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REPORT ON THE ADDED VALUE OF GEOLOGY FOR COASTAL VULNERABILITY AND CLIMATE CHANGE ASSESSMENT – V1

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Executive Summary

Coastal areas across Europe are facing increasing risks due to climate change, sea-level rise, and human activities, making coastal vulnerability assessments critical for sustainable management and adaptation. As part of the Geological Service for Europe (GSEU) project, this report—Deliverable D5.1 under Work Package 5 (WP5) – Coastal Vulnerability Assessment & Optimized Offshore Windfarm Siting—demonstrates the added value of geological and hydrogeological data in addressing these challenges.

The report is the result of collaboration among 26 European Geological Survey Organizations (GSOs), bringing together expertise in coastal vulnerability, environmental monitoring, and geological assessments. The overarching aim is to provide actionable insights to support EU policymakers, coastal managers, and stakeholders in their efforts to mitigate risks and enhance resilience in coastal zones.

This document explores the following key themes:

Understanding Coastal Vulnerability Through Geological and Hydrogeological Data

The interaction between geological processes and coastal vulnerability is complex. To ensure effective risk assessments, the project investigates:

- Submarine and coastal groundwater discharge of pollutants and nutrients: Identifying and assessing sites across Europe where concentrated groundwater discharge affects coastal ecosystems.
- Vertical land motion (VLM) and its contribution to relative sea-level changes: Using European Ground Motion Service (EGMS) and InSAR techniques to monitor ground subsidence and uplift trends that influence coastal stability.
- Long-term coastal evolution and sea-level rise impacts: Analyzing how coastal dynamics, sediment transport, and erosion patterns vulnerability over decades to centuries.

These assessments provide a scientific basis for adaptation strategies, offering a more precise understanding of coastal hazards and their drivers.

Establishing a European Network of Coastal Sites and Knowledge Sharing Initiatives

A key component of this project is to foster cross-border cooperation by establishing a cluster of European coastal sites. This cluster is designed to:

- Enhance collaboration among Geological Surveys by sharing data, methodologies, and expertise.
- Improve data harmonization and accessibility, particularly for pollutant and nutrient dispersion studies.
- Facilitate transnational policy integration by aligning coastal risk assessments with EU directives such as the Marine Strategy Framework Directive (MSFD) and EU Maritime Spatial Planning Directive (2014/89/EU).

Advanced Monitoring and Assessment Techniques

A major strength of this study lies in its use of cutting-edge geospatial technologies and monitoring tools, including:

- Interferometric Synthetic Aperture Radar (InSAR) and GNSS data to measure ground deformation and subsidence trends.
- Remote sensing and LiDAR for high-resolution mapping of coastal topography and erosion patterns.
- Hydrological and sedimentological analyses to track pollutant movement and groundwater interactions in vulnerable coastal zones.

These methodologies provide unprecedented accuracy in detecting risks associated with relative sea-level rise, land subsidence, and coastal erosion.

Policy and Decision-Making Support for Coastal Adaptation

The integration of geological and hydrogeological insights into EU coastal management policies is crucial for addressing climate-induced coastal risks. This report:

- Evaluates existing policy frameworks to determine the extent to which geological factors are considered in coastal planning.
- Identifies gaps in current monitoring efforts, emphasizing the need for more comprehensive data collection and real-time hazard assessments.
- Recommends enhanced coordination between Geological Surveys, policymakers, environmental agencies, and researchers to develop evidence-based coastal adaptation strategies.

Key Findings and Recommendations

The findings highlight the growing need for geological data in coastal risk management and adaptation planning. The report concludes with the following key recommendations:

- Expand coastal vulnerability assessments by incorporating geological and hydrogeological data into national and EU-level decision-making.
- Strengthen the European network of coastal monitoring sites to improve data harmonization and policy integration.
- Increase collaboration among Geological Surveys and environmental agencies to advance coastal risk research and mitigation strategies.
- Improve accessibility of geological datasets to support cross-border knowledge exchange and policymaking.
- Enhance public and stakeholder engagement to raise awareness of the role of geology in coastal resilience.

Conclusion

This report underscores the critical role of geology and hydrogeology in understanding and mitigating coastal vulnerability. By integrating geological data with advanced monitoring techniques and collaborative research efforts, European countries can enhance their preparedness for the long-term impacts of climate change and sea-level rise.
This deliverable is the first version (V1) of D5.1, and future updates will expand on these findings with refined datasets, additional case studies, and further policy recommendations.

Abbreviations	
AL	Albania
BE	Belgium
CMES	Copernicus Marine Service
CPF	Coastal Flood Plain
CY	Cyprus
D	Deliverable
DEM	Digital Elevation Model
DK	Denmark
EE	Estonia
EC	European Commission
EGDI	European Geological Data Infrastructure
EGMS	European Ground Motion Service (Copernicus)
EGS	EuroGeoSurveys
EMODnet	European Marine Observation and Data Network
ES	Spain
ES-C	Catalonia, Spain
EU	European Union
FAIR	Findability, Accessibility, Interoperability, Reusability
FI	Finland
FO	Faroe Islands
FR	France
GIA	Glacial Isostatic Adjustment
GNSS	Global Navigation Satellite Systems
GR	Greece
GSE	Geological Service for Europe (organization)
GSEU	Geological Service for Europe (project)
GSO	Geological Survey Organization
H2020	Horizon 2020
HR	Croatia
IE	Ireland
InSAR	Synthetic Aperture Radar Interferometry
IPCC	Intergovernmental Panel on Climate Change
IS	Iceland
IT	Italy
ITRF	International Terrestrial Reference Frame

LiDAR	Airborne Light Detection and Ranging
LT	Lithuania
LV	Latvia
MT	Malta
NGO	Non-Governmental Organization
NL	The Netherlands
NO	Norway
PCA	Principal Component Analysis
PL	Poland
PLR	Piecewise linear regression
PT	Portugal
RSLR	Relative Sea-level rise
SE	Sweden
SI	Slovenia
SLR	Sea-Level Rise
SRTM	Shuttle Radar Topography Mission
STS	Seasonal Trend Linear-decomposition
T	GSEU Task
TLS	Terrestrial laser Scanner
UA	Ukraine
UAV	Unmanned Aerial Vehicle
UK	United Kingdom
VLM	Vertical land motion
WP	Work Package

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1. Introduction

1.1. General Elements

As part of the Geological Service for Europe (GSEU) project, twenty-six GSOs share their expertise as part of Work Package 5 (WP5) “Coastal vulnerability assessment and optimized offshore windfarm siting”. The primary objective of the WP5 is to create products that will enable governments, industry, cultural heritage organizations and the marine research community to make informed decisions regarding the sustainable development, management and protection of coastal environments and the seabed. Coastal areas are sensitive zones requiring careful management under increasing pressure due to human activity (e.g. urbanization), climate change (in particular sea-level rise) and extreme weather events. The assessment of the vulnerability of coastal zones requires an interdisciplinary approach, considering the major control of geomorphology and surface geology on coastal evolution and associated risks.

Coastal vulnerability and its changes with the ongoing climate change are the primary objectives of Task 5.1 (hereby T5.1). It aims to demonstrate how coastal vulnerability assessments and coastal adaptation to sea-level rise can be supported by geological and hydrogeological information, by the following three subtasks:

- T5.1.a - Instigating a cluster of European sites concerned by concentrated pollutants and nutrients submarine and coastal groundwater discharge (lead by SGU) (see Chapter 2)
- T5.1.b - Explaining and projecting spatiotemporal patterns of vertical ground motion (VGM) in European coastal areas, and their contribution to relative sea-level changes (lead by BRGM, BGS) (see Chapter 3)
- T5.1.c - Improving coastal vulnerability assessments addressing coastal evolution at decadal to centennial timescales and sea-level rise impacts (lead by BRGM) (see Chapter 4)

A key objective is to meet the project's expectations while simultaneously enhancing the visibility of geological surveys in the field of coastal vulnerability assessments. This effort builds upon a cluster of European sites and pan-European assessments from related projects, ensuring a comprehensive and integrated approach to understanding and mitigating coastal risks. Its main challenges include mapping expertise on coastal vulnerability across Europe, which could stimulate new European, national, or regional projects by fostering collaboration between GSOs and research teams.

This report aims to enhance the understanding of coastal and submarine groundwater discharge of pollutants and nutrients across Europe, establishing a network of key sites and initiatives. It compiles knowledge on emblematic locations, assesses data availability, and provides basis for integration of geological and hydrological factors into EU decision-making. The project also investigates spatiotemporal patterns of vertical land motion (VLM) in European coastal regions, evaluating their impact on relative sea-level rise using the European Ground Motion Service (EGMS) and advanced InSAR techniques, especially. Additionally, this report focuses on coastal vulnerability assessments over long timescales, analyzing coastal dynamics, key parameters, and variations in public policy approaches across Europe. Finally, this report aims at exploring how geological and hydrogeological data contribute to coastal adaptation strategies, by the role played by the GSOs aiming to strengthen resilience to sea-level rise and environmental changes. This report is a preliminary assessment (Version 1 of D5.1) and will be followed by a Version 2 in a near future.

1.2. Precautions and restrictions

This project focuses solely on European mainland coastal regions of the European partner countries. With exception of the Faroe Islands, which are represented in the GSEU project by the Faroese Geological Survey, the numerous overseas territories of the partner countries are not considered in this report. Because of their high exposure to coastal risks, unique climate conditions and geological conditions which are often not present on the mainland (e.g. coral reefs), the analysis for these territories is complex, while having only limited relevance to the mainland Europe. Addressing these specificities requires tailored approaches that integrate geological and hydrological assessments alongside environmental, social, and economic considerations. It is therefore out of scope of the T5.1. It is, however, recommended to address the risk in these highly vulnerable projects in the future.

2. Submarine and Coastal Groundwater Discharge of Pollutants and Nutrients: Instigating a Cluster of European Sites

Submarine and coastal groundwater discharge of pollutants and nutrients is a critical issue in European coastal areas, particularly in the context of future climate change and sea-level rise. Addressing these discharges is vital to mitigating risks of pollutant and nutrient dispersal and preserving coastal ecosystems. A coordinated effort to identify and study emblematic European sites with concentrated submarine and coastal groundwater discharge can provide valuable insights. This involves collecting and harmonizing knowledge, highlighting the role of Geological Surveys in applying advanced methods and technologies, and recognizing existing initiatives and collaborations at national and international levels. Enhanced collaboration within the Geological Surveys of Europe (GSEU) could maximize benefits by promoting data integration, sharing decision-making practices aligned with EU Directives and Marine Spatial Planning, and fostering sustainable coastal management strategies.

The coastal zone is a changing and vulnerable environment. Both human and natural impacts can lead to flooding and erosion problems, saltwater intrusion, decreasing ground water levels and discharge of nutrients as well as environmental contaminants, which in turn likely lead to increased risks and altered living conditions for people and nature. Future climate change, leading to sea-level rise and an expected increase in episodes of intense rainfall, is likely to exacerbate these issues.

For this reason, it is important to map and monitor the coastal zone, and any changes that might occur over time, thus be able to take adequate measures to lower the negative impact in the coastal zones. Doing this, it is important to share knowledge in these issues, both between different geological surveys (or corresponding organizations) and any other stakeholder that this might concern.

Benefiting from the network set up within the GSEU, with the aim to work and share knowledge in these issues, a questionnaire dedicated to submarine and coastal groundwater discharge of pollutants and nutrients was sent out to all working members within WP5.

2.1. Collecting Knowledge on European Emblematic Sites

Here is a question of establishing forms of cooperation for knowledge sharing among Geological Surveys in Europe to reduce and prevent the risk of pollution and nutrient dispersal in coastal areas through groundwater discharge and surface runoff, addressing the impacts of future climate change and sea-level rise, while also fostering a network of European sites affected by these issues.

To support the T5.1.a, an online questionnaire dedicated to submarine and coastal groundwater discharge of pollutants and nutrients has been designed and sent to the GSEU WP5 partners, in July 2024, to be closed at the end of September. Later, in the late November, the questionnaire was reopened to increase the number of respondents answering it, to be closed again at the end of 2024. The questionnaire was realized with the SoSci Survey Online tool (https://www.soscisurvey.de/). It contained both closed and open questions and took about 30 minutes to complete.

This questionnaire was divided into three main parts:

The first section aimed at identifying **current conditions and future work** of coastal territories over European coasts (instigate a cluster of European sites concerned by concentrated pollutants and nutrients, submarine and coastal groundwater discharge; collaborations; impact of human activities, etc.) (The complete online questionnaire is given in the related Annex.)

- The second section aims to provide elements about **data, and especially data availability** (Table 2).
- The last section aims at highlighting geological and hydrological considerations into decision-making processes and **EU directives** (Table 3).

The complete online questionnaire is given in the related Annex.
Respondent answering the questionnaire at the end of 2024, are represented on a 2021 European map on Figure 2-1.

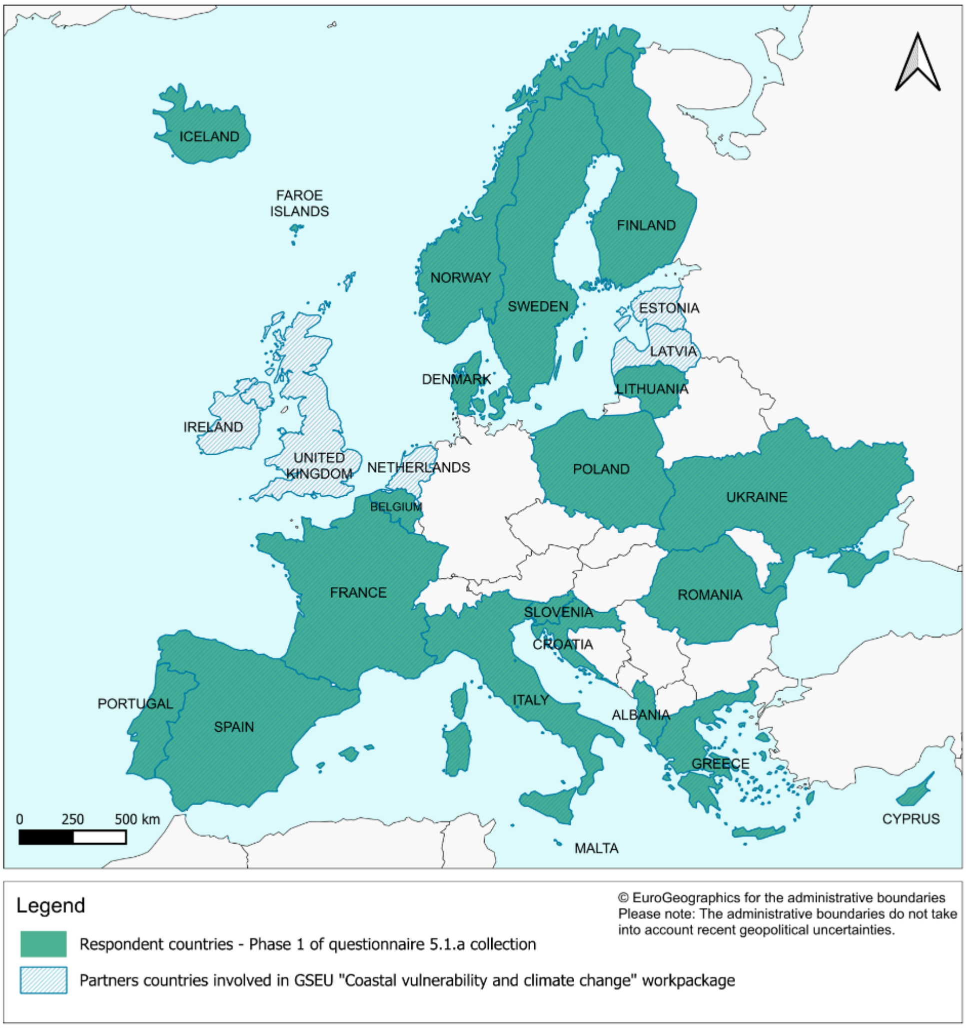

Figure 2-1 - Map of the countries responding to the questionnaire T5.1.a about concentrated pollutants, nutrients submarine and coastal groundwater discharge.

2.2. Identifying Current Initiatives and Collaborations

This section presents results from the first section of the questionnaire T5.1.a.

A future cluster of European sites

To reduce or prevent the risk of pollutants and nutrients spreading in coastal areas, for example through groundwater discharge, in relation to future climate change and sea level rise, the objective for T5.1.a is to instigate a cluster of European sites concerned by concentrated pollutants and nutrients, submarine and coastal groundwater discharge.

Figure 2-2 - Map showing potential areas (red dots), which could form a future cluster of European sites sharing knowledge of impact on elevated levels of pollutants, nutrients, and submarine and coastal groundwater discharge. A table with the precise location is given in the related Annex.

Respondents were asked about three questions that aim to **gather information about national examples of areas or activities impacted by pollutant and nutrient dispersal**, **their associated risks, and the role of GSOs:**

- Example Identification: Suggest a specific site, activity, or business from their country that could serve as a representative study area for assessing pollutant or nutrient dispersal risks.
- Site Details and Risk Management: Describe the site's location, the type of activity or business involved, the pollutants or nutrients present, and the associated risks. Indicate if any measures are underway to prevent or mitigate these risks.
- Role of Geological Surveys: Outline GSO's contributions to this area, including any innovative methods or technologies tested. Highlight how these efforts address future climate change impacts, such as increased runoff, flooding, storms, and sea level rise.

This information would help share experiences and strategies among Geological Surveys and other stakeholders across Europe.

An initial list of 41 potential sites, which could form a future cluster of European sites sharing knowledge about relatively elevated levels of pollutants, nutrients, and submarine and coastal groundwater discharge, was drawn up based on responses from participating countries (see Table 5 and Figure 2-2). At this stage, these are the first proposals made by the GSOs in their responses to the questionnaire (without selection). Of course, this list remains preliminary and will be subject to change and to the addition of new countries and emblematic sites over the first half of 2025 (final list will be published in the Version 2 of this D5.1 deliverable).

In some cases, the coastal area needs to be defined more clearly in terms of coordinates. This also applies to the different coastal area's impact factors and ecosystem impact. What are the impact factors of the different coastal areas, and how are the ecosystems on the coast affected by these? It is a topic that needs to be addressed more thoroughly and shared in the forthcoming work (Version 2 of this D5.1 deliverable) in GSEU and the subgroup of WP5. For example, nutrient emissions from agriculture can lead to locally high concentrations of nitrogen compounds and phosphates in groundwater, causing eutrophication in areas like Puck Bay, Poland. Similarly, inland mining activities in Portugal impacts the Algarve coastal zone by discharging elevated levels of trace metals, which can accumulate in vulnerable areas such as marshes, disrupting ecosystems and contaminating sediments. In Spain, the coastal ecosystem of La Pineda is affected by elevated levels of microplastics. In Greece, agriculture and over pumping in the Lerapetra area result in groundwater salinization and nitrate pollution. Meanwhile, in Sweden, seabed erosion at Beckholmen releases contaminated sediments, leading to elevated levels of heavy metals and PCBs in the water column. In several of these coastal areas, monitoring programs or projects have been established to track the levels of these substances and their effects, providing valuable opportunities for sharing knowledge and experiences.

Collaborations

While addressing GSOs participation *"in any current initiatives or collaborations among GSOs about pollutant and nutrient dispersal in coastal areas in general (but also for example through groundwater discharge, in relation to future climate change and sea level rise)"*, several respondents noted their involvement in ongoing work through the EMODNET (European Marine Observation and Data Network) and GSEU (Geological Surveys of Europe) initiatives. However, a common theme among responses is the perceived lack of broader collaboration among GSOs in projects specifically focused on pollutant and nutrient dispersal in coastal areas. This includes areas impacted by groundwater discharge, with a particular emphasis on future climate change and rising sea levels. The feedback suggests a need for increased cooperative efforts to address these environmental challenges comprehensively. Respondents pointed out that while certain regional projects are being undertaken, there seems to be a gap in collaboration across different Geological Surveys in this field. Respondents were also asked about their participation in current initiatives or collaborations at a national level aimed at addressing pollutant and nutrient dispersal in coastal areas, including those related to groundwater discharge, and in the context of future climate change and sea level rise. A third of the respondents stated that they were not involved in such initiatives or collaborations. However, two-thirds reported participating in activities addressing pollutant dispersal in one or more coastal areas, indicating varied levels of engagement across different regions.

Impact of human activities impacting dispersal of pollutants and nutrients in the coastal zone

Considering GSO's knowledge of coastal territories in their country, respondents were asked to name the top (1-3) human activities, past or present, with the highest risk for leading to dispersal of pollutants and nutrients in the coastal zone due to future climate change and sea level rise.

Figure 2-3 - Word cloud about human activities, past or present, with the highest risk for leading to dispersal of pollutants and nutrients in the coastal zone due to future climate change and sea level rise, based on respondents.

A word cloud summarizing the main feedback from respondents highlights terms related to human activities, environmental concerns, and industrial processes that influence coastal areas and ecosystems (Figure 2-3). Prominent words like *Agriculture, Industry, Wastewater*, and *Pollution* point to major sectors and issues contributing to nutrient and pollutant dispersal. Terms such as *Urbanization, Port, Dredging,* and *Farming* indicate specific activities impacting coastal environments. Environmental challenges are emphasized with words like *Discharge, Spills, Chemical, Nutrients*, and *Eutrophication*, while *Treatment, Protection*, and *Supply* suggest management efforts. Collectively, these terms reflect the interplay between human activities and environmental impacts in coastal zones.

Based on these answers, the three highest risks are from (1) agriculture, followed by insufficient (2) waste water collection and treatment, and then by (3) industrial activities.

Activities to be supported for future cooperation within the GSE-framework

Respondents were asked to rate the importance of various activities aimed at preventing pollutant and nutrient dispersal within coastal areas. They were asked to evaluate these activities both in the context of their own country and in terms of the greatest potential benefits from future cooperation within GSEU project partners and naturally by the GSE. In relation to the sensitivity of coastal zones and the risk of pollutant and nutrient dispersal, respondents were also asked to identify which activities they considered most important or relevant. This set of activities provides a framework for understanding priorities at both national and transnational levels to mitigate coastal environmental risks.

Figure 2-4 shows that “Mapping of sources of pollutants/nutrients that could have negative effects in the coastal zone” and “Mapping of geological/hydrogeological parameters in relation to the dispersion of pollutants/nutrients” are among the three most important activities to undertake in order to prevent the dispersion of polluting substances, regardless of whether this is done in international collaboration or independently. Activities ranked as highly important, which are considered to benefit significantly from future cooperation within GSEU, include “Mapping of coastal erosion”, “Mapping of dispersal risks close to identified sensitive areas (e.g., Natura 2000 sites or areas with high environmental value)”, “Identifying parameters of relevance for modelling future climate change and its effect on dispersal conditions”, and “Developing and utilizing a Coastal Vulnerability Index (CVI) to assess the dispersal of pollutants/nutrients”. Among these, "Mapping of coastal erosion" is ranked as the top priority to be undertaken within GSEU/GSE and is also regarded as the activity that would gain the most from such cooperation.

Later, respondents were asked to provide suggestions on important factors or future actions needed to enhance collaboration between GSOs in addressing pollutant and nutrient dispersal in coastal zones. This would involve fieldwork, sampling, and laboratory analyses, with the aim of standardizing methods for data collection, data sharing, and monitoring across the different GSOs.

To ensure future collaborations in the T5.1.a and the full involvement of its partners, respondents were asked which focus topics their organization would like to discuss in potential future WP5 workshops. The suggested priorities were: (1) mapping of saltwater intrusion, (2) mapping of coastal erosion, and (3) mapping of coastal groundwater levels, listed in this order of importance.

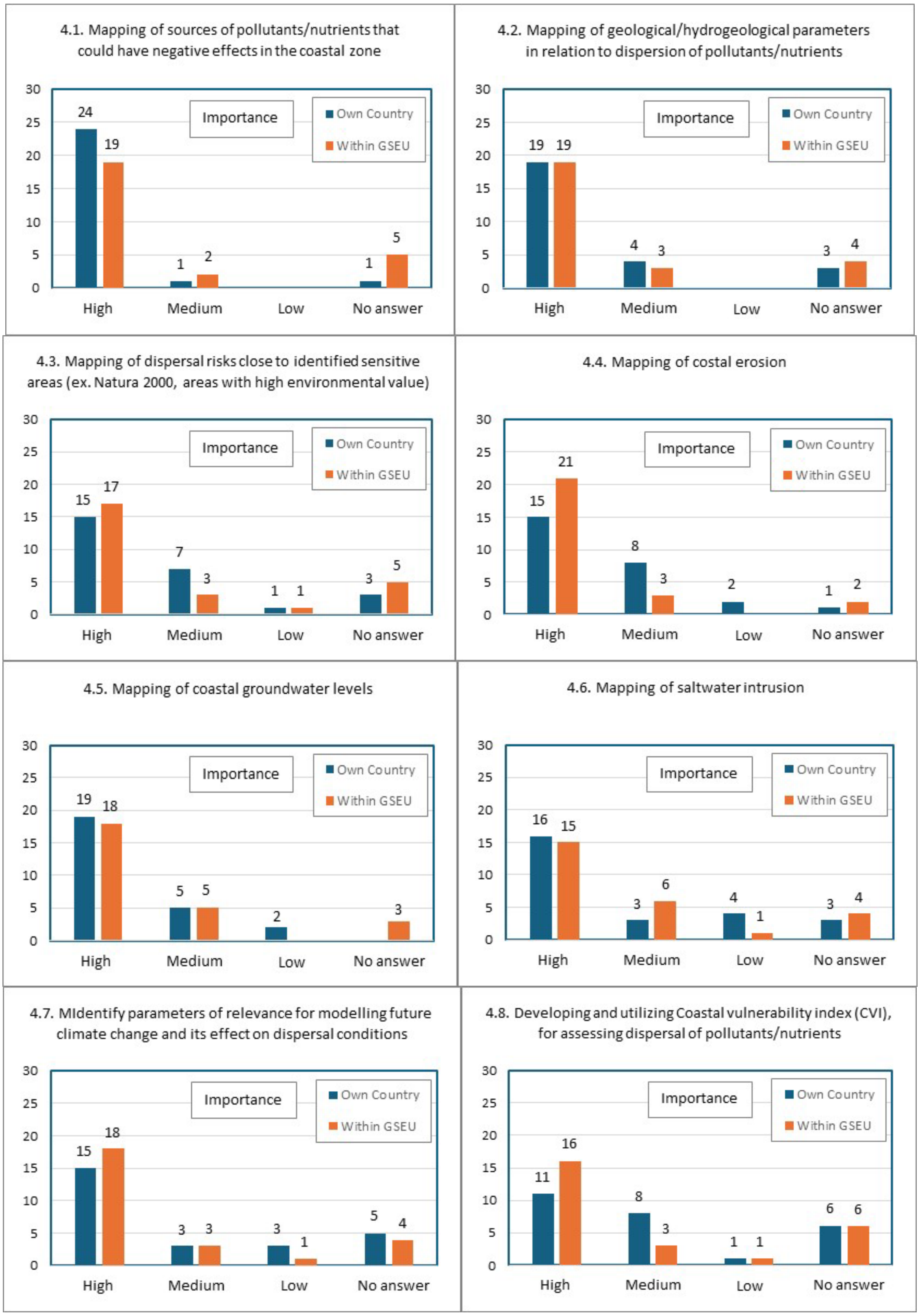

Figure 2-4 - Activities, ranked by the respondents, believed to benefit greatest from future cooperation within the GSEU-framework or by their own country, to prevent the dispersal of pollutants and nutrients in coastal areas.

More generally, feedback from partners indicated the need for workshops focusing on **mapping and monitoring coastal dynamics** to address pollution and nutrient dispersal. Key topics should include mapping saltwater intrusion, coastal erosion, and geological or hydrogeological parameters, as well as salinization and sediment contamination. Developing and utilizing tools like the Coastal Vulnerability Index (CVI) and employing integrated monitoring methods for groundwater-induced pollution were highlighted as key points. Additionally, participants proposed discussions on emerging contaminants such as microplastics, nanoplastics, and surface runoff, with particular attention to their dispersal under climate change, sea level rise, and episodic rainfall events. Specific case studies, such as Poland's 4D cartography and the Scheldt estuary's evolution, demonstrate practical applications of these topics. Discussions are also proposed around the **impacts of human activities and future collaborations**. Topics include coastal line changes, landslide protection, and predicting red tide processes. A focus on modelling future sea level rise and coastal erosion is seen as critical, along with identifying parameters relevant to assessing climate change effects. Establishing common methods to evaluate pollution through groundwater discharge, fostering collaboration through research projects, and leveraging data and technology for mapping and monitoring are priorities. Participants expressed interest in addressing pollutants in populated areas, highlighting the need for joint policy development and cooperation across GSOs.

2.3. Data and Data Availability

This section presents results from the second section of the questionnaire T5.1.a.
In this section, respondents of the questionnaire were asked about two complementary aspects:

1) **Existing data on pollutants/nutrients**: This point focused on understanding whether there is existing data or monitoring activities related to pollutants and nutrients in coastal sediments, waters, or the coastal zone. Respondents were invited to share insights into ongoing investigations, monitoring networks, and any available information about the presence, concentration, and impacts of pollutants and nutrients in these areas.
2) **Existing data on geological (and geomorphological) information**: This aspect aimed to assess the availability and monitoring of geological data relevant to coastal zones. Respondents were asked about data that could support understanding pollutant and nutrient dispersal, such as sediment composition, coastal morphology, hydrodynamic parameters, and other geological factors influencing pollutant behavior in coastal environments.

These two points were designed to provide a comprehensive view of the current state of data collection and monitoring in coastal zones, addressing both environmental and geological dimensions.

Data status on pollutants/nutrients

First, respondents were asked whether they had knowledge of their country investigating or monitoring pollutants and nutrients in coastal sediments, waters, or the coastal zone in general.

Examples of the answers:
In Catalunya, ICGC analyses sand samples for heavy metals, while the Catalan Water Agency (ACA) monitors the quality of water in coastal bathing areas. Similarly, Romania focuses on monitoring pollutants and nutrients in coastal waters through Romanian Waters 'National Administration' and GeoEcoMar. However, Romania lacks a systematic network for data collection, with limited attention given to sediments. Greece, through HSGME, actively monitors coastal sediments and waters across

vulnerable areas, including major gulfs (Saronic, Thermaikos, Amvrakikos, and Corinth) and islands like Crete. The monitoring is consistent and carried out locally, with a focus on both sediments and water quality. In Albania, the GSO publishes annual environmental impact reports, with a focus on pollutants in coastal zones.
The Croatian GSO, under Croatian Waters (Hrvatske vode), oversees water management along the coast as mandated by the Water Act. In Iceland, the Iceland Geological Survey monitors runoff waters from treatment plants and glacial floodwaters but does not extend its monitoring to offshore coastal waters. Meanwhile, Poland operates an extensive groundwater monitoring network with about 1,400 observation points, some of which are in coastal areas. This monitoring, led by the Polish Geological Institute – National Research Institute, focuses on assessing groundwater quality and quantity.
In Slovenia, the Geological Survey of Slovenia collaborates with the Slovenian Environment Agency (ARSO) and the National Laboratory of Health, Environment and Food (NZLOH) to monitor surficial waters. Cyprus, on the other hand, actively monitors pollutants and nutrients in coastal waters, sediments, and zones to comply with European Union (EU) directives such as the Water Framework Directive (WFD) and the Marine Strategy Framework Directive (MSFD). The goal is to protect ecosystems and manage pollutants in areas like Larnaca Bay, Limassol, and Paphos.
In Lithuania, marine waters are monitored by the Environmental Agency, but the data is not publicly accessible, and there are no activities focused on coastal sediments. In Portugal, the NOR-WATER project, led by CIIMAR, identifies emerging pollutants in Galicia and North Portugal. Other initiatives, such as the AQUIMAR Project and MONIAQUA program, focus on monitoring pollutants like NOx, PO4, and other parameters in transitional and coastal waters.
The Royal Belgian Institute of Natural Sciences oversees monitoring inorganic pollutants in the Belgian Coastal Zone (BCZ). In Sweden, the GSO conducts nutrient monitoring in the coastal zone, covering water columns, sediments, and biota. Similarly, in Malta, the Energy and Water Agency monitors coastal groundwater bodies, transitional waters, and coastal waters. Finally, the Faroese Geological Survey (Jarðfeingi) conducts mandatory seabed substrate tests for nutrients and pollutants to support fish farming practices.

Overall, while most countries have active programs for monitoring pollutants and nutrients in their coastal zones, the scope and focus of these programs vary widely. Some countries lack systematic data collection networks or publicly available data, while others employ comprehensive and multi-faceted approaches to assess water and sediment quality. About the question *“How is it investigated, e.g. sampling techniques, frequency, and substances?”*, it appears that monitoring is performed in water and sediment, both in national and regional program, of metals, nutrients microplastics and emerging substances, at various time scales, from twice a month to once a year or more seldom, depending on type of media (sediment, water), sometimes along transects, by grab sampling and automatic samplers. Although what is monitored in the different programs differs a lot. Levels of substances in biota seems not to be monitored by the GSOs. Responses show that the ownership of the monitoring data belongs generally to the “Research Institutes” carrying out the monitoring program or the organization who have funded the monitoring, generally a National Water or Environmental Protection Agency. Data is in many cases (but not all) available in geodata format. In many cases, data is known to be delivered to EMODNET, ICES, OSPAR or Eionet Water (WISE). However, in some cases the partners lacked the information whether these data are delivered to EMODNET, ICES or another open database or whether they are openly accessible at all.

Data status of geological (and geomorphological) data

For the question, *"Is your country investigating or monitoring geological parameters of relevance to the dispersal of pollutants/nutrients in the coastal zone (try to think from source to sea)? Examples of parameters are groundwater discharge, submarine landslides, water level changes, wave erosion, sea-floor bottom type, particle movement, accumulation areas, sediment accumulation rates"* respondents' answers reveal the following findings: the most commonly monitored geological parameter is the sea-floor bottom type, followed by sediment accumulation rates, water level changes, wave erosion, particle movement, and submarine landslides. Groundwater discharge is also monitored but to a lesser extent compared to the other parameters.

These results reflect the diverse focus on geological factors influencing pollutant and nutrient dispersal in coastal environments. What *is investigated and how (e.g. techniques and frequency)?* Respondents highlight several elements: sea surveys, seabed substrates (using acoustic-seismic survey methods including also seabed substrate sampling). Sedimentation rates are studied using coring and various dating methods. Groundwater discharge gets monitored by temperature and electrical conductivity probes at discharge points. Here again, the ownership of data belongs generally to the "Research Institute" carrying out the monitoring program or the organization who have financed the monitoring, generally a National Water or Environmental Protection Agency. Data is in many cases (but not all) available in geodata format. In many cases (but not all) data are open and delivered to EMODNET, ICES or EGDI. Data may also be made accessible to the public through national platforms or the website of the organizations that was responsible for carrying out the monitoring.

GSEU T5.1.a partners were also asked to identify the institutions or organizations responsible for conducting investigations and monitoring of pollutants and nutrients in coastal sediments, waters, or the coastal zone in general, as well as those overseeing geological parameters relevant to pollutant and nutrient dispersal in the coastal zone. The responses enabled us to synthesize these elements into a comprehensive table (Table 1).

When asking about data each GSO considers as the most important to collect and harmonize in order to reduce and prevent the risk of pollutant/nutrient dispersal in the coastal zone due to future climate change and sea level rise, respondents emphasized the importance of collecting and harmonizing data on pollution sources on land and in sediment, groundwater levels, sea level elevation, coastal erosion, sediment and land stability, soil properties, hydrodynamics at the coast, and the risk of flooding.
From each country's perspective, submarine groundwater discharge data were highlighted as the most challenging to collect, due to the complexity of tracking groundwater flow paths into the sea across varying spatial and temporal scales. Other challenges include collecting data on coastal erosion and shoreline changes, over-pumping impacts, and the risk of flooding.

Table 1 - List of institution or organization responsible for carrying out the investigations/monitoring of pollutants/nutrients in coastal sediments (waters or the coastal zone in general) and geological parameters of relevance to the dispersal of pollutants/nutrients in the coastal zone**.** PN = Pollutants Nutrients, GD = Geological Data

Country	Institution or Organisation	Data status	
		PN	GD
Albania	Albanian Geological Survey	X	X
	Ministry of Environment	X	
Belgium	Vrije Universiteit Brussel	X	
	Flanders Marine Institute		X
Croatia	Croatian Waters	X	X
	Croatian Hydrographic Institute		X
	Croatian Oceanographic and Fisheries Institute		X
	Croatian Geological Survey		X
Cyprus	Department of Fisheries and Marine Research	X	X
	Rural Development and Environment	X	
	Geological Survey Department	X	X
	Department of Environment	X	X
Denmark	The Danish Centre For Environment And Energy	X	
	Aarhus University	X	
	Geological Survey of Denmark and Greenland		X
Faroe Islands	The Environment Agency	X	
	Faroese Geological Survey		X
Finland	The Centres for Economic Development, Transport and the Environment	X	
	Geological Survey of Finland		X
France	Water Agencies	X	
	French Geological Survey	X	X
	Ifremer (French Research Institute for Exploitation of the Sea)	X	
	DREAL (Regional Directorates for Environment, Planning, and Housing)	X	
	Public Health Agencies (ANSES, Santé Publique France)	X	
	local authorities	X	
Greece	Hellenic Centre of Marine research	X	X
	Hellenic Survey of Geology & Mineral Exploration	X	X
	The Ministry of Environment and Energy	X	
	General Secretariat of Environment	X	
Iceland	Reykjavík Energy	X	
	The Environment Agency of Iceland	X	X
Italy	Regional environmental protection agencies	X	
	Italian National Institute for Environmental Protection and Research	X	
Lithuania	Environmental Agency	X	
	Lithuanian Geological Survey		X
Malta	The Energy and Water Agency	X	X
	Environmental and Resource Authority	X	
Norway	Geological Survey of Norway	X	X
	Research institute for water and the environment		X
	Norwegian Environmental Agency		X
Poland	Chief Inspectorate of Environmental Protection	X	
	Polish Geological Institute	X	X
Portugal	The Portuguese Environment Agency	X	
	Portuguese Institute for Sea and Atmosphere	X	X
Romania	Romanian Waters National Administration	X	X
	Geoecomar	X	
Slovenia	The National Laboratory of Health, Environment and Food	X	
	Slovenian Environment Agency	X	
Spain	The Catalan Water Agency	X	
	Oceanographic Institute of Spain	X	
	Geological Survey	X	X
	Spanish Oceanographic Institute	X	X
	Spanish Geological Mining Institute		X
	Cartographic and Geological Institute of Catalonia		X
	Universities of Balearics Islands		X
Sweden	The Swedish Environmental Protection Agency	X	
	County Administration Boards of Sweden	X	
	Swedish Agency for Marine and Water Management	X	
	The Swedish Museum of Natural History	X	
	Swedish Meteorological and Hydrological Institute	X	
	Geological Survey of Sweden	X	X
	Swedish Maritime Administration		X
Ukraine	Ukrainian Scientific Centre of Ecology of the Sea	X	
	The Public Organization Ukrainian Association of Geologists		X

When addressing the need for a data gap analysis to estimate the risk of pollutant and nutrient dispersal in the coastal zone, respondents overwhelmingly agreed that a data gap analysis would be crucial to identify missing data necessary to estimate the dispersal of pollutants and nutrients in coastal zones, effectively. Respondents also suggest that the most suitable approach would involve a collaborative and multidisciplinary (mixed) committee. This committee should bring together key stakeholders, including:

1. Geological Surveys: For their expertise in subsurface processes, geological mapping, and coastal dynamics.
2. Governmental Organizations or Agencies: To provide regulatory frameworks and align the analysis with national and regional policies.
3. Research Institutions: For their advanced methodologies, technological innovations, and capacity for detailed scientific studies.
4. Private Companies: To contribute technical expertise and tools, particularly in areas such as remote sensing, monitoring, and data processing.
5. International Institutions: Entities like GSEU, EGS and EMODnet can play a pivotal role in data harmonization, sharing best practices, and ensuring the analysis aligns with European-wide objectives.

