Sea level Rise in Europe: Adaptation Measures and Decision Making Principles

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Abstract

Sea level rise (SLR) will increasingly impact European countries in the coming decades, posing challenges for coastal decision-making and the design and implementation of adaptation measures to address coastal risks. The impact of SLR extends its physical damages, encompassing socio-economic and environmental repercussions. European countries are engaged in the development and implementation of adaptation measures to bolster coastal resilience. While significant strides on SLR adaptation have been made in recent years, this paper aims to provide a catalogue of adaptation measures in European basins to guide towards their design and implementation and presenting approaches suitable for supporting coastal adaptation decision making and addressing uncertainty. The assessment of SLR adaptation measures in Europe is based on the cataloguing of 17 measures following IPCC classification of *accommodate, protect, advance,* and *retreat* responses to SLR, supplemented with sub-key types of measures ranging from socio-economic, physical and technological, nature- and ecosystem-based. Surveying relevant literature in the European sea basins, the paper uncovers that adaptation strategies in Europe's coasts constitute a mix of hard and soft measures, planning measures, policy developments, and stakeholder and community engagements. Across all basins, a common theme is the shift towards a combination of traditional engineering solutions with soft measures, including nature-based solutions, integrating local communities into decision-making processes, and emphasizing the importance of continuous monitoring and flexible management strategies. In addition, the context, decisions, and experiences with coastal adaptation vary considerably across places and regions in terms of the time horizons considered, the scale of investments involved, and the risk acceptance preferences of decision-makers and their constituencies. In this sense, the paper provides an overview of the common features of coastal adaptation decisions and the key aspects that need to be considered in coastal adaptation decision making, i.e. considering multiple criteria and interests, implementing low regret and flexible options, keeping future options open, factoring SLR into decisions that need to be taken today.

1 Introduction

Global costal systems are witnessing the increase of sea level rise (SLR), ocean acidification, and rising ocean temperature severely exposing people in low-lying areas to natural hazards and leading to significant environmental and socio-economic damages (Merkens et al., 2016). European coasts are subjected to an increase of sea levels and an increase of SLR adverse impacts, in particular, coastal flooding, saltwater intrusion, coastal erosion and negative impacts on ecosystem and estuaries affecting the ability of coasts to adapt to the changing climate (as demonstrated in Van De Wal et al., 2023).

A major concern for many countries is *how* to reduce exposure to SLR and enhance coastal resilience. For several centuries decision-makers have implemented traditional engineering solutions, herein referred to as grey options, as they dominated thinking and practice in coastal protection against SLR (Sancho, 2023; Kraus, 1996; Van Koningsveld et al., 2008). Recent body of scientific evidence is proving that context-adjusted nature- and ecosystem-based solutions (i.e. green and blue options) as well as hybrid solutions can similarly reduce the risk of coastal flooding and erosion induced by SLR (Kuwae & Crooks, 2021).

Despite the growing attention on coastal adaptation, there is limited reporting of adaptation measures in peer-reviewed literature and in policy documents as they often present broad objectives rather than detail concrete measures. While systematic reviews have been done on global civil and environmental infrastructures of coastal adaptation to SLR (Nazarnia et al., 2020) on the role of protected areas in community adaptation in coastal (Ferro-Azcona et al., 2019); on studies performing socio-economic assessments of climate-change adaptation in coastal areas (Riera-Spiegelhalder et al., 2023); on the limits of participation and co-production in climate adaptation within European coastal communities (Sartorius et al., 2024)); and on public preferences of coastal adaptation measures (Mallette et al., 2021), European regional studies on adaptation solutions encompassing multiple types of measures – civil infrastructures, nature-based solutions, social, economic and institutional – are lacking.

To facilitate climate action against SLR the International Panel on Climate Change (IPCC) identifies four types of responses to SLR that guide countries in designing effective adaptation strategies: *(i) accommodate, (ii) protect, (iii) advance*, and *(iv) retreat* (Oppenheimer et al., 2019). These represent four different approaches to adapt to natural hazards by reducing risks, exposure, and vulnerability in low-lying coastal areas. Similarly, the European Environment Agency (EEA) developed the Key Type of Measures for Adaptation to Climate Change framework to report climate adaptation actions in the EEA member countries. It has two categories of measures (*key types* and *sub-key types*) ranging from socio-economic, to physical and technological, nature- and ecosystem-based ones (Leitner et al., 2020). The advantage of using frameworks is that they help to standardise existing efforts to climate adaptation and capitalise on individual action for collective action while guiding towards the development of new efforts.

