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Predicting ecotopes from hydrodynamic model data: Towards an ecological assessment of nature-based solutions

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A B S T R A C T

Estuaries worldwide are of substantial ecological value due to the presence of various gradients, such as salinity. Preserving the natural value of estuaries is vital for meeting the climate stabilization goals of the Paris Agreement. Recognizing nature as a stakeholder is imperative, given the surpassing value of ecosystem services over global gross domestic product. Quantifying the current ecological state and future ecological shifts faces challenges, including variable dependencies, spatial-temporal disparities, and the limitations in available information. This study introduces EMMA (Ecotope-Map Maker for Abiotics), a method for quantifying the effects of human interventions or climate change scenarios on estuarine ecosystems by linking abiotic characteristics derived from a hydrodynamic model to ecotopes. The Western Scheldt, an estuary connecting the Scheldt river to the North Sea in the Netherlands, serves as a case study. The method successfully reproduced an existing ecotope-map, which is dependent on real-time data such as aerial photographs. The developed method not only proves applicable in assessing the current ecological state and future ecological shifts for hypothetical scenarios but also demonstrates utility in predicting future situations, providing valuable insights for decision-makers in estuarine ecosystem management and contributing to climate and environmental preservation goals.

1. Introduction

Estuaries, where fluvial freshwater meets saline seawater, are of great ecological significance due to the presence of various gradients, such as salinity and temperature, as well as patches of calm waters. The salinity gradient contributes to the conductivity of water, which is the beginning of many chemical and biological processes while the temperature gradient plays a key role in many growth, reproduction and degradation processes [1]. Hosting diverse wildlife, these environments provide critical habitats for various species, offering shelter, breeding grounds, and nurseries for marine life [2]. Furthermore, estuaries play a crucial part in filtering sediment and pollutants before they reach the oceans [3]. The ecosystems in estuaries rank first among the most productive regions of marine ecosystems due to the high biomass of benthic algae, sea-grasses, salt marsh grasses and phytoplankton [4].

These estuarine ecosystems can be classified into ecotopes, which represent the potential occurrence of a habitat, characterized by relatively homogeneous areas identifiable by their geomorphological and hydrological characteristics, and further defined by their vegetation structure linked to the abiotic conditions in combination with land use [5,6].

The concept of ecotopes finds application across the globe, as evidenced by various publications spanning different regions. Examples include studies from Belgium [7], the United States [8], South Africa [9], and China [10]. These studies address diverse geographical areas and employ a range of methodologies, which are largely based on aerial photographs and alike. The concept of ecotopes serves as a valuable ecological classification system [e.g., 5,11], and have the potential to play a vital role in interdisciplinary communication, connecting for example hydrologist, ecologists, engineers and decision-makers. Various classification systems for ecotopes have been developed [7,9,10,12,13]. While many of these systems emphasize the ecological occurrence of organisms, often relying on aerial photographs. However, [14] introduced 'A Dutch Ecotope System for Coastal Waters' (ZES.1), which prioritizes measurable and objective abiotic characteristics for ecotope distinction, making it particularly suitable for modeling purposes. Abiotic characteristics in this context refer to non-living chemical and physical factors affecting the environment, e.g., temperature, water quantity, and salinity [15].

ZES.1 is a hierarchical classification system for ecotopes, based on

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abiotic characteristics that predominantly define potential ecological communities in the Netherlands [14]. This hierarchy is structured based on the dominance of abiotic characteristics. They have established classes based on their relevance to the occurrence of ecological communities, and thresholds based on national and international systems. The classes, in hierarchical order, are: *Salinity, Substratum 1, Depth 1, Hydrodynamics, Depth 2*, and *Substratum 2*. In Fig. 1, an overview is depicted of the classes, displaying the hierarchy as well as the optional categories within the classes. These categories are assigned based on thresholds. From an ecological perspective, establishing strict thresholds is challenging, as transitions between ecological communities tend to be gradual. Nevertheless, to map ecotopes clear and univocal thresholds are desired, and thus [14] determined thresholds as accurately as possible. Each category has a corresponding label, for instance, the label 'B' within the *Salinity* class, signifies category Brackish. The labels are added in brackets in Fig. 1. The labels are then combined to form the ecotope-label. As an illustration, the ecotope-label, B2.112f denotes an ecotope situated in brackish water (B), with soft substratum (2), located in the sub-littoral zone (1), exhibiting high-energy conditions (1) in deep waters (2), and featuring fine sands (f).

A detailed overview of which category corresponds with which label, and the definitions of the thresholds can be found in Appendix A.

In addition to their ecological value, estuaries hold substantial value for humans as well: they supply fertile soil for agriculture, offer easy access to shipping routes, and aid in water purification. This explains why 21 of the world's largest cities are located nearby estuaries [16]. Moreover, estuaries serve as carbon sinks, capable of storing organic carbon long-term [17].