This mixed approach ensures the integration of diverse expertise, fostering both the technical depth and policy alignment needed for effective risk estimation and management in the coastal zone. Respondents agreed about that fact that EMODNET (European Marine Observation and Data Network) is a key initiative that provides a unique and valuable platform for the collection, harmonization, and dissemination of marine data across Europe, including pollutant and nutrient dispersal in coastal zones. It fosters collaboration among geological surveys, environmental agencies, and research institutions, offering both opportunities and challenges in terms of future work within your own country, as well as for cross-border cooperation across the EU.

2.4. Geological and Hydrological Considerations into Decision-Making Processes and EU Directives

This section presents results from the third section of the questionnaire T5.1.a.
Respondents were asked to what extent they believe the work under the Marine Strategy Framework Directive (MSFD) incorporates geological and hydrological considerations into decision-making processes to identify and prioritize areas for pollution mitigation and to guide the implementation of sustainable land use practices aimed at reducing nutrient runoff. It appears that many of the respondents were not familiar enough with the MFSD to be able to comment on this. Among the respondents who were a bit more familiar with the MFSD, there were opinions that important geological and hydrological considerations had been incorporated in the Descriptors of the MFSD, and that they could be of crucial importance for identifying and prioritizing areas for pollution mitigation in order to guide sustainable land use practices to reduce nutrient runoff. The opinion of some other respondents was that the considerations in MFSD were of less importance.

Respondents were also asked about the extent they believe the work with EU Directive 2014/89/EU creates a common framework for Maritime Spatial Planning (MSP) in the European Union, incorporating geological and hydrological considerations into decision-making processes to help identify and prioritize areas for pollution mitigation and guide the implementation of sustainable land use practices to reduce nutrient runoff. It seems that many of the respondents were not familiar enough to have a clear opinion if the EU Directive incorporated geological and hydrological consideration that could be helpful to identify and prioritize areas for pollution at the coast. This point will be explored further by the T5.1, and the results will be presented in the Version 2 of this deliverable D5.1.

2.5. Conclusion

There is an important need for collaboration among the respondents working to reduce and prevent the risk of pollution and nutrients spreading in coastal areas, through groundwater discharge, surface runoff, in relation to future climate change and sea level rise. It is also agreed among the respondents that GSEU and EMODNET are excellent platforms for collaboration, sharing knowledge and data of dispersal of pollutants, although not always used extensively.

One way to increase collaboration among the different GSOs could be to organize different workshops with different focuses/activities. For example, the activities that were agreed in the questionnaire among the respondents to be the most important to reduce and prevent the risk of pollution and nutrients spreading in coastal areas, through groundwater discharge, surface runoff, in relation to future climate change and sea level rise : “Mapping of sources of pollutants/nutrients that could have negative effects in the coastal zone”, “Mapping of geological/hydrogeological parameters in relation to dispersion of pollutants/nutrients”, and “Mapping of costal erosion” also in relation to dispersion of pollutants/nutrients. This could be done for the different coastal areas, which were identified in the survey as possible coastal areas to share knowledge on monitoring, preventing and taking measures against the spread of pollutants and nutrients in the coastal zones.

Additionally, a gap analysis could be done based on these potential coastal areas to identify if crucial data is missing to evaluate dispersal of pollutants and nutrients dispersal in the coastal zones. Whether this is something that could be done within GSEU or should rather be carried out by an organization outside GSE could be a task for upcoming work within WP5.

3. Spatiotemporal Patterns of Vertical Land Motion in European Coastal Areas: Implications for Relative Sea-Level Change

Coastal regions across Europe are subject to vertical land motion (VLM), a key factor influencing relative sea-level change. Understanding the spatiotemporal patterns of VLM is essential for improving coastal risk assessments and adaptation strategies. This section provides an overview of coastal VLM processes, explores detection and projection methods, and examines their direct link to relative sea-level rise. A pan-European assessment of contemporary VLM, based on European Ground Motion Service (EGMS) data, offers new insights into national to regional trends. Additionally, advanced automatic tools for analyzing InSAR time series are applied to detect motion patterns, with the coastal areas of the UK being used as an example. Finally, emblematic case studies of subsidence hotspots in the Netherlands, France, Greece and Italy, illustrate the localized impacts of land motion, highlighting key challenges for coastal resilience planning.

3.1. Introduction to Coastal Vertical Land Motion (VLM)

Vertical land motions (VLM) in coastal zones are hazardous, when it comes to subsidence, because they can amplify sea-level rise, enhance groundwater salinization, and inflict damage to the built environment. Especially the progressively downward movement of coastal land, known as land subsidence, is a main driver for relative sea-level rise and coastal flooding. The coastal areas of Europe are heavily populated; they accommodate the continent's major urban populations and economic centers. Furthermore, low-lying coastal soil is often in use for agriculture, the coastlines attract major tourism, and harbors valuable ecosystems. Protecting these areas by mitigating coastal vertical land is therefore of utmost importance.

Coastal vertical land motions can be divided into two categories: **i) naturally occurring processes**, and **ii) anthropogenically-induced processes**. Both categories encompass a suite of processes that might be very location specific, dictated amongst others by local geological conditions and human activities. Whereas the spatial influence of other processes, especially those naturally occurring, can stretch-out over many countries.

Natural coastal VLM

The main naturally occurring coastal vertical land motion processes are **tectonics and glacial isostatic adjustments (GIA)**. These processes influence land elevation over large distances; the main tectonic processes resulting in coastal subsidence are related to the collision between the African and European plates. The Mediterranean Rhone (France) and Po River (Italy) basins are prime examples of structural lows created by plate tectonics, but also the coastal plains of the Netherlands have been subsiding by the influence of this plate collision.

GIA are VLM instigated by the growing and melting of ice-sheets during Pleistocene glaciations, lowering and uplifting the solid Earth by their masses. The effects of GIA increase proximal to areas of Pleistocene glaciation. The major glaciated areas comprised Scandinavia, the northern part of the British Isles, the Baltic states, and coastal Denmark and Poland. There, GIA results in gradual coastal uplift throughout the Holocene, whereas south of that line GIA results in lowering (Simon *et al.* 2018). Over the course of the Holocene, GIA rates are decreasing; nevertheless, combined with local tectonics, its results in a complex interplay of long term and large spatial scale coastal vertical movements, exemplified in coastal Poland, Scotland and the coastal stretch of Belgium, the Netherlands and Germany, where GIA contributed to differential rates of relative sea-level rise during the past millennia (Barlow *et al.,* 2014; Kiden *et al.,* 2002; Vink *et al.,* 2007; Zuchiewicz *et al*., 2024).

Natural compaction, or autocompaction, of unconsolidated sediments is a third regional scale coastal VLM process. It often affects sediments of Quaternary and Tertiary age. Autocompaction is the process of pore water expulsion and creep of sediments by stress inflicted by loading of naturally deposited overburden. This results in thickness reduction and in situations without ongoing sedimentation, leads to surface elevation loss. On large spatial scales, this process coincides with structural basins, as tectonic activity creates long-term sediment depocenters. In the coastal plains of Netherlands for instance, autocompaction of some 400 m thick fluvial and coastal deposits contribute ca. 10% to the total observed subsidence (Verberne *et al.,* 2025b). On regional scales, it occurs for instance within deeply incised areas near coastal fluvial systems or delta lobes, such as the Tagus River in Portugal (Vis *et al.,* 2016), or the Danube River delta in Romania (Vespremeanu-Stroe *et al.*, 2017), where autocompaction has been driving natural fluvial behavior for millennia. In highly dynamic environments such as the tidal marshes of the Venice Lagoon in Italy, besides sedimentation, also biomass production of salt marsh vegetation influences aggradation and autocompaction (Zoccarato *et al*., 2019).

In general, soft soils such as clay and peat are most prone to autocompaction, leading to irreversible subsidence. However, superimposed on long-term subsidence trends in soft coastal soil are seasonal or daily oscillations of VLM. Seasonal changes in pore water pressure by fluctuating soil moisture and phreatic groundwater elevations instigates elastic soil responses, consequently swelling and shrinking surficial clay and peat beds. This means in autumn and winter, when precipitation is relatively high and evaporation low, soil swells, whereas in spring and summertime the soil shrinks by reversed hydrological conditions. Daily changes in VLM are caused by tidal movements, changing the pore pressures in soft sediments, primarily in salt marsh environments.

A sudden form of natural coastal VLM is the **formation of sinkholes**. Their often unexpected formation can lead to dramatic effects, not only regarding coastline morphology, but also loss of human lives and estates. This form of natural subsidence is in Europe mainly centered around Mediterranean coastlines and requires near surface brittle or soluble bedrock material. There, different causes leading to natural sinkhole formation have been documented. A sinkhole hotspot is for instance Malta, where primarily downward gravitational effects result in caprock collapses (Devoto *et al.,* 2021). Also, the Apulia coastal plain in southern Italy is a prime example. There, the mixing of saline sea water and fresh terrestrial water enhances karst formation in soluble bedrock (Bruno *et al.,* 2008). These sinkholes reach depths up to 4 m with diameters of over 50 m.

VLM by the cooling of lava flows is perhaps the most peculiar form of coastal subsidence. This form of VLM is of course restricted to areas with volcanic activity, and for instance reported for many areas in Iceland (Wittmann *et al*., 2017). But also, in less volcanically active areas this results in coastal subsidence, where it reveals that the process is gradual. Subsidence by thick lava sheet cooling at the Spanish island of Lanzarote for instance exemplifies that this process can last for centuries, with present-day subsidence rates of 6mm/yr some 300 years after the initial eruption (Purcell *et al.,* 2022).

Anthropogenically-induced coastal VLM

The main cause for anthropogenically-induced coastal subsidence is the **subsurface extraction of resources**; primarily **groundwater**, but also by the **mining** of hydrocarbons (Italy and the Netherlands), salt (the Netherlands), Potash (France and Spain), and coal (England) (Fokker *et al.,* 2018; Humphries, 2001; Teatini *et al.*, 2005). Others are **building settlement and compaction** by the artificial loading of soil, both often restricted to urbanized areas or infrastructural works. Activities in the shallow unconsolidated subsurface resulting in subsidence are often concentrated in the onshore part of coastal areas, whereas deeper bedrock related mining activities are also conducted directly offshore. In the latter case, when proximal to the coastline, offshore activities can lead to onshore subsidence. Furthermore, in practice, anthropogenically-induced subsidence can be caused by superimposed human activities at different depths (Candela and Koster, 2022; Fibbi *et al.,* 2024; Verberne *et al.,* 2025b) (Figure 3-1).

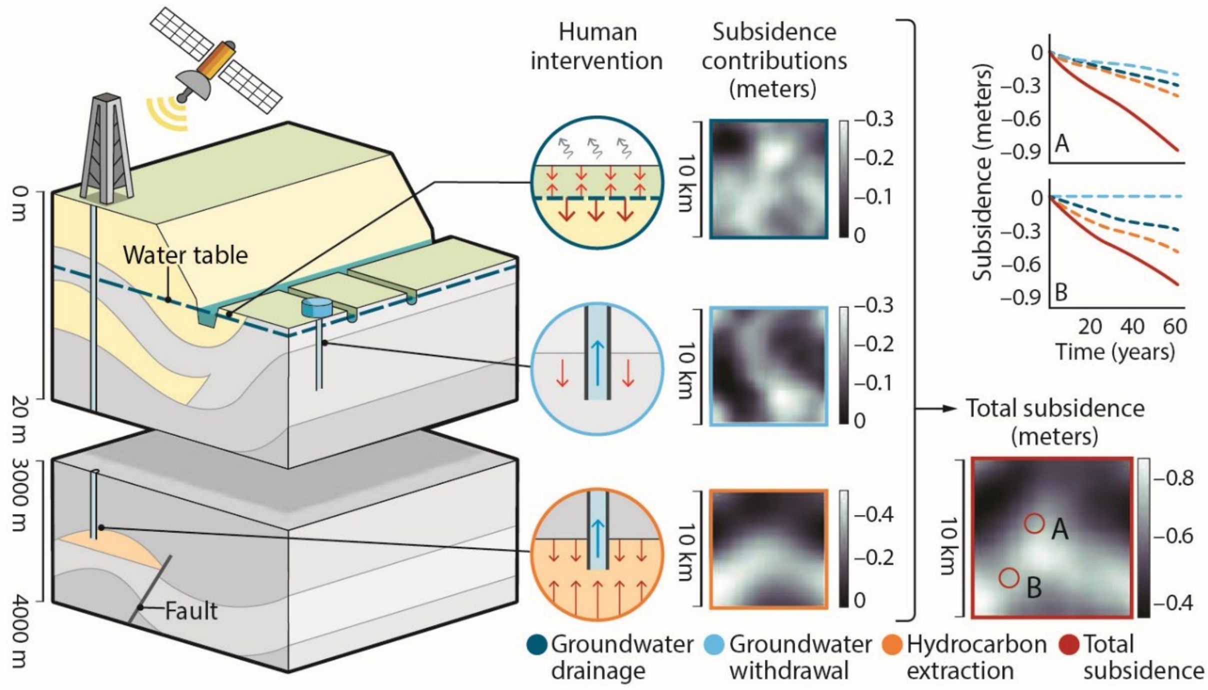

Figure 3-1 - Schematic overview of superimposed human-induced subsidence processes in a coastal setting (Candela and Koster, 2022).

Groundwater extraction takes place from aquifer systems at tens to hundreds of meters depth. The subsurface in many coastal plains commences with a succession of fine grained and organic material of Holocene age. In this setting, the coastal plain succession acts as an aquitard, requiring groundwater withdrawal from depths below the Holocene sequence. When the rate of withdrawal exceeds the rate of natural replenishment, pore pressures in the aquifer and surrounding aquitards decrease. Aquifers themself compact, depending on its geomechanical properties, primarily permeability, porosity, and compressibility (Gambolati and Teatini, 2024). However, aquitard compaction is considered the prime contributor in groundwater withdrawal related subsidence, due to its high compressibility. Thick aquitard sequences can compact for years after groundwater withdrawal is terminated.

Subsidence by groundwater extraction is often localized around pumping sites, nevertheless, especially for urban areas, many extraction sites can form larger clusters. Examples are the coastal plain of Belgium (Botey i Bassols *et al.,* 2023), where 20th century severe aquifer-system depletion resulted in almost 10 cm of subsidence; elevation loss partly recovered by elastic rebound of the aquifer system after excessive pumping was prohibited in the 1990s. That this form of subsidence is often concentrated around urban areas is exemplified by Tomás *et al.* (2013). In their overview paper of subsidence in Spain, they show that several coastal cities like Barcelona and surrounding urban centers, and Almeria on the east coast of Spain are subsidence as a result of groundwater extraction.

Human-induced coastal subsidence on the largest scale (10 - 100 km) is often the result of **artificially lowered phreatic groundwater levels**. Water levels are kept low to enable agriculture and urbanization on soft coastal soils. Prime examples are centuries of coastal subsidence along the clayey and peaty southern and eastern North Sea coasts, stretching from northern France, via Belgium and the Netherlands, into Germany and Denmark (Bogemans *et al.,* 2024; Hadler *et al.,* 2024; Koster *et al.,* 2018a; Ouchaou *et al*., 2024). For centuries, these subsiding areas were affected by a series of floods, resulting in loss of life and property, but also in changing coastal morphology. Twentieth century construction of modern coastal defense systems and water management infrastructures diminished the threat of flooding, however, subsidence progressively continues.

In several cases to reclaim land, the water levels of inundated coastal plains or open water bodies were completely lowered. Especially in the 20th century, coastal land reclamation commenced on industrial scales. Prime examples are the polders of Po river plain in Italy (Thiéblemont *et al*., 2024) and in Lake IJssel, the Netherlands (Fokker *et al.,* 2019). In the latter, after reclamation, the surface has locally been lowered by over 2 m in just over 50 years, primarily by the shrinkage of subtidally deposited clay beds. Locally, soft coastal plains have been improved by anthropogenic soils to raise their elevation or increase their load-bearing capacity. This is a practice that has been conducted for centuries in the peaty coastal plain of the Netherlands, resulting in anthropogenic soils of up to 5 m in thickness in urban centres such as Amsterdam (Koster, 2016). The stress induced by anthropogenic soil on peaty or clayey substrates instigates subsidence; after which areas are raised again. Due to the slow pace of peat and clay consolidation such processes can last for centuries. In the case of the Dutch coastal cities Rotterdam and Amsterdam it was found that the artificially raised soil is mitigating peat oxidation and CO2 emissions, as the meters thick overburden pushed surficial peat beds meters below the phreatic groundwater table, shielding it off from the atmosphere (Koster et al., 2018b). Negative consequences of artificially raised soil is the differential settlement of coastal linear infrastructures such as road and railways, as they cross different coastal morphological settings, resulting in increased maintenance costs. For example, in the Friesland coastal plain of northern Netherlands (Verberne *et al*., 2024). On the most local scale, buildings themselves can subside when constructed on soft coastal soil. In Tuscany (Italy) for instance, industrial buildings are identified that have been subsiding up to 45 years after their construction, with rates close to 5 mm/yr (Ciampalini *et al.,* 2019). Also cultural heritage sites can be damaged by differential settlement and tilting, especially when initial ground conditions are disturbed by modern influences such as increased water pumping activity, like the 1000 CE Porta Adriana in Ravenna (Italy) (Teatini *et al.,* 2005).

Coastal subsidence by hydrocarbon extraction takes place above fields both **onshore and offshore**. The largest onshore gas field of Europe is the Groningen gas field, in the northern coastal plain of the Netherlands, active from 1963 to 2023. The field covers an area of 900 km^2 with a maximum reservoir thickness of 240 m (van Eijs and van der Wal, 2017), resulting in a subsidence bowl with maximum depths of 30 to 40 cm (Fokker and van Thienen-Visser, 2016). Gas reservoir depletion both onshore and offshore Ravenna (Italy), resulted in local subsidence bowls with rates up to 5 to 10 mm/yr (Teatini *et al.,* 1998; Verberne *et al.,* 2025b). In both the cases of Groningen en Ravenna, the subsidence bowls created by deep gas extraction are superimposed to shallow subsidence processes resulting from phreatic groundwater level lowering and pumping.

The **second resource extraction from bedrock leading to subsidence** is near **coastal mining**. Subsidence stemming from mining activity is often concentrated very locally, and results from subsurface cavity compaction or collapse. For instance, in 1990, in Northern-Ireland, the cavity of an abandoned salt mine collapsed, resulting in the formation of a meters deep coastal depression that quickly inundated (Bell *et al*., 2005). A prime example of a coalbed exploitation that stretches out both onshore and offshore is the Durham coalfield, where the mining led to 4 to 5 m of subsidence (Humphries, 2001). Salt solution mining in the northern coastal plain of Netherlands happens at the greatest depths in the world, creating local scale subsidence bowls. The coastal Barradeel site for instance is mined since 1995 from a depth of 2.5 to 3 km, producing caverns with a radius of 20-30 m and a height of 300-400 m, with a maximum permitted subsidence of 35 cm (Fokker *et al.,* 2018). In the coastal plain of southern France, near Vauvert, salt solution mining resulted in the past decades in a subsidence bowl with a maximum depth over 50 cm, stretching out over more than 5 km (Furst *et al.,* 2021).

3.2. Detection and Projection Methods

Detection, measurement, and modelling methods include any of the previously listed VLM processes, such as natural processes (such as tectonic activity, isostatic rebound, volcanic activity, sediment compaction, or apparent vertical displacement caused by global and regional sea level changes) and human-induced processes (groundwater, oil and gas extraction, land reclamation, mining activities). From a measurement perspective, coastal vulnerability has also been assessed from horizontal or a mix of horizontal and vertical displacements with a larger horizontal displacement magnitude. These also include natural processes, such as the lateral retreat of shorelines due to wave action and tidal currents, the lateral collapse of coastal slopes, such as landslides that usually displace laterally but with an additional vertical component, and anthropogenic processes that are largely related to large-scale removal of sand from beaches or riverbeds that accelerate shoreline retreat.

The role of remote sensing datasets

Depending on each process and the availability of the data, the right datasets can be chosen to detect, estimate, and possibly predict the development of the studied phenomena. **Remote sensing techniques** have been the preferred methods for estimating VLM coastal vulnerability parameters because they offer extensive coverage, allowing a comprehensive overview, and ever-increasing temporal resolution. The availability of past remote sensing datasets is partially due to sensors coupled to airplanes operated historically by the military for cartographic applications and nowadays due to the increase of satellite missions. Among the different remote sensing techniques, several mapping capabilities have been used to assess different processes associated with coastal vulnerability. **Digital elevation models (DEMs) and military aerial photographs** transformed into photomaps through orthorectification processes are the preferred, if not the only direct, way to assess historical coastal processes over large extents. A good example is on the south coast of Portugal, in the Algarve, where photogrammetric methods have been used to detect and measure cliff retreats (Redwijk *et al.,* 2008 and

2010). The authors recovered and triangulated past aerial images from the military repository. After recovering these assets in a cliff failure inventory, statistical methods could then be applied to assess the instability of the cliffs correlated with predisposing factors based on geology and geomorphology and perform assessments on a regional scale (Marques *et al.,* 2013).

Multispectral and hyperspectral images such as Sentinel-2A can also be used indirectly to trace tracks in vegetation and directly to measure the rate of change in the shoreline in mm/year (Pardo-Pascual, 2012; Boumboulis *et al.,* 2021; Hastuti *et al.,* 2022). DEMs extend these estimations and analyses by providing the height dimension. Although in the past, digital elevation models (DEMs) were also obtained by photogrammetry techniques together with land surveying, now other remote sensing methods have been playing a role. Airborne Light Detection and Ranging (LiDAR) on top of manned and now Unmanned Aerial Vehicle (UAV) (Chust *et al.,* 2010; Stockdon *et al.,* 2002; Schmid *et al.,* 2011; Klemas, 2013), facilitate the surveys and radar systems. those used in the Shuttle Radar Topography Mission (SRTM) provide regular updates of coastal environments enabling automated mapping (Kulp & Strauss, 2018; Zhang *et al.,* 2019). Techniques based on **Global Navigation Satellite Systems (GNSS)**, especially when utilizing Network or Real-Time Kinematic positioning and total stations, offer precise and efficient location data for accurate reconstruction of beach and dune morphometry despite the limited number of measurable points**. Terrestrial Laser Scanners (TLS)** are also known for their high precision but often require extensive survey sessions and lengthy data processing.

Recent advancements in **radar interferometry**, specifically **Interferometric Synthetic Aperture Radar (InSAR)**, have emerged as highly effective tools for monitoring coastal degradation processes. These technologies provide exceptional temporal resolution and extensive spatial coverage, largely due to the launch of Sentinel-1 as part of the Copernicus program, along with the accessibility of its imagery at no cost. InSAR effectively measures ground movement, which is crucial for assessing changes in coastal landscapes. Moreover, its integration with other technologies allows the derivation of high-resolution digital elevation models and the evaluation of displacement rates, which are instrumental in estimating coastal erosion and evaluating potential flood scenarios.

However, it is essential to recognize that while remote sensing offers invaluable data and insights, it does not preclude the continued use of ground-based, in situ measurements, or other complementary remote sensing techniques. Traditional methods remain essential to validate and complement remote sensing data. For example, InSAR measurements require several processing stages with numerous parameters customized to specific case studies. At larger scales, such as national or continental assessments of EGMS, complementary datasets are needed for validation.
This can be validated with: 1. complementary GNSS or levelling campaigns for time series estimation consistency (Martins *et al.,* 2024); 2. LIDAR for height estimation (Martins et al., 2025b); 3. Corner reflectors for geopositioning accuracies (Martins *et al.,* 2024), among other validation approaches that include ancillary data or geological constraints depending on the type of deformation process (Calero *et al.*, 2023; Calero *et al.,* 2024).

In recent years, **machine learning algorithm development** and the increase in **big data computational power** have opened new capabilities to harvest the aforementioned data from remote sensing techniques for coastal applications. Several studies report on using deep learning techniques to detect coastlines and shorelines, coastal variations due to climate change or classification of soft cliff dynamics (Pradeep *et al.,* 2022; Dang *et al.,* 2022). A pertinent example is the global study of Kulp and Strauss (2019). Using a new DEM derived from applying neural networks to reduce SRTM error (called the CoastalDEM), the authors predict three times what would have been predict using SRTM-based values. The authors predict that "190M people (150–250 M, 90% CI) currently occupy global land below projected high tide lines for 2100 under low carbon emissions." This highlights the pressing need for accurate elevation data to help us understand coastal vulnerability in response to sea-level rise. In summary, combining advanced remote sensing techniques, traditional validation methods, and machine learning approaches presents a comprehensive framework for assessing coastal vulnerabilities. It underscores the necessity of continued research in this critical area.

Spatio-temporal modelling techniques

Different families of methods exist to extract the spatiotemporal components of the phenomena while leveraging each type of data used.

Geostatistical and statistical methods are amongst the most used. Purely spatially speaking, when data needs to be interpolated and spatial variability needs to be mapped, such as erosion or sedimentation, kriging and its variants are good initial approaches. **Autoregressive models or semivariograms** can help identify spatial dependencies in coastal processes and quantify spatial correlations in ground motion or shoreline changes. Purely in time, **temporal statistical models** such as time series analysis fitting linear, polynomial or more complex models allow us to estimate trends and understand the temporal behavior of the data being used. Moving window regression techniques can capture temporal shifts. However, within the statistical methods, **multivariate data analysis** has proven to be the most efficient yet complex way to analyze spatiotemporal data. These methods, reducing the dimensionality of complex datasets (such as long time series of a large number of measurement points such as the ones resulting from InSAR), can also help reduce the analysis time. These methods can go from traditional principal component analysis (PCA) to models involving ML approaches such as autoencoders (Manders and Martins, 2024).

Many of these methods are applied to remote sensing datasets through physical modelling to simulate the underlying processes driving coastal vulnerability. GIS-based methods are used to map scenarios and perform easy and quick buffer and geospatial overlay analysis.

3.3. Link with Relative Sea-Level Changes

Sea-level rise (SLR) along coastal areas is often expressed as **relative sea-level rise (RSLR)**: the sum of SLR and VLM. This means that from a subsiding coastal area's point-of-view SLR is amplified. In general, **human-induced subsidence rates** are one or two orders of magnitude higher than **natural rates**. Therefore, RSLR primarily affects populated coastal zones with abundant human subsurface activities. The strong connection between human subsurface activities, resulting subsidence, and consequently RSLR, has made it the most imminent natural hazard for coastal Europe since ancient times.

Human-induced RSLR has been threatening inhabitants of coastal Europe for millennia, even in times when global mean sea-levels were not rising. In the Netherlands for instance, archaeological evidence was found indicating that humans drained the peaty plains of several estuaries from the Late Iron Age onwards (ca. 2500 years BP), leading to decimeters of subsidence and RSLR (Vos, 2015; Pierik *et al.,* 2017). To mitigate the threat of floods, inhabitants designed a series of dikes and novel drainage infrastructures. Despite their efforts, the area was severely affected by floods and coastal inundation, resulting in depopulation. However, the tides brought-in sediments, covering the peaty plain with clay and sand, enabling settlers to return centuries later. Eventually, alternating periods of subsidence, RSLR, floods, abandonment, sedimentation, and return, would last until modern times (Vos, 2015). This pattern has also been observed along the coastal plains of Belgium and northern France, which were affected by human-induced RSLR at least since Roman times (Bogemans *et al.*, 2024; Ouchaou *et al.,* 2024).

Another hotspot of coastal land loss by RSLR instigated by **anthropogenic subsidence** is the Late Middle Ages Wadden Sea region of Denmark, Germany, and northern Netherlands (Vos and Knol, 2015; Hadler *et al.,* 2024). There, entire settlements including houses, churches and agricultural infrastructure can now be found submerged offshore resulting from RSLR (Wilken *et al.,* 2024). This dramatic result of RSLR is because of subsidence instigated by centuries of coastal peatland drainage and exploitation. The drowning of European coastal land in the Middle Ages and onwards was not necessarily a gradual process; large parts of the coastline were already embanked, therefore the drowning of subsided land was often sudden when embankments breached during storm surges.

Increased deforestation during and after Roman times resulted in coastal and delta progradation in many areas around the Mediterranean Sea (Maselli and Trincardi, 2013). However, in view of contemporaneous SLR, this has been leading to a peculiar type of coastal land loss. The driving force of land loss is sediment decline by modern levee construction and damming of river branches. This hampers sediments from reaching the shores, making them unable to withstand SLR. When these plains are also subjected to subsidence, like the Ebro Delta in Spain which has been sinking with <1 to 2.3 mm/yr during the past decades (Rodriguez-Lloveras *et al.,* 2020), RSLR is severely threatening the viability of these areas.

At present, in view of global SLR, the awareness of incorporating coastal VLM to determine future impacts has been growing. Many SLR projection studies have been incorporating the effects of GIA, including the IPCC (Oppenheimer *et al.,* 2019). However, in many European coastal areas, the effects of GIA relative to human-induced subsidence, are negligible. Often, these studies acknowledge the existence of human-induced subsidence overprinting natural rates, they neglect them in their analyses because of the lack of large spatial scale models and data. In practice, neglecting human-induced VLM results in mismatches between regional and local RSLR predictions. For instance, Li *et al.* (2024), found mismatches for the Oka estuary in northern Spain between IPCC projections that rely on large regional GIA models and local observations. By incorporating Holocene timescale sea-level data and measurements from GNSS stations they improved local projections, although modern human components were not disentangled from natural drivers. Also **for sea-level projections on European scales, the use of local VLM data is promoted** (Melet *et al.*, 2024). In their comprehensive overview of regional to local scales RSLR in Europe, they present a selection of natural and human-induced VLM drivers and techniques that the SLR-community could utilize to determine local rates, promoting future use of EGMS.

Nevertheless, the awareness within the SLR-community that VLM besides GIA should be incorporated in future sea-level projections is growing, primarily on large spatial scales (Nicholls *et al.*, 2021; Oelsmann *et al.,* 2024). On more local scale, several studies focused on the impacts of VLM on RSLR for low-lying urbanized coastal plains of Italy, although they do not rely in subsidence models (e.g. Antonioli *et al.,* 2017; Aucelli *et al.,* 2017). They found for instance in the Volturno River plain that the surface area lying below mean sea-level will increase by 50% until 2065, based on the IPCC most extreme scenario (RCP 8.5). In total, the Italian coastal plains can lose 5500 km2 of surface area by RSLR in 2100.

3.4. First pan-European Contemporary Coastal Vertical Land Motion Assessment Based on EGMS

Mapping vertical ground movements on a supra-regional scale has long been a challenge hampered by a lack of suitable data and services. Coastal subsidence hot-spots could be identified through dedicated local to regional InSAR studies, GNSS and tide gauge measurements or levelling surveys (Raucoules *et al.,* 2008; Wöppelmann *et al.,* 2013; Raucoules *et al.,* 2013; Poitevin *et al.,* 2019), but such analyses were not possible at the whole European coast scale. To overcome this obstacle, a consortium of European researchers combined radar interferometry (InSAR) and the Global Navigation Satellite System (GNSS) and developed the Copernicus European Ground Motion Service (EGMS).

As part of GSSEU, BRGM leads this work carried out in close collaboration with CoCliCo project (Coastal Climate Core Services; European Union's Horizon 2020 research and innovation programme)[1], using data from the European Copernicus Land Monitoring Service, EGMS service and CLC, and the SONEL platform.

The EGMS product

EGMS uses Synthetic Aperture Radar Interferometry (InSAR) data derived from Sentinel-1 to detect and measure ground movements across Europe with millimeter precision. The EGMS aims to provide consistent, updated, standardized, harmonized across national borders and reliable information regarding natural and anthropogenic ground motion phenomena over Europe (Crosetto and Solari, 2023). EGMS relies on the advances and improvements of the advanced Differential InSAR (A-DInSAR) data processing and analysis techniques, also referred to as Persistent Scatterer Interferometry (see Crosetto *et al.,* 2016; Crosetto *et al.,* 2021). EGMS products are being made by the consortium ORIGINAL (OpeRatIonal Ground motion INsar Alliance) comprising four different InSAR Processing Entities using methods proven over the last two decades. All algorithms and methods used to produce EGMS products are detailed in the document *Algorithm Theoretical Basis Document* (Ferretti *et al.,* 2023).

Methods

The study of **Thiéblemont *et al.* (2024) performed the first pan-European analysis of contemporary vertical land motion in coastal flood plains (CFPs) based on EGMS** (Figure 3-2). They relied on the first update of the Ortho product (Level 3) covering the period 2015-2021 (released in 2022), which provides horizontal and vertical land velocity components resampled on a 100 m resolution grid and anchored to a geocentric reference frame GNSS model. Datasets were obtained from EGMS web portal[2], where 100 km x 100 km geotiff raster tiles of the vertical velocity can be downloaded. More than 400 tiles were downloaded to cover the entire European coast and were merged into one large pan-European raster file. This file was then clipped to a European coastal mask that include a 1 km wide shoreline band and 41,000 CFPs (Lincke *et al.,* 2022). CFPs are contoured using the 30-m resolution

[1] https://coclicoservices.eu/
[2] https://egms.land.copernicus.eu/

Copernicus Digital Surface Model GLO-30 (ESA Sinergise, 2021), considering a bathtub flooding approach (including hydraulic connections) calculated for a 1-in-100-year event combined with a 2-m sea-level rise.

Figure 3-2 - Location of coastal flood plains (CFPs) in Europe (in black) as defined in Thieblemont *et al*. (2024).

The geodetic reference frame used to calibrate EGMS can strongly affect the vertical land velocity estimates and needs to be accounted for carefully, especially for coastal applications where the need of sub-mm/yr precision in VLM is required for comparison with SLR changes (as opposed e.g. to landslides or earthquakes that are also characterized by EGMS). The GNSS model used to calibrate EGMS is constructed from the EUREF network expressed in the European geodetic reference frame ETRF2000. As coastal sea-level applications require precision and stability of positioning of the geodetic reference frame, VLM are generally expressed within ITRF (Wöppelmann and Marcos, 2016). In comparison with using ITRF2014, Thiéblemont *et al.* (2024) found that ETRF2000 leads to an overestimated subsidence that increases with latitude and that needs to be corrected.

Key results

The European assessment of the mean vertical land motion in CFPs based on EGMS found that **50% of the European CFPs spatial extent is, on average, experiencing subsidence at a rate stronger than 1 mm/yr** and **10% are uplifting at a rate larger than 0.5 mm/yr**. If the GIA contribution is removed, it reduces the CFPs area uplifting to 5% and the CFPs area subsiding at rates lower than 1 mm/yr to slightly less than 20% (on average). This shows the substantial first-order effect of GIA in both land uplift and subsidence trends across Europe. The results at the country scale are shown on Figure 3-3**.**

The vertical range velocity classes are simplified and assume that uplifting (subsiding) CFP corresponds to an average larger (lower) than 1 mm/yr (-1 mm/yr) and is considered as stable otherwise (i.e. in the range -1 to 1 mm/yr). As expected, CFPs of northern European countries (i.e. Norway, Sweden, Finland and Estonia) are mostly uplifting on average as a consequence of the GIA effect. Just southward of these four uplifting countries, Latvia, Lithuania, Denmark, UK and Ireland show rather stable vertical land motions, and further south, a widespread subsidence (with exceptions such as Belgium). More specifically, In Germany and the Netherlands, a vast majority (near 75% of the total area) of CFPs are experiencing an average subsidence, which is consistent with the combined effect of GIA and more localized subsidence of other origin (see Introduction). Among the countries of southern Europe with expanded CFPs, Italy, Greece and Romania have more than 75% area of their CFPs that are subsiding on average. Finally, in the Western Europe, more than half of CFPs in France and Portugal are subsiding on average.

Beside the use of EGMS for the continental and country-scale assessment, the study also demonstrates how to take advantage of the pixel scale estimate. It identified subsiding coastal areas (e.g. Schiavonea) that were not previously recognized or considered in previous pan-European coastal impact assessments. The averaged results combined with the European land cover dataset allow drawing a significant overall behavior. Indeed, they found that **urban areas and ~16 million residents are experiencing almost a 1 mm/yr subsidence on average** (if discarding the uplifting regions due to GIA). For coastal airports and for harbors, the average land motion drops to a 1 to 1.5 mm/yr subsidence leading to a substantial relative sea-level rise enhancement locally. Indeed, this locally enhances the relative SLR rate by about one third (in comparison with the ongoing climate-induced regional mean sea level in Europe which has risen by an average of 2-4 mm/year over the past 30 years[3]) and demonstrates the significance of subsidence in Europe when considering coastal flood risk. This may have direct consequences on emerging risks and 21st century sea-level rise adaptation planning, and need to be considered to update previous coastal flooding risk assessments (e.g. Hauer *et al.,* 2021).

Coastal adaptation practitioners need to determine whether observed Vertical Land Motions (VLMs) can be reliably projected into the future, as this is crucial for refining sea-level scenarios used in risk assessment and adaptation planning. Another key challenge is supporting decision-making for specific infrastructure, as EGMS data reveal that some coastal defenses, such as dikes, are subsiding,

[3] https://climate.copernicus.eu/climate‑indicators/sea‑level

potentially due to their own weight. Ensuring continued EGMS observations is essential to confirm trends and detect non-linearities.

