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Predicting habitat changes in the Tagus Estuary induced by climate change

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Ai miei genitori:
questo traguardo è anche vostro.

Abstract

This study examines the potential impacts of sea level rise and temperature increase, both consequences of climate change, on the salt marsh habitat of the Tagus estuary. The focus is on the common species *Spartina maritima* and its habitat suitability under future climate scenarios. The primary objective was to analyse the effects of a predictive model using a Habitat Suitability Index (HSI), based on data labelled as the Reference Year, covering the period from October 2019 to September 2020.

The HSI model was developed using MATLAB to assess changes in habitat suitability based on bathymetry, salinity and temperature data. Two future climate scenarios were considered, incorporating projected sea level and temperature rises.

The results indicate that the Tagus estuary's salt marsh habitat is vulnerable to climate change impacts. While the estuary shows some adaptability, it is also susceptible to seasonal fluctuations that could accelerate habitat transformation and biodiversity loss.

Keywords: Climate change; Sea level rise; Temperature rise; Estuaries; Predictive modeling; Habitat changes; Tagus estuary; Habitat Suitability Index (HSI); Salt marsh; *Spartina maritima*

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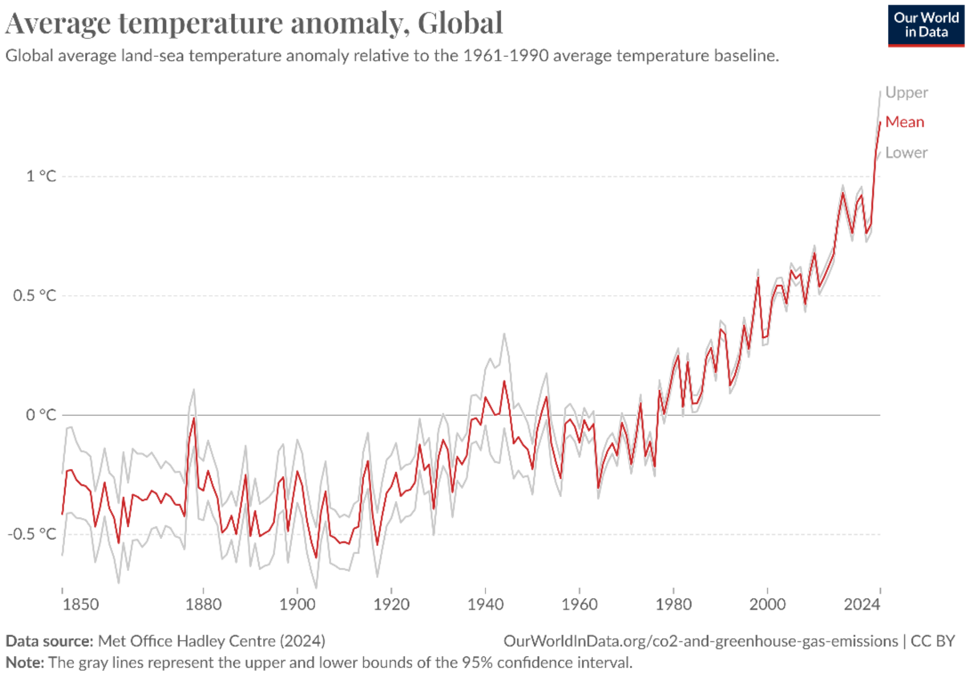
Introduction

Significant changes in the climatic conditions on Earth have already been taking place for decades. 2024 set the record for the warmest day ever measured in recent history: on the 22nd of July, the daily global average temperature was 17.16°C. Moreover, the ten years with the highest annual maximum daily average temperatures are the last ten years, from 2015 to 2024 (Copernicus, 2024).

Looking at the trends of global average temperature anomalies (Figure 1), there is a neat tendency of them increasing, if compared to the past.



Average temperature anomaly, Global

Global average land-sea temperature anomaly relative to the 1961-1990 average temperature baseline.

Data source: Met Office Hadley Centre (2024) OurWorldInData.org/co2-and-greenhouse-gas-emissions | CC BY

Note: The gray lines represent the upper and lower bounds of the 95% confidence interval.

Figure 1 - Global average temperature anomalies (Our World in Data, 2024)

When looking at the so-called Keeling curves (Figure 2 and Figure 3), the carbon dioxide concentration has almost always been constantly increasing since pre-industrial times, and its slope and seasonal fluctuations have been drastically rising and changing respectively from the 1960s on.

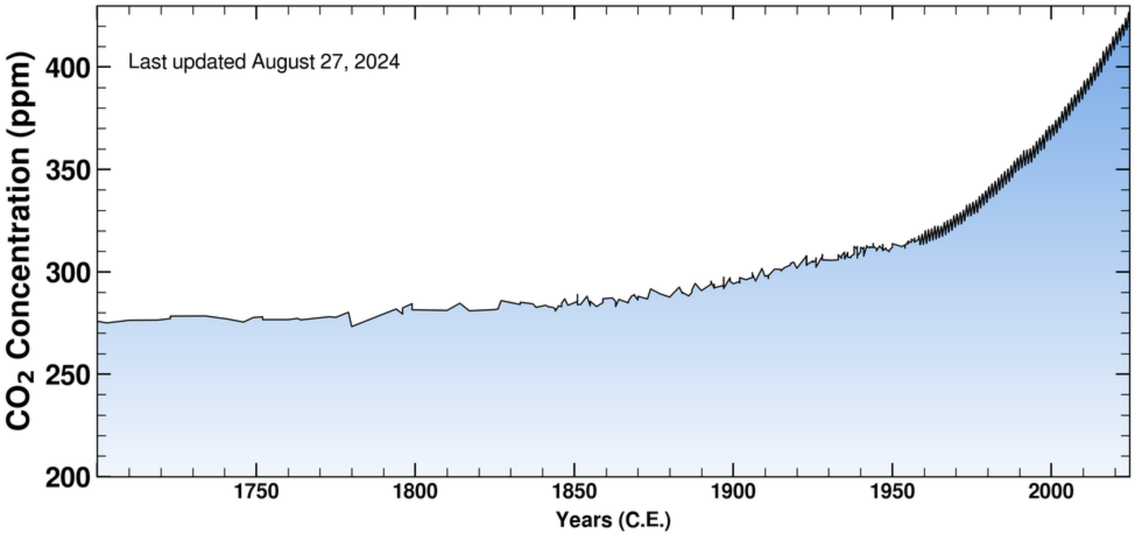


Figure 2 - 1700-present Keeling curve (Scripps Institution of Oceanography at UC San Diego, 2024)

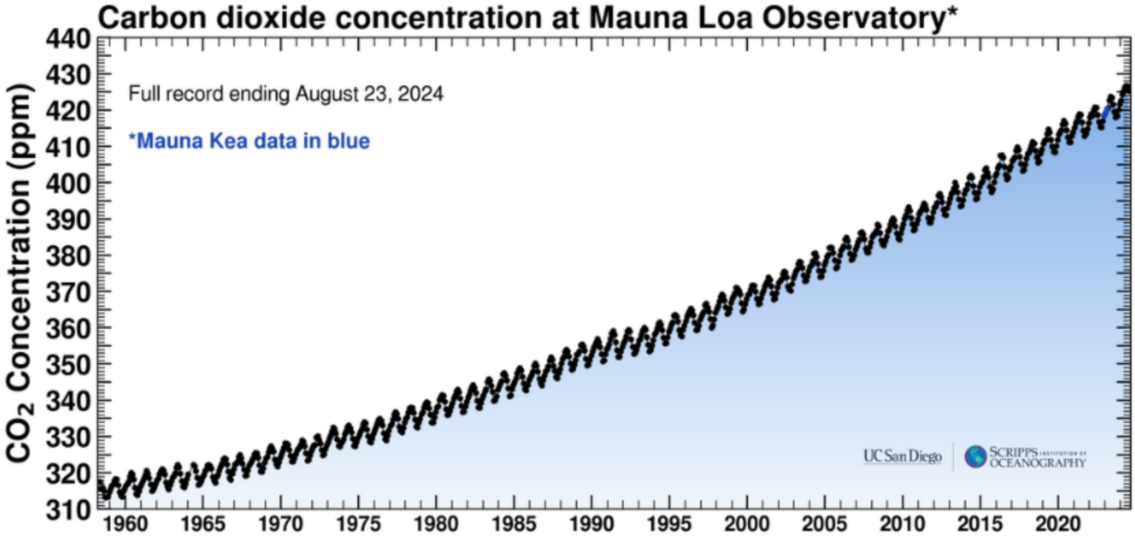


Figure 3 – 1960s-present Keeling curve (Scripps Institution of Oceanography at UC San Diego, 2024)

Global greenhouse gas emissions have continued to increase in the last years, and this will lead to increasing global warming, making it more likely of reaching 1.5°C by the 21st century and harder to stay below 2°C in the future scenarios considered by scientists. Moreover, increments of global warming will with high confidence augment hazards, but also relevant and fast reductions in greenhouse gas emissions would lead to an attenuation in global warming within around two decades, and to changes in atmospheric composition in a few years with high confidence (IPCC, AR6, 2023).

Modifications in the global mean Sea Level Rise (SLR) has also been associated with the climatic change effects and the trend in its variation is visibly increasing, as shown in Figure 4. Since 1993, there has been an uplift in SLR of about 104.7 mm (NASA, 2024).

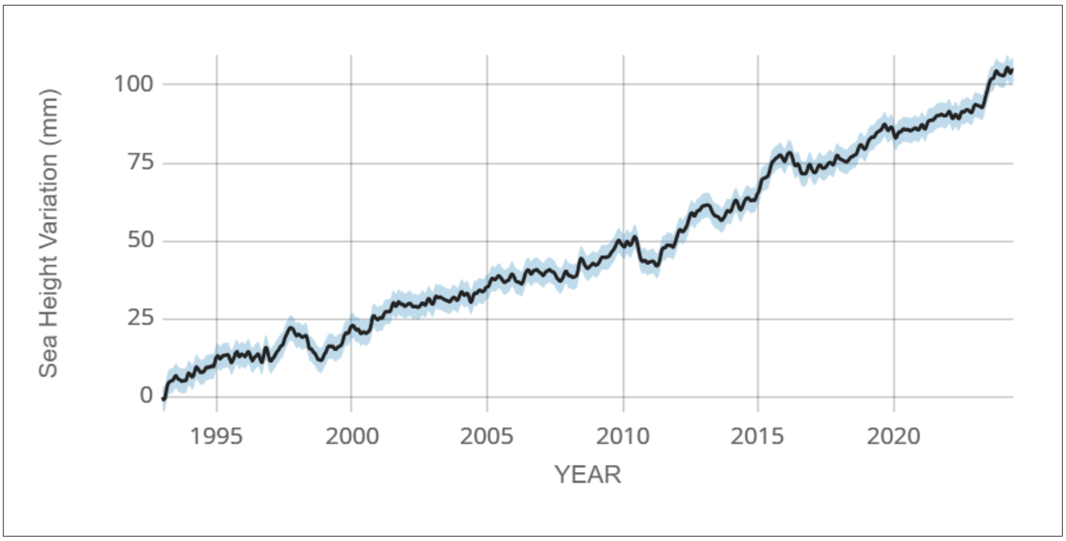


Figure 4 – Global mean Sea Level Rise: in black the measurements, in blue the uncertainty range (NASA, 2024)

Floods, fires and glaciers melting are also increasing all over the world, demonstrating that climate change is a planetary phenomenon. Nonetheless, its implications are particularly challenging for sensitive environments like estuaries, because it mostly affects the least resistant places or the least prone to adapt.

Estuaries are among the most ecologically relevant and vitally rich ecosystems known, being confluence areas between terrestrial and marine environments. They are defined by complex hydrodynamics, widespread biodiversity and, as they host a multitude of habitats and species, the impact of any transformation is very worthy of attention.

The Tagus Estuary, located near Lisbon, the capital of Portugal and a major European city, is one of the largest and most important estuaries in Southern Europe. Hosting nearly 3 million people, it experiences significant anthropogenic pressure, particularly in areas with extensive infrastructure and agricultural development. While this pressure is less evident in regions dominated by natural environments, human presence is widespread, and the impacts have been further amplified by climate change. Biodiversity loss, sea level rise increase, coastal salinization and temperature fluctuations are some of them. The estuary itself is at risk because the current saltmarsh area could be gradually submerged by the sea level rise (SLR) and shift upwards, forming a coastal lagoon where it originally was and permanently transforming the estuarine habitats asset.

The different estuarine habitats would therefore be affected by this transitioning in space and more worrying effects are expected as average temperatures and sea levels rise. A reduction or potential loss in some birds' population has already been documented: the Tagus estuary is the most important wetland for some species like the waders, and anthropic activities led to loss in roosting sites. In addition, some species of fish like the *Lusitanian toadfish* are spreading northward from the saltmarsh to the freshwater zone due to water temperature and salinity increase and this is putting some of the other species' habitats in the upper estuary at risk.

Spartina maritima, a halophytic grass commonly found in European salt marshes, plays a crucial role in stabilizing sediment, supporting biodiversity, and maintaining the overall health of estuarine systems.

In the context of the Tagus Estuary, *Spartina maritima* has traditionally thrived within intertidal zones, where it contributes to the ecological balance and resilience of the ecosystem. However, with the increasing threats posed by climate change, the distribution, health, and habitat suitability of *Spartina maritima* are undergoing significant shifts. Understanding how these factors influence the species' habitat quality is essential for developing effective conservation strategies and managing the long-term sustainability of the estuary.

One way of analyzing these ecosystems and their future potential modifications is through suitability indexes. The Habitat Suitability Index (HSI) is a parameter that indicates the ability of an ecological system to support one or more species, and it can be referred to several environmental variables: survival rate, mean salinity, predator abundance, seagrass cover, etc. It varies from 0 to 1 as it associates a value belonging to this range according to the correlation between habitat quality and species' abundance in a certain environment. The HSI can be used to evaluate the habitat changes in the Tagus estuary, along with a data analysis.

This study explores the potential impacts of a 0.5 meter increase in water level and the same SLR increase coupled with a 2°C rise in water temperature on the Habitat Suitability Index (HSI) for *Spartina maritima* within the Tagus Estuary. The results of the two future scenarios are compared with the baseline data addressed as Reference Year, covering the period of October 2019 – September 2020.

The aim of the research is to answer to these questions: how will this area be in the next years? How can we predict ecosystem changes?

There is an urgent need in scientifically documented studies on ecosystem changes linked to climate change and this research has as its objective predicting habitat changes in the Tagus estuary and in providing future scenarios for decision-making and policy makers, which becomes particularly relevant given the importance of biodiversity conservation and sustainable management in an area that is home to an enormous natural richness.

Given the results, adaptation strategies to climate change could be suggested, to prevent future habitat loss. These also must consider cooperation through the different institutions and stakeholders involved, as well as integrating local structures and favouring the participation of local actors to maximize the final goal of building adaptive capacity and resilience.

The present work is divided into 5 chapters: the first one is dedicated to a review of papers inherent the topic and the methodology adopted; the second one gathers informations about the study area and habitats for a general overview of the case; the third one explains in detail the methodology used in this research; the fourth collects the results and describes the most important characteristics extracted from the data analysis, together with a deep statistical and sensitivity analysis; the fifth summarizes all the outcomes of the study and sorts out the conclusions.

1 Literature review

This chapter reviews relevant literature on hydrodynamic modeling, species abundance tracking, and habitat threats in estuarine environments, while keeping a particular focus on the Tagus estuary. It aims to highlight previous studies that inform our understanding of ecosystem changes, species interactions, and the impacts of human activities and climate change. By examining past research, the review highlights how species interactions and environmental transformations, brought by human activities and climate change, affect estuarine ecosystems. The goal is to build a foundation for this research, which will investigate species resilience using advanced tools of analysis in the context of climate-driven estuarine changes.

The hydrodynamic modeling of surface water simulations in the Tagus estuary is performed using MOHID, a software already well validated and consolidated in several studies (de Pablo et al., 2019, 2022).

Species abundance studies in the estuary provide essential context for understanding the estuary's ecological dynamics. Soles' presence was tracked in a study on the Tagus estuary using statistical analysis and Habitat Suitability Indexes (HSI), although the study is somewhat dated (Vinagre et al., 2006). A more recent HSI research focused on Submerged Aquatic Vegetation (SAV) in the Everglades National Park in Florida, USA, offering insights into uncertainty and sensitivity analyses in aquatic environments, though the geographical differences limit direct comparisons with the Tagus estuary (Zajac et al., 2015).

Both the native species in the Tagus estuary, *Spartina maritima*, and the invasive one, *Spartina alterniflora* exhibit a similar and wide range of salinity tolerance, with optimal growth conditions between 10.7 and 32.3 ppt, growth usually reduced for values higher than 35 ppt and with ideal mean air temperature between 15 and 24°C (Adams and Bate, 1995; Crosby et al., 2016). However, the invasive species also show greater adaptability in fluctuating salinity environments, posing a threat to the native ones, which are declining in European saltmarshes (Chelaifa et al., 2010).

The study on *Spartina alterniflora* (Crosby et al., 2016), while focused on U.S. saltmarshes, provides relevant insights into the ecological adaptability of invasive species. This is pertinent to understanding potential threats to the Tagus estuary, where *Spartina maritima*, a native species, faces competition from invasive species. *Spartina patens*, another non-native species competing with the native *Halimione portulacoides* for space and resources in the Tagus estuary, is a biodiversity risk because it makes heavy metals such as Cu, As, Zn and Pb more bioavailable (Human et al., 2020).

