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Anthropogenic Impacts on Sea-Level Rise: A multidisciplinary approach to incite solutions for coastal areas

Rita Gonçalves Couto

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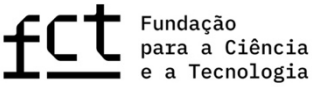
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“Many individuals are doing what they can. But real success can only come if there is a change in our societies and in our economics and in our politics.”

-Sir David Attenborough

“Greenhouse gas emissions keep going. Global temperatures keep rising. And our planet is fast approaching tipping points that will make climate chaos irreversible. We are on a highway to climate hell with our foot still on the accelerator.”

-António Guterres, Secretary-General of the United Nations

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To all my friends, the ones I had and the ones I made along the way

Para o meu avô Luciano,

Index

List of Abbreviations VIII

List of Figures X

List of Tables XII

Sumário XIII

Abstract XV

Introduction 1

Chapter I – An Introduction to Climate Change 3

1.1. Climate Change Terminology 3

1.2. Climate Change Evolution Over Time 3

1.3. Greenhouse Gases Emissions and Global Surface Temperature Trends 4

1.4. Sources of Greenhouse Gases 5

1.5. Ocean Warming 8

1.6. Weather and Climate Extremes 9

1.7. Climate Change Impacts 10

..... 13

1.8. Future Scenarios, Gaps and Needs 14

Introduction and Chapter I references 15

Chapter II - Sea-Level Rise 27

2.1. Global Mean Sea Level 27

2.2. Cities affected by Sea-Level Rise 28

2.3. Sea-Level Rise and Coastal Erosion 30

2.4. Sea-Level Rise and Saltwater Intrusion 31

2.5. Innovative Solutions to tackle Sea-Level Rise 31

2.6. Final Remarks and Future Scenarios 34

2.7. References 34

Chapter III - Venice as a case study for Artificial Defences in Coastal Marine Environments 43

3.1. Introduction 43

..... 46

3.2 Materials and Methods 46

3.2.1. Seafloor mapping 46

3.2.2. MBES (Multibeam Echo-sounder System) 47

3.2.3. Bathymetry data 47

3.2.4. Manual morphology identification 48

3.2.5. Automatic morphology identification 48

3.2.6. Backscatter data 49

3.2.7. Ground-truth data 49

3.3. Results and Discussion 52
3.4. Conclusions and Final Remarks 67
3.5. References 69

Chapter IV - Stakeholders Perception Analysis **75**
4.1. Introduction 75
4.2. Methods 77
4.3. Results 77
4.4. Discussion and Final remarks 82
4.5. References 83

Thesis Final Remarks and Recommendations **86**

Thesis Annex **88**

Annex I **88**

Annex II **93**

Annex III **95**

Annex IV **97**

List of Abbreviations

CC: Climate Change

IPCC: Intergovernmental Panel on Climate Change

ACC: Anthropogenic Climate Change

GW: Global Warming

CO_2: Carbon dioxide

O_2: Oxygen

CH_4: Methane

N_2H: Nitrous oxide

GHG: Greenhouse Gases

GST: Global Surface Temperature

EU: European Union

WMO: World Meteorological Organization

UNEP: United Nations Environment Program

UN: United Nations

RCP: Representative Concentration Pathway

IOC: Intergovernmental Oceanographic Commission

SDG: Sustainable Development Goals

SLR: Sea-Level Rise

OW: Ocean Warming

SWI: Saltwater Intrusion

NY: New York

MoSE: Modulo Sperimentale Elettromeccanico

MBES: Multibeam Echo-sounder System

NbS: Nature-based Solutions

VL: Venice Lagoon

BS: Backscatter

HIPS: Hydrographic Information Processing System

SIPS: Side Scan Information Processing System

DEM: Digital Elevation Model

BPI: Bathymetry Position Index

S1: Scour 1

S2: Scour 2

S3: Scour 3

D1: Dune 1

D2: Dune 2

PT: Portugal

PMA: Porto Metropolitan Area

IT: Italy

List of Figures

Figure 1.- General goal and chapters' goals. Source: The author. 2
Figure 2.- Greenhouse effect. Solar radiation (yellow arrow) passes through the atmosphere, heating the earth's surface. Some energy is re-emitted as infrared (red arrows) and some is absorbed by CO_2 and water vapor, in the atmosphere. Adapted from: Anderson et al. (2016). 4
Figure 3.-Sources of GHG. Source: The author. 8
Figure 4.-Losses and damages for ecosystems and human systems scheme. Source: The author. 13
Figure 5.-World map with some of the most affect areas by sea-level rise and floods. 1- Mississippi Delta and New Orleans, US; 2- New York City, US; 3- Venice, Italy; 4- Shanghai, China; 5- Jakarta, Indonesia. Source: The author. 28
Figure 6.-Venice lagoon from satellite image. Source: ArcGIS pro. 30
Figure 7.- The city of Venice and the Lido inlet. The Lido is one of the three MoSE's locations and this thesis' study area. Source: The author. 33
Figure 8.-The city of Venice and Lido inlet in the Venice Lagoon from satellite image. Source: ArcGIS pro. 46
Figure 9.-Study area with the sampling points. 50
Figure 10.- Bathymetry of the Lido inlet collected in March 2024. 52
Figure 11.- Bathymetries of the Lido inlet collected in 2011, 2013, 2016 and 2021. 53
Figure 12.-Map of the bathymetric difference between 2024 and 2021. The blue areas are deposition (□ >0.4), the orange areas are erosion (□ <-0.4) and the green areas are stable (-0.4>□ >0.4). 54
Figure 13.- Maps of bathymetric differences between 2013- 2011, 2016- 2013 and 2021-2016 datasets, respectively. The blue areas are the deposition (□ >0.4), the orange areas are erosion (□ <-0.4) and the green areas are stable (-0.4>□ >0.4). 54
Figure 14.- Bathymetric map representing the erosional features obtained in 2024: scour 1, scour 2 and scour 3 in purple, blue and orange, respectively. 55
Figure 15.- Scour holes evolution. Evolution extent during the 13 years of surveys. Each year is represented by a different colour. 56
Figure 16.-Graph relative to S1, S2 and S3 area evolution through the survey years. 57
Figure 17.-Bathymetric map representing the depositional features obtained in 2024: dune field 1 in green and dune field 2 in red. 59
Figure 18.- Dune fields evolution through the 13 years of surveys. Each colour represents the shape and size for one of the years. 60
Figure 19.-Graph relative to D1 and D2 area evolution through the survey years. 61

Figure 20.- D1 profile in 2021 and 2024. 61
Figure 21.- Lido inlet location of the MoSE barriers (red rectangles), the breakwater and the navigation channels (Treporti and San Nicolò), as well as the artificial island (blue circle). 62
Figure 22.- Folk's Gravel-Sand-Mud ternary diagram for 2024 sediments results. 63
Figure 23.- Sediment samples' results. Each diagram represents the type of sediment presented in each sample by percentage (%). The results were obtained from gradistat where % of gravel, sand and mud are represented by the colours green, purple and blue, respectively. 64
Figure 24.- Backscatter classification for 2024 survey. 65
Figure 25.- Backscatter classification associated with sediment grain-size. 65
Figure 26.- MoSE expected chain reaction of events following the present trends. Source: The author. 68
Figure 28.- Positive relation graph between sea level rise and climate change for both questionnaires (in percentage). 79
Figure 27.- Main climate change drivers answers for Portugal and Venice, Italy (in percentage). 79
Figure 29.- MoSE comprised information regarding its knowledge, effectiveness, investment and decision-making process (in percentage). 80
Figure 30.- Poor communication between decision-makers, scientific community and public in Portugal and Venice, Italy (in percentage). 80
Figure 31.- Solution implementation in Portugal (in percentage). 81
Figure 32.- CNR LITUS motorboat and Grab support. 95
Figure 33.- Van Veen Grab. 95
Figure 34.- Antenna (Trimble GA830) and rimble SPSS855 GNSS modular receiver, respectively. 96
Figure 35.- Sample collection. 96

List of Tables

Table 1.- Alterations done over the years in Lido inlet related to the MoSE construction. 45
Table 2.- MoSE closures. Source: https://www.mosevenezia.eu (visited last on August 2024). 45
Table 3.-Inner and outer radius values established to perform the BPI. 49
Table 4.- Dispersion of the size of the granules in relation to the sample's average. 51
Table 5.-Area values during the survey years for the scours. 56
Table 6.-Volume differences during the survey years for the scours. 57
Table 7.-Area differences during the survey years for the dunes. 59
Table 8.-Volume differences during the survey years for the dunes. 60
Table 9.- List of recommendations arising from major conclusions of this work. 87
Table 10.- Gradistat sediment samples results. 93
Table 11.-Sections and questions performed in both questionaries, Portuguese and English. 97

Sumário

As alterações climáticas são uma questão multifatorial que constituem um dos maiores desafios que a sociedade do século XXI enfrenta. De acordo com o último relatório do painel intergovernamental para as alterações climáticas (IPCC), as tendências que hoje observamos resultam do impacto direto de atividades antropogénicas. Estas atividades contribuem para o aumento de emissões de gases de efeitos de estufa, que por sua vez aquecem a superfície do planeta levando a uma série de consequências em cascata. Várias atividades humanas, como a indústria, a agricultura e os meios transporte são passivas de aumentar nas próximas décadas, uma vez que a necessidade de produção irá aumentar, levando ao aumento da queima de combustíveis fósseis e de emissões. Deste modo, não só a temperatura continental irá aumentar ainda mais, mas também a dos oceanos. As consequências que advêm para os ecossistemas e para o ser humano são inúmeras, e se não forem abordadas com a devida brevidade, atenção e preocupação, o resultado pode ser pior do que é esperado.

A subida do nível médio das águas do mar é uma das consequências do aumento da temperatura, que por sua vez desencadeia as suas, tais como cheias, intrusão de água salgada e erosão costeira. Com a previsão de uma subida de 60 cm até 2100, considerando um cenário de emissões de gases elevadas, as pessoas, infraestruturas, património cultural e diversos ecossistemas serão colocadas em risco. Em última instância, poderá originar um fenómeno de migrações climáticas.

Uma das muitas cidades afetadas pela subida do nível da água é Veneza, Itália. Esta cidade histórica, propícia a submersão, e a sua Lagoa são extremamente modificadas pelo ser humano. Tal como outras cidades que padecem do mesmo problema, urge um investimento efetivo na investigação de desenvolvimento de soluções para o risco emergente de cheias. Uma das soluções foi o MoSE (*Modulo Sperimentale Elettromeccanico*), um sistema de barreiras que ajuda a proteger a cidade contra episódios de cheias. Desde o início da operação, em 2020, os impactos para a Lagoa são ainda incertos. A contínua monitorização do sistema é crucial para a avaliação de impacto e eficiência. Neste âmbito, o objetivo central da presente tese foi avaliar os impactos da operação do MoSE na morfologia sedimentar da lagoa, focando a investigação numa das reentrâncias costeiras (Lido). Para tal, foi utilizado um sistema de mapeamento acústico (MBES- Multibeam Echo-sounder System). Os resultados obtidos indicam que, nos últimos anos, o regime erosivo tornou-se mais predominante e parece ter originado uma série alterações na morfologia do Lido, incluindo a diminuição drástica de tamanho de uma das morfologias. Esta observação poderá indicar um possível desaparecimento acelerado, comparando com anos anteriores. Foi também observada uma possível interferência no

transporte de sedimentos, que parece ter levado à sua perda em direção ao mar. Além disso, foram estabelecidos outros impactos possíveis para o ecossistema decorrentes das operações do MoSE, tais como intensificação da poluição da água e/ou desequilíbrio das cadeias tróficas da Lagoa.

Com a crescente subida do nível do mar, é provável que as operações do sistema barreira se tornem mais frequentes, pelo que é possível que os impactos se intensifiquem, levando a alterações e consequências sem precedentes. De uma forma geral, estas soluções, apesar de adaptativas, podem trazer resultados benéficos. De modo a compreender o conhecimento da comunidade em relação aos impactos das alterações climáticas e, a sua perceção em relação à existência de soluções (sucesso e impacto) foi realizado um questionário em Veneza. Os resultados revelaram que maioria dos participantes em Itália tinha conhecimento do MoSE, mas incerteza quanto à sua eficácia na proteção da cidade e quanto à justificação do seu investimento. Foi também realizado um questionário semelhante em Portugal, para avaliar o conhecimento e recetividade destas soluções tecnológicas, bem como das alterações climáticas. A maioria dos participantes apoiou a investigação e o investimento em soluções, mas não demonstrou certeza quanto à sua implementação em tempo útil. Em ambos os questionários, os participantes foram também inquiridos sobre a comunicação entre comunidade científica, decisores políticos e restantes cidadãos, e ambas as sondagens mostram resultados pouco positivos.

Esta tese adota uma abordagem de resolução de problemas multidisciplinar e sublinha a necessidade da realização de mais estudos morfológicos do fundo do ecossistema costeiros e avaliação do transporte de sedimentos no futuro, juntamente com estudos ecológicos e ecotoxicológicos paralelos para avaliar, de uma forma mais completa, os impactos do MoSE no Lido. Paralelamente enfatiza o aumento do envolvimento da comunidade em processos de tomada de decisão. Além disso, sublinha a importância de melhoria de comunicação e troca de informação entre todos os sectores societais interessados em medidas adaptativas melhores e mais sustentáveis, para a subida do nível do mar e para outros efeitos diretos ou indiretos das alterações climáticas.

Palavras-Chave: Alterações Climáticas; Subida do Nível do Mar; Soluções Adaptativas; Sistema MoSE; Envolvimento da Sociedade.

Abstract

Climate change is a multifactorial issue that poses one of XXI society's greatest challenges. According to the last Intergovernmental Panel on Climate Change report, the trends we see today are related to anthropogenic activities. These activities contribute to greenhouse gas emissions increase that in turn increase global surface temperature, originating a cascade of consequences. Several human activities, such as agriculture, industry and transport will tend to increase in the upcoming decades since the demand will also increase. Therefore, fossil fuel burning and gas emissions will be accelerated. Consequently, not only does the surface temperature rise but so does the ocean.

Climate change consequences for both ecosystems and humans are numerous, and if not handled with brevity care and attention needed, the outcome can be worse than we expect. The sea-level rise, a consequence of increased temperatures, originates its own, such as coastal floods, saltwater intrusions and coastal erosion. With the prediction of a 60 cm rise by 2100, under high emissions scenarios, several people, coastal infrastructures, cultural heritage and various ecosystems will be at risk. This can eventually result into a climatic migration challenge to face in the future.

One of the many cities that suffer from sea-level rise is Venice, Italy. This historical city, prone to submersion and its Lagoon are significantly altered by anthropogenic activities. Ergo, like so many others, had to come up with solutions to tackle the increasing flood risk. One solution in place is the MoSE (Modulo Sperimentale Elettromeccanico), a barrier system that helps in high-water episodes. Since the beginning of the operation in 2020, its impacts on the lagoon are still unsure. The continuous monitorization of the system is crucial for impact and efficiency assessment. Within this ambit, the main goal of the present thesis was the MoSE impact assessment on the Lagoon's seafloor morphology, focusing on one of its inlets, Lido by using an acoustic mapping system (MBES- Multibeam Echo-sounder System). The results indicate, in recent years, an erosional regime prevalence, that seems to have led to several changes in the seafloor morphology, among them drastic changes in one of the dunes. This observation might indicate a possible disappearance, compared to previous years. It was also noticed a potential interference with the inlet's sediment transport which seems to have led to seaward sediment loss. It was also recognized other possible ecosystem disruptions that arise from MoSE operations such as increased water pollution and/or changes in the Lido's trophic chains.

With the increase rise of sea level, the MoSE system operations are likely to become more frequent, so the impacts can intensify leading to unprecedented changes in the inlet. For the most part, this adaptative solutions can be beneficial. In order to understand and beware of community's perception regarding climate change and solution success, a

questionary was conducted in Venice. The results revealed that the majority of the participants in Italy knew what MoSE was but showed uncertainty regarding its effectiveness in protecting the city and its investment. To contrast, a questionnaire in Portugal was conducted, to access knowledge and receptivity for this kind of technology, as well as climate change. The majority of participants support solution investigation and investment but are not certain as to its on-time implementation. For both questionaries, the participants were also surveyed on communications between scientific community, decision makers and common citizen, and in both surveys the feedback was not positive.

This thesis provides a multidisciplinary issue solving approach and highlights the need to carry out more seafloor morphological studies and sediment transport in the future together with parallel ecological and ecotoxicological studies to access, more broadly, further impacts on the inlet's environment. It also emphasises the need to increase community involvement in decision-making processes. As well as better communication between all society members that are interested in improved and more sustainable adaptative measures for sea-level rise, and other effects of climate change.

Key words: Climate Changes; Sea-Level Rise; Adaptative Solutions; MoSE system; Stakeholder's Engagement

Introduction

Climate Change (CC) is considered one of the biggest challenges society faces nowadays (Jain et al., 2023). It is a complex issue that involves environmental, ecological, socioeconomic and sociopolitical matters (Abbass et al., 2022). According to the latest Intergovernmental Panel on Climate Change (IPCC) report between 3.3 and 3.6 billion people live in a highly vulnerable CC context, and with mass mortality events recorded on land and ocean ecosystems (IPCC, 2023), we are approaching more rapidly and intensely future negative scenarios. Logically, these challenges are interlinked and must be addressed with the utmost brevity. So effective adaptation and mitigation measures are needed to help limit vulnerabilities and increase coping capacities in the face of CC impacts (Sharifi, 2023).

In that sense, this master's Thesis was developed to address the climate change problem and consider the adaptation measures in motion by assessing their pros and cons. Plus, by querying people's perception of the problem, it was intended to understand the level of knowledge and support these strategies have or could have if proven to be beneficial. These adaptative strategies need to respond effectively to the challenges we are facing and the ones in the future, keeping in mind that all solutions must not benefit us at the expense of other living beings.

The organization of the present Thesis was made as follows: Chapter One: An Introduction to Climate Change Thematic; Chapter Two: Sea-Level Rise; Chapter Three: Venice as a Case Study for Artificial Defences in Coastal Marine Environments; Chapter Four: Stakeholders Perception Analysis; Thesis Final Remarks and Recommendations.

The general Thesis aim is to investigate the challenges, impacts and current solutions to tackle the effects of sea-level rise in coastal cities and ecosystems.

The goal of the first chapter is to address the CC problem, mainly based on the IPCC's latest report. The second chapter is focused on the rise of sea levels, aiming to address this CC consequence and some solutions to tackle it, already implemented or being tested worldwide. The third chapter represents the foundation of this work and aims to investigate how changes in seafloor morphology are related to one specific anthropogenic structure (MoSE system) built to face sea-level rise in Venice, Italy. This chapter was developed and conducted in CNR-ISMAR, Venice through an internship funded by the ERASMUS+ programme from January 2024 to May 2024. The last chapter seeks to access stakeholders' perceptions of CC and compare two realities: a community with an implemented technology with the receptivity of another to future solutions (Figure 1).

In the end, it should be clear how climate change, namely the sea-level rise, is related to anthropogenic activities. It should also be clear that only by involving all interested parties

(scientists, citizens and politicians) will sustainable solutions be effectively implemented and monitored to create healthy lives on a healthy planet, for all.

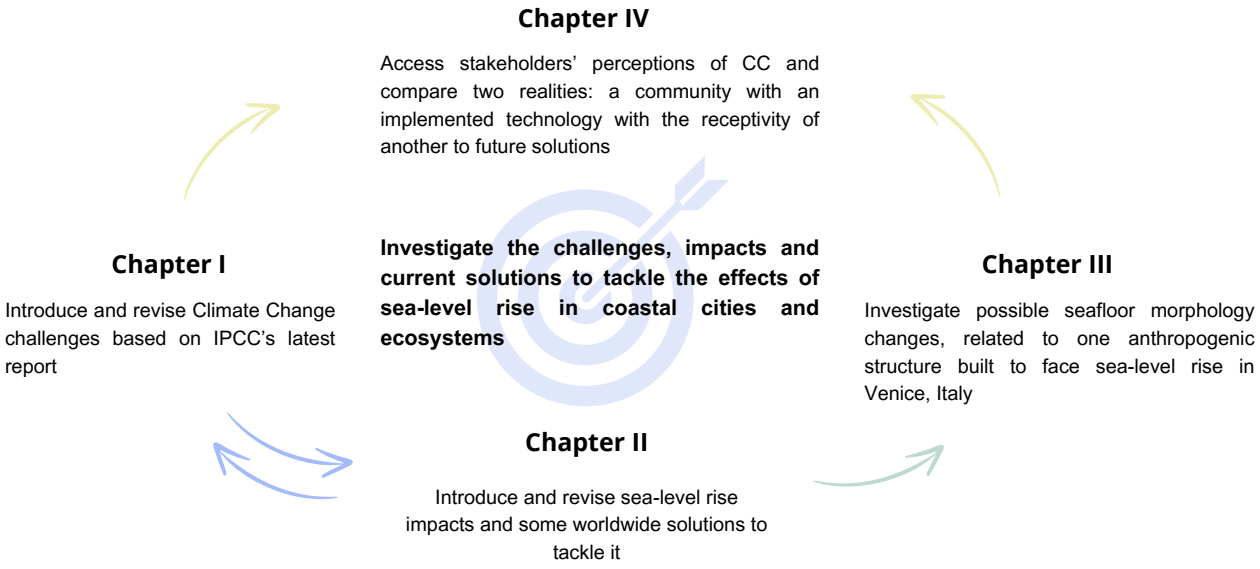


Figure 1.- General goal and chapters' goals. Source: The author.

Chapter I – An Introduction to Climate Change

Chapter Resume

This first Chapter aims to address the CC problem mainly based on the latest IPCC report. It focuses on how the increased emissions of greenhouse gases lead to increased temperatures which in turn triggers more effects such as increased sea-level rise, weather extremes and ocean warming. Although, natural causes are described as influencers of climatic changes, this chapter serves to demonstrate how the anthropogenic actions and activities have been increasing the magnitude of the effects. Also, consequences that arise from CC are mentioned for the human society but more importantly for the ecosystems since the latter has great repercussions on the former. Lastly, it is highlighted the need for effective solutions and multidisciplinary approaches to fulfil the climate political agendas and assure the next generations' future by adopting an interdependent attitude towards the climate.