The contribution of this paper is twofold. First, in an effort to facilitate the diversification of local and national adaptation strategies portfolios for decision-makers, it collects and discusses 17 coastal adaptation measures implemented in European basins and it provides a categorisation following the frameworks of the IPCC and EEA. Second, it presents approaches suitable for supporting coastal adaptation decision making and addressing uncertainty. In doing so, this paper aims at filling the research gap within the coastal adaptation strategies landscape and provide new analysis and reflections on the existent adaptation measures in European basins and support decision-making.

As for the structure, section 2 and its subsections present a state-of-the-art of SLR adaptation measures in Europe and aims to provide guidance for the design and implementation of adaptation policies in European basins. The section is further complemented by a series of in-depth analyses showcasing the implementation of adaptation measures in Venice, Italy, in Aveiro, Portugal and the Wadden Sea. Section 3 and its subsections first briefly reviews decision science terminology and then present key aspects that need to be considered in coastal adaptation decision making, together with some example tools that can be used for addressing them.

2. Assessment of adaptation measures in Europe

A systematic scientific literature review was carried out, consisting of 247 scientific peer reviewed articles, reports, policy documents and other grey literature to identify a list of adaptation measures, provide their description, and find examples of best practices. The literature was collected through an iterative mixed-method approach (Figure 1). First, 127 articles were identified using Web of Science Core Collection, searching the keywords 'coastal adaptation' OR 'coastal governance' AND 'sea level rise' (Topic) AND 2017-2023 (Year Published) AND Europe (Topic). The review considered papers written between 2017 and 2023 as to find the most up-to-date literature and provide emerging contexts and measures regarding SLR. Second, grey literature was included: 43 strategies, management and adaptation plans from different countries, regions, and cities as well as 32 others sectoral reports and documents, comprising Maritime Spatial Planning country information. Third, 45 additional scientific studies were identified through references in peer-reviewed papers and included in the literature review. A selection of the literature was carried based on the following criteria: the type of adaptation option (green, blue and grey), the sea-basin (Mediterranean basin, North Sea, Black Sea, Eastern Atlantic, Artic basin, and Baltic Sea), and type of impact (coastal flooding, saltwater intrusion, coastal erosion and negative impacts on ecosystem and estuaries). For a targeted collection of the literature, we have limited the search words, however, further research could be broadened to incorporate additional keywords such as "coastal strategy," “coastal defence” "adaptation to coastal flooding," "adaptation to coastal erosion," "adaptation to saltwater intrusion," and "adaptation of coastal ecosystems."