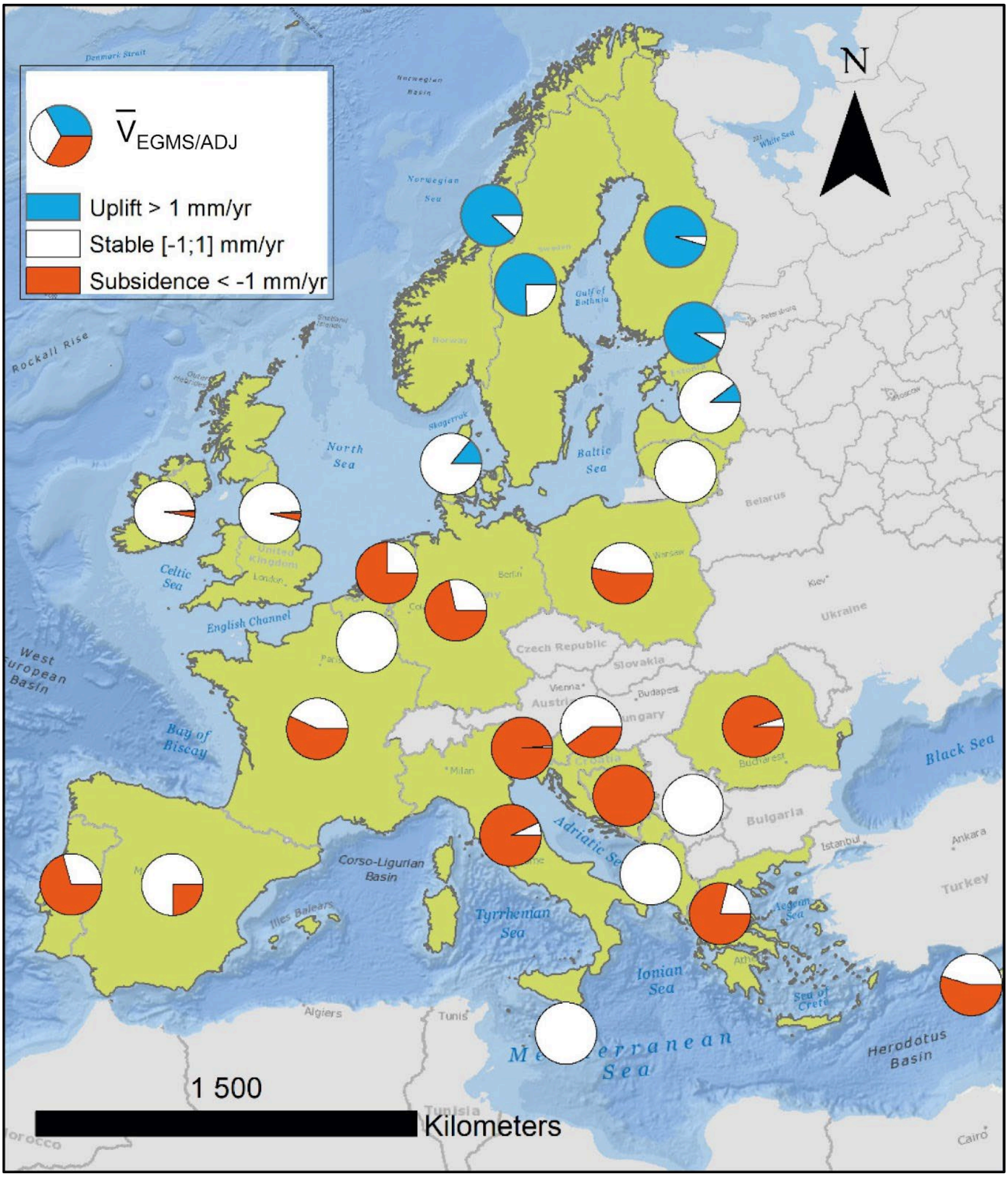

Figure 3-3 - The distribution of in the coastal floodplain per European coastal country. The blue, white and red areas indicate the proportion per country of coastal floodplain area that are, on average, uplifting (> 1 mm/yr), stable (between -1 mm/yr and 1 mm/yr) and subsiding (<- 1 mm/yr), respectively (Source: Thieblemont *et al.,* 2024).

Despite these challenges, our study highlights the potential for a dedicated service to support coastal adaptation, complementing EGMS and similar global initiatives. While EGMS is part of the Copernicus Earth Observation programme, transforming its data into actionable insights for coastal practitioners requires further analysis.

3.5. Automatic Tools to Analyses the InSAR Time Series and Extract Patterns of Motions: Application to the Coastal Area in UK

This work, carried out by the British Geological Survey (BGS) focuses on automatic tools used to analyses InSAR time series and extract patterns of motions, and applies to the coastal area in UK.

Methods

In this framework, BGS used a Seasonal Trend Linear-decomposition and Piecewise Linear Regression (STL-PLR) tool developed in-house (Hourston et al., 2024). This tool decomposes EGMS time series into a general segmented trend, its seasonal component, and residual signals (Figure 3-4), by first applying the Seasonal Trend Linear-decomposition (STL) to extract the trend and seasonality components of the signal. Then, an automated piecewise linear regression (PLR) is used to fit the trend with a variable number of linear segments, depending on the trends in the displacement time series.

This technique allows BGS to expand beyond merely distinguishing between uplifting, subsiding or stable indicators provided by most tools analyzing patterns within InSAR time series. Indeed, by using the STL-PLR they can define a new category of "non-linear" moving points, B by identifying breakpoints at which time the motion pattern changes, either by accelerating or decelerating. The stable category is determined by a deformation velocity threshold, which corresponds to 1.5σ, where σ is the standard deviation of the deformation rate of the UK's coastlines. Any InSAR point moving at a rate within plus or minus this number is assigned "linear-stable". The variable number of linear segments used in the PLR is determined by gradually increasing the number of segments being used to fit the trend and comparing the resulting adjusted R^2 coefficient of both models. If the increase in the new model's adjusted R^2 is larger than 3%, then the more complex model is accepted, and again a new segment is added. This process continues until this increase in adjusted R^2 becomes equal to or smaller than 3%, at which point BGS consider the algorithm to have converged, and the necessary label is assigned to the timeseries. The algorithm also calculates the deformation velocity of each segment present in each time series, and attaches the corresponding observation date at which each segment begins and ends in a Python dictionary, creating a full database of the deformation velocities and the periods of time at which these velocities are sustained. BGS has defined four classes: linear-stable, linear-uplift, linear-subsiding, and non-linear. Any time series with a breakpoint within the series are assigned to the non-linear category (Barnard *et al.,* 2024; Hourston *et al.*, 2024). BGS also has the capability to create another category of InSAR points which show strong seasonal trends, due to the STL aspect of the algorithm which provides a strength rating describing how strongly influenced the InSAR signal is by seasonal behaviors. Seasonal behaviors of ground motion are largely due to the superficial geology (such as peat), or the bedrock in cases of clay-related shrink-swell motions.
A further tool BGS has developed is the Non-linear Time series Analysis tool that was developed to further break down the non-linear grouping into more accurate descriptions of the ground motion behavior. The addition of this tool allows to identify 10 basic types of ground motion behavior (Figure 3-5).

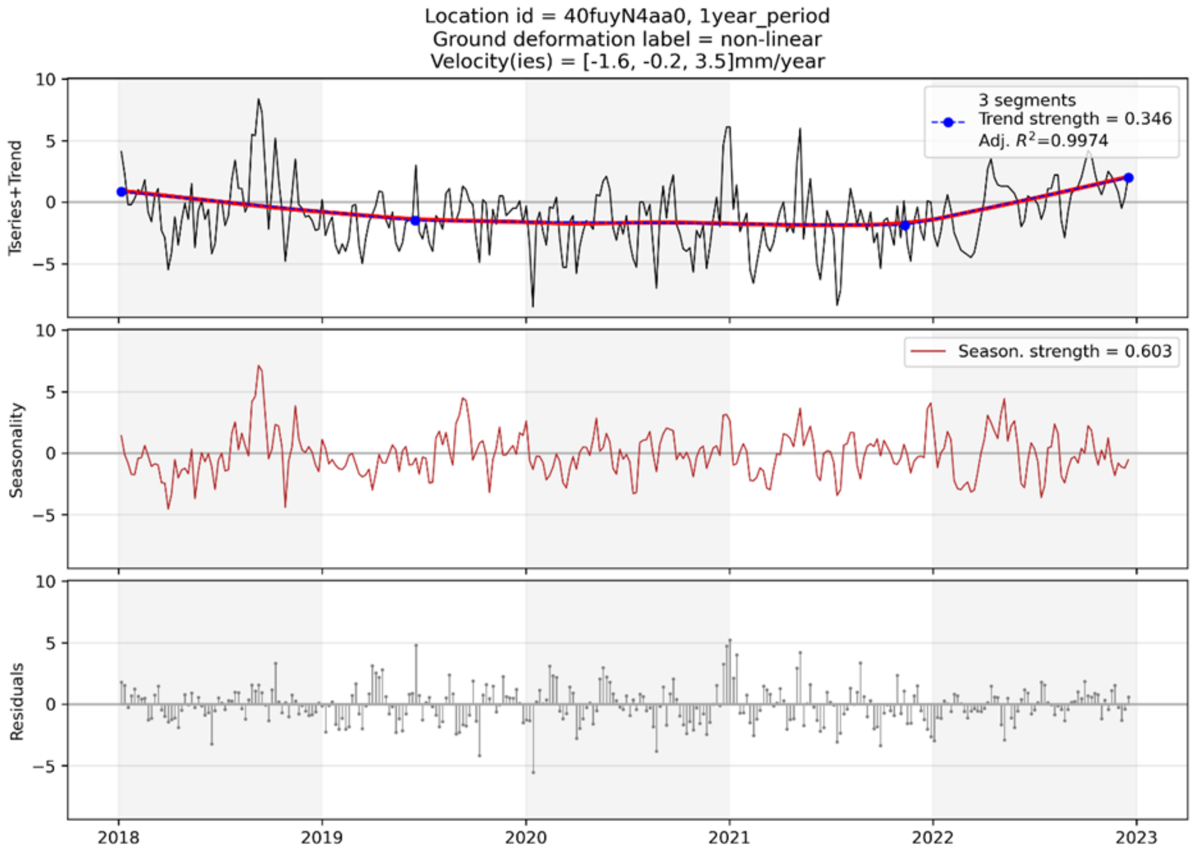

Figure 3-4 - An example of a seasonally decomposed InSAR time series from England, demonstrating a non-linearly behaving ground deformation pattern. The velocities listed in the title correspond to the three segments determined by the STL-PLR algorithm. The seasonal strength of this signal is 0.45, determined by the STL algorithm, and indicates that 45% of the signal is dominated by seasonal motions. Therefore, the deformation cannot be largely due to a seasonal driver such as rainfall and is more likely to be related to anthropogenic activity on the surface, or unseasonal weather changes such as heatwaves.

The tool takes the breakpoints in time and the deformation rates of each segment (both determined by the STL-PLR tool during the regression) and depending on a user-specified threshold, assigns the velocities of each segment to a color. The tool then visualizes the time series as a horizontal bar from the observation start date to the end date, with each time segment colored in a user-specified color scheme representing its velocity of deformation. This provides a more accessible way to communicate the accelerations or decelerations of the ground in an area of interest. One example of how the tool works is shown in Figure 3-6, which has taken 27 InSAR MPs over Hatfield Moors, a peatland in eastern England, and visualized the deformations through time as a series of colors.

BGS applied the STL-PLR tool to the Level 3 (ORTHO) 2018-2022 EGMS-derived vertical deformation times series over England and Wales. This results in a classification being assigned to each InSAR measurement point. To enable better decision-making for coastal managers, who are typically interested in spatially broad patterns of motion, it needs to spatially and visually simplify these measurements. BGS do this first by assigning each InSAR pixel with an elevation according to the 50m resolution NEXTMap British Digital Terrain Model (Intermap Technologies, 2007).

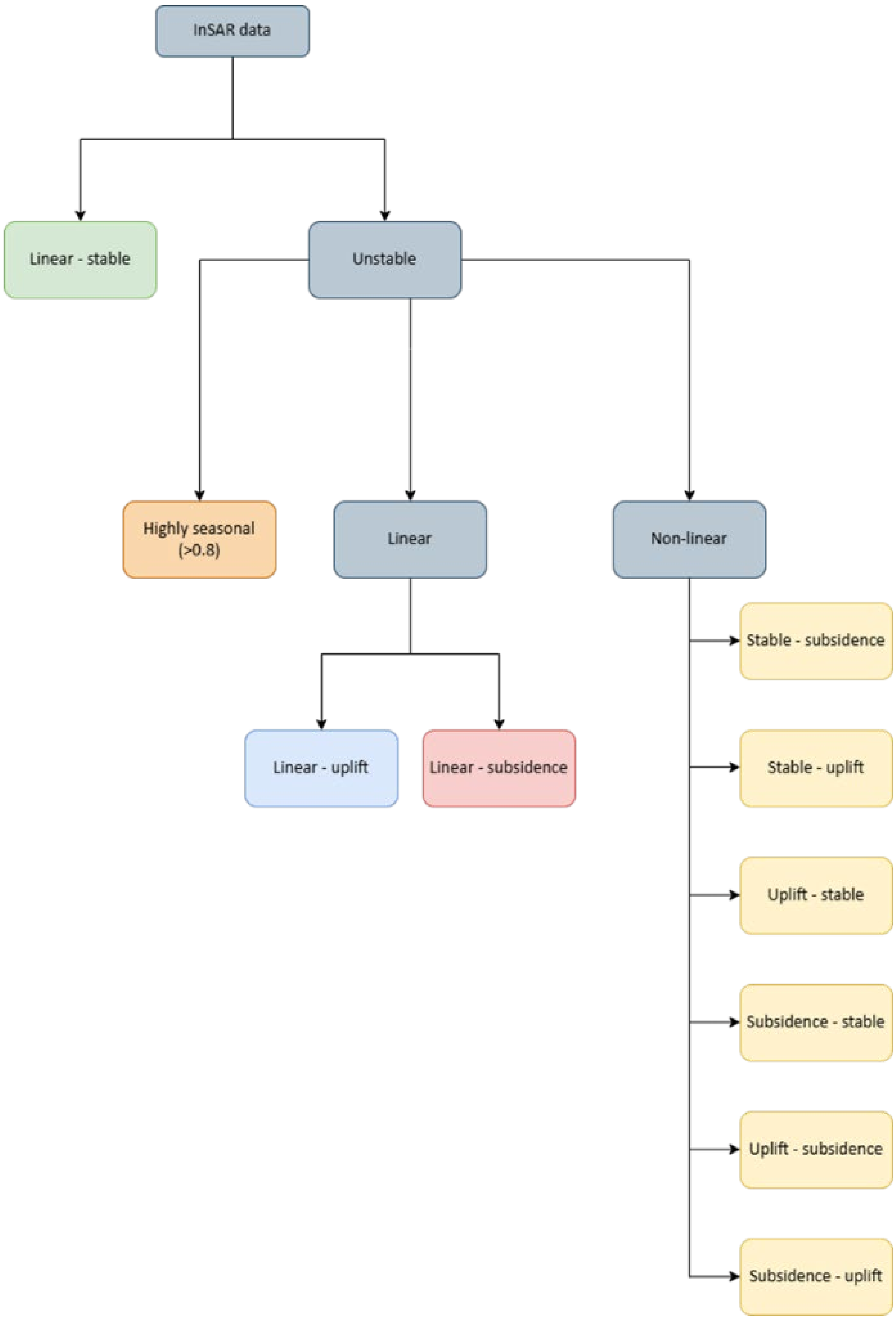

Figure 3-5 - A chart demonstrating the 10 possible groupings of our Linear and Nonlinear Time series Analysis tools.

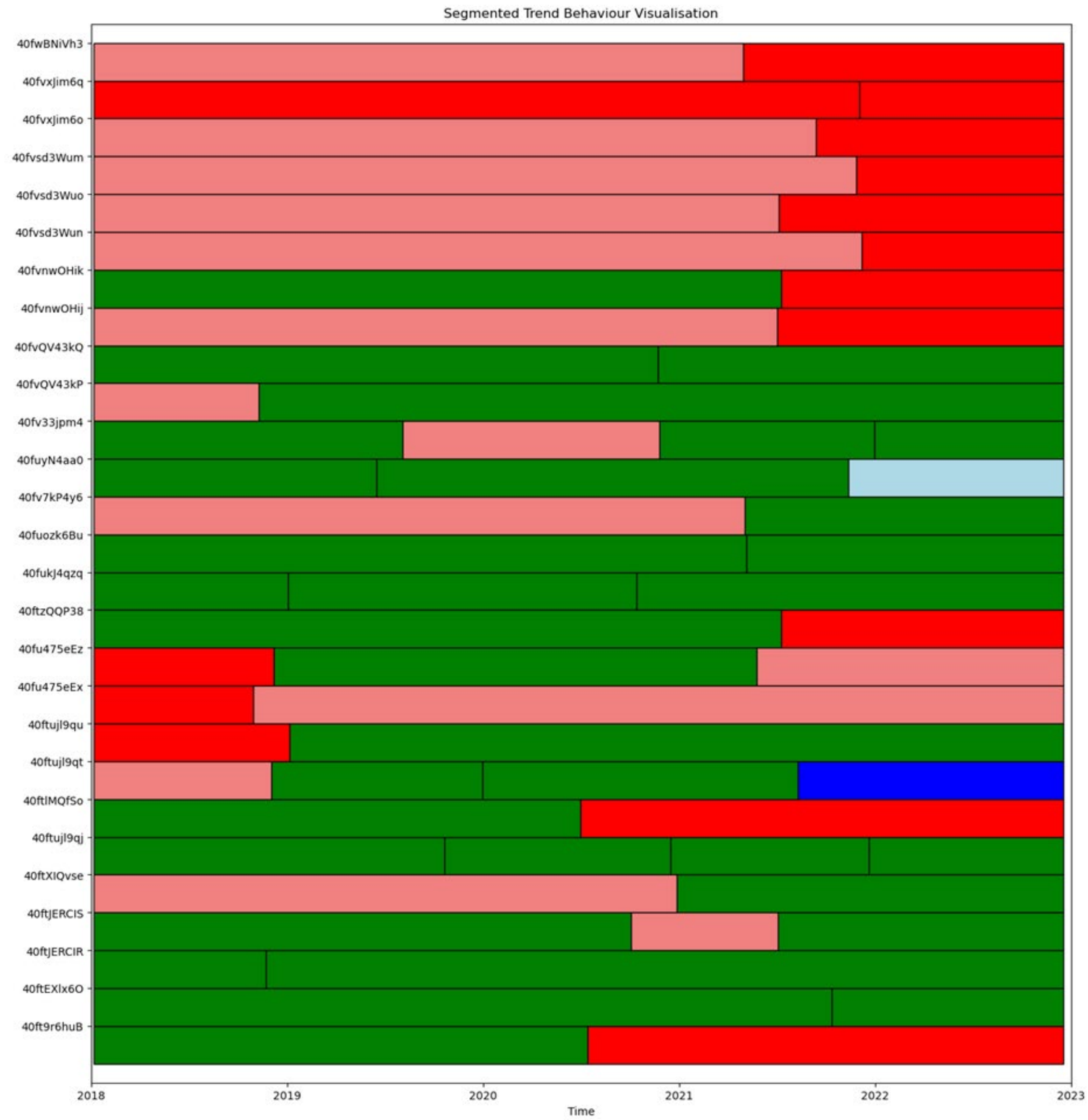

Figure 3-6 - The results of the Nonlinear **I**nSAR Time series Analysis tool over Hatfield Moors. The EGMS identification labels are on the y-axis, the length of observation on the x-axis. This user specified that the darkest red color represents subsidence quicker than -4 mm/year, the pale red represents subsidence between -2 and -4 mm/year. The green bars indicate a stability threshold, which in this example is any deformation rates between -2 and +2 mm/year. The pale blue bars are uplift between +2 and +4 mm/year, and the darkest blue is uplift at rates quicker than +4 mm/year (Source: BGS)

Then, BGS extracts all pixels located at elevations ≤10m which predominantly reflect coastal lowland areas. They manually remove isolated in-land pixels, which are related to mining and quarrying activities, and produce a 1x1 km grid over the UK and determine the modal deformation behavior of all pixels within each grid (Figure 3-7). BGS's tool then enables plotting simplified barycenter (median and mean) time series of all pixels within each of the grids (Figure 3-8). BGS finally compared the predominant motion pattern with both the bedrock and superficial geology available at 50k through the BGS Geology dataset[4] to support interpretation of the potential source of ground motion observed over large areas.

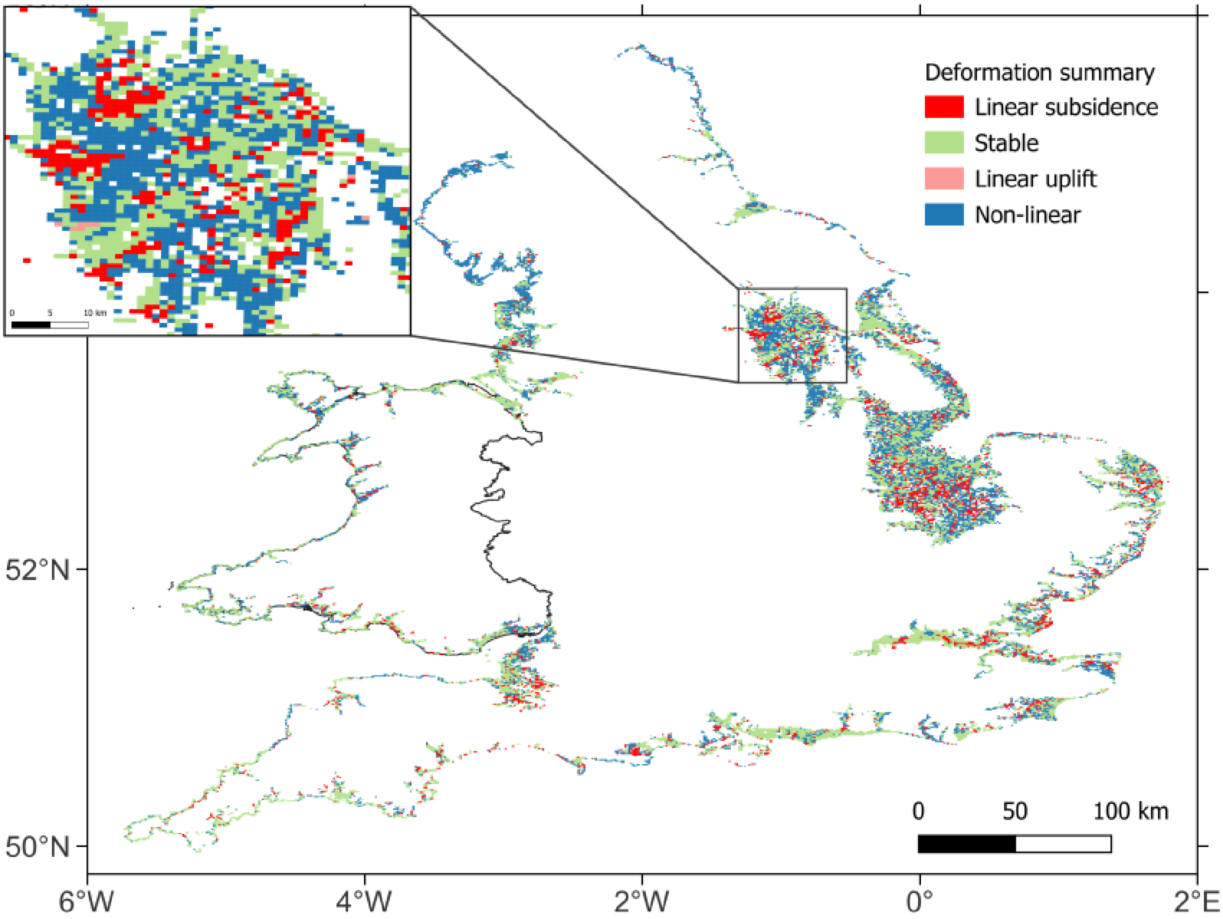

Figure 3-7 - Spatial summary of deformation time series trends across coastal lowlands of England and Wales (Source: BGS)

Key results

Results show that 13.9% (equivalent to 2,243 km^2) of the coastal region in the south and east coast of England exhibit predominantly linear-subsidence deformation behavior, 47.5% (7,659 km^2) is stable and 0.2% (36 km^2) show linear-uplift behavior. The dominant deformation pattern is non-linear with 38.4% (6,188 km^2) of the coastland lowland areas showing this behavior in the time series. Majority of the uplifting points are in the north-east of England, where the geology is largely limestone, sandstone and siltstones and the south-east, lying on clay formations.

A good spatial correlation can be highlighted with the superficial geology; subsidence (linear and non-linear) dominates in areas of thick superficial peats, clays and silts such as the alluvium along the Thames Estuary and the Fens area north of Cambridge. Areas predominantly composed of superficial sands and gravels show greater stability. Within the subsidising areas the identification of non-linear

4 https://www.bgs.ac.uk/datasets/bgs-geology-50k-digmapgb/

behavior is key to understanding the timing of subsidence change which helps make the link to the underlying process and hence enables a consideration of how the process might change in response to climate change.

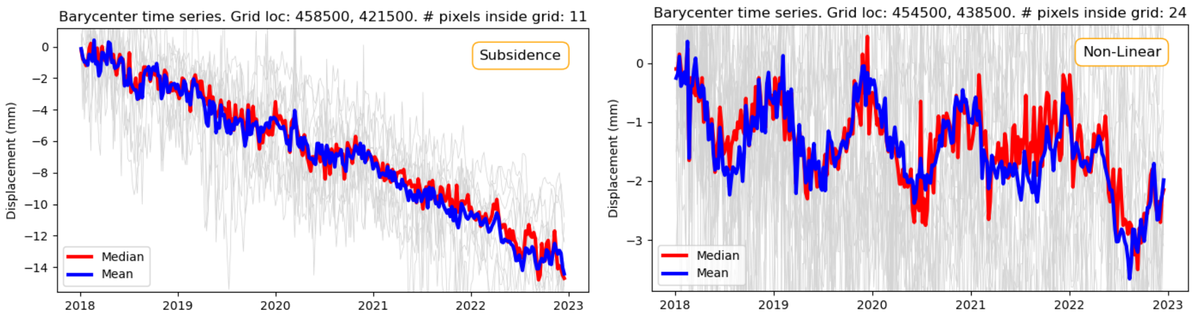

Figure 3-8 - Examples of barycenter time series for selected points indicated in the inset on Figure 3-7 for linear subsidence (left) and non-linear motion (right). Grey lines are the individual pixel time series while the red and blue are the barycenter median and mean respectively (Source: BGS)

Coastal VLM, and subsidence in particular, represent a major threat for the coastlines of England and Wales with linear and non-linear velocity rates of -30 to -40 mm/yr in some areas, which is more than two times the rate of SLR expected by the Intergovernmental Panel on Climate Change (IPCC, 2021) by 2100. So identifying and characterizing VLM along the coast now is a key aspect to mitigate the impact of natural hazards in the future. The ML tools developed will allow BGS to process these large amounts of EO data in a timely manner, and automatically extract areas of active ground movement to inform policy makers, local governments and hazard warnings, which is particularly relevant given the increasing frequency and severity of storms facing Britain due to climate change.

British GSO will further expand this work to better analyze in detail the effects on the relationship between of geology (superficial vs bedrock and anthropogenic deposits/factors) and on ground stability conditions with a particular focus on identifying the causes of non-linear motions and the acceleration or deceleration observed in time series. Finally, we will also incorporate impact-related information including people and assets exposed to coastal hazards.

3.6. Emblematic Case Studies as Coastal Subsidence Hotspots

In addition to its use for pan-European assessment, EGMS is also highly relevant to detect and characterize low-lying coastal region in state of subsidence. An example is provided on Figure 3-9 for two very large subsiding coastal flood plains and two more localized ones, but with a very strong subsidence.

Some of these particular cases of coastal subsidence hot-spots will be illustrated in this section by national case studies in the Netherlands (from TNO), France (from BRGM), Greece (from HSGME) and Italy (from ISPRA).

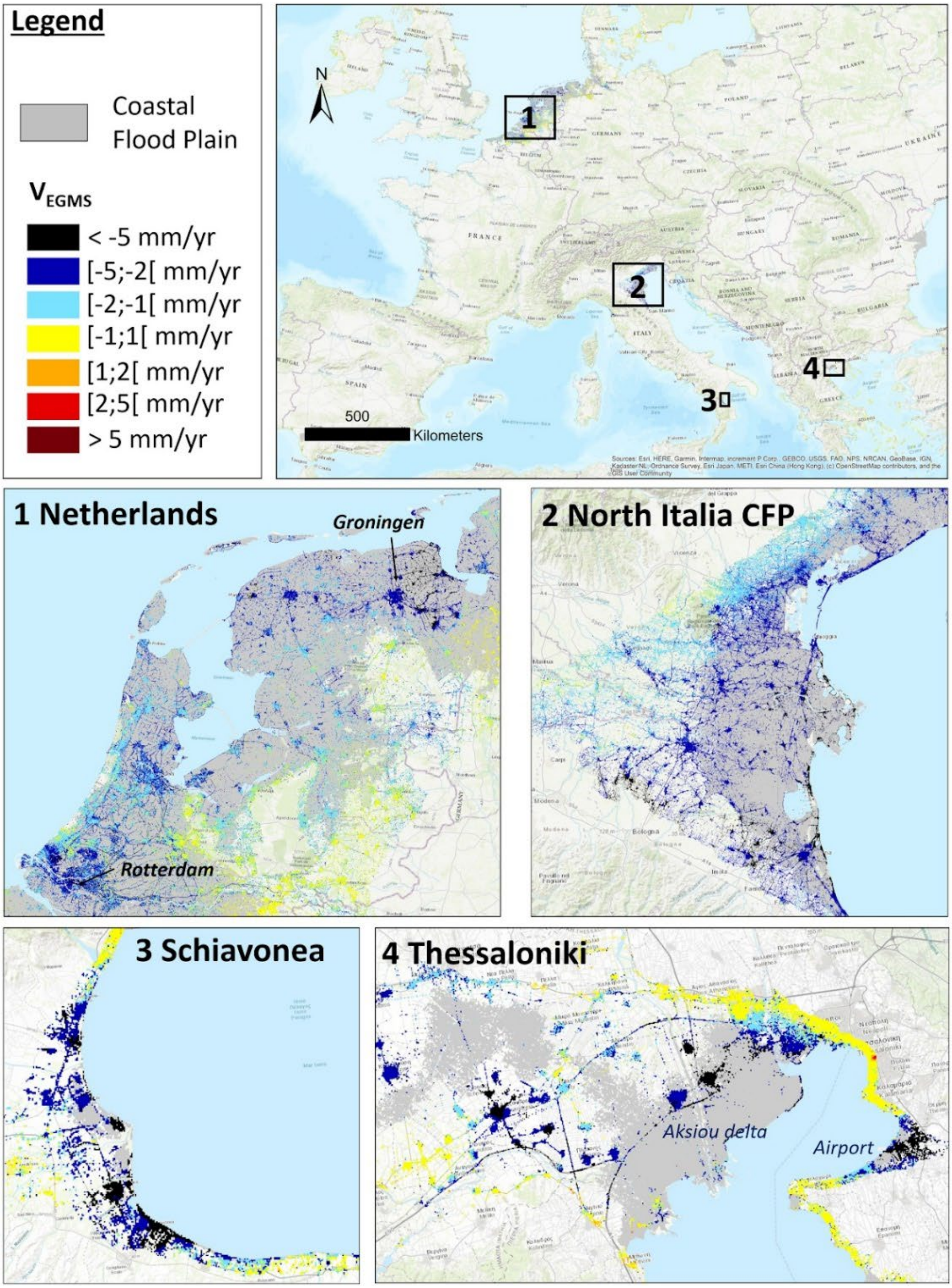

Figure 3-9 - Illustration of two large scale subsidence hot-spots in the Netherlands (1), Northern Adriatic (2), and two local scale subsidence hot-spots around Schiavonea in Italy (3) and Thessaloniki in Greece (4). Coastal flood plains are shaded in grey, and EGMS pixels and associated land vertical velocities are coloured (see Legend) (Source: Thieblemont et al., 2024)

Subsiding reclaimed coastal polders: case study in the Netherlands

Approximately half the surface area of the Netherlands is a low-lying coastal plain. This coastal plain accommodates most of the countries' major urban and economic centers. At present, approximately half of this coastal plain subsided below mean sea-level, primarily resulting from peatland mining and drainage (Koster *et al.,* 2018a). Large parts of the coastal plain that is now elevated above mean sea-level reached these elevations after a series of inundations and floods, resulting from coastal subsidence by artificial drainage of soft soil. The newly brought-in sediments elevated parts of the area to coeval mean high-water, re-elevating the area (Koster *et al.,* 2020). Most of the peatlands subside with rates of <1 - 5 mm/yr (Conroy *et al.,* 2024). Locally, superimposed on shallow subsidence processes are hydrocarbon and salt mining activities, with maximum subsidence up to 40 cm (Fokker *et al.,* 2018).

Among the fastest subsiding coastal areas in the Netherlands are the reclaimed Flevoland polders. These polders were reclaimed from coastal Lake IJssel in the 1960s. The lake bed consisted of a sequence of tidal deposits (mainly clay) intercalated with peat beds, with locally a thin sandy cover. After reclamation, the former submerged lake floor has been severely subsiding, losing between 1 - 2 m of elevation, with present day polder elevations ranging between 0.5 and 4.5 m below mean sea-level (Figure 3-10).

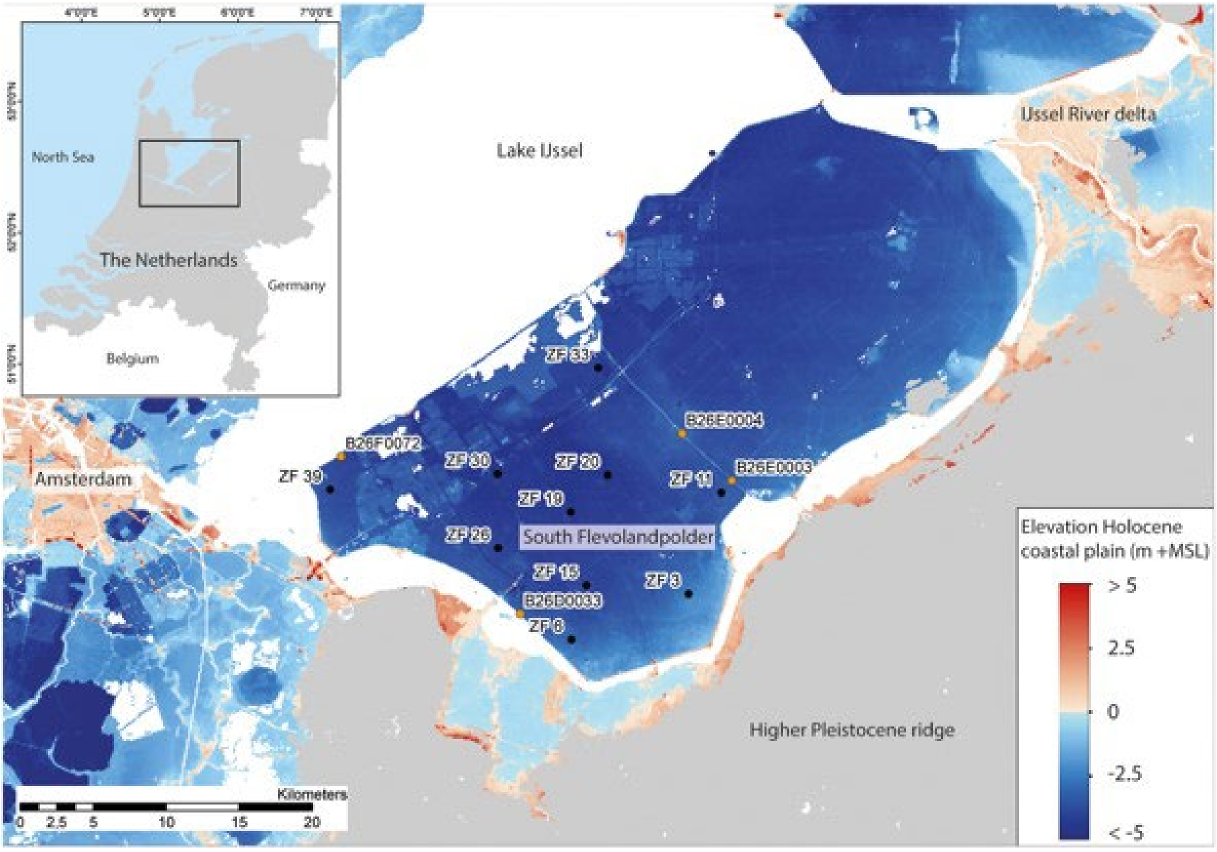

Figure 3-10 - Digital elevation model of the low-lying and subsiding Flevolandpolder. The area is situated several meters below mean sea-level, partly resulting from human-induced subsidence (Fokker *et al.,* 2019).

To understand the contribution of different subsidence processes to total subsidence, and forecast future scenarios to support mitigation strategies, several studies were initiated using geological and groundwater information, geodetics and InSAR, and advanced geomechanical modelling. Fokker *et al.* (2019) identified that during the first 60 years of reclamation, the irreversible shrinkage of tidal clay was the main driver, induced by the progressive lowering of phreatic groundwater levels. Even though subsidence observations revealed that the pace of subsidence was slowing down, the policy of periodically lowering water tables to adjust for subsidence keeps the surface to lower by clay shrinkage.

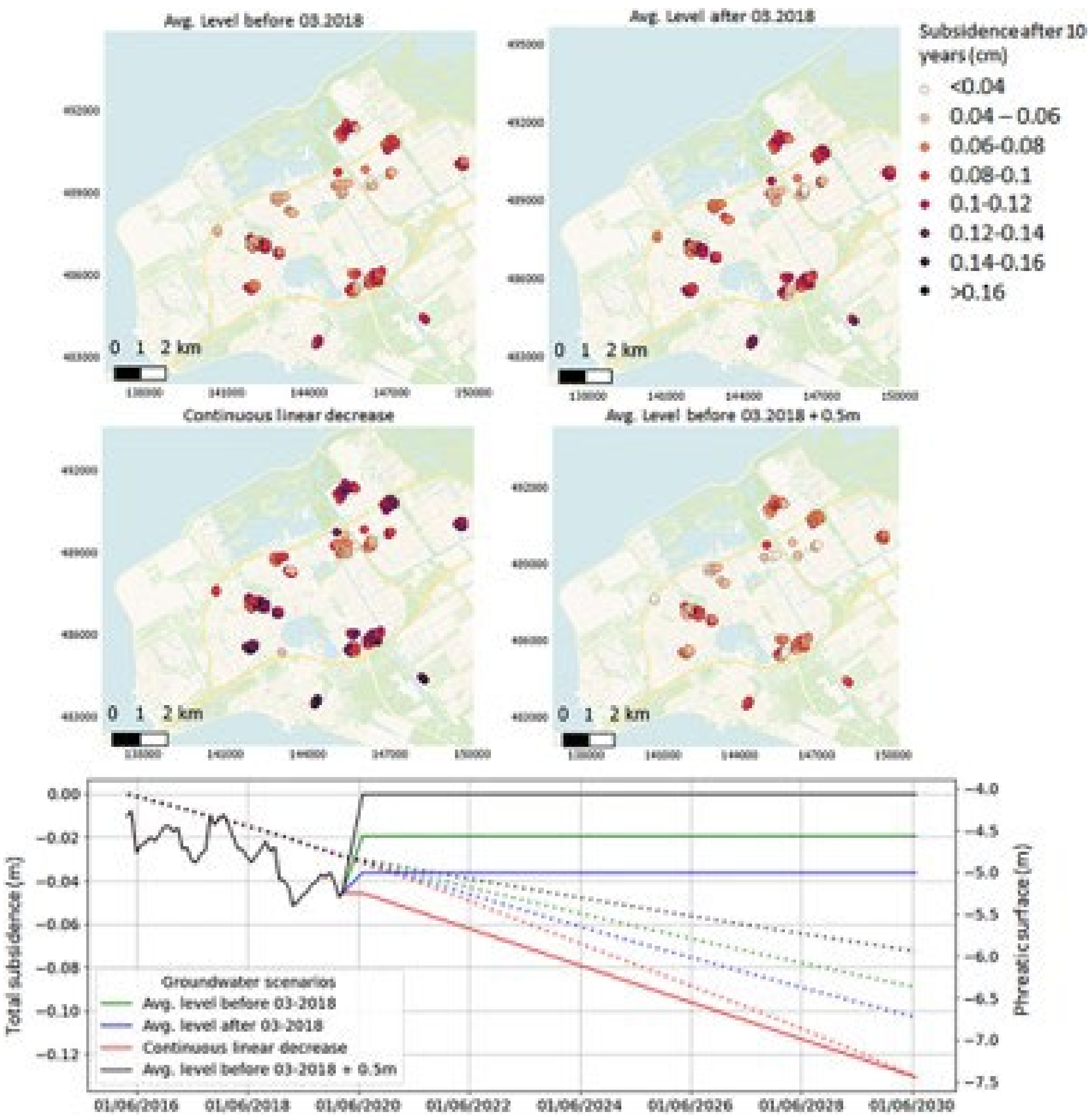

Figure 3-11 - Future estimates for Almere for different groundwater management scenarios. The maps show estimated subsidence for InSAR points on free field objects (i.e. not on buildings). The graph shows the scenario for one InSAR point: the solid lines represent different groundwater scenarios, and the dotted lines corresponding subsidence rates (Verberne *et al.,* 2023).