After examining the resilience and competition of plant species in fluctuating estuarine conditions, it is important to consider how these habitat changes also affect faunal populations. A study about wader populations in the Tagus estuary tested the correlation between habitat loss and human activity. The Tagus wetland is important for birds' species conservation because it is among the most important in Europe for waders in the East Atlantic Flyway and the second most important in the Iberian Peninsula. Anthropic activity has mainly caused a loss in the "roost sites" for these birds, limiting access to feeding sites and leading to survival rate reduction. As a results, 3 of the 5 most important wader species have declined: Dunlin, Gray Plover and Redshank (Catry et al., 2011).

From research on two fish species in the Mira estuary, in Portugal, it has emerged that the toadfish has practically confined the eel in the upper estuary, in the areas furthest from the ocean. The toadfish is also tending to colonize the upstream part due to water temperature increase linked to climate change and this puts the eel habitats (which are already decreasing) at risk (Costa et al., 2008). Forecast models for marine migrants and estuarine species, 2 important guilds detected in the Tagus estuary, discovered that marine migrants species tend to occupy its upper part (with more fresh water), but given the increase in salinity (due to the reduction in rainfall and sea level rise linked to climate change), these species are at risk because their habitats are decreasing (França, 2023). Understanding how increased temperatures impact non-native species in the Mediterranean (Vinagre et al., 2014) offers predictive insights for species survival in the Tagus estuary, where climate change poses similar risks. Heat Stress Proteins (HSP) are substances that express their biological function when cells are exposed to high temperatures or stress conditions, protecting them from possible damage. Species living in warmer waters naturally produce more HSP and therefore they are more resistant to thermal stress, while those living in colder waters are less so. Furthermore, in general species living higher up in the coast are more resistant than species further down the coast (Madeira et al., 2012). A possible northward migration of non-native species enhanced by climate change could limit their survival rate in environmental conditions which are not optimal for them.

Higher temperatures and less food available will also increase the development times of the larvae for some species like the Soles, which therefore will stay in the nursery areas of the estuary for longer and mature later. This is a threat for the species' survival because the population's renewal would take longer and so the eggs' production (Sardi et al., 2023). The Tagus estuary is subjected to strong human pressures, but it is also very resilient as its vulnerability is not particularly high. But the saltmarsh and intertidal habitats, being important nurseries for fishes, are exposed to threats and vulnerable, affecting the fish communities as a result (França et al., 2012).

Conservation and sustainable management would help mitigate the impacts of climate change and reduce pollution. New policies and regulations are needed to restore the salt marshes, for example by replanting or strengthening the native species. It is then crucially relevant to first recognize which are the current and future threats and vulnerabilities for estuarine habitats: salinization in the estuary and change in river flow, excessive nutrients' gain leading to eutrophication and habitat loss brought by land use changes are among some of the most important.

During a 2021 expert conference in Lisbon, which focused on the main threats facing the Tagus estuary, habitat and biodiversity degradation emerged as the most critical issue discussed. Drivers, influencing factors, ecosystem functions, services affected and proposed solutions were listed for each group of problems. Human impacts were highlighted as main causes for salt marshes: pollution from runoff, impermeabilization and climate change with SLR, temperature and precipitation trends alterations (Stratoudakis et al., 2022).

The implementation of the new Lisbon airport poses even a new threat for biodiversity and species conservation. The new international airport project in Montijo may lead to a loss of up to 30% of the conservation value of the Tagus estuary in terms of intertidal feeding areas of wintering birds alone (Catry et al, 2022).

Lastly, while the estuary faces numerous threats, there are also signs of ecosystem recovery. A study conducted by the Centre of Marine Sciences of Algarve (CCMAR), showed recent trends of seagrass recovery results in the Portuguese estuaries, after decades of decline (de los Santos et al., 2019). This underscores how certain species may experience reversal effects as environmental conditions shift within estuarine habitats. Moreover, the intricate hydrodynamics of these complex systems can often yield unexpected outcomes when key environmental variables are altered.

In summary, the reviewed studies provide critical insights into the ecological dynamics and threats in estuarine environments, particularly in the Tagus estuary. While much work has been done on species abundance, habitat degradation, and human impacts, significant gaps remain in understanding how these factors interact under current and future climate conditions for species in saltmarshes. This research aims to fill these gaps by leveraging advanced hydrodynamic modelling and focusing on species resilience in the face of environmental change.

2 General overview

2.1 Study area description

The Tagus estuary is located in central Portugal on the Western coast, in the Estremadura and Southern Ribatejo region and in proximity of the capital, Lisbon. Geographically, the area is comprised between the 38º 40' N and 39º 05' N parallels and the 9º 20' W and 8º 45' W meridians, developing on the NNE-SSW and ENE-WSW directions. The Estuary is 34 km long and 15 km wide and it measures 320 km^2 on average, between high (340 km^2) and low tide (300 km^2). Maximum depth is 10 m and highest sea level rise registered is 11 m. It is the country's largest wetland and one of the most important in Europe, for size and biodiversity.

The estuary sees its main fluvial contributions to the ecosystem coming from the Tagus and the Sorraia rivers, both ending up flowing in it before merging with the Atlantic Ocean waters. The Tagus originates in Sierra de Albarracín in Spain and with its 1100 km is the longest river in the Iberian Peninsula. It has asymmetrical banks: the north one is more regular and urbanized, characterized by higher human pressure, with visible engineering solutions and barriers for protection; while the south one shows higher irregularities, it is mostly dedicated to agricultural and rural purposes, subjected to less anthropic pressure, with predominant nature and where habitat changes are directly influencing the ecosystem's vulnerability.

This is where the Tagus Estuary Natural Reserve is mainly based, occupying a relevant part of the estuary, measuring about 140 km^2. It is located across the municipalities of Alcochete, Benavente and Vila Franca de Xira, and it is one of the 10 largest Natural Reserves in Europe. Figure 5 displays a map of the Natural Reserve's and municipalities' borders.

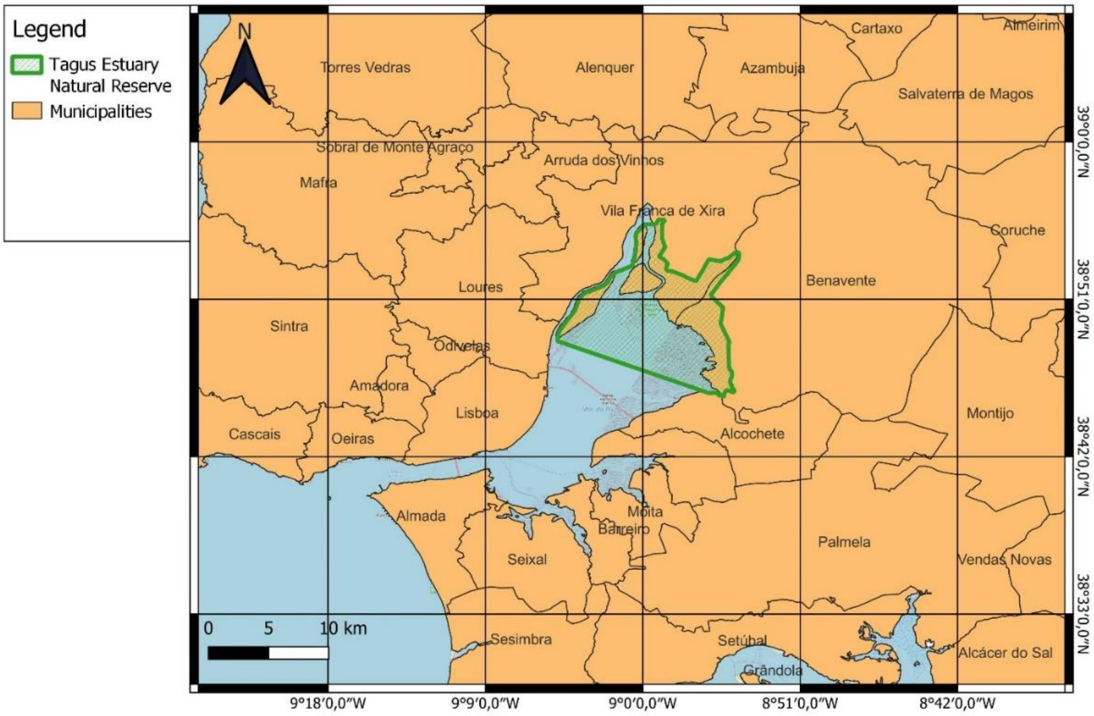


Figure 5 – Tagus Estuary Natural Reserve Map (GIS, 2024; Portal de dados abertos da Administração Pública, 2018; Ramsar Sites Information Service, 1992)

The green perimeter highlights the Natural Reserve area, as established by the Ramsar Convention in 1980.

It was created to protect the migratory aquatic birds, and it is of great relevance for species like the black cowbird and the pink flamingoes. It has been estimated that the estuary receives 120.000 birds each migrating season. Furthermore, the Natural Reserve is an important breeding area for various fish species.

The Tagus estuary is morphologically divided in four different sections (Figure 6):

1. Muge – Vila Franca de Xira: the northernmost, fluvial sector defined by a 600 meters wide channel within a broad alluvial plain. It is a low-salinity, freshwater zone with a predominantly sandy riverbed. The area is notable for its "*mouchões*", or fluvial islands, which provide habitats for a variety of plant species.
2. Vila Franca de Xira – Sacavém: the upstream sector of the estuary, characterized by the formation of multiple channels resulting from vegetation accumulation forms.
3. Sacavém - Praça do Comércio: in this section, the estuary broadens into a basin called *Mar da Palha*, formed by the junction of two smaller estuaries sited in the left bank: Montijo and Barreiro. Sandbanks and bays characterize the landscape, giving distinct geomorphological features to the area.
4. Praça do Comércio – Bugio: the final sector that connects the estuary to the ocean, predominantly with marine characteristics due to its proximity to the Atlantic.

The saline intrusion under normal hydrological conditions reaches as far as Vila Franca de Xira, 50 km from the estuary’s mouth. The northern boundary of tidal influence extends to Muge, 80 km from the same reference point. The downstream limit of the estuary lies in the Tagus channel, approximately in Bugio (de Sousa Costa, 2017). Figure 6 illustrates the Tagus estuary from the satellite, with the municipalities and locations mentioned above highlighted in the map.

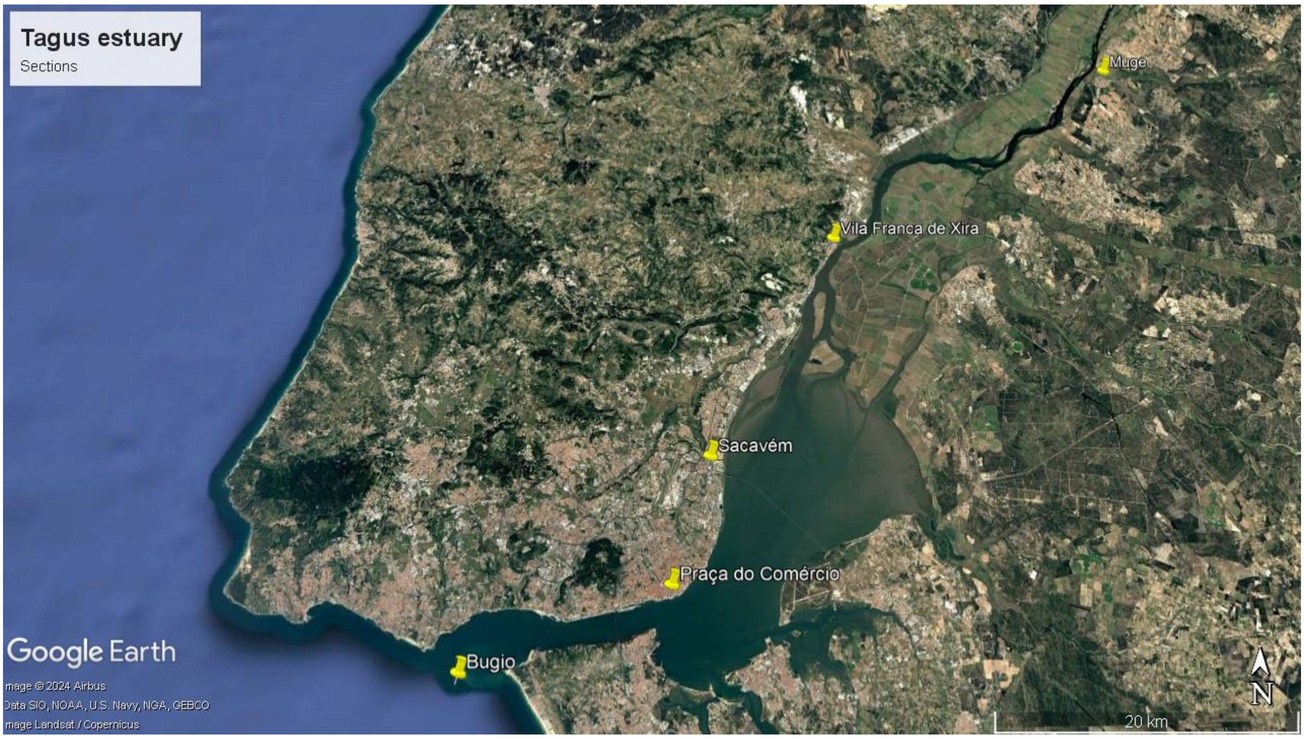


Figure 6 - Satellite image of the Tagus estuary (Google Earth, 2024)

The estuary’s geological formations are originated from the central and western part of Spain, with presence of schists, quartzites and granites from the Central Iberian Zone in the north banks, and carbonate, granitoid and pelitic rocks from the Ossa Morena in the south (Freire, 2003).

Sediments in the estuary come from both fluvial sedimentation and oceanic intrusion, with the first ones not reaching the most interior part of the estuary and the second ones found further than Cacilhas (Freire, 2003).

The richness of these sediments supports thriving ecosystems and plays a crucial role in protecting against coastal erosion. Sediment deposition helps stabilize shorelines, contributing to improved water quality. Nutrient inputs come from both freshwater runoff and tidal flushing, enriching the estuary's biodiversity and ecosystem health.

In addition to its environmental significance, the Tagus estuary has a robust legislative framework protecting its unique ecosystems. Key milestones in its legislative history include:

- 1976 - Creation of the Tagus Estuary Natural Reserve (DL 565/76)
- 1980 - Recognized in Wetlands of International Importance under the Ramsar Convention
- 1988 – Designation as a Special Protection Area (SPA) under EU legislation
- 1994 – Inclusion in the Special Protection Area for Wild Birds under Directive 79/409/EEC

Several stakeholders and institutions are actively involved in managing and preserving the Tagus estuary at local, regional, and national levels, including:

- ICNF (Instituto da Conservação da Natureza e das Florestas)
- RNET (Reserva Natural do Estuario do Tejo)
- Câmara Municipal de Lisboa
- República Portuguesa
- SPA (Special Protection Area under European Legislation as part of the Natura 2000 network)

Together, these geological, ecological, and legislative factors highlight the complexity of the Tagus estuary and its importance as a protected natural area.

2.2 Climate and tidal trends

The current climatic and tidal conditions in the study area are essentially addressed in this paragraph, in order to understand its ecological settings and then to be able to anticipate the potential environmental changes.

Two key factors influencing the estuarine environment are water temperature and salinity, which directly impact species distribution, nutrient cycling, and overall ecosystem functioning. The following diagram (Figure 7) shows the mean water temperature of the Atlantic Ocean near Lisbon, providing valuable insights into the seasonal temperature variations that influence the estuary.

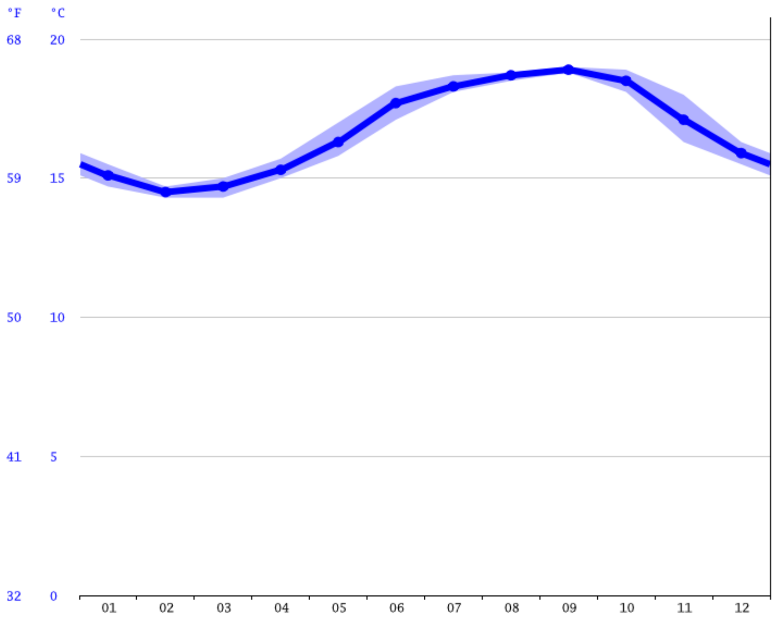


Figure 7 - Average water temperature of the Atlantic Ocean in Lisbon (Climate-Data, 2024)

The annual mean water temperature of the Atlantic Ocean in Lisbon is approximately 16.80°C. The minimum value is reached at the end of February, at approximately 14.30°C, whereas the average highest peak is in the first half of the month of September, recording around 19.00°C (Climate-Data). Freshwater temperatures in the Tagus river ending channel are on average about 10°C in winter and 24°C during the summer.

Sea surface salinity levels have shown a general increase in the Atlantic Ocean, with "saline areas becoming saltier" as global sea surface temperature rise. After the 1950s, surface salinity pattern amplifications (amplitude of change between saline and fresh regions) was 54 ± 10% higher than before (Gould and Cunningham, 2021). This trend poses potential risks to the estuary's ecosystems, particularly for species with lower tolerance for elevated salinity concentrations.