However, pressure on estuarine ecosystems has increased due to human activities. Estuarine ecosystems are facing threats induced by urbanization and climate change. Urban development leads to increased runoff of sediments, nutrients, pollutants, pharmaceuticals, and toxins. This impacts estuarine filtration capacity, resulting in issues like eutrophication and declines in aquatic life [18]. Climate change exacerbates these problems with altered river flows, extreme storms, sea-level rise, and potential contamination of drinking water supplies [19].

To meet the climate stabilization goals of the Paris Agreement, preservation of estuaries is crucial [20]. With this in mind, recognizing nature as a stakeholder is imperative, as ecosystem services surpass global gross domestic product [21], stressing the significance of nature's value. However, quantifying natural assets for stakeholder analyses remains challenging due to the dependence on multiple variables, difference in spatial and temporal scales, and the occurrence of non-linear relationships [22]. These challenges complicate the quantification of the current ecological state and of future ecological shifts. Addressing this issue illuminates the ecological implications of human interventions, climate change scenarios and preservation efforts in estuaries.

This paper aims to develop a method to quantify the effects of human interventions or climate change scenarios on estuarine ecosystems, by linking abiotic characteristics from a hydrodynamic model to ecotopes and thereby enabling scenario-based ecotope-studies. Subsequently, ecotopes may be linked to various units, e.g., ecosystem services, biodiversity, and/or CO_2 capture etc. By linking ecotope-availability exclusively to abiotic characteristics, instead of, for example aerial photographs, a possibility is created to investigate the current ecological state and anticipate future ecological shifts resulting from human interventions or climate change scenarios. This methodology provides a flexible tool for decision-making and research purposes.

2. Methodology

First we present the developed method, where after we present the case study area, the Western Scheldt in Section 2.2. The model as such is described in Section 3.1.

2.1. Method development

We have developed a method, named Ecotope-Map Maker based on Abi- otics (EMMA), which utilizes abiotic characteristics to predict the poten- tial occurrence of ecotopes. EMMA utilizes output data of a hydrodynamic model, which is after processing classified, followed by the integration of these classified labels into an ecotope-map. The classification is based on a revised version of ZES.1, incorporating its hierarchical structure, classes, labels and thresholds [14,23].

2.2. Case study: Western Scheldt

The Western Scheldt has been used as case study, as Bouma et al. [14] is largely based on this estuarine system. Subsequently, the study by Nnafie et al. [24] on the morphological responses of the system to historic closures of side-channels of the Western Scheldt forms the basis of our proof-of-concept of EMMA. The could-be bathymetries resulting from Nnafie et al. [24] illustrate how EMMA can be used to assess the current ecological state and future ecological shifts for hypothetical cases.

The Western Scheldt is the estuary of the Scheldt river connecting it to the North Sea, as shown in Fig. 2. It is among the busiest waters of the world since it links the Port of Antwerp with the open sea. Its navigation channel has undergone significant deepening since 1970, leading to notable morphodynamic changes [25,26].

The Western Scheldt encompasses mudflats, salt marshes and dunes; it is a dynamic, well-mixed water system influenced by strong currents and tides driven by the North Sea [25,27].

The area is protected under Natura-2000 legislation due to the presence of rare habitats, a substantial bird population, and marine mammals, as well as being a crucial migration, nursery, and juvenile habitat for fish [28].

2.3. Validation of EMMA

We used hydrodynamic model output data of 2013 [29] as input for EMMA. This output is generated with Delft3D Flexible Mesh, an open-source hydrodynamic modeling software, which simulates hydrodynamic processes by solving the Reynolds-averaged Navier-Stokes equations [30].

This model has been developed by Tiessen et al. [29]. The average error in flow velocity was 0.14 ms^{-1}, a satisfactory margin for the intended purposes. Moreover, it operates within a two-dimensional horizontal framework, a fitting approach given that the Western Scheldt estuary is well-mixed [25,29].

Note that for this application, it is assumed that all substrate is soft, as rocky shores are scarce in the Netherlands.

The resulting ecotope-map is then compared to an existing ecotope-map of the Western Scheldt [23]. The ecotope-map from [23] incorporates (1) a ground-level elevation map derived from laser altimetry and soundings; (2) a drought duration map based on ground-level elevation; (3) a geo-morphology map from aerial photos and field measurements; (4) a flow velocity map using modeling and elevation data; and (5) a salinity map generated by modeling and continuous measurements. These components, along with the label classification detailed in Appendix A, constitute the ecotope-map.