Verberne *et al.* (2023) shows that at present, the contribution of clay shrinkage to total subsidence in the Flevolandpolder is approximately 6 mm/yr, whereas the contribution of the oxidation of peat beds is 0.2 mm/yr. This was derived by data assimilation parameter optimization using InSAR, a groundwater model, a lithology model, and physics-based models. For future estimates, essential for mitigation strategies, Verberne et al. (2023) ran several scenarios of groundwater management 10 years into the future for the city of Almere in the southwest of the Flevolandpolder (Figure 3-11). The maps show that most future subsidence is expected in the southwest and northeast of Almere. The graph shows that for scenarios where the phreatic groundwater level is not further lowered, subsidence by clay shrinkage and peat oxidation will continue. Also, roughly, for every 1 m lowering of phreatic groundwater levels, the area will subside with 1 cm per 5 years.

Dike stability from the European Ground Motion Service: case study in the Netherlands

The Netherlands has an extensive flood defenses and dikes network with more than 22,500 km of dikes, dams and dike relics[5] (Figure 3-12). This includes different types of dikes, such as sea dikes, river dikes, and canal dikes, making them crucial barriers to protect the country from flooding. As explained in the above sections, subsidence processes, both natural processes enhanced by anthropogenic activities and climate change, can highly risk the integrity of the dike network and influence the Dutch delta. Identifying and mapping dikes at risk can help reinforce dike networks.

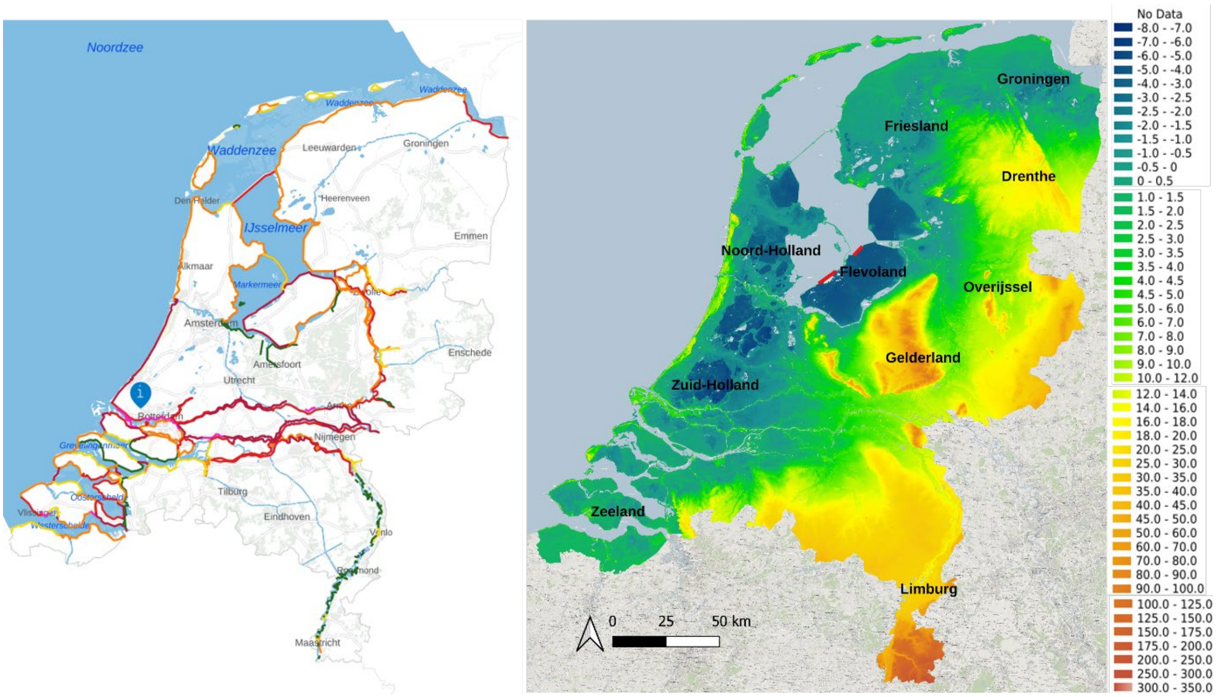

Figure 3-12 - Maps showing important dykes, dams and dunes in the Netherlands (on left), and showing the two selected dikes (red lines) in the province of Flevoland to demonstrate results on top of the digital elevation model (on the right).

[5] Netherlands Dikes and Levees: Effective Flood Defenses, Dike map | Dutch Dikes

Method

In this study, TNO is exploring the potential and the applicability of EGMS over the Dutch dikes to detect potential indications of instability. While for the UK side, the focus is on time series, here, the focus is purely spatial detection under the assumption of a linear model fit (or velocity rate) in time. The method developed by Martins & Davids (2025a) is applied, for which differential displacements are estimated from InSAR measurement points. The method provides a magnitude and displacement direction for any resultant InSAR-based EGMS level products.

For dike stability, TNO first applies the method over Ortho-Level 3 EGMS products for both East/West and Vertical products (see Calero *et al.*, 2024 for EGMS product description). This way, it ensures a country-wide application for spotting vulnerable areas. After identifying potential anomalies, TNO moves to detailed level products L2a and L2b and time series analysis. For the time series analysis, they will apply an extension of the method described in Manders & Martins (2024).

Initial results

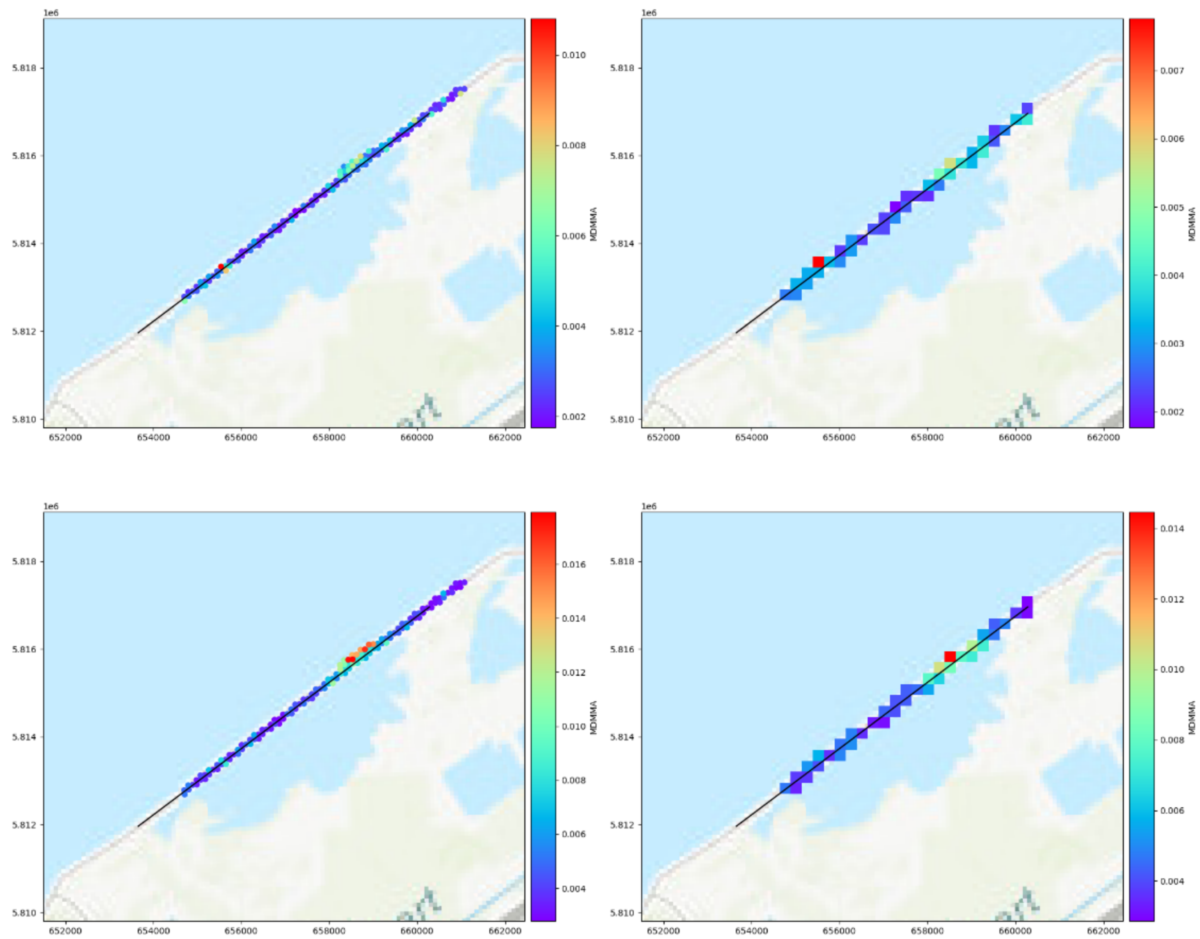

Figure 3-13 - Figures showing initial results on the application of the MDDMA method Martins & Davids (2025a) to a dike section. Top: East/west Ortho-Level 3 EGMS products. Bottom: Vertical Ortho-Level 3 EGMS products. The left-hand figures show the MDDMA application at the InSAR measurement point location, and the right-hand figures show the gridded results. MDDMA units are in mm/year/m.

TNO applied the differential displacements detection method, the Mapping differential displacements: magnitude and azimuth (MDDMA), to Ortho-Level 3 EGMS products to a series of dike sections. In Figure 3-13 and Figure 3-14, TNO displays two dike sections with the corresponding East/west Ortho-Level 3 products on top and Vertical Ortho-Level 3 at the bottom. The left figures show the MDDMA estimated at the InSAR point location, and the right figures show the gridded results within a 50 m grid cell size.

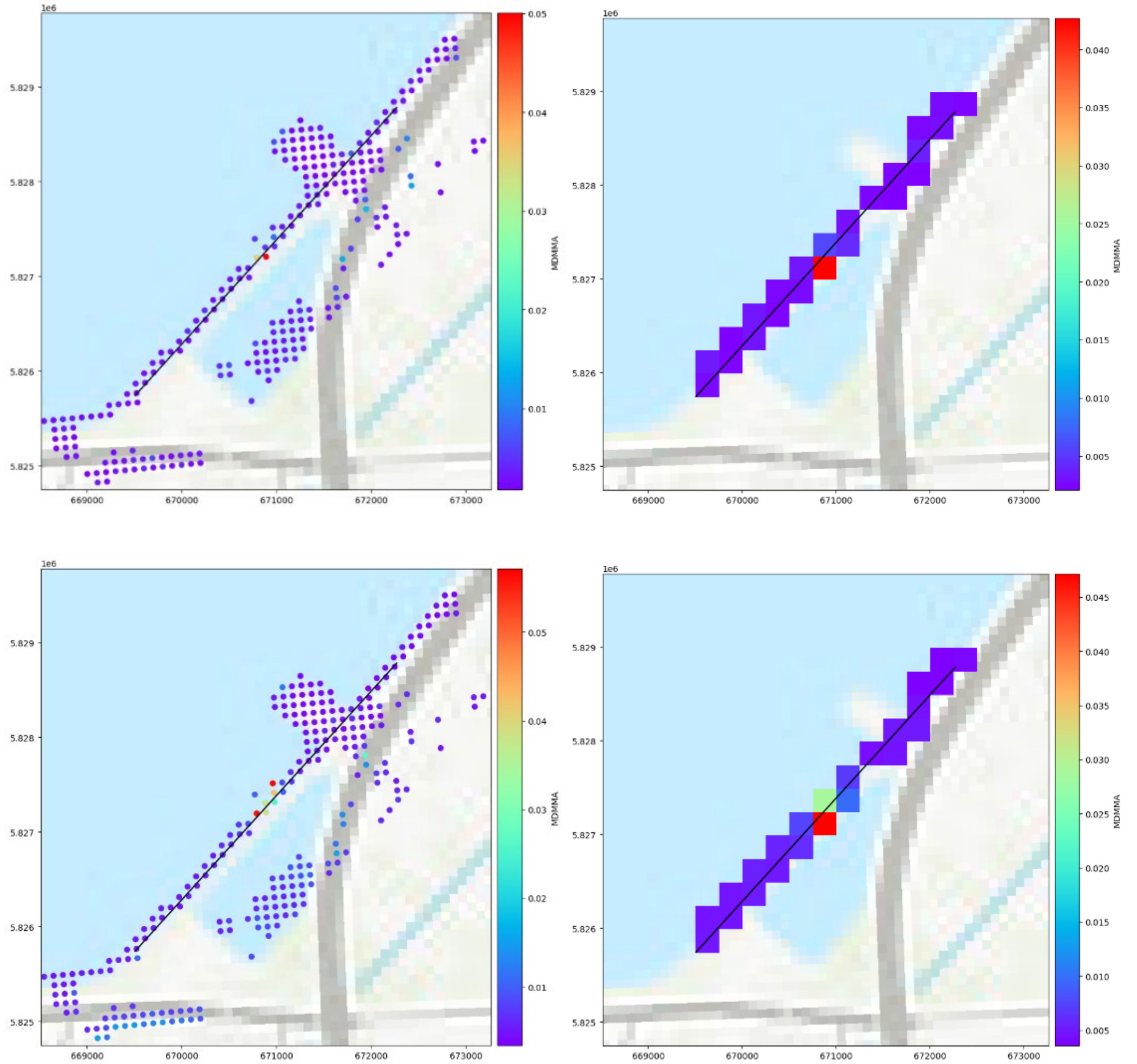

Figure 3-14 - Figures showing initial results of the MDDMA method Martins & Davids (2025a) to a different dike section from Figure 3-13. Top: East/west Ortho-Level 3 EGMS products. Bottom: Vertical Ortho-Level 3 EGMS products. The left-hand figures show the MDDMA application at the InSAR measurement point location, and the right-hand figures show the gridded results. MDDMA units are in mm/year/m.

These initial results are promising, showing the potential for fast detection when applied to the entire country. While a few steps are still under development, such as the normalization of the MDDMA values. This can be observed by the magnitude of the MDDMA values between the two presented dike sections.

In contrast, larger MDDMA values are displayed in red; their magnitudes are quite different, so their relative MDDMA value should be estimated for better identification of potential critical sites. This process, once refined, will significantly enhance our ability to identify and address potential dike instability.

On top of the aforementioned results, looking at the gridded results (right column of Figure 3-13 and Figure 3-14), the importance of analyzing both east/west and vertical directions of displacement. In Figure 3-14, the high MDDMA value occurs at the exact location for horizontal and vertical displacements, but the same does not happen in Figure 3-13. A result that is sometimes neglected is that horizontal displacements are important. However, the analysis is not without challenges. Spatial and temporal assumptions can undermine the detection, and areas lacking measurement points or facing complex coastal environments pose additional interpretation difficulties. Furthermore, landslides, which may occur in directions not captured by InSAR (namely north/south direction), complicate our assessment of dikes oriented east-west and hinder interpretation. For this reason, integrating satellite data with in-situ observations is a challenging yet necessary approach.

Subsidence hot spots in France: cases study along the English Channel and Mediterranean coasts

Le Havre Harbor, located in northern France along the English Channel, is the France's second largest port in terms of maritime traffic and the leading port for container traffic. This area is subject to **subsidence due to a combination of geological and anthropogenic factors** (EGMS average vertical displacement rate reach -2.88 mm/yr on this area; Figure 3-15, top). The area is characterized by **Quaternary deposits and reclaimed land**, particularly in the port infrastructure. These materials are prone to compaction over time, leading to ground settlement. **Human activities**, such as **construction**, loading activities in the harbor, and the **extraction or redistribution of subsurface water**, have also contributed to subsidence. The harbor's extensive industrial and logistical facilities make it critical to monitor ground stability to ensure the integrity of infrastructure. Studies have used techniques such as InSAR (Interferometric Synthetic Aperture Radar) to measure deformation rates and identify subsidence hotspots. This monitoring is essential to address challenges posed by ground instability, rising sea levels, and increased storm surges linked to climate change. The continued adaptation of engineering solutions and resource management strategies is necessary to maintain Le Havre Harbor's operational capacity and protect its vital economic functions.

Palavas-les-Flots, a coastal town in southern France (along the mediterranean coast), is situated in a low-lying area highly susceptible to subsidence and coastal challenges. The region is characterized by **a combination of natural and anthropogenic factors contributing to ground subsidence**. Natural processes include the **compaction of Holocene sediments in the lagoonal and deltaic environment**, which have accumulated over millennia. Human activities, such as **groundwater extraction and coastal development**, have exacerbated the phenomenon (EGMS average vertical displacement rate is about - 6.22 mm/yr on this area; Figure 3-15, center). Studies indicate that subsidence rates in this area can lead to increased vulnerability to sea-level rise and coastal flooding, particularly given its proximity to the Mediterranean Sea and its relatively flat topography. Monitoring and mitigation strategies, often coordinated by regional authorities and research organizations, aim to address these risks and enhance the resilience of Palavas-les-Flots to future challenges linked to climate change and land use pressures.

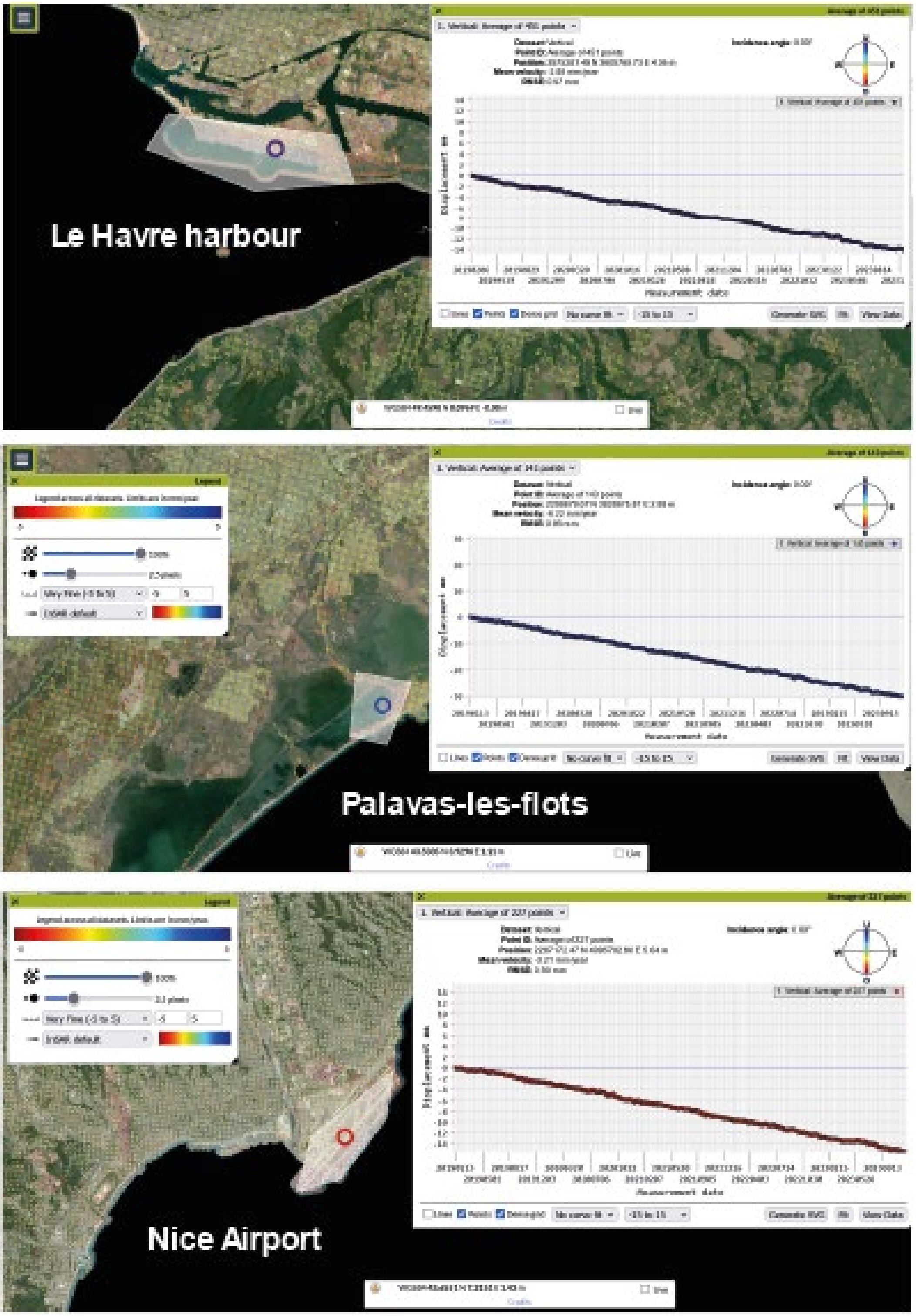

Figure 3-15 - Average vertical displacement extracted from EGMS product for 3 subsidence hot-spots in France: La Havre harbour (top), Palavas-les-flots (centre), Nice Airport (bottom) (Source: EGMS, Copernicus[6]).

[6] https://egms.land.copernicus.eu/

Nice Côte d'Azur Airport, located along the French Riviera, is built on reclaimed land adjacent to the Mediterranean Sea. This location makes it susceptible to subsidence, primarily due to the **consolidation of artificial and natural sediments used in its construction**. The airport rests on Quaternary deposits, including alluvial and marine sediments, which are prone to compaction under the weight of infrastructure and changes in groundwater levels. Anthropogenic factors, such as construction activities and water management practices, have exacerbated ground settlement in some areas. Additionally, the coastal location makes the site vulnerable to rising sea levels and potential storm surges, which can compound the impacts of subsidence (EGMS average vertical displacement rate is about – 3.21 mm/yr on this area; Figure 3-15, bottom). Monitoring efforts, including geotechnical surveys and satellite-based methods like InSAR, have been employed to track ground deformation at the airport. The airport has been the subject of several scientific studies focusing on its subsidence issues. The study of Cavalié *et al.* (2023) utilized Synthetic Aperture Radar (SAR) data spanning from 1992 to 2020 to monitor the airport's subsidence dynamics. Their findings revealed a decrease in the maximum downward motion rate from 16 mm per year in the 1990s to 8 mm per year in recent times. Despite this deceleration, sediment compaction remains active. A previous study by Cavalié *et al.* (2015) also investigated the dynamics of the Var delta, where the airport is situated. This research provided detailed quantification of delta subsidence, compaction, and interactions with man-made structures, offering insights into the ongoing deformation mechanisms affecting the airport. These data inform maintenance and adaptation strategies to ensure the stability and safety of critical infrastructure in this economically and strategically significant location. Continued surveillance and proactive resource management are essential to mitigate subsidence-related risks at Nice Airport.

Subsidence in Thessaloniki (Greece): Causes, Impacts and Monitoring

Significant rates of subsidence are prominent in the broader region of Thessaloniki (Northern Greece). The phenomenon manifests in several locations along the coasts of Thermaikos Gulf such as the deltaic plains of Axios and Gallikos Rivers, the Metropolitan area and the Airport of Thessaloniki. The wider territory of Axios Delta in the northern shores of Thermaikos Gulf, displays strong rates of subsidence as shown by Thieblemont *et al.* (2023) ($V_{EGMS} < -5$ mm/yr in Figure 3-9).

Alluvial sediments which have been deposited in this region during the past 2.5 ka, created a dynamic deltaic environment (Loupasakis *et al.,* 2020) (Figure 3-16). Natural processes and human interventions, such as the construction of embankments and drainage canals, affected the morphology and hydrodynamics of the region significantly (Mouratidis and Constantini, 2011). In Kalochori and Sindos (Figure 3-16), two settlements built on the banks of Gallikos River, a few kilometers west from the center of Thessaloniki, subsidence rates have been following an increasing trend since the 1960’s. This phenomenon is mostly attributed to human activity (Mouratidis and Constantini, 2011). The extensive overuse of the local reservoirs for industrial and irrigation purposes resulted in the drop of the piezometric level of ground water in this area. The latter caused the compaction of the poorly consolidated Quaternary sediments which occupy the lowlands of Gallikos River (ind. Andronopoulos et al., 1991; Hadzinakos *et al.,* 1990; Rozos and Hadzinakos, 1993; Loupasakis and Rozos, 2008; Mouratidis and Constantini, 2011).

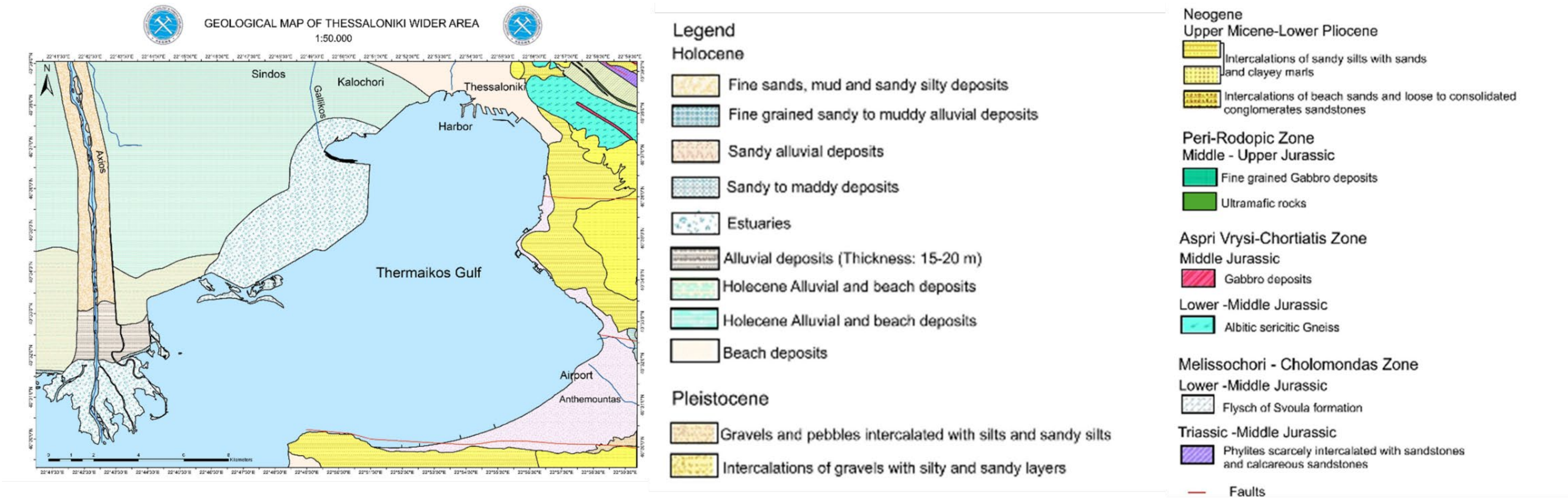

Figure 3-16 - Geological map of the greater Thessaloniki area. Extracted from the Geological Map of Greece (Scale 1:50.000; HSGME, 2024).

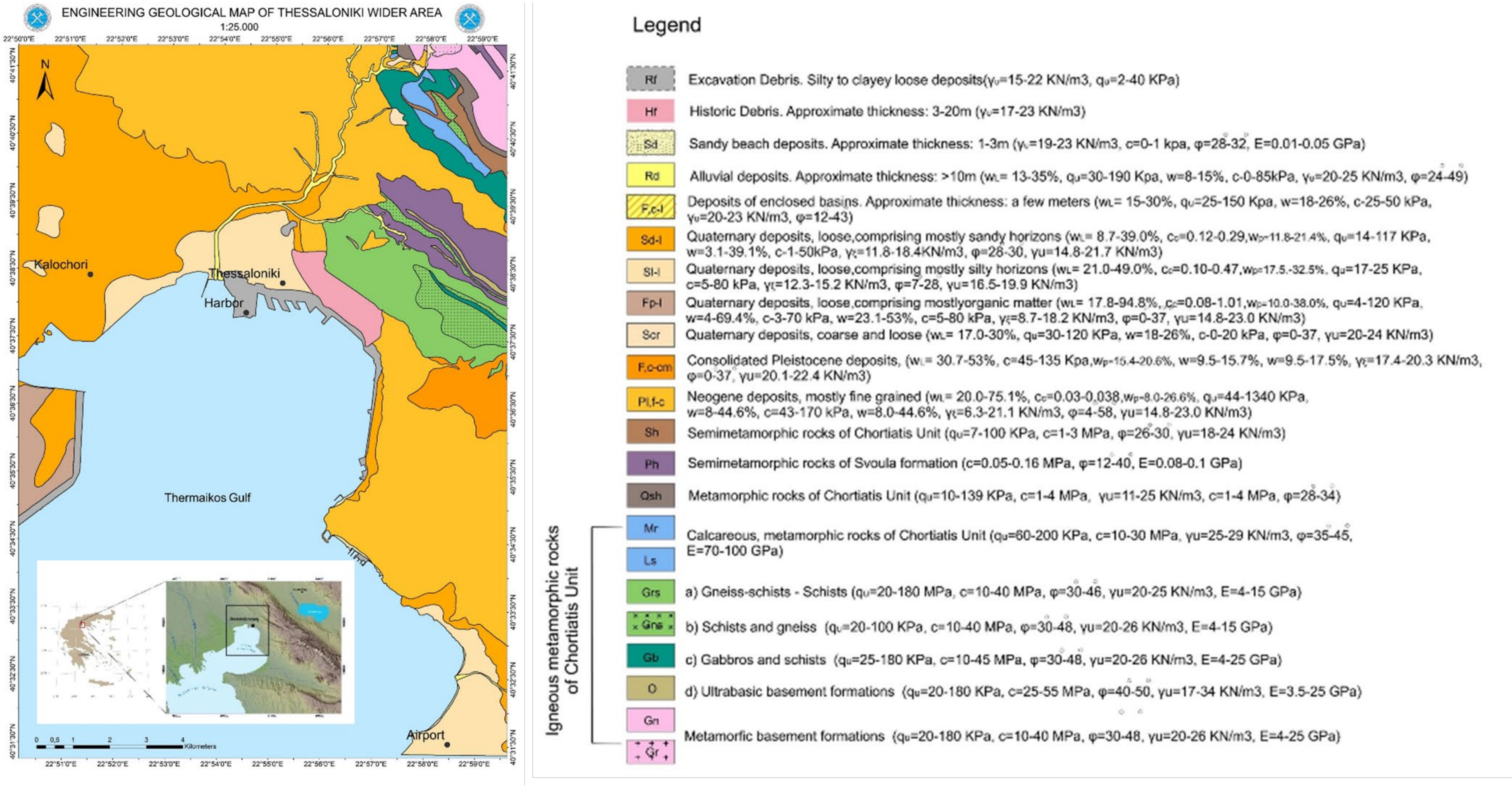

Figure 3-17 - Engineering geological map of the greater Thessaloniki area, Scale 1:25.000; HSGME after Rozos *et al.* (2004).

Coastal regression and considerable marine invasion have been observed especially in the village of Kalochori (e.g. Stiros *et al.,* 2001; Mouratidis *et al*., 2009; Loupasakis and Rozos, 2010; Ganas *et al*., 2017), whereas uneven ground settlement increases damage risk for the facilities in one of the most significant industrial districts in Greece. Consistent monitoring has been performed in the Kalochori – Sindos area during the past 25 years using various methods of data acquisition and analysis such as GPS, InSAR methods and satellite images. Vertical displacement of more than 3 m has been reported for this region (Stiros *et al*., 2001), whereas data collected during the period from 1992 to 2001 yielded deformation rates which reached up to 4.5 cm/yr (Raucoules *et al.,* 2008; Mouratidis *et al*., 2009; Loupasakis and Rozos 2010). Lower values of 1 to 3.4 cm/yr were published in more recent studies (Constantini *et al.,* 2016; Svigkas *et al.,* 2016, 2020; Elias *et al.,* 2020). Lately, a maximum rate of 1.5 cm/yr was measured in Sindos, using high accuracy levelling data collected between 2018 and 2020 (Kalaitzis *et al*., 2023). Notably, an inversion of the downward displacement was observed in 2010s corresponding to the partial recovery of the groundwater supplies after a period of decreased industrial activity in the region. However, ground water levels have been dropping again since 2016, coinciding with the resurgence of the local manufacturing sector. This phenomenon showcases the major impact of the anthropogenic factor in the subsidence phenomena of this region (Svigkas *et al.,* 2016, 2020; Loupasakis *et al*., 2020).

Although the town of Thessaloniki is seriously affected by tectonism and seismic activity, the metropolitan area is generally not prone to ground deformation (Raucoules *et al.,* 2008; Mouratidis *et al.,* 2009). However, subsidence is present in the harbour of the city, that was built on heterogeneous Quaternary and Neogene deposits including artificial fills and natural sediments with varying geotechnical properties (Figure 3-17). As a result, the harbour's infrastructure faces challenges and continuous monitoring, and maintenance are required to ensure stability (Loupasakis *et al.,* 2020).

The area surrounding Thessaloniki Airport ("Macedonia International Airport") is objected to significant displacement demonstrating values greater than 2 cm/yr (Raucoules *et al*., 2008; Raspini *et al.,* 2014). In line with the previous cases, alluvial deposits of Quaternary and Neogene ages are prevalent in this region which is part of the estuary of River Anthemountas (Figure 3-16). In the absence of any significant tectonic structures, the observed deformation is associated with activities related to the activity of the airport (Raucoules *et al.,* 2008; Mouratidis and Constantini 2011; Loupasakis *et al.,* 2020; Svigkas *et al.,* 2020).

In summary, the wider area of Thessaloniki (Northern Greece) has been seriously affected by strong subsidence phenomena related mostly to human activity which have been present in this region since the 1960s. Numerous studies performed in this vicinity throughout the years show the continuous and ongoing character of this phenomena (Svigkas *et al*., 2020; Loupasakis *et al.,* 2020), whereas impacts are obvious in the industrial and urban infrastructure of the subsidence prone areas. Assigning observed ground deformation to the decline of the groundwater table underscores the importance of organized resource management efforts and strategies to mitigate subsidence effects and ensure stability in the affected areas. **Hellenic Survey of Geology and Mineral Exploration (HSGME)**, plays a significant role in subsidence assessment in Thessaloniki and other parts of Greece, while conducting geological and hydrogeological studies, collecting data, and producing maps that are essential for understanding subsidence phenomena. HSGME's involvement ensures a scientific basis for addressing subsidence issues and informing strategies to mitigate risks in Thessaloniki and other affected areas.

Effects of subsidence and sea level rise along the Italian coastlines

Land subsidence is a concern in many coastal plains in Italy, particularly in the low-lying areas already facing sea level rise due to climate change (Figure 3-9). These coastal plains include agricultural and urban areas, highly valuable lagoon environments, archaeological and touristic sites, and industrial zones. Many factors contribute to subsidence along the Italian coastal areas: anthropogenic activities, e.g., groundwater exploitations, development of newly built-up areas, and natural mechanisms related to the morphological setting and the subsoil characteristics. Many studies used satellite interferometric data to provide a comprehensive picture of the land subsidence in some Italian coastal plain (Alberico and Matano, 2024; Antonellini *et al.,* 2020; Di Paola *et al.,* 2023; Da Lio and Tosi, 2018; Matano *et al.,* 2018; Perini *et al*., 2017; Scardino *et al.*, 2022; Solari *et al.,* 2018; Tosi *et al*., 2018).

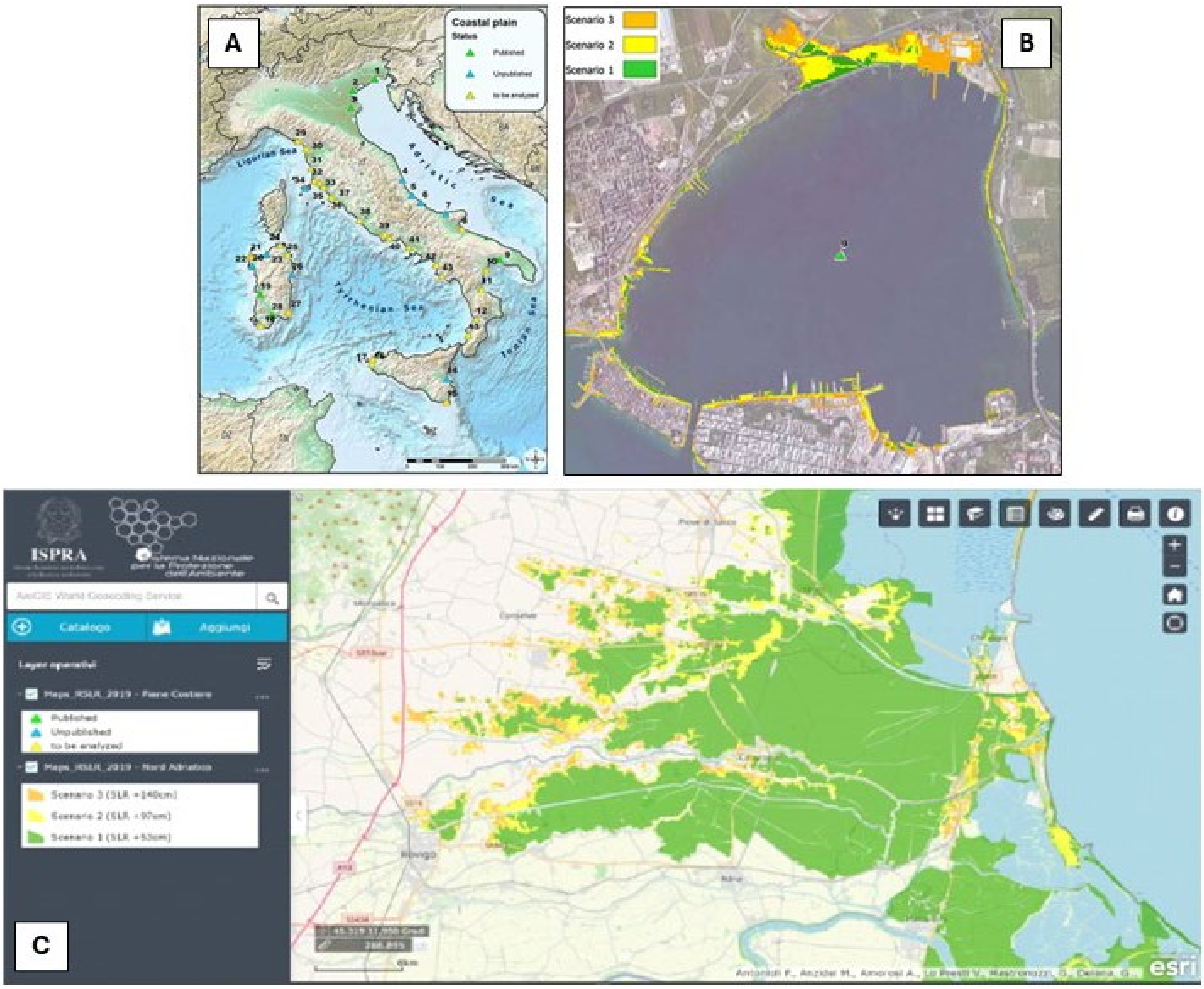

Figure 3-18 - A) Italian coastal plain areas, B) relative sea level rise scenarios for 2100 for some Italian coastal areas; C) Geological Survey of Italy Portal[7] (Source: ISPRA).