The Tagus estuary is classified as mesotidal, with tidal amplitudes ranging between 0.75 meters and 4.3 meters (Rilo et al., 2014). Tidal oscillations vary throughout the year, impacting the estuarine system's water levels, sediment transport, nutrient exchange; with the main influence upon tides' amplitudes in time attributed to the phases of the moon. Figure 8 is the tidal amplitude in January and Figure 9 is the tidal amplitude in August.

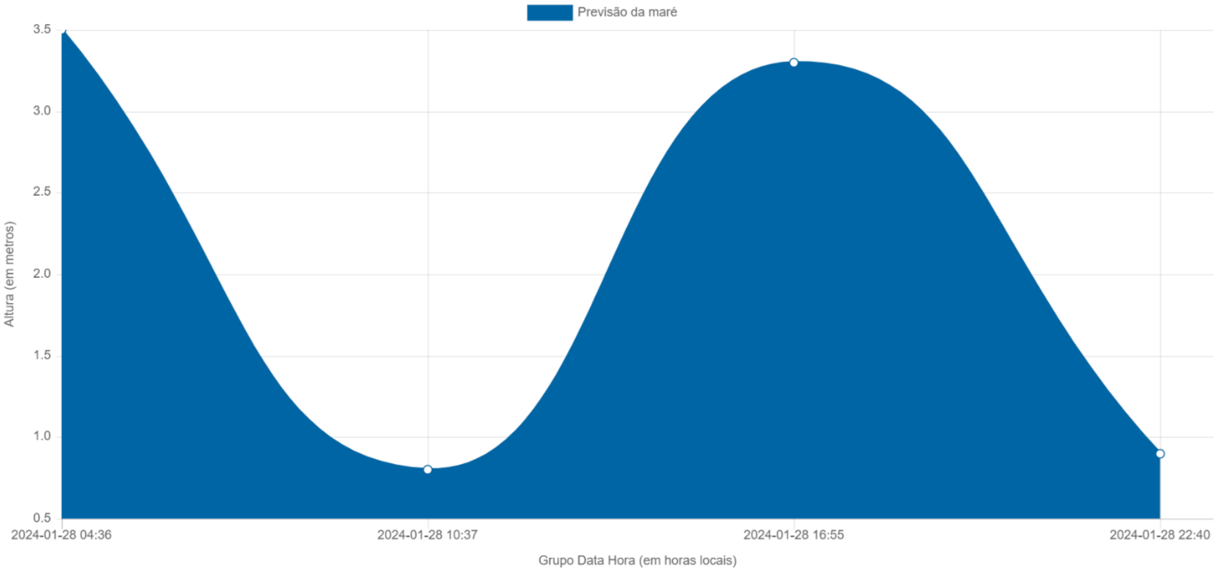


Figure 8 - Tidal amplitude in the Tagus estuary in January. Time on the x axis, height in meters on the y axis. (Instituto hidrográfico, 2024)

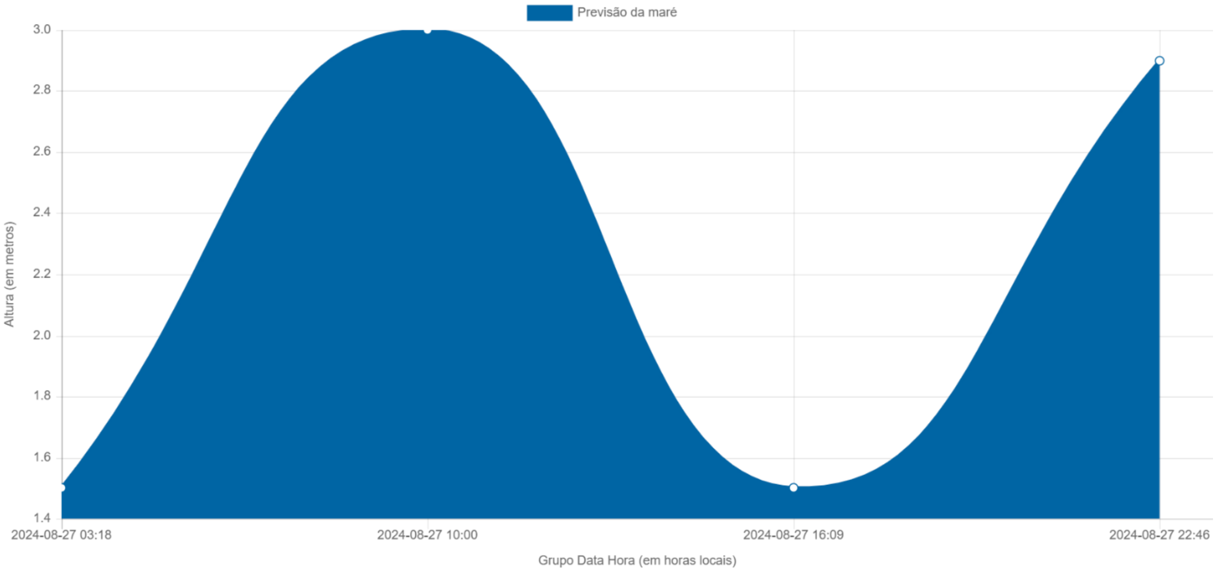


Figure 9 - Tidal amplitude in the Tagus estuary in August. Time on the x axis, height in meters on the y axis (Instituto hidrográfico, 2024)

The blue areas represent the tides' amplitude forecast. The seasonal variations in tidal amplitude further influence the estuarine dynamics, affecting the distribution of habitats and the availability of resources for various species. During high tides, water intrudes further into the estuary, influencing salinity levels, while lower tides expose mudflats that provide critical feeding grounds for birds and other wildlife. These climate-related factors underscore the importance of monitoring temperature, salinity and tidal oscillations in the Tagus estuary to predict their ecological impacts and develop adaptive management strategies.

2.3 Habitats

The study area can be broadly categorized into homogeneous habitat groups: tidal freshwater zones, salt marshes, intertidal and subtidal substratum and seagrass beds (França et al., 2009).

- **Tidal freshwater**

The northern part of the estuary is interested by two major rivers: the Tagus and the Sorraia, as well as other minor tributaries.

- **Salt marshes**

Salt marshes, also addressed as coastal wetlands, are positioned in the intertidal zone between high and low tide. These areas serve as "nurseries" for a wide variety of plant and animal species. Based on the tidal flooding frequency, salt marshes can be distinguished in two zones: the high marsh, which is submerged only during occasional storms, and the mid-to-low marsh, which is more frequently submerged. The plant species zonation (height of the marsh in which they are found) within these marshes depends on their tolerance to submersion and the frequency of flooding. Salinity in these areas tends to increase during high tides, in periods of high evaporation and in dry seasons.

Salt marshes are important in nutrient recycling, hosting various decomposer organisms that transform organic matter and release essential nutrients like phosphorus and nitrogen into the ecosystem.

Vegetation encountered in the salt marshes in the Tagus estuary are:

- Atlantic and Continental marshes and meadows, characterized by pioneer vegetation of *Salicornia* and other annual species, found in muddy and sandy areas, as well as meadows of *Spartina*;
- Mediterranean, thermo-Atlantic salt marshes and meadows. These marshes consist of Mediterranean and thermo-Atlantic halophilic shrubs and Mediterranean salt meadows. Mediterranean salt steppes, known for their halophilic and gypsophilic characteristics, are also present (Habitats Directive, Annex I; ICNF).

- **Intertidal and subtidal substratum**

Intertidal soft substrata refer to unvegetated areas found between the high and low tide zones, composed of sediment types that range from fine silts to coarse sand. Intertidal hard substrata, on the other hand, may include vegetated or unvegetated habitats within the same tidal range and are made up of solid materials like gravel or bedrock. Subtidal soft substrata consist of permanently submerged habitats that are unvegetated and formed from sediments varying between fine silts and coarse sand. Meanwhile, subtidal hard substrata encompass permanently submerged areas, which can be vegetated or unvegetated, and characterized by hard materials like gravel or bedrock (França et al., 2009).

- **Seagrass beds**

These areas include sea cliffs and pebble beaches with annual vegetation, typically where tidal debris accumulates. The marine and tidal environments feature sandbanks that remain submerged under shallow water, estuaries, swamps, and sands exposed at low tide (Habitats Directive, Annex I; ICNF).

2.4 Species

2.4.1 Fauna

The Tagus estuary hosts a wide variety of species: 35 mammals, 194 birds, 9 reptiles, 11 amphibians and 101 fishes, 40 of which with regular presence. Birds and fishes are the most common species to be found.

Around 100,000 wintering birds regularly occur, exceeding the figure of 120,000 birds during periods of migratory passage. The estuary hosts, on average, around 54% of the waders, 30% of the anatids and 4% of the wintering ardeids recorded in Portugal. Birds in the estuary are then classified based on their interaction with the area, indeed some of them only spend winter, others only use it for reproduction and some others are only passage birds (ICNF).

The most frequent wintering species, counted as maximum % of individuals in January in relation to the European total in different census years are:

- Tailor, *Recurvirostra avosetta* (20.1% - 1989);
- Right-billed Sandpiper, *Limosa limosa* (11.8% - 1992);
- Gray Plover, *Pluvialis squatarola* (5.4% - 1987).

The most relevant birds' species that only use the site for reproduction, in % of couples in relation to the European total per census year, are:

- Stilt, *Himantopus himantopus* (5% - 1990);
- Sea partridge, *Glareola pratincola* (>4% - 1992);
- Red or imperial heron, *Ardea purpurea* (2% - 1991).

Passage birds in the estuary, as % monthly-month/year of census are:

- Right-billed Sandpiper, *Limosa limosa* (20.5% Feb./1992).
- Flamingo, *Phoenicopterus roseus* (>1% June-Nov/various);

Lastly, the Reserve still appears to support 40 to 50% of the national breeding population of hen harriers or sap eagles (*Circus aeroginosus*) (ICNF).

Estuaries are important for the preservation of coastal fish stocks due to their function as *nursery zones*: areas where fish larvae and juveniles develop. The Tagus estuary is preferred by sea basses (*Dicentrarchus labrax)*, soles (*Solea solea* and *Solea senegalensis)* and 16 other fish species that use it in this role, although not preferential. It presents conditions for the spawning and growth of species such as the croaker (*Argyrosomus regius)* and the coastal population of anchovies (*Engraulis encrasicolus)*.

The resident species of commercial importance found in the estuary are the small sand goby (*Pomatoschistus minutus),* which is the most abundant, the Lusitanian toadfish (*Halobatrachus didactylus)* and the anchovy.

It is also an important transition zone for diadromous fishes (which means that they migrate to spawn between the sea and fresh water): the sea lamprey (*Petromyzon marinus*), the river lamprey (*Lampetra fluviatilis*), the shad (*Alosa alosa*), the yellowtail (*Alosa fallax)* and the eel (*Anguilla anguilla*). Freshwater species can also be found in the upper part of the estuary, while coastal marine species such as the imperial kingfish (*Arnoglossus imperialis)* and the kingfish (*Atherina presbiter)* use this area as a feeding site (ICNF).

The decomposing plant matter, mostly produced by the salt marsh, and the microalgae that develop on the surface of the substrates are consumed by benthic beings (invertebrates and small fishes). They constitute the nourishment base for fish at high tide and birds at low tide, so these species play a fundamental role in the estuarine food web. The most found in the Tagus estuary are the earthworm (*Hediste diversicolor)*, the waterworm (*Peringia ulvae)*, the lambujinha (*Srobicularia plano)*, the isopod (*Cyathura carinata)*, the amphipod (*Melita palmata)*, the shrimp (*Palaemonetes varians)*, the green crab (*Carcinus maenas)* and the sand goby (ICNF). Intertidal zones are crucial for the survival of these species, which is one of the reasons why they need preservation efforts.

2.4.2 Flora

Most of the plant species in the Tagus estuary area are halophytic, which means they are highly salt-tolerant. The estimated biomass production is at 17790 tons of carbon/year (ICNF).

The species found in salty waters, according to ICNF, are: *Spartina maritima*, *Halimione portulacoides*, *Sarcocornia fruticose*, *Sarcocornia perenne*, *Salicornia nitens* and *Arthrocnemum* spp.

Spartina maritima is usually found in submerged areas, it is a strong halophyte specie, as it can live in waters with high salinity and in a wide range of salinity levels. It is also tolerant to varying temperatures as it can withstand both relatively high and low temperatures compared to the surface water average for short periods, making it well-adapted to estuarine environments.

In the Tagus Estuary, where freshwater from the river mixes with seawater, salinity can fluctuate. Species like *Spartina maritima* can typically tolerate salinity levels ranging from around 5 ppt to 35 ppt. It may typically prefer salinity levels closer to seawater for optimal growth, although usually salt marsh plants are reluctant to water environments with salinity higher than 35 ppt. Water temperature and daily tidal flushing are fundamental for the salt marsh plant, because studies have proved that dry conditions influence the proper development of *Spartina maritima* (Adams and Bate, 1995). Figure 10 and Figure 11 are photographs representing *Spartina Maritima* in the municipality of Alcochete, taken during field visits in the Natural Reserve.

Figure 10 - Spartina maritima in the Natural Reserve in Alcochete, 24th of June 2024

Figure 11 - Spartina maritima at low tide in the Natural Reserve in Alcochete, 24th of June 2024

Spartina maritima acts to desalinate high salinity water, as a filter for the freshwater runoff and it is important for species and for carbon sequestration. Oxygen levels are usually extremely low in the soil where *Spartina* grows, giving the "rotten eggs" smell.

In the Tagus estuary, vegetal species other than halophytes are typically found in areas where the tide reaches less frequently or where freshwater inflows occur, such as *Suaeda vera*, *Aster tripolium*, *Puccinellia maritima* and *Inula crithmoides*. Further upstream, in zones with lower salinity, species like *Scirpus maritimus* and *Phragmites australis* can be found (ICNF).

3 Methodology

This study combines the results from a hydrodynamic model with coding tools, to generate an indicator, the Habitat Suitability Index (HSI), that could help judge the quality of evolving environmental conditions in the Tagus estuary linked to climate change.

Hydrodynamic simulations for the estuary were conducted using MOHID, a three-dimensional water modelling software developed by MARETEC (Marine and Environmental Technology Research Center) at Instituto Superior Técnico (IST), part of Universidade de Lisboa, Portugal. This software allows to analyze the water cycle with a wide selection of processes, scales and systems. The MOHID Water model is already validated for the Regions of Freshwater Influence (ROFI) in the Tagus estuary with numerical modelling results (de Pablo et al., 2019).

The simulation model was implemented for three cases: the first one is the baseline data, addressed as the Reference Year, and two future scenarios, named as SC1 and SC2.

A MATLAB code (included in the Annex) was created to handle the elevated spatial and temporal amount of data for each case. Particularly, bathymetric data were processed to map the species using the estuary's geometry. Tidal oscillations bring out values at certain time intervals in the upper part of the estuary where no water is recorded, so a counter was generated to filter out these points in time, in order not to alter the actual water values. Then, salinity and temperature values were extracted and suitability indexes were created. Lastly the HSI, integrating salinity and temperature as environmental factors, was employed.

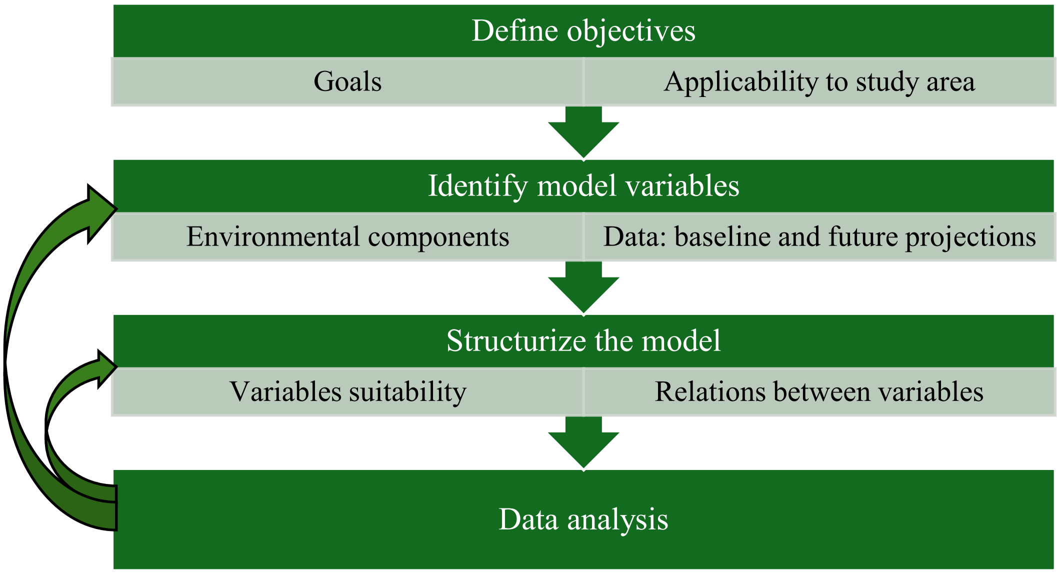
Data analysis focused on the statistical examination of key environmental parameters including salinity, water temperature and Habitat Suitability Index (HSI), to better understand the current and future trends.

A sensitivity analysis was conducted to assess the robustness of the HSI model and identify which parameters most significantly impact the index.

The main part of this research was conducted from MOHID's simulation results through the Habitat Suitability Index (HSI) method, a practical function that evaluates habitat quality or habitat loss by creating a scale from 0 to 1 and associating a value on this scale to each variable of the model. The HSI can gather many different causes and contributing factors to an environmental concern in a single function, and it allows to easily compute and interpret its results.