1.1. Climate Change Terminology

Climate Change (CC) is an occurring process that can be defined as the systematic changes in average weather conditions (Weber, 2010). It is known for changes in expected weather that vary according to different geographical scales and periods. Temperature and rainfall patterns are among the physical indicators of climate change (Naz et al., 2022).

In recent decades, there has been a debate among the public, decision-makers, and the scientific community (Weart, 2010; Weber, 2010) on whether "CC" is the appropriate term to use when explaining the environmental changes that humankind is facing. Only by the end of the XX century was human influence on climate change considered (Weart, 2010). Unarguably, CC results in weather variabilities and those changes are more frequent now than ever (Abunyewah et al., 2023). So, many studies in this area have been conducted to understand all the factors, mechanisms and variables involved (Koutsoyiannis, 2003; G. Hansen, 2015). But in fact, the right terminology regarding the focus of this thesis is Anthropogenic Climate Change (ACC) term. Henceforth, when using the CC abbreviation, it refers to ACC.

1.2. Climate Change Evolution Over Time

CC is not a new age topic, and it was first observed three centuries ago when Nobel prize winner Arrhenius theorized the influence of carbon dioxide (CO_2) concentration in the atmosphere and temperature changes (Arrhenius, 1896; Ramanathan & Feng, 2009). After the 1950s, this topic was brought up again by several researchers but not addressed by the media with proper importance (Höök & Tang, 2013). In the 1980s, the World Meteorological

Organization (WMO) and the United Nations Environment Programme (UNEP) conducted investigations on CO_2 and other gases (Höök & Tang, 2013) . Additionally, the discovery of the ozone hole in 1987 (Bodansky, 2001) spurred a wave of environmental awareness and concern about global environmental problems. These developments led to the establishment of the Intergovernmental Panel on Climate Change (IPCC) in 1988, which marked a significant commitment by governments to address environmental issues.

Since its establishment, the IPCC has developed six reports that assessed several climate problems. The latest one has unequivocally related human activities to Global Warming (GW) and consequently Global Surface Temperature (GST) increase (IPCC, 2023). This report serves as the basis for the topics addressed in the next sections of this chapter.

1.3. Greenhouse Gases Emissions and Global Surface Temperature Trends

Since 1970 GST has increased more than in any other period in the last 2000 years (Chandra Voumik & Sultana, 2022). From 2011-2020 (9 years) temperature was 1.1°C than the period between 1850 and 1900 (50 years), meaning that in a shorter period, the temperature increased more (IPCC, 2023). With each increment of temperature, climatic changes and extremes become more noticeable and widespread, so the United Nations (UN) Conference Of the Parties 26 (COP 26) has suggested a limitation of global temperatures of 1.5 °C by the end of this century (Chandra Voumik & Sultana, 2022).

This temperature increase is mainly due to Greenhouse Gases (GHG) emissions increase, namely CO_2, methane (CH_4) and nitrous oxide (N_2H) (Montzka et al., 2011; Kabir et al., 2023; Wang et al., 2023), via the well-known greenhouse effect (Figure 2). Without this phenomenon, the earth would be -21°C and no life would exist (Anderson et al., 2016). The influence of a greenhouse gas, such as CO_2, on climate relies on its ability to absorb infrared radiation, therefore increasing the earth's surface temperature, and its atmosphere persistence (Montzka et al., 2011; Al-Ghussain, 2019). The problem lies with the increase of GW not the process itself.

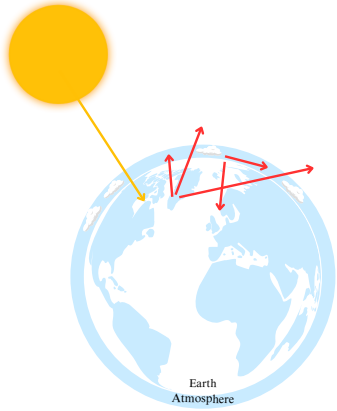


Figure 2.- Greenhouse effect. Solar radiation (yellow arrow) passes through the atmosphere, heating the earth's surface. Some energy is re-emitted as infrared (red arrows) and some is absorbed by CO_2 and water vapor, in the atmosphere. Adapted from: Anderson et al. (2016).

According to the latest IPCC report, from 2010 to 2019 the GHG emission rate was higher than in any other decade even though, the growth rate was lower compared to the 2000-2009 decade. It was also reported that the increase in GHG emissions was driven by human activities with the energy, industry, and agriculture/land use sectors being the most relevant (IPCC, 2023). As the population grows so does the necessity for basic needs resulting in higher demands for energy, food and other supplies, which in turn increases the amount of burned fossil fuels that leads to GHG emissions increase (Jeffry et al., 2021).

As mentioned before CO_2 is one of the GHG gases and its atmospheric concentration has been a discussion topic for over 100 years (Johnson et al., 2007). The pre-industrial levels were 290-295 ppm (parts per million) (Bolin et al., 1979) and in 2019 the concentration reached 410 ppm (IPCC, 2023). This increment, according to many studies, is visible more so in the last century (Hansen et al., 2000; Jeffry et al., 2021; Sethi et al., 2021; Lyu et al., 2022; Kabir et al., 2023).

Besides CO_2, CH_4 is the most abundant GHG (Montzka et al., 2011) contributing to 20% of changes in climate (Lyu et al., 2022). Its relative concentration has increased twice as fast as CO_2 concentration reaching its highest value in 2020 with 2.5 times pre-industrial levels (Jackson et al., 2021).

The last most abundant gas is N_2H, considered to be the largest anthropogenic stratospheric ozone depleting source (Davidson & Kanter, 2014). According to AR5 IPCC synthesis report, this gas has shown a steady increase in the recent years (IPCC, 2015) still when comparing AR5 report to the AR6 N_2H increase was 20% and 23%, respectively, since 1750.

1.4. Sources of Greenhouse Gases

In the previous section, it is noticeable the increase of all GHG. Naturally, the most known emission source is fossil fuel burning, related to mankind activities, that will further be explained in this section, but natural sources also account for a significant part of emissions and exchange (Crow et al., 2019). So, natural sources and their contribution will be attended as well as anthropogenic sources of CO_2, CH_4 and N_2H (Figure 3).

Natural sources or biogenic can be defined as sources originating from animals, plants and microorganisms that suffer from both natural and anthropogenic perturbations (Tian et al., 2016; Lv et al., 2024).

One natural source of CO_2 is soil respiration that through plants controls the amount of CO_2 that goes to the atmosphere (Raich et al., 1992; Schlesinger et al., 2000). Soil serves as a carbon sink (Yadav & Wang, 2017) and through nutrient cycle regulation by microbial

activities emits GHG (French et al., 2009). Another source is related to atmospheric decay and biomass burning. Since biomass combustion is considered carbon flux neutral, the amount of CO_2 released from biofuel combustion equals the amount sequestered (Mathews, 2008; E. Johnson, 2009; Booth, 2018). Nonetheless, according to Cherubini et al. (2011) before being recaptured by biomass, carbon molecules interact while in the atmosphere therefore contributing to climate warming. Another source is volcanic activity (Camarda et al., 2019; Fischer et al., 2019) that emits not only CO_2 but also other GHG by active volcanic eruptions and dormant volcanoes (Yue & Gao, 2018). Other natural events such as forest fires, and earthquakes also take part in the emission of CO_2 (Yue & Gao, 2018).

Regarding CH_4 natural sources, wetlands, termites, and hydrates (Megonigal & Guenther, 2008; Allen, 2016) are some of the main contributors. Wetlands are believed to be the largest biogenic emission source of CH_4 (Z. Wang et al., 1996; Petrescu et al., 2010), accounting for 20-31% of global emissions (Chang et al., 2023). Another biogenic source is the anaerobic fermentation of ruminants, which produces methane as a byproduct. The amount of methane emitted depends on feed intake (Thompson et al., 2020). In fact, according to Getabalew et al. (2019), this natural process is responsible for one-third of agricultural methane emissions.

According to the AR6 report (IPCC, 2023), the above-mentioned GHG are derived as follows: 34% from the energy sector, 24% from the industry sector, 22% from AFOLU (Agriculture, Forestry, and Other Land Use), 15% from the transportation sector, and finally 6% from buildings. Overall, the primary emission source, common to all the above sectors is fossil fuel burning (Yue et al., 2018; Martins et al., 2019; Ağbulut et al., 2021).

Fossil fuels refer to coal, oil and natural gas which are used for different purposes from heating to the production of plastic (Uusitalo, 2022). Since the 1960s, a clear increase in GHG emissions derived from fossil fuels has been observed, representing an increase of five times (Yue et al., 2018). In 1960, CO_2 emission through coal combustion was 75.59% and oil combustion was 22.5%, but between 1960 and 2018, there was a significant reduction to 29.09% due to European mitigation programs, but oil emissions increased to 41.82% (Paraschiv & Paraschiv, 2020).

It can be said that our society is heavily reliant on fossil fuel consumption, and it significantly shapes our day-to-day lives. In 2019, the global energy system depended on fossil fuels for 85.5% of its energy, but this percentage varied among different countries. For example, the EU (European Union) was 75.4% dependent on fossil fuels. The same study indicated that out of 87 countries, 45 of them consumed more fossil fuels than they produced (Ediger, 2019).

Besides the clear effect on GW due to GHG emissions, fossil fuels cause health problems affecting populations' life quality (Martins et al., 2019). Hence, it is important to explain how the energy and industry sectors emit such large quantities of GHG.

When it comes to the agriculture sector, there are several ways it can contribute to GHG emissions. Firstly, through the consumption of fossil fuels during equipment manufacture, fertiliser inputs, and machinery operations, which emits CO_2 (Johnson et al., 2007; Gołasa et al., 2021). Secondly, emissions of CH_4 occur through anaerobic processes in soils, anaerobic fermentation in ruminants and termites' intestinal (Johnson et al., 2007; Thompson et al., 2020). It is important to note that agriculture contributes to 50% of the total CH_4 emissions that go into the atmosphere (Shakoor et al., 2021). Lastly, agricultural activities such as animal manure and crop production (use of synthetic fertilisers), contribute to around 68% of N_2O emissions (Benbi, 2013; Shakoor et al., 2021).These contributions are not new to the scientific community. A review paper published in 1994 found that 25%, 65%, and 90% of total anthropogenic sources of CO_2, CH_4, and N_2O, respectively, were due to agriculture and land clearing (Duxbury, 1994). Agriculture and all its activities are contributing to climate change, but the relationship is bilateral since this sector is seriously impacted by its outcomes. The world's crop production is extremely vulnerable to rising temperature trends (Abbass et al., 2022) that are a result of increased gas emissions. Even more, together with intensive practices that disrupt nutrient cycles, poor management will also affect this sector's productivity (Purwanto & Alam, 2020). With the current prediction of food demand, these pressures on land will increase and so will its negative feedback on the sector (Theurl et al., 2020).

Deforestation is another source of GHG. Forests that cover 31% of the world's land, store about 1'085 Gt of carbon and remove 7.6 ±49 Gt CO_2 every year, a crucial characteristic for reaching climate neutrality set by the Paris Agreement (Chiriacò et al., 2024). So logically its loss presents a great challenge. Agriculture and pasture are believed to be the primary forces of deforestation (Prochazka et al., 2023) and the major drivers of Earth's forest reduction (Olofsson et al., 2008).In fact, related to some setbacks, the year 2021 had the highest deforestation rate in the Brazilian Amazon, reaching a loss of 13.038 km^2 (Silva-Junior et al., 2023). Inevitably, the conversion of forests to agricultural crop fields leads to the loss of sequestered carbon stocks (Kaupper et al., 2020), increasing GHG emissions (Shakoor et al., 2021).

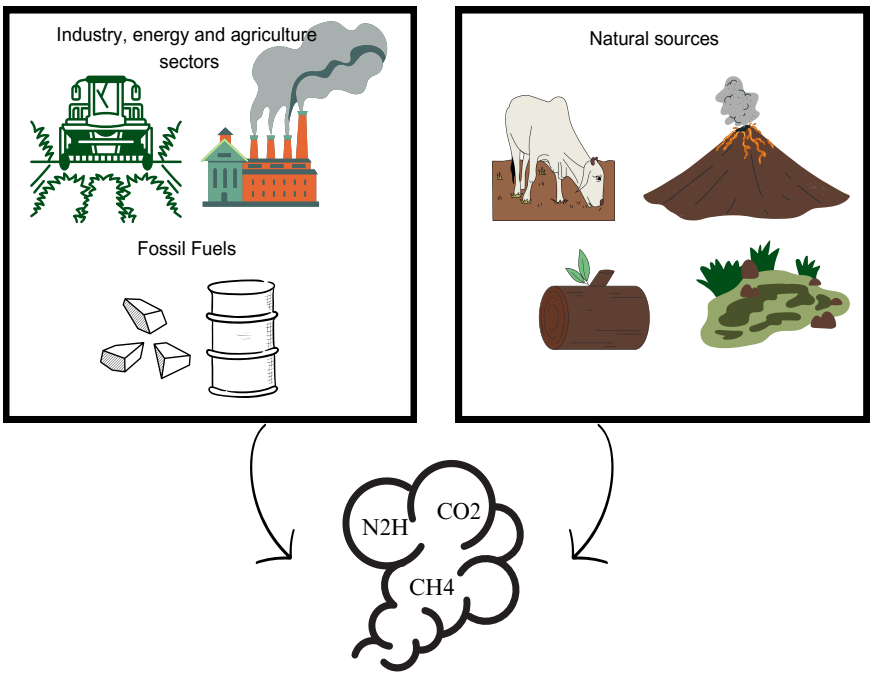


Figure 3.-Sources of GHG. Source: The author.

1.5. Ocean Warming

Climate change creates an energy imbalance through heat-trapping and 93% of that imbalance is accumulated in the ocean, increasing its heat content (L. Cheng et al., 2019). So, through increased CO_2 levels (Munday et al., 2012) an overall increased temperature, leads to warmer oceans (Garcia-Soto et al., 2021). According to the IPCC report in 2023, the ocean has been warming since the 1970s and anthropogenic influence is thought to be the principal driver. In fact, the rate of warming during 2010-2019 was twice the warming rate of the long-term record (Garcia-Soto et al., 2021). Although most studies focus on surface ocean temperature, changes in the thermocline and abyss have also been observed (Abraham et al., 2013)

The impact of Ocean Warming (OW) is very broad and complex, and as almost every climate change topic, acts in a chain reaction. Impacts can be divided into two categories, physical/chemical effects and biological effects. The sea level rising, the oxygen (O_2) levels declining, the CO_2 levels increasing, the ice sheets melting, and the rainfall intensity increasing (Yao & Somero, 2014; L. Cheng et al., 2019) are all considered physical and chemical effects very well linked. For example, in response to warmer ocean temperatures ice caps will melt faster so the sea level will rise faster (Golledge & Nicholas Golledge, 2020). Plus, since temperature increases, ocean water expands, contributing to about 43% of sea- level rise (SLR) (Abraham et al., 2013; G. C. Johnson & Lyman, 2020). Regarding biological effects, reproduction, metabolism, and development are impacted since marine organisms are thought to be more sensitive to temperature variations (Yao & Somero, 2014). For example, seagrass, a marine angiosperm with millions of years that provides socio-economic services and nursery habitats for various marine species is suffering a critical decline globally due to factors such as ocean warming. Consequently, seagrass

species are dying and are predicted to be extinct in a near future (Nguyen et al., 2021). In Australia, due to temperature increase predictions, changes in species distribution and their habitats are predestined to happen and so are changes in population dynamics and structure (Wernberg et al., 2011). Another example is coral reefs, which are under increasing threat linked to the increase in sea temperature. This leads to declines in calcification, disrupting their growth and increasing bleaching events (Razak et al., 2020). More so, a study conducted in 2022, showed that under high emissions of GHG, 90% of marine life is set to disappear (Boyce et al., 2022).

1.6. Weather and Climate Extremes

According to the IPCC, a weather or climate event is considered extreme if the variable lies above (or below) a threshold value near the upper (or lower) end of the ever-seen value range, so events that occur in periods shorter than a month are considered weather extreme, and over a month are considered climate extremes (Mika, 2013). It is also important to take into consideration the term used when mentioning changes in extremes, frequency and magnitude, since conclusions regarding GHG forcing climate extremes may differ as well as GW increase. For example, changes in the magnitude of temperature extremes were shown to have a linear decency with GST. On the other hand, changes in frequency are not prone to be linear and can be exponential for increases in warming values (IPCC, 2023).

In the last decades, scientific research has implicated human activities in climatic changes (regional and global). Yet this established relationship has raised many questions regarding a clear cause-effect (Hulme, 2014). So, although with all relevant variables and determinants, many studies have considered that human activities alter the frequency and intensity of many weather and climate events (Ebi et al., 2021; Clarke et al., 2022; Zittis et al., 2022). In the latest IPCC report, human influence on many climate extremes across the globe, such as heatwaves, heavy precipitation, and droughts was strengthened, compared to the previous report (AR5). Hot extremes have become more frequent since the 1950s, and marine heaves have doubled since the 1980s with a very likely human contribution since 2006 (IPCC, 2023). Therefore, it is imperative to describe the extreme changes related them to CC.

Firstly, heat and cold extremes are changing in rate and intensity, with heat events becoming more common than cold (Heim, 2015; S. Campbell et al., 2018; Clarke et al., 2022; Tripathy et al., 2023). In pre-industrial times, a heatwave would have 1 in 10 chances of occurring in a year and is now predicted to occur 2.8 times more frequently and be 1.2°C hotter (Clarke et al., 2022). It is well-known that increase in heat exposure poses harmful consequences to human health, including mortality (S. Campbell et al., 2018). A study in

2021 found that 37% of deaths heat related could be related to CC (Vicedo-Cabrera et al., 2021).

Droughts have various hydrological and socioeconomic impacts e.g. risk of wildfires, loss of crops, and health impacts but are often slow-developed events (Mukherjee et al., 2018). However, the frequency and intensity of droughts are increasing with GST rise and changes in precipitation patterns. This extreme event has affected more than a billion people in the last decades, more intensely in Africa where mass migration, famine and conflicts have emerged (Ebi et al., 2021). Inextricably linked to droughts are wildfires. In spite of having other drivers (fuel availability, wind speed) (Clarke et al., 2022), climate change has been a major contributor to fire season duration and extension (Ebi et al., 2021). A study done in southern Europe concerning wildfire drivers showed that in the absence of other drivers CC would lead to higher burnet area values (Turco et al., 2019).

Since the 1950s, heavy precipitation has become more intense and recurrent in most parts of the world, mainly due to CC (Clarke et al., 2022). Extreme events of precipitation are increasing, and sub-daily datasets suggest an intensification of this extreme that was not expected (Fowler et al., 2021). Its impact in societies through flooding that has shown to be more intense due to CC impact (Clarke et al., 2022). Nonetheless, it is important to mention that precipitation patterns changes are a combination of GHG influence and location internal variability (Dai et al., 2018).

1.7. Climate Change Impacts

The stress caused by CC inevitably leads to threats that can either be noticeable such as increased temperature or unnoticed at first sight. In order to have a better view of the impacts, Figure 4 divides the losses and damages for ecosystems and for human systems, as they are interlinked.

Biodiversity and ecosystem services are pressured by habitat change and invasive species that can be accelerated and intensified by CC. Moreover, socio-economic development, and political or cultural beliefs policies underlie those driving forces of CC (Omann et al., 2009). These accelerated climatic changes threaten the survival of many species and have already led to extinctions (Pettorelli et al., 2021). Take the example of the emperor penguin, the iconic symbol of Antarctica if present rates of increasing temperatures persist, over 90% of the colonies will cease to exist by the end of the century (Fretwell et al., 2023).

Ocean and coastal ecosystems provide uncompensated services to our society and since CO_2 levels are increasing, a direct impact on species population size, and abundance distribution has been observed, ultimately affecting the whole trophic chain. Moreover, if ocean acidification trends continue growth and survival of half of benthic species will be

reduced (A. K et al., 2023). On another note, GW has caused a significant shift in phase and temperature amplitude of seasons. So, seasonal cycles in temperate latitudes are no longer defined by four seasons (Wang et al., 2021). Naturally, this affects species distribution.

CC can be associated with multifactorial stress combination meaning that a combination of more than one stress (extreme temperatures, CO_2, intense precipitation) could have a greater impact on an ecosystem such as forests. Their dynamics, structural complexities and benefits to society are jeopardized by the added aggravation of increased vulnerability to outbreaks and fires (Pascual et al., 2022). A study done in 2021 regarding Europe's forests (which cover 33% of the continents' land surface) stated that 33.4 billion tons of forest biomass could suffer relative losses when exposed to fires (34%) and insect outbreaks (26%) (Forzieri et al., 2021).

The decline in biodiversity leads to the erosion of our economy's foundations, livelihoods and quality of life (Pettorelli et al., 2021), so inevitably human systems suffer all kinds of consequences. Migration is a response mechanism for one to cope with climate pressure (Qing et al., 2024). As GHG emissions go up so goes the GST, increasing the possibility of droughts. Ergo, this chain reaction will have direct and indirect effects on land degradation that in turn contributes to CC as the soils reduce their carbon sequestration capability. Plus, it exerts pressure on rural areas which might lead to migration, especially in low-income countries (Hermans et al., 2021).

The previously mentioned loss of seasons raises many challenges such as the intensification and expansion of zoonoses in the upcoming decades (Semenza et al., 2018; Ryan et al., 2019; Rocklöv et al., 2020; Ewing et al., 2021). Vector-borne, water-borne, food-borne, rodent-borne, and air-borne zoonoses under some climate prediction models can change geographically, causing poleward expansion (e.g., leishmaniasis), alterations in timing and seasonality of some diseases (e.g., dengue fever) (Rupasinghe et al., 2022). According to Ryan et al. (2019), the Aedes-borne viruses, Dengue and Zika, are expected to shift poleward and increase their population size, especially in higher-income regions.

Species range shifts due to OW can affect our economy. For example, jellyfish population outbreaks in the Mediterranean have had unfavourable impacts on local economies such as tourism and fishing (Ruiz et al., 2012). Besides shifting species distribution OW can affect fish stocks, primary productivity, growth and distribution of fish population resulting in food-webs reorganization and exploited marine species' yield alterations (Mendenhall et al., 2020). As a result of CC, a decline of 50% in the maximum catch potential of exploited fish in tropical regions is expected by 2050, potentially creating local and international conflicts (Simpson et al., 2021). It is important to highlight that fisheries provide protein for at least one-half of the world's population (Gomez-Zavaglia et al., 2020).