Relative sea level rise scenarios for 2100 for some Italian coastal areas have been developed by researchers from ISPRA - the Italian GSO -, ENEA (National Agency for New Technologies, Energy and

[7] http://portalesgi.isprambiente.it/en/news/news/sea-level-rise-scenarios-italian-coastal-plains

Sustainable Economic Development), INGV (Istituto Nazionale di Geofisica e Vulcanologia), CNR (National Research Council of Italy), and the Universities of Bari, Bologna, Cagliari, Padua and Trieste. These maps result from the work of these team made of researchers from many institutes during last 20 years activity (Vector Project, RITMARE Project). Three scenarios have been considered (Antonioli *et al.*, 2017): IPCC - 530 mm minimum; IPCC - 970 mm maximum for RCP 8.5; Rahmstorf, 2007 - 1400 mm maximum. ISPRA, by means of the Geologic Survey of Italy's web portal, make available to the public the maps of the "Sea Level Rise of Italian coastal plains for the year 2100" (Figure 3-18). In detail, in Italy, the areas more affected by the combination of subsidence and sea level rise include the Po Plain, lagoon areas of the Adriatic coast (Tosi *et al.*, 2016) and the large coastal plains along the Italian Tyrrhenian coast (Di Paola *et al.*, 2021). These coastal zones are characterized by significant land subsidence rates exceeding 5 mm/year, as well as the issue of permanent flooding due to their proximity to the sea, which, with its rate of change, also influences the salinization of groundwater (IPCC, 2023).

3.7. Conclusion

The analysis of spatiotemporal patterns of vertical land motion (VLM) in European coastal areas highlights the critical role of both natural and anthropogenic factors, alongside geological assets, in shaping coastal dynamics. By leveraging remote sensing datasets, geological data, and advanced spatio-temporal modelling techniques, this study underscores the importance of incorporating localized VLM data into sea-level rise projections. The pan-European analysis using EGMS data reveals that 50% of European coastal flood plains (CFPs) experience subsidence exceeding 1 mm/yr, while 10% exhibit uplift rates greater than 0.5 mm/yr, directly influencing flood risk. These findings emphasize the need to account for subsidence, uplift, and the influence of geological assets in the future coastal risk assessments and adaptation planning, ensuring that emerging risks are effectively managed, and existing flooding risk frameworks are updated to reflect these dynamics. Further work, involving the GSOs and the communities focused on coastal vertical land motions and relative sea-level rise in Europe (UNESCO's working group on land subsidence (LaSII); International panel on land subsidence (IPSL)), and related projects (for e.g. CoCliCo, PROTECT) are central to discussions on the implications for relative sea-level change and aims to inform effective coastal management strategies.

4. Coastal Vulnerability Assessments over long Timescales, and Sea-Level Rise Impacts

This section is structured into six subparts, each addressing a crucial aspect of coastal vulnerability assessment. It begins with a general overview of coastal dynamics and vulnerability, outlining key processes such as coastal migration. The second subpart focuses on the collection of knowledge regarding European coasts, highlighting the methodologies and data collected from an online questionnaire that mobilized GSEU WP5 partners. The third subpart identifies the key parameters influencing the vulnerability of coastal territories across Europe, providing an overview of emblematic sites in different countries to illustrate regional variations. The fourth subpart offers an intercomparison between countries, examining how coastal risks and vulnerability are considered within public policies and governance frameworks. The fifth section introduces the Coastal Vulnerability Index, a tool used to quantify and assess coastal susceptibility to environmental changes. Finally, the last subpart presents case studies and datasets, emphasizing the role of GSOs in improving estimations of coastal vulnerability to sea-level rise, considering geological and hydrogeological data, and thereby supporting more effective adaptation strategies.

4.1. General Elements about Coastal Dynamics and Vulnerability

Recent studies indicate that extreme sea levels in Europe could rise by as much as one meter or more by the end of this century due to climate change. Rising sea levels will have significant impacts on coastal geology and hydrogeology, affecting sediment transport, coastal aquifers, and land stability. In areas with soft sedimentary deposits, subsidence and increased erosion will exacerbate flooding risks, while regions with limestone and karst formations may experience enhanced groundwater salinization and cave collapses due to changing hydrogeological conditions.

Countries like the Netherlands, Belgium, and parts of Germany have low-lying coastlines, making them highly susceptible to flooding. These regions are underlain by unconsolidated sediments and clay-rich deposits, which contribute to land subsidence when combined with excessive groundwater extraction. The Netherlands, for instance, has implemented extensive coastal defenses through its Delta Works program to mitigate these risks. However, continued subsidence due to both geological and hydrogeological factors necessitate ongoing adaptation efforts. Mediterranean countries face challenges such as coastal erosion and saltwater intrusion into freshwater systems. The geology of these regions, often composed of carbonate rock formations, makes them particularly vulnerable to groundwater salinization, as sea level rise push saltwater further inland. Additionally, karstic coastal areas in Italy and Greece may experience increased rates of subsurface erosion and sinkhole formation due to shifts in groundwater flow dynamics. The Atlantic-facing countries, including France, Portugal, and Ireland, are experiencing increased storm frequency and intensity, leading to accelerated coastal erosion. The geological composition of these coastlines varies from hard rock formations to softer, more erodible sedimentary deposits in parts of Portugal and Ireland. Increased storm surges and wave action will accelerate sediment displacement, reshaping beaches and estuaries while posing risks to groundwater quality through heightened saltwater intrusion into coastal aquifers.

Low-lying coastlines with high population densities and small tidal ranges are most vulnerable to sea-level rise and coastal flooding, particularly where adaptation is hindered by a lack of economic resources or other constraints. The hydrogeological impacts of rising sea levels include the contamination of drinking water sources in deltaic and alluvial coastal zones, requiring costly desalination or aquifer

recharge solutions. In areas where groundwater-dependent agriculture is prevalent, such as southern Spain and parts of Italy, saline intrusion could severely impact crop yields and local economies.
European countries are employing a mix of hard (e.g., sea walls, breakwaters) and soft (e.g., beach nourishment, wetland restoration) engineering solutions to combat coastal erosion and flooding. It is important to note that geological and hydrogeological considerations are increasingly being integrated into these strategies, such as: managed retreat (allowing coastlines to naturally evolve by relocating infrastructure away from high-risk zones); groundwater management (implementing artificial recharge and controlled pumping to mitigate saltwater intrusion); nature-based solutions (restoring coastal wetlands, which provide natural flood protection while enhancing groundwater storage and filtration).
Understanding the specific vulnerabilities of European coasts to climate change and sea-level rise is crucial for developing effective adaptation strategies. Continuous monitoring, research, and investment in sustainable coastal management practices are essential to mitigate the adverse effects on both natural ecosystems and human societies, considering both surface and subsurface geological and hydrogeological dynamics.
The new EMODnet Geology map of coastal type (freely accessible from the EMODnet Geology portal[8]) provides harmonized information on the types of European coasts, based on satellite and field data (Figure 4-1). Builds on the EUROSION map of coastal type[9] (2004) released almost twenty years ago, this EMODnet Coastal type map allows to fill gaps and gives a first-order indication of vulnerability and resilience for policy makers, identifying areas of potentially irreversible future change. This important data product allows users to visualize pan-European coastal type at different spatial scales and enables users to distinguish areas marked by:

- **Rocky cliffs:** Areas where steep rock formations dominate the coastline. These are found (but not exclusively) in countries such as the **United Kingdom** (e.g., White Cliffs of Dover, Scotland), **France** (e.g., cliffs of Étretat, Normandy), **Spain** (e.g., Asturias, Cantabria), **Portugal** (e.g., Algarve region), **Italy** (e.g., Amalfi Coast, Cinque Terre), **Norway** (fjords and coastal cliffs), **Ireland** (Cliffs of Moher), and **Greece** (e.g., Santorini).
- **Sandy beaches:** Regions characterized by stretches of fine sand, often accompanied by dunes. Countries featuring these include (but not exclusively) **Spain** (e.g., Costa Brava, Costa del Sol), **France** (e.g., French Riviera, Landes, southern North Sea coasts), **Italy** (e.g., Tuscany, Sardinia), **Portugal** (e.g., Ericeira beaches), **Germany** (e.g., Baltic Sea and North Sea coasts), **Netherlands** (e.g., Zeeland, North Holland), **Greece** (e.g., Cyclades and Dodecanese islands, Crete), and **Denmark** (e.g., western North Sea coast).
- **Muddy coasts:** Areas where deposits of mud prevail, typically found in low-energy environments such as estuaries. These are prominent in the **Netherlands** (e.g., Wadden Sea region), **Germany** (e.g., Baltic Sea and North Sea coasts), **Denmark** (e.g., North Sea coastal areas), **France** (e.g., Loire and Seine estuaries), and the **United Kingdom** (e.g., Thames Estuary, Wash areas), but not exclusively.
- **Salt marshes:** Coastal wetlands periodically flooded by tides, supporting specific vegetation. These are notable in **France** (e.g., Charente-Maritime, Camargue), **Spain** (e.g., Doñana National Park), **Portugal** (e.g., Ria Formosa in the Algarve), **Netherlands** (e.g., Wadden Sea zones), and **Germany** (e.g., North Sea coastal marshes).
- **Low rocky coasts:** Coastlines made up of low-lying rocks, often interspersed with small coves. These are found in **Ireland** (e.g., Connemara), **Norway** (south-western coastline), **Sweden** (e.g.,

[8] EMODnet Geology portal: www.emodnet-geology.eu
[9] EUROSION: http://www.coastalwiki.org/wiki/EUROSION_project and http://www.eurosion.org/

Bohuslän coast), **Finland** (Finnish archipelago), **Croatia** (e.g., Adriatic coast with numerous bays and coves), and **Greece** (e.g., Ionian and Aegean islands).

Figure 4-1 - EMODnet Geology map on coastal type for the European coastlines (12-05-2021 version; available on www.emodnet-geology.eu; last accessed on 28/01/2025)

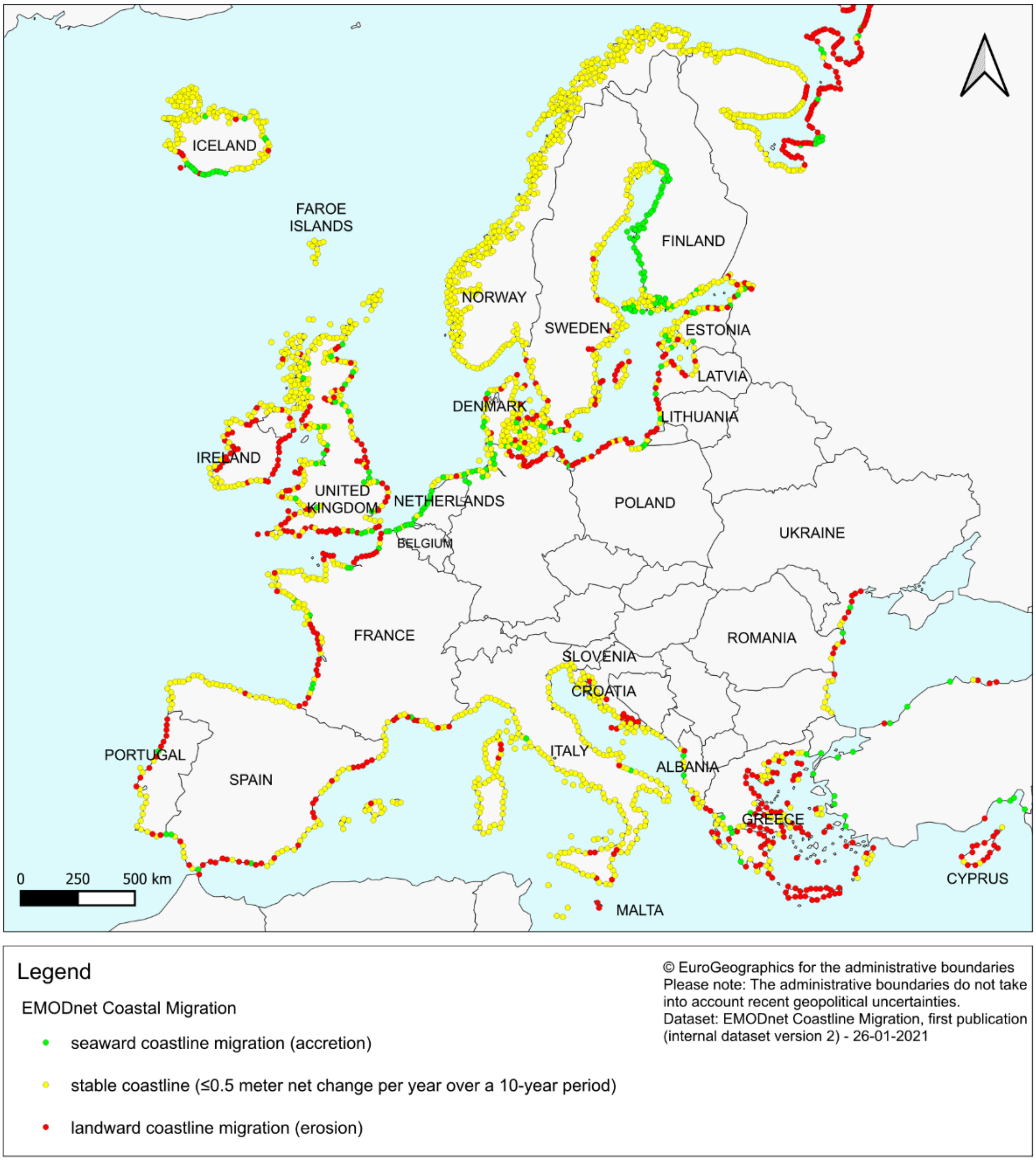

Figure 4-2 - EMODnet Geology map on coastal migration for the European coastlines (26-01-2021 version; available on www.emodnet-geology.eu; last accessed on 28/01/2025)

It also provides insights into the distribution of urbanized and developed zones along European coasts, highlighting areas of significant human influence and infrastructure development. Urbanization along European coasts is often concentrated near natural harbors, estuaries, and flat lowlands. These areas are favorable for settlement, trade, and agriculture but are also increasingly vulnerable to coastal erosion, flooding, and sea-level rise. This is the reason why the spatial distribution of urbanized zones underscores the need for integrated coastal zone management (ICZM). Protecting these areas from climate change impacts while balancing economic, environmental, and social priorities is a growing challenge.

These classifications enhance the understanding of coastal dynamics and facilitate the integrated management of coastal zones across Europe. They also provide essential insights for managing coastal risks, conserving ecosystems, and planning land use in different European countries.

In a complementary way, the EMODnet Geology shoreline-migration map, released in 2021 (and freely accessible from the EMODnet Geology portal, allows policy makers, together with national and regional coastal managers, to determine large-scale coastal behavior and identify of coastline changes and areas that experienced strong shoreline migration rates. This dataset is based on field measurements and aerial photography and covers time periods up to decades (Figure 4-2). Considering that the previous 2019 map[10], based on satellite monitoring with more complete coverage, tends to overestimate erosion of cliffed coasts, the 2021 map appears particularly valuable for cliffs, which are prevalent along European coastlines, particularly since state-of-the-art satellite-monitoring methods aren't yet suitable for imaging erosion of non-sandy types of coastline. This 2021 data product was created at the European scale to validate and complement full-coverage data from earth observation, which are reliable for sandy coasts but still unreliable for cliffed coasts. Of course, it can be used for pan-European decision making and large-scale marine spatial planning but not for local and/or regional risk assessment.

4.2. Collecting Knowledge on the European Coasts

To support the T5.1.c, an online questionnaire dedicated to coastal vulnerability assessment has been designed and send to GSEU partners concerned by the coastal issues in WP5, by the end of 2023. The questionnaire was realized with the SoSci Survey Online tool. It took about 30 minutes to complete, and it is divided into two main parts:

- The first section aims at identifying the key parameters influencing the vulnerability of coastal territories over European coasts and providing an overview of emblematic sites across countries and
- The second section aims at providing elements for an up to date inter comparison between countries concerning the consideration of coastal risks and vulnerability in public policies.

Note that European countries were consulted in two separate phases. A 1rst collection phase occurred between Oct. 2023 and early 2024 and was done online. Then a 2nd collection phase occurred between Dec. 2024 and Jan. 2025 with countries which could now involve in T5.1 on coastal vulnerability.

Respondent details

Before entering the main content of the questionnaire, the respondent was asked to provide some details on himself with: name of organization, name / first name of respondent, e-mail, optional additional information. The information provided by this way were stored solely for survey purposes, in compliance with GDPR rules. These elements were only used to contact respondent and clarify answers when necessary and to attribute answers to the corresponding country.

[10] First pan-European shoreline-migration map since 2004 | European Marine Observation and Data Network (EMODnet)

1st section: Key parameters
This first section aims at identifying the key parameters influencing the vulnerability of coastal territories over European coasts and providing an overview of emblematic sites across countries involved in the WP5 (Table 6 in the related Annex).

2nd section: Public policies
This second section aims at providing elements for an up to date inter comparison between countries concerning the consideration of coastal risks and vulnerability in public policies (Table 7 in the related Annex).

Respondent countries

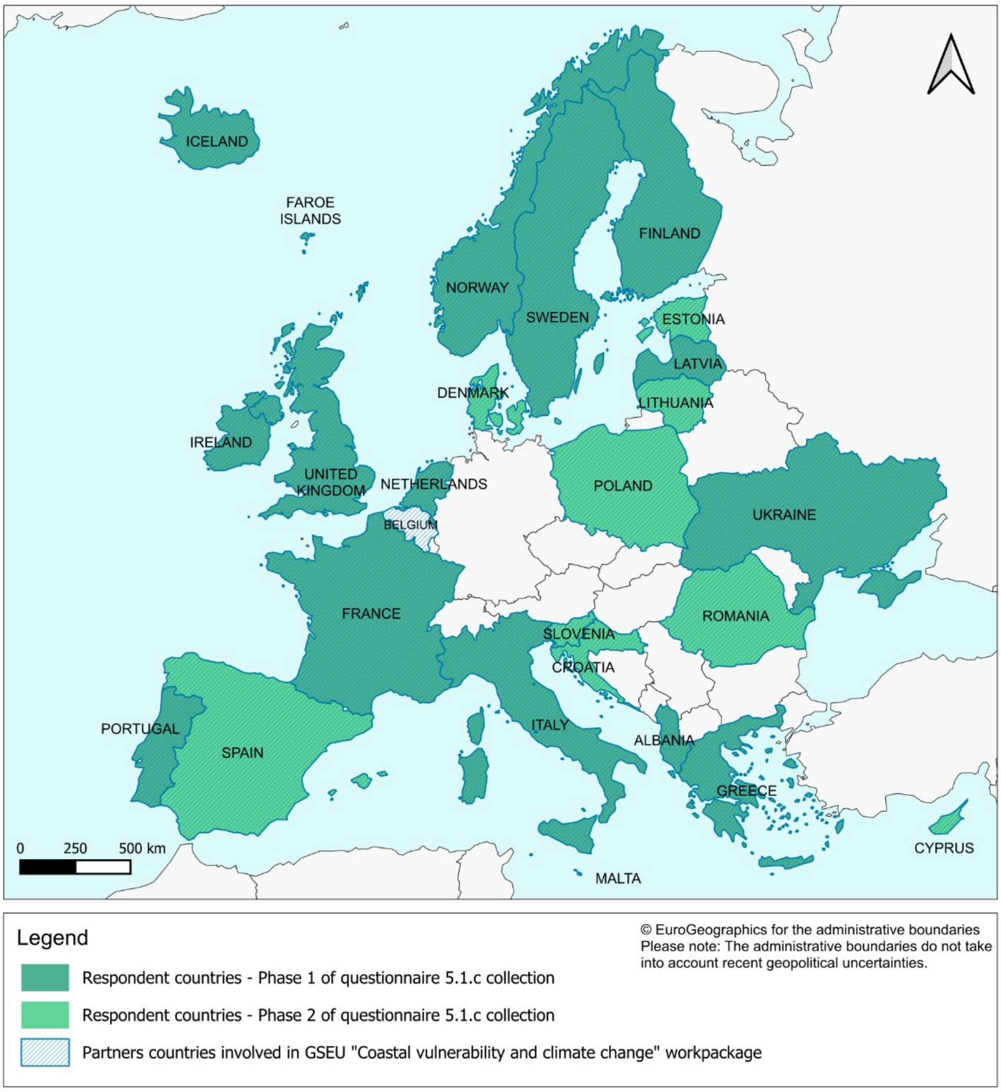

Figure 4-3 - Distribution of countries responding to questionnaire T5.1.c about "Coastal vulnerability assessments addressing coastal evolution at decadal to centennial timescales and sea-level rise impacts", among the partner countries involved in WP5, during the 1st collection phase (Oct. 2023 to early 2024), then during the second phase (Dec. 2024 to Jan. 2025).

Among the 28 partners (26 countries) targeted by the questionnaire, 18 partners (17 countries) answered for a total of 22 individual entries during 1rst collection phase, and 9 partners (9 countries) answered during 2nd collection phase.

4.3. Identifying the Key Parameters Influencing the Vulnerability of Coastal Territories over European Coasts and Providing an Overview of Emblematic Sites across Countries

Parameters

The "Parameters" part shows a high rate of responses, all of the 17 respondent countries (phase 1) have rated at least 7 out of the 12 proposed parameters (Figure 4-4). Fifteen of them have also provided explanations and examples.

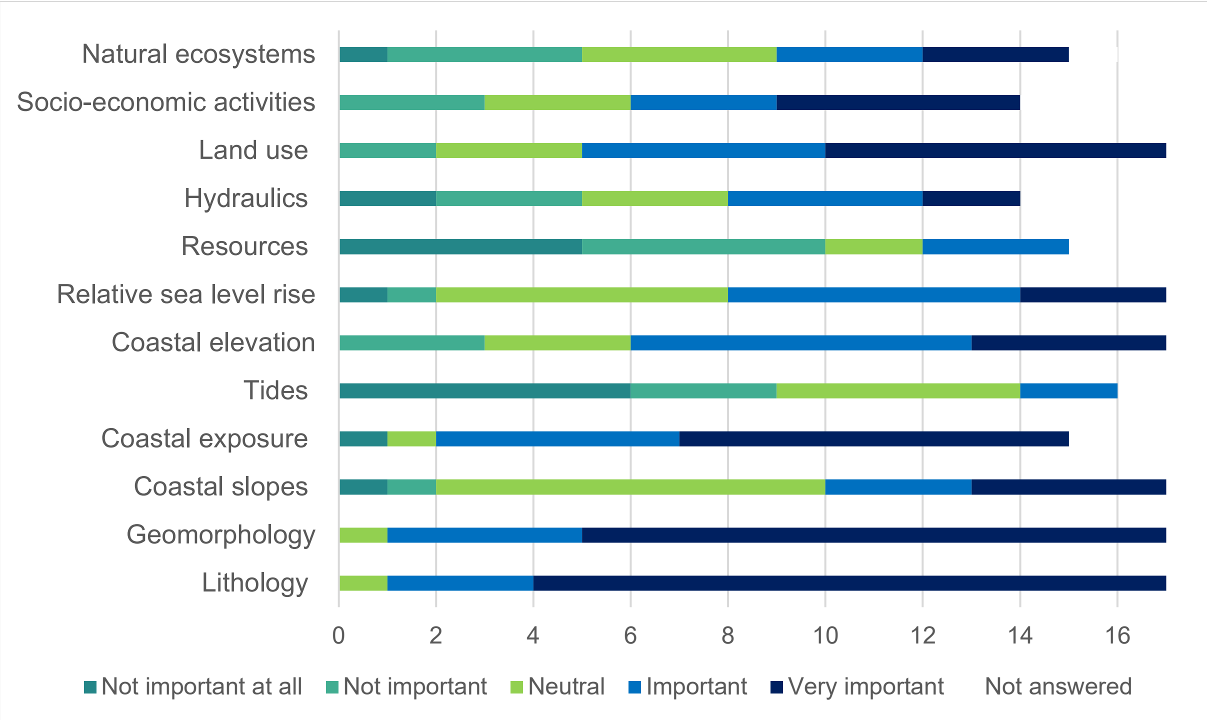

Figure 4-4 - Global view of parameters' influence results.

From these results, we can see that **geomorphology** is the parameter that appear to be the most important for all the respondents followed by **lithology** and **coastal exposure**. **Land use** and **socio-economic activities** are also reported as important or very important by more than half the respondents. On the contrary, **tides**, **resources** and **natural ecosystems** are less identified as key parameters for coastal vulnerability.

Figure 4-5 presents the same results by country and highlight the differences between respondent countries. The results from multiple respondents within the same country (whether from the same institution or different ones) have been reviewed on a case-by-case basis to ensure consistency or consensus, as appropriate, in consultation with the relevant respondents.

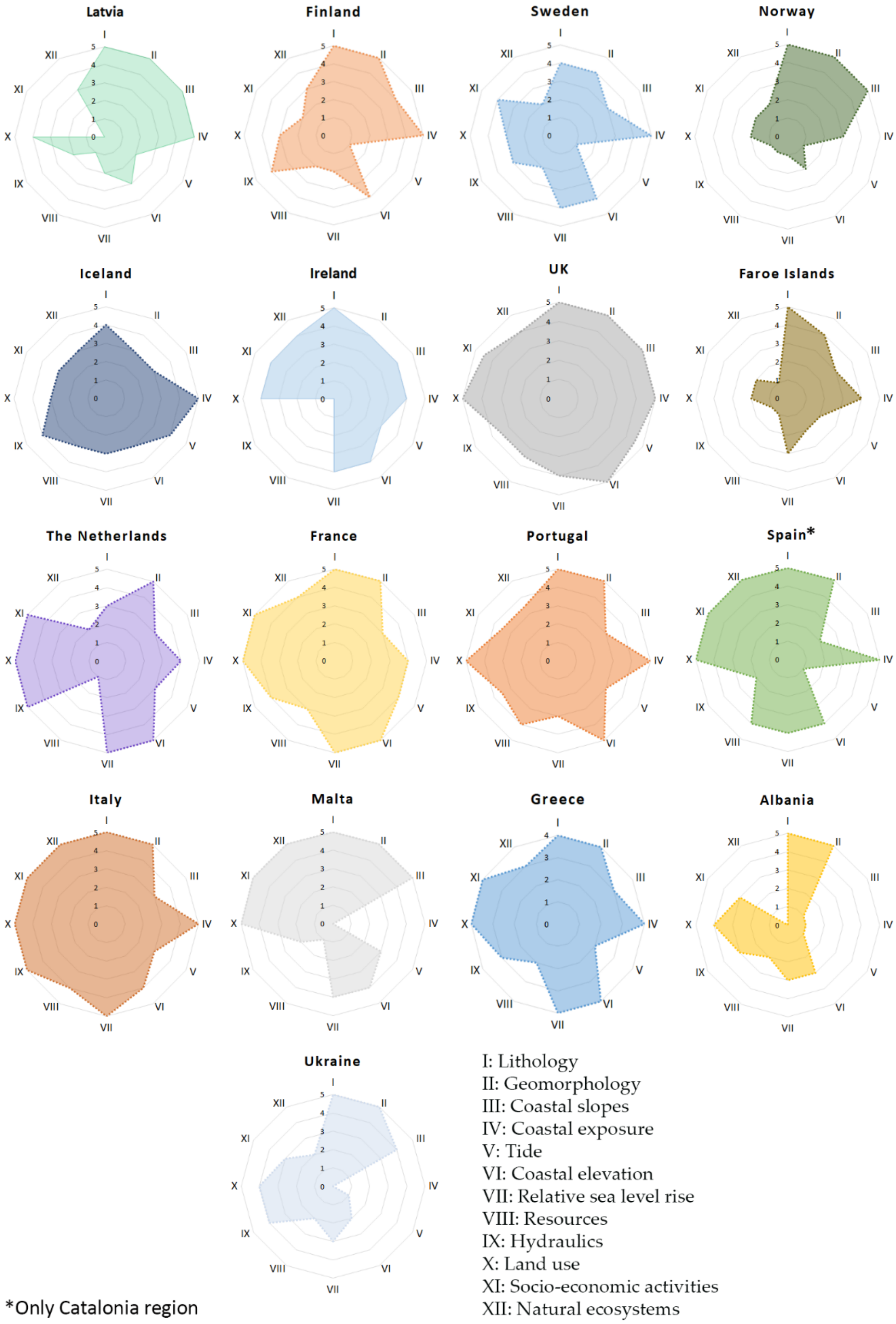

Figure 4-5 - Importance of influencing parameters according to respondent countries (5 = very Important; 1= Not important at all; 0=not answered) (phase 1).

If not representing the whole coasts in Europe, the respondent countries already cover a large part of European coastal length and a great variety of coast types. The littoral zone is highly diverse even on a single country. For example, Portuguese coasts comprise several coastal types and habitats with a wide range of morpho-sedimentary environments, such as beaches, cliffs, estuaries or lagoons. Italy is another example as the Italian coastal environments are very diversified from the morphological, ecosystemic, socio-economic point of view. Thus, in this context, almost every factor is important.

Geomorphology appears to be the most important parameter. Indeed it greatly impacts the risk level faced by regions. For instance, geomorphology makes low-lying areas more vulnerable in Portugal, in Southern Sweden or in the Netherlands, whereas sea level rise and coastal erosion is a minor problem in Northen Sweden or in Norway which are more concerned by landslides/rockslides or avalanches along steep slopes.

Lithology is also important. For example, varying (heterogenic) lithology (e.g., Precambrian bedrock vs. sedimentary bedrock) is an important parameter influencing the coastal vulnerability in Finnish coastal areas. Acid sulphate soils (ASS) are also an environmental problem in the Finnish coastal areas, where human activities and coastal exposure can affect/enhance the metal loads from the ASS soils. Lithology is also important for Swedish coast with the North coastline mainly composed of crystalline rock whereas the southern part is generally formed on glacial sediments.

Relative sea level rise is still quite low in the Finnish, Icelandic and northern Swedish coastal areas due to glacio-isostatic land uplift. In south Sweden on the contrary, glacio-isostatic rebound has stopped. Greece is characterized "*by complex geology and an active tectonic setting, that affects and shapes the landscape and the coastal areas, accordingly, causing also sea-level rise*", whereas Iceland is on an active rift zone.

Considering "**socio-economic factors**" covered in the questionnaire, it is important to notice that some coastlines are very populated. For example, in Catalonia (Spain), the 70 coastal municipalities represent 6.7% of the territory area, but concentrate 43.3% of the country's population and a very large part of its economic activity, including tourism (CADS, 2021). In Portugal, ¾ of the population lives in the coastal zone and the system is, in some sectors, under intense human pressure leading to conflicts between natural and human-induced coastal behaviors. The socio-economic parameters are given a more important place in countries where the coast hosts a large part of the population and economic activities (for example Catalonia in Spain, Italy, Malta, France, United-Kingdom or the Netherlands). Coastal zones also contribute greatly to gross domestic product (up to 85% in Portugal for example). In those countries, land use is also identified as a very important parameter. In Portugal, about approximately 30% of the coastline has been altered by human occupation. The intense and growing human activity on the coast, and also on hydrographic basins, has promoted a reduction in the sediment supply favoring a strong erosion evolution at some coastal sectors: about 50% of the sandy shore (~ 178 km of coastline) shows an erosional trend, being more severe in the northwest coastal sector of Portugal. Also in Greece, recently the increasing occurrence of extreme weather conditions has greatly affected the coastline in many places (Evelpidou *et al.,* 2023; Karkani *et al.*, 2023).

Considering **tides** and **coastal exposure**, Baltic Sea is micro tidal while the "Portuguese coast is high-mesotidal and presents different characteristics regarding wave energy and climate at the western and southern coasts, owing to the different exposure to the North Atlantic. For example, the western Portuguese coastline is fully exposed to the strong energetic marine wave climate, which, in combination with an NNW-SSE orientation, induces a southward net potential littoral drift. The southern coast has milder conditions and except during the SE wave regime events, the dominant waves derive from W and SW, driving an easterly directed littoral drift and longshore currents, with magnitudes varying according mainly to wave exposure, sediment availability and local geomorphology. Exposure to wave regime leads to a more vulnerable Portugal west coasts. In the mediterranean sea, the astronomical tidal variation on the Maltese islands is insignificant (30 cm). However, mereologically forced events such as atmospheric tsunamis (Seiche oscillations/waves) do occur in low lying localities and disrupt socio-economic activity. This phenomenon is locally known as *il-milghuba*. Low lying localities, particularly ones which have expanded seawards through land reclamation are particularly vulnerable. These locations are also vulnerable to seismic sea waves, such as the inundation of Msida creek (+1.41m) (Mottershead, Bray, & Soar, 2018) following the 28th December 1908 Messina Strait Earthquake.

The coastal zone of the northwestern part of the Black Sea develops in complicated geological conditions. There are following types of rocks on the coastal slope: loess-like loams, red-brown clays, pontic limestones, meotic clays, and landslide complexes (Zelinsky *et al.,* 1993). Landslides are formed in the places where the abrasive post-Pontic plateau reaches to the sea level. That plateau completed by a series of Neogene sediments (Meotic and Pontic clays, limestones, red-brown clays), covered with loess rocks. A stepped combhilly surface is typical for less high landslide slopes (from 20 to 40 m). The steepness of these slopes is 15-35 degrees. Such a relief is observed in the Sanzheika stationary section. Landslide complexes in the form of limestone blocks and patches of Meotis clays covered by sands and silts of modern marine and biogenic sediments are presented on the underwater slope. Abrasion is one of the main factors in the violation of slope stability. Abrasion activity of the sea excludes the possibility of long-term stabilization of landslide slopes. The coastline recedes at a rate of 0.1-2 m / year, the rate of bottom abrasion is 0.005-0.030 m / year (Pedan et al. 2021a). During periods of active landslide movements, the bottom of the abrasion scarp moves towards the sea and the abrasion activity decreases. The linear retreat of the cliff and the volume of the water erosion of rocks at the sites of long-term observation are interchangeable indicators, since they correlate quite well (the correlation coefficient $r = 0.95$ at a significance level of $p < 0.05$).

The beach is the most dynamic element of the coastal zone, which responds to natural and artificial interventions in the development regime. The supply of the beaches is complex, the main source of sediment is the erosion of the cliff and shelf. Depending on the width and sediments volume, the beach completely or partially dampens the energy of the waves. It is known, that in the current sea hydrodynamic regime, a beach 35-40 m wide is able to completely protect the coast from erosion in the study area; with a smaller beach width, the coast is destroyed with different intensity (Zelinsky *et al.,* 1993). Due to the fact that the seashores of the northwestern part of the Black Sea are predominantly composed of loose, easily eroded rocks, more than 75% of the sedimentary mass is carried outside the coastal zone into the open sea because of differentiation processes influence. (Pedan *et al.,* 2021a, Pedan *et al*., 2021b)

4.4. Inter comparison between countries concerning the consideration of coastal risks and vulnerability in public policies

Coastal risk management

For this question, the interviewees were asked which level of governance is involved in coastal risk management in their country. From the answers showed in Figure 4-6, local level government is the less identified as "fully implicated", but at the same time the only government level not identified as "not implicated".

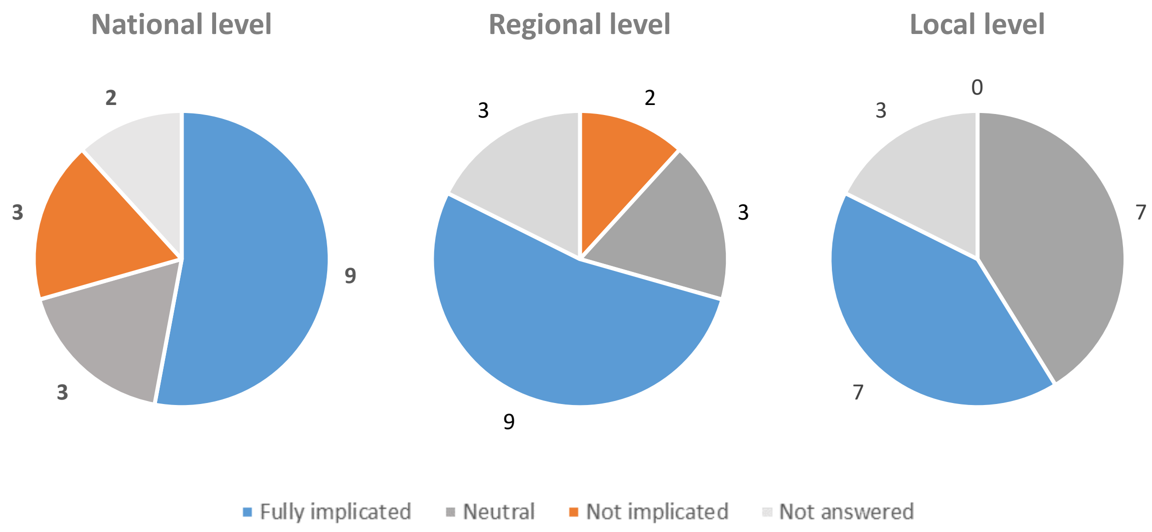

Figure 4-6 - Importance given to national, regional and local level in coastal risk management in the 17 respondent countries (phase 1).

Regional level and national level are both identified as fully implicated in 9 countries out of 17. It is to be noted that 4 countries identified no level as "fully implicated" whereas 5 countries indicated the three levels (national, regional and local) to be fully implicated. Four countries identified 2 levels as fully implicated in coastal risk management (2 for regional and national levels, 1 for local and national levels and 1 for local and regional levels) and 2 other countries indicated that only one level is fully involved in coastal risk management (1 at national level and 1 at regional level).

As suggested by these results, the role of local and regional authorities is heterogeneous among European countries and even within countries. For example, the involvement of local and regional authorities is not uniform throughout Greece as it is not governed by a general framework. In UK, if *"local and regional authorities have significant responsibilities in coastal risk management, they often work in coordination with national government agencies, such as the Environment Agency in England, to ensure a holistic and coordinated approach to coastal protection and resilience. But the division of responsibilities may vary in different parts of the UK, as some powers are devolved to the regional governments of Scotland, Wales, and Northern Ireland".* In addition, with two to three levels of governance involved in coastal risk management in most of the respondent countries, the distribution of coastal planning powers is very complex.