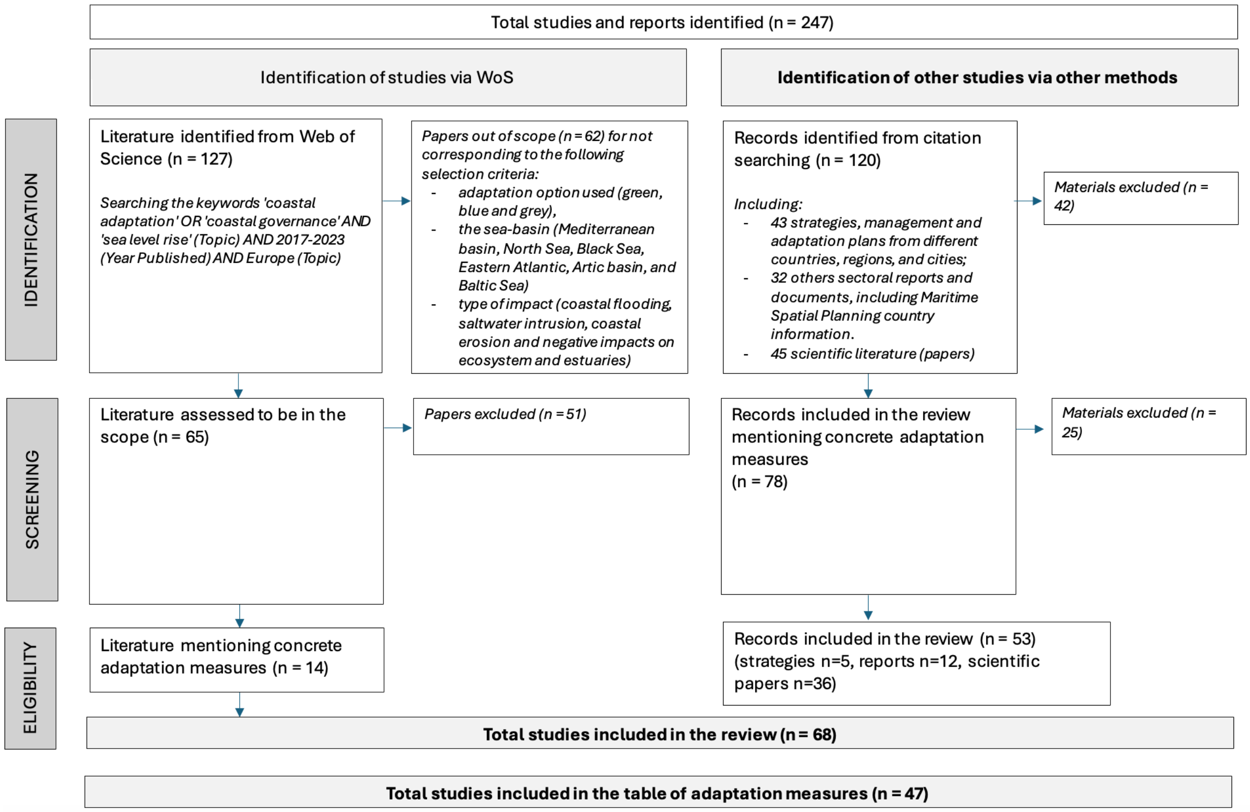


Figure 1 – Methodological systematic review process

The main outcome of the literature review, which is represented in Table 1, is the collection and categorisation of 17 adaptation measures to SLR focusing on European sea basins and targeting four climate impacts: *coastal flooding, saltwater intrusion, coastal erosion and impacts on ecosystem* and *estuaries* (see Van De Wal et al., 2023). Table 1 lists the identified measures and provides information on the type of response, the sub-key type of measure (sub-KTM), the sea basin, the impact and the literature.

The top-level categorisation of adaptation measures is along the four main types of responses to SLR identified by the IPCC. First, *accommodation* measures that involve preparing for and responding to coastal hazards. They include a range of responses, such as using early warning systems, building flood-proof structures, managing groundwater, and implementing insurance and policy instruments. Second, *protection* measures that aim to reduce risks and impacts of coastal hazards through hard defence and soft defence measures. Additionally, nature or ecosystem-based adaptation measures are also considered as protective measures. Third, *advance* measures that include strategies such as raising and advancing coastal land, for example, through creating new raised ports, raising urban embankments, and creating vegetated areas to promote natural land growth. Lastly, *retreat* measures that involve relocating human activities and infrastructure away from high-risk coastal areas to less vulnerable ones.

Adaptation measures are further categorised along the sub-KTM dimension developed by the EEA (Leitner et al., 2021). This categorisation is based on five main Key Types of Measures (KTM) and 11 sub-KTM, namely Governance and Institutional (policy instruments; management and planning; coordination cooperation and network) (see Bisaro et al., 2024), Economic and Finance (financing and incentive instruments; insurance and risk sharing instruments), Physical and Technological (grey options; technological options), Nature Based Solutions and Ecosystem-based Approaches (green options; blue options), and Knowledge and Behavioural change (information and awareness raising; capacity building, empowering and lifestyle practices).

It should be noted that it can be difficult to draw clear distinctions when categorising measures, as the adaptation measures identified in the table can often be implemented at different levels of governance and at different spatial scales (see Bisaro et al., 2024). Moreover, some measures may in practice include activities across multiple sub-KTM and even combine multiple types of responses. For example, urban land raising (advance measure) may be appropriately combined with improved building codes (accommodation measure) in order to effectively reduce coastal risks as in Hamburg Hafen City (Bisaro et al., 2020). To ease the categorisation, the measures were classified based on the primary response and sub-KTM addressed.

Response		**Adaptation measure**	**Sub-KTM**	**Sea Basin**	**Impact**	**References**
Accommodate	1	Flood-proofing and raising buildings	Grey options	North Sea, Mediterranean Sea	Coastal flooding, coastal erosion	(Dal Cin et al., 2021); (Ventimiglia et al., 2020); (Oppenheimer et al., 2019); (Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente, 2016).
	2	Adaptation measures to increase resilience of critical infrastructure	Grey options	Mediterranean Sea	Coastal flooding	(Cavalié et al., 2023); (Koks et al., 2023)
	3	Adaptation of groundwater management	Management and planning	North Sea	Coastal flooding, saltwater intrusion	(Ministerie van Infrastructuur en Waterstaat, 2023); (Ward et al., 2020); (Oppenheimer et al., 2019)
	4	Sustainable fisheries and aquaculture management	Management and planning	Baltic Sea	Impacts on ecosystems and estuaries	(Payne et al., 2021); (Oppenheimer et al., 2019)
	5	Climate risk insurance schemes	Insurance and risk sharing instruments	Mediterranean Sea	Coastal flooding	(Bednar-Friedl B. et al., 2022); (Oppenheimer et al., 2019); (Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente, 2016)
	6	Consideration of climate change in credit risk and project finance assessments	Insurance and risk sharing instruments	Mediterranean Sea	Coastal flooding	(Ministerie van Infrastructuur en Waterstaat, 2023); (Ministerio para la Transición Ecológica y el Reto Demográfico (MITECO), 2020); (Oppenheimer et al., 2019); (Netherlands Sovereign Green Bond, 2019)