Another economic loss can be related to SLR floods. Kirezci et al. (2020) projected that in the RCP (Representative Concentration Pathway) 8.5 scenario, an increase of 46% of global assets would be at risk of flooding by the end of this century.

CC and air pollution pose significant consequences for human health (D'Amato et al., 2016; Orru et al., 2017 Kumar, 2021; Burbank et al., 2023). GW makes cities warmer and at the same time urbanization intensifies this heating, so it is expected by the middle of this century an increased risk of poor health in cities globally (Kumar, 2021). Because of poor air quality, an increased susceptibility to respiratory infections can be noticed (Burbank et al., 2023). At the same time, the number of deaths might increase. An empirical study during 1991-2018 found that 37% of mortality burdens heat-related could be attributed to human-induced warming (Vicedo-Cabrera et al., 2021).

As mentioned before, the agriculture system contributes to and is affected by CC. The temperature rise, precipitation changing patterns and extreme weather events are impacting food production globally (Brenton et al., 2022). Wheat and maize fields are expected to reduce by 4-6% for each temperature degree increase (Anderson et al., 2020). Droughts and floods can cause unwanted effects on crops such as rice, cotton, and soybean (Gomez-Zavaglia et al., 2020). As the population grows, so does the number of interventions on nature, e.g. tearing down forests to make pasture fields or use of pesticides to increase crop yield, its effects have consequences on an environmental level that will negatively affect agriculture, endangering human subsistence (Wu & Etienne, 2021).

Such cause-effect relations between eco and human systems can lead, in the worst-case scenario, to a mass extinction (Pascual et al., 2022).

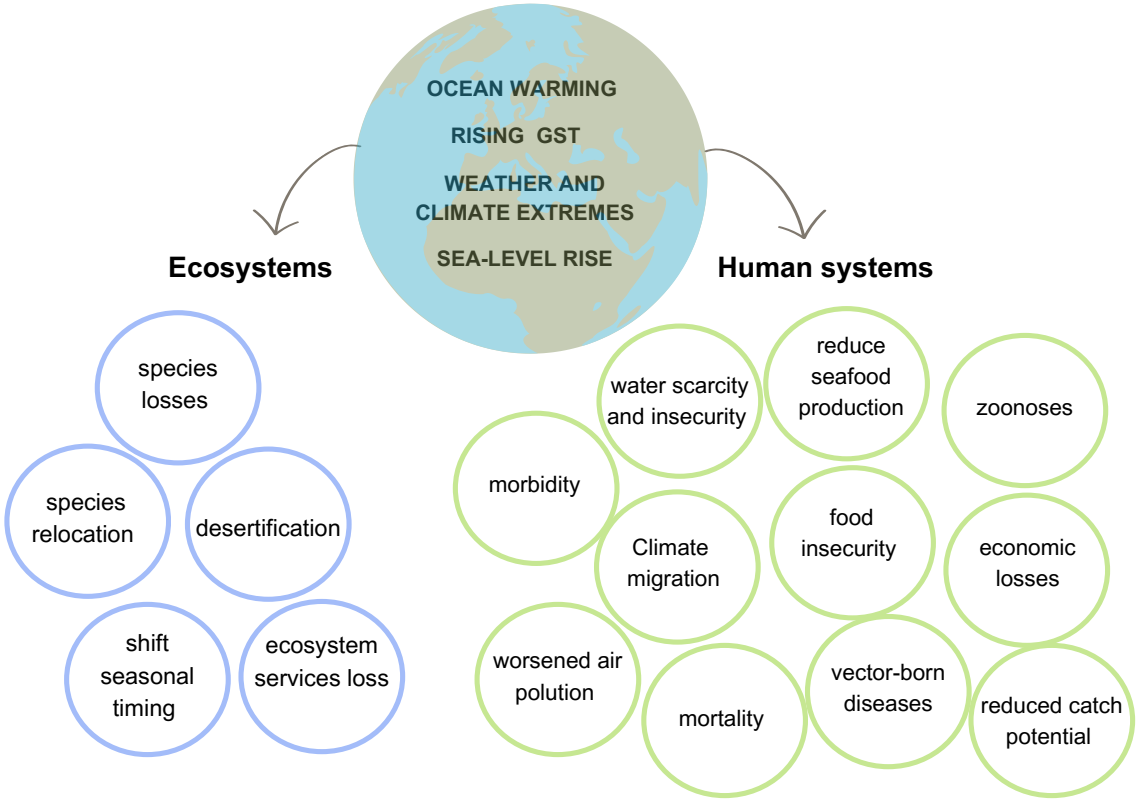


Figure 4.-Losses and damages for ecosystems and human systems scheme. Source: The author.

1.8. Future Scenarios, Gaps and Needs

The impact of human activity on the climate is generating profound repercussions on the planet's health, including on human health. It is crucial to take proactive measures to adapt and protect both humans and the planet (Jain et al., 2023). Adaptation to CC involves making changes in ecological, economic, and social systems to minimize the negative effects (Cheng et al., 2022). As defined by the IPCC adaptation is "the process of adjustment to actual or expected climate and its effects" (IPCC, 2014, 2023). In contrast, mitigation focuses on addressing the drivers of climate change, such as reducing greenhouse gas emissions (Sharifi, 2020).

While mitigation aims to reduce long-term risks, adaptation strives to address current risks resulting from a lack of mitigation efforts and present circumstances (Sharifi, 2020).

Both adaptation and mitigation are crucial from economic and environmental standpoints, requiring attention at both national and international levels (Abbass et al., 2022). The UN has acknowledged the importance of addressing climate change through the Paris Agreement on Climate Change, that has the ultimate goal of limiting global warming to 1.5°C, by declining greenhouse gas emissions (https://unfccc.int/process-and-meetings/the-paris-agreement), and through the Sustainable Development Goals (SDG) of Agenda 2030. Other international organizations (such as WHO and UNEP) and individuals have also acted in this regard, with focus on changing consumer behaviours (Fisher & Nasrin, 2021). To achieve the objectives outlined in the Paris Agreement, it is essential to establish robust legal frameworks for implementing legislation and best practices (Eskander & Fankhauser, 2020).

The IOC (Intergovernmental Oceanographic Commission) as part of UN proclaimed the Decade of Ocean Science in 2021-2030, an idea linked to the 2030 agenda (Ryabinin et al., 2019). The purpose behind is to transform ocean science solutions for sustainable development by understanding pollution sources, protecting and restoring marine ecosystems, supporting a sustainable food supply, investing in ocean-based solutions to tackle CC, by educating society on changing ocean conditions and values related to human well-being and giving access to equitable information (Blasiak et al., 2023).

The Ocean Decade can strengthen international cooperations to generate knowledge, solutions and science to preserve our planet’s largest ecosystem and ensure their role in the future. As said by UN Secretary-General, António Guterres - “Our failure to care for the ocean will have ripple effects across the entire 2030 Agenda”.

The clear link between human health and the surrounding environment (Zhang et al., 2022) underscores the urgent need to address climate change and its negative impacts. One of the best approaches to meet the goals proposed in SDG and the Paris Agreement is by adopting the One Health Concept in all sectors, to ensure optimal health and well-being for

humans, animals, and the environment through sustainable measures (Prata et al., 2022). Ultimately, there is a need to shift away from individualistic and utilitarian ideas towards the environment.

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Chapter II - Sea-Level Rise

Chapter Resume

Chapter II explores the problematic of increased global mean sea level, how it happens, how it has been developing in recent years and the issues that arise from it, such as floods. By mentioning that coastal zones are the ones most affected by flooding events, this chapter provides examples of impacted coastal areas by increased sea-level rise and flood risk, including the city of Venice. At the same time, it lists some solutions in place and innovative ideas that aim to delay as much damages and losses as possible due to floods as a consequence of SLR.

Ultimately, it mentions the need to restructure ways of approaching this issue since ideally, all should comprise mitigation and adaptation measures, to ensure a sustainable future for all.

Moreover, this chapter introduces the case study in Venice, where one solution, the MoSE (*Modulo Sperimentale Elettromeccanico*) barrier system is already implemented and will be the focus of the next chapter.

2.1. Global Mean Sea Level

According to the IPCC (2023) report, the average rate of sea-level rise (SLR) from 1901 to 1971 was 1.3 mm/year, from 1971 to 2006 was 1.9 mm/year and finally from 2006 to 2018 was 3.7 mm/year. So, the trend in the latest years is significantly higher, mainly due to human influence. It is predicted that by 2100 sea level will rise by 60 cm due to OW and melting glaciers, under higher emission scenarios (Khojasteh et al., 2021; Costa et al., 2023; Rocha et al., 2023). These projections of global SLR are under different RCPs, where the lowest concentration of GHG will contribute to a 0.61m increase and the highest can reach up to a 1.10 m increase (Dong et al., 2022).

This is a slow-onset process that poses threats to millions of people, coastal infrastructures, many ecosystems, and cultural heritage on coastlines (Martyr-Koller et al., 2021).

There are two main factors responsible for sea level variations, changes in ocean volume due to temperature change and net transfer of terrestrial water storage (land ice and ground water) (Minunno et al., 2023; Rocha et al., 2023). As a consequence of the previously explained GST increase, seawater expands. According to Widlansky et al. (2020), seawater density becomes more sensitive to temperature changes therefore accelerating the rise. In fact, by using a climate model, the same author showed a tendency for increased sea level variability as the temperature increases. Besides expanding seawater, temperature increase leads to ice and glacier caps melt which have a direct impact on SLR (Shukla et al., 2017). Logically, GHG emissions also exert effects on increasing SLR (Minunno et al.,

2023) due to thermal expansion (Zickfeld et al., 2017; Zanna et al., 2019). Moreover, GHG emissions have effects on ocean chemistry namely ocean acidity since oceans function as a carbon sink (Rehdanz et al., 2006).

The IPCC has reported coastal environments to be the most dynamic interface between land and sea (Roy et al., 2023). As sea level rises many islands are at risk of disappearing, inducing island populations relocation. This poses a significant migration challenge for this century (Xie et al., 2021).

With SLR, the risk of flooding affecting coastal communities increases (Siegert et al., 2020; Ghanbari et al., 2021), mainly impacting 10% of the world's population who live in low-lying coastal zones (Cazenave et al., 2014; Golledge et al., 2020; McMichael et al., 2020; Siegert et al., 2020) and affecting its infrastructures and country's economy (Neumann et al., 2015; Spencer et al., 2022). Coastal systems, such as tidal wetlands are extremely valuable and vulnerable ecosystems (Kirwan & Megonigal, 2013). The hydrodynamics and sediment fluxes of tidal networks are heavily influenced by populated areas (Madricardo et al., 2017). As a result, these ecosystems undergo many changes and are put at risk due to the pressure of SLR, eventually leading to flooding events and habitat loss (Viezzoli et al., 2010; Madricardo et al., 2017).

2.2. Cities affected by Sea-Level Rise

The map on Figure 5 represents some of the cities affected by SLR that will be addressed in this section.

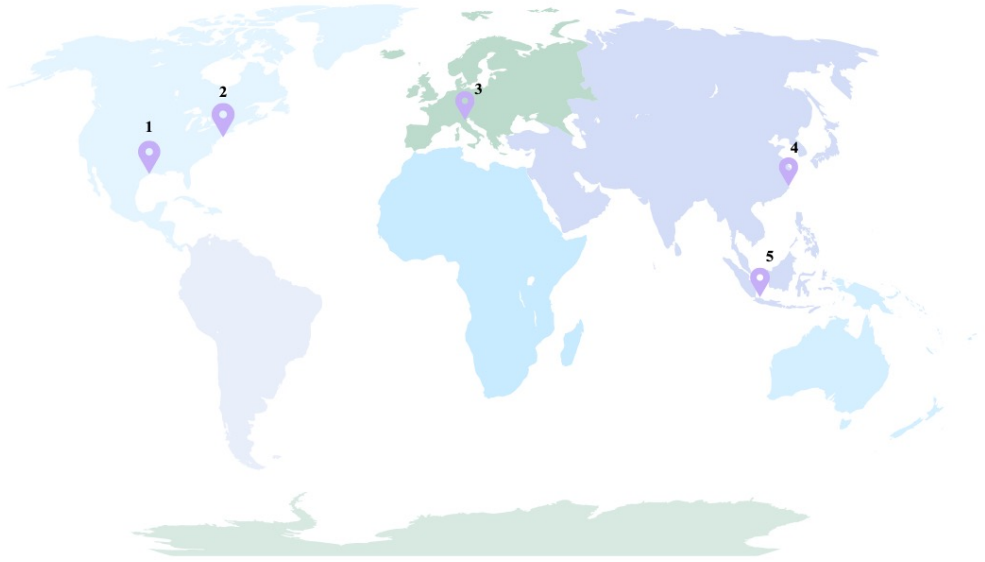


Figure 5.-World map with some of the most affect areas by sea-level rise and floods. 1- Mississippi Delta and New Orleans, US; 2- New York City, US; 3- Venice, Italy; 4- Shanghai, China; 5- Jakarta, Indonesia. Source: The author.

China is a great example of SRL combined with heavy pressures on coastal areas, especially in major delta regions (Yin et al., 2010). Taking the city of Shanghai as an example of a flood-prone city, according to Yin et al. (2011) because it is a flat and low-lying place, a possible total inundation of the city using a simulator, showed numerous consequences for the thousands of people.

In New York City (NY), SLR contributes more to flood risk increase than storm surges (Rahmstorf, 2017). Another significant factor contributing to increased water flow in the NY region is a weakened North Atlantic circulation, resulting from ice loss and diminishing glaciers, leading to heat accumulation and thermal expansion (Gornitz et al., 2020). Overall, SLR increases the likelihood of storm surges, thereby increasing floods in low-lying areas of the city, as evidenced by previous events (Marcos et al., 2015; Sweet et al., 2018). Yin et al. (2017) report that 60% of SLR is driven by climate-related factors

In the American Midwest, well-being and economic stability are threatened due to river floods (Shirzaei et al., 2021). Due to its vulnerable location and CC, severe floods of the Mississippi River are set to increase, threatening cities' futures (Reed et al., 2020; Fazey et al., 2021). Cities like New Orleans were noticed to be flood-endangered during the greatest flood of the United States in 1927 (Driessen & Van Ledden, 2013). In fact, New Orleans has been considered an indicator for threatened coastal areas impacted by the rising sea levels due to CC (Cannon et al., 2020). With the combination of all the above-mentioned factors, cities located in the Mississippi delta will suffer from much more severe and major events in the near future.

Another region, particularly vulnerable to coastal flooding is Indonesia, specifically Jakarta since it is already subjected to regular floods (Ward et al., 2011). In the last decades, Jakarta has been experiencing a large population growth as well as economic, leading to land subsidence issues which in turn can aggravate the already existing floods and enhance CC impacts (Takagi et al., 2016). A study done in 2011 conducted a climate risk assessment, stating floods as the highest natural disaster and the growing incidence of SLR in Jakarta, mainly in the below-sea-level lands (Firman et al., 2011).

In the Mediterranean basin, several vulnerable coastal systems are affected by both natural and anthropogenic pressures, with the historical city of Venice (Italy) being a paradigmatic example (Carbognin et al., 2010). Venice and its shallow lagoon, the largest in the Mediterranean region (Molinaroli et al., 2019; Toso et al., 2019; Lionello et al., 2021), represent a UNESCO World Cultural and Natural Heritage site (Madricardo et al., 2017). Due to its location (situated 80 cm above the mean sea level) (Umgiesser, 2020), pumping

water practice, natural sinking (Molinaroli et al., 2023), and land subsidence (Tosi et al., 2014), it is a city prone to progressive submersion (Carbognin et al., 2010) (Figure 6).



Figure 6.-Venice lagoon from satellite image. Source: ArcGIS pro.

Considering its origin, Venice has had minor sea level oscillations (Carbognin et al., 2010) with the most severe flood event occurring in 1966 (Carbognin et al., 2010; Trincardi et al., 2016; Lionello et al., 2021). Since then, Acqua-Alta events (high-water-flooding events) have been more frequent (Molinaroli et al., 2023) and the city has sunk 25 cm over the past century (Tosi et al., 2013). A study conducted in 2017, about sea level changes by the year 2100, found a 30% chance of flood for the lowest SLR case scenario and more than 85% chance, for the worst-case scenario (Antonioli et al., 2017). In this scenario, the ultimate consequence for the city of Venice would be a threat to its existence.

Besides floods, events such as coastal erosion, saltwater intrusion and shoreline relocation are set to increase because of SLR, functioning as a chain reaction (Fiori & Anderson, 2022; Neumann et al., 2015; Stronkhorst et al., 2018).

2.3. Sea-Level Rise and Coastal Erosion

At the beginning of this century, the relation between SLR and coastal erosion had already been observed so was its implication in shoreline retreat (Leatherman et al., 2000). Sand erosion rates are expected to increase in the near future (Masselink et al., 2018; Athanasiou et al., 2020), due to SLR, shoreline retreat and erosion (Vousdoukas et al., 2020). It is a problem that impacts around 70% of the world's sandy beaches, reducing plant and animal communities' living areas (Feagin et al., 2005). Besides, coastal areas are well known for being among the most developed areas so other factors such as migration, urbanization and population enhance CC effects (Vousdoukas et al., 2020).

2.4. Sea-Level Rise and Saltwater Intrusion

The intrusion of saltwater (SWI) causes salinization, which is expected to increase due to rising sea levels driven by CC (S. W. Chang et al., 2011; Abd-Elaty et al., 2021, 2022). A study conducted in the Netherlands showed that if the sea level rises 0.5m per century, salinity in all low-lying regions would increase (Oude Essink, 2001). SWI limits soil productivity due to aquifer contamination, thereby affecting agriculture and industrial growth in coastal regions (Abd-Elaty et al., 2022; Tarolliid et al., 2023). As coastal populations grow, so does their demand for goods. However, if the coastal aquifers are contaminated, the capability to supply water diminishes, resulting in overall water scarcity (Polemio & Walraevens, 2019; Bellafiore et al., 2021). Taking Vietnam as an example, this country is already facing many problems related to SWI, especially in coastal areas, restricting their already limited access to freshwater (Xiao et al., 2021). Another study, also conducted in the Vietnam region, estimated thousands of acres of agricultural losses due to SLR (Vu et al., 2018).

2.5. Innovative Solutions to tackle Sea-Level Rise

SLR impacts human and ecosystem health in many aspects. It poses a severe threat to sustainability, especially in coastal regions, so it is an imperative matter to find solutions and alternatives that are effective and present minimum impact for the ecosystems. This section will describe examples of solutions present in literature to tackle this hurdle.

Burger et al. (2017) developed a framework plan for solution implementation for an area near NY city, considering the region's topography, ecological connections, anticipation of climate changes to enable humans and other living beings to stay within their region and not to be relocated. The plan presents several measures:

- Identification of new areas in the region suitable for shifted habitats.
- Restoration of degraded inland areas.
- Fostering new locations of endangered habitats such as salt marshes.
- Removal of infrastructures to establish new communities.
- Change from vertically designed buildings to horizontal design together with a hybrid system of infrastructures to protect larger areas.
- Repurpose abandoned sites such as sand mines.
- Change vegetation in some areas and therefore creating habitats and establish new corridors of movement.
- In cities with islands, raising the ground level will help in the sinking process and create new transportation networks.
- Identification of transition areas depending on SLR projection.

Brown et al. (2020) assessed flood risk through SLR scenarios and stated that seawalls and land raising are the most viable options to reduce flood risk in the Maldives region. Even though, the authors believe that it might not be enough for the current rapid changes in sea level.

Manes et al. (2023) state that Nature-based Solutions (NbS), like protecting and enhancing mangroves and coral reefs, are of high importance when it comes to protection of coastal areas in Brazil. The authors revealed a 2.5 times reduction risk for the Brazilian coastline by implementing such NbS, enhancing even more the need to maintain, protect and restore those habitats to guarantee the livelihoods of its habitants. Also, Doelle et al. (2023) refer to NbS as ecosystem-based adaptations to implement in coastal areas most affected by SLR, focusing more specifically on mangroves. Other authors have also considered mangroves as one of the most resilient NbS options to keep up with the rise of the sea level (Blankespoor et al., 2017; Best et al., 2018; Cahoon et al., 2021; Siegersma et al., 2023). These solutions rely on biodiversity to help people adapt to extreme effects of CC but also provide them with other ecosystem services (provisioning, regulating).

For cities like New Orleans, already mentioned as highly affected by SLR, the creation of marshes between sea and city will provide extra water storage, attenuate storm surges and reduce flood risks in heavily dense areas. In the Belgian Scheldt estuary, a protection project involved the creation of tidal marshes in reclaimed wetlands, aimed to reduce flood risk and propagation of storm surges (Temmerman et al., 2013). However, NbS need to be adapted to the type of ecosystem (e.g. estuary, sandy coastlines) (Temmerman et al., 2013).

For the city of Venice, another paradigmatic example of a SLR threatened city, several measures were adopted in the latest years to protect the city from flooding events, such as restoration of the seawalls, nourishing eroded beaches, elevation process, and construction of lagoons wetlands (Molinaroli et al., 2019). The last and newest adaptation measure adopted is the MoSE (Modulo Sperimentale Elettromeccanico) barrier system. The MoSE barrier consists of 78 mobile gates installed in the three inlets of the Venice lagoon (VL), including this thesis' study area (Figure 7) (Trincardi et al., 2016; Molinaroli et al., 2019; Toso et al., 2019; L. Janowski et al., 2020). The mobile barriers are built to protect the city from up to 3 m tides, considering the future predictions of SLR (L. Janowski et al., 2020). These barriers pump air into the gates to empty the water causing them to rotate upward until emerging above the sea level, therefore separating the Adriatic Sea from the lagoon (Trincardi et al., 2016; Toso et al., 2019; Mel et al., 2021. Since the MoSE's first activation, closure time of the barriers has varied between a few hours to 24h for high tides that have happened four times per year (Baldassarre et al., 2023). According to Umgiesser (2020), if

no closure of the barriers occurs, the city will be flooded for more than 1000h per year if sea level rises 50 cm. However, if barriers do close, the time of flooding can go from 18h to 100h (in the worst-case scenario). Albeit the author states that MoSE barriers are only predicted to protect the city to a certain level of sea rise. If levels are too high, the barriers will need to close once a day, approximately. This would not be convenient for the city nor for barriers as they are not adapted to that many closures.