2.4. Implementation of EMMA

In order to demonstrate a possible implementation of EMMA, morphological data was used from Nnafie et al. [24]. This study explores the impact of secondary basins on estuarine channel depth. Results demonstrate that channels in estuaries with secondary basins are shallower. Closure of these basins deepens the channels, primarily due to reduced landward sediment transport driven by tidal asymmetry. Notably, estuarine channel depth is significantly reduced when

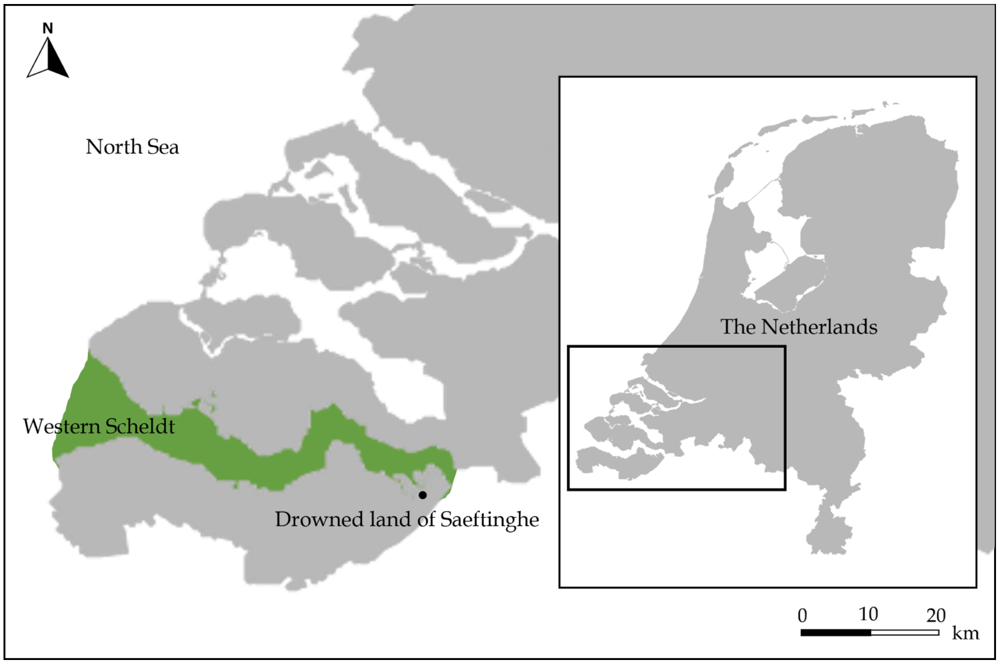

Fig. 2. Geographic location of the Western Scheldt, in the Southwestern part of the Netherlands.

secondary basins are situated along the northern estuarine margin.

The morphodynamic study by Nnafie et al. [24] provides a valuable source of potential morphological developments of the Wester Scheldt. In combination with EMMA, this data allows the investigation of what the ecological impact is of these estuarine modifications by translating the model data from Nnafie et al. [24] to ecotope-maps.

3. Results

In this section, we describe the resulting method, present and describe the ecotope-maps derived from both the validation and implementation steps.

3.1. Method description: EMMA

An overview of the work-flow is depicted in Fig. 3. In the following sub-sections these steps are clarified.

Input: Hydrodynamic data

To operate effectively, EMMA requires spatiotemporal data on salinity, flow velocity and water depth, with temporal statistics calculated independently within the spatial domain. Key statistics derived from this hydrodynamic data, include temporal mean, standard deviation, median and maximum values. It is important to note that data with a relatively large timescale (at least one year) is preferred, due to the slow reponse dynamics of ecotopes and to encompass seasonal variations.

Step 1: Processing hydrodynamics

EMMA extracts key statistics from the hydrodynamic data, such as (1) the mean and standard deviation of the salinity [PSU]; (2) the mean water depth [m]; (3) the median and maximum flow velocity [ms^{-1}]; (4) the inundation duration [%]; and (5) the inundation frequency [yr^{-1}]. In addition, EMMA approximates grain sizes using median flow velocity and the Shields formula (Eq. (1)), although this formula is valid under permanent and uniform flow:

$$d = \frac{u^2}{\Psi \cdot \Delta \cdot C^2} \tag{1}$$

With: d [m], the grain-size diameter; u [ms^{-1}], the median flow velocity magnitude; Ψ [–], the Shields parameter ($\Psi = 0.07$); Δ [–], the dimensionless grain size (1.58 for non-cohesive sediments); and C [$m^{\frac{1}{2}}s^{-1}$], the Chézy value ($C = 50\ m^{\frac{1}{2}}s^{-1}$).