	7	Integration of climate change adaptation in coastal zone management plans	Policy instruments	Eastern Atlantic	Coastal flooding, coastal erosion	(Bednar-Friedl B. et al., 2022); (McEvoy et al., 2021) (OECD, 2019); (Ministerio de Agricultural y Pesca, Alimentación y Medio Ambiente, 2016).
	8	Early warning systems and flood preparedness	Technological options	Eastern Atlantic, Mediterranean Sea	Coastal flooding	(Maritime Spatial Plan of Estonia, 2022); (Oppenheimer et al., 2019); (Climate Change Adaptation Development Plan until 2030 of Estonia, 2017); (Estrategia de Adaptación al Cambio Climático de La Costa Española, 2016)
	9	Develop a risk culture within the population	Information and awareness raising	Baltic Sea, Eastern Atlantic, Mediterranean Sea	Coastal flooding	(Zeng et al., 2020); (Stelljes et al., 2018)
Protect	10	Hard defence for coastal management (dams, dikes, levees etc.)	Grey options	Eastern Atlantic, North Sea	Coastal flooding, coastal erosion	(Ministerie van Infrastructuur en Waterstaat, 2023); (Del-Rosal-Salido et al., 2021); (Egberts & Riesto, 2021); (Estrategia de Adaptación al Cambio Climático de La Costa Española, 2016) (Koningsveld et al., 2008)); (Hinkel et al., 2014); (Lincke & Hinkel, 2018); (Tiggeloven et al., 2020)); (Vousdoukas et al., 2020a); (Hinkel & Nicholls, 2020)
	11	Restoration and management of coastal ecosystems	Green and blue options	Eastern Atlantic	Impacts on ecosystems and estuaries, coastal flooding, coastal erosion	(Moraes et al., 2022); (Programa de Ação Para a Adaptação Às Alterações Climáticas, 2019); (Estrategia de Adaptación al Cambio Climático de La Costa Española, 2016); (Buisson et al., 2012); (Barbier et al., 2011)
	12	Beach and shoreface nourishment	Green and grey options	Eastern Atlantic, North Sea, Mediterranean Sea,	Coastal flooding, coastal erosion, impacts on ecosystems and estuaries	(Tiede et al., 2023); (Ministerie van Infrastructuur en Waterstaat, 2023); (Saengsupavanich et al., 2023); (Sancho, 2023); (Mendes et al., 2021); (de Schipper et al., 2021); (Staudt et al., 2021); (Pinto

						et al., 2020); (Buisson et al., 2012)
	13	Other soft defence measures for coastal management (reloading littoral strips, cliff reshaping, polymer grids)	Green, blue, and grey options	Eastern Atlantic	Coastal erosion	(Oppenheimer et al., 2019); (Programa de Ação Para a Adaptação Às Alterações Climáticas, 2019); (ClimateAdapt, 2016b); (Buisson et al., 2012)
Advance	14	Rising and advancing coastal land	Green options	North Sea, Eastern Atlantic	Coastal flooding, coastal erosion, impacts on ecosystem s and estuaries	(Van Den Hoven et al., 2022); (ClimateAdapt, 2016b); (Moraes et al., 2022); (Laporte-Fauret et al., 2021); (Bisaro, 2019); (Schuerch et al., 2018); (Estrategia de Adaptación al Cambio Climático de La Costa Española, 2016)
Retreat	15	Planned relocation	Managemen t and planning	Eastern Atlantic, Mediterrane an Sea	Coastal flooding, coastal erosion, impacts on ecosystem and estuaries	(Sayers et al., 2022); (Portugal's Adaptation Communication to the United Nations Framework Convention on Climate Change, 2021); (OECD, 2019); (Thorsen et al., 2021); (Schuerch et al., 2018; Van Den Hoven et al., 2022)
	16	Restricting new developments in flood prone areas	Managemen t and planning	North Sea	All	(Ministerie van Infrastructuur en Waterstaat, 2023); (Oppenheimer et al., 2019)
	17	Managed realignment	Green and blue option	Mediterrane an Sea Baltic Sea	Coastal flooding	(Schuerch et al., 2018; Van Den Hoven et al., 2022); (Thorsen et al., 2021); (Bisaro et al., 2024)

Table 1: Adaptation measures to sea level rise.

The literature review shows that accommodation measures are the most widely discussed, followed by protection measures, advance measures, and finally retreat measures. The most common sub-KTM is management and planning, followed by grey, green and blue options, insurance and risk sharing instruments, and technological options. The sea-basins most covered in the literature are, respectively, the Eastern Atlantic, the Mediterranean Sea, the North Sea, and the Baltic Sea. Lastly, most measures focus on avoiding coastal flooding and erosion, while studies on ecosystems, estuaries, and saltwater intrusion are very scarce. Based on the categorisation described above, the following section looks at each measure individually.