Another city that has had several problems with SLR is Miami, US that was considered to be the most vulnerable city to SLR in the world (Wdowinski et al., 2016). Since the beginning of the last century, the city has implemented several measures from construction of wood and rock groins to elevate street levels, in the most vulnerable areas (Molinaroli et al., 2019). In fact, Miami Beach administration has invested in water catchment basin instalments and pumping stations to deal with current sea levels (O'Donoghue et al., 2021). A study published last year interviewed Miami Beach residents concerning the problematic of SLR and the adaptation in-situ VS mobility/relocation. The authors found that more than half (57%) of the residents preferred in situ solutions (Seeteram et al., 2023), evidencing the need for long-term adaptations when facing CC.



Figure 7.- The city of Venice and the Lido inlet. The Lido is one of the three MoSE's locations and this thesis' study area. Source: The author.

2.6. Final Remarks and Future Scenarios

To address the SLR issue, the same approaches mentioned in Chapter I, adaptation and mitigation, can be applied. To successfully adapt to SLR, institutions must negotiate and address the ever-changing demands we face, to ensure social and environmental justice (Hurlimann et al., 2014). It is extremely difficult to predict the height of SLR in the future even with IPCC RCPs scenarios and, although several ways to mitigate these impacts can be considered, ultimately all involve the control and /or reduction of GHG emissions (Dong et al., 2022).

Since SLR as a consequence of GHG and GST, leads to its consequences, it is important to keep in mind that we are living in the Decade of Ocean Science for Sustainable Development from 2021 to 2030, which is inherently linked to the SDGs (Haward et al., 2021). The SDG 13 for climate action of the UN's 2030 Agenda (Pérez-Peña et al., 2021) considers both adaptation and mitigation by integrating climate change into national policies, monitoring processes and improving climate change capacity in the least developed countries (Campbell et al., 2018). The SDG 14: life below the sea, also contributes to minimising the impacts of CC in an indirect way, by aiming to conserve the oceans, seas and marine resources in a sustainable way (Recuero Virto, 2018; Haward et al., 2021).

Both goals emphasize the need for transformative and urgent action to avoid further consequences and assure a sustainable future for the upcoming generations (United Nations, 2023). They also emphasize the linkage between ecological and social issues, since we cannot address the former without paying close attention to the latter (Haward et al., 2021). This Chapter serves also as part of the introduction for the following chapter, since one of the solutions mentioned, the MoSE system in Venice was studied closely.

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Chapter III - Venice as a case study for Artificial Defences in Coastal Marine Environments

Chapter Resume

Many coastal cities are greatly affected by sea-level rise and the consequences are unimaginable. Venice is a city threatened by SLR thus, several measures have been implemented over the years to help protect the city and all its inhabitants. The focus of this Chapter is to contribute to the monitoring of the recently implemented defence (the MoSE-Modulo Sperimentale Elettromeccanico- barrier) in the inlets of the Venice Lagoon (VL). The impact of the newly introduced hard-infrastructures on the seafloor morphologies and sediment transport regime was evaluated. High-resolution multibeam surveys and geomorphometric analysis were used to assess the possible effects of erosion, deposition, and changes on seafloor morphology related to the construction of the MoSE infrastructure in correspondence to the VL inlets. By comparing repeated surveys and sediment sampling campaigns carried out in the last decade, the results indicate an overall change in the inlet's sediment regime and seafloor morphologies due to past and current human-made alterations. The prevalence of the erosional regime over the depositional in one inlet was documented, as well as deepening and shrinking of some morphologies. Based on this year's recent observations, an increased seaward sediment transport is hypothesized. These trends are thought to be related to recent operations of the MoSE system, that have altered the inlet's hydrodynamics and therefore created geomorphological alterations. The mentioned changes were foreseen in previous studies, but a direct correlation has not yet been established. The system has fulfilled in part its objective, protecting the city from *high water* events, nonetheless further impacts on inlets, where the MoSE system has been installed, and the Lagoon need further investigations, as well as close monitoring to implement if proven needed adaptative measures.

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3.1. Introduction

Sea-Level Rise (SLR) is a consequence of Climate Change (CC), increasing the risk of flooding coastal areas by a lot, jeopardizing 10% of the population who live in coastal zones (Siegert et al., 2020; Ghanbari et al., 2021). Coastal barriers are complex systems that delimit coastal lines (Fogarin et al., 2019) such as coastal lagoons connected to open sea

through inlets (Toso et al., 2019). Like many other ecosystems, lagoons have undergone rapid morphological changes due to human interventions, which can lead to altered sediment fluxes, changes in morphodynamics and ecological processes, and changes in the chemical and physical properties of the water (Fogarin et al., 2019; Mishra et al., 2022), as well as increased floods and habitat losses, likely to increase due to CC (Madricardo et al., 2017). However, inlet seafloor morphology responses to anthropogenic interventions are poorly known (Toso et al., 2019).

Understanding the lagoons' and tidal inlets' dynamics including changes in morphologies is important to manage and protect this type of ecosystem from direct pressures and CC (Scarpa et al., 2022). As CC exacerbates coastal floods, effective adaptation strategies need to be supported by comprising policies, risk assessments, and non-structural measures (Mel, 2021).

The focus of this Chapter is the VL, the coastal system surrounding the city of Venice (Figure 8). Due to its location, it is prone to sink (Fogarin et al., 2019) since it is situated only 80 cm above sea level (Umgiesser, 2020). More importantly, it can be considered a "human-oriented ecosystem" (Fogarin et al., 2019) since the start of the 16th century, due to huge human alterations of the lagoon system (Scarpa et al., 2022).

The VL is a microtidal estuary (Amos et al., 2010) located in the Veneto region, in the northwestern Adriatic Sea (Ravera, 2000; Ghezzo et al., 2010; Allegri et al., 2024). It is the largest lagoon in the Mediterranean (Madricardo et al., 2017) that started to form 7500 years ago. In the lagoon, there are several small islands and the main one, where most of the population resides (Allegri et al., 2024).

A sandy island system functions as a barrier that separates the lagoon from the sea (Lionello et al., 2021). The water renewal inside the lagoon with the Adriatic Sea is made by the tidal cycle through three inlets: Lido, Malamocco and Chioggia (Ravera, 2000; Ghezzo et al., 2010; Fogarin et al., 2019). Four semidiurnal and three diurnal tides have a significant contribution to the sea surface elevation in the northern Adriatic Sea, resulting in a mixed regime (Book et al., 2009). The VL can be defined as a confined lagoon, where the main forces of circulation are tides and wind. It has an average depth of 1.5 m but with a few deeper channels (15 m) leading inwards from each inlet into the basin (Ravera, 2000; Ghezzo et al., 2010; Umgiesser et al., 2021). It also includes tidal flats, canals, fishponds, reclaimed areas (Fogarin et al., 2019) and salt marshes (15% coverage) (Umgiesser et al., 2021). It is an environment periodically subject to *high water* (*Acqua Alta*) events related to the combination of the astronomical tide maxima and the persistence of the Scirocco wind from the southeast enhancing the overall northern Adriatic Sea level and the so-called *seiche* effect (Vilibić, 2006; Lionello et al., 2021). The highest *high water* event was in 1966

with a level of 194 cm, whereas the second highest was in 2019 with 187 cm (Umgiesser, 2020).

The tidal regime of the lagoon has been affected by large jetty construction, fish farming, and urban development (Fogarin et al., 2019; Finotello et al., 2022).

Since the *Acqua Alta* is a multifaceted issue, the MoSE project represented an important step forward to protect the city, despite the high maintenance cost (Alberti et al., 2023). To investigate the possible impacts of these infrastructures on the lagoon seafloor and the sediment transport, this chapter will focus on the Lido Inlet, the study area, that was most affected by human interventions over the last two centuries (Molinaroli et al., 2023). The Lido Island, to the south of the Lido inlet, described in the first century as "tenue praetentum litus" (thin beach) is a 12 km sandy barrier that separates the lagoon from the sea. Over the years, the Lido inlet has undergone intense changes in its morphology due to urban development (Molinaroli et al., 2023). In Table 1 it is possible to see the changes this area has undergone in the most recent years. Overall, the MoSE construction has led to an increase in current velocities, sedimentary changes (transition from depositional to erosive) and general sediment loss (Scarpa et al., 2022).

Table 1.- Alterations done over the years in Lido inlet related to the MoSE construction.

Year	***Intervention***
2006	Excavations for MoSE started
2010	MoSE trench excavation completed
	Beginning of the lunata breakwater
2012	Breakwater almost completed
2013	First mobile gates installed in Treporti channel
	First trial of the barrier in Treporti channel
	Construction of Lunata breakwater completed
2014	All Treporti channel mobile gates are installed
2016	All structured work finished
2020	First closures of the barrier

The MoSE only started to operate in 2020 (Alberti et al., 2023). Until the present time, the barriers have been activated 84 times (Table 2). Normally, the barriers are submerged in the water and raised when sea levels are expected to rise over 110 cm, with an average closing time of 4/5 hours (Alberti et al., 2023).

Table 2.- MoSE closures. Source: https://www.mosevenezia.eu (visited last on August 2024).

Year	***Number of closures***
2020	13 (October to December)
2021	7 (January to February)
	13 (November to December)
2022	11 (November to December)
2023	8 (January to August)
	17 (October to December)
2024	15 (January to March)

Venice and its lagoon (Figure 8) iconically recall the peril represented by climate change and mean sea-level rise. Therefore, the *Acqua Alta* issue requires coordinated action of multiple stakeholders, including the local community, to actively contribute to ensure the sustainable preservation of this unique site. The main objective of this chapter is to evaluate the impacts of MoSE on seafloor morphology, using high-resolution multibeam surveys. This work was developed as part of an internship funded by the ERAMUS+ programme, in CNR-ISMAR (Venice, Italy).



Figure 8.-The city of Venice and Lido inlet in the Venice Lagoon from satellite image. Source: ArcGIS pro.

3.2 Materials and Methods

3.2.1. Seafloor mapping

Records of seafloor mapping go back to the first technique of water depth measures in ancient Egypt (Mayer, 2006; Wölfl et al., 2019). Since then, evolution happened and one of the first bathymetric maps of the ocean floor allowed the understanding of plate tectonics and shattered the concept of static and featureless seafloor (Chiocci et al., 2011; Dierssen & Theberge, 2014).

In comparison to the terrestrial maps, the production of marine ones is very challenging and expensive (C. J. Brown et al., 2012). The existing methods (aerial and satellite) only allow the mapping of shallow and transparent coastal waters due to their limit in light penetration (C. J. Brown et al., 2012). In the last few years, seafloor mapping importance was recognized by international initiatives, such as the 2015 and 2017 SDGs. The SDGs aim to

conserve and incite suitable use of seas and other marine resources as well as promote their research and observation by 2030 (Wölfl et al., 2019) Therefore, many efforts in seafloor mapping are globally ongoing to properly understand seafloor nature influencing the benthic habitats, the hydrodynamics and sediment and biota transport (Mayer et al. 2018). Ultimately, mapping the seafloor is the first step in exploring the marine environment that needs to be monitored and protected from CC and SLR impacts (L. Janowski et al., 2020).

3.2.2. MBES (Multibeam Echo-sounder System)

MBES is an acoustical mapping system that measures water depth in a single transmission (Simons & Snellen, 2009) that became first available in the 1970s (Wölfl et al., 2019). It is able to collect 2 types of data: bathymetry and backscatter intensity, creating geo-referenced data, warranting high resolution and full seabed coverage (Janowski et al., 2018; Madricardo et al., 2019). With MBES is possible to achieve the same resolution witnessed in satellite and airborne optical remote sensing used in land mapping (C. J. Brown et al., 2019). Moreover, it allows precise mapping in shallow waters and gives new information about seafloor processes impacted by anthropogenic activities making it possible to estimate its consequences on sea morphology and habitats (Madricardo et al., 2019; Toso et al., 2019).

3.2.3. Bathymetry data

During this work, five bathymetric datasets were analysed: from four previous campaigns (2011, 2013, 2016 and 2021) and a new dataset collected in 2024. In the 2011 and 2013 campaigns the MoSE was not yet completed, only in 2016 were installed. The MoSE started to be operational in September 2020.

Data acquisition

The data relative to 2011 was collected by the institute Idrografico della Marina Militare (I.I.M). The data set of 2013 was collected by CNR-ISMAR of Venice as part of the RITMARE flagship project. The collection was done on board the LITUS 10-m vessel. The 2016 collection was made by a collaboration between I.I.M and CNR-ISMAR of Venice, from April 2016 to May 2016. The MBES was used on board of a 10-m long CNR-ISMAR and a 7-m long I.I.M vessel (for more details on the instrumental setup see Toso et al. 2019). The 2021 data was collected in June 2021 as part of the *Venice 2021- For a regulated lagoon* project with the same MBES system of 2013, i.e. a Konsgberg EM2024DC (Madricardo et al. 2017) mounted on the same research vessel. In 2024, the data was collected in March on board LITUS (Annex III, Figure 32) with a single head MBES Kongsberg EM2040 compact set for 360 kHz (same settings as in 2013). A Seapath 380 system supplied by RTK automatically registered the ship positioning (0.01 m horizontal

accuracy). For the correction of pitch, roll, heave and yaw movements of the boat the Kongsberg motion sensor MRU 5 and a Dual Antenna GPS integrated with the Seapath were used. Sound velocity was continuously measured by a Valeport mini SVS sensor and the velocity profile was regularly collected to account for temperature and salinity changes. The bathymetry data for 2011, 2013 and 2016 was processed using CARIS Hydrographic Information Processing System (HIPS) and Side Scan Information Processing System (SIPS) software to control sound velocity variation, tides, and basic quality of bathymetric data (Toso et al. 2017). Once processed the data was exported as a text file(.txt) and then converted into a raster file by Global Mapper software. Afterwards, by using ArcGIS, a Digital Elevation Model (DEM) was created to then proceed to the data analysis. GIS is a computer system which captures, stores, simulates, analyses, and displays geospatial data (Oksuztepe & Yildirim, 2024). The data collected can then be displayed and summarized in georeferenced maps. In this thesis we used ArcGIS Pro v 2.9.5 and ArcMap v 10.8.1. All data sets and maps produced were referenced to the World Geodetic System datum 1984 and projected into the Universal Transverse Mercator reference system, Zone 33N. For the data of 2021 the processing was done using Qimera v.2.5.1 (Quality Positioning Services BV,Zeist, Betherlands). It includes sound speed correction, removal of erroneous soundings, and correction of tidal errors. For 2024, a more recent version of Caris HIPS and SIPS 11.0.lnk was used.

3.2.4. Manual morphology identification

The manual morphology identification was conducted for all bathymetric datasets. To identify the seafloor morphologies, the bathymetric layer and the hill-shade layer were layered. Also, the isobaths were added, using the *contour* function of ArcGIS, in order to improve the identification of the depression and elevated areas.

3.2.5. Automatic morphology identification

For the scours, the Bathymetry Position Index (BPI) function was applied to the bathymetry using the Benthic Terrain Modeler function of ArcMap to classify the benthic environment and extract the main morphological benthic features. For the analysis, a bathymetry raster with a 2m resolution was applied and revealed to be enough to identify the main morphological features. To perform this analysis, the parameters in Table 3 were established to identify the three main erosive features (scours) in the study area. Once the BPI function was completed, it was possible to extract the three scours, converting the rasters into shapefiles. Then, the area and volume of the scours were calculated. This procedure was repeated for all datasets. To calculate the volume difference for all the morphologies, the datasets used (at 0.5m resolution) were the depths' difference of bathymetries.

Table 3.-Inner and outer radius values established to perform the BPI.

Scours	Inner radius	Outer radius
S1	15	250
S2	15	250
S3	15	500

For the depositional features (dunes), the Aspect-Slope surface function was used to analyse the bathymetry rasters. This function is a combination of the slope, which gives information about the rate of elevation change, and the aspect, that identifies downslope direction. By applying this function to the bathymetries, a raster with information about the steepness and direction of the seafloor terrain was obtained. Once performed, the aspect was classified based on the direction of the channel, in this case, it was northwest (NW), south (S) and southeast (SE) directions. The raster was then reclassified using the *reclassify tool*. After that, two shapefiles were created to extract the morphologies. Then, the area and volume were calculated. For the D1, based on the fundamental parameters that enable the characterization of a dune field (Cisneros et al.,2020), it was possible to calculate its profile.

3.2.6. Backscatter data

After the data was cleaned with HIPS and SIPS, a new backscatter mosaic was created using a geocoder with an AVG (Angle Varying Gain) 300 filter. The classification of the backscatter was done using ArcGIS. The raster was reclassified, using the *Reclassify* tool, into 3 classes following the Jenks algorithm (Jenks Natural Breaks) as in Toso et al. (2017).

3.2.7. Ground-truth data

This step was conducted before the MBES data collection so that afterwards the results could be interpreted correctly, allowing a more accurate characterization of the seafloor.

The sediment sample collection was done on the 19th of February 2024. It was previously decided to collect samples in 3 different locations, 3 scours, 2 dunes and 2 deposition sites (Figure 9). For each location, 3 replicates were analysed. In total, 21 samples were collected. The position of the samples was within the most dynamic area, according to the bathymetric data of previous years.

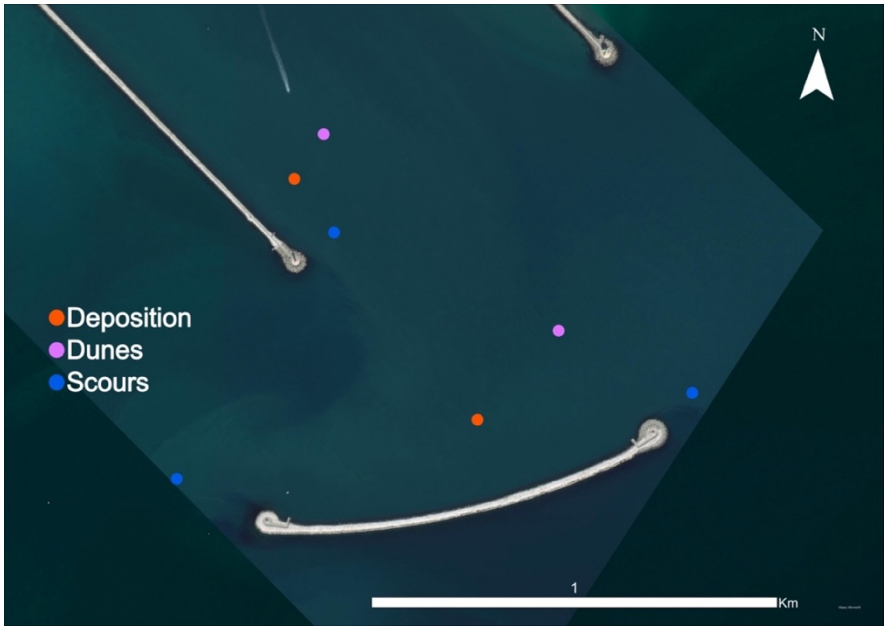


Figure 9.-Study area with the sampling points.

The sampling was done using LITUS, equipped with a Van Veen grab (surface area of 0.1 m^2, volume of approx. 17 L) (Annex III, Figure 33). Firstly, the antenna (Trimble GA830) was connected to a Trimble SPSS855 GNSS modular receiver (Annex III, Figure 34).

The exact coordinates of each sampling point were taken when the grab was still in the air and saved to be inserted in an MS Excel file afterwards. To obtain the correct position, the GPS system with RTK (Real Time Kinematics) online correction was used. After the collection of all samples (Annex III, Figure 35), and after checking the labels, they were frozen at -20°C until the analysis was carried out.

For the granulometry and optical analysis, the laboratory protocol for the sediment analysis was adapted from Toso et al. (2017) and can be found in Annex I.

Since two instruments (LISST by volume % and mechanical sieving by weight %) were used to analyse the two fractions (<1 mm and >1 mm), a series of calculations were carried out in order to unify the two analyses and obtain percentages by total sample weight.

Fine fraction (<1 mm)

Each % in volume was transformed into fraction of weight according to the proportion:

$$W_{<1mm}: x = 100: \%vol$$

where $W_{<1mm}$ is the total weight of the fine fraction **(A)** for each sample, x is the fraction of weight to be found for each particle size range (1.9 µm to 322 µm), and %vol is the % in volume for each particle size range as calculated by the LISST.

Coarse fraction (>1 mm)

As mentioned in the protocol particle sizes obtained for each sample were from 31.50 mm to <1 mm.

To obtain the weight for only fraction >1 mm **(B)**, the material remained in the bottom after mechanical sieving (<1mm) was subtracted from the total weight of each sample (>1mm). Afterwards, to obtain the total weight of sample I, the fraction <1 mm was added to the weight of each sample of the fraction >1 mm **(A+B)**.

Finally, the weight for each particle size range, for both fractions <1 mm and >1 mm, were transformed into percentages of weight (%weight) according to the proportion:

$$W: C = \%weight : 100$$

where W is the weight fraction for each particle size range (31.50 mm to 1.9 μm), C is the total weight of the sample and %weight is the percentage by weight to be obtained for each analysed particle size range of each sample.

After the data is ready to be processed by Gradistat, a software that is integrated in Microsoft Excel worksheet (Blott et al., 2001) which provides particle sizes using the Folk and Ward method (Folk & Ward, 1957). The scale used was in microns (method of geometric moments) to obtain:

- Mean, i.e. the average diameter of the particles
- Classification (sorting), i.e. the dispersion of the size of the granules in relation to the sample's average. See Annex II, Table 10.
- Mode, i.e. diameter of the most frequent particles
- D_{50}, i.e. diameter for which 50% of the particles are fine

Table 4.- Dispersion of the size of the granules in relation to the sample's average.

Very well sorted	<1.27
Well sorted	1.27-1.41
Moderately well sorted	1.41-1.62
Moderately sorted	1.62-2.00
Poorly sorted	2.00-4.00
Very poorly sorted	4.00-16.00
Extremely poorly sorted	>16.00

3.3. Results and Discussion

3.3.1. Bathymetry

From the analysis of the bathymetric data, it was possible to build a DEM for 2024 (Figure 10), 2021, 2016, 2013 and 2011 (Figure 11) in the Lido inlet.

For all the bathymetries the depth ranged from a minimum of -1 m to a maximum of -18 m. All the bathymetry values are represented in a chromatic scale, where the green colour represents deeper areas, and the brown represents shallower. All DEMs are represented by their bathymetry and hillshade overlapping. It was possible to highlight a series of underlying shapes within the study area.