Step 2: Defining thresholds

This step is optional, as thresholds defined for brackish and saline waters in the Netherlands can be directly applied to global temperate regions. These thresholds, established by Bouma et al. [14] and extended by Paree [23], may serve as preliminary approximations for different regions. Notably, for the location-specific threshold, the flooding duration for *Depth 2*, a deliberate decision was made on the

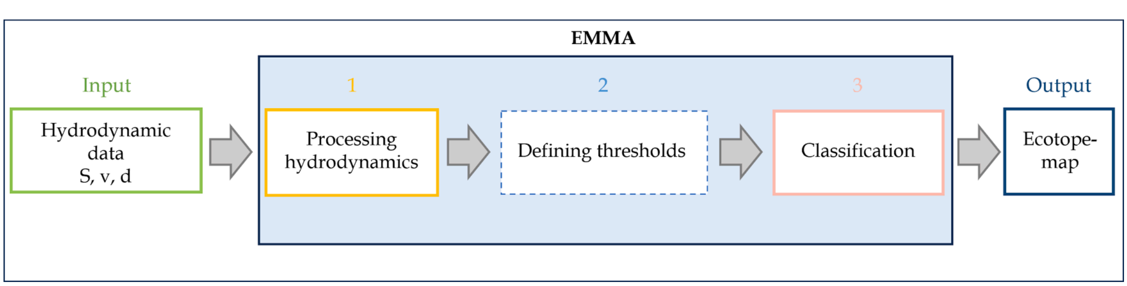

Fig. 3. Work-flow of EMMA from left to right. Step 2, Defining thresholds, is optional, and if skipped EMMA's default thresholds are used, which are representative for the Western Scheldt.

value of the thresold, due to the absence of location details in ZES.1 [14].

Step 3: Classification

The data is classified based on the defined thresholds (Appendix B). For example, when the mean salinity equals 10 PSU, and has a standard deviation of 2 PSU, then the *Salinity* label is set to B (*Brackish*).

Output: Ecotope-map

When all the labels within the six classes are defined, the ecotope labels are determined by concatenating these labels. Finally, the ecotope-map can be derived, visualizing the potential ecotope distribution, as will be demonstrated in the Western Scheldt case study.

3.2. Results of validation

The resulting ecotope-maps from the validation step are illustrated in Fig. 4, with a progressive increase in detail observed as we move from Fig. 4a to d.

With an ecotope-map of the Western Scheldt generated by EMMA and the map by Paree [23], it is possible to define the performance of EMMA at various levels of detail (Table 1); the performance is defined as the percentage of grid points sharing identical labels in the ecotope-map produced by EMMA compared to Paree [23].

The notable decline in performance becomes evident as we progress from level 2 to level 3, and further deteriorates at level 4. This can be attributed to several factors, including the dependence of *Depth 2* on *Depth 1* (Fig. 1), and the cumulative effect of errors; inaccuracies at level 1 propagate and decrease the accuracy of predictions at subsequent levels.

3.3. Results of estuarine modifications

Due to the minor differences in model set-up between Tiessen et al. [29] and Nnafie et al. [24], the impact of closing of side-channels of the Western Scheldt are compared to the reference case of Nnafie et al. [24]: Fig. 5a serves as a reference for the modified morphologies of the Western Scheldt without side-channels, relative to the Figs. 5b tm 5e which distinctly include side-channels. In Fig. 5, various configurations of the side-channels within the bathymetry are depicted. We chose level of detail 2, allowing for a preliminary overview of the differences between the figures. This is also the level of detail at which the performance of EMMA is good (Table 1).

Fig. 5b introduces an upstream south-side channel in the bathymetry. Notably, this adjustment results in a reduction of marine ecotopes within the middle of the estuary (Z2.21 and Z2.22 for $x = 40$–50 km) and in the bend ($x = 60$ km). Additionally, there appears to be a reduction in the brackish area (B2.11, B2.12, B2.21 and B2.22) between 65 km and 70 km.

In Fig. 5c a downstream side-channel is added on the northern side. This modification results in a slight elongation of marine influence (i.e., Z2.21) around $x = 50$ km with an expanded area around $x = 60$ km.

Fig. 5d introduces another side-channel on the southern side, although situated further downstream compared to Fig. 5b. The resulting ecotope-map highlights a downstream reduction of marine influence (Z2.22, around $x = 10$ km) relative to the reference in Fig. 5a. Furthermore, the low-energy zones (Z2.22) increases in acreage around $x = 40$ km, while the high-energy zones (Z2.21) increased around $x = 70$ km.

In Fig. 5e all the aforementioned side-channels are incorporated. In comparison to the reference Fig. 5a, the high-energy zones (Z2.21) exhibits elongation between over $x = 45$–60 km. Additionally, the high-energy, sub-littoral ecotope (Z2.11) gains more acreage around $x = 70$ km and the area of the brackish ecotopes is further reduced.