2.1 Types of responses to sea level rise

i) Accommodate

Accommodation measures encompass a range of biophysical, architectural, and institutional responses. They do not directly prevent coastal impacts but rather mitigate coastal risks by reducing the vulnerability of coastal residents, ecosystems, human activities, and the built environment, thus enhancing coastal communities' resilience. Accommodation is usually implemented in response to coastal hazards, coastal flooding, salinisation and other sea-borne hazards rather than directly to address SLR. The main advantage of accommodation measures is that they are generally both low-cost and highly cost-efficient in all contexts. This high benefit-cost ratio means that implementing them is much cheaper than not intervening (Oppenheimer et al., 2019). Accommodation measures can have additional advantages by producing and disseminating useful information, raising awareness of coastal risks among residents and promoting safer behaviour (Bongarts Lebbe et al., 2021).

Flood proofing and raising buildings is an adaptation measure that involves the use of buildings techniques with specific designs and materials that are primarily aimed at flood risk reduction. Dry and wet-proof techniques have shown their effectiveness to reduce impacts of short periods of flooding (Ventimiglia et al., 2020). For long periods of high water, an appropriate measure is raising buildings by elevating their height or constructing new ones at higher elevations (pile-dwelling construction/building on stilts). These can mitigate the risk of flooding and coastal inundation. Floating/amphibious buildings also offer the opportunity to float when flooding occurs for several months (Dal Cin et al., 2021). In the Netherlands, the latter technique has been experimented with houses capable of adapting to different water levels (Oppenheimer et al., 2019). In Spain, the National Adaptation Plan focuses on the importance of using flood-proofed materials and building designs for critical infrastructure in coastal cities (Estrategia de Adaptación al Cambio Climático de La Costa Española, 2016).

Increasing resilience of critical infrastructure involves solutions mainly composed of grey measures. Critical infrastructure are assets that are essential for the maintenance of vital societal functions, mainly in the transport and energy sectors, e.g., ports, airports, highways, or nuclear power plants. Critical infrastructure is often located near the coast, as for example, Schiphol Airport at 4m below sea level in the Netherlands or the Nice Côte d'Azur Airport in France at three metres above sea level (Cavalié et al., 2023). The risks do not only relate to the possible asset damages but also concern the potential blockages and the disruption of economic activities that may result from infrastructure failure as it could substantially increase the severity of the impact (Koks et al., 2023). This measure does not consist of precise preventive actions but instead involves methods to mitigate the risk to uphold the functionality of the infrastructure. An example of how port authorities are dealing with climate change risks is provided by government-led Ports of Spain which manages 28 ports in the country. The Port Authority has adopted several measures to adapt to flooding and storm surges, including advanced early warning systems, a new Spanish Ports Strategic Plan, and the implementation of a Port Climate Change Observatory (see Box on 'Climate change impacts and adaptation: status and challenges for the Spanish Ports system' in Bisaro et al., 2024). This critical infrastructure perspective is rarely addressed in the scientific literature and is more studied in the US than in Europe (Koks et al., 2023).

The sub-KTM management and planning includes among others **adaptation of groundwater management**. Groundwater is an overexploited resource that is being used globally at an alarming and unsustainable rate, affecting its capacity to act as a natural buffer against coastal flooding (Ward et al., 2020). In turn, the conservation of groundwater reservoirs, the limit of water use and the optimisation of water reuse can avoid salinisation and increase the adaptive capacity of coastal areas. This calls for human activities conducive to the preservation and sustainable management of groundwater resources, in particular through improved land management practices in upper basins or in urban areas through rainwater harvesting and the use of pervious pavements (Oppenheimer et al., 2019). For instance, the Freshwater Delta Programme in the Netherlands aims to prevent water shortage in the present and near-future (2050), and includes comprehensive measures to maintain a healthy groundwater system, using spatial planning and other context-specific strategies (Ministerie van Infrastructuur en Waterstaat, 2023). The multiple benefits of a sustainable groundwater management make it both an accommodation and protection measure. For a more extensive discussion on prevention and adaptation measures to limit groundwater salinisation, see (Van De Wal et al., 2023).

The sub-KTM management and planning also includes **sustainable fisheries and aquaculture management**. Over recent years, the literature and political action in Europe has focused more on overexploitation of the living marine resources than climate change impacts which is a severe issue particularly in southern Baltic States (Payne et al., 2021). Within studies that focus on climate-related drivers of fisheries and aquaculture, ocean warming and acidification are considered more influential than SLR (Oppenheimer et al., 2019). However, future projections on SLR and their implications for fisheries and aquaculture are an understudied area.