The deepest areas are within a large scour hole located at the seaward end of the southern jetty, with a maximum depth of -18 m.



Figure 10.- Bathymetry of the Lido inlet collected in March 2024.

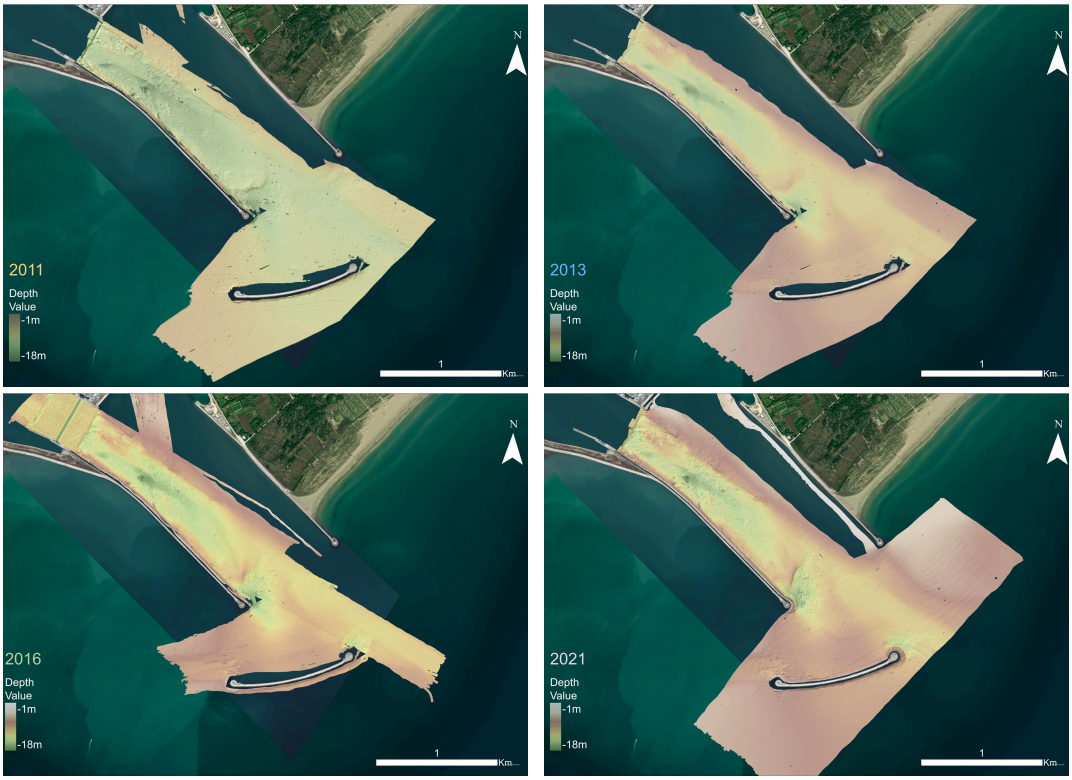


Figure 11.- Bathymetries of the Lido inlet collected in 2011, 2013, 2016 and 2021.

By observing the bathymetries and the areas of interest, it is possible to see that some changes have happened regarding shapes, areas and position. To verify these changes, the differences of the bathymetries were calculated through the *raster calculator* tool obtaining the maps presented in Figures 12 and 13. These maps show the areas that suffered erosion (Δ <-0.4) and deposition (Δ >0.4) when comparing data sets of 2024 to 2021, 2021 to 2016, 2016 to 2013 and 2013 to 2011.

In the course of the first two years (2011 to 2013), erosive processes (orange) were prevalent, especially on the end of the breakwater. The deposition (blue) occurred predominately at the lagoon-side of the breakwater. From 2013 to 2016, the depositional processes intensified closer to the breakwater site.

In the 2021-2016 map, we can observe that mainly depositional processes happened in the southern part of the inlet as well as along the jetty with erosion happening easternmost side of the breakwater.

For the current year, comparing with the 2021's data (Figure 12), it is possible to see that erosive processes are dominant, with very few areas of deposition. The most intense erosion occurred inside the inlet channel.

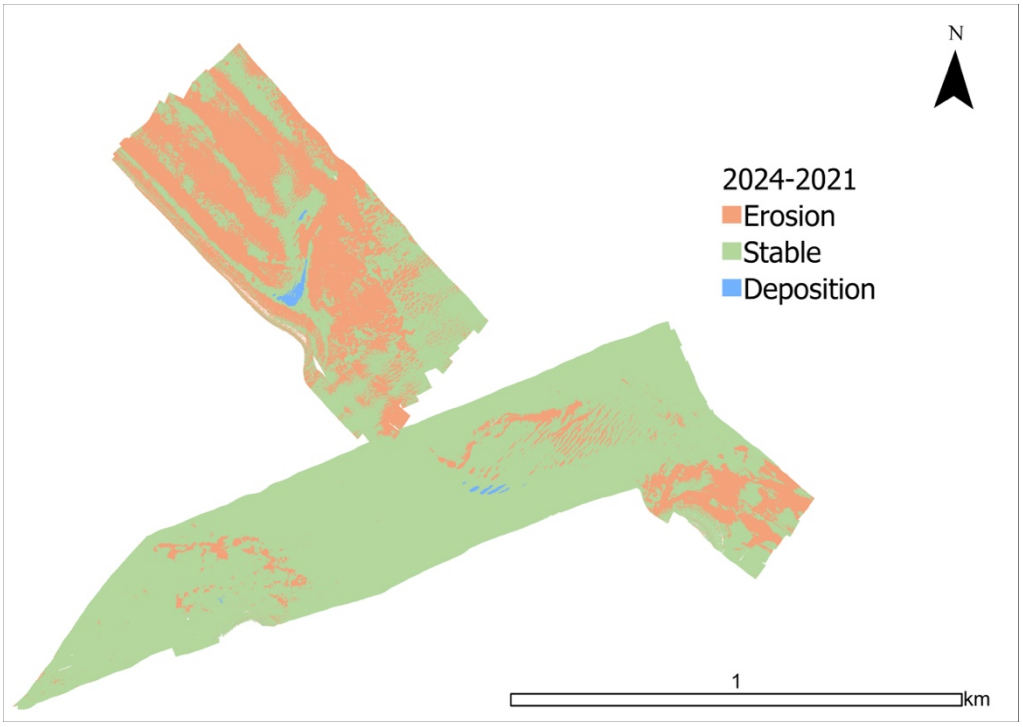


Figure 12.-Map of the bathymetric difference between 2024 and 2021. The blue areas are deposition (Δ >0.4), the orange areas are erosion (Δ <-0.4) and the green areas are stable (-0.4>Δ >0.4).



Figure 13.- Maps of bathymetric differences between 2013- 2011, 2016- 2013 and 2021-2016 datasets, respectively. The blue areas are the deposition (Δ >0.4), the orange areas are erosion (Δ <-0.4) and the green areas are stable (-0.4>Δ >0.4).

3.3.2. Erosional features

Scour holes are depressions in tidal channel beds that originated from erosive processes, induced by hydrodynamic processes (Ferrarin et al., 2018).

By the analysis of DEMs, it was possible to identify 3 scour holes and compare their change throughout the survey years. The Scour 1 (S1) is located at the seaward end of the southern jetty, while the Scours 2 and 3 (S2 and S3) are on either side of the breakwater (Figure 14). As mentioned previously to see the evolution of the morphological features in this location, four surveys prior to 2024 were analysed. All scours were present in all years, except for the 2011 survey.

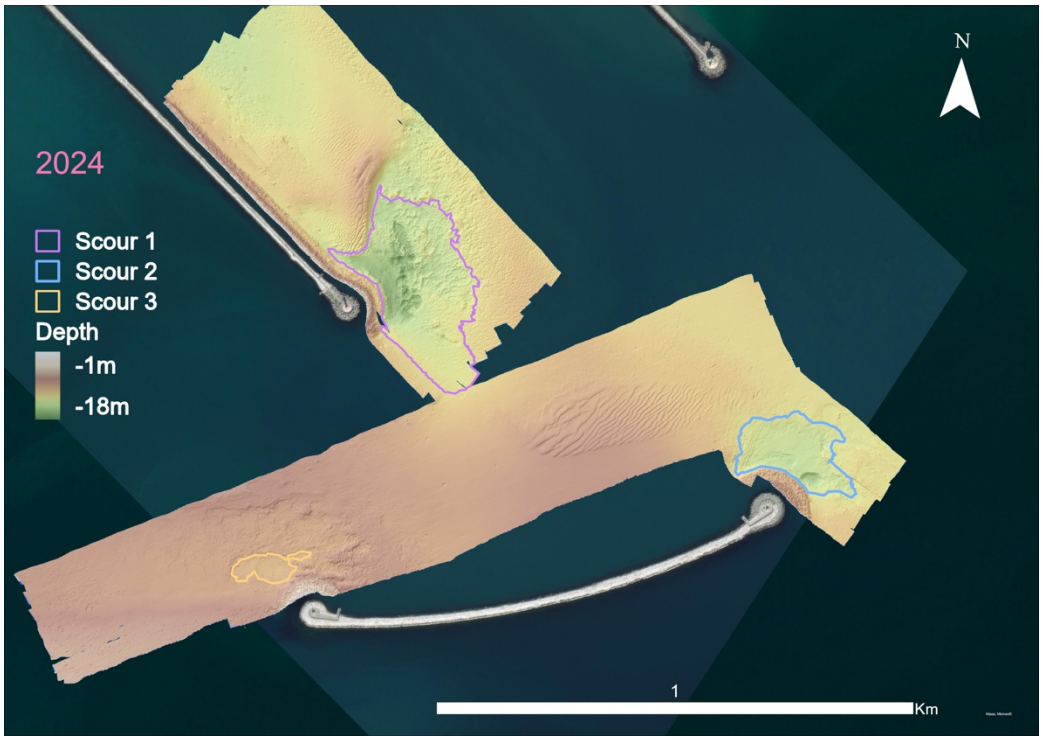


Figure 14.- Bathymetric map representing the erosional features obtained in 2024: scour 1, scour 2 and scour 3 in purple, blue and orange, respectively.

Area and shape

Scour 1: For S1 there was an area increase from 42862 m^2 to 68738 m^2 from 2021 to 2024 (Table 5). From 2016 to 2021 a reduction from 84199 m^2 to 42862 m^2. For the other data sets, an increase of 10027 m^2 and 6591 m^2 from 2011 to 2013 and 2013 to 2016, was observed, respectively. These findings are corroborated by the size and shape represented in Figure 15.

Scour 2: For S2 there was an increase of 6023 m^2 from 2021 to 2024. From 2016 to 2021 a decrease of 6351 m^2 (Table 5). From 2011 to 2016, a gradual increase in the area, from 0 m^2 to 11234 m^2 to 27063 m^2 was observed. As for the shape and size, they did not fluctuate much, although some changes can be seen from 2013 to 2024 (Figure 15).

Scour 3: For S3 an abrupt decrease of 62004 m^2, from 2021 to 2024 as seen in Table 5 and also a drastic change in size and shape, confirmed by the scour's outline (Figure 15). From 2011, when the scour was not yet formed until 2021, we see a gradual increase in its area from 0 m^2 to 27523 m^2 to 66349 m^2 to 68252 m^2.

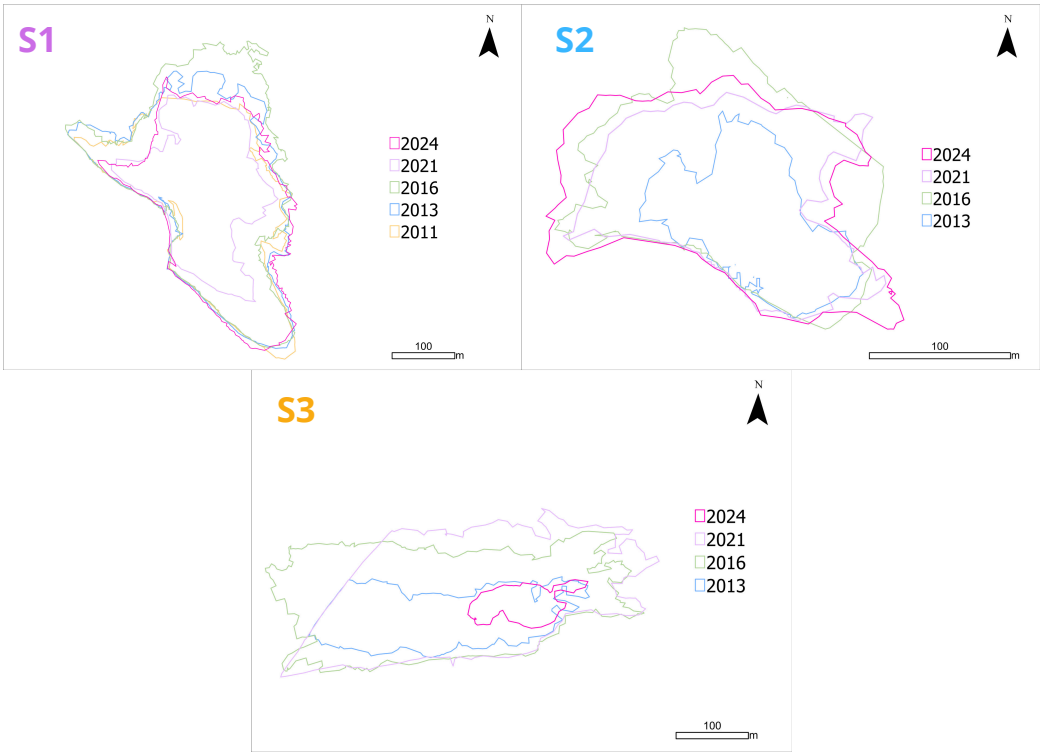


Figure 15.- Scour holes evolution. Evolution extent during the 13 years of surveys. Each year is represented by a different colour.

Table 5.-Area values during the survey years for the scours.

Morphology	2024(m^2)	2021(m^2)	2016(m^2)	2013(m^2)	2011(m^2)
S1	68738	42862	84199	77608	67581
S2	26735	20712	27063	11234	0
S3	6248	68252	66349	27523	0

Volume difference

Scour 1: S1 suffered from marked erosion from 2021 to 2024. As can be seen in Figure 12, most of the area occupied S1 is represented by orange which means a pronounced erosion occurred leading to a sediment loss of 24436 $m^{3,}$ which is equivalent to a loss of 8145 m^3/year (Table 6). From 2016 to 2021, since the volume difference value is positive (9483 m^3) and the map in Figure 13 shows depositional processes, this can indicate a fill-up of the scour hole. As for 2016-2013 and 2013-2011, there was also a sediment loss, observed by the predominance of erosive processes (Figure 13).

Scour 2: For S2 there was a loss of sediments for all differences between all data sets, and when looking at the maps in Figures 12 and 13 it is possible to see that the north end of the breakwater is predominantly orange, meaning erosive processes are dominant.

Scour 3: From 2021 to 2024 there was less sediment loss compared with all the other scours, only 810 m^3 (Table 6). Even though there are erosive processes, especially in the north part of the feature (Figure 12), most of the area is stable.

From 2016-2021, a fill-up of sediments is noticed, especially in the northern part of the scour (Last map in Figure 13), the same happened in S1. From 2013 to 2016 and from 2011 to 2013, the sediment loss (-28443 m^3 and -50687 m^3 , respectively) is corroborated by Figure 13.

Table 6.-Volume differences during the survey years for the scours.

Morphology	**2024-2021 (m^3)**	**2021-2016 (m^3)**	**2016-2013 (m^3)**	**2013-2011 (m^3)**
S1	-24436	9483	-16813	-30340
S2	-14921	-10334	-20547	-19831
S3	-810	31104	-28443	-50687

Over the years evolution

It is possible to see that the scours' area has changed throughout the years of surveys (Figure 16). We see that in 2011 only the S1 existed. Two additional scours, S2 and S3, at the breakwater ends, were formed after that survey. The results also highlight that until 2016 all the scours increased their area progressively but then the evolution started to be more inconsistent

As for volume difference, for all 3 scours, there was a general loss of sediments except for S1 and S3 between 2016 and 2021 where there was a fill-up of sediments.

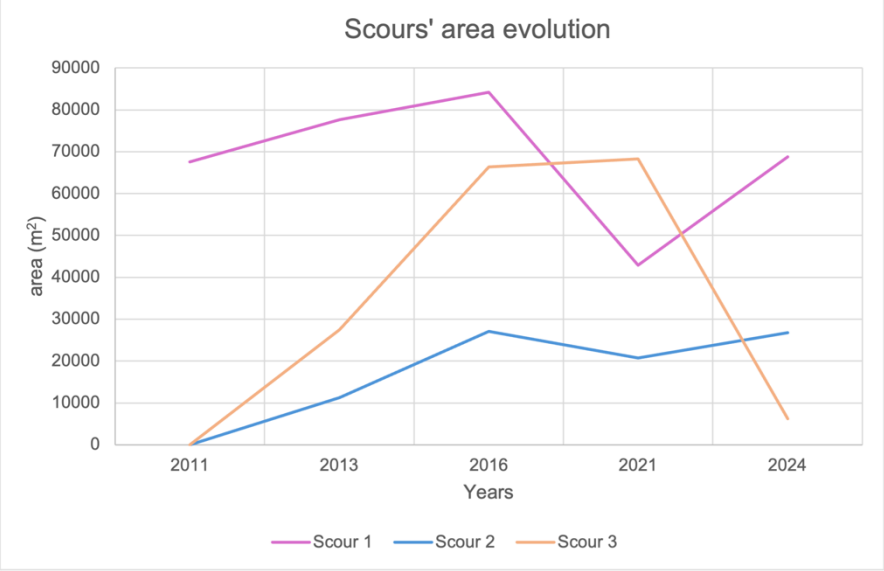


Figure 16.-Graph relative to S1, S2 and S3 area evolution through the survey years.

Scour formation around coastal structures has been well documented (Cho, 2020; Zhao, 2022; Chen et al., 2023; Xu & Huang, 2023). As mentioned previously, S2 and S3 only appeared between the 2011 and 2013 surveys, this is mainly due to the ending of the breakwater construction in 2013 (Table 1) (Molinaroli et al., 2023). The differences seen between 2016 and 2021, where there is a fill-up of sediments for some of the scours and a prevalence of depositional processes (Figure 13) might be related to the fact that after the construction of the breakwater and the MoSE barriers started to operate, the scours adjusted to the new configuration and slow down the erosive processes, also observed between 2013 and 2016 (Toso et al., 2019). After the MoSE started to operate, the timeline between 2021 and the current year, we observed a general loss of sediments and a prevalence of erosive processes, shifting from the previous regime in 2016-2021. These findings were foreseeable as it was thought that the system would affect the lagoon's hydrodynamics, influencing sediment transport and balance, preventing the import from the sea, resulting in sediment loss (Madricardo et al., 2017; Finotello et al., 2022). Although made in another VL inlet, a study in 2019 found that the dredging operations of the barriers were responsible for deepening the channel and increasing current velocities (Fogarin et al., 2019), which can also support our findings.

Not only does the overall loss of sediment within the inlet affect the lagoon's morphological features, but it also can affect the MoSE foundation and threaten its stability.

3.3.3. Depositional features

By the analysis of Aspect-Slope surface model it was possible to identify 2 depositional features: Dune field 1 (D1) and Dune field 2 (D2) (Figure 17). Underwater dunes result from sediment transportation related to flow velocity. The migration of a dune is dependent on its nature and hydrodynamic factors (Cassol et al., 2022).

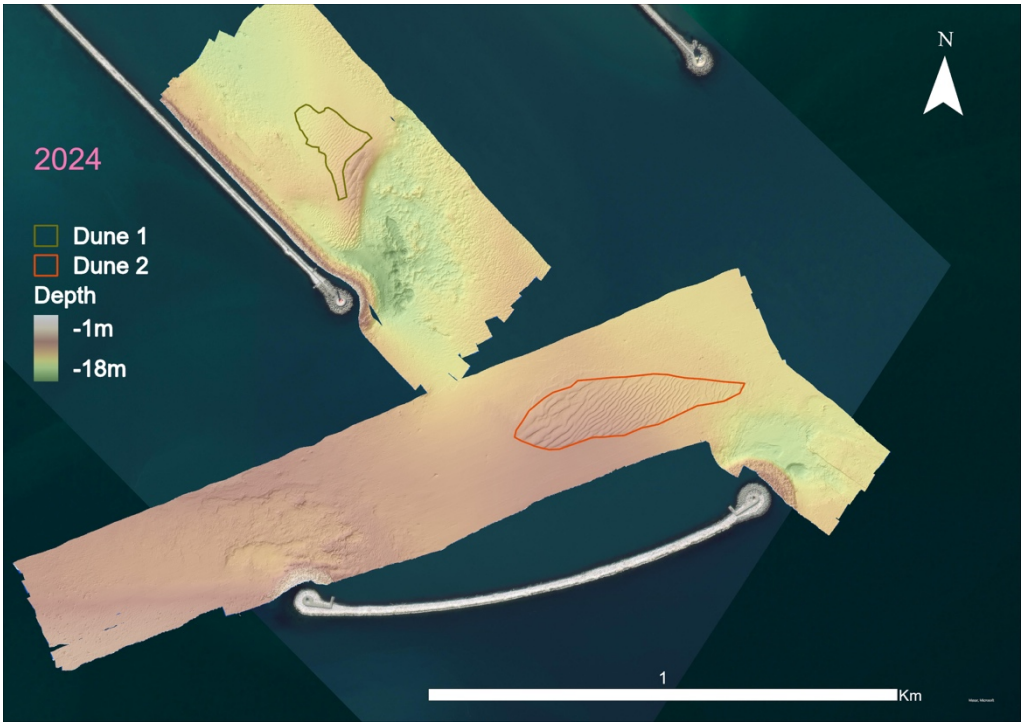


Figure 17.-Bathymetric map representing the depositional features obtained in 2024: dune field 1 in green and dune field 2 in red.

Area and shape

Dune field 1: In 2024 D1 experienced its smaller area of the 5 surveys, 13310 m^2 as can be seen in Table 7 and in Figure 18 in pink.

Dune field 2: For D2 it is possible to observe in the Figure 18 that it has changed quite a lot in terms of orientation, shape and size. From 2016 to 2021 there was an area reduction from 54967 m^2 to 40612 m^2. From 2021 to 2024 there was an area increase of 3978 m^2 (Table 7).