A proper HSI model was defined through the following steps:

a) Definition of the objectives
b) Identification of the model variables
c) Structuring the model



(EPA, 2016)

3.1 Definition of the objectives

The goal is to obtain a function that will quantify the current habitat quality for some of the species involved in the study and its changes due to climate change future scenarios highlighted by the IPCC and several other scientific studies. The reference situation will then be compared to the future scenarios using the same function and only modifying the SLR and temperature, so that the differences will be related to climate change only. The scope is then to verify if climate change will modify habitats in the Tagus estuary.

The study area is mainly the estuary saltmarsh zone and the most frequent vegetal species there are:

- *Spartina maritima*
- *Halimione portulacoides*
- *Sarcocornia fruticose*

Spartina maritima will be the main subject of the analysis, as the three species behave similarly and there is more literature data available for *Spartina* in the study area (ICNF; Vinagre et al., 2011).

The applicability of this approach to the study area was already widely tested in past research (Vinagre et al., 2006).

3.2 Identification of the model variables

3.2.1 Environmental components

A similar study (Vinagre et al., 2006) selected sediments, depth, bathymetry, temperature, salinity and intertidal presence as environmental components to adopt as variables for the HSI function. The ones identified here are bathymetry, salinity and temperature as an attempt to simplify the model. Bathymetry was used to track *Spartina* in the estuary, as the specie is only found in a certain bathymetric interval, while salinity and temperature were chosen as the model variables, because they are crucial components to determine whether the habitat can be suitable for *Spartina* or not.

3.2.2 Database

Baseline data

The estuary water dataset from which the analysis starts is a year period in a set of hourly data that goes along October 2019 – September 2020, named as "Reference Year". This year was in normal climate conditions, being neither too humid or too dry in the estuary, compared to the previous and following years. The choice is supported by a study conducted at MARETEC and shown in Figure 12 (Mateus and Pinto, Instituto Superior Técnico, Universidade de Lisboa, Ce2coast, 2023).

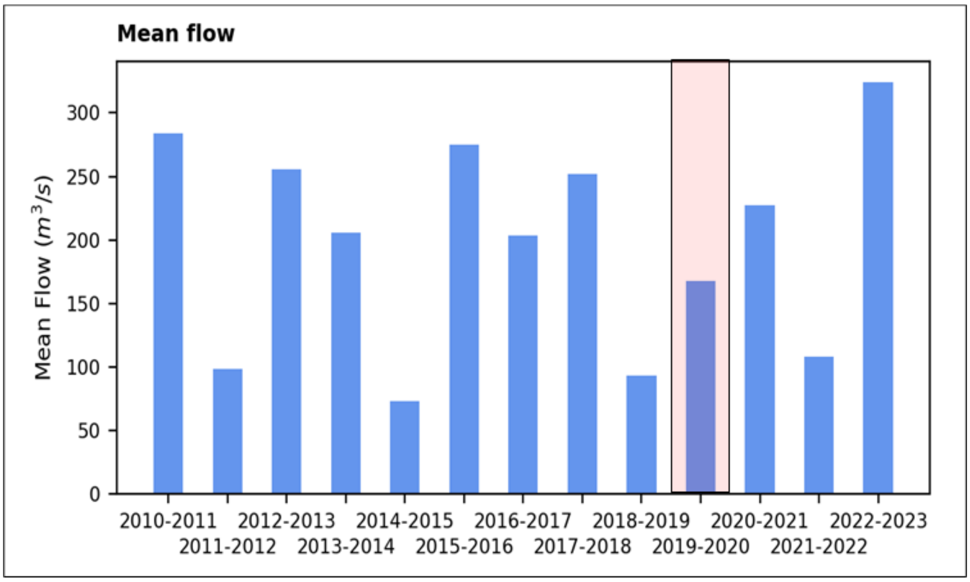


Figure 12 - Average annual flows in the Tagus estuary (MARETEC, 2023)

The set of data elaborated in MOHID produced the results that are analyzed in this study. The database used is limited to the surface water and the software creates a 405x351 grid, collected in HDF5 file formats. Salinity and temperature hourly data were extracted for the selected period and then combined to obtain a set for each month and for the whole Reference Year.

The MATLAB code was implemented to apply the bathymetry mask range, chosen between the minimum value (-4.41 m) and +1.50 m based on the criteria for which *Spartina* survives up to a certain water height and the average length of the species was considered. Then the annual set of salinity and temperature corresponding to the set of bathymetric coordinates was extracted (5618 cells out of 142155 in the grid), excluding the no water values due to the tidal daily oscillation. The categorization of the suitability indexes and eventually the calculation of the average HSI for each month and for the entire year was performed.

Future projections

The following predictive projections, from the MARETEC study, were considered:

- sea level rise of +0.5 m (conservative estimate from Mateus and Pinto, 2023);
- ocean temperature rise of 2.4°C for the period 2041-2060 and 4.4°C according to IPCC's very high GHG emissions scenario, an estimated prediction on sea water warming for the Atlantic higher than 3°C and a very likely range between 1.6 and 2.8°C for the 2081-2100 period (Cheng et al., 2022).

This research will consider two future scenarios based on these projections: the first case only considers the increase in SLR of 0.5 m (SC1), the second case combines the 0.5 m increase in SLR and an average increase in sea water temperature of 2°C (SC2).

The MARETEC research resulted in all the projections leading to an increase in salinity for the effect of SLR. The future scenarios recorded a maximum average salinity increase of 2.5 ppt. Minimum and maximum temperature values increased on average of 0.5°C in SC2, whereas in SC1 the minimum and maximum are usually about 1°C lower and higher respectively.

Salinity showed a higher variation compared to temperature. The salinization would eventually preclude the use of water for agriculture purposes. There is a potential risk for the estuary to shift from saltmarsh areas to a chocked coastal lagoon (Mateus and Pinto, 2023). The effects of SLR could lead the estuary in becoming flood-dominant, with risks of losing up to 40% of the current intertidal areas by 2100 (Guerreiro et al., 2015).

The potential effects on the estuary are threatening the plant species' survival, the stability of salt marshes and biodiversity.

The possible outcomes for the future habitat changes in the Tagus estuary are:

- Salinity increase for both scenarios.

- Optimal conditions for *Spartina maritima*'s growth will be found northern from the current position: the halophytic species are expected to shift in the upper part of the estuary due to salinization.
- The current salt marshes can transform into lagoons due to SLR, leading to loss in habitats and biodiversity.

3.3 Structuring the model

Suitability and HSI functions

Temperature and salinity ranges were selected through literature review and adapted to the present case study, to assess the optimal conditions for the species (Adams and Bate, 1995; Crosby et al., 2016). This allowed to create a set of two suitability indexes for salinity and temperature on which the Habitat Suitability Index was then based. Table 1 and Table 2 collect the intervals adopted.

Table 1 – Salinity Suitability Index

Salinity [ppt]	$SI_{salinity}$
12-29	1.00
10-12, 29-31	0.85
8-10,31-33	0.70
6-8,33-35	0.50
4-6,35-37	0.10
0.01-4	0.05

Table 2 – Temperature Suitability Index

Temperature [°C]	$SI_{temperature}$
15-24	1.00
24-26	0.50
11-15	0.50
26-28	0.10
<11	0.10

The Habitat Suitability Index (HSI) was then calculated as an unweighted geometric mean function (Vinagre et al., 2006):

$$\text{HSI} = \sqrt{SI_{salinity} \cdot SI_{temperature}}$$

This is a multiplicative approach, which means that whenever one of the variables will be assigned with a 0 value, the HSI will be 0 for its nature. This could potentially be a limiting factor, as the absence of one factor can not completely exclude the presence of the others and it does not necessarily mean no suitability for at least some of the species. A similar computation for the HSI was already tested in past research (Crawshaw, 2015, following Oldham et al., 2000 and Brady, 2010).

It was then possible to implement the Reference Year and the future scenarios HSI data on the OpenFlows FLOOD software, obtaining HSI maps.

The HSI values were evaluated with a qualitative set of labels for data analysis, as reported in Table 3 below.

Table 3 – Habitat Suitability Index scores and categories

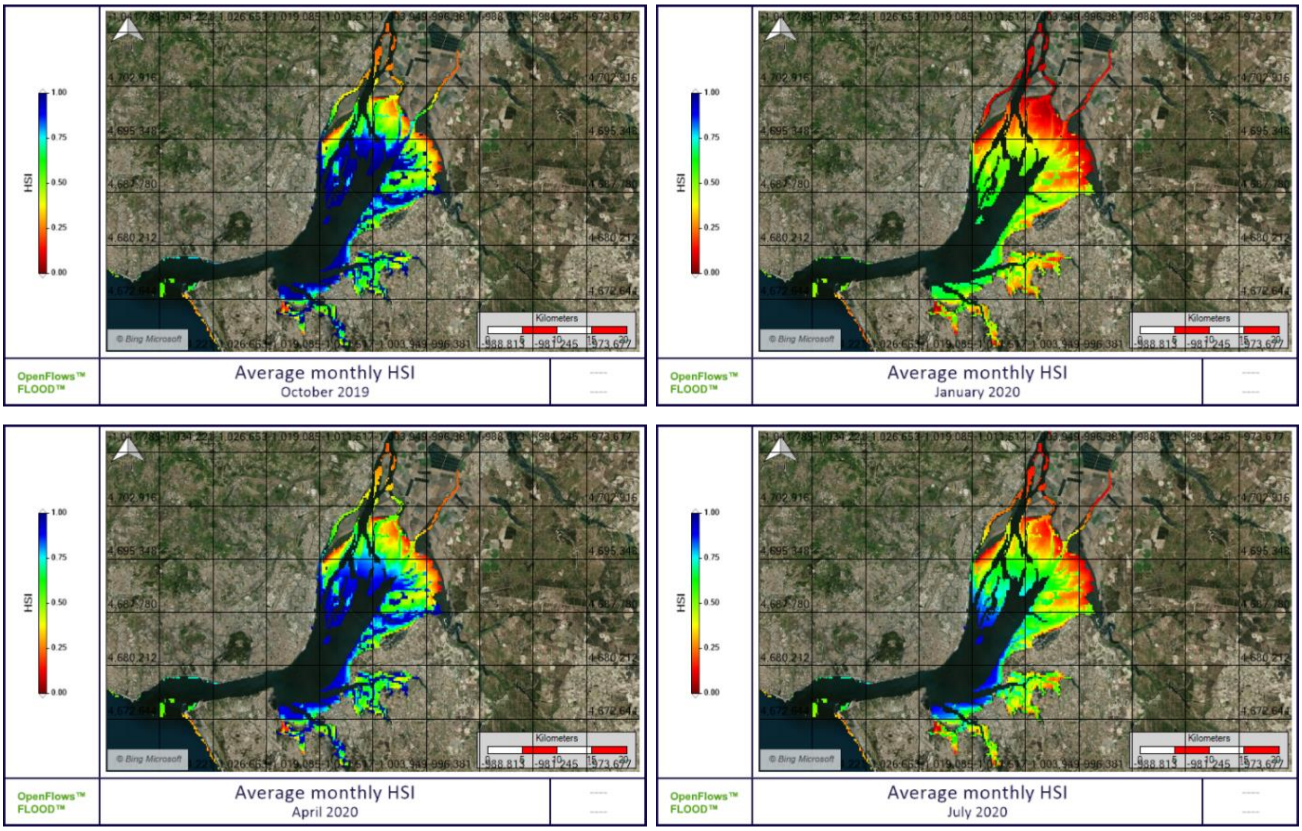
HSI Scores	HSI Categories
0.8-1	**Excellent**
0.6-0.8	**Good**
0.4-0.6	**Fair**
0.2-0.4	**Poor**
0-0.2	**Very Poor**

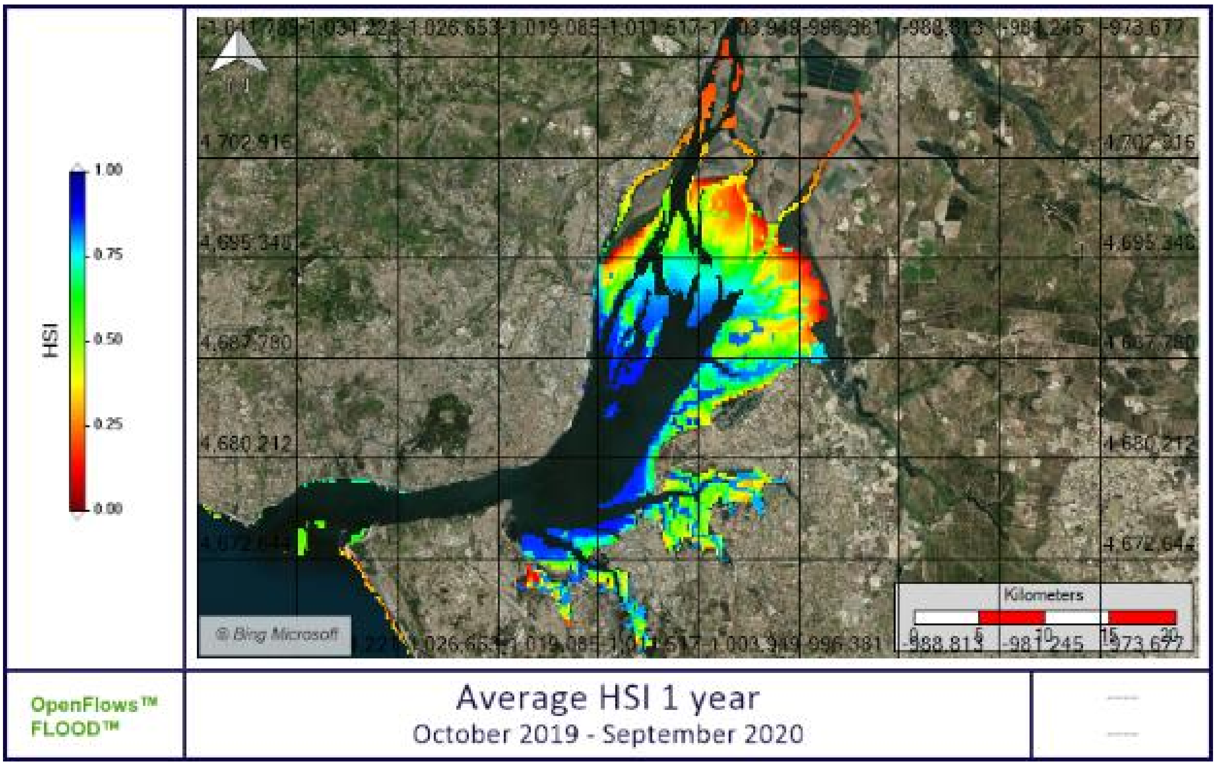
4 Results and data analysis

4.1 Results

4.1.1 Baseline case: the Reference Year (RY)

The maps below illustrate the Habitat Suitability Index (HSI) for *Spartina maritima*_obtained using OpenFlows FLOOD software. Four seasonal maps, with a span of three months in between them, are shown, representing the average HSI values for the months of October 2019, January 2020, April 2020 and July 2020, along with an additional map for the annual average HSI. Each map uses a color scale ranging from red (HSI = 0) to blue (HSI = 1), with blue indicating highly suitable habitats for the species. Uncolored grid points represent areas without water or locations excluded by the bathymetry mask, where water levels exceed the threshold suitable for *Spartina*'s growth. Figures 13 gather the HSI maps for the Reference Year.





Figures 13 – Maps of average monthly and annual HSI in the Reference Year (OpenFlows FLOOD)

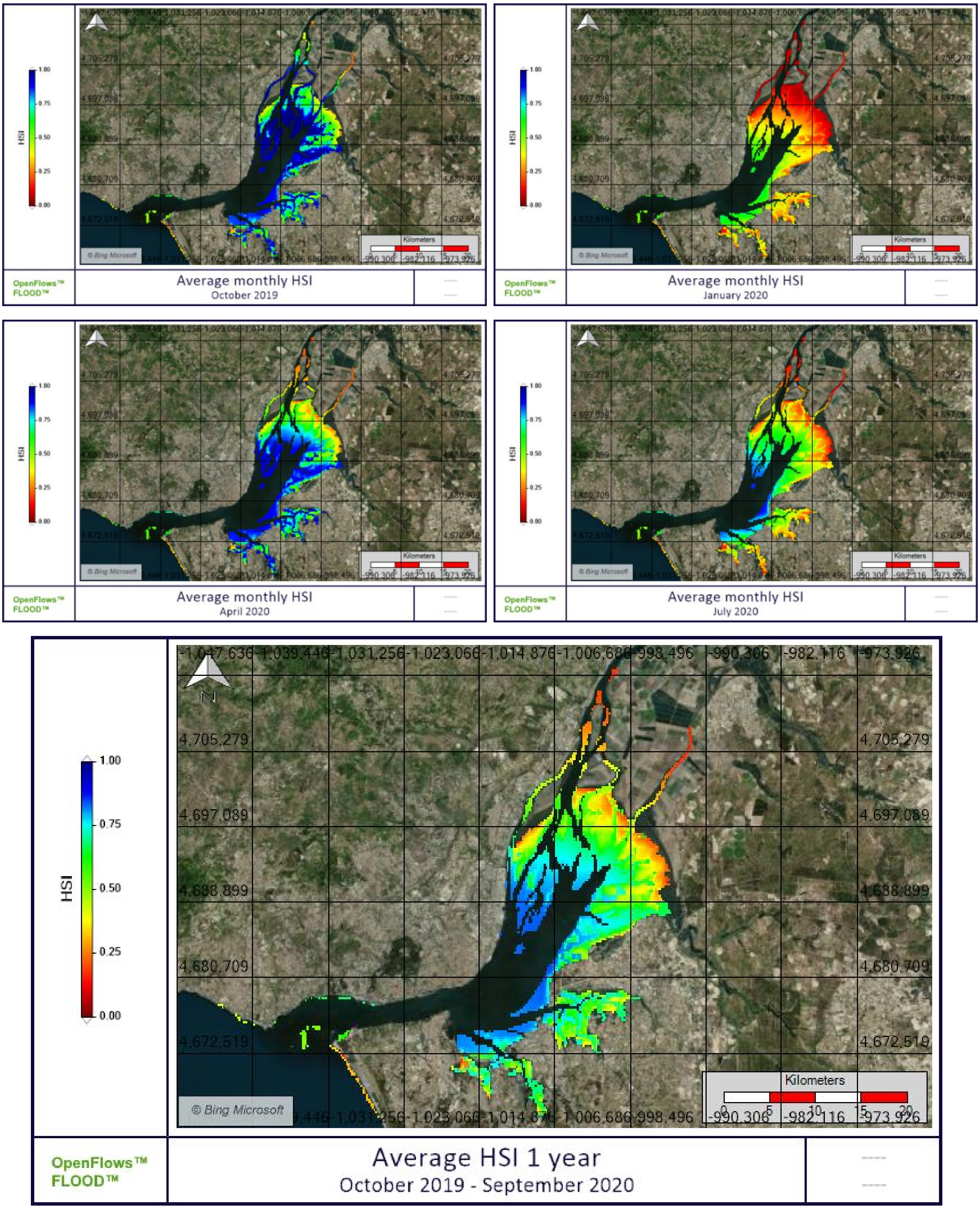
Upon visual analysis, January emerges as the most critical month, showing no high HSI (blue) values, and features more low-suitability zones compared to other months. July follows as another challenging month for *Spartina*, though it shows a few areas of high suitability, particularly around Alcochete, Barreiro, and Seixal and in the middle part of the estuary.