Climate risk insurance schemes can play an important role in enhancing coastal resilience and reducing vulnerability. These mechanisms can provide financial security to coastal communities and businesses to mitigate the financial impacts of loss events such as coastal flooding and storm events (see Bisaro et al., 2024). They have been mainly used in the context of agriculture and urban areas (Oppenheimer et al., 2019). The European insurance industry has developed flood-specific products, notably through risk-based flood insurance schemes that can induce risk-averse behaviour and is also investing in the field of risk analysis (Bednar-Friedl et al., 2022). Spain has developed specific insurance and reinsurance schemes like the ‘extraordinary risk insurance’ for risks specifically deriving from SLR in coastal areas including extraordinary floods and atypical cyclonic storms (Estrategia de Adaptación al Cambio Climático de La Costa Española, 2016). More recently governments are funding post-disaster mechanisms, making flood insurance compulsory or taking on the role of reinsurer in public-private partnerships. Well-designed insurance schemes may also include measures such as reduced prices of the insurance if the homeowners implement preventive adaptative measures, e.g, not keeping high value items on the ground floor, which increase overall effectiveness of insurance (Bednar-Friedl et al., 2022). However, when poorly designed, insurance schemes can also perpetuate the risk and incentivise maladaptation. An example is the provision of insurance pay-outs to rebuild assets in a location that is increasingly experiencing flood risk without proportionally increasing premiums. Moreover, increasing climate risks could put a strain on public budgets, leading to the withdrawal of support for publicly funding insurance potentially reducing the availability or affordability of insurance products for poor households and some households in high-risk areas. Similarly, increasing risks may lead to decreased offerings of private insurances due to either insolvency or them exiting the markets (Bednar-Friedl et al., 2022).

Addressing **climate change in credit risk and project finance assessments** is an accommodation measure as it orients investors towards projects that enhance adaptation. Consideration of climate change in credit and finance assessments can thus mobilise financing specific projects against SLR through the public and private sector, international climate funds, and other innovative financing solutions. In 2019, the Netherlands issued the first certified Sovereign Green Bond by a European country (Netherlands Sovereign Green Bond, 2019). A large proportion of the bond proceeds were used to fund the Delta program, a sophisticated flood risk management system that enhances resilience to SLR as well as improve freshwater supply, among other benefits. The Delta program has also a specific Delta Fund, which is a separate item of the central government budget and includes 21 billion euros available for the period 2023-2036 (Ministerie van Infrastructuur en Waterstaat, 2023). An example of tools for financing adaptation projects is raising funds from the sale of new generated lands coming from the implementation of advance measures (Oppenheimer et al., 2019). Another example is provided by PIMA Adapta, Plan for the Promotion of the Environment for the Adaptation to Climate Change in Spain, an operational tool that finances adaptation projects using emission rights, among others (Plan Nacional de Adaptacion al Cambio Climatico 2021-2030, 2020).

The literature emphasises the key role of **integrating SLR information in coastal adaptation strategies and plans.** An illustrative case is Spain. Since 2004, Spain has prioritised climate change adaptation measures that protect its vulnerable coastline. The first National Plan for Adaptation to Climate Change (PNACC), approved in 2006, identified coastal impact assessment as a priority. The second (2009-2014) and third (2014-2020) PNACCs, identified coastal zones and the development of a strategy for the adaptation of the coasts to climate change as a priority line of action, which was de facto adopted in 2016 (Estrategia de Adaptación al Cambio Climático de La Costa Española, 2016). The current PNACC (2021-2030) forsees the development of risk analysis tools and the definiton of adaptation initiatives on the coasts and at sea, the facilitation of coastal and marine adaptation through regulatory frameworks, the integration of coastal risks into plans and programs, and the fostering instituional coordination and social participation for adaptation on the coast and at sea.

SLR entered innovative governance instruments that have been developed to overcome administrative barriers in coastal governance. For instance, the 2023-2027 Toulon Bay Contract which involves 40 local stakeholders in a decentralised, participatory, bottom-up approach to adapt to flooding and erosion risks (Métropole Toulon Provence Méditerranée, 2023). Further information on coastal governance instruments is provided in the section on Equity and Social Vulnerability in Bisaro et al., 2024).

The literature also stresses the importance of studying multiple time horizons and different scenarios of SLR. The effectiveness of some adaptation strategies has been compromised by the use of only few scenarios and the use of single time horizon as opposed to multiple (OECD, 2019). For example, in Venice's adaptation pathways, only SSP1–2.6 and SSP5–8.5 were considered without using intermediate scenarios. As such, once critical relative sea level thresholds will be reached, the remaining upper limit will represents a low-likelihood but high-impact storyline (Bednar-Friedl et al., 2022). Similarly, if planning accounts only for the short term they may no longer be adequate once the adaptation measures are finally completed, especially, given that major permeant interventions may take a long time to be implemented (Bednar-Friedl et al., 2022).

