variables with historical data, while the others still need a longer monitoring period. Therefore, equalizing the information level of all variables should be the first task to consider in future works, by applying the method systematically over the next few years, if possible *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, *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.

EstuarIndex has limitations that can be grouped into 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 to the aim of the design, since the requirement of being a method applicable not only by scientists, but also by technicians of the official institutions in charge of the environmental management of each zone. It 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 reasoned weighting of the variables, first by factors and, second, by variables within the factors.

Conclusions

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.

Although it seems to be a suitable methodology, there are still some challenges to face for the wide application of the *EstuarIndex*. First, the calculation of some variables requires specific information, sometimes not easy to find. Second, it is necessary the tuning of the weighting of the factors and variables proposed, which will require the application to 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, and also, if possible, a comparison between results obtained by other authors applying other methods for the same purpose.

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, keeping in mind the importance of the connectivity of the different subsystems that compose it. 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, as a preliminary example, 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). Therefore, 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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