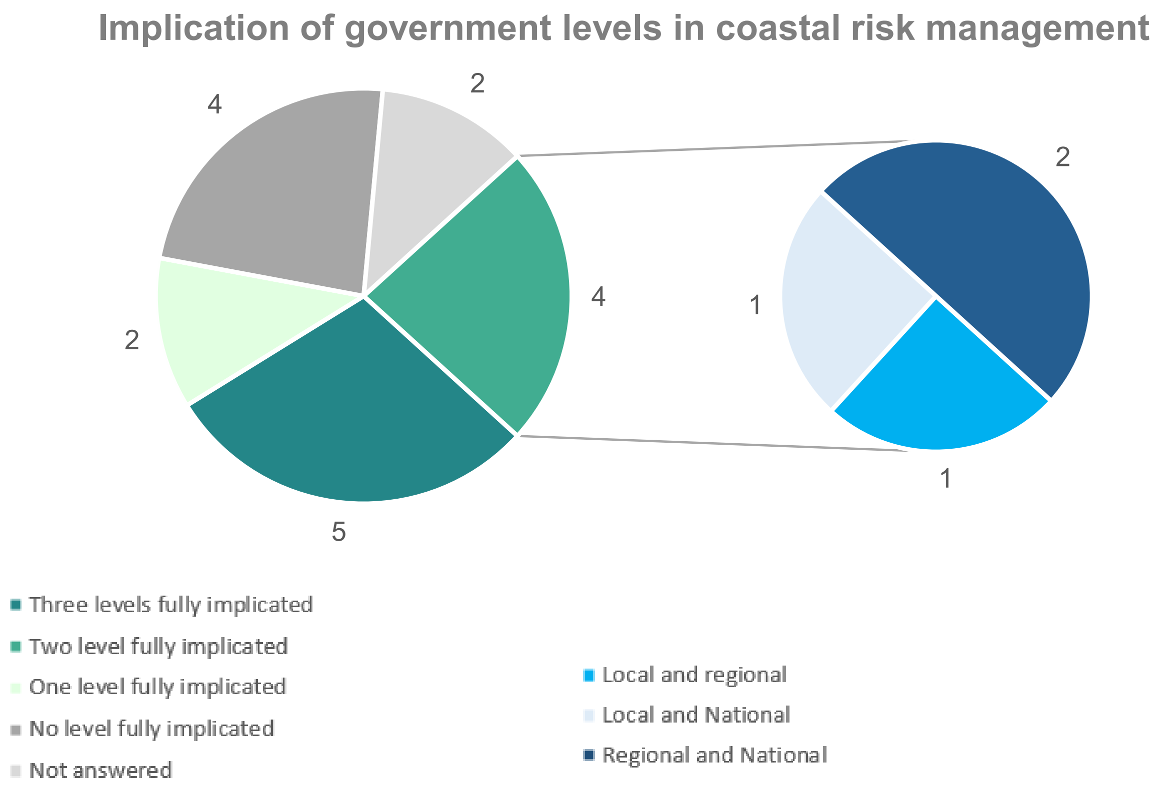

Figure 4-7 - Number of government levels fully implicated in coastal risks management by countries (phase 1).

In some countries, local and/or regional authorities have to **implement national directives**. For example, Norwegian local authorities have to follow the national guidelines and recommendations from the Norwegian Water Resources and Energy Directorate (NVE). Dutch regionally (provincial) authorities also have to execute national policies, while in France it is local authorities (town or inter-municipalities) that have to implement national policies or even regional policies such as Risks Prevention Plans (PPR), or flood prevention action programs (PAPI). In Portugal local governments are responsible for the implementation of policies and management plans. In Malta, environmental management/policy responsibilities fall upon national authorities. Thus, local and regional authorities have a role at the administrative levels only. In Iceland, "*monitoring or mapping out potential coastal hazards is done on a project-by-project, or case-by-case basis, and a nationwide system has not been implemented yet. Each municipality has their own responsibility and road administration for the coastal areas*".

Local and regional authorities are also **involved in or responsible for planning the territory** such as in Catalonia (Spain), UK or France. Indeed, in the UK, local authorities, such as district and borough councils, "*are responsible for land-use planning and development control in coastal areas. They regulate construction and development to minimize risks associated with coastal hazards*". In France, local authorities play a critical role in managing land use and implementing policies related to sustainable development, risk management, and environmental preservation. They utilize several frameworks and regulatory tools to achieve these goals. At the municipal level, the PLU (Local Urbanism Plan) defines zoning and land-use regulations, specifying permissible land uses, building densities, and environmental protections to balance urban development with ecological concerns. For broader, intercommunal cooperation, the PLUi (Intercommunal Local Urbanism Plan) aligns urban planning and development strategies across multiple municipalities, ensuring coordinated approaches to land use, infrastructure, and environmental management. At a regional scale, the SCoT (Territorial Coherence Scheme) provides a strategic framework for integrating urban, environmental, economic, and social objectives, fostering coherence among local development policies. Additionally, the GEMAPI (Management of Aquatic Environments and Flood Prevention) policy, implemented by intercommunal bodies since 2018, focuses on managing aquatic environments, maintaining riverbanks, and preventing floods, with an emphasis on adapting to climate change. Together, these tools empower local authorities to address urbanization challenges, promote sustainability, and ensure cohesive regional development.

Local and regional authorities are also often **responsible for protection structures and works**, from single maintenance works to more complex and complete actions. In Catalonia, local authorities manage temporary installations and repair damage caused by storms. They are also responsible to undertake coastal strengthening works in Latvia. In Greece, in most cases, the local and regional authorities intervene only after the coastline has been affected (Kontopyrakis *et al.,* 2024) while Ukrainian local and regional authorities are engaged in maintaining the operation and development of new coastal protection structures. Dutch local authorities realize different works "*from simple issues like optimal beach width to acceptable dual-use protection measures like man-made dunes with a built-in parking garage*". In the UK "*local and regional authorities work together to assess and manage coastal erosion risks. They may implement erosion control measures, such as beach nourishment, seawalls, and managed retreat strategies. They implement flood defense systems, maintain existing infrastructure, and provide flood risk information to residents and businesses*". In UK and France for example, local authorities are also responsible for coordinating emergency response efforts during coastal disasters, such as storm surges or severe flooding. "*They work with emergency services to evacuate residents and provide shelter, food, and medical support when necessary*".

UK local authorities are **deeply involved in coastal risk management**. "*Local councils often develop shoreline management plans that provide a long-term strategy for addressing erosion and flood risks along the coast*". In addition, *"local and regional authorities cooperate with the Environment Agency in England, Natural Resources Body for Wales, and the Scottish Environment Protection Agency in Scotland to manage flood risks along the coast and they implement flood defence systems".* UK local and regional authorities also "*play a crucial role in **raising awareness** among residents and businesses about coastal risks. They provide information on flood zones, evacuation plans, and steps individuals can take to prepare for emergencies".* In the UK, local councils often "*allocate budgets for coastal risk management projects and may seek external funding sources, such as grants and subsidies, to support these initiatives*". Dutch regional (provincial) authorities also plan and fund plans.

In other countries, local and regional authorities have to deal with budget issues. For example, Swedish local authorities have to deal with coastal erosion. They get support from the county administration boards. However, there are facing significant issues with financing and outdating planning laws. National government lack interest for this issue and the planning laws allow the construction of houses in vulnerable areas (based on plans drawn up in the 1960s). In Sweden, individual landholders are responsible to protect their property at their own costs, but permission should be sought from the county administration board to implement a coastal project. However, this last point is often overstepped and landholders go ahead and protect their own property. In some places (for example Löderup strandbad), these individual protection actions increase erosional problems for neighbors.

In the UK, "*local councils are increasingly involved in developing climate adaptation and resilience plans to address long-term coastal risks, including the potential effects of climate change, such as rising sea levels. They collect and maintain data related to coastal conditions, erosion rates, and flood risk assessments. This data is vital for informed decision-making and future planning. In addition, UK local and regional authorities also provide flood risk information to residents and businesses.*"

Definition of policy and decision-making objectives

For this section, interviewees were asked *"In your country, which level of governance is the most involved in the definition of policy and decision-making objectives? (Territorial management, coastal protection, adaptation measures)".* The results presented in Figure 4-8 show that the definition of policy and decision-making objectives are mainly supported at the National level which is fully involved in 8 (out of 17) countries followed by the regional level. Local level is only indicated as fully implicated in 2 countries.

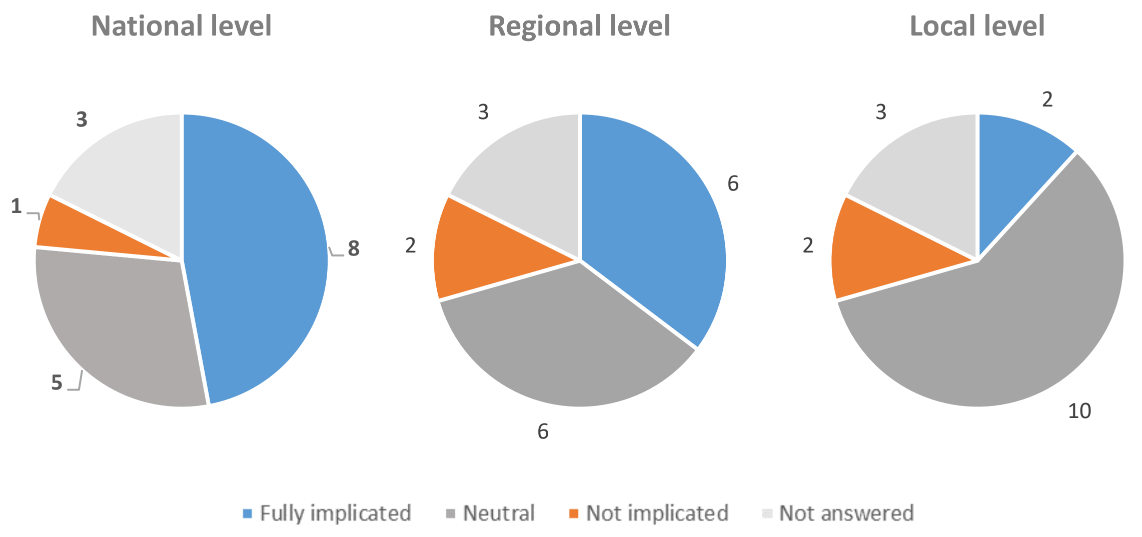

Figure 4-8 - Importance given to national, regional and local level in coastal policy definition for the 17 respondent countries (phase 1).

For example, in France or in the Netherlands, the main policies and strategies, in line with various European directives, are a national responsibility whereas the practical implementation is partly determined by provincial and local authorities. In the same way, the definition of policy in Greece is mostly in the jurisdiction of the general government at a national level, however, specific policies for territorial management, coastal protection and adaptation measures are not thoroughly covered by Greek regulations. In Latvia, active protection is also rare and mostly take place at the local governance level. Several countries are particularly noteworthy and merit being highlighted in this context. Their unique contributions, coastal characteristics, and approaches to addressing key challenges provide valuable insights and strengthen the overall analysis:

UK is the only country having identified the 3 levels of governance as fully implicated (Figure 4-9). Indeed, in the UK, "*policy and decision-making objectives are defined and determined at multiple levels* *of governance, with varying degrees of involvement and authority. The level of governance that is most involved in setting policies and objectives can depend on the specific policy area. However, as a general guideline:*

1. *National Government: The national government, which includes the UK Parliament and the UK government departments, is typically the most involved in defining policies and objectives for a wide range of issues, including matters of national significance, such as defense, foreign affairs, immigration, and fiscal policies. National government sets the overarching legal and regulatory framework for the entire country.*
2. *Devolved Administrations: In the UK, Scotland, Wales, and Northern Ireland have devolved administrations with varying degrees of legislative powers. In these regions, the devolved parliaments/assemblies and their respective governments have significant authority over areas such as education, healthcare, transportation, and certain aspects of social policy. They are responsible for setting policies and objectives in these devolved areas.*
3. *Local Authorities: Local government bodies, including county councils, borough councils, and city councils, have a substantial role in defining and implementing policies at the local level. They manage issues such as local planning, housing, transportation, waste management, and some aspects of social services.*
4. *Regional Bodies and Partnerships: In certain cases, regional bodies and partnerships may also be involved in policy development for specific issues, especially those that cross administrative boundaries, like regional economic development, environmental initiatives, and transportation planning.*
5. *Public Consultation: At various levels of government, public consultation processes are used to gather input and feedback from the public and stakeholders, which can influence policy decisions.*

In summary, the level of governance most involved in defining policy and decision-making objectives can vary depending on the policy area and the distribution of powers between the national government, devolved administrations, and local authorities. The UK operates under a system of parliamentary democracy and devolution, where different layers of government have specific responsibilities and areas of influence. This distribution of powers is meant to ensure that decisions are made at the most appropriate level of government for effective and responsive governance."

Also, in Finland, "*policy and decision-making objectives are determined through a multi-level governance system. The most involved level in defining these objectives can vary depending on the specific issue, but generally, policy and decision-making in Finland are characterized by a cooperative and decentralized approach involving various levels of government. The key levels of governance involved in defining policy and decision-making objectives in Finland include:*

- *National Government: The Finnish national government plays a significant role in setting overarching policies and objectives. It establishes national strategies and guidelines that impact various areas.*
- *Regional and Municipal Governments: Finland is divided into regions and municipalities. Regional governments and municipalities have substantial autonomy in managing local affairs, including e.g., education and social services. They have the authority to make decisions and set policies that are relevant to their specific regions."*

Levels of governance involved in the definition of policy and decision-making objectives

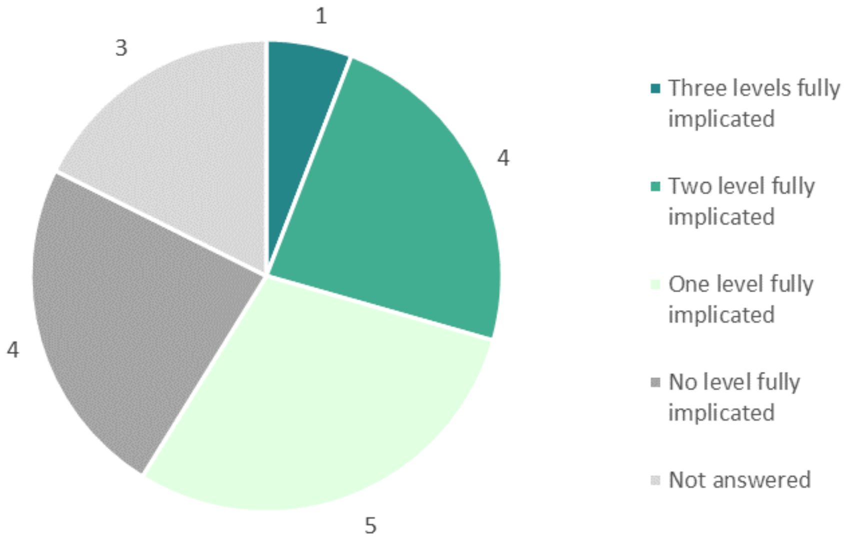

Figure 4-9 - Levels of governance involved in the definition of policy and decision-making objectives.

Coastal erosion and flooding hazards in regulation

In European countries, the regulatory approach to coastal erosion and coastal flooding hazards varies, with some policies addressing them jointly and others separately. The European Union's Floods Directive (2007/60/EC) focuses on managing flood risks, including those from sea water, but does not explicitly address coastal erosion, prompting discussions on integrating it into flood risk management plans. In contrast, initiatives like EUROSION advocate for sustainable coastal erosion management, emphasizing that while erosion cannot be entirely controlled, it can be managed in an economically and environmentally sustainable manner. Nationally, approaches differ: some countries integrate coastal erosion and flooding into comprehensive coastal zone management strategies, while others treat them under separate frameworks, creating challenges for cohesive adaptation measures in regions where both hazards coexist. The European Environment Agency (EEA) highlights the interconnected impacts of sea-level rise, flooding, and erosion on settlements, infrastructure, and natural systems, underscoring the need for integrated management. Efforts continue at various governance levels to harmonize policies and promote comprehensive coastal risk management across Europe.

Partners interviewees were here asked if coastal erosion and coastal flooding hazards were considered jointly or separately in their current regulation. The results for this question (Figure 4-10) show that coastal erosion and coastal flooding are mainly considered separately in the countries of this study. Indeed, six countries declared that the two coastal hazards are considered separately in current regulations (Sweden, Italy, Finland, Spain, Malta and France) while four countries indicated it is considered jointly (The Netherlands, UK, Greece and Ukraine).

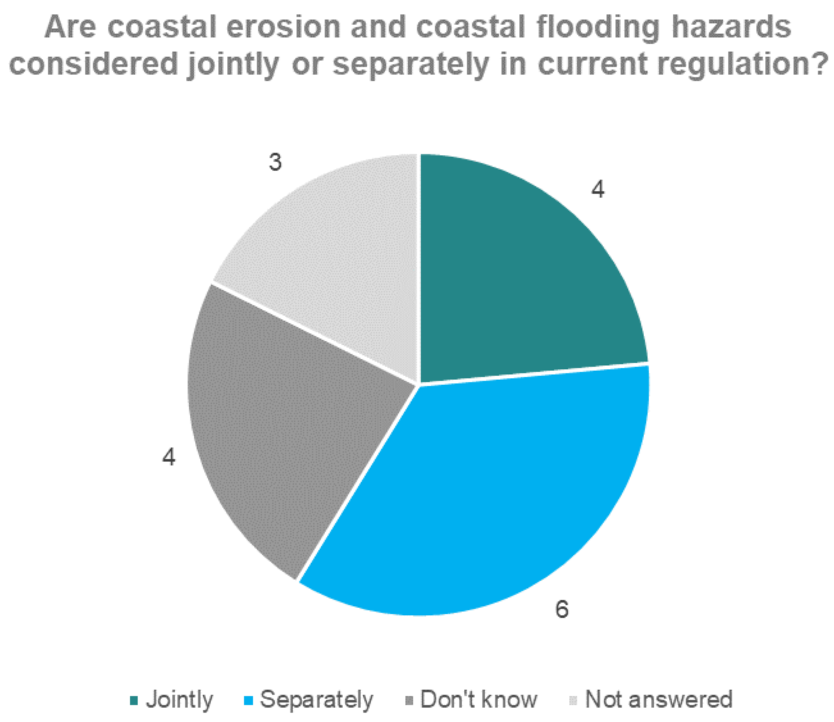

Figure 4-10 - Coastal erosion and coastal flooding management in current regulations across the respondent countries (phase 1).

In the United Kingdom, "*coastal erosion and coastal flooding hazards are typically considered jointly in current regulations and coastal management strategies. This integrated approach recognizes that the two hazards are often interconnected and that addressing one without considering the other can lead to incomplete and ineffective coastal risk management.*
Key points regarding the joint consideration of coastal erosion and coastal flooding in the UK's regulations and policies include:

1. *Shoreline Management Plans (SMPs): One of the primary tools for addressing coastal risks in the UK is the development of Shoreline Management Plans (SMPs). These plans are comprehensive and strategic documents that cover entire lengths of the coastline and consider both erosion and flooding risks. SMPs classify coastal areas into four zones: "Hold the Line," "Advance the Line," "Managed Realignment," and "No Active Intervention." Each zone represents different management approaches for addressing both erosion and flooding hazards.*
2. *Integrated Risk Assessments: Coastal management in the UK involves integrated risk assessments that take into account various hazards, including erosion and flooding. These assessments consider the potential impacts of climate change, sea-level rise, and extreme weather events on coastal areas. This integrated approach allows for more robust and adaptable planning.*
3. *National Policy Statements: The UK's national policy statements related to infrastructure and planning often include considerations for coastal risk management. These statements emphasize the importance of considering coastal erosion and flooding together, particularly in the context of critical infrastructure projects.*
4. *Collaboration: National, regional, and local authorities collaborate to develop and implement coastal management strategies. This collaborative approach ensures that erosion and flooding risks are addressed in a coordinated manner.*

5. *Community Engagement: Local communities are often involved in the decision-making processes related to coastal risk management. They have a say in how their areas are managed to mitigate both erosion and flooding risks, promoting resilience and sustainability.*

It's important to note that the UK recognizes the changing nature of coastal risks due to factors like climate change and sea-level rise. This recognition has led to more adaptive and flexible approaches to coastal management, where strategies are regularly reviewed and updated to account for evolving conditions. While coastal erosion and coastal flooding are managed jointly in the UK, the specific approaches and priorities may vary in different regions based on local conditions, resources, and objectives. The overarching goal is to balance the protection of coastal communities and infrastructure with the preservation of the natural coastal environment."

To note, the current legislative framework in Greece, does not yet deal in detail with coastal erosion and flooding; thus they are dealt with jointly in terms of protection of the natural environment of the coastal zone (Giannakourou and Balla, 2015). Conversely, floods are also given more attention than erosion in Finland and Sweden, but also in the Netherlands where flood risk is considered in light of both overtopping and erosion. In addition, in several countries, coastal flooding is considered within Flood Directive or Flood risk management plan. It is at least the case for Malta, Italy and even in Greece.

In French regulation, coastal erosion and marine flooding are addressed through distinct frameworks, reflecting a dichotomy in their management and regulatory treatment. **Marine flooding** is primarily regulated under the framework of flood risk management plans (PPRi - Plans de Prévention des Risques d'Inondation), which focus on protecting people, property, and infrastructure from flooding risks, including those caused by storm surges and sea-level rise. These plans are mandatory in areas identified as at risk and often include zoning restrictions, building codes, and adaptation measures. In contrast, **coastal erosion** is governed separately, under a more fragmented set of policies that fall within broader coastal and land-use management frameworks. In France, the government now considers that coastal erosion is a gradual and therefore predictable risk and does not induce an unpredictable threat to safety and human life. Marine flooding, on the other hand, is considered a major risk (a sudden or chronic physical event likely to cause damage). This dichotomy between coastal erosion and flooding can lead to challenges in implementing coordinated adaptation strategies, especially in regions where erosion and flooding are interrelated hazards. Efforts to bridge this gap are ongoing, with increasing recognition of the need for integrated approaches that address both phenomena simultaneously, particularly in the context of climate change and rising sea levels.

Sea level rise (SLR) in current policies

Here, the interviewees were both asked:

- whether sea level rise is taken into account in different regulations. As shown by Figure 4-11, sea level rise is mainly integrated in regulations on coastal flooding (10 countries) and coastal adaptation measures (9 countries).
- "what are the related framework documents for your country? (national directive or guide, current law marking a significant paradigm shift on this subject, national management strategy and possible regional/local variations, etc.)".

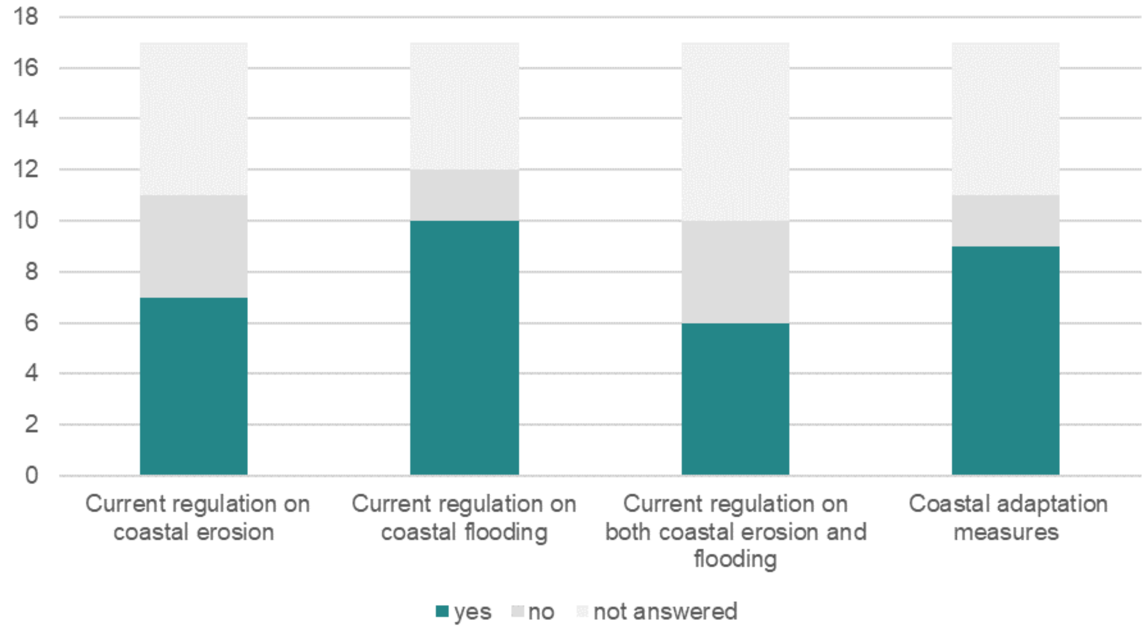

Figure 4-11 - Integration of sea level rise in current policies.

In Iceland, areas of known flooding by sea or rivers have special building plans for bridges, wave guards, and extended coastal fills to add to harbor or construction areas. This is done on a local basis and not implemented in a consistent planning at a nationwide scale. In Italy, SLR is taken into account in the current regulation and coastal adaptation measures, but methodologies or national guidelines are not yet defined. It is important to note that in Latvia, there are currently no information on sea level rise in current regulations.

"In Portugal, the development and implementation of coastal planning plans (POOC) are regulated by Decree-Law No. 159/2012, of 24 July. The Portuguese Coastal Planning Plans (POOC - Planos de Ordenamento da Orla Costeira) establish regimes for safeguarding natural resources and values, through guiding and management principles and standards. They cover a strip along the coast, which is called the terrestrial protection zone, with a maximum width of 500 m counted from the limit of sea waters to land and a maritime protection strip up to the bathymetric level of 30 m, with the exception of areas under port jurisdiction. Prior to the change in the territorial management system resulting from the publication, in 2014, of the General Bases Law for Public Soil Policy, Territorial Planning and Urbanism, POOCs were approved for the entire strip coast between Caminha and Vila Real de Santo António."

The 2021 French « Climate and resilience » law (*Loi Climat et Résilience /* no. 2021-1104 of 22 August 2021 on combating climate change and building resilience to its effects) represents a significant step forward in addressing environmental challenges, including coastal erosion. This legislation introduces several measures to enhance the management of coastal risks, particularly in areas vulnerable to shoreline retreat due to climate change and rising sea levels. Key measures related to coastal erosion from the « Climate and resilience » law are:

- Local Maps of Exposure to Shoreline Retreat: The law mandates the development of these maps to identify areas at risk of coastal retreat over defined time horizons (30 and 100 years). These maps serve as critical tools for guiding land-use planning and adaptation strategies at the municipal level, ensuring that future developments account for projected shoreline changes.

- Adaptation of Urban Planning Rules: Local authorities are required to integrate these exposure maps into urban planning documents, such as PLU and PLUi, to restrict or regulate construction in high-risk areas. This measure aims to prevent further development in zones likely to be affected by coastal retreat.
- Relocation Strategies: For properties already located in areas of high vulnerability, the law facilitates mechanisms for managed retreat, including financial support for relocation and compensation for property owners whose assets are deemed unsustainable in the long term.
- Prohibition of New Construction in Risk Zones: In the most at-risk zones, where shoreline retreat is expected to have significant impacts, new construction may be prohibited, prioritizing safety and long-term sustainability over short-term development.
- Enhanced Local Governance: The law empowers municipalities and intercommunal bodies to take a more active role in managing coastal risks, fostering collaboration between local, regional, and national authorities.

The French « Climate and resilience » law marks a shift toward proactive and anticipatory coastal management, integrating scientific projections of coastal retreat into spatial planning and risk management, which requires to take into account SLR in coastal erosion assessment. By requiring local exposure maps and embedding these into urban planning, the legislation strengthens the capacity of local governments to address the challenges of coastal erosion. It also highlights the importance of balancing development needs with environmental and safety concerns, promoting long-term resilience in coastal areas. Now enshrined in the 2021 law, the French National Strategy for Integrated Coastal Zone Management (SNGITC), adopted in 2012, provides a comprehensive framework for sustainable coastal management, balancing environmental preservation, socio-economic activities, and adaptation to climate change. It emphasizes a participatory and integrated approach, encouraging coordination among stakeholders, including national authorities, local governments, and private actors. The strategy aims to address key challenges such as coastal erosion, biodiversity conservation, and sustainable land use. It advocates for the integration of climate resilience into planning processes, the preservation of natural coastal dynamics, and the reduction of risks linked to sea-level rise. Through the SNGITC, France seeks to align local and national policies with international commitments, fostering a sustainable and adaptive management model for its diverse coastal zones.

In the United Kingdom, "*coastal flood and erosion risk management is governed by a series of framework documents, policies, and legislation. These documents provide guidance and set out the strategic approach to managing these risks. Some of the key related framework documents and legislative measures include:*

- *The Flood and Water Management Act 2010, which provides the legal framework for managing flood risk, including coastal flooding, and it established the Flood Reinsurance Scheme. It sets out the responsibilities of various authorities and organizations in managing flood risk.*
- *The National Flood and Coastal Erosion Risk Management Strategy for England, which outlines the government's approach to managing flood and coastal erosion risks in England. It sets out the long-term vision, objectives, and actions for reducing these risks.*
- *The Shoreline Management Plans (SMPs), that are developed by the Environment Agency and other risk management authorities to assess the risks associated with coastal erosion and flooding along the English and Welsh coastlines. They provide a strategic overview of the policies for managing these risks and are periodically reviewed and updated.*

- *The Coastal Change Policy and Guidance (CCPG), which provides guidance on how local authorities and organizations should manage coastal change. It covers issues related to erosion, flooding, and coastal defense, and it emphasizes the need for sustainable and adaptive approaches.*
- *The Joint Nature Conservation Committee (JNCC) Coastal Erosion Risk Management (CERM) Framework, which provides guidance on managing coastal erosion in a manner that considers and protects the environment and habitats along the coast.*
- *The Scotland's National Flood Risk Management Strategy, where flood risk management is governed by this strategy, which outlines the approach to managing flood and coastal erosion risks in Scotland.*
- *The Wales Coastal Erosion Risk Management Strategy, where this strategy provides the approach to managing coastal erosion risks and includes measures to adapt to climate change.*
- *The Northern Ireland Flood Risk Management Plan, which outlines the approach to managing flooding and coastal erosion risks.*

All these documents provide the overarching framework for coastal flood and erosion risk management in the UK, with specific regional and local plans and strategies developed to address the unique challenges of each area."

For all the laws and strategies mentioned here, it is important to consult the most up-to-date versions of these documents, as they may be periodically reviewed and revised to account for changing conditions and new information.

4.5. The Coastal vulnerability Index

The Coastal Vulnerability Index (CVI) is one of the most common and simple methods to assess coastal vulnerability to sea level rise, especially due to erosion and/or inundation (Gornitz, 1991). This is an essential tool used in European coastal vulnerability and climate change studies to evaluate and rank the susceptibility of coastal areas to hazards such as erosion, flooding, and sea-level rise. It integrates multiple physical, geological, and socio-economic parameters to provide a comprehensive vulnerability assessment.

Key insights into its use across Europe include:

- **Assessing Sea-Level Rise Impacts**
  CVI is widely applied to assess the potential impacts of sea-level rise on low-lying coastal areas. Countries like the Netherlands, Belgium, and Denmark, with extensive low-lying coastal zones, utilize CVI to develop adaptive strategies and protective measures.
- **Mapping Erosion-Prone Areas**
  CVI has been used in Portugal, Spain, and Italy to identify sandy beaches and cliffs that are particularly vulnerable to coastal erosion, aiding in the design of shoreline stabilization projects.
- **Guiding Policy and Management**
  In the United Kingdom, France, and Germany, CVI results inform national and regional policies, such as Integrated Coastal Zone Management (ICZM) and Marine Spatial Planning (MSP). For example, in the UK, studies use CVI to evaluate coastal resilience under different climate change scenarios.

- **Regional and Cross-Border Collaboration**
  Transnational studies, such as those in the Baltic Sea and Mediterranean, mobilize CVI to harmonize vulnerability assessments across borders. This fosters regional cooperation in addressing shared challenges like flooding and habitat loss.

Parameters considered in CVI calculations are based on a combination of natural and anthropogenic factors. In particular, this can include geophysical and geomorphological factors (coastal slope, geomorphology, lithology, wave exposure, and tidal range), socio-economic factors (population density, land use, and the economic value of coastal infrastructure), and environmental sensitivity (ecosystems at risk, such as wetlands and dunes). Every implementation brings benefits and challenges. CVI provides a standardized, scalable approach for assessing vulnerability, enabling comparisons between regions and informing proactive risk mitigation strategies. The variability in data availability and resolution across Europe can influence the precision of CVI applications. Continuous improvements in data harmonization, such as those promoted by EMODnet and other EU initiatives, aim to address these limitations. The CVI remains a critical framework in Europe, contributing to evidence-based planning, enhanced resilience, and sustainable coastal management in the face of climate change.

CVI calculation generally requires 4 steps (Figure 4-12) The identification of key variables driving coastal evolution (commonly 6 to 7 parameters). CVI calculation. For example, U.S. Geological Survey (USGS) uses 6 parameters: geomorphology, shoreline change rates, coastal slope, relative sea level rate, mean significant wave height, mean tidal range. The second step generally uses semi quantitative scores to evaluate the parameters. After aggregation, the CVI results are generally distributed in categories.

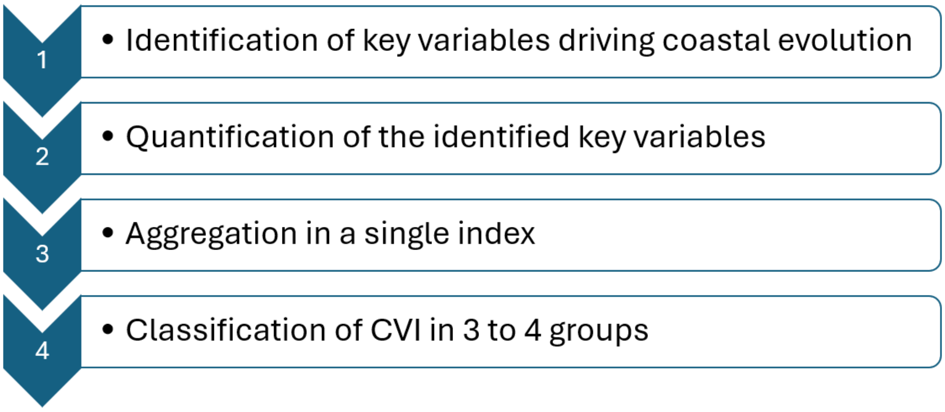

Figure 4-12 - CVI calculation steps.

Original CVI does not include socioeconomic aspects while the socioeconomic component is very important in vulnerability assessment. This is why some authors decided to use the original CVI in association with other indexes able to more properly represent the complexity of the coastal system also in relation to socio-economic aspects; and others modify/extend the original formulation of the CVI taking into account variables representing the socio-economic systems (for e.g. Multi-scale CVI). For example, Özyurt et al. (2008) developed a modified CVI focusing specifically on sea level rise impacts. This index is subdivided into 5 sub-indexes focusing on coastal erosion, flooding due to storm surges, permanent inundation, salt water intrusion to groundwater resources and salt water intrusion to rivers/estuaries.

Several European countries are documented in the study by Rocha *et al*. (2023) and the document from European Environmental Agency (ETC CCA, 2011).

4.6. Cases Study and Datasets: the Role of GSOs in Improving the Estimation of Coastal Vulnerability to the Effects of Sea-Level Rise

This section presents five key contributions from GSOs related to coastal studies and vulnerability assessments. It begins by exploring the application of the Coastal Modelling Environment to regions such as Andalusia (Spain) and Happisburgh in East England (UK), discussing the long-term planning challenges and the role of geological surveys in addressing these issues. Additionally, the report delves into Latvia’s evolving coastline, highlighting the use of geological monitoring and remote sensing tools like Sentinel-2 data and LIDAR technology for advanced coastal monitoring, with a focus on future prospects within Latvia's GSO. The national datasets for Poland's coastal vulnerability analysis are also examined, followed by a case study on Italy’s coastal vulnerability, particularly in relation to coastal dynamics, landslides, and habitats. Lastly, the Portuguese GSO's vulnerability assessment of coastal erosion is presented, detailing the role of the LNEG in identifying vulnerable areas and monitoring sediment load from the Douro River.

Application of the Coastal Modelling Environment to Andalusia (Spain) and Happisburgh in East England (UK)

The long-term planning problem

After a major failure of coastal protection infrastructure, removal of about 1 km of coastal defense along the otherwise protected cliffed coastline of Happisburgh (Figure 4-13), East England, triggered a period of rapid erosion over 20 years of about 140 m (Payo *et al*., 2018). As defense infrastructure continue aging, local planners need to understand what adaptation options they have at their disposal. If they continue removing coastal defenses, the eroding cliff will be adding sand and gravel to the beach that will serve as a natural protection against coastal erosion (Lopez *et al.,* 2020), but they need to know in advance how much protection is expected to be gained and how much of the cliff will be lost and where in the incoming years up to 2100.

The planner has a different problem along the Andalusia coastline in Southern Spain. The regional government of Andalusia has several responsibilities regarding the use of the coastal public domain, primarily governed by Spain's Coastal Law (Ley de Costas). One of them is granting Concessions: The government can grant concessions for the use of the coastal public domain. These concessions allow private entities to use certain areas for specific purposes, such as tourism or commercial activities, while ensuring that the public interest is maintained. The maximum duration for which the government can grant concessions to use the coastal public domain is 75 years.

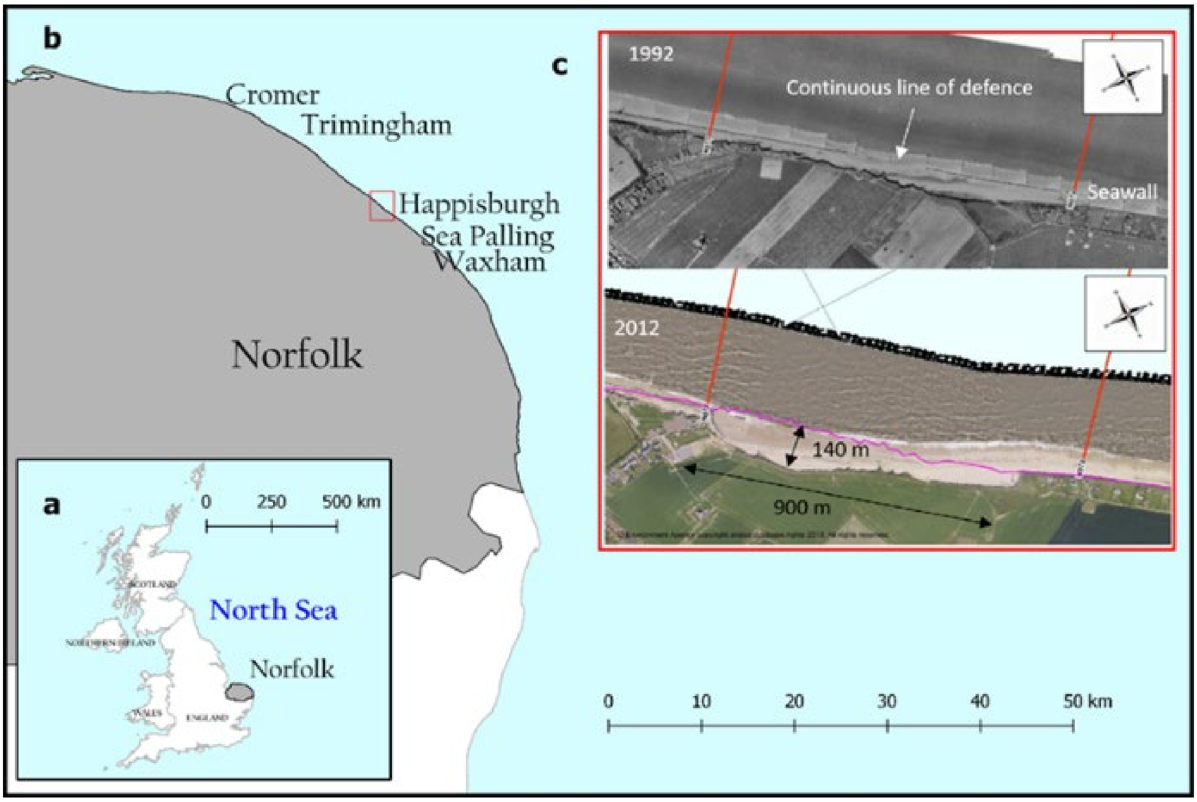

Figure 4-13 – Happisburgh's county of Norfolk (grey polygon) on the east coast of England, the grey lines represent the administrative boundaries of the different UK regions; (b) study site location (red rectangle) and nearby locations mentioned on this manuscript; (c) aerial images of Happisburgh taken in 1992 and 2012 by the Environment Agency; showing the formation of an embayment. Red lines indicate the location of profile monitoring surveys, and the magenta line shows the approximate cliff toe position in 1992. Source: Payo, Walkden *et al.* (2018).