4. Discussion

The developed model, EMMA (Ecotope-Map Maker based on Abiotics), presents a promising approach for ecotope mapping in estuarine ecosystems. The key advantage lies in its independence on expensive ecological field measurements. EMMA relies on readily available data from hydrodynamic models, specifically requiring salinity, water depth,

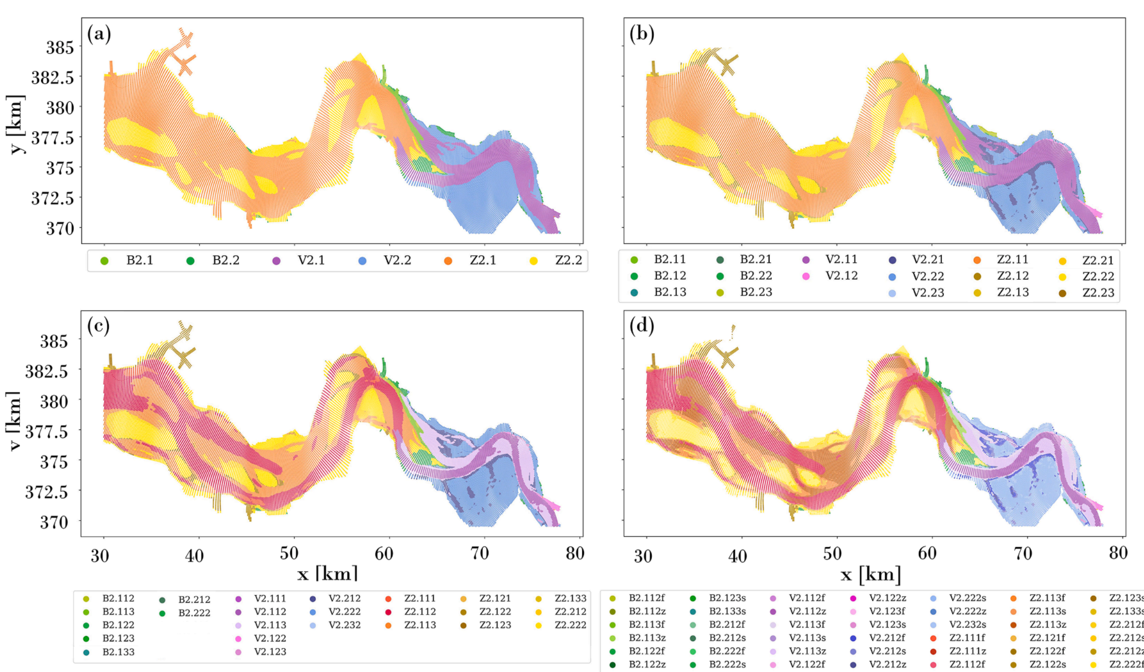

Fig. 4. Ecotope map of the Western Scheldt with increasing levels of detail as defined in Fig. 1: **(a)** level of detail 1, this includes labels for *Salinity, Substratum 1 and Depth 1*; **(b)** level of detail 2, this includes the aforementioned labels along with *Hydrodynamics*; **(c)** level of detail 3, this includes the aforementioned labels along with *Depth 2*; and **(d)** level of detail 4, this includes the aforementioned labels along with *Substratum 2*.