In contrast, October is the most favorable month, with extensive high-suitability zones (dark blue), followed by April, which shows similar, though slightly lower, suitability values.

High HSI values tend to be concentrated at least 1 km away from the coast, while lower values are predominantly found along the northern estuary and near the coastline, where tidal fluctuations leave these areas without water for part of the day.

4.1.2 First future scenario: +0.5m SLR (SC1)

The first future scenario involves a projected sea-level rise (SLR) of half a meter compared to the baseline case. The simulations was modeled by adjusting the baseline bathymetry to simulate the higher water column. This scenario aims to illustrate the potential impacts of SLR on habitat suitability for *Spartina*. The maps are displayed in Figures 14 for Scenario 1.



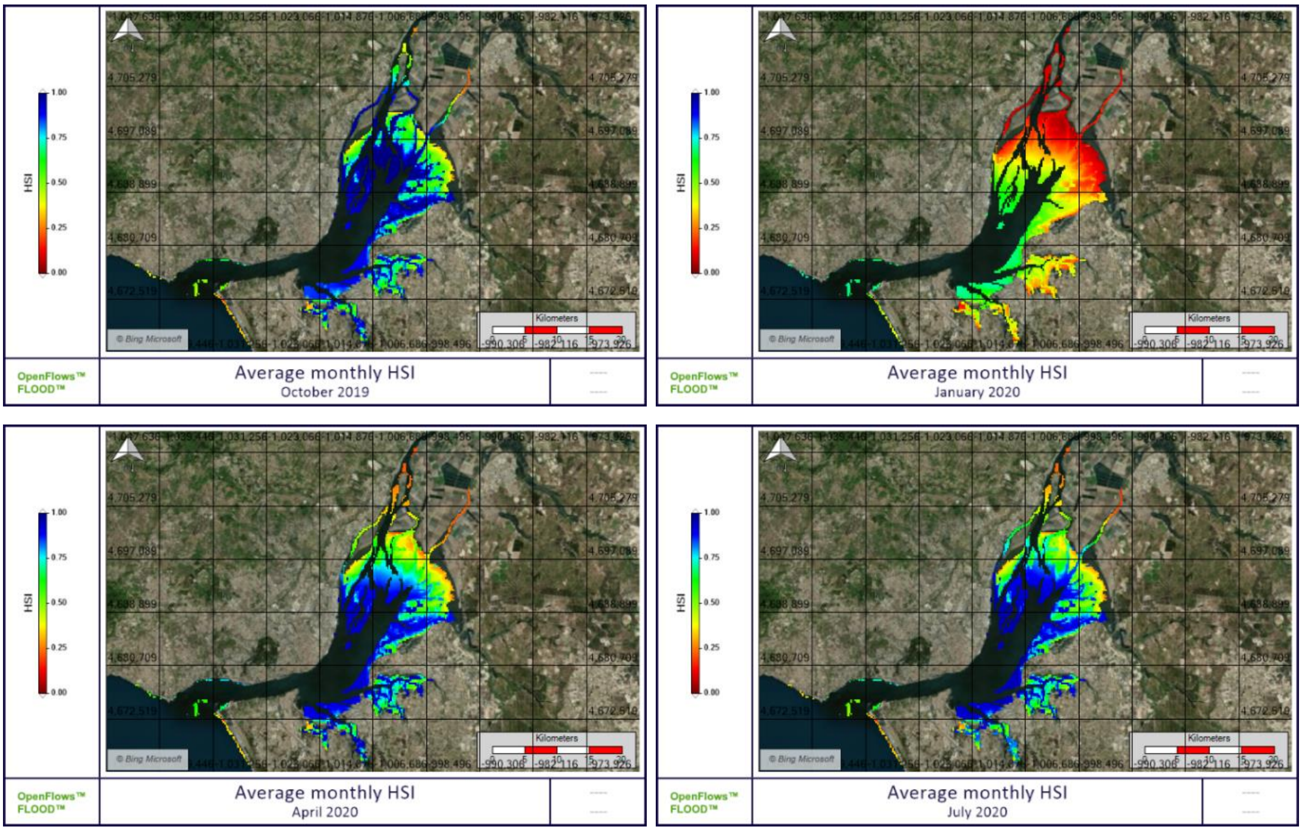
Figures 14 - Maps of average monthly and annual HSI in the first scenario (OpenFlows FLOOD)

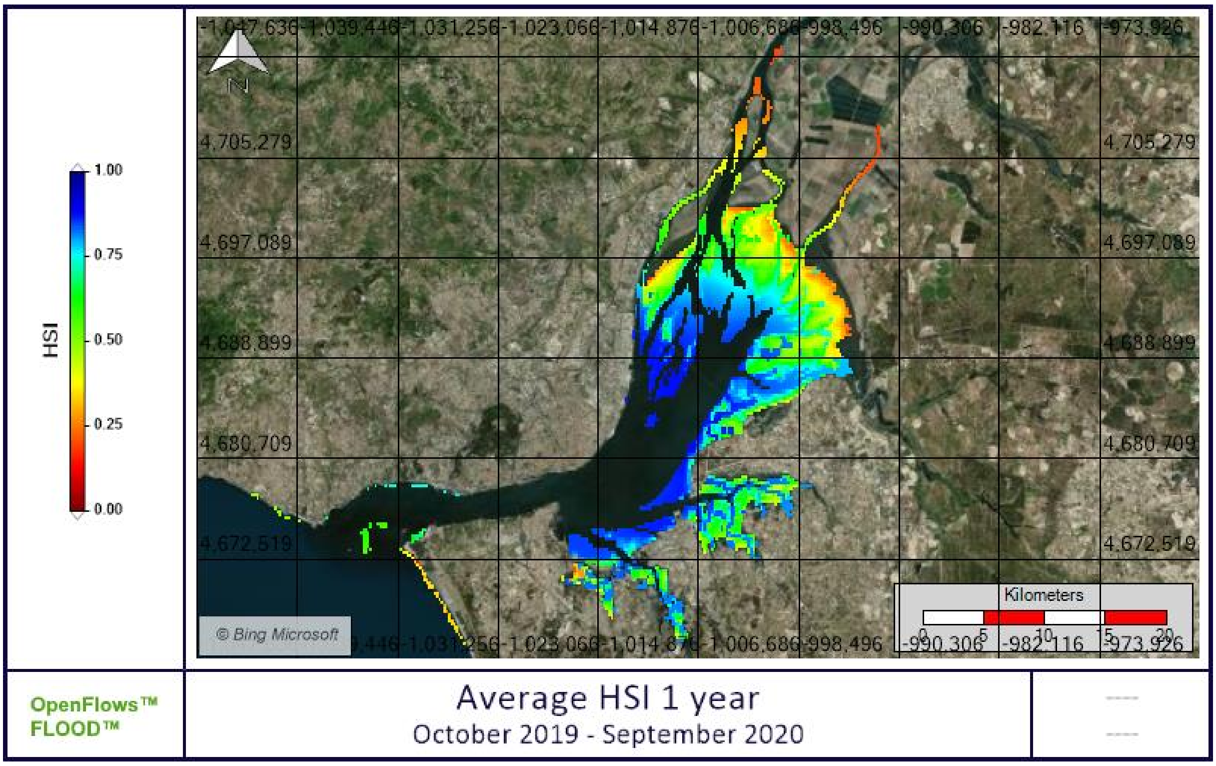
As observed in the baseline case, January remains the most critical month, lacking high-suitability (blue) values. July also shows limited suitable spots, but October continues to display the most favorable conditions for *Spartina*, followed by April, which still presents a lighter blue distribution of HSI values.

The spatial distribution of high suitability remains consistent with the baseline case, with favorable conditions appearing over 1 km from the coast, and low-suitability values concentrated in the northern estuary and near the coastline, where tidal variability causes periodic drying.

4.1.3 Second future scenario: +0.5m SLR & + 2°C T (SC2)

The second future scenario also considers a sea-level rise of half a meter, while incorporating a 2°C increase in water temperature, allowing the simulation to account for both changes in sea level and temperature. This scenario combines two possible projections to explore the combined effects of rising sea levels and warming waters on *Spartina* habitats. The maps are displayed in Figures 15 for Scenario 2.





Figures 15 - Maps of average monthly and annual HSI in the second scenario (OpenFlows FLOOD)

In this scenario, January, October, April and the annual map are very similar to the previous scenario. However, July undergoes a radical change, visibly showing extensive high-suitability areas in the estuary.

It also clearly emerges that in every scenario, *Spartina* prefers saltier waters, as the HSI is higher far from the main freshwater sources, but this is only true up to a certain extent of salinity, as the index is lower in correspondence of the oceanic coastline. Moreover, this is also partly due to the effect of the tidal oscillation on the HSI, that is why this will be further investigated in the following section.

4.1.4 Influence of the tidal oscillation

In addition to the HSI analysis, a count of the hours without water was conducted for each month and the entire year. This was performed using MATLAB, where an if-condition was integrated into a for-loop to differentiate salinity and temperature values addressed to water presence. The "Open Points" HDF5 data was instrumental in tracking whether each grid cell was water-covered (value 1) or dry (value 0), and the cumulative hours of water absence were calculated for each period. This counter specifically tracks areas affected by the tide and the values are collected in Table 4.

Table 4 – No water values counter in the Reference Year (RY), Scenario 1 (SC1) and Scenario 2 (SC2)

Hours without water (on average)	RY	SC1	SC2
October 2019	153	102	103
January 2020	162	106	106
April 2020	142	91	92
July 2020	154	100	101
October 2019 – September 2020	1819	1189	1192

In the Reference Year, April is the month with the lowest number of hours without water (~6 days) and January the one with the highest number (~7 days). This is also due to precipitation and temperature patterns in the Tagus estuary as well as local factors in that period. In total, about 76 days out of 366 accounted for no water in the points influenced by the low tide.

In SC1, again April is the month with the lowest number of hours without water (~4 days) and January the one with the highest (~4.5 days). This is due to the SLR change which shifts the tideline northward and reduces the hours without water at the same coordinates. In total, about 50 days out of 366 accounted for no water in the points influenced by the low tide. The trend remains the same as the Reference Year, but the SLR significantly changes the tide's frequency.

In SC2, similarly to the previous scenario, April is the month with the lowest number of hours without water (~4 days) and January the one with the highest (~4.5 days). In total, about 50 days out of 366 accounted for no water in the points influenced by the low tide. The trend remains the same as the first scenario, as the temperature rise of 2°C is not influencing the tide line as much as the SLR. However, it should be noted that the total number of hours without water is slightly higher in this second scenario, meaning that even if the temperature rise effect is way milder than the SLR, it is still contributing to slightly increase it, in contrast to the SLR.

4.2 Data analysis

4.2.1 Statistical analysis of the environmental variables

The HSI definition is strongly dependent on the environmental variables, in this case salinity and temperature. To better interpret the Index, it is particularly important to better understand how their distributions behave. This section deeply analyzes them through a statistical investigation. Each one of the following graphs (Figure 16 - Figure 20) underlines the salinity and temperature trends in various periods.