How can geological surveys help addressing these problems?

The **British Geological Survey** is helping planners in UK and Spain addressing these problems by providing the evidence for robust decision making. This evidence can be in the form of better understanding of the main drivers and controls of observed historical coastal changes or by developing innovative software models and data that enable decision makers to explore different 'what if' scenarios. Previous sensitivity studies suggest that beach thickness plays a major role in coastal recession at Happisburgh. These studies were limited, however, by a lack of beach volume data. In a study by Payo, Walkden *et al.* (2018), they have integrated the insights gained from their understanding of the Quaternary geology of the area, a novel non-intrusive passive seismic survey method, and a 3D novel representation of the subsurface source and transportable material into a Coastal Modelling Environment (CoastalME)[11] (Payo *et al.,* 2017) to explore the role of beach thickness on the back wearing and down wearing of the cliffs and consolidated platform, respectively. Results show that beach thickness is non-homogeneous along the study site: they estimate that the contribution to near-shore

[11] The CoastalME software is a Free Open Source and Software for geospatial modelling to simulate decadal and longer coastal morphological changes and available here: https://www.osgeo.org/projects/coastalme/

sediment budget via platform down wearing is of a similar order of magnitude as sediment lost from the beach and therefore non-negligible. They have provided a range of evidence to support the idea that the Happisburgh beach is a relatively thin layer perched on a sediment rich platform of sand and gravel. This conceptualization differs from previous publications, which assume that the platform was mostly till and fine material. This has direct implication on regional sediment management along this coastline.

The study by Torrecillas et al. (2024) represents the first attempt to map the sediment thickness spatial distribution along the Andalusian coastal zone by integrating various publicly available datasets: the Sediment Thickness Model (STM) of Andalusia (called STMA) (Figure 4-14). The modelled sediment thickness has been used (Cobos *et al.*) to make quantitative predictions of morphological change at a scale that is relevant to longer-term strategic coastal management in Andalusia. The methodology and tools used for this study are transferable to any study area.

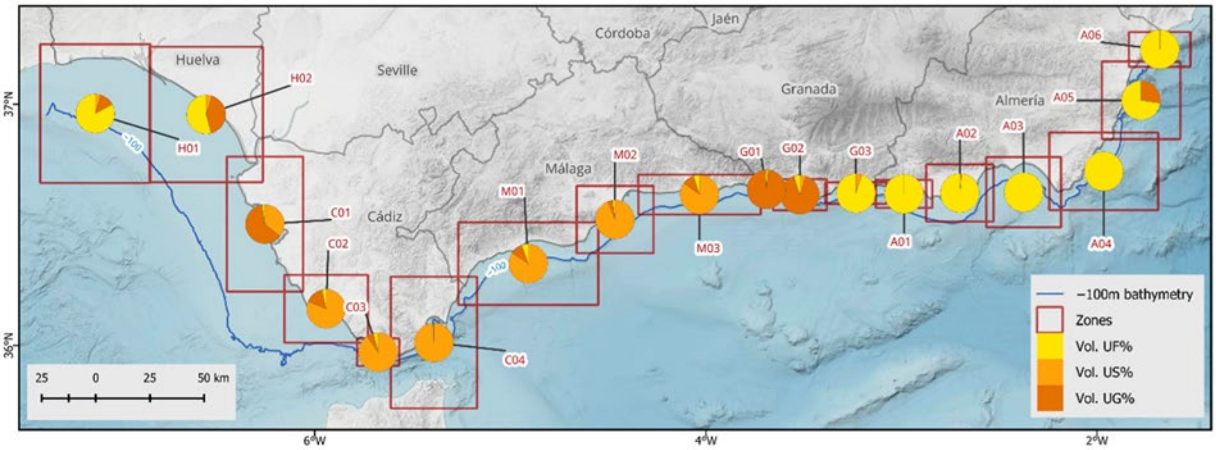

Figure 4-14 - Pie chart of unconsolidated material volume along a 100 m-buffer coastline in each STMA zone: Unconsolidated Fine (UF), Sand (US), and Gravel (UG) sediments. Source: Torrecillas, Payo *et al.* (2024).

Latvia's evolving coastline: Insights from Geological monitoring and remote sensing

Overview of the Baltic Sea coastline in Latvia

The Baltic Sea coastline in Latvia stretches 497 km (253 km along the open Baltic Sea and Irbe Strait and 234 km along the Gulf of Riga), is shaped by ongoing geological processes, showcases diverse features despite the region's uniform geological composition. About 140 km consist of gently sloping shores formed by sediment accumulation, while 150 km are characterized by steep, eroded coastlines of varying heights and compositions. The remaining 200 km are relatively stable under current conditions (Latvijas Universitātes Ģeogrāfijas un Zemes zinātņu fakultāte, 2014). Systematic geological research of the Baltic Sea began in the 1870s, and coastal monitoring in Latvia started in 1987, followed by various research efforts. Since the mid-20th century, research methods have evolved, including historical and cartographic analysis, remote sensing, field studies, modelling, and sediment mechanical composition analysis and other methods (Lapinskis, 2010). However, not all data and methods are fully compatible or comparable.

GSO's involvement in coastline monitoring using Sentinel-2 data

The **Latvian Environment, Geology and Meteorology Centre (LEGMC)** remotely monitors coastline of Latvia using Sentinel-2 mission from the European Space Agency. LEGMC experts leverage the capabilities of the dual satellite system which orbits the Earth at an approximate altitude of 750 km. Monitoring is performed regularly, with new data acquisition frequency over any location of Latvian coastline between 2 to 5 days, and pixel spatial resolution of 10 meters. Sentinel-2 data are specifically processed to inquire information about water-land boundary – waterline – changes over time. Data processing involves sequential steps, such as satellite data pre-processing, cloud removal, waterline extraction and analysis of shoreline changes, including quality control and comparison of measurements to tide gauge data. In depth description of analysis can be found at Zandersons *et al.* (2024).

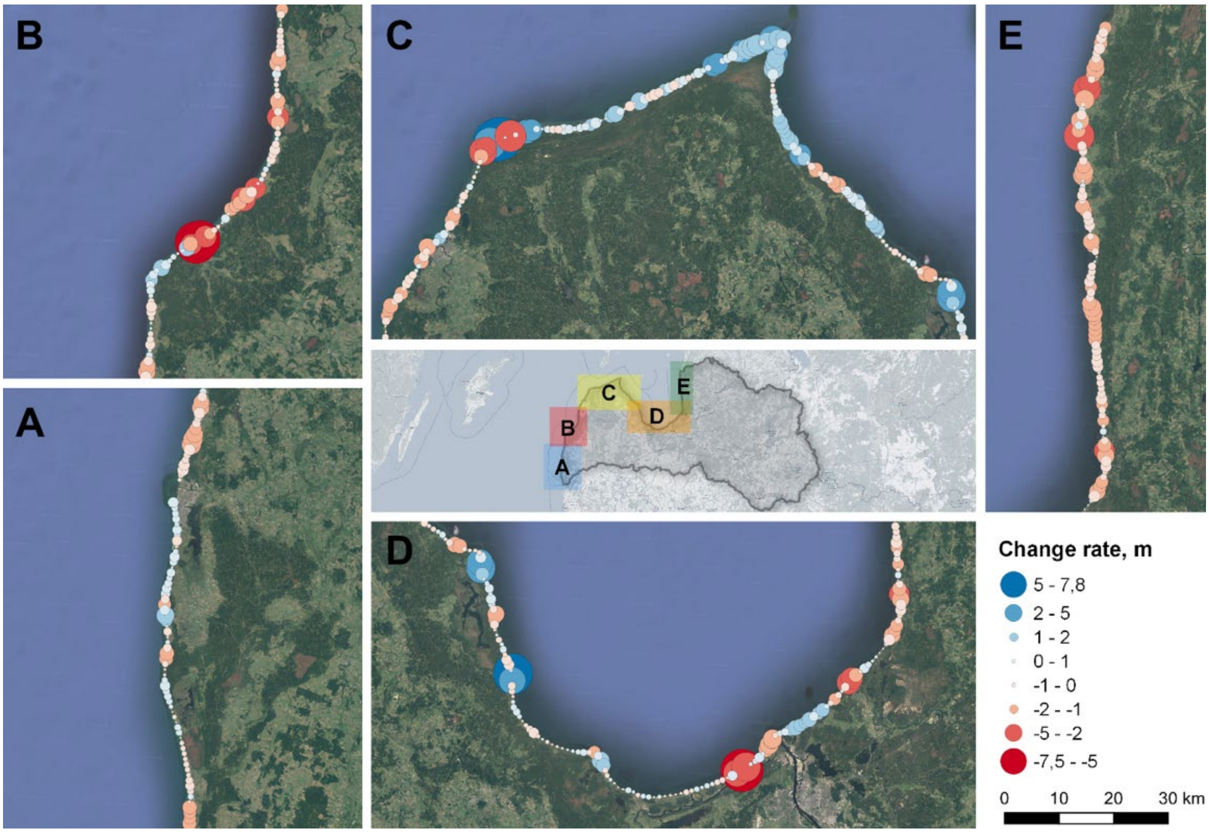

***Figure 4-15** - Change rate of Latvian coastline. Point size and colour indicates change rate. Red indicates sections with retreating coastline, while blue – sections with advancing coastline (Source: LEGMC)*

During the pilot study ("Integration of climate change policy in sectoral and regional policies" in the framework of the Norwegian Financial Mechanism Programme 2014-2021, project No. LV-CLIMATE-0001) over a 10 km long stretch of coastline near Bernāti, Latvia, method was verified against measurements from high-resolution Airbus Pléiades satellite measurements and unmanned aerial observations in the summers of 2021-2023. Root mean square error (RMSE) of waterlines was calculated to be in the range of 5.0-5.4 m. Coastline change using Sentinel-2 data was initially calculated for the period of 2017-2022. Most significant changes were observed near the man-made structures and cape features of the shore (**Figure 4-15**). The data are now processed operationally, adding new information annually. LEGMC also works to increase the span of measurements from 2015 until 2017 (see Zandersons et al., 2024 for further details on monitoring results).

Advanced coastal monitoring with LIDAR (laser scanning) data: future perspectives within Latvia's GSO

To assess potential coastal vulnerability in Latvia's beach zone, laser scanning is being tested to identify areas where material migration occurs through erosion or accumulation. In Latvia, the entire beach coastal zone has been surveyed using laser scanning from 2014 to 2019 by Latvian Geospatial Information Agency (LGIA). The case study area of Bernāti was scanned in 2016 and is compared with the measurements carried out by LEGMC, conducted in 2023. The laser scanning density of measurement points is at least 4 points per m², thus ensuring sufficiently good accuracy of the output data. To carry out the comparison, two separate ground surface models need to be created from each year's data, after which one surface is subtracted from the other. A volume model is obtained that contains positive and negative values, illuminating areas and volumes that have changed. These models can be processed to highlight areas with the most significant changes. This data can serve to identify sections that require closer attention for regular monitoring. Currently, a new laser scanning period is taking place in Latvia, which will allow comparisons across the entire beach area of Latvia.

National datasets for Poland coastal vulnerability analysis and works

The coastal zone of the Baltic Sea in Poland has always played a significant role due to economic, social, and political reasons. Especially in contemporary times, issues related to spatial planning in this zone and the location of major infrastructure investments along the coast have gained importance. This has led to the need for particular attention to be paid to the processes occurring along the coastline and the threats arising from the specific interaction between the marine and terrestrial environments. For this reason, the **Polish Geological Survey (PSG)** has undertaken activities aimed at creating a comprehensive **geological model of the Polish coast**, enhanced by the modelling of erosional and depositional processes, including forecasting changes in the position of the coastline (Uścinowicz and Szarafin, 2018; Uścinowicz et al., 2021, 2024a, 2024b). The work also includes the identification and modelling of hydrogeological conditions and the assessment of geo-hazards. The basis of these efforts lies in the integration of existing data scattered across various research institutions and research conducted by PSG along the Polish coast (including marine areas). The compilation of data (collected, measured, and processed) allows for the expansion of the knowledge base, which forms the foundation for the development of the coastline change model (Figure 4-16).
Research activities enable the identification of changes in the morphology of the coast, geological structure, and hydrogeological conditions in the Baltic coastal zone. As a result of these efforts, a series of thematic geological maps and predictive models of coastline changes are produced. Due to the specificity of the coastal zone, the research is carried out in two parallel tracks, distinguishing between the marine and terrestrial parts. The preliminary phase involves data gathering, which includes acquiring and organizing information from external institutions as well as internal data. This data serves as the initial and fundamental resource of information required for the completion of the task and forms the base for all project work. The collected data is organized thematically within the Central Geological Database. The geological assessment of the coastline and the land area is primarily based on geological fieldwork, such as drilling, but also on studies that involve the verification of previous geological mapping, sediment sampling, geophysical surveys, and coastal monitoring using drones and LIDAR (Figure 4-17). Additionally, the hydrogeological conditions of the coastal zone are examined by describing the hydro-structural system and groundwater circulation.

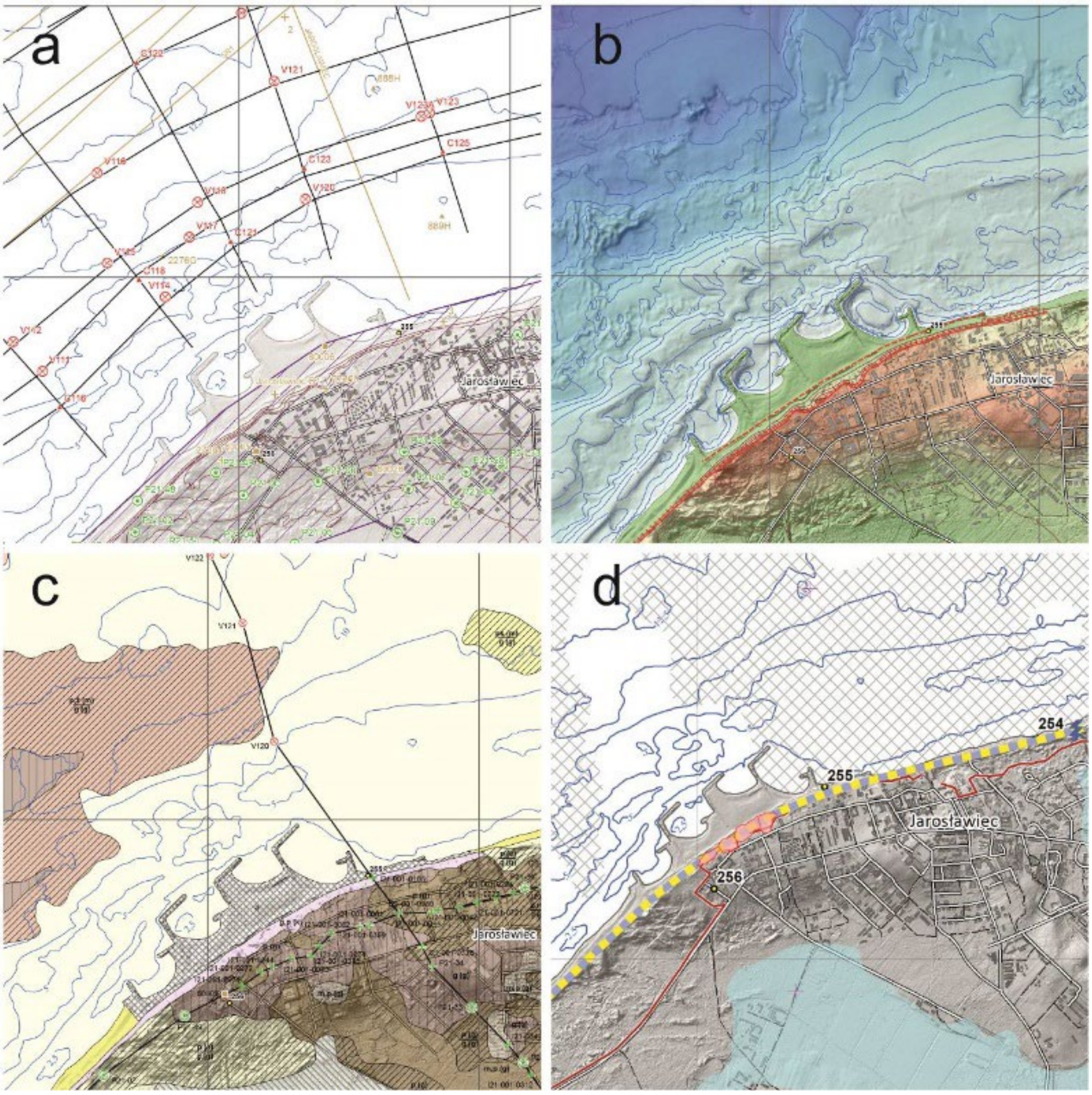

Figure 4-16 - Examples of maps created as a result of research conducted by Polish Geological Survey on the coastal zone: a - documentation map of the research; b - elevation map; c - lithogenetic map; d - geo-hazard map (Source: Polish Geological Survey).

The geological assessment of the marine area includes the creation of a detailed bathymetric map and seismo-acoustic profiling along specific tracks to obtain an image of the sub-surface geological structure, as well as seabed mapping using side-scan sonar. Complementing the aforementioned work are geological surveys, such as core sampling from sediments and surface samples from the seabed.
In the analytical phase, significant attention is given to constructing a set of models that describe, among other things, the overall structure of selected cliff areas, which serves as the starting point for model-based studies assessing the potential stability of slopes. Another part of the work involves creating predictive models (decadal scale) of coastline changes along barrier coastlines, as well as morpho-geological models that depict the general features of geological units and terrain morphology.

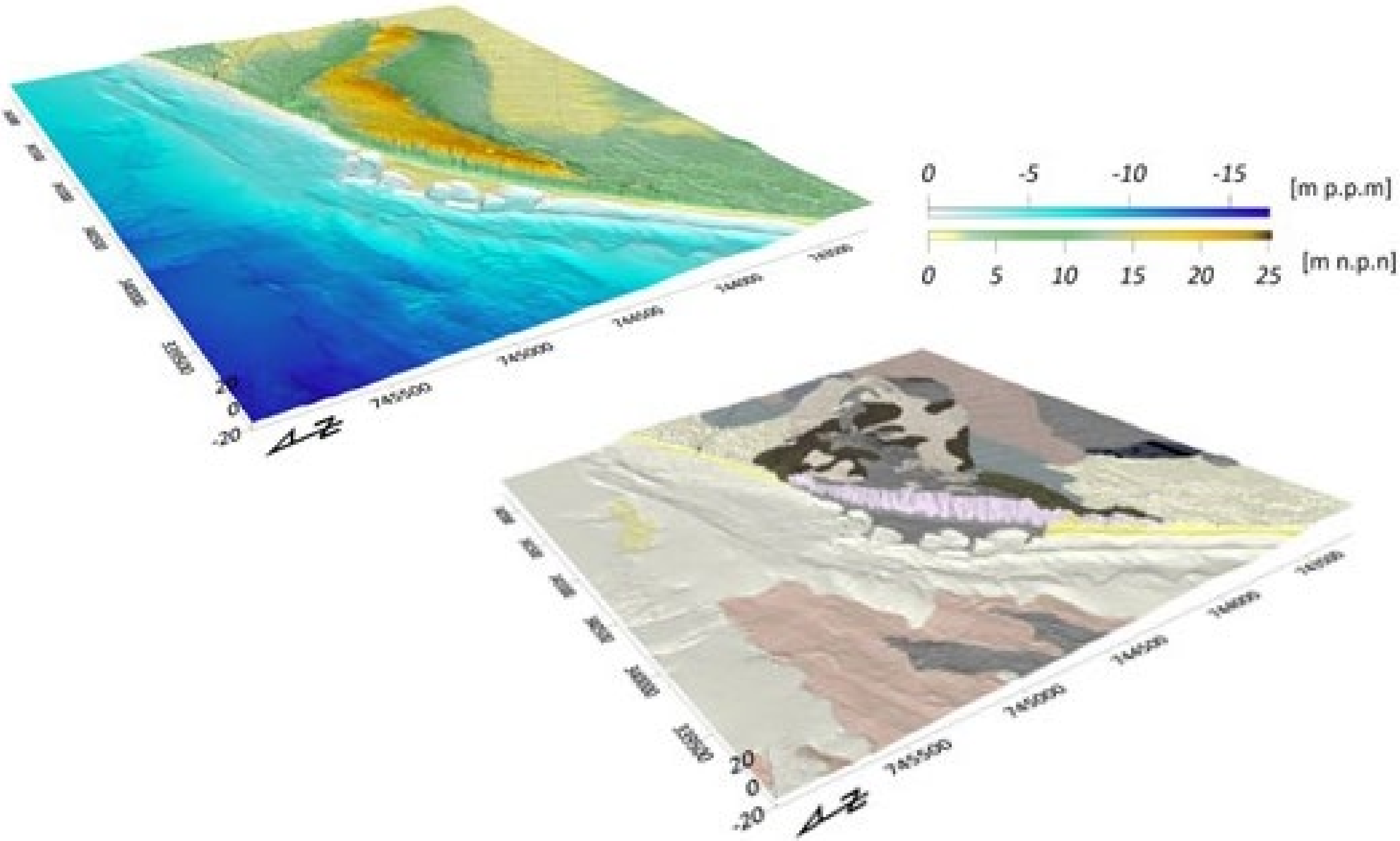

Figure 4-17 - Example of morphological and geological model of the coastal zone in the vicinity of Jarosławiec village (Polish Baltic coast) (Source: Polish Geological Survey)

Additionally, hydro- and litho-dynamic models are created to indicate the rate and direction of sediment movement on the seabed.
As a result of these actions, a comprehensive set of information is produced, which forms the basis for both specialized studies (maps, documentation, scientific publications, etc.) and broader works intended for wider audiences (e.g., popular science articles, etc.).
However, the primary outputs are presented in the form of basic maps at a scale of 1:10,000, where the common feature is the presentation of the overall image of the coastal zone, without distinguishing between the marine and terrestrial parts.
In general terms, the conducted work is practical in nature, aiming for the effective use of environmental data. According to the standards of the Polish Geological Survey, most of the geological data collected is geoprocessed and stored within the Central Geological Database. This means that the data can be reused and adapted for relevant needs and made available to potential stakeholders.

Coastal vulnerability analysis: the Italian case study

The Italian case study is focused on coastal vulnerability analysis along Italian coastline (8,329 km) using available national datasets for: coastal features, coastal erosion, coastal landslides, wave features, land subsidence, sea level rise and exposed elements (built-up areas, rail & road networks, population, natural ecosystems).

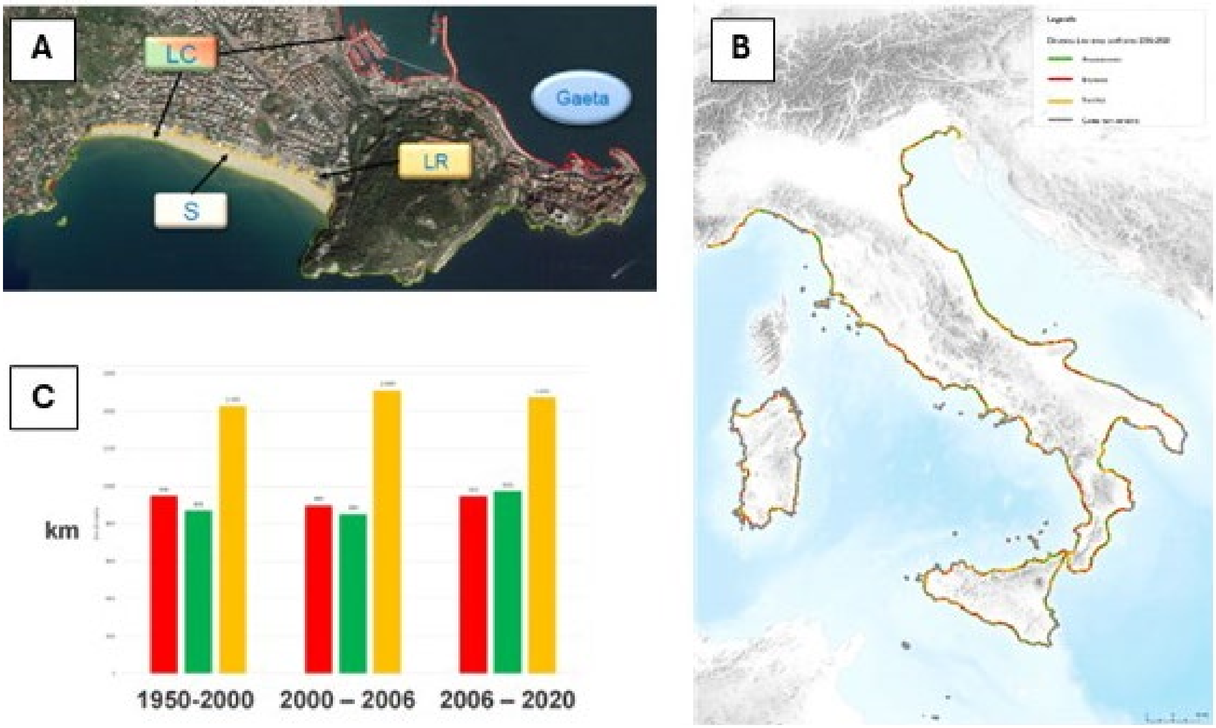

Figure 4-18 - A) natural and artificial coastline (LC), backshore line (LR) and beaches near Gaeta village; B-C) map and diagram representing coastal segments suffering coastal erosion (in red), segments with accretion (in green) and stable segments (in yellow) (Source: ISPRA[12])

The Italian GSO, ISPRA, has monitored the coast and **coastal dynamics** at a national level over a period of about 20 years (Figure 4-18) with the characterization of natural and artificial elements of the

12 https://sinacloud.isprambiente.it/portal/apps/sites/#/coste

coastline (LC), the backshore line (LR) and the polygons of the beaches, derived from photointerpretation of aerial and satellite images. Four coastlines have been realized: the 1950 “historical” coastline (digitization of 1:25,000 topographic map); 2000 and 2006 (digitization of orthophotos, resolution of 1 and 0.5 m); 2020 coastline (Google Maps images, resolution < 0.5 m).

The **coastal landslides** have been extracted from the Italian Landslide Inventory, which is operated by ISPRA, Regions and Autonomous Provinces and contains to date more than 635,000 landslides (Figure 4-19). Regarding coastal landslides, the most frequent types of movement are rock falls or topples, followed by rotational/translational slides and complex landslides. Most of the Italian rocky coasts are affected by slope instability phenomena, as rock falls and topples affecting sea-cliffs in Salento peninsula (Apulia region, southern Italy). A peculiar case exists in some sectors of the Adriatic coast, where landslides involve coastal hills or abandoned cliffs that are now located a few hundred meters from the present-day low-lying sandy coast. Moreover, along wide coastal sectors of Campania and Calabria regions, where a layer of soil, debris or loose volcanic rocks covers steep slopes of bedrock plunging into the sea, rapid debris flows, triggered during short and intense rainfall, represent the main hazard (Iadanza *et al.,* 2009).

The **coastal habitats** have been extracted from the habitat mapping project *Carta della Natura* (ISPRA, 2009; Angelini *et al.,* 2009; Laureti, 2023) with Minimum Mapping Unit - MMU = 1 hectare and Minimum Mapping Width - MMW = 20 m; habitat classification system based on the Palaearctic classification (Devillers and Devillers-Terschuren, 1996). Four indices have been developed to describe the state of each ecotope: Ecological Value (quality of the ecotope from an ecological point of view), Ecological Sensitivity (intrinsic predisposition of the ecotope to be degraded by an external disturbance), Anthropogenic Pressure (external disturbance due to human activities), Environmental Fragility (state of vulnerability of the ecotope from a natural and environmental perspective) (Figure 4-20).

Figure 4-19 - A) coastal landslides in Italy; B) example map of Guvano landslide (Liguria region) (Source: ISPRA[13])

[13] https://idrogeo.isprambiente.it/

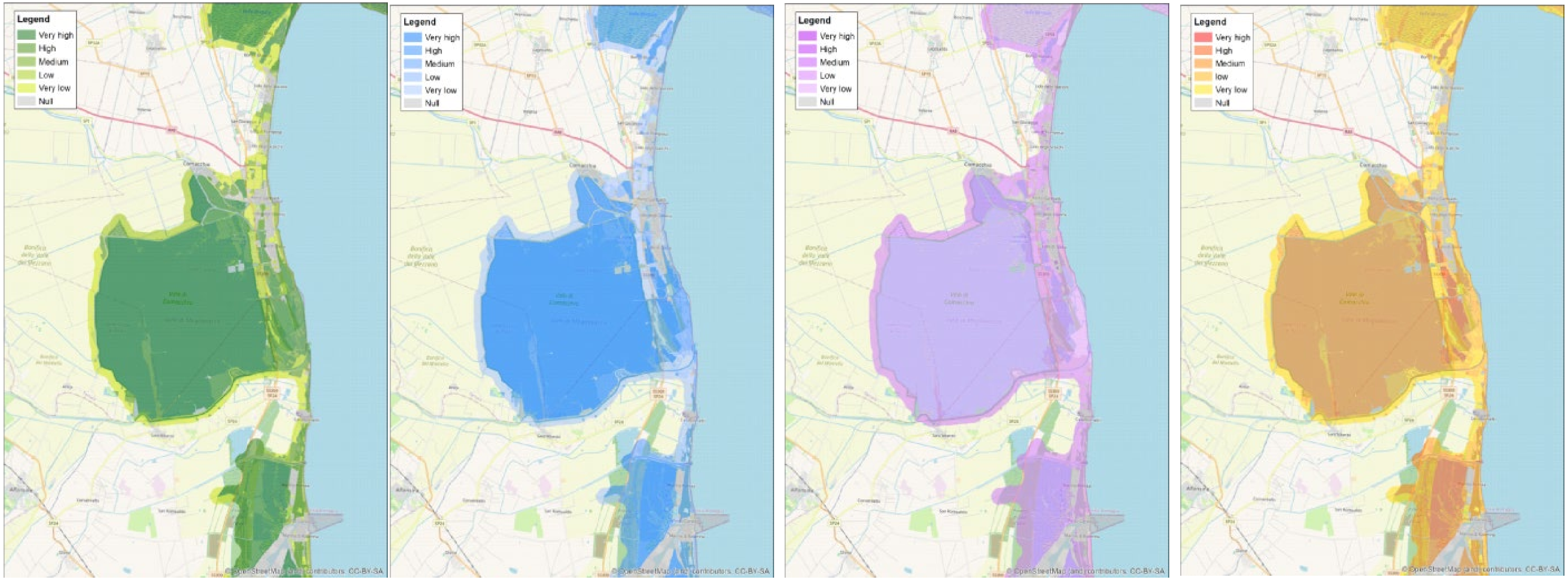

Figure 4-20 - From left to right, maps of Ecological Value, Ecological Sensitivity, Anthropogenic Pressure, and Environmental Fragility indices (Valli di Comacchio, NE Italy) (Source: ISPRA**)**

The Portuguese Geological Survey's vulnerability assessment of coastal erosion

Role of the Portuguese GSO

Increasing knowledge on coastal evolution is crucial considering the urgent need to identify suitable responses for successful adaptive coastal management, to address the rising coastal risks, associated with climate change. This issue is quite relevant in Portugal given the extension of its mainland coast (about 940 km) characterized by a wide morphological and geological diversity, comprising several types of environments, with beaches, wetlands, and hardened and steep coasts as the main typologies. Similarly to many worldwide countries, the Portuguese coastal environments are critically endangered by flooding and erosion. As a contribution to the fostering of sustainability, defense and enhancement of the Portuguese coastal zone, LNEG conducts a **national programme on high-resolution geological cartography and coastal erosion vulnerability assessment**. Several layers of information have already been produced for specific sectors and data issued as open-source digital format at **LNEG GeoPortal**[14]. The Portuguese GSO's action is focused on two levels: i) at a national level, by compiling and making available data to improve the understanding of the evolution and dynamics of coastal stretches for the past decades and ii) at a regional level, providing a case study to access information on sediment load from the main riverine discharge to the coast at the northern sector, through the analysis of satellite images. This is particularly important as assessing the sediment budget and significant sediment sources for littoral drift is an essential stage to achieve the integrated and sustainable management of coastal zones in the short, medium, and long term.

Portuguese vulnerability areas to coastal erosion

Maps of coastline evolution (for the last 50 years) using long-term change rates between 1958 and 2010, were previously produced allowing an extensive perception of vulnerability areas to coastal erosion, for the low-lying sandy areas at the mainland Portuguese territory (Ponte Lira *et al.,* 2016). The achievement of updated and reinterpreted regional to local scale information, on long-term coastline evolutionary trends, is particularly valuable in areas with relevant erosion. That is the case of the center of the Portuguese western coast, which is significantly endangered by erosion (Figure 4-21 A). Thus, the safety measures in those sectors should be strongly supported and backed up by scientific information.

The Portuguese GSO, through a national programme handling a multivariable approach to comprehending long-term coastal dynamics and coastal evolution assessment on the high-resolution scale (10 m spaced data points), aims to contribute information that helps to find suitable strategies for successful adaptive coastal planning and management. Digital maps depicting the long-term coastline evolution through the rate of coastline change for the Figueira da Foz-Nazaré coastal sector at the western coast (Rebêlo and Nave, 2022) and Faro–Vila Real de Santo António coastal sector, at the Algarve region (Nave and Rebêlo, 2021) have already been released. Within this context, nine historic coastline positions were determined for the last nearly 7 decades allowing access to the coastline trend and variability for a certain period through the SCE - Shoreline Change Envelope parameter. This parameter is one of the Digital Shoreline Analysis System (DSAS) outcome products [an add-in within the ESRI ArcGIS© Software] constituting a measure of the total change in coastline movement, considering all available shoreline positions, and reporting their distances, without referencing their specific dates. This information is valuable when the total movement is larger than the distance between the oldest and the youngest coastline (Net Shoreline Movement – NSM). Additionally, the absolute

[14] https://geoportal.lneg.pt/mapa/?Mapa=GeologiaCosteira

value of the ratio between both parameters, CO-Index: Abs[NSM/SCE], provides information on the difference between the length of the total coastline displacement and the length between the oldest and the newest coastline (Figure 4-21 B). These parameters, in addition to the Change of Rate (the statistical parameter Linear Regression Rate) and NSM dataset, bring new insights into shoreline oscillation at a local scale. These allowed us to disclose several segments with relatively small COindex, pointing out that maximum shoreline displacement in those areas is much larger than the displacement between the oldest shoreline and the newest.

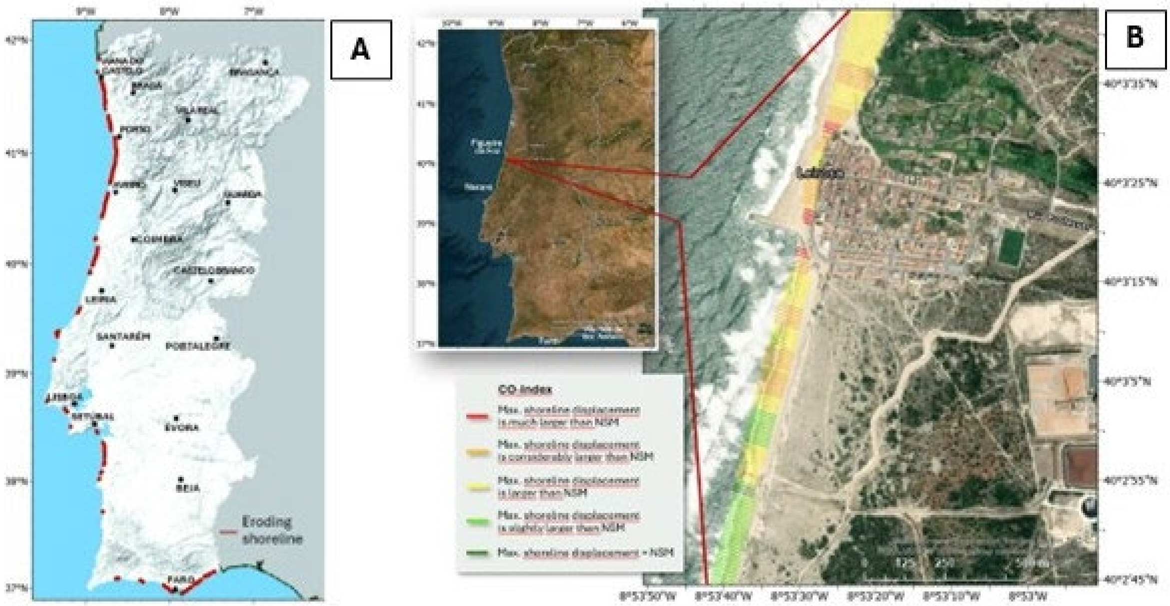

Figure 4-21 - Maps of A) eroded sectors of the coastline (1958-2021) (Source: APA, 2022), and B) detailed view of CO-Index: Abs[NSM/SCE], in a local area on the western Portuguese coast.

The quantification of the coastal area that was lost or gained during the nearly seven decades, due to the shoreline displacement, revealed the loss of 117 ha (1 170 000 m^2) along 31 km and the gain of 46 ha (460 000 m^2) along 21 km within the analyzed western sector, between Figueira da Foz and Nazaré (Rebêlo and Nave, 2022). For the southern Algarve region, at Faro-Vila Real de Santo António sector, 176 ha (1 760 000 m^2) were gained along 29 km, while 198 ha (1980000 m^2) of land were lost along 24 km. Detailed maps of lost or gained coastal land areas were produced within GSEU 5.1 project and will be issued as open data at LNEG GeoPortal, as shown in Figure 4-21 B, as an illustration model.

Portuguese case study - Sediment load from Douro River

Evaluation of sediment load from the most relevant riverine discharge at the northern sector (Douro River) is being conducted at LNEG by analyzing Satellite data from Copernicus. Assessing the sediment budget and significant sediment sources for littoral drift is essential to achieve the integrated and sustainable management of coastal zones in the short, medium, and long terms. A semi-analytical approach will be applied to Sentinel-2 (MSI) images to retrieve high spatial resolution of total suspended solids within a frame window.