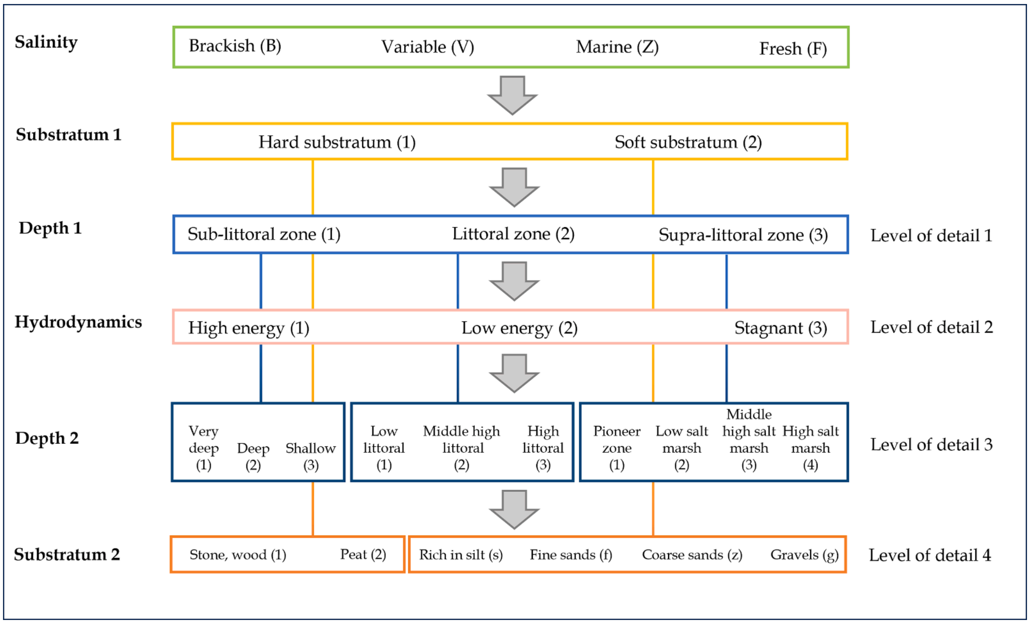

Fig. 1. Overview of ZES.1 [14]. The diagram presents the classification hierarchy, indicating the association of each category with its corresponding label (in brackets). Vertical lines depict the underlying dependencies, and levels of detail are outlined on the right side. An ecotope-label is defined by obtaining one label in each class.

Table 1
Performance of EMMA compared to ecotope-map by Paree [23]. Performance is expressed as percentage of agreement between EMMA and Paree [23].

Level of detail	Corresponding category	Performance
Level 1	Depth 1	80.9 %
Level 2	Depth 1, Hydrodynamics	73.5 %
Level 3	Depth 1, Hydrodynamics, Depth 2	23.7 %
Level 4	Depth 1, Hydrodynamics, Depth 2, Substratum 2	9.5 %

and flow velocities. This feature enables the model's application in assessing the current ecological state and future ecological shifts not only for hypothetical scenarios but also for predicting future situations, offering valuable insights for decision-makers [e.g., 31,32].

The ecotope-map produced for the Western Scheldt presents a close approximation of reality, capturing the overall pattern and areas at Levels 1 and 2. Nevertheless, the dynamic nature of the system and the presence of unconsidered parameters can influence the accuracy. Factors such as urbanization, pollutants, dredging activities, extreme weather events, and specific habitat features, like shell banks, need to be accounted for when interpreting ecotope-maps [18,33,34]. Incorporating these parameters, when sufficient information is available, could enhance the model's accuracy.

Furthermore, the Western Scheldt contains a substantial amount of silt, which poses challenges for this method as the Shields formula is unsuitable for fine materials [35]. Incorporating a morpho-dynamic model could improve grain-size precision, as required at Level 4, but would significantly compromise EMMA's simplicity and usability, given the often unavailability of such models. Additionally, predicting substrate is considered challenging when silt is present in the water system due to factors like silt supply, benthic organism presence, micro-algae [e.g., [36–39]], and due to its cohesiveness, which allows it to persist in high-velocity areas [e.g., 40].

While EMMA serves as a valuable tool for preliminary design stages, it is essential to recognize that the ecotope-map's accuracy is limited by the spatial scale of the underlying hydrodynamic model. Strict requirements for the temporal scale, including a complete spring-neap cycle and yearly-average values for river discharge, are necessary to obtain valid ecotope-maps for decision-making purposes. Considering the time it takes for ecotopes to develop or adjust is crucial to ensure a comprehensive understanding of the system's ecological value. Furthermore, it is important to acknowledge the necessity of utilizing calibrated and validated data as input in EMMA, to ensure the reliability of its outputs. This becomes especially important when applying EMMA in locations other then The Western Scheldt Estuary.

The input for EMMA largely originates from the output of a hydrodynamic model. However, the two substratum-labels (*Substratum 1* and *Substratum 2*) cannot sufficiently be determined based on such data: (1) *Substratum 1* has to be predefined, as this is unrelated to the hydrodynamic conditions but is a geological feature instead; and (2) *Substratum 2* is hard to determine based on hydrodynamic data, as the silt content is only partly determined by the hydrodynamics [e.g., 41].

In the assessments, no value was yet assigned to the ecotopes, as the translation from the morphodynamic study by Nnafie et al. [24] to ecotope-maps functions as a proof-of-concept. However, it is feasible to introduce a value system based on the specific context. For instance, if one is aware that an endangered species thrives in a particular ecotope, adjustments can be made to enhance and prioritize that ecotope.

5. Conclusion

This research aimed to develop a method for analyzing the current ecological state and potential future ecological shifts in estuaries when implementing nature-based solutions. The developed model, EMMA, successfully reproduces the ecotope-map by Paree [23]. EMMA's ability to predict ecotope distributions without relying on aerial photographs or real-time data makes it versatile and applicable to hypothetical scenarios, providing valuable insights into the ecological state and incorporation of ecological impacts in decision-making.

However, challenges remain, especially in modelling silt and addressing potential overestimations in the hydrodynamic model. Despite these challenges, EMMA's wide range of applications, including assessing hydrodynamic modifications and their ecological impacts, make EMMA a useful tool for decision-making and ecological assessments. The resulting ecotopes can be translated to ecosystem services, biodiversity metrics, CO_2 capture, and other important metrics for informed decision-making.