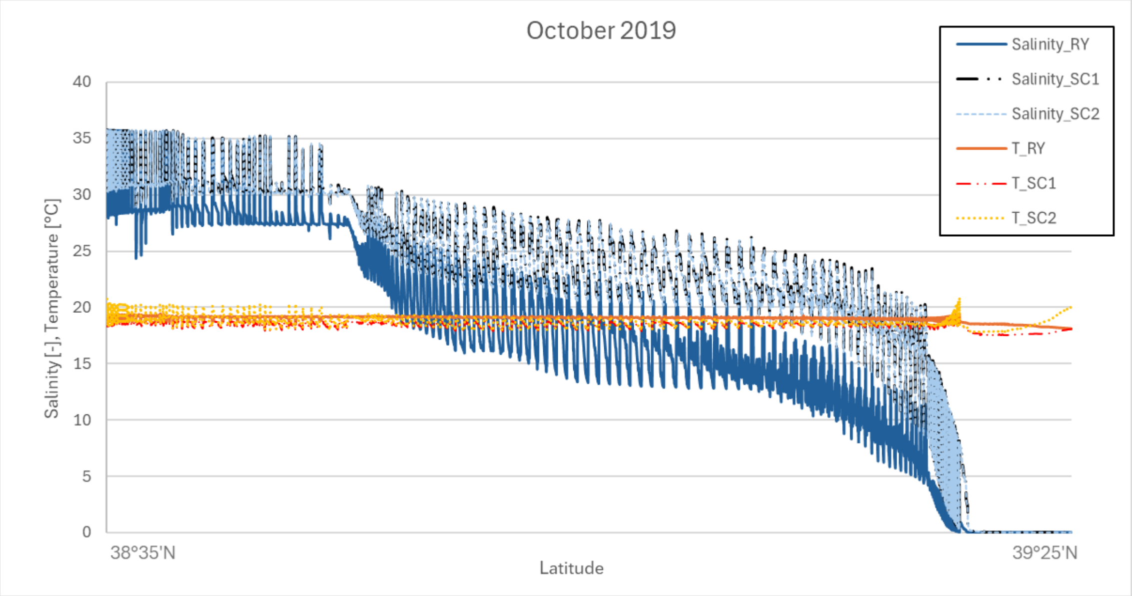


Figure 16 – Salinity and Temperature temporal average series in October

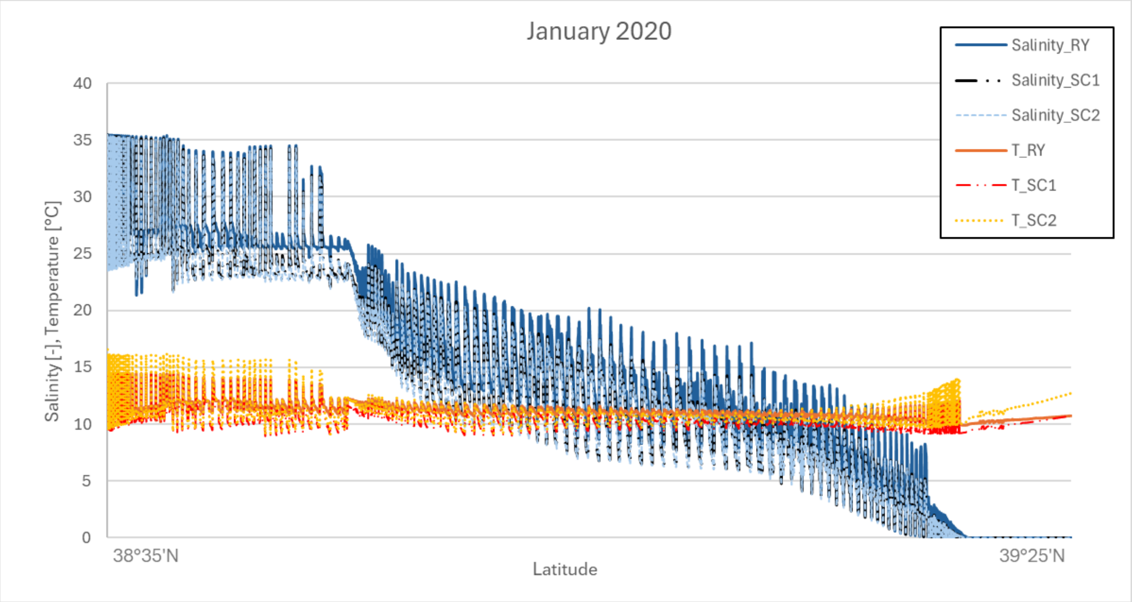


Figure 17 - Salinity and Temperature temporal average series in January

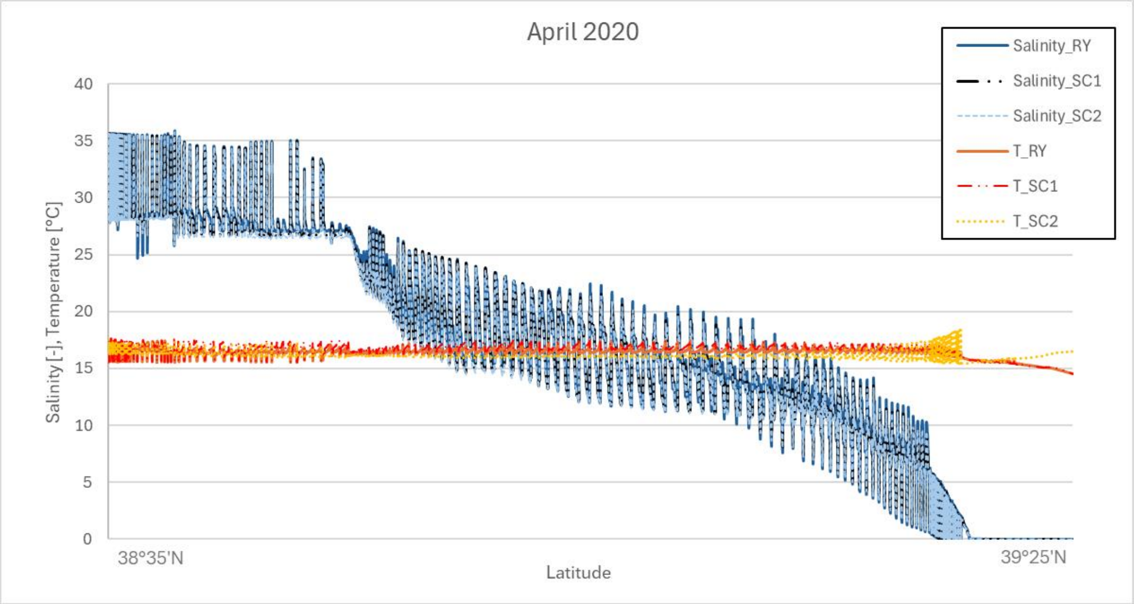


Figure 18 - Salinity and Temperature temporal average series in April

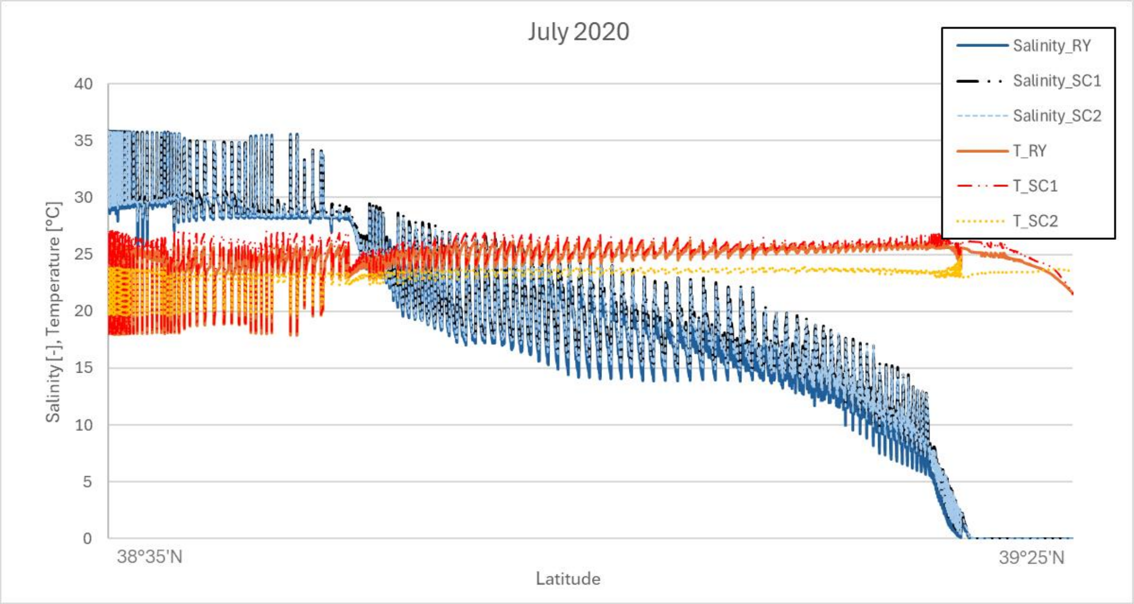


Figure 19 - Salinity and Temperature temporal average series in July

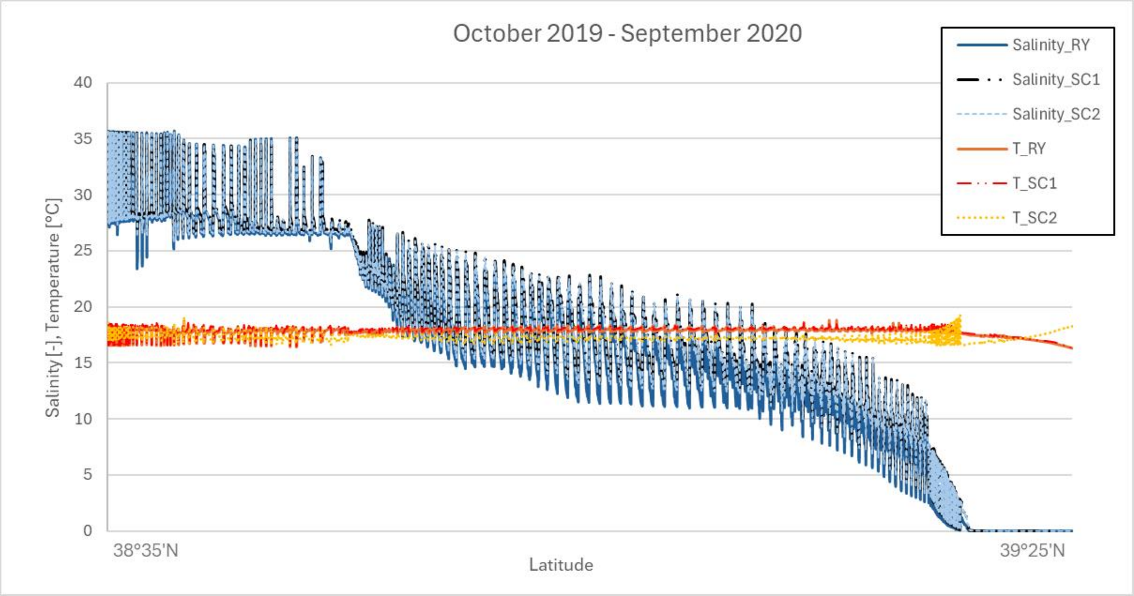


Figure 20 - Salinity and Temperature temporal average series in the whole year period (from October to September)

As follows, in Table 5, the main statistics about the analysis for both salinity and temperature are gathered, in every analyzed period.

Table 5 – Environmental variables statistical analysis

		Reference year			**Scenario 1**			**Scenario 2**		
		range	**μ**	**σ**	**range**	**μ**	**σ**	**range**	**μ**	**σ**
OCT	**SAL**	0.01 – 35.84	**16.75**	10.32	0.01 – 35.84	**21.70**	10.10	0.01 – 35.84	**21.56**	10.06
	T	12.94 - 24.55	**19.00**	1.92	12.79 - 23.61	**18.38**	2.10	12.85 - 23.74	**18.70**	2.14
JAN	**SAL**	0.01 – 35.71	**14.39**	10.17	0.01 – 35.71	**12.94**	9.59	0.01 – 35.71	**12.80**	9.53
	T	5.80 - 15.35	**11.14**	1.27	5.54 - 15.35	**10.34**	1.26	5.65 - 17.30	**10.97**	1.45
APR	**SAL**	0.01 – 35.91	**16.28**	10.61	0.01 – 35.91	**16.28**	10.39	0.01 – 35.91	**16.12**	10.33
	T	10.10 - 21.89	**16.32**	1.61	9.14 - 23.39	**16.62**	2.55	9.21 – 21.19	**16.09**	1.77
JUL	**SAL**	0.01 – 35.92	**17.73**	10.52	0.01 – 35.92	**18.69**	10.35	0.01 – 35.92	**18.40**	10.24
	T	16.06 – 31.83	**24.74**	1.98	16.02 – 32.19	**25.28**	1.81	17.94 – 27.87	**23.31**	1.13
YEAR	**SAL**	0.01 – 35.92	**15.95**	10.37	0.01 – 35.92	**17.12**	10.46	0.01 – 35.92	**16.92**	10.39
	T	5.80 – 31.83	**17.76**	4.58	5.54 – 32.19	**17.90**	5.40	5.65 – 27.87	**17.24**	4.28

Mean salinity is increasing in both scenarios, compared to the Reference Year, apart from January, in which there is a slight decrease, and April, which shows minimal to no change. Scenario 2 consistently registers a slightly lower mean salinity compared to Scenario 1.

Mean temperature is generally lower in both scenarios, with the exceptions of April and July, which have an increase in Scenario 1 and a decrease in Scenario 2. In the colder months mean temperature is increasing in Scenario 2 if compared to Scenario 1. The annual average temperature is mostly influenced by warmer months like July.

Maximum average salinity increase in a month is 4.95 ppt, which strips down to 1.17 ppt in the whole year average. The same temperature average values are 0.54°C and 0.14°C respectively. It is critically relevant to understand that standard deviations are significantly different for the two environmental variables, with temperature consistently exhibiting lower standard deviations compared to salinity across all periods. This indicates that temperature values show less variability. Salinity, on the other hand, has higher standard deviations, indicating greater variability.

Although, salinity ranges remain relatively constant over time, whereas temperature ranges are more sensitive to changing conditions and less stable. Additionally, the intervals of temperature's distributions are generally narrowing in Scenario 2, when compared to scenario 1, meaning that increasing temperatures by 2°C in oceanic water with a fixed SLR led to a thermic flattening.

This difference in variability highlights key characteristics of the two environmental variables:

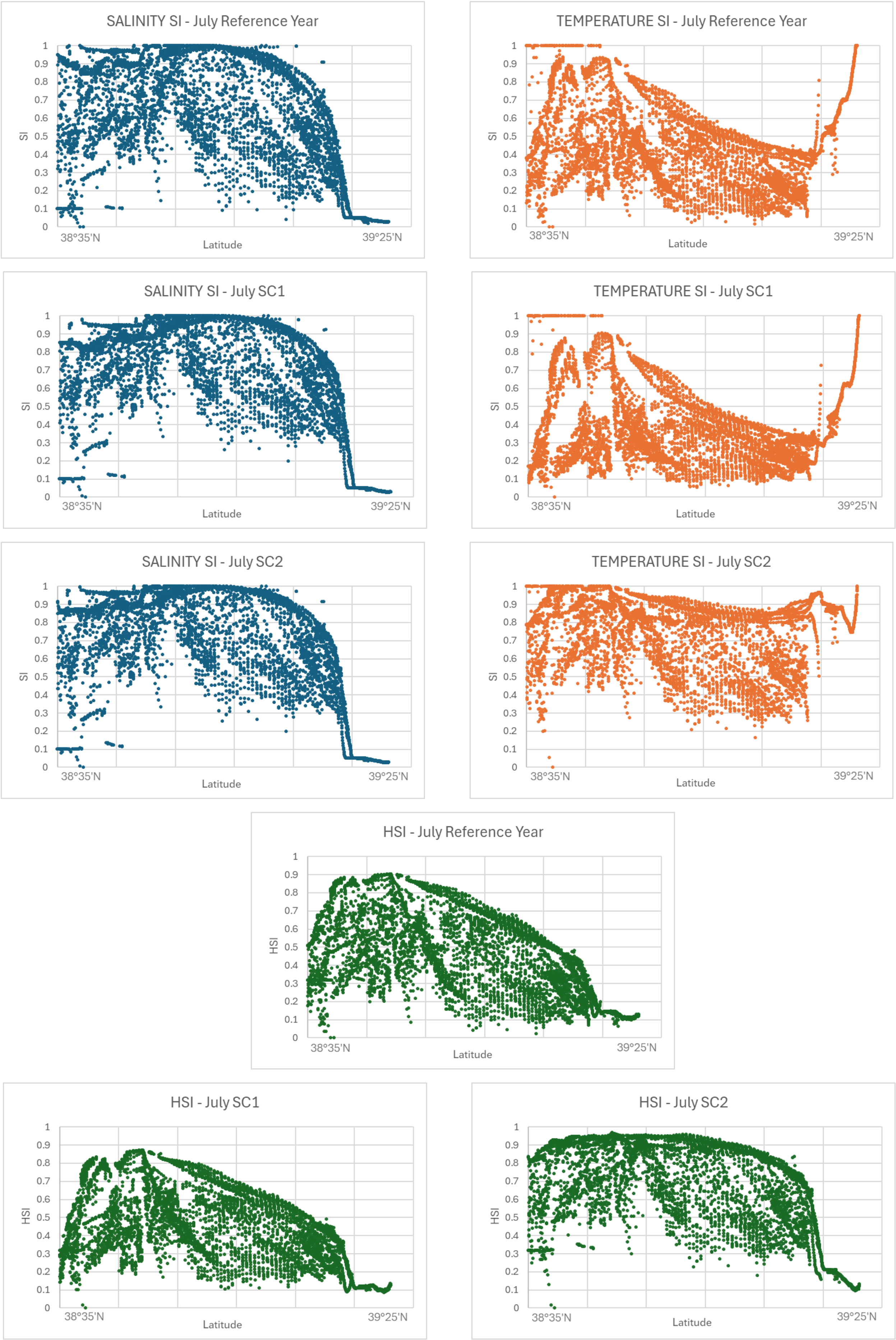
- Salinity shows significant fluctuations but tends to remain within a relatively fixed range, indicating a more consistent behaviour in its extremes.
- Temperature, while showing low variability overall, tends to have lower stability and higher sensitivity to external changes in a narrower range.

These distinctions are critical for understanding their influence on the HSI. Though, it is important to first note that the species in focus for this case study are particularly salt-tolerant, making salinity variations less impactful on their overall habitat suitability. For other species, especially those found further north in the estuary, salinity tolerance may be reduced and therefore an increase in salinity may be more harmful.

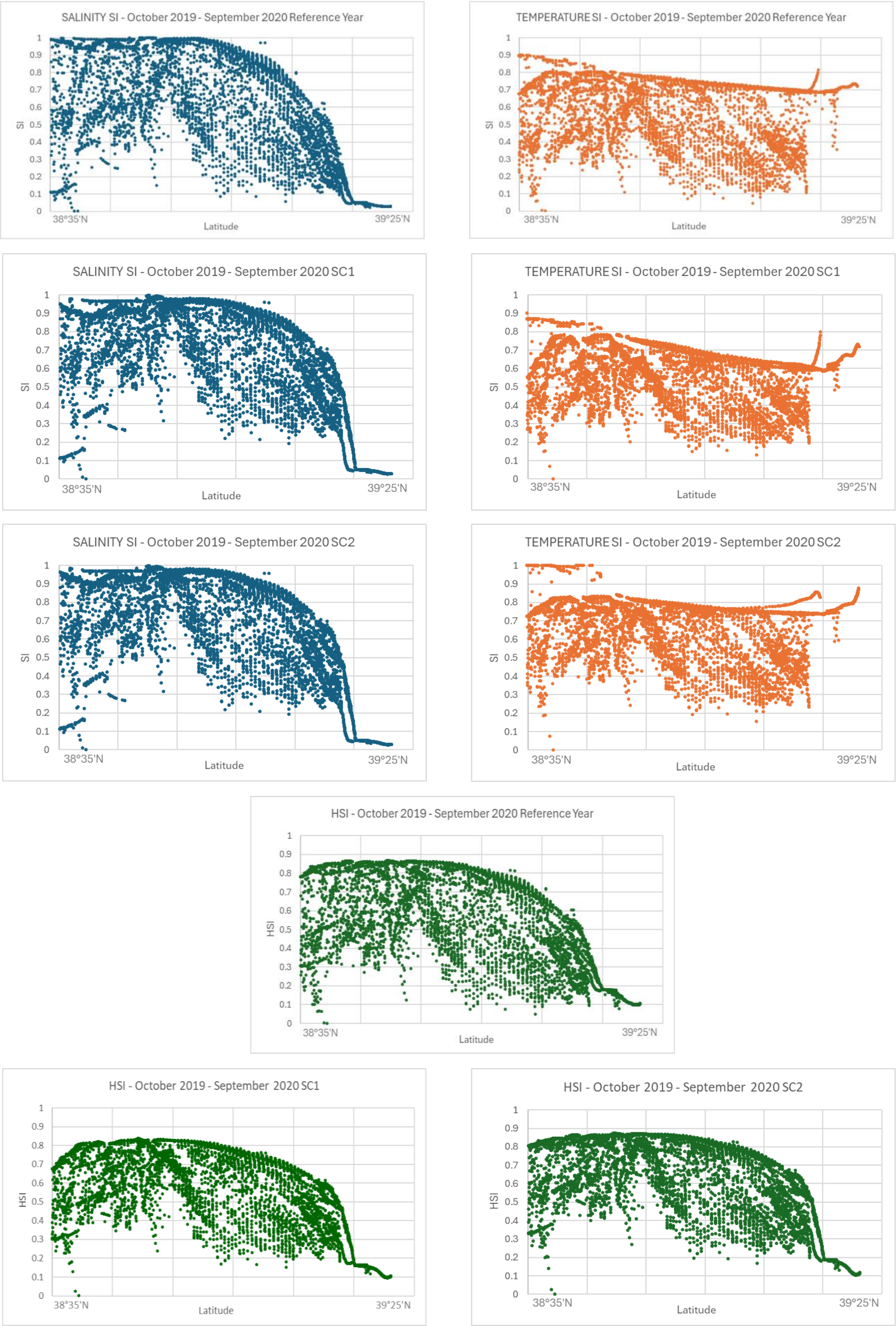
Additionally, the estuary's complex hydrodynamics, characterized by varying water densities, the upwelling phenomenon and tidal influences, play a significant role in shaping the environmental conditions. These dynamic factors can amplify or mitigate the effects of both salinity and temperature, further influencing the HSI and the habitat's overall suitability for the species.