The implementation responses to SLR have been facilitated by the advancement of predictive tools and cartographic techniques designed to forecast the extent and repercussions of such rise and the subsequent floodings (Mcleod et al., 2010). Technological options include **early warning systems and flood preparedness** and they support all types of responses to varying degrees. They are conventionally considered as an accommodation measure because they allow people to remain in the hazard-prone area but help improve preparedness and response by providing advance warning in the face of imminent danger. However, early warning systems are also used in other types of responses, such as in protection (in the case of mobile protection defences like the Thames Barrier and MOSE barrier in Venice, see Box 1) and retreat (in the case of extreme events evacuating people) responses. They have short implementation time and low impact on the environment, but their implementation and effectiveness depend largely on good forecasting, predictable hazardous events and definition of adequate early warning indicators (Oppenheimer et al., 2019). Thus, they are less well-suited to accommodate slow onset change. Spain's adaptation plan has examples of early warning systems and also evacuation protocols, which are carried out in coordination with society organisations as well as local communities affected by the dangers (Estrategia de Adaptación al Cambio Climático de La Costa Española, 2016). Estonia offers another interesting case of actions aimed at improving knowledge of SLR and flood preparedness. Its strategy incorporates an accommodation measure to develop sea level forecasting systems for areas prone to coastal flood (Climate Change Adaptation Development Plan until 2030 of Estonia, 2017). As a result, Estonia has implemented a Maritime Spatial Plan for 2022, which includes a study of the expected SLR along the -3m contour from the coast, specifically in the Pärnu Bay area (Maritime Spatial Plan of Estonia, 2022).

Developing a risk culture within the population sub-categorised as information and awareness raising, relies on the understanding of how people perceive risk and act in particular ways (Zeng et al., 2020). This can be an effective adaptation measure as some of the basic requirements for successful collaboration in communities to manage and cope with extreme events are ‘culture of risk memory’, ‘trust in scientific information and community’, as well as trust in coastal authorities (Stelljes et al., 2018). This measure could be equally considered part of a long-term retreat measure because developing a risk culture it prepares the population to a potential future relocation.

ii) Protect

Protect measures aim at reducing the risks and impacts of coastal hazards. These measures typically entail the construction and upgrade of hard and soft defences (OECD, 2019) but can also refer to restoration and management of coastal ecosystems.

Hard defence for coastal management includes the implementation and upgrade of physical structures such as dams, dikes, levees, groynes, breakwaters, artificial reefs, seawalls, jetties, storm surge gates, flood barriers, and other types of defences. These are classified as grey measures that aim to prevent coastal erosion and flooding.

Hard defences have been very widely applied for centuries to prevent coastal erosion and flooding. The North Sea coastline of Belgium, the Netherlands and Germany is protected through dikes systems, complemented with other measures such as sand nourishment, dunes and surge barriers. Hard defences have been also implemented to counter relative SLR caused by land subsidence, such as areas with young sediments like the Italian Po delta, the Netherlands, Northern Germany (van Koningsveld et al., 2008).

Some advantages of hard defences are that they have long-life spans, and their costs are reasonably well known and can be estimated. Generally, hard defences are highly effective at protection, but generally remains a small risk of failure unless defences are built so wide that they cannot breach (De Bruijn et al., 2013). There are also economic motivations linked to the cost-benefit ratio of investments. Generally, hard protection measures are economically beneficial in urban areas, as they have high benefit-cost ratios, and this has also been widely found to be true under 21st century SLR (Hinkel et al., 2014; Lincke & Hinkel, 2018; Tiggeloven et al., 2020; Vousdoukas, Mentaschi, et al., 2020b). For rural and less densely populated areas, hard protection is generally not economically beneficial, which suggests that alternative measures, in particular ecosystem-based measures or retreat, are often better solutions (Hinkel & Nicholls, 2020).

Negative consequences of coastal protection infrastructure include the need for ongoing maintenance and alterations in natural coastal dynamics, due to for example, loss of plants and mosses Hard defence measures can also negatively impact cultural heritage- by changing the existing landscape (Egberts & Riesto, 2021). Some examples of this can be seen in the national adaptation plans of Spain (Estrategia de Adaptación al Cambio Climático de La Costa Española, 2016) and the Netherlands (Ministerie van Infrastructuur en Waterstaat, 2023). An example of hard defence in a context of cultural heritage and landscape protection is the renowned MOSE system in Venice that after several decades of discussion and development has entered in operation on 3 October 2020 (see Box 1 below).

On 4 November 1966, due to an extreme and unexpected meteorological event the water level reached 194 cm above the historical mean sea level and remained above 110 cm for 22 hours. On 16 April 1973, the Italian Parliament promulgated the first Special Law for Venice, declaring the protection of Venice and its lagoon to be of primary national interest. Figure 1 demonstrates how the frequency of floods in the city increased from 30 to 95 events per decade, 1970-1079 and 2010-2019 (Fig. 1).