Moreover, while EMMA was originally developed for the Western

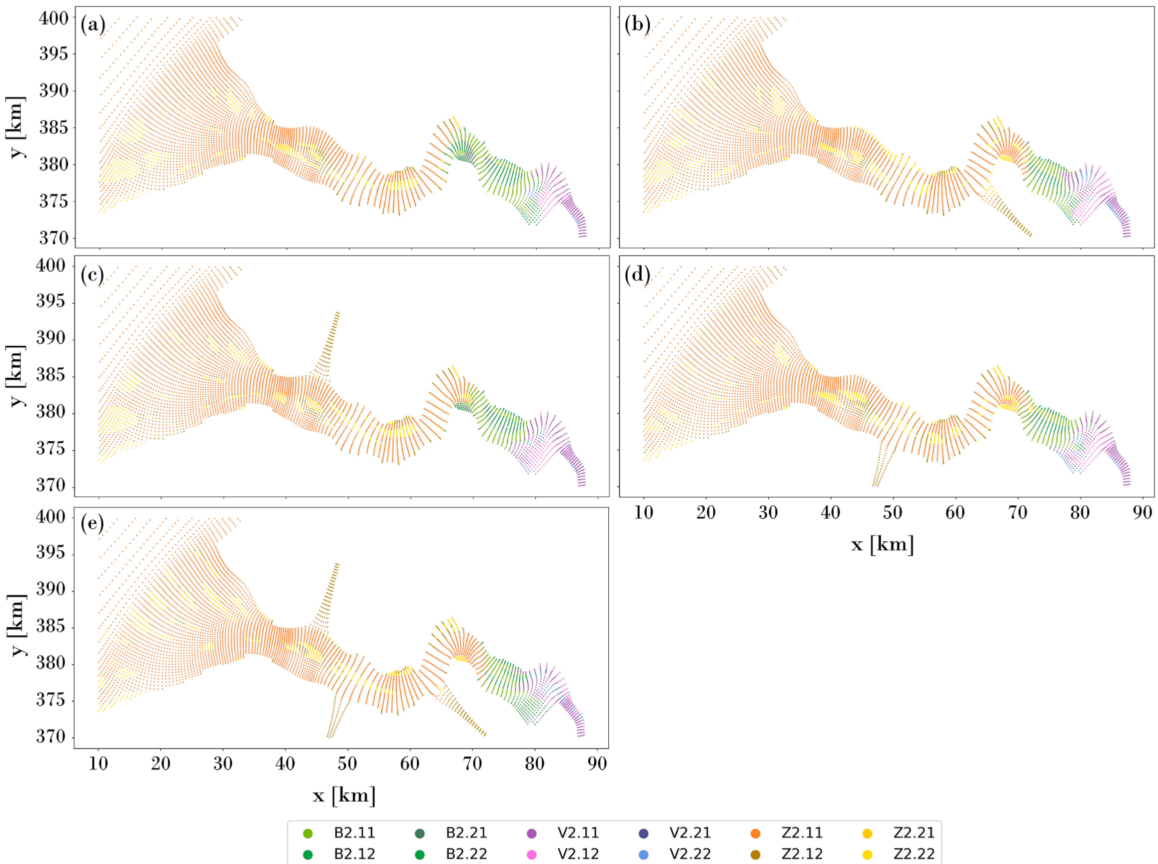

Fig. 5. Ecotope-maps for morphological variations of the Western Scheldt as predicted and labelled by Nnafie et al. [24]: **(a)** reference case; **(b)** side-branch 5; **(c)** side-branch 1; **(d)** side-branch 3; **(e)** side-branch 513

Scheldt Estuary, its modular design and adaptable framework allow for potential application in other aquatic systems worldwide. With its capacity to integrate local hydrodynamic models and ecotope classification systems, EMMA offers a flexible approach that can be customized for different regions and environmental conditions. By considering factors such as temperature variations and refining definitions to suit specific ecosystems, EMMA can be expanded to encompass a diverse range of aquatic environments, including marine waters and riverine systems. Its modular structure facilitates the integration of new data and methodologies, making it a promising tool for ecosystem management beyond the Western Scheldt.

All in all, EMMA offers a promising approach to predict and analyze the current ecological state and potential future ecological shifts in estuaries. We demonstrated its potential in predicting the ecological state in supporting the assessment of (nature-based) solutions. The model's independence from aerial photographs and real-time data allows for broad applicability, making it a valuable tool in addressing ecological challenges and supporting sustainable management and conservation efforts in estuarine ecosystems. The model's simplicity, efficiency, and ability to work with existing hydrodynamic models make it an asset for ecotope mapping and decision-making processes.