Table 7.-Area differences during the survey years for the dunes.

Morphology	2024(m^2)	2021(m^2)	2016(m^2)	2013(m^2)	2011(m^2)
D1	13310	32352	67199	116157	142511
D2	44590	40612	54967	13573	30695

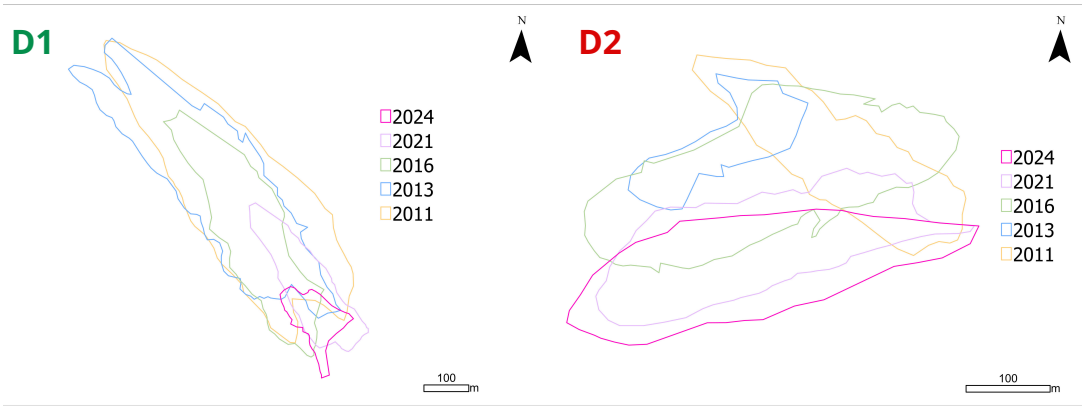


Figure 18.- Dune fields evolution through the 13 years of surveys. Each colour represents the shape and size for one of the years.

Volume difference

Dune field 1: From 2011 to 2013, there was a loss of sediments of 6387 m^3 which can be observed in the map 2013-2011 (Figure 13) in the northern part of the inlet where some areas show erosion. As for 2016-2013 and 2021-2016, there was a sediment fill-up, also observed in Figure 18 by the blue areas predominant in the D1 location. As to the present year, since the prevalence was the erosive regime (Figure 12), D1 lost 5376 m^3 of sediment (Table 8).

Dune field 2: For D2, except in the interval 2021-2016, a general sediment loss was obtained which is in concordance with the erosive regime in Figure 13. As for 2021-2016, since the depositional regime superimposes the erosive, we obtained an increase in sediments during that timeline.

Table 8.-Volume differences during the survey years for the dunes.

Morphology	**2024-2021 (m^3)**	**2021-2016 (m^3)**	**2016-2013 (m^3)**	**2013-2011 (m^3)**
D1	-5376	15707	7436	-6387
D2	-7605	25700	-2387	-1893

Over the years evolution

It is possible to see by Figure 18 that both dune fields have changed a lot during the 13 years of surveys, especially D2, where we see changes in orientation and location. D1 seems to follow an area reduction trend (Figure 19), with the dune field becoming smaller every year. As for the D2, the trend is not so linear, there are some oscillations (e.g., increase from 2013 to 2016, decrease from 2016 to 2021).

In 2021, for D1, the average dune wavelength and height are l= 5.25 m and H=0.1 m, respectively and in 2024, l= 5 m and H=0.07 m. There seems to be a simplification of the dune field 1, where it reduces its average wavelength and height length (Figure 20).

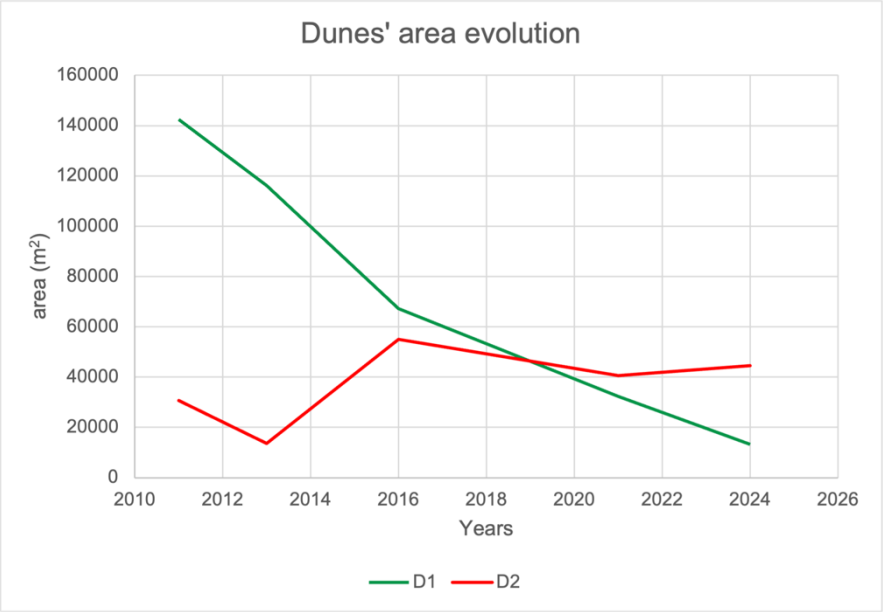


Figure 19.-Graph relative to D1 and D2 area evolution through the survey years.

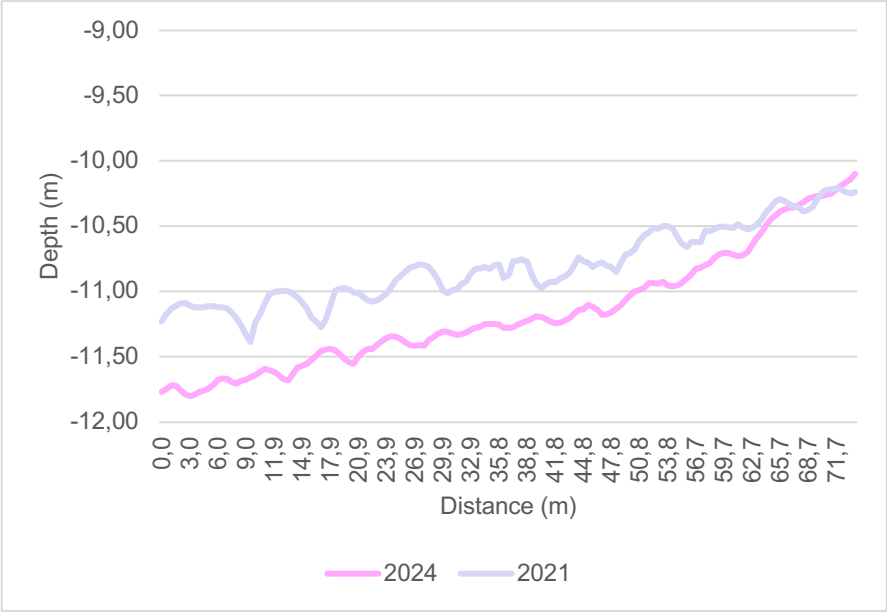


Figure 20.- D1 profile in 2021 and 2024.

Dunes' size and shape are a result of dynamic interactions between sufficient sand supply, water depth, flow velocity, and sediment size grain, which in turn influence their migration rates (Wienberg et al. 2005; Kubicki, 2008). Therefore, dunes' alterations cannot be explained only by a variable, even though it is clear that dunes can and will change their morphology if hydrodynamics and/or sedimentologic conditions change (Wienberg et al. 2005). In fact, the main controlling factor is the local hydrodynamics (Geng et al., 2024). A study conducted in 2021, investigated the effect of the partial closure of the VL during the opening of the MoSE barrier in the Lido inlet (Figure 21) and concluded that the impact of the closure was significant for the lagoon's hydrodynamics (Mel, 2021) affecting also the seafloor sediments.

Out of the two dune fields, D1 was the one with the most visible alterations, especially in the last survey (2024), where the dune seems to be disappearing (Figure 17/18). These changes can be related to the increase of the current velocity in the inlet (Ghezzo et al., 2010), as well as altered hydrodynamic regime in the Lagoon (Finotello et al., 2022) and consequent erosion of the seafloor. Our results confirm those of Toso et al. (2019) who predicted that D1 would slowly disappear.



Figure 21.- Lido inlet location of the MoSE barriers (red rectangles), the breakwater and the navigation channels (Treporti and San Nicolò), as well as the artificial island (blue circle).

3.3.4. Ground-truth

As explained in the material and methods section, 7 collection points were done (see Figure 9), obtaining a total of 21 samples (3 replicates per location). After processing the granulometric data, the sediments were classified according to Folk's Gravel-Sand-Mud ternary diagram (See Annex II, Table 10) (Folk & Ward, 1957).

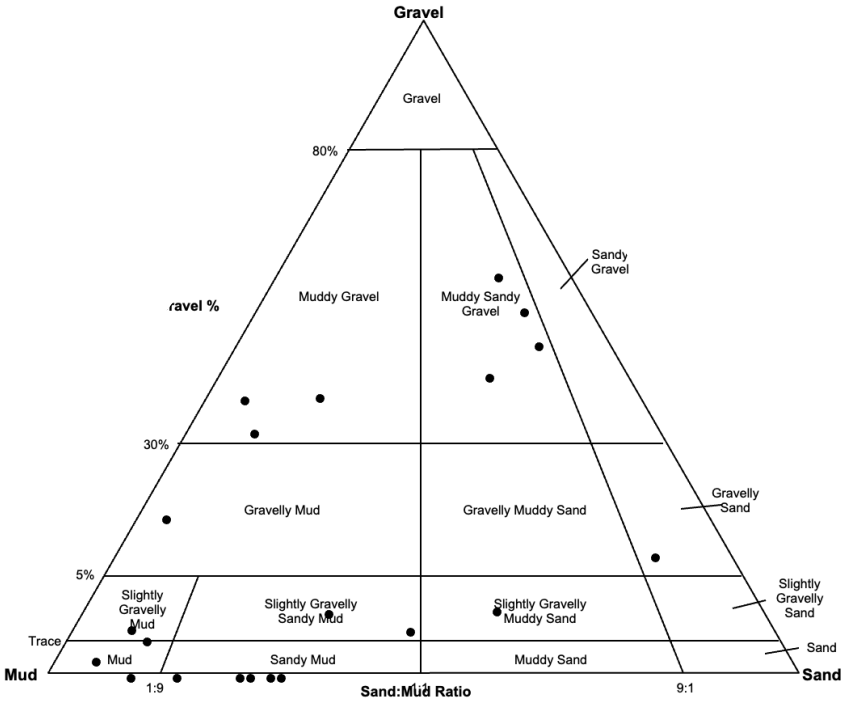


Figure 22.- Folk's Gravel-Sand-Mud ternary diagram for 2024 sediments results.

After analysing the diagram (Figure 22), we see that the distribution of the samples is scattered, but the majority are located on the bottom left side of the diagram, indicating a high mud and sandy mud content. The mean diameter is broad, going from 2 mm to 12 µm. The 21 samples' classification identifies 9 groups:

1. "Gravelly" Mud
2. Sandy Mud
3. Mud
4. Slightly "Gravelly" Mud
5. Slightly "Gravelly" Sandy Mud
6. Muddy "Gravel"
7. Muddy Sandy "Gravel"
8. "Gravelly" sand
9. Slightly "Gravely" Muddy Sand

It must be noted that in this area we do not find gravel. Using the term gravel, we intend here to indicate the presence of shells in the samples. Overall, we can join them into 3 major groups, gravel, sand and mud. As shown in Figure 23, the three scours contain mainly mud (blue), with S2 and S3 having a small percentage of sand (purple) and S1 of gravel (green). As for the dune fields, D1 shows an elevated percentage of gravel (green colour, Figure 23) and D2 of mud and sand (blue and purple, respectively in Figure 23). The deposition site 1 (Dep1), the one near the jetty shows the 3 types of grain-size sediments whereas the deposition site 2 (Dep2) near the breakwater shows more content in mud.

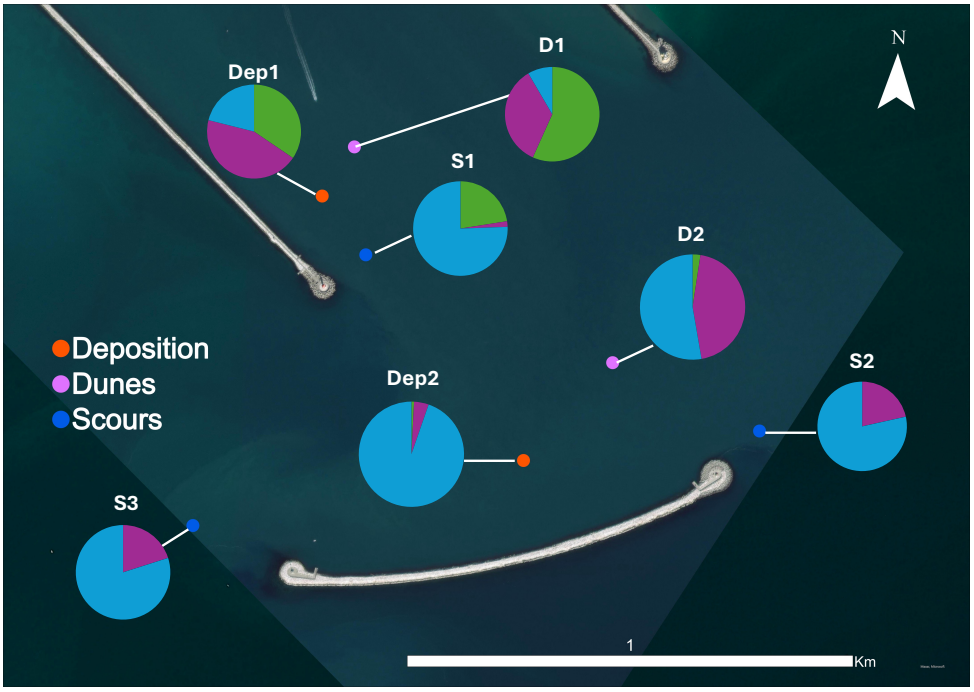


Figure 23.- Sediment samples' results. Each diagram represents the type of sediment presented in each sample by percentage (%). The results were obtained from gradistat where % of gravel, sand and mud are represented by the colours green, purple and blue, respectively.

3.3.5 Backscatter data classification

Backscatter (BS) intensity gives information about signal absorption and scattering properties of the water, as well as water-seabed interface interaction (Huang et al., 2018). Its importance lies in the valuable information obtained from MBES to map seafloor habitats (Hasan et al., 2012).

As explained in the methodology, the BS was classified, according to Jenks' algorithm, into these 3 classes (Figure 24): low, intermediate and high intensity.

In 2024, the lowest values (green) are located in the most inner part of the canal, close to the breakwater, and with a few small areas near the scours. As approaching the MoSE

position in the inlet (Figure 24), the backscatter signal seems to become higher (red). BS intensity is related to sediments dimension: coarse sediments have high backscatter values and finer sediments have low backscatter values (Toso et al., 2019). Therefore, Figure 25 represents the BS results related to the sediments dimension.

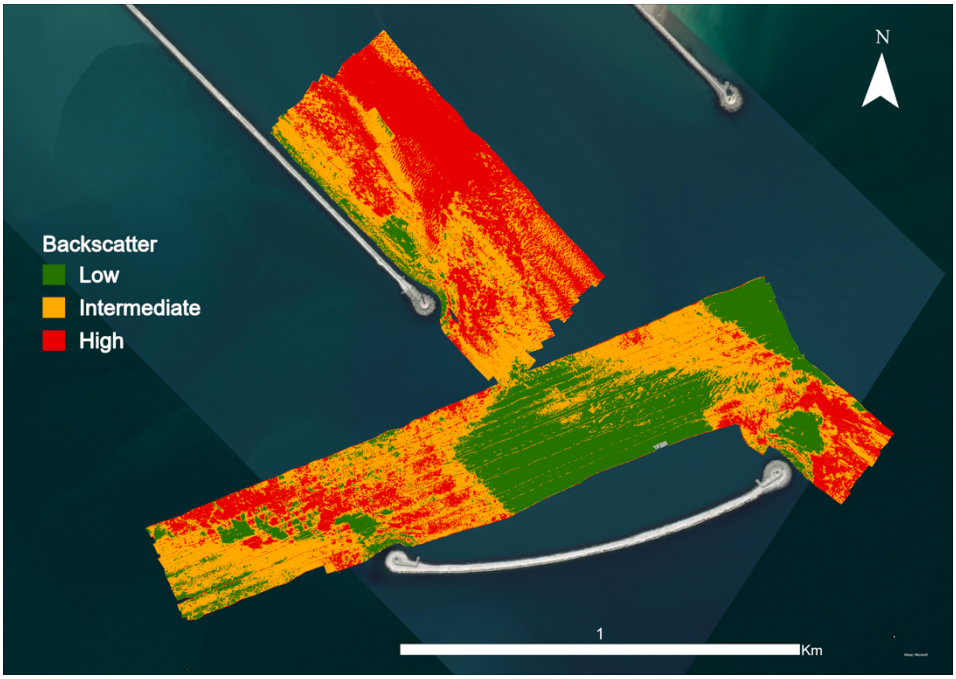


Figure 24.- Backscatter classification for 2024 survey.

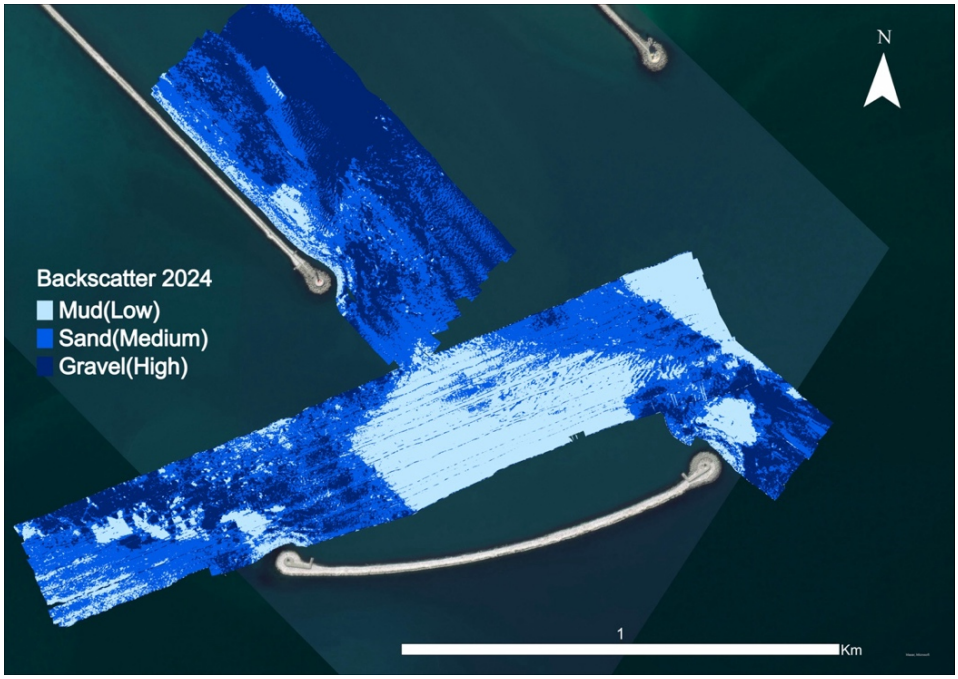


Figure 25.- Backscatter classification associated with sediment grain-size.

The lido inlet was considered to have a depositional regime, before the most recent modifications (Helsby, 2008). After the recent alterations in the inlet (Table 1 and Figure 21), some studies have shown the same trends: alteration of hydrodynamics with loss of sediments and increased current velocities. Ghezzo et al. (2010) showed that the altered configuration of the inlet increased the current velocities with possible transport of sediments outwards the inlet. In another study where it was estimated the sediment transport from acoustic measurements a tendency of the VL to lose sediments was shown, also associated with past morphological changes (Defendi et al., 2010). More recently, Finotello et al. (2022) observed an enhanced net-sediment export and prevented import from the sea, originating also an insufficient sediment supply (Donnici et al., 2017). In another VL inlet to the south (Chioggia), a similar study to the one presented in this thesis detected an increase in the current velocity as well as erosion and deepening of the inlet channel due to processes related to the installation of the MoSE system (Fogarin et al., 2019).

In the recent years (2021-2024), a mainly erosive regime was observed. This regime differs immensely from the previous one, from 2016-2021 (Figure 13) where there is clearly more deposition than erosion. As mentioned before, some studies predicted the prevalence of erosive regime with overall sediment loss, which was also corroborated by this year's backscatter and grain size analyses where we see the prevalence of muddy sediments and reduced content of sandy sediments (Figure 25). In microtidal lagoons, the sediment granulometry occurrence is dominated by coarse particles closer to sea inlets (Zaldívar et al., 2008). Venice as it is characterized as a microtidal lagoon, is composed by fine or very fine sand (Amos et al., 2010). Nonetheless, from the results obtained we see that sand (intermediate/ medium BS) is less prevalent than mud, so we hypothesise that all of the changes above mentioned are enhancing the seaward flux of sand. In the VL Chioggia inlet, the same trend was observed: enriched in muddy sediments and depleted in sandy deposits (L. Janowski et al., 2020).

The fact that the grain size and sediment distribution seem to have suffered alterations, might influence directly other processes since the nature of sediment can have an impact on benthic habitats, microorganisms (Zaldívar et al., 2008) and changes in primary production (Mežine et al., 2019). It is important to highlight that the sedimentation rate can define the lagoon's survival in medium and long term (Donnici et al., 2017). However, since we observed deposition as well in one of the scours more studies focused on sediment transport to and from the inlet are recommended to verify and strengthen the erosive tendency in the future.

These accentuated trends might be related to the beginning of the MoSE system operation (Table 2) since it was predicted that the MoSE system would affect the lagoon's

hydrodynamics, including sediment balance (Madricardo et al., 2017). Even the partial operation of the MoSE was thought to impact significantly hydrodynamics (Mel, 2021). Not only does this infrastructure have an impact on the ecosystem but the existence of risk associated with the infrastructure conservation is likely (Ghezzo et al., 2010).

3.4. Conclusions and Final Remarks

The MoSE barrier system was designed to protect Venice, a city that is prone to flood events against high-water episodes (Ferrarin et al., 2022). According to the present findings, the MoSE operations, so far 84 closures in 4 years, had an impact on the lagoon's sedimentary processes and seafloor morphology, which have contributed to significant changes in the Lido inlet.