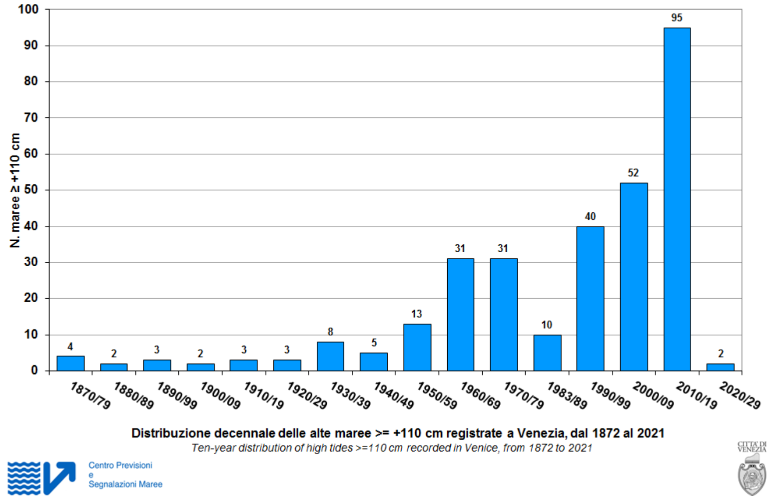


Figure 2 *Number of city flooding events in Venice per decade. The distribution indicates the number of events with a sea level higher than 110 cm (The original source of this figure is Municipality of Venice- Centro Previsioni e Segnalazioni maree).*

After a long period of discussions, prototype testing, and design revisions, the construction of the MOSE barriers began in 2003 and became operational for the first time on 3 October 2020, effectively protecting the Venice centre and all the lagoon settlements. The MOSE barriers are an essential part of a much wider safeguarding approach, that includes littoral island defence, adaptation measures in the urban settlements, ecological end morphological restoration of the lagoon (the largest in the Mediterranean Sea, ca. 550 km^2), de-pollution, and defence measures in the lagoon basin (2.068 km^2).

The 'Venice SLR defence approach' is a mixture of protection and accommodation interventions, which represent a continuation of what the Serenissima Republic of Venice did in its millenary history. The narrow littoral islands of Pellestrina and Lido, which separate the Venice lagoon from the Adriatic Sea, were made of sandbanks when the lagoon was formed around 6,000 years ago. But already seven centuries ago, the need to protect the coastal settlements from sea storms led the Republic of Venice to develop a complex defence system made of wooden poles ("palade") that were regularly renovated. In the XVIII century, this defence was replaced by massive stone seawalls ("murazzi") placed on the shore. Since 2000, the ancient seawalls have been repaired and reinforced by a new shore, in the form of gyrons, built in front of them, with sand taken from the Adriatic Sea. It is the largest confined sand nourishment that occurs in Europe (Fig. 3).

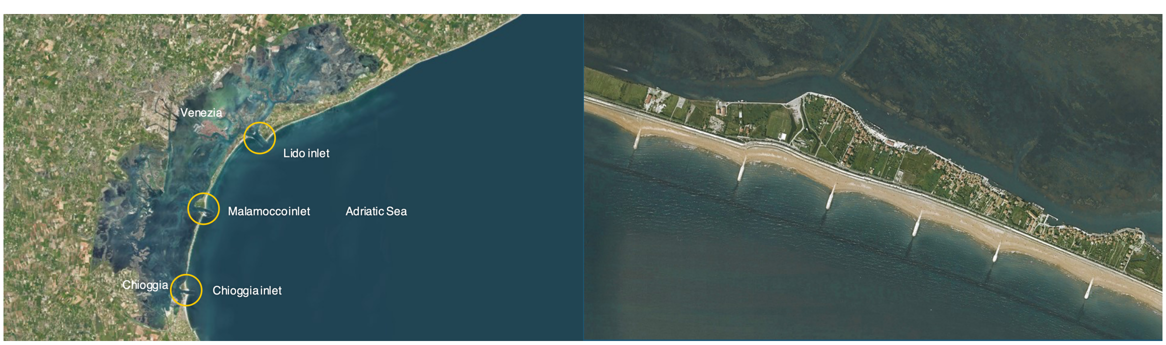


Figure 3 *(left) The lagoon of Venice and its three inlets (The original source of this figure is: Courtesy of Consorzio Venezia Nuova- Concessionary of Ministry of Infrastructure of Italy).* ***Figure 4*** *(right) The new shore realized in front of the old "murazzi" in the Pellestrina island (The original source of this figure is: Courtesy of Consorzio Venezia Nuova- Concessionary of Ministry of Infrastructure of Italy)*

The