4.2.2 Statistical analysis of the suitability indexes

Dispersion distribution of the Suitability Indexes for both salinity and temperature are illustrated in the following diagrams (Figures 21 and Figures 22). They serve as a tool to visualize how the optimal conditions for species are shifting in the study area with the scenarios and to display which factor is influencing the HSI the most.



Figures 21 – Suitability indexes mean for the month of July in the Reference Year, Scenario 1 and Scenario 2



Figures 22 - Suitability indexes for the annual mean in the Reference Year, Scenario 1 and Scenario 2

Two main characteristics are extrapolated from these diagrams:

1. HSI shifts towards northern latitudes in the estuary (as seen for July).
2. The HSI dispersion shape follows the salinity dispersion shape (as seen for example in the annual graphs).

Table 6 below shows the statistical characteristics of the indexes for each period and scenario.

Table 6 – Suitability indexes statistics

		Reference Year		**Scenario 1**		**Scenario 2**	
		μ	**σ**	**μ**	**σ**	**μ**	**σ**
OCT	**SI_SAL**	0.60	0.46	0.68	0.41	0.68	0.41
	SI_T	0.79	0.40	0.84	0.35	0.84	0.35
	HSI	**0.63**	0.44	**0.72**	0.39	**0.72**	0.39
JAN	**SI_SAL**	0.53	0.46	0.55	0.45	0.55	0.45
	SI_T	0.25	0.22	0.19	0.19	0.26	0.23
	HSI	**0.33**	0.28	**0.28**	0.24	**0.32**	0.26
APR	**SI_SAL**	0.58	0.46	0.64	0.44	0.64	0.44
	SI_T	0.72	0.40	0.74	0.36	0.78	0.36
	HSI	**0.60**	0.42	**0.63**	0.38	**0.64**	0.38
JUL	**SI_SAL**	0.59	0.45	0.67	0.43	0.67	0.43
	SI_T	0.45	0.39	0.38	0.33	0.75	0.36
	HSI	**0.44**	0.37	**0.43**	0.31	**0.66**	0.38
YEAR	**SI_SAL**	0.57	0.46	0.64	0.44	0.64	0.44
	SI_T	0.58	0.40	0.57	0.37	0.67	0.38
	HSI	**0.52**	0.40	**0.54**	0.37	**0.59**	0.38

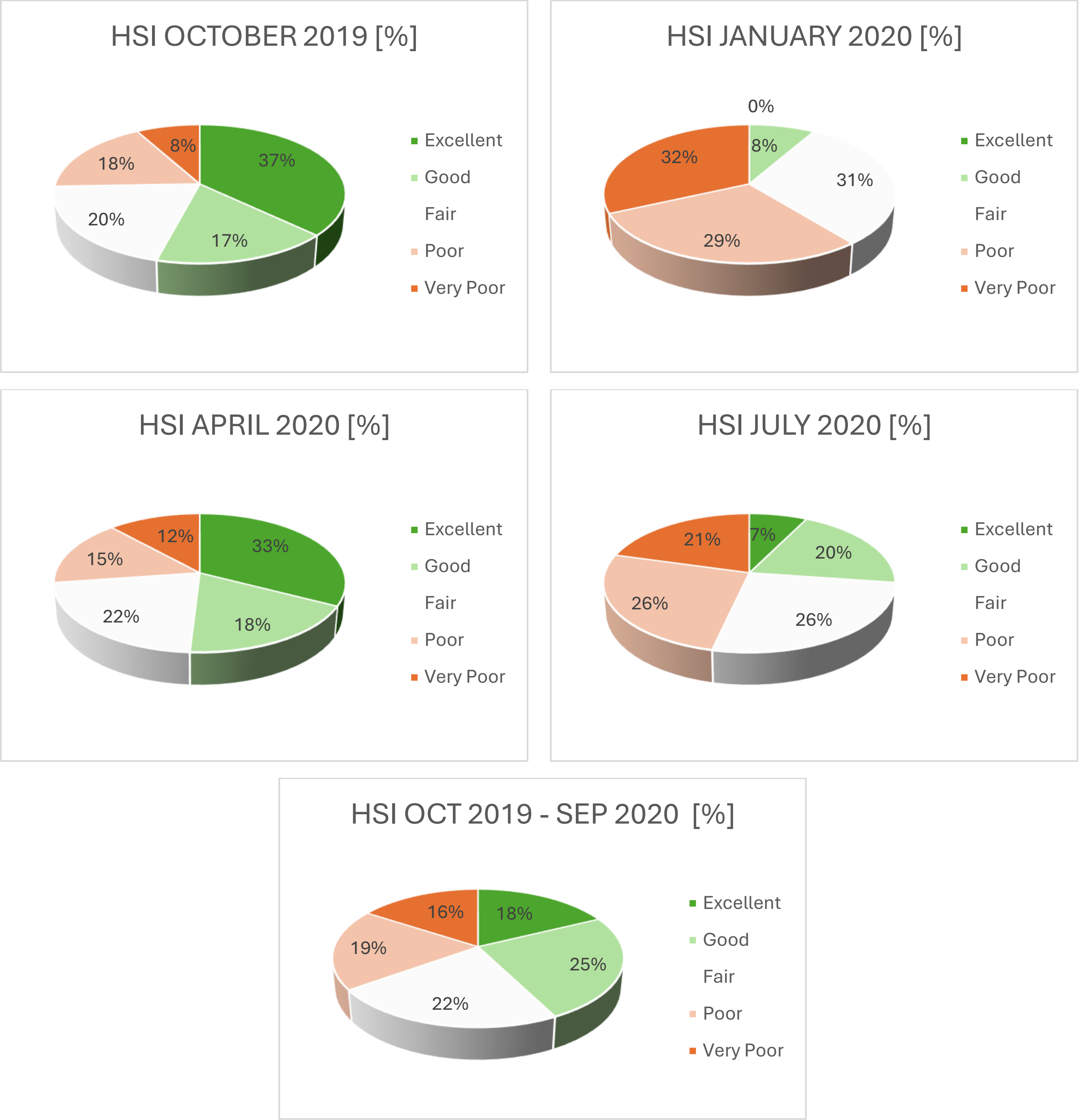
The cumulative index is higher in the future scenarios for *Spartina*. January has a lower HSI in SC1, whereas July has a higher HSI in SC2 at lower salinities, corresponding to higher latitudes. This analysis leads to the following results:

- Optimal conditions for halophytes in saltmarshes are found further north in the estuary with increasing SLR.
- Salinity is generally the main impacting factor for *Spartina* in the Tagus estuary, but temperature suitability indexes seem to be generally improving the HSI.

4.2.3 Average HSI values

The average HSI values were analyzed through a counter that grouped them in categories and calculated the percentage out of the 5618 points of the bathymetric filter in the grid. The graphs

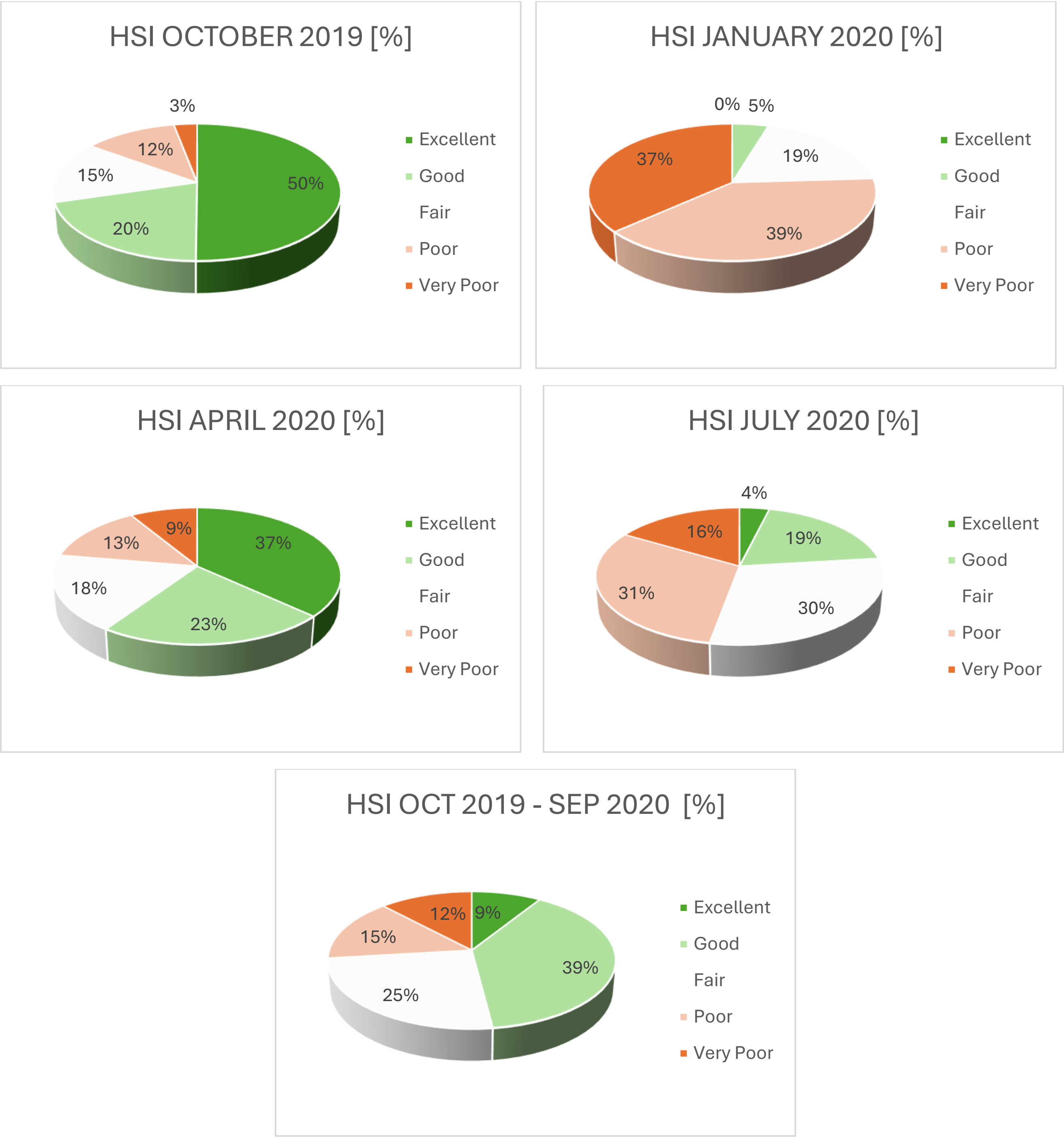
(Figures 23) collecting these mean HSI results through space are shown as follows and they basically indicate, on average, in how many points of the selected bathymetry the quality index is good or not for *Spartina*.



Figures 23 – Reference Year HSI graphs

The analysis confirms that the autumn and spring months are the most suitable for *Spartina* in the Reference Year and that the winter month is the absolute least suitable, followed by the summer period. The whole year average reflects an overall ordinary situation with 43% of “Excellent” or “Good” and 35% of “Poor” or “Very Poor” Habitat Suitability Index. The remaining 22% is labelled as “Fair”. This is the baseline result that will be used to judge the two predictive scenarios linked to climate change that will be investigated in this study.

Like the Reference Year analysis, data was analyzed in Scenario 1 using average values for each month and year. The pie charts (Figures 24) present the mean HSI results across the grid, offering a quantitative overview of *Spartina*’s habitat suitability.

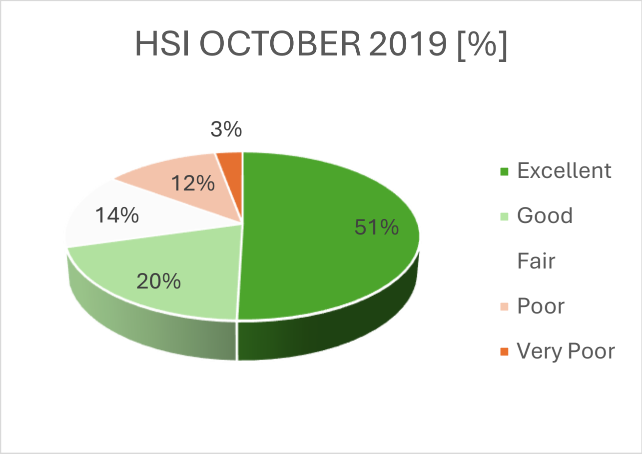


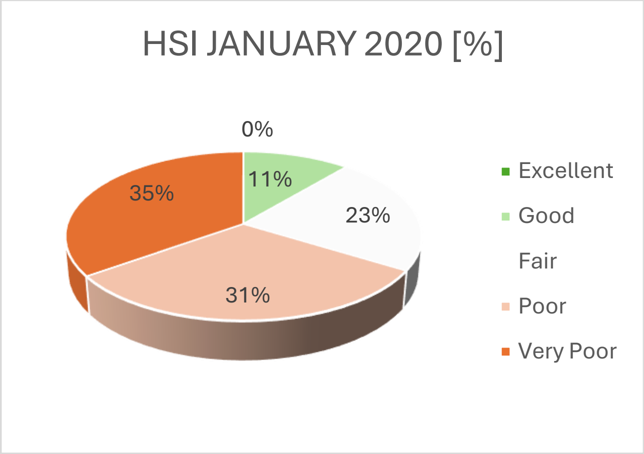
Figures 24 – First future scenario HSI graphs

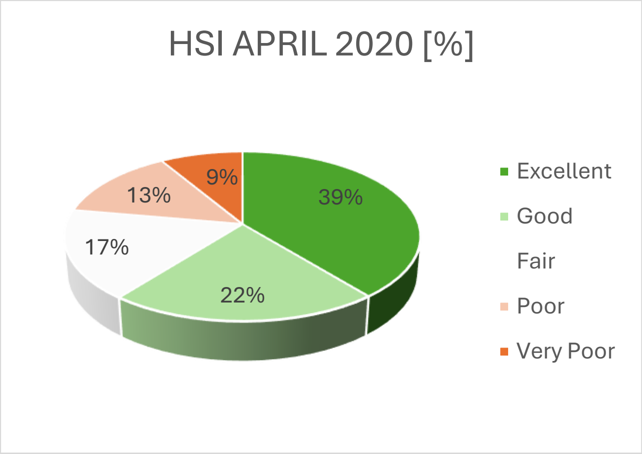
The first scenario analysis, similarly as in the Reference year, results in the autumn and spring months as the most suitable for *Spartina*, the winter month being the absolute least suitable, followed by the summer period. The whole year average reflects an overall ordinary situation with 48% of “Excellent” or “Good” and 27% of “Poor” or “Very Poor” Habitat Suitability Index. The remaining 25% is labelled as “Fair”.

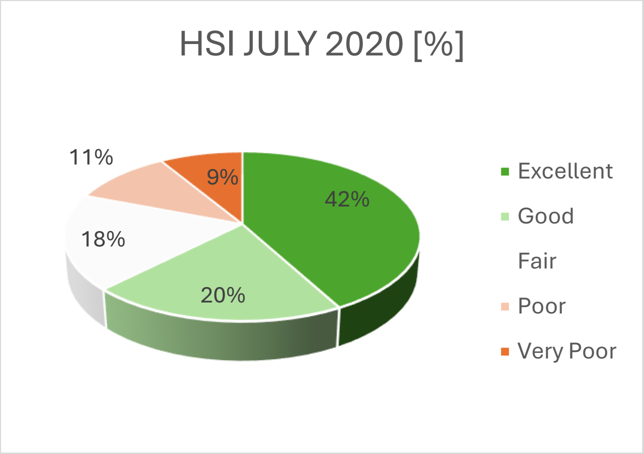
Compared to the baseline case, this scenario shows a slight improvement in HSI due to the increased sea level, with the up and mid label categories increased and the lower ones decreased. But there is a significant difference when comparing the monthly average situations: sea level rise exacerbates the HSI trends by improving conditions in the most suitable months and worsening the least suitable months.

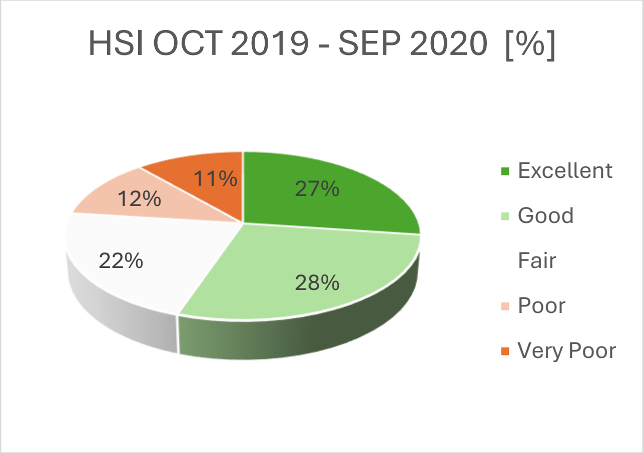
For the second scenario, similarly, the pie charts (Figures 25) display the mean HSI results across the grid, providing a quantitative assessment of the species’ suitability.