The latest IPCC report already predicted an increase in the SLR due to anthropogenic activities, and in the case of Venice, under higher emission scenarios (RCP 8.5) a 58 cm to 110 cm rise is set to happen by 2100 (Zanchettin et al., 2021). As the flood events become more frequent due to CC so will the use of the barriers, and the lagoon may turn into a regulated system, with changed hydrodynamics and morphodynamics (Scarpa et al., 2022), ultimately affecting the primary production of the lagoon (Figure 26) (Mežine et al., 2019). It was predicted that the increase of only 30 cm would result in 100 closers per year (Mel et al., 2021) and the increase of 50 cm would result in 300 and 430 closures (Umgiesser, 2020). Up to a certain point, the increased number of closures may accelerate the trends found on the Lido inlet, namely the prevalence of erosive processes, thus causing negative feedback on the structure, threatening its stability in the future (Madricardo et al., 2017) Simultaneously, the purpose for which it was designed might be lost since the system might not cope with extended closing times (Figure 26). While observing the BS and grain-size results, finer sediments are found in the most southern part of the breakwater and sandy sediments are up north of the breakwater, creating a slower flux in the south where finer sediments are trapped (Dep 2) and more energetic flux to the north. This may change in case the barrier closers increase, since when if the MoSE is active for long periods there is no flux. Therefore, the present erosive regime can be diverted into depositional, affecting the barrier's operations by increasing the need for cleaning operations due to sediment accumulation.

The VL has been under other anthropogenic pressures besides infrastructure construction, such as pollution, overtourism, industrial and agricultural runoff, and water traffic (Basili et al., 2022; Frignani et al., 2005; Gomiero et al., 2013). Logically, the lagoon's sediments have shown high levels of historical contamination, including heavy metals (Zonta et al., 1994) and other compounds such as PCBs and HCBs (Frignani et al., 2005). Moreover, with the intensification of tourists' affluence, faecal pollution increases as well as particle resuspension due to water traffic (Basili et al., 2022). Naturally, dredging activities and/or

changes in seabed disturb the contaminated sediments, possibly leading to their resuspension and impacts on aquatic food chains (Pizzini et al., 2021). In fact, it is predicted that with the increased operation of the barriers, the oxygen levels would be rapidly depleted, macro and microorganisms would be harmed, and organisms' life cycles would be altered (Baldassarre et al., 2023), as well as an increase in toxic substance build-up due to reduced flushing of the lagoon (Mel, 2021). All these cumulatively result in ecosystem damage (Figure 26).

However, so far, the MoSE has proven to be effective in protecting a UNESCO cultural site from high tides and preventing it from being flooded for several hours. Thus, it has been delaying greater flood impacts on its inhabitants and ecosystem. It is safe to say that, after four years of running, surely it has prevented the city's partial submersion multiple times.

In this sense, the MoSE barrier system has been able to fulfil its main goal, though taking into consideration, the complex net of chain reaction events that this solution has shown or might show, it is of paramount importance to study more profoundly these effects by investing in future monitoring studies. Not only to verify the trends we have observed in this thesis but also to better understand and connect these events and their impacts on the Lagoon and the city of Venice.

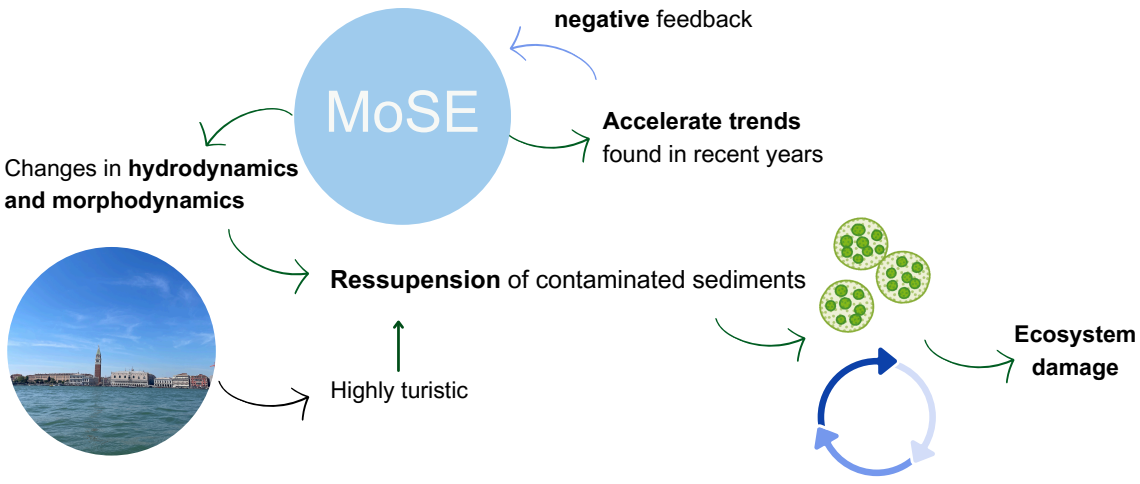


Figure 26.- MoSE expected chain reaction of events following the present trends. Source: The author.

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Chapter IV - Stakeholders Perception Analysis

Chapter Resume

Due to climate change, many coastal areas are affected by floods due to rising sea levels. Portugal (PT) and Italy (IT) are part of the Mediterranean region which is extremely exposed to its impacts. Due to SLR complexity, efforts have been made to develop effective solutions to tackle it, especially at the local scale. To implement proper policies, increasing climate change warmness and effectively exchanging information with all of society is pivotal. This Chapter aims to analyse the community's perception and knowledge about climate change and its consequences, as well as the global implementation of solutions and the shared responsibility of key societal sectors. The study focused on communities in the Venice region (IT), where technology is already in use, and in the Porto Metropolitan Area (PT), where the population openness to future technological solutions was examined. In addition, participants' opinions on good communication between decision-makers, the scientific community and the public are also probed. The results, even though not representative of both populations, found that 81% of PT and 72% of IT participants relate SLR with climate change. Regarding solution knowledge in PT was 41% positive, and in IT, 43% did not know about MoSE existence. The great majority of participants (63%) in IT, did not know if the barrier was helping the city nor if the investment was justifiable (60%). According to 86% of the participants in IT, the decision-making process failed to include them. In PT, 84% showed interest in learning about possible solutions, agreeing with solution implementation and investment, 73% and 78% respectively. Nonetheless, 48% believe they might not be implemented promptly. For both questionaries, communication between decision-makers, the scientific community and the public was not positive. In the end, we concluded that the exchange of knowledge needs to be improved as well as channels of communication between all social sectors involved and affected by the process of solution-making. The successful accomplishment will not only help with solution implementation but also increase people's awareness of the problem by involving them in a decision that will affect them and their future generations.

4.1. Introduction

Many coastal cities have increasingly suffered from floods due to CC. According to the IPCC, the Mediterranean region is particularly vulnerable to its impacts, including coastal flooding. In fact, the sea level is projected to rise during the coming decades and so are the number of people exposed to it (IPCC, 2023). Portugal (PT) and Italy (IT) are part of the Mediterranean region, so naturally are affected by SLR.

The Portuguese coast has been suffering from increased coastal flooding in several locations in recent decades (Carneiro-Barros et al., 2023). It is highly diversified with coastal

systems, including lagoons and also characterized by heavily human settling with strategic economic importance (Ribeiro et al., 2021; Tavares et al., 2021). The coastal zone is extremely exposed with emphasis on coastal erosion (Tavares et al., 2021), in fact, around 67% of the coastline is at risk (Taveira-Pint et al., 2022). Hence, there is a need to strengthen coastal defences (Schernewski et al., 2011).

The northern part of Portugal, where the Porto Metropolitan Area (PMA) is located, is most favourable to flood events due to its precipitation susceptibility. The PMA is a highly dense population area (Santos et al., 2018) that has been exposed to floods for several centuries, especially in the city centre, near the Douro River (Alcoforado et al., 2021). In fact, Santos et al. (2018) showed that the number of flood occurrences was higher on the riverside in contrast to peripheral areas, mainly due to a higher population density and urbanization, characterizing PMA with high exposure to flood risk. Another example is the Aveiro Lagoon, which due to its location, is prone to floods under the present climate conditions, posing a great impact in Aveiro Port (Ribeiro et al., 2021). These are examples of Portuguese coastal systems greatly threatened by the increasing risk of floods and thus more vulnerable to rising sea levels.

The Italian coast flood-prone risk has been greatly documented (Perini et al., 2016; Calabrò et al., 2019; Viero et al., 2019; Barbaro et al., 2020; Unguendoli et al., 2023). The northern part of Italy is considered to be one of the most flood-prone regions in Europe (Viero et al., 2019), including the historical city of Venice and its lagoon (Alberti et al., 2023).

Naturally, CC has become a complex topic that involves ecological, environmental, political and socio-economic matters (Abbass et al., 2022). Given the widespread impacts forecasted to occur by the end of the century, several efforts were made to mobilize the public and policymakers to support CC mitigation and adapt policies (Masri et al., 2020). Adaptation of strategies to a local scale is extremely important, so it can be easier to prepare for adverse effects in the projected areas and facilitate local communities and decision-makers' engagement (Ramalho et al., 2022).

The perception of CC serves as a foundation to make policies for CC issues, since only by being aware of their existence will integration into policies, projects, plans and daily activities be possible (Yu et al., 2013). Therefore, it is of the utmost urgency to understand the public's awareness and knowledge regarding this issue. To resist climate change, we need political action and in turn, political action requires public support (Holub & Schü ndeln, 2023), even more of a reason to involve the common citizens.

Therefore, this Chapter aims to provide some insight into people's perception of the climate change problem and, more specifically of the sea-level rise in PT and IT since both countries are affected by it. It was also intended to understand participants' opinions regarding the

possible application of public funds in solutions. Ultimately, a poll regarding the interface science-decision makers-community was also conducted. Ergo, two versions were done, one in English and one in Portuguese. The English version was done in Italy (Venice) and contained a section regarding the solution previously studied, the MoSE (Modulo Sperimentale Elettromeccanico) barrier system.

4.2. Methods

The questionnaires were prepared using Microsoft Forms, in Portuguese and in English and were conducted from April 2024 to August 2024. Participation was voluntary, with no compensation and done anonymously. It followed the GDPR guidelines (https://europa.eu/youreurope/citizens/consumers/internet-telecoms/data-protection-online-privacy/index_en.htm) in Portuguese RGPD (https://europa.eu/youreurope/business/dealing-with-customers/data-protection/data-protection-gdpr/index_pt.htm).

After a brief explanation as to why this questionnaire was being developed, the first section contained questions regarding, age, sex, level of education and area of residency (in Portugal's case was divided into two options, coastal and inland). The second section consisted of several questions regarding CC knowledge. The third section was regarding people's belief in CC consequences. The fourth section contained questions about possible solutions implementation but also questions concerning the parties involved in solution making and effectiveness in their execution. For the survey done in Venice, Italy a fifth section regarding the MoSE was added to better understand the public's perception (Annex IV, Table 11).

Statistical analysis: Survey data was analysed using IBM SPSS Statistics (Version 29) software to perform statistical tests, including comparing means, regression and crosstabs procedures.

4.3. Results

During the survey period, we obtained 301 answers, 222 for the Portuguese version and 79 for the English version conducted in IT. The study population for the PT version included 64% female participants and 36% male. For the IT version, 53% were female and 47% male.

4.3.1. Stakeholders' perception in Venice Region (IT)

100% of the inquiries believe in climate change and consider it a concern. The attribution of the biggest driver of CC lay with mainly anthropogenic causes (75%) (Figure 27), but some believed it to be both natural and anthropogenic (24%). Regarding the most relevant consequence, 37% answered GST rise and 22% SLR. Some participants believed they had

sometimes experienced CC-related events (62%) and 38% said many times, mainly related to extremely high temperatures (35%). 72% believe that climate change/global warming is associated with SLR (Figure 28), and some participants did not know about solutions implemented globally (56%) whilst 44% did know. All the participants affirmatively said that these solutions were a good application of the public's funds.

Moving to the sections regarding the MoSE barriers system (Figure 29), the knowledge about its existence was split between knowing about it (43%) and not knowing (44%). The majority said they did not know if the MoSE was helping the city with floods (63%), and only 35% of the participants answered affirmatively. The same trend was observed in the questions regarding the justification of the public fund investment in the project where 60% answered they did not know if it was justifiable, and 37% said it was. Regarding inclusivity, almost all participants said they were not included in the process of decision-making (96%). Moving to actual implementations, 80% stated that policymakers, citizens, the industrial sector and scientific researchers should all be part of it. Good communication between the scientific community and decision-makers and the rest of the citizens was not positive overall, 37% and 94%, respectively (Figure 30). The participant's gender, academic degree and age didn't have a significant effect on the community perceptions, nor on the knowledge about MoSE existence ($p>0.05$).

4.3.2. Stakeholders' perception in Porto Metropolitan Area (PT)

The majority of participants believed in CC (99%), and it was part of their concerns list (97%). Additionally, most participants attributed CC to both natural and anthropogenic causes (54%) whilst only 43% attributed to only anthropogenic causes (Figure 27). Of all the consequences of CC, 77% considered the rise of GST the most important one.

59% of the participants thought they have experienced at some point one or more events related to CC and 6% many times, meaning that 65% of the people who answered believe they have experienced a GW-related event. As to what events they have experienced, heat waves and loss of seasons were the most answered, 35% and 30%, respectively. In relation to the SLR problem, 81% of the participants believe it is related to climate change/global warming (Figure 28).

Moving to the last section of the PT questionnaire regarding the possible solution and their implementations, 42% of the participants stated they did not know about solutions for SLR worldwide, but 41% stated they did know. Only a small percentage answered there weren't any (5%). When asked about investigation for possible solution implementation in Portugal (Figure 31), 73% of the participants agreed, they also agreed that it would be a good investment of the public funds (78%). Most participants (84%) showed interest in learning about possible solutions and wanted to be involved (Figure 31).

Regarding actual implementation, 86% considered that the scientific community, decision-makers, the industry and the public should all be involved in the decision-making processes. The perception of good interaction between the scientific community and decision-makers and with the rest of the citizens was not positive, 77% and 64%, respectively (Figure 30). Nonetheless, there was a silver lining where 48% of the participants might believe that if proven beneficial for all, the solutions would be implemented on time. Still, a significant percentage (32%) do not believe it will happen. Age, academic degree and gender didn't have a significant effect on the above answers ($p>0.05$).

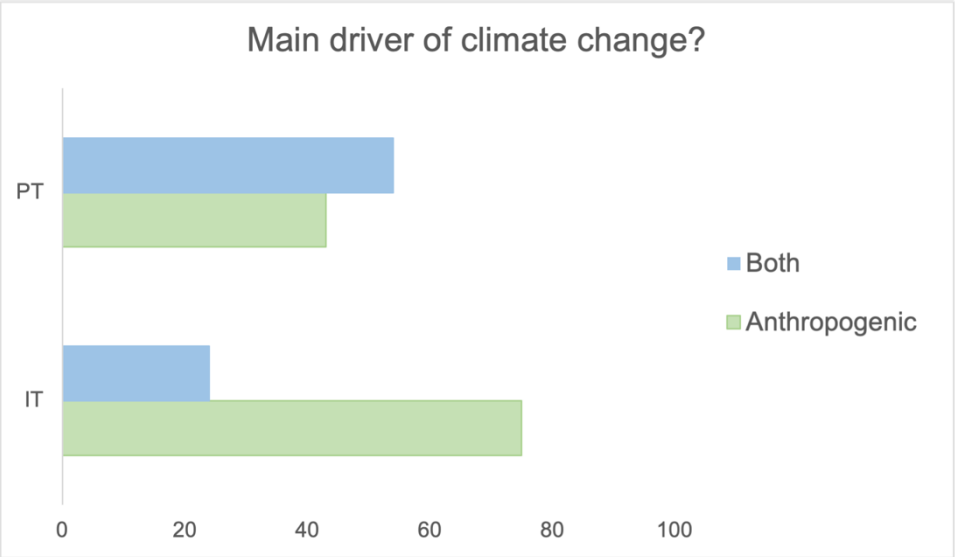


Figure 28.- Main climate change drivers answers for Portugal and Venice, Italy (in percentage).

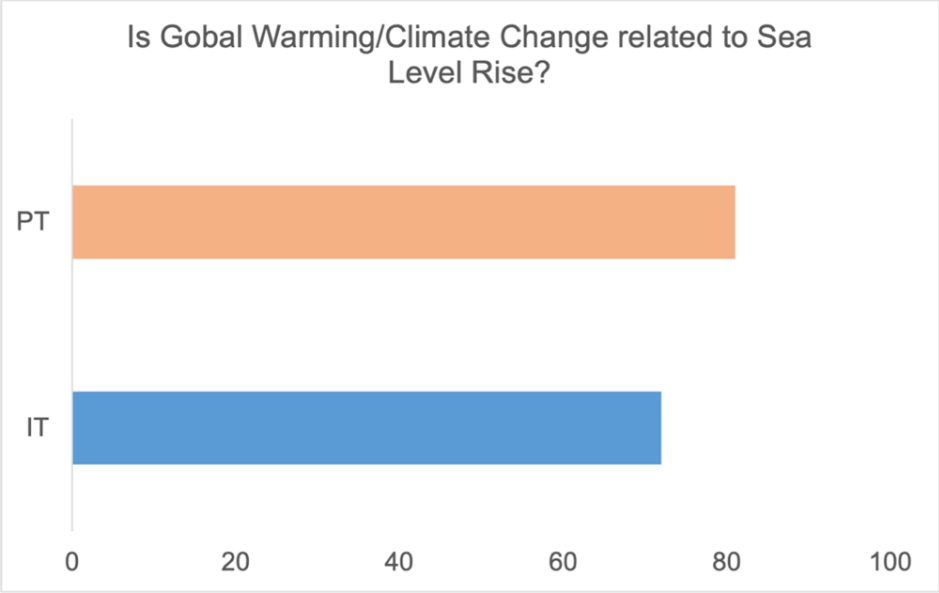


Figure 27.- Positive relation graph between sea level rise and climate change for both questionnaires (in percentage).

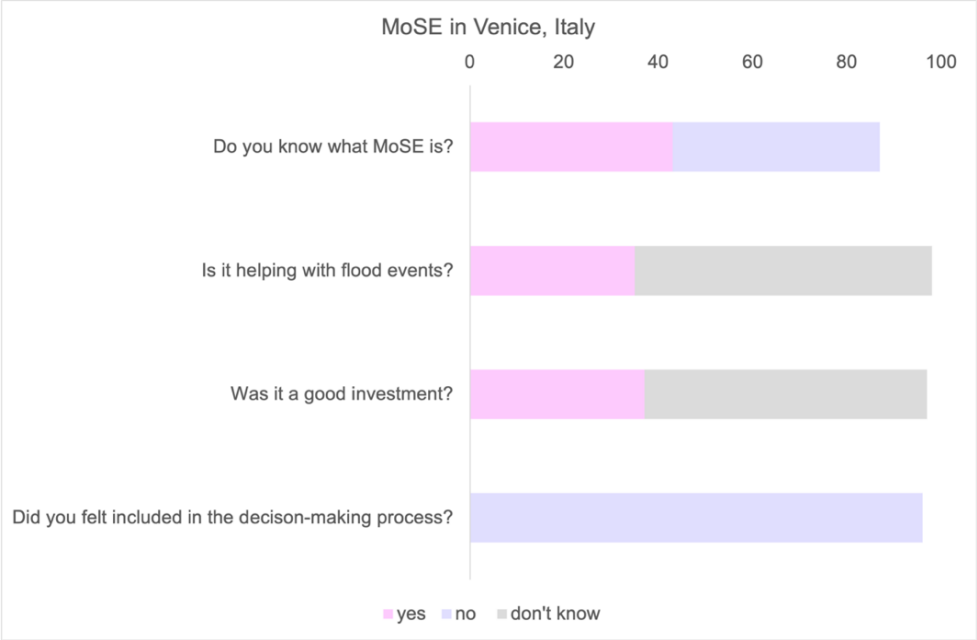


Figure 29.- MoSE comprised information regarding its knowledge, effectiveness, investment and decision-making process (in percentage).

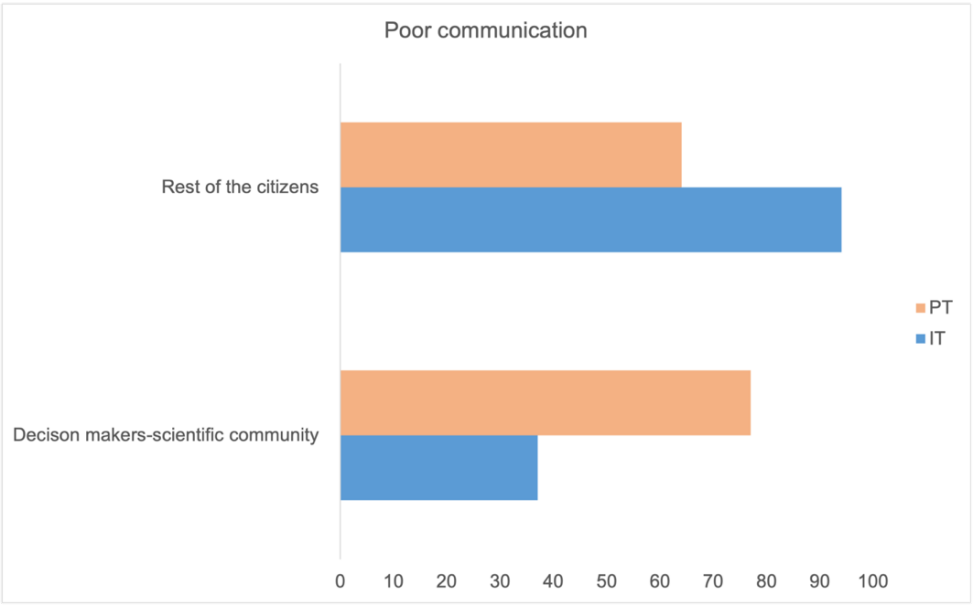


Figure 30.- Poor communication between decision-makers, scientific community and public in Portugal and Venice, Italy (in percentage).