Software availability

This study showcases the abilities and applications of the open-access tool EMMA [Ecotope-Map Maker based on Abiotics; 42], which is a Python-based processing tool translating hydrodynamic model output data to ecotopes.

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CRediT authorship contribution statement

Soesja Brunink: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gijs G. Hendrickx:** Writing – review & editing, Software, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Overview Classes, Variables, Thresholds and Labels

Table A1
Overview of the defined classes with corresponding variables, thresholds and labels as defined by Bouma et al. [14]. Note that for Substratum 1 there are no variables defined.

Class	Variables	Threshold definition	Label
Salinity	mean salinity ($\bar{s}$ [PSU])	$\alpha \cdot \sigma_{sal} > \bar{s}$	V (Variable)
	standard deviation of salinity ($\sigma_{sal}[PSU]$)	$s_{fresh} \leq \bar{s} \leq s_{marine}$	B (Brackish)
		$\bar{s} \geq s_{marine}$	Z (Marine)
		$\bar{s} \leq s_{fresh}$	F (Fresh)
Substratum 1			1 (hard substrate)
			2 (soft substrate)
Depth 1	mean water depth ($\bar{d}$ [m])	$\bar{d} < d_{sub}$	1 (sub-littoral)
		$d_{supra} \geq \bar{d} \geq d_{sub}$	2 (littoral)
		$\bar{d} > d_{supra}$	3 (supra-littoral)
Hydrodynamics	maximum velocity ($u_{max}[\mathrm{ms}^{-1}]$)	$u_{max} = 0$	3 (stagnant)
		if sub-littoral	
		$u_{max} \geq u_{sub}$	1 (high-energy)
		$u_{max} < u_{sub}$	2 (low-energy)
		if littoral or supra-littoral	
		$u_{max} \geq u_{littoral}$	1 (high-energy)
		$u_{max} < u_{littoral}$	2 (low-energy)
Depth 2	mean water depth ($\bar{d}$ [m])	*if sub-littoral*	
	inundation duration (t [%])	$\bar{d} < d_{sub,1}$	1 (very deep)
	inundation frequency (f [yr^{-1}])	$d_{sub,2} \geq \bar{d} \geq d_{sub,1}$	2 (deep)
		$\bar{d} > d_{sub,2}$	3 (shallow)
		if littoral	
		$t \leq t_{littoral,1}$	1 (low littoral)
		$t_{littoral,1} \leq t < t_{littoral,2}$	2 (middle high littoral)
		$t \geq t_{littoral,2}$	3 (high littoral)
		if supra-littoral	
		$f \geq f_{supra,1}$	1 (potential pioneer zone)
		$f_{supra,2} \leq f < f_{supra,1}$	2 (low salt marsh)
		$f_{supra,3} \leq f < f_{supra,2}$	3 (middle salt marsh)
		$f < f_{supra,3}$	4 (high salt marsh)
Substratum 2	median grain size ($d_{50}[\mu\mathrm{m}]$)	$d_{50} \leq d_{silt}$	s (rich in silt)
		$d_{50} \leq d_{fine}$	f (fine sands)
		$d_{50} \leq d_{coarse}$	z (coarse sands)
		$d_{50} > d_{coarse}$	g (gravel)

Appendix B. Thresholds as used in EMMA

Table B1
of threshold variables along with their corresponding values, as originally defined by Bouma et al. [14]. Refined values for certain thresholds are provided additionally. The units for each threshold are presented in the last column.

Class	Threshold variable	Threshold value in [14]	Refined threshold value	Unit
Salinity	α	4	-	-
	S_{fresh}	5.4	-	PSU
	S_{marine}	18	-	PSU
Depth 1	d_{sub}	MLWS (-2.31)		m
	d_{supra}	MHWN (1.85)	-	m
Hydrodynamics	u_{sub}	0.8	0.7 [23]	ms^{-1}
	$u_{littoral}$	0.2	0.7 [23]	ms^{-1}
Depth 2	$d_{sub,1}$	-30 (for North Sea)	-	m
	$d_{sub,2}$	-20 (for North Sea)	-10 [23]	m
	$t_{littoral,1}$	25	-	%
	$t_{littoral,2}$	75	-	%
	$f_{supra,1}$	300	-	yr^{-1}
	$f_{supra,2}$	150	-	yr^{-1}
	$f_{supra,3}$	50	-	yr^{-1}

(*continued on next page*)

Table B1 (*continued*)

Class	Threshold variable	Threshold value in [14]	Refined threshold value	Unit
Substratum 2	d_{silt}	25	-	μm
	d_{fine}	250	-	μm
	d_{coarse}	2000	-	μm

Note: MLWS and MHWN are location dependent. The values between brackets are suggested for the Western Scheldt [14]

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