Figures 25 - Second future scenario HSI graphs

The second scenario analysis, like the first, shows that autumn is the most suitable and winter the least suitable seasons for *Spartina*. However, and that is the main difference between the two scenarios, the summer month behaves in a very similar way to spring, increasing the average HSI drastically. The annual average reflects a situation with 55% values categorized as "Excellent" or "Good" and 23% as "Poor" or "Very Poor" in terms of Habitat Suitability Index. The remaining 22% is labeled as "Fair."

Compared to the baseline results, there is a slight improvement in the annual HSI under this scenario, with higher sea levels increasing the mid-to-upper suitability categories and reducing the lower ones.

In comparison to the first scenario, the increase in water temperature by 2°C is also improving the annual average but there is a significant difference in seasonal variations mainly brought by the trend change in the months of January and July, also seen as the most critical in the previous cases.

4.2.4 Sensitivity analysis

A sensitivity analysis was conducted on the baseline data to understand which is the impact of the environmental variables on the HSI function without considering the hydrodynamics complex effects on the estuary. The Reference Year average HSI was compared to the same set of data with a 15% increase on the salinity temporal data and with a separate 15% increase on the temperature temporal data. The results, gathered in horizontal histograms, are shown in Figure 26.

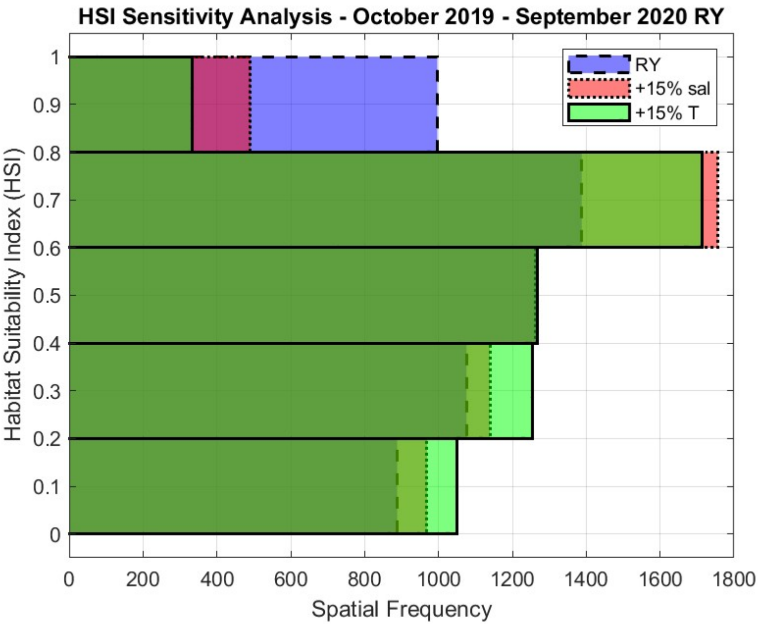


Figure 26 – Sensitivity analysis on the baseline data (MATLAB, 2024)

The blue histogram represents the baseline, the red one is illustrating the increase in salinity and the green one the increase in temperature, both by 15%. The sensitivity analysis resulted on average in lower HSI values when increasing only temperature while keeping salinity constant than vice versa. Even if in each case HSI is worsening when increasing the variables' values, more "Excellent" HSI are linked to higher salinities in comparison to the same rate of temperature variation. There is a decrease of 51% in the highest HSI category when increasing salinity by 15% and a decrease of 67% when increasing temperature by 15%, compared to the Reference Year. On the other hand, the lowest HSI category has seen an increase of 8% in the first case and 15% in the second one. This analysis did not include the complexity of the estuary's hydrodynamics, as it was conducted for the only purpose of testing the impact of oscillations in the environmental variables on the HSI variability. HSI is more sensitive to temperature increases when only considering the environmental variables' influence on the function.

5 Conclusions

The present study aimed at predicting habitat changes induced by climate change in the Tagus estuary, in Portugal. Hydrodynamic models' results were used to analyse the suitability conditions for halophytic species in the salt marsh areas, with a particular focus on *Spartina maritima*. Future projection scenarios included a +0.5 m sea level rise (SLR) (Scenario 1 or SC1) and a +0.5 m SLR combined with a +2°C oceanic water temperature (Scenario 2 or SC2). These scenarios were compared to a baseline case (Reference Year or RY) to assess potential ecosystem modifications across different periods.

The HSI maps highlighted January as the month with the lowest suitability values and October the one with the highest in all scenarios. SC2 showed a significant difference in July, with higher values compared to SC1.

The statistical analysis confirmed winter and summer months as the most critical, with summer being particularly vulnerable to change. Salinity and temperature values in the Tagus estuary varied differently across the two future scenarios.

Mean salinity generally increased in both scenarios due to the higher sea level and advancing tideline, which led to a greater influx of oceanic water. However, in January, a decrease in mean salinity was observed. This was attributed to the mixing of denser ocean water with lower-density freshwater from the north part of the estuary, leading to stratification and reduced salinization. The tidal influence during this period was also weaker, resulting in longer periods without water covering the coastline. In SC2 mean surface salinity in estuarine waters was slightly lower compared to SC1, mainly due to the reduced density brought by a warmer oceanic flux. Overall, the expected trend of increased salinity with sea level rise was confirmed, though exceptions were observed due to the complex hydrodynamics of the estuary, particularly the interaction between water currents and tidal oscillations.

In SC1, mean temperature decreased in October and January due to the influx of ocean water, which, despite being generally warmer than freshwater in these months, remains denser. Conversely, in April and July, mean temperature increased as colder ocean water mixed with warmer, less dense freshwater.

In SC2, during autumn and winter, mean temperature in the estuary was higher than SC1 due to the influx of warmer oceanic water, but remained lower than RY, due to the increased water density from SLR. Whereas during summer and spring, mean temperature was lower than both RY and SC1, mainly because of the higher volume of oceanic water, warmer than in SC1, but still colder than freshwater.

On an annual average, salinity and temperature both increased slightly in SC1. In SC2, salinity decreased slightly compared to SC1, while temperature decreased compared to both SC1 and RY. Temperature exhibited lower variability compared to salinity, but its distribution narrowed in SC2, suggesting a higher sensitivity to environmental changes and reduced stability.

HSI was generally found to be more influenced by salinity distributions than by temperature. In January, SC1 showed lower HSI values, while July had higher HSI in SC2, generally at lower salinities, particularly in the northern parts of the estuary. The potential upward movement of habitats within the estuary, due to increased salinity and an advancing tideline, presents a well-founded and real threat. The hypothesis of a shift towards a flood-dominant estuary, supported by scientific studies (Guerreiro et al., 2015) should be closely monitored.

The average annual index slightly improved across the two scenarios: passing from the baseline "Excellent" or "Good" of 43% and "Poor" or "Very Poor" of 35% to SC1 with 48% and 27% and SC2 with 55% and 23% respectively. The "Fair" values did not show relevant alterations.

The sensitivity analysis did not account for variations in hydrodynamics, as it was designed solely to evaluate the impact of oscillations in environmental variables on HSI variability. Results showed that increasing temperature while keeping salinity constant led to lower HSI values on average, compared to increasing salinity while keeping temperature constant. Even if in each case HSI is worsening when increasing either variable, more "Excellent" HSI values are linked to higher salinities in comparison to the same rate of temperature variation. When increasing salinity by 15% the highest HSI category showed a decrease of 51% but when increasing temperature by 15% the decrease was of 67% compared to the Reference Year. The lowest HSI category saw an increase of 8% in the first case and 15% in the second one. HSI appears to be more sensitive to temperature increases when hydrodynamics complexities are excluded.

The main findings of the study have several implications, which will be gathered in the key points below.

- Salinity in the Tagus estuary exhibits a wider variation range and variability compared to temperature, making it the leading driver component of habitat changes.
- Sea Level Rise (SLR) induced by climate change is likely to increase salinity levels benefiting salt-tolerant species like *Spartina maritima*, but may be negative for other species, naturally found less adapted to these conditions.
- Ocean water temperature increases do not necessarily and linearly correlate with poorer Habitat Suitability Index (HSI) values for *Spartina maritima* due to the complex estuary hydrodynamics, as evidenced by the index improvement in SC2 during the summer period.

- There is a high possibility that habitats may shift northward within the estuary, a trend that might be exacerbated by SLR and an advancing tideline.

For future research, it is recommended to widen the scope to include other species to gain a more holistic and comprehensive view of how biodiversity and habitats might shift under climate change. Expanding the study to also incorporate more environmental variables would further enhance the detail level and completeness of the analysis.

Applying a similar modeling approach to other estuaries, saltmarshes and ecosystems could help assess regional and global impacts, with particular emphasis on hydrodynamic complexities and long-term monitoring. This would improve predictions on how estuaries like the Tagus may evolve in response to these changes. Additionally, future studies should explore mitigation strategies to preserve critical habitats, while also addressing challenges posed by rising sea levels and temperature shifts. This dual focus on adaptation and protection will be crucial for safeguarding biodiversity against climate change.

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ANNEX

A1 - BATHYMETRY FILTER COORDINATES EXTRACTION

```
clear;
clc;
% DAT bathymetry file name
datfile = 'Tagus200m_Omnias.dat';

% Open DAT file
fid = fopen(datfile, 'r');

% Initialize arrays: XX, YY and griddata2D
XX = [];
YY = [];
griddata2D = [];

% Initialize counters
xx_count = 0;
yy_count = 0;
grid_count = 0;
total_lines = 0;

% Read each row of the DAT file
line_number = 1;
while ~feof(fid)
    % Read current row
    line = fgetl(fid);

    % Increase the total number of rows
    total_lines = total_lines + 1;

    % Check for empty rows
    if isempty(line)
        continue;
    end

    % Read XX values
    if line_number > 16 && line_number <= 421  % 405 elements
        XX(end+1) = str2double(line);
        xx_count = xx_count + 1;
    end

    % Read YY values
    if line_number > 424 && line_number <= 775  % 351 elements
        YY(end+1) = str2double(line);
        yy_count = yy_count + 1;
    end

    % Read griddata2D values
    if line_number >= 778 && line_number <= 142932
        % Translating each row in numerical values
        griddata2D_line = str2num(line); % str2num reads more values in one row

        % Check if griddata2D_line is empty and adds the values
        if ~isempty(griddata2D_line)
            griddata2D = [griddata2D; griddata2D_line];
            grid_count = grid_count + numel(griddata2D_line);
        end
    end
```

```
    % Adding the row number
    line_number = line_number + 1;
end

% Close the DAT file
fclose(fid);

% Checking the number of elements
num_elements = numel(griddata2D);
expected_elements = numel(XX) * numel(YY);

fprintf('XX counter: %d\n', xx_count);
fprintf('YYcounter: %d\n', yy_count);
fprintf('Griddata2D counter: %d\n', num_elements);
fprintf('Expected elements counter: %d\n', expected_elements);
fprintf('Total rows counter: %d\n', total_lines);

if num_elements ~= expected_elements
    error('Expected griddata2D elements do not match the expected matrix
dimensions');
end

% Converting griddata2D in a 2D matrix
griddata2D = reshape(griddata2D, [numel(XX), numel(YY)]);

% Finding the element indexes in the desired interval
intervallo_batimetria = find(griddata2D >= -4.41 & griddata2D <= 1.5);

% Looking for the coordinates (row and column) matching the indexes in the
bathymetry interval
[row, col] = ind2sub(size(griddata2D), intervallo_batimetria);

% Display the coordinates
disp('Coordinates (J, I):');
disp([row, col]);

% Save the coordinates (J, I) in an Excel file in two columns
output_excel_file = 'coordinate_batimetria.xlsx';
coords = [row, col];
writematrix(coords, output_excel_file);
disp(['Coordinates (J, I) saved: ', output_excel_file]);
%%
% Creating an empty grid matrix 405X351
target_rows = 405;
target_cols = 351;
grid = NaN(target_rows, target_cols);

% Assegning a value to the coordinates matching the grid 405x351
for i = 1:length(row)
    % Checking the coordinates in the grid limits
    if row(i) <= target_rows && col(i) <= target_cols && row(i) >= 1 && col(i) >=
1
        grid(row(i), col(i)) = 1;
    end
end
```

A2 - MAIN CODE

```
clear;
clc;
% Read the indexes (J, I) of the coordinates from the Excel file
coords = readmatrix('coordinate_batimetria.xlsx');

% Read the salinity and temperature data from the HDF5 file for the specific
coordinates
salinity_data = hdf5read_salinity('TempSal_Surface_september2020.hdf5', coords);
temperature_data = hdf5read_temperature('TempSal_Surface_september2020.hdf5',
coords);
open_points_data = hdf5read_open_points('TempSal_Surface_september2020.hdf5',
coords);

nCoords = size(coords, 1);
nTimeSteps = size(salinity_data, 2); % Assuming the data is NxT
no_water_counter = 0;
salinity = NaN(nCoords, nTimeSteps);
temperature = NaN(nCoords, nTimeSteps);

for i = 1:nCoords
    for j = 1:nTimeSteps
        if open_points_data(i, j) == 1  % Water value (1)
            salinity (i,j) = salinity_data(i, j);
            temperature (i,j) = temperature_data(i,j);
        else
            no_water_counter = no_water_counter + 1;
        end
    end
end
% Save the selected salinity
dlmwrite('salinity_selected.txt', salinity);
disp('Salinity data successfully saved');

% Save the selected temperature
dlmwrite('temperature_selected.txt', temperature);
disp('Temperature data successfully saved');

disp(['Total number of hours without water:',
num2str(no_water_counter/(nCoords))]);
%%
% Calculate the salinity suitability index
for i = 1:nCoords
    for j = 1:nTimeSteps
           salinity_value = salinity(i, j);

          % Suitability index for salinity
            if (salinity_value >= 12) && (salinity_value < 29)
             SI = 1;
           elseif (salinity_value >= 10) && (salinity_value < 12) ||
(salinity_value >= 29) && (salinity_value < 31)
             SI = 0.85;
           elseif (salinity_value >= 8) && (salinity_value < 10) ||
(salinity_value >= 31) && (salinity_value < 33)
             SI = 0.7;
           elseif (salinity_value >= 6) && (salinity_value < 8) || (salinity_value
>= 33) && (salinity_value < 35)
             SI = 0.5;
           elseif (salinity_value >= 4) && (salinity_value < 6) || (salinity_value
>= 35) && (salinity_value < 37)
```

```
             SI = 0.1;
           elseif (salinity_value >= 0.01) && (salinity_value < 4)
             SI = 0.05;
           else
             SI = 0;
           end
           salinity_SI(i, j) = SI;
    end
end
% Save the salinity suitability index in an Excel file
writematrix(salinity_SI, 'salinity_suitability_index.xlsx');
disp('Salinity Suitability Index successfully saved');

% Calculate the temperature suitability index
for i = 1:nCoords
    for j = 1:nTimeSteps
           temperature_value = temperature(i, j);

           % Suitability index for temperature
          if (temperature_value >= 15) && (temperature_value < 24)
            SI = 1;
           elseif (temperature_value >= 24) && (temperature_value < 26) ||
(temperature_value >= 11) && (temperature_value < 15)
            SI = 0.5;
           elseif (temperature_value >= 26) && (temperature_value < 28) ||
(temperature_value < 11)
            SI = 0.1;
           else
            SI = 0;
           end
           temperature_SI(i, j) = SI;
    end
end
% Save the temperature suitability index in an Excel file
writematrix(temperature_SI, 'temperature_suitability_index.xlsx');
disp('Temperature Suitability Index successfully saved');

% HSI CALCULATION
% Calcolate the Habitat Suitability Index (HSI)
HSI = sqrt(salinity_SI .* temperature_SI);

% Save the Habitat Suitability Index (HSI) in an Excel file
writematrix(HSI, 'HSI.xlsx');
disp('Habitat Suitability Index successfully saved');
%%
% MONTHLY AVERAGE CALCULATION
% Mean for each row
HSI_mean = mean(HSI,2);

% Excel file name for the mean values
output_excel_file = 'HSI_mean.xlsx';

% Save the HSI_mean matrix in an Excel file
writematrix(HSI_mean, output_excel_file);
disp('Average HSI successfully saved');

% CREATING THE GRID
% Insert the HSI values in a 405*351 grid
% Target dimensions
target_rows = 405;
target_cols = 351;
```

```
% Create an empty HSI_grid matrix of 405 x 351 dimensions
HSI_grid = NaN(target_rows, target_cols);

% Extract the J and I coordinates
J = coords(:, 1);
I = coords(:, 2);

% Populate the HSI_grid with the HSI values using the J and I coordinates for the
first column
for idx = 1:length(J)
    % Check that the coordinates are inside the grid limits
    if I(idx) <= target_rows && J(idx) <= target_cols && I(idx) >= 1 && J(idx) >=
1
        HSI_grid(J(idx), I(idx)) = HSI_mean(idx, 1);
    end
end

% REPRODUCTION OF THE TEXT FILE
% Create a column to read the results in an OpenFlows format
total_values = target_rows * target_cols;

% Convert the HSI_grid in a column vector with the specified order
HSI_column_vector = strings(total_values, 1);
index = 1;
for col = 1:target_cols
    for row = 1:target_rows
        HSI_column_vector(index) = num2str(HSI_grid(row, col));
        index = index + 1;
    end
end

% Output file name
output_text_file = 'HSI_grid_output_column.txt';

% Read the first 777 and the last rows in the 'Tagus200m_Omnias.dat' file
file_content = readlines('Tagus200m_Omnias.dat');
first_777_lines = file_content(1:777);
last_line = file_content(142933);

% Combine data
combined_vector = [first_777_lines; HSI_column_vector; last_line];
% Save the combined vector in the text file
writematrix(combined_vector, output_text_file, 'Delimiter', 'tab');
disp('Text file successfully saved');
```