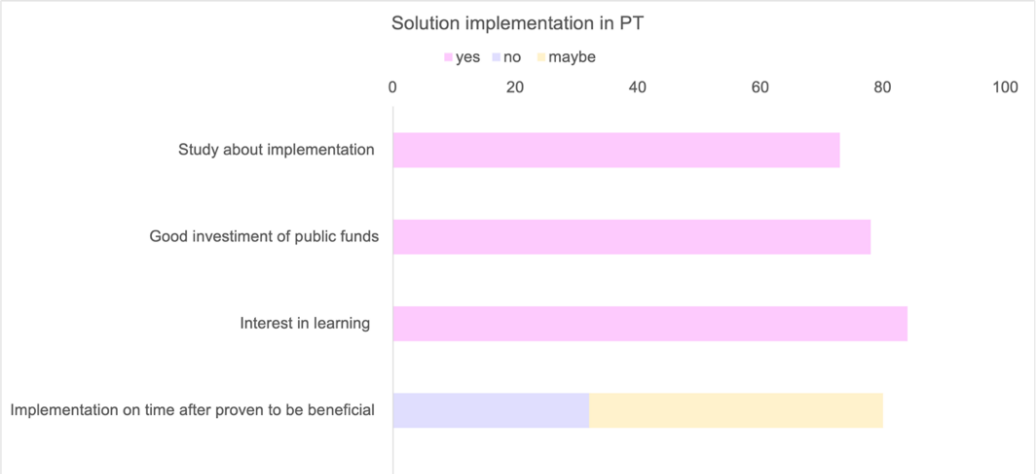


Figure 31.- Solution implementation in Portugal (in percentage).

4.4. Discussion and Final remarks

The IPCC's latest report has associated the galloping rise of the sea level with anthropogenic activities (IPCC, 2023). However, we observed that in PT the main driver for CC was associated with natural and anthropogenic causes whilst in IT, it was mainly attributed to anthropogenic causes. This may be related to the fact that Venice, as previously mentioned, has been suffering from several anthropogenic pressures that have altered the ecosystem into a man-made one, and events of high water (*Acqua Alta*). Although the majority of the participants in PT were from the coast, the effects felt may not be as intense as in a closed system like Venice, so that can bias people's answers. Another reason might be linked to the personal experience with climatic changes. Since only climate change's consequences can be experienced directly, people's perception of detecting some instead of others, such as SLR, influences their experience. Some studies have documented this relationship (Whitmarsh, 2008; Weber, 2010; Akerlof et al., 2013; Borick & Rabe, 2017; Lujala & Lein, 2020). In both surveys, negative feedback regarding communication with the public was observed which strengthens the need to improve information access and solutions engaging in decision-making processes. Especially in Venice, where the percentage of people who knew about MoSE was relatively low. More so, considering that this solution has been discussed for some time. The fact that in the Portuguese survey, the great majority showed interest in learning more about possible solutions, also contributes to the idea of public engagement improvement. Additionally, related to decision-making processes, both questionnaires showed an agreement in involving all social sectors (from decision-makers to the public) in discussing and implementing possible solutions processes, which enhances the need for better exchange of information. The results of these questionnaires do not represent the Portuguese population or the Venetian. The limitation of this section also lies with the low response number. Nonetheless, these questionnaires allowed us to verify three key points: (i) people are concerned about climate change and relate it to rising of sea level; (ii) the public knowledge in Venice about the MoSE was low and due to that the perception regarding its effectiveness on flood events protection and the justification of public funds application is not beyond doubt; (iii) In Portugal, the approval of fund application in solutions is positive, and even though people consider that there is poor communication, especially between the scientific community and decision-makers, they have shown hopefulness about possible solution implementation. So, in future adaptation plans for climate change, communication among technical experts, decision-makers and the public is key to adopt new policies and/or reforming existing ones. More so, there is a need to increase the public engagement in the decision-making processes not only to help expedite solution implementation but also to

increase people's sense of belonging through reflection and evaluation of their and future generations long-term welfare. The unsuccessful collective communication might become a barrier for improvement and adjustment to current rampant trends.

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Thesis Final Remarks and Recommendations

Climate change is an interdisciplinary subject with severe ecological, social and economic repercussions. The last IPCC report highlights that anthropogenic activities are exacerbating and accelerating global warming, resulting in the rise of the sea level and increased risk of floods, mainly in coastal ecosystems such as lagoons. Solutions to tackle the problem and allow cities to adapt to current and future trends are imperative. The MoSE has helped retain the period of floods, fulfilling its original purpose but has altered the lagoon's dynamics and morphology. The implementation of these technologies requires a continuous investment in scientific and technological monitoring. In this sense, the present Thesis and other mentioned studies provide valuable contributions.

Moreover, as the MoSE has shown to pose slight impacts on other lagoon processes such as food chain interactions and water contamination, it is of utmost importance the parallel research involving ecology and ecotoxicology expertise, to provide information on possible short- and long-term impacts for the ecosystem, due to the predictable operation frequency increase. As with any other adaptative or mitigation measure, benefits and disadvantages are likely to exist. Nevertheless, if the benefits are overcompensating, the focus should lie on existing technology optimization. This way, it is possible to improve an already-in-place solution and maybe adapt it to other affected areas. The effectiveness of adaptative measures will increase if integrative solutions address ecosystem risks as well as social issues.

This Thesis results also highlight the importance of co-designing these technological solutions to tackle sea-level rise, by increasing multidisciplinary teams to develop efficient but sustainable nature-adapted solutions without increased risk of further ecosystem disruption. In the future when addressing adaptative measures and design of solutions NbS should be taken into consideration options since they are more suitable for each ecosystem and can provide protection as well as additional benefits to the livelihoods of the populations.

Moreover, adaptative measures need to involve all social sectors, especially local communities that are directly affected by such initiatives. The engagement of the citizens in decision-making processes is crucial for public policy success. As such, the improvement of knowledge exchange and transmission between the scientific community, decision-makers and the public is essential to create a more informed and involved society that wants to participate in solution implementation. Only by understanding how solutions work and what they will affect, can people understand and support the investment needed.

Hereafter, what is expected is better collaboration and realization of the unpredicted and unprecedented changes we face. Based on this thesis's main findings, Table 9 lists some

recommendations to improve existing technology by studying broadly its arising issues. Not only to improve but to adapt it to other possible locations which thus echo the urge to deal with sea-level rise and climate change as an interdisciplinary matter. Therefore, involving all parties responsible and capable of generating knowledge, solutions and science to improve decision-making.

The window to act is becoming narrower so only by working effectively and cooperatively together will we get the chance to reverse our actions. Only by reducing the pressures we instigated on the ecosystem and effectively tackling the outcomes, will we ensure our future coexistence with the planet.

Table 9.- List of recommendations arising from major conclusions of this work.

Recommendations	***Description***
Seafloor morphology mapping and acoustical surveys	Verify and validate current trends found in Chapter III, with the goal of implementing adaptative measures if needed.
Ecological and ecotoxicological parallel studies	Improve knowledge and identify impacts on the lagoon's ecosystem to help develop new expertise approaches to solve the issue.
MoSE optimization	Develop new tools and expertise to try and adapt the MoSE operations to minimize its impact on the lagoon while protecting the city from floods
Community involvement	Enhance or implement better communication practises to allow all the community to be involved in decision-making processes
Strength interface scientific community-decision-makers-public	Implement effective and conscious ways to share information based on good governance principles that will benefit us and ultimately the ecosystems

Thesis Annex

Annex I

Protocol for sediment analysis

Once thawed (2 days at 20°C) the sediment samples are analysed in the laboratory using a multi-step procedure.

Before starting the analysis, all samples are transferred to glass flasks, previously labelled with site location and replicate number.

1.Washing

The collected samples contained a high amount of salty/brackish water. So, it was necessary to eliminate the salt to prevent material aggregations. The sediments are placed carefully in a glass flask and then immersed in pure MilliQ water for approximately 24 hours (Figure 1). After that time, it is expected a clear water (Figure 2). Before immersing the sediments in water, they are weighted. The process is repeated twice until the salt is completely removed. The water is removed with a pipette.



Figure 1.-Example of a sediment sample immersed in MilliQ water in the beginning of the washing process.

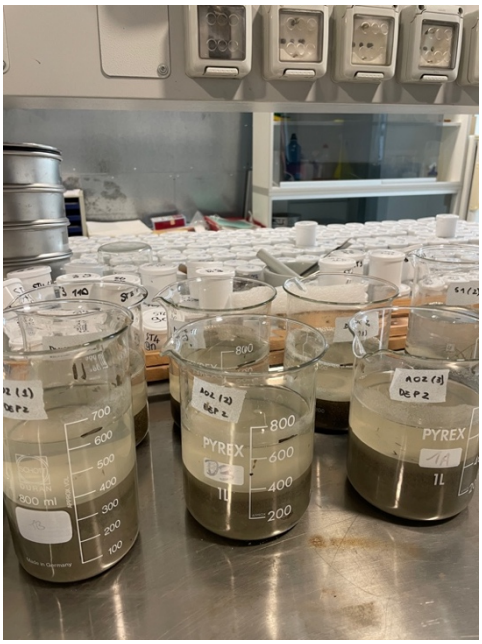


Figure 2.- Example of a sediment sample immersed in MilliQ water after 24 hours.

After washing, each sample is divided into two aluminium containers based on their size: >1 mm and <1 mm (Figure 3). To perform this separation, each sample is placed in a 1 mm sieve that has a bottom tray underneath (to collect the <1mm sediments) (see Figure 4). Then, other sieves are stacked on top of each other (see Figure 5) so that we can place the samples in a mechanical shaker called “vibroscreen” (see Figure 6) for 10 minutes. In the

end, the samples are transferred to their respective container and weighted. There was a total of 42 trays (2 trays per replicate).



Figure 3.-Sample divided into two sizes <1 mm and >1 mm.



Figure 4.- Sample being placed in the 1mm sieve.



Figure 5.- Stacked sieves.



Figure 6.- Stacked sieves in the vibroscreen.

3.Drying

The samples are then dried in an oven at 60° C for 24 hours (or until complete water evaporation). This indication is given by colour change taken on by the Silica Gel; a silicon dioxide polymer that is exploited for its dehydrating and absorbent properties (see Figures 7 and 8).



Figure 7.- Samples inside the oven at 60°C.



Figure 8.- Silica gel colour once the samples were dried.

3.Homogenization

Once the drying process is complete, the samples below 1 mm are delicately handled in a mortar and pestle to remove aggregates. This step is performed on the entire sample, paying particular attention to the coarser fraction (avoiding shattering bivalve caps and shells. Through this operation, all the aggregates that may be present in the fine component are broken down. This step is crucial to avoid errors in the interpretation of the granulometric analysis.

4. Second Sieving

The final step makes use of the same sieves used in step 2, but they are arranged in series, each retaining the fraction of sediment with dimensions smaller than the former. The sieves are stacked in decreasing order concerning the mesh width: 31,50 mm, 16 mm, 8 mm, 4 mm, 2 mm, 1 mm and bottom (<1 mm) (see Figure 9 and 10).

The sample is placed inside the upper sieve and then on the mechanical shaker, for 5-8 minutes.

Afterwards, each fraction is weighted and compared to the total sample (dry weight) to obtain the material weight percentage for each sieve.



Figure 9.- Sediments retained in the bottom tray (< 1 mm).



Figure 10.- Shells and bivalve caps retained in the 16 mm sieve.

5. Optical analysis

All sediments with grain sizes smaller than 1 mm, are weighed and used for optical analysis using the LISST-100X Type-C (Laser In-Situ Scattering and Transmissometry). This instrument is capable of measuring the average diameter of solid particles in different classes (range of 1.9-322 µm). This type of measurement is part of the optical particle size analysis techniques based on the measurement of the diffraction patterns generated by the interaction of the sample particles with the laser beam. The scattered light is captured by a 32-ring detector, where each ring measures the scattering intensity of the laser beam. The instrument carries out a large number of measurement sequences, to obtain a series of statistically relevant values. To mathematically convert the obtained particles´ concentration in scattering intensities, software provided by the manufacturers is used (LISST-SOP version 5.1.6).

Firstly, white calibration with distilled water is done. For each sample, a few µg of sediment are added to a beaker containing 100-150 ml of Milli-Q water. Then, it is submitted to an ultrasound bath for 2-3 minutes, to facilitate the granules' separation.

Finally, the solution is poured into a special cell for laser reading (Figure 11). The program was set to Random Shape as it assumes that the particles can have different shapes. Approximately 30 measurements are done for each analysis, to have a series of data to

obtain the mean. Between every new reading, the cell is emptied and cleaned with Milli-Q water.

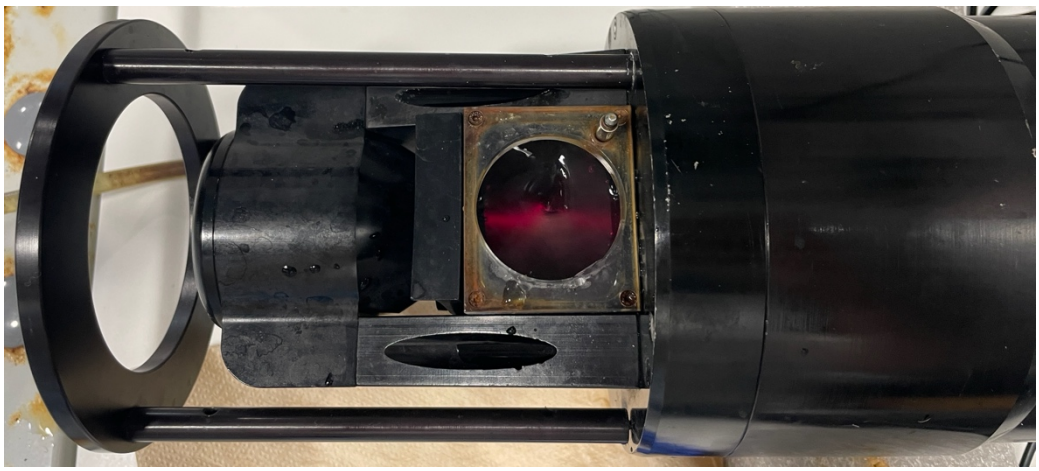


Figure 11.-LISST laser (red light) analysis a sample.

Annex II

Table 10.- Gradistat sediment samples results.

		Sample type	Textural group	Mean (μm)	Sorting (μm)	Mode 1 (μm)	Mode 2 (μm)	Mode 3 (μm)	D_{50} (μm)	% gravel	% sand	% mud
S1	2	Bimodal, Extremely Poorly Sorted	Muddy Gravel	99,28	16,74	12,85	6000,0		15,93	33,3%	5,3%	61,4%
	3	Bimodal, Extremely Poorly Sorted	Muddy Gravel	140,4	20,15	12000,0	12,85		27,31	39,0%	2,5%	58,5%
	4	Unimodal, Very Poorly Sorted	Gravelly Mud	64,90	13,98	12,85			12,55	17,1%	1,6%	81,3%
S2	1	Bimodal, Very Poorly Sorted	Sandy Mud	25,84	5,140	5,600	297,5		12,35	0,0%	22,4%	77,6%
	2	Bimodal, Very Poorly Sorted	Sandy Mud	28,99	4,782	297,5	9,200		14,22	0,0%	27,1%	72,9%
	3	Bimodal, Poorly Sorted	Sandy Mud	14,07	2,666	10,88	297,5		12,24	0,0%	11,0%	89,0%
S3	1	Bimodal, Poorly Sorted	Sandy Mud	26,16	3,995	12,85	297,5		15,52	0,0%	20,7%	79,3%
	2	Bimodal, Very Poorly Sorted	Sandy Mud	29,99	4,359	12,85	252,5		17,17	0,0%	25,5%	74,5%
	3	Unimodal, Poorly Sorted	Mud	16,44	2,228	15,15			15,85	0,0%	6,4%	93,6%

		Sample type	Textural group	Mean (μm)	Sorting (μm)	Mode 1 (μm)	Mode 2 (μm)	Mode 3 (μm)	D_{50} (μm)	% gravel	% sand	% mud
D1	1	Bimodal, Very Poorly Sorted	Muddy Sandy Gravel	2642,9	4,512	1500,0	23750,0		2237,0	54,2%	38,2%	7,7%
	2	Unimodal, Very Poorly Sorted	Muddy Sandy Gravel	2928,3	4,474	1500,0			2619,7	60,2%	30,9%	8,9%

	3	Bimodal, Very Poorly Sorted	Muddy Sandy Gravel	1643,9	5,767	1500,0	297,5		1920,3	48,3%	43,6%	8,1%
D2	1	Trimodal, Very Poorly Sorted	Slightly Gravelly Muddy Sand	85,98	5,245	252,5	15,15	1500,0	157,4	2,9%	59,6%	37,5%
	2	Trimodal, Very Poorly Sorted	Slightly Gravelly Sandy Mud	38,63	5,475	12,85	110,0	1500,0	29,45	2,8%	31,7%	65,5%
	3	Polymodal, Very Poorly Sorted	Slightly Gravelly Sandy Mud	48,68	5,067	214,0	153,5	15,15	52,08	1,5%	45,9%	52,6%
Dep1	1	Trimodal, Very Poorly Sorted	Muddy Sandy Gravel	628,4	13,64	252,5	12000,0	15,15	349,2	43,0%	38,2%	18,8%
	2	Unimodal, Poorly Sorted	Gravelly Sand	287,0	3,550	252,5			247,0	9,7%	82,6%	7,7%
	3	Bimodal, Extremely Poorly Sorted	Muddy Gravel	211,2	20,20	12000,0	15,15		75,31	39,5%	12,0%	48,5%
Dep2	1	Unimodal, Poorly Sorted	Slightly Gravelly Mud	16,10	2,254	12,85			14,87	1,6%	4,3%	94,1%
	2	Bimodal, Poorly Sorted	Slightly Gravelly Mud	16,55	2,320	10,88	29,35		15,05	0,8%	6,3%	92,9%
	3	Unimodal, Moderately Sorted	Slightly Gravelly Mud	13,00	1,996	10,88			12,11	0,3%	2,6%	97,2%

Annex III



Figure 32.- CNR LITUS motorboat and Grab support.



Figure 33.- Van Veen Grab.



Figure 34.- Antenna (Trimble GA830) and rimble SPSS855 GNSS modular receiver, respectively.



Figure 35.- Sample collection.

Annex IV

Table 11.-Sections and questions performed in both questionaries, Portuguese and English.

2nd Section- Climate Change Concepts
Acredita na existência das alterações climáticas/Do you believe in the existence of climate change? Sim/Yes Não/No Não sei/ Don´t know
As alterações climáticas são uma preocupação para si/ Does climate change concerns you? Sim/Yes Não/No Não sei/ Don´t know
Na sua opinião, qual o maior impulsionador das alterações climáticas/In your opinion what is the biggest driver of climate change? Causas naturais/ Natural causes Causas antropogénicas/Anthropogenic causes Ambas/Both
Destas opções, qual considera ser a mais importante quando se fala de alterações climáticas/ Among the different climate change effects, which one do you consider to be the most relevant? Subida da temperatura média global(aquecimento global)/GST rise Subida do nível dos oceanos/SLR Subida da temperatura nos oceanos/ocean warming Eventos climáticos extremos/weather and climate extreme events
Considera que já tenha experienciado algum evento/s relacionados com aquecimento global/ Have you ever experienced any event/s related to global warming? Sim, muitas vezes /Yes, a lot of times Sim, algumas vez /Yes,sometimes Não, nunca /No Não tenho a certeza/ Don´t know
Se respondeu sim na pergunta 9, indique qual destas alterações experienciou/ Perda das estações do ano Cheias Secas
3rd Section- Consequences of Climate Change

Acredita que as alterações climáticas, nomeadamente o aquecimento global, podem estar relacionadas com fenómenos, como a subida do nível da água do mar/Do you believe that climate change, namely global warming, may be related to the average rise in sea levels? Sim/Yes Não/No Talvez/Maybe Não sei/ Don´t know
Quais as consequências para o meio ambiente/What are the consequences for the ecosystems? Perda de biodiversidade/Biodiversity loss Desaparecimento de habitats/habitats loss Bio invasões/Bio invasions Desertificação/Desertification Extinções/Extinctions Alterações do padrão de vida das espécies/altered species patterns Todas acima mencionadas/all of the above Nenhuma/None
Quais as consequências para o ser humano/What are the consequences for the human being? Migrações climáticas/climate migrations Perda de bens culturais/Cultural losses Perda de qualidade de vida/Loss of life quality Doenças transmitidas por vetores/vesctor-borne diseases(e.g. Malaria) Destruição de cidades/Infrastructure damages Todas acima mencionadas/all of the above Nenhuma das acima mencionada/none
4th Section-Possible Solutions
Relativamente à subida do nível da água do mar, conhece alguma das soluções implementas globalmente/ Regarding sea level rise, do you know any of the solutions implemented globally? Sim conheço/Yes Não conheço/ No Não sei/ Don't know Não acho que existam/ I don´t think there are any

Considerando as soluções que são implementadas noutros países, pensa que alguma poderia ser implementada em Portugal?(PT version only) Sim Não Talvez Não sei
Considera a implementação destas soluções numa boa aplicação dos fundos públicos/Do you consider that these solutions are a good application of public funds? Sim/Yes Não/No Talvez/maybe Não sei/don´t know
Gostaria de saber mais sobre possíveis soluções e como funcionam? (PT version only) Sim Não Talvez
Na sua opinião, que setores sociais deveriam estar envolvidos na implementação de possíveis soluções/ Which social sectors should be involved in possible solutions impletatation? Decisores políticos/Policy makers Cidadãos/Public Sector industrial/Industrial sector Investigadores/Researchers Todos acima mencionados/All of the above
Na sua opinião, acha que há uma boa interação entre a comunidade científica e os decisores políticos/ In your opinion, is there a good communication between the scientific community and policy makers? Sim/Yes Não/No Não sei/don´t know
E com os restantes cidadãos/ And with the common citizen? Sim/Yes Não/No Não sei/don´t know

How would you like to be involved in the implementation of adaptation measures and possible solutions? (ENG version only) Questionnaires Council meetings Participatory seminars and briefing sessions I wouldn´t like to be involved
Acredita que os decisores políticos, caso se prove que as soluções beneficiem todos, iriam implementá-las a tempo? (PT version only) Sim Não Talvez Não sei
5th MoSE in Venice, Italy
Do you know what MoSE is? Yes No Don´t know
Do you think it has been helping Venice regarding the floods problematic? Yes No Don´t know
In your opinion, was MoSE a good application of public ´s funds? Yes No Don´t know
Did you felt included in the decision-making process? Yes No Don´t know