5. Importance of Geological and Hydrogeological Data in Coastal Vulnerability and Adaptation to Sea-Level Rise Assessment

The impact of geological and hydrogeological data in assessing coastal vulnerability and adaptation to sea-level rise is a critical element in addressing the challenges posed by climate change. Coastal areas are particularly sensitive to sea-level rise, which can lead to flooding, erosion, saltwater intrusion into freshwater aquifers, and other environmental changes. Geological and hydrogeological data play an essential role in understanding the complex interactions between land, sea, and groundwater systems. Geological and hydrogeological data collected by GSOs through coastal surveys and observatories are fundamental to understanding and managing coastal vulnerability to sea-level rise. The role of GSOs in observation, research, and data acquisition is crucial for the development of adaptive strategies and policies that can protect coastal communities and ecosystems from the impacts of climate change.

Coastal surveys and observatories along the European coasts

European scale

As in the rest of the world, the European coastal regions are monitored through a network of surveys and observatories dedicated to understanding and managing coastal environments. These initiatives provide critical data for assessing coastal dynamics, hazards, and ecosystem health. By way of illustration, but not exhaustively, a number of initiatives can be highlighted:

- **JERICO-RI (Joint European Research Infrastructure for Coastal Observatories)[15]:** JERICO-RI is a pan-European research infrastructure that integrates multidisciplinary platforms to assess changes in coastal marine systems. It bridges existing continental, atmospheric, and open ocean research infrastructures, filling a key gap in the European Strategy Forum on Research Infrastructures (ESFRI) landscape. JERICO-RI establishes a framework for observing, analysing, understanding, and forecasting coastal marine system changes.
- **EuroGOOS (European Global Ocean Observing System) Coastal Working Group[16]:** The EuroGOOS Coastal Working Group examines the entire value chain from coastal in situ observations, satellite data, ocean forecasts, and analysis to products and services for coastal users. The group assesses the sustainability and fitness for purpose of existing systems and identifies future steps needed to secure and improve all elements of the coastal value chain to better serve end users and stakeholders.
- **EU Blue Economy Observatory[17]:** Launched by the European Commission, the EU Blue Economy Observatory monitors and analyses economic activities related to oceans, seas, and coasts. It serves as a knowledge dissemination platform aimed at promoting the sustainability of ocean-related activities, helping to put the EU on the path towards a sustainable, carbon-neutral, and circular blue economy.

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[15] https://www.jerico-ri.eu/
[16] Coastal Working Group - EuroGOOS
[17] https://blue-economy-observatory.ec.europa.eu/

- **Coastwatch Europe**[18]**:** Coastwatch Europe conducts surveys designed to provide an overview of the state of the coast. Involving volunteers from various backgrounds, participants survey chosen 500-meter stretches of coast around low tide, recording observations on the survey questionnaire while on the shore. This citizen science work can be augmented with water tests, and the collected data is pooled to provide a snapshot of the state in areas surveyed at that time.

GSOs are also key contributors to the **European Marine Observation and Data Network (EMODnet)**[19] programme, which aims to assemble and disseminate marine data, including geological information, to support sustainable management of Europe's marine resources, particularly through the **Geology portal**. Their role encompasses multiple essential activities, including **data collection and integration**, where they gather and harmonize information on seabed composition, coastal erosion rates, and geological hazards to create consistent datasets. They contribute to **mapping coastal and seabed geology**, developing detailed maps and classifications of coastal types and geological features. These organizations are also instrumental in **coastal erosion monitoring**, providing insights that inform climate adaptation and risk management. Through their work, they support **Marine Spatial Planning (MSP)** by delivering data that balances competing coastal and marine uses, such as habitat protection and resource development. By **facilitating access to data** via the **EMODnet platform**, they empower policymakers, researchers, and the public with reliable, open-access information. Furthermore, their efforts in **collaboration and networking** foster Europe-wide partnerships, integrating expertise to address shared coastal challenges. Collectively, these contributions ensure the sustainable management of Europe's coastal and marine environments and enhance resilience to climate change.

National, regional and local scale

These coordinated efforts across Europe enhance the understanding of coastal processes, support sustainable management practices, and contribute to the resilience of coastal communities against environmental challenges. In addition to these pan-European initiatives, several local and regional coastal observatories across Europe play a crucial role in monitoring and managing coastal environments:

- In **England**, the **National Network of Regional Coastal Monitoring Programs**[20] comprises six regional coastal monitoring programs, each tailored to the specific characteristics of their respective regions. They collect essential data to support informed coastal management and engineering decisions. Also, serving as the data management and regional coordination center for the Southeast Regional Coastal Monitoring Programme, the **Channel Coastal Observatory (CCO) (United Kingdom)**[21] plays a pivotal role in collecting and managing coastal data to inform sustainable management practices.
- In **Germany**, the **Spiekeroog Coastal Observatory,** located in the southern North Sea, focuses on understanding coastal processes and their interactions with regional and global environmental changes (Zielinski *et al.*, 2022). It provides valuable insights into the dynamics of the Wadden Sea ecosystem.

[18] Surveys | Coastwatch Europe
[19] https://emodnet.ec.europa.eu/en
[20] See National Network of Regional Coastal Monitoring Programmes - Programme design or National Network of Regional Coastal Monitoring Programmes - Filter
[21] https://edmo.seadatanet.org/report/1110

- **MyCOAST**[22] is a project that promotes the sharing and interoperability between coastal observatories and EU data infrastructures, in order to strengthen the use and the dissemination of downstream applications of the Copernicus Marine Service. It aims to enhance the capabilities of intermediate users in managing coastal environments, in filling the gap between the output of large-scale European programs and the end-users through the transnational coordination of coastal observatories.

These observatories or networks, among others, contribute significantly to the comprehensive monitoring and management of Europe's diverse and dynamic coastal regions. The involvement of geological services can take place at different spatial scales: from local to regional and national.

For example, in France:

- The **French Coastline Observatories Network**[23] (called **RNOTC** for *Réseau National des Observatoires du Trait de Côte*) federates more than 20 national and local organisations responsible for monitoring coastlines across France (both mainland and overseas). It aims to enhance the understanding of coastal dynamics and support effective management strategies.
- The **French geological survey (BRGM)** has been involved in setting up this national network at a very early stage (as part of the French National Strategy for Integrated Coastline Management – SNGITC –), working with the Ministry for the Environment and other research institutes and government agencies. The French GSO has been involved in the **development of regional observatories and coastal monitoring operations**, in partnership with government departments and local authorities, it capitalises now on a wealth of experience as prime contractor or partner in a number of local or regional coastal observatories, in French mainland [Observatoire de la côte de Nouvelle-Aquitaine, Observatoire de la côte sableuse catalane, Réseau d'Observation du Littoral de Corse, Observatoire du littoral du Pays de Monts, etc.] and oversea territories [Observatoire du littoral de Nouvelle-Calédonie ; Observatoire de la dynamique côtière de Guyane, Observatoire de la dynamique du littoral Martiniquais, Observatoire du littoral des Îles de Guadeloupe, Observatoire du littoral de Mayotte, La Réunion, etc.]. Within this scope, French GSO leads monitoring campaigns that are essential for understanding coastal dynamics and informing management strategies to mitigate erosion and other coastal hazards (from the event, to seasonal, and longer time scales).
- In France, research and higher education establishments also organize detailed coastal observations at pilot sites within the scope of the **Service National d'Observation DYNALIT**[24] labelled by INSU (National Institute of Sciences of the Universe), one of the elementary observation networks making up the ILICO Research Infrastructure. It is coordinated by university research laboratories, and manages long-term acquisition, collection and consistent implementation of metrological data quality in 30 local study sites (sandy coasts, cliffs, estuaries) distributed on all French coastlines.

The role of Geological Survey Organizations (GSOs) in coastal observatories

GSOs can play a pivotal role in coastal observatories by providing scientific expertise, data, and tools necessary for understanding and managing coastal systems. Their contributions span a wide range of

[22] MyCOAST, a transnational coordination of coastal observatories | CMEMS
[23] https://observatoires-littoral.developpement-durable.gouv.fr/
[24] https://www.dynalit.fr/dynalit_uk

activities and disciplines, including geoscience, hydrogeology, and coastal engineering. Key roles generally include:

Data Collection and Monitoring

- GSOs use advanced technologies such as LiDAR, InSAR, and ground-penetrating radar to monitor coastal dynamics, including erosion, sediment transport, and subsidence.
- They contribute to the development of monitoring networks that integrate geological, hydrological, and environmental data to assess coastal vulnerability.

Geological and Hydrogeological Assessments

- GSOs analyse subsurface geology and groundwater systems, offering critical insights into sediment composition, aquifer behaviour, and subsidence processes.
- Hydrogeological expertise is applied to study saltwater intrusion and the effects of groundwater extraction on coastal stability.

Risk Assessment and Hazard Mapping

- GSOs play a key role in producing hazard maps for coastal erosion, marine flooding, and subsidence. These maps guide policymakers, urban planners, and emergency responders in risk mitigation.
- They also contribute to climate impact assessments, helping to predict how sea-level rise and extreme weather events may affect coastal areas.

Informing Policy and Decision-Making

- GSOs provide evidence-based recommendations to support national and regional policies on coastal management.
- Their work underpins compliance with European Union directives, such as the Floods Directive, the Marine Spatial Planning Directive, and the Marine Strategy Framework Directive.

Supporting Coastal Adaptation Strategies

- GSOs contribute to designing adaptation measures, such as nature-based solutions (e.g., wetland restoration) and hybrid infrastructure.
- They model future scenarios to evaluate the effectiveness of proposed adaptation strategies under different climate and geological conditions.

Collaboration and Capacity Building

- GSOs often collaborate with academic institutions, research institutes, NGOs, and government agencies to enhance the capacity for coastal monitoring and management.
- They contribute to transnational projects, such as JERICO-RI, MyCOAST, Copernicus, to harmonize methods and share best practices across Europe.

Public Awareness and Education

- GSOs engage with stakeholders and the public to raise awareness about coastal hazards and the importance of sustainable coastal management.
- They can provide educational materials and organise or take part in workshops to disseminate findings.

Figure 5-1 – Overview of the roles of GSOs in coastal observatories

By integrating geological and hydrogeological expertise into coastal observatories, GSOs ensure that coastal management decisions are grounded in robust scientific evidence, enhancing the resilience of coastal communities to environmental challenges.

Geological and hydrogeological assessment in GSOs coastal vulnerability & climate change activities (e.g. observation, research, data acquisition)

In coastal observatories and coastal vulnerability assessment programs, GSOs play a major role in **geological and hydrogeological assessments**, contributing to the understanding and sustainable management of coastal systems. Here's a detailed breakdown of their contributions:

For geological assessment:

1. **Subsurface geology mapping**
    - GSOs map the stratigraphy, lithology, and structural geology of coastal areas to identify sediment types, bedrock formations, and fault lines.
    - This information is critical for understanding sediment transport, erosion processes, and the stability of coastal cliffs and beaches.
2. **Sediment dynamics**
    - GSOs analyze sediment sources, pathways, and sinks to track coastal erosion and accretion patterns.
    - They study the impact of natural forcings (e.g., waves, tides, and currents) and human activities (e.g., dredging, construction, coastal defenses) on sediment budgets.
3. **Landform evolution**
    - Long-term geological records help predict how coastlines may evolve under changing environmental conditions, such as sea-level rise and extreme weather events.
    - GSOs assess areas prone to subsidence, landslides, or cliff retreat.

For hydrogeological assessment:

1. **Groundwater monitoring**
    - GSOs study aquifers in coastal areas to understand groundwater flow, recharge rates, and interactions with seawater.
    - Monitoring changes in groundwater levels helps assess the risk of saltwater intrusion, a major issue in low-lying coastal regions.
2. **Saltwater intrusion studies**
    - GSOs use hydrogeological data to model the extent of saltwater intrusion caused by over-extraction of groundwater and sea level rise.
    - These studies inform sustainable water management practices to protect freshwater resources.
3. **Submarine groundwater discharge (SGD)**
    - GSOs investigate SGD processes, where groundwater flows directly into the sea, often carrying nutrients or pollutants.
    - Understanding SGD remains essential for managing pollutants and nutrient spreading and mitigating pollution in coastal ecosystems.
4. **Soil and aquifer compaction**
    - GSOs assess compaction processes in aquifers due to natural sediment settling or human-induced activities like groundwater extraction.

- This helps identify regions at risk of subsidence, which can exacerbate relative sea-level rise in low-lying coastal territories.

Applications of GSO's work

By integrating geological and hydrogeological expertise into coastal observatories, GSOs play a valuable role in safeguarding coastal resources and mitigating risks associated with natural and anthropogenic changes along the European coastlines, while considering 4 key applications (see below in Figure 5-2) :

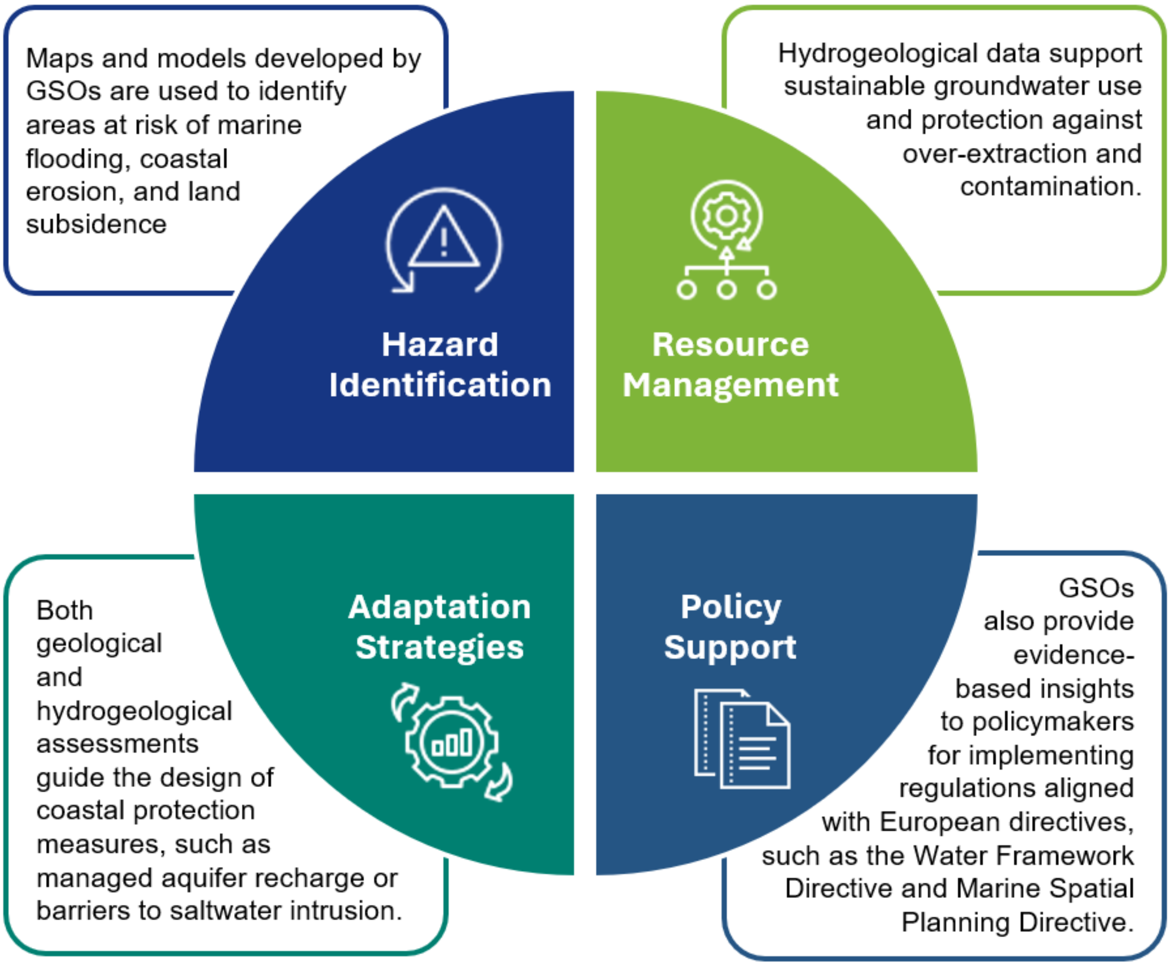

Figure 5-2 - Key applications of GSO's work in coastal vulnerability and climate change assessment: examples for hazard identification, resource management, adaptation strategies and policy support.

6. Conclusions and recommendations

Key Findings and recommendations for reducing the impacts of sea-level rise along the European coastlines:

- **Accelerating sea-level rise and coastal subsidence**
  European low-lying coastal areas face a dual challenge: global sea-level rise driven by climate change and local subsidence caused by both natural/geological and anthropogenic processes. Vertical land motion (VLM) increases relative sea-level rise in many areas, increasing vulnerability in already vulnerable coastal areas. Subsidence due to natural sediment compaction, groundwater extraction, and urban development significantly amplifies coastal risks (like coastal flooding at high tide, flooding during storms, salinization, coastal erosion, permanent flooding of low-lying areas).
- **Vulnerability of coastal floodplains**
  Coastal floodplains, home to dense populations, critical infrastructure, and vital ecosystems, are highly exposed. Regions such as the Netherlands, Northern Germany, and Italy's Po River Delta are particularly at risk. But many other coastal areas identified as subsidence hot spots in France, Greece, UK, etc. are also at risk. The combined effects of sea-level rise, subsidence, and extreme weather events, including storm surges, pose severe threats to human lives, economic assets, and biodiversity.
- **Knowledge gaps and monitoring needs**
  Data on subsidence rates, geological conditions, and hydrogeological processes remain incomplete and inconsistent across Europe. The absence of harmonized monitoring networks in some countries limits the ability to develop coordinated and effective adaptation strategies across the EU. Nevertheless, the involvement of GSOs in various national, European and international research networks and projects, as well as in coastal observation networks and the acquisition of various types of data, is an extremely positive element, a source of improvement and encouragement.
- **Role of geological and hydrogeological information**
  Comprehensive geological and hydrogeological data are crucial for understanding coastal subsidence dynamics and groundwater interactions. Such data form the foundation for vulnerability assessments and inform the design of adaptation measures to mitigate sea-level rise impacts.

Some preliminary recommendations have been formulated based on the findings gathered during the work carried out under T5.1; however, these are expected to be further refined and enriched during the GSEU project, following complementary and collaborative efforts currently underway:

- **Enhancing monitoring and data integration**
  Establishing a harmonized European monitoring network for vertical land motion, utilizing technologies such as InSAR and GNSS, while integrating geological and hydrogeological datasets with socio-economic and climatic data, is essential to enhance the accuracy and effectiveness of vulnerability assessments, and relative sea-level rise assessment.
- **Adopting adaptive land-use planning**
  It is crucial to implement land-use policies that discourage development in high-risk areas, promote managed retreat where necessary to relocate vulnerable populations and assets to safer locations, and encourage the restoration of floodplains to enhance natural water retention and reduce the impact of marine flooding and coastal retreat.
- **Improving groundwater management**

To minimize compaction-related subsidence, it is important to reduce groundwater extraction in subsiding areas and promote the use of alternative water sources alongside advanced recharge techniques. Also, to reduce and prevent the risk of pollution and nutrient spread in coastal areas through groundwater discharge and surface runoff, especially in relation to future climate change and rising sea levels, it is essential to address the existing gap in data required to evaluate the dispersal of pollutants and nutrients in these zones.

- **Regional collaboration and knowledge sharing**
  Establishing a "Geological Service for Europe" is crucial to coordinate efforts and share best practices, methodologies, and case studies across countries, about coastal vulnerability assessment.
- **Long-term modelling and scenario planning**
  Develop predictive models that incorporate geological, hydrological, and socio-economic variables to forecast future risks is a prospective approach that make sense, like using scenario planning to test the effectiveness of proposed adaptation strategies under different climate and subsidence trajectories.

By leveraging geological and hydrogeological insights, European nations can better assess risks, enhance coastal resilience, and mitigate the impacts of sea-level rise. A coordinated, science-driven approach that balances short-term actions and long-term planning is crucial for safeguarding low-lying coastal areas and their communities.

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8. Annex I – Consortium Partners

	Partner Name	Acronym	Country	Task 5.1
1	EuroGeoSurveys	EGS	Belgium	
2	Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek	TNO	Netherlands	✓
3	Sherbimi Gjeologjik Shqiptar	AGS	Albania	✓
5	Bureau de Recherches Géologiques et Minières	BRGM	France	✓
6	Ministry for Finance and Employment	MFE-CSD	Malta	✓
7	Hrvatski Geološki Institut	HGI-CGS	Croatia	✓
8	Institut Royal des Sciences Naturelles de Belgique	RBINS-GSB	Belgium	✓
9	Państwowy Instytut Geologiczny – Państwowy Instytut Badawczy	PGI-NRI	Poland	✓
10	Institut Cartogràfic i Geològic de Catalunya	ICGC	Spain	✓
12	Department of Environment, Climate and Communications - Geological Survey Ireland	GSI	Ireland	✓
13	Agencia Estatal Consejo Superior de Investigaciones Cientificas	CSIC-IGME	Spain	✓
15	Geološki zavod Slovenije	GeoZS	Slovenia	✓
17	Istituto Superiore per la Protezione e la Ricerca Ambientale	ISPRA	Italy	✓
20	Institute of Geological Sciences National Academy of Sciences of Ukraine	IGS	Ukraine	✓
23	Geologian Tutkimuskeskus	GTK	Finland	✓
25	Ministry of Agriculture, Rural Development and Environment of Cyprus	GSD	Cyprus	✓
26	Norges Geologiske Undersøkelse	NGU	Norway	✓
27	Latvijas Vides, ģeoloģijas un meteoroloģijas centrs SIA	LVGMC	Latvia	✓

28	Sveriges Geologiska Undersökning	SGU	Sweden	√
29	Geological Survey of Denmark and Greenland	GEUS	Denmark	√
30	Institutul Geologic al României	IGR	Romania	√
33	Elliniki Archi Geologikon kai Metalleftikon Erevnon	HSGME	Greece	√
35	Lietuvos Geologijos Tarnyba prie Aplinkos Ministerijos	LGT	Lithuania	√
38	Eesti Geoloogiateenistus	EGT	Estonia	√
40	Íslenskar Orkurannsóknir	ISOR	Iceland	√
41	Instituto Português do Mar e da Atmosfera	IPMA	Portugal	√
42	Jarðfeingi	Jardfeingi	Faroe Islands	√
48	United Kingdom Research and Innovation - British Geological Survey	UKRI-BGS	UK	√

9. Annex II – Task 5.1a Online Questionnaire

Table 2 - Questions of the first section of the T5.1.a online questionnaire

1 – To reduce and prevent the risk of pollutants and nutrients spreading in coastal areas, for example through groundwater discharge, in relation to future climate change and sea level rise, the objective for 5.1a is to instigate a cluster of European sites concerned by concentrated pollutants and nutrients, submarine and coastal groundwater discharge.

a. **Please give a suggestion of a particular object, place or human activity which would serve as good example of such a study area from your country?**
[free-format text]

b. **Please describe place names, type of activity/business, type of pollutant (including nutrients), geographic location and risks for the study area above. Is work ongoing to prevent or reduce risk, and in that case, what?**
[free-format text]

c. **What is the role of your Geological Survey in relation to this study area? Consider if any new methods or technologies have been undertaken or tested in your given example that could be worth mentioning for other Geological Surveys. Future climate change can include effects such as increased runoff, and more frequent floodings and storms, in addition to sea level rise.**
[free-format text]

2 – Collaborations

a. **Are you participating in any current initiatives or collaborations among Geological Surveys aimed at addressing pollutant and nutrient dispersal in coastal areas in general, but also for example through groundwater discharge, in relation to future climate change and sea level rise? If so, please describe.**
[free-format text]

b. **Are you participating in any current initiatives or collaborations on a national level, aimed at addressing pollutant and nutrient dispersal in coastal areas, for example through groundwater discharge, in relation to future climate change and sea level rise? If so, please describe.**
[free-format text]

3 – Considering your knowledge of coastal territories in your country, name the top (1-3) human activities, past or present, with the highest risk for leading to dispersal of pollutants and nutrients in the coastal zone due to future climate change and sea level rise?

Activity 1: [free-format text]

Activity 2: [free-format text]

Activity 3: [free-format text]

4 – In the table below please rate the importance of different activities regarding work to prevent pollutant and nutrient dispersal within coastal areas. Rate the importance of activities both within your own country and where you would see the greatest benefit of future cooperation within GSEU.

In relation to the sensitivity of coasts and risk of pollutant and nutrient dispersal, which activities do you consider the most important or relevant for:

A. your country

	lower importa		higher importa	Not working with this
Mapping of sources of pollutants/nutrients that could have negative effects in the coastal zone	○	○	○	○
Mapping of geological/hydrogeological parameters in relation to dispersion of pollutants/nutrients	○	○	○	○
Mapping of dispersal risks close to identified sensitive areas (ex. Natura 2000, areas with high environmental value)	○	○	○	○
Mapping of coastal erosion	○	○	○	○
Mapping of coastal groundwater levels	○	○	○	○
Mapping of saltwater intrusion	○	○	○	○
Identify parameters of relevance for modelling future climate change and its effect on dispersal conditions	○	○	○	○
Developing and utilizing Coastal vulnerability index (CVI), for assessing dispersal of pollutants/nutrients	○	○	○	○
Your own suggestions of activities:	○	○	○	○
Your own suggestions of activities:	○	○	○	○
Your own suggestions of activities:	○	○	○	○

B. within GSEU

	lower importa		higher importa	Not working with this
Mapping of sources of pollutants/nutrients that could have negative effects in the coastal zone	○	○	○	○
Mapping of geological/hydrogeological parameters in relation to dispersion of pollutants/nutrients	○	○	○	○
Mapping of dispersal risks close to identified sensitive areas (ex. Natura 2000, areas with high environmental value)	○	○	○	○
Mapping of coastal erosion	○	○	○	○
Mapping of coastal groundwater levels	○	○	○	○
Mapping of saltwater intrusion	○	○	○	○
Identify parameters of relevance for modelling future climate change and its effect on dispersal conditions	○	○	○	○
Developing and utilizing Coastal vulnerability index (CVI), for assessing dispersal of pollutants/nutrients	○	○	○	○
Your own suggestions of activities:	○	○	○	○
Your own suggestions of activities:	○	○	○	○
Your own suggestions of activities:	○	○	○	○

1. Can you give suggestion on important factors or future actions needed to facilitate the collaboration between Geological Surveys in relation to pollutant and nutrient dispersal in coastal zones?

[free-format text]

2. If there were to be a workshop/-s in the future between Geological Surveys within the framework of GSEU WP 5.1a, which focus topics would your organization like to discuss?

[free-format text]

Table 3 - Questions of the second section of the T5.1.a online questionnaire.

5. Data status pollutants / nutrients a. Do you have knowledge if your country is investigating or monitoring pollutants/nutrients in coastal sediments, waters or the coastal zone in general? [free-format text] b. How is it investigated, e.g. sampling techniques, frequency, and substances? A brief description is sufficient. [free-format text] c. Which institution or organization is responsible for carrying out the investigations/monitoring? [free-format text] d. Who is the data owner and is the data available in a geodata format? [free-format text] d. Are the data open and if so, is it delivered to EMODNET, ICES or another open database? [free-format text]
6. Data status geological data a. Is your country investigating or monitoring geological parameters of relevance to the dispersal of pollutants/nutrients in the coastal zone (try to think from source to sea)? Examples of parameters are ground water discharge, submarine landslides, water level changes, wave erosion, sea-floor bottom type, particle movement, accumulation areas, sediment accumulation rates. [free-format text] b. What is investigated and how, e.g. techniques and frequency? A brief description is sufficient. [free-format text] c. Which institution or organization is responsible for carrying out the investigations/monitoring? [free-format text] d. Who is the data owner and is the data available in a geodata format? [free-format text] e. Are the data open and if so, is it delivered to EMODNET, ICES or another open database? [free-format text]
7. What data do you think is most important to collect and harmonize in order to reduce and prevent the risk of pollutant/nutrient dispersal in the coastal zone due to future climate change and sea level rise? a. in your country? [free-format text] b. by the EU Geological Surveys? [free-format text]
8. From your country's perspective, what data is the biggest challenge to collect and make available in the context of preventing the risk of pollutant/nutrient dispersal in the coastal zone due to future climate change and sea level rise? [free-format text]
9. Would a data gap analysis be needed to be able to estimate risk of pollutant and nutrient dispersal in the coastal zone? a. in your country? [free-format text] b. by the EU Geological Surveys? [free-format text]
10. If you think a data gap analysis is necessary, who is the most suitable actor/responsible to perform a data gap analysis of necessary data to estimate risk of pollutant and nutrient dispersal in the coastal zone? This could be the Geological Survey, governmental organizations, institutions or agencies, research institutions, private enterprises, international institutions e.g. GSEU, EMODNET etc. [free-format text]
11. How do you see EMODNET as an opportunity for future work with data within your country, but also for cooperation between geological surveys regarding pollutant and nutrient dispersal in the coastal zone? Are there limitations? Are there benefits? [free-format text]

Table 4 - Questions of the third section of the T5.1.a online questionnaire.

12. To which extent do you think the work with MFSD incorporate geological and hydrological considerations into decision-making processes to help identify and prioritize areas for pollution mitigation and guide the implementation of sustainable land use practices to reduce nutrient runoff? [free-format text]
13. To which extent do you think the work with EU Directive 2014/89/EU to create a common framework for Maritime Spatial Planning in the European Union, incorporate geological and hydrological considerations into decision-making processes to help identify and prioritize areas for pollution mitigation and guide the implementation of sustainable land use practices to reduce nutrient runoff? [free-format text]

Respondent details

Before entering the main content of the questionnaire, the respondent was asked to provide some details, to provide necessary information of the respondents: name of organization, name / first name of respondent, e-mail, optional additional information. The information provided in this way were stored solely for survey purposes, in compliance with GDPR rules. These elements were only used to contact respondents and clarify answers when necessary and to attribute answers to the corresponding country.

Respondent countries

Among the 28 partners (26 countries) targeted by the questionnaire, a total of 22 GSOs or similar organisations answered the questionnaire, representing:

1. Albania
2. Belgium
3. Croatia
4. Cyprus
5. Denmark
6. Faroe Islands
7. Finland
8. France
9. Greece
10. Iceland
11. Italy
12. Lithuania
13. Malta
14. Norway
15. Poland
16. Portugal (2 institutes)
17. Romania
18. Slovenia
19. Spain (2 institutes)
20. Sweden
21. Ukraine

10. Annex III – Coastal Areas that could form a Sharing Knowledge Cluster

Table 5 - Identified coastal areas that could form a future cluster of European sites sharing knowledge of coastal vulnerability relatively elevated levels of pollutants, nutrients, and submarine and coastal groundwater discharge.

Country	Area	WGS 84, N	WGS 84, E
Albania	Cluster zone of Shengjini	41° 48′ 49”	19° 35′ 38”
Belgium	The Belgian coast zone	51° 13' 48"	2° 54' 36"
Croatia	Rijeka	45° 19′ 38”	14° 26′ 28”
	Neretva delta	43° 1' 31.3"	17° 33' 49.4"
	Split	43° 30' 29.3"	16° 26' 24.7"
Cyprus	Kiti-Pervolia	34° 55' 0"	33° 37' 45"
Denmark	Horsens Fjord	55° 50′ 50”	9° 57′ 39”
Faroe islands	Faroe islands	61° 30' 18.3"	-6° 46' 9.0"
Finland	Hanko-Lappohja	59° 49' 56.6'	22° 58' 14.5"
Greece	Gulf of Corinth	38° 30′ 0”	22° 15′ 0”
	Prefecture Evoikos Gulf	38° 16' 48"	24° 13' 48"
	Gulf of Argolis	37° 39' 60.0"	22° 49' 60.9"
	Eleusis Bay	38° 1' 0.0"	23°31'60"
	Saronic Gulf	37° 45' 47"	23° 41' 27"
	Pireus	37° 56' 50.8"	23° 38' 13.5"
	Ierapetra, Crete	35° 0' 42.7"	25° 44' 32.4"
Iceland	Vatnajökull	64° 27' 18.0"	-17° 3' 56.6"
Italy	Delta Po River	44° 58' 7.19"	12° 32' 29.4"
	Vento coastline	45° 43' 59.9"	11° 51' 0.0"
	Emilia coastline	44° 3' 34"	12° 34' 6.0"
Lithuania	Klaipėda port	55° 43' 1.99"	21 °07' 3.0"
Malta	Coast of Gozo	36° 1′ 5.3”	14° 15′ 5.2”
Norway	Oslofjorden	59° 49' 60.0"	010° 40' 0.0"
Poland	Puck Bay catchment area	54° 40′ 0.12”	18° 34′ 59.9”
Portugal	Algarve coast	37° 1' 9.7"	-7° 55' 49.6"
Romania	Danube Delta	45° 7' 9.2"	29° 41' 57.8"
	The Black Sea Coast	44° 9' 22.6"	28° 43' 30.5"
Slovenia	Rižana	45° 0' 32.34"	45° 32' 20.40"
	Badaševica	45° 32' 31.20"	13° 43' 8.40"
	Piran	45° 32' 20.40"	13° 31' 51.60"
	Port of Koper	45° 33' 14.40"	13° 44' 16.80"
Spain	Mallorca Island	39° 42' 37.3"	2° 59' 42.5”
	Fangar Bay	40° 46' 45.7"	0° 44' 22.1"
	Alfacs bay	40° 36' 24.5"	0° 38' 44.4"
	Ebro delta	40° 42' 34.4"	0° 44' 20.5"
	La Pineda beach	41° 04' 36.4"	1° 10' 58.3"
	Sant Adrià del Besòs	41° 25' 18.8"	2° 14' 1.4"
Sweden	Beckholmen	59° 19' 9.0"	18° 05' 60.0"
Ukraine	Odessa	46° 27' 60.0"	30° 43' 60.0"
	Yugny	46° 58' 60.0"	31° 57' 60.0"
	Chernomorsk	46° 19′ 44”	30° 39′ 34”

11. Annex IV – Task 5.1c Online Questionnaire

1st section: Key parameters

This first section aims at identifying the key parameters influencing the vulnerability of coastal territories over European coasts and providing an overview of emblematic sites across countries involved in the WP5 (Table 6).

Table 6 – Questions relating to the first section of the T5.1.c online questionnaire.

Considering your knowledge of coastal territories in your country, rate the following parameters regarding their influence on coastal vulnerability

	0 (not important at all)	1	2	3	4 (very important)	don't know
Lithology (geological coastal type)	○	○	○	○	○	○
Geomorphology (coastal feature / Coastal erosion and accretion / Shoreline changes and evolution trends / etc.)	○	○	○	○	○	○
Coastal slopes (intertidal area / shallow water / etc.)	○	○	○	○	○	○
Coastal exposure (to extreme weather conditions : wave, wind, surge…)	○	○	○	○	○	○
Tides (tidal range / highest water level / etc.)	○	○	○	○	○	○
Coastal elevation (significant part of low-lying areas / wetlands / etc.)	○	○	○	○	○	○
Relative sea level rise	○	○	○	○	○	○
Resources (fluid extraction / etc.)	○	○	○	○	○	○
Hydraulics (hydraulic connectivity / drainage network / rivers and groundwater)	○	○	○	○	○	○
Land use (coastal urbanization / infrastructure)	○	○	○	○	○	○
Socio-economic activities	○	○	○	○	○	○
Natural ecosystems	○	○	○	○	○	○

Could you please explain in few sentences your choices regarding influencing parameters? Is there dedicated documentation or work that sheds light on your choices above?
Please do not hesitate to indicate references if available.

[free-format text]

Could you please indicate examples of areas (emblematic areas, richly or still poorly documented) that illustrate the importance of the following parameters?
Please think about providing references (reports, scientific papers, database, etc.) if available.

Lithology (geological coastal type)	
Geomorphology (coastal feature / Coastal erosion and accretion / Shoreline changes and evolution trends / etc.)	
Coastal slopes (intertidal area / shallow water / etc.)	
Coastal exposure (to extreme weather conditions: wave, wind, surge...)	
Tides (tidal range / highest water level / etc.)	
Coastal elevation (significant part of low-lying areas / wetlands / etc.)	
Relative sea level rise	
Resources (fluid extraction / etc.)	
Hydraulics (hydraulic connectivity / drainage network / rivers and groundwater)	
Land use (coastal urbanization / infrastructure)	
Socio-economic activities	
Natural ecosystems	

[free-format text]

2nd section: Public policies

This second section aims at providing elements for an up to date inter comparison between countries concerning the consideration of coastal risks and vulnerability in public policies (Table 7).

Table 7 – Questions relating to the second section of the T5.1.c online questionnaire.

Which level of governance is involved in coastal risk management in your country?

	Not implicat		Fully implicat	Don't know
National level	○	○	○	○
"Regional" level	○	○	○	○
Local level	○	○	○	○

What is the role of local and regional authorities?

[free-format text]

In your country, which level of governance is the most involved in the definition of policy and decision-making objectives? (Territorial management, coastal protection, adaptation measures)

	Not involvec		Fully involved	Don't kow
National level	○	○	○	○
"Regional" level	○	○	○	○
Local level	○	○	○	○

Please explicate if appropriate

[free-format text]

Are coastal erosion and coastal flooding hazards considered jointly or separately in current regulation?

- **Jointly**
- **Separately**
- **Don't know**

Please explain (if appropriate) elements in connection with the previous question in the event of a possible erosion/flooding dichotomy. Please do not hesitate to indicate references.

[free-format text]

Is Sea Level Rise taken into account in:

	yes	no	Don't know
Current regulation on coastal erosion	☐	☐	☐
Current regulation on coastal flooding	☐	☐	☐
Current regulation on both coastal erosion and flooding	☐	☐	☐
Coastal adaptation measures	☐	☐	☐

What are the related framework documents for your country? (national directive or guide, current law marking a significant paradigm shift on this subject, national management strategy and possible regional/local variations, etc.)
Please remember to include references.

[free-format text]

Respondent countries

Among the 28 partners (26 countries) targeted by the questionnaire, 18 partners (17 countries) answered for a total of 22 individual entries during 1rst collection phase, and 9 partners (9 countries) answered during 2nd collection phase.

Figure 4-3 represents the respondent countries on a 2021 European map, and the list of respondent countries is mentioned below:

1st phase

1. Albania
2. Faroe
3. Finland
4. France
5. Greece (3 respondents, 1 institute)
6. Iceland
7. Ireland
8. Italy
9. Latvia
10. Malta
11. Norway
12. Portugal (3 respondents, 2 institutes)
13. Spain (only Catalonia region)
14. Sweden
15. The Netherlands
16. UK (2 respondents, 1 institute)
17. Ukraine

2nd phase

18. Croatia
19. Cyprus
20. Denmark
21. Estonia
22. Lithuania
23. Poland
24. Romania
25. Slovenia
26. Spain

Note: Only the results from the first phase of responses to the online questionnaire have been included in this Version 1 of the deliverable, as several recent submissions were received during the drafting phase. However, all responses from participating countries will be fully incorporated and analyzed in the final version of the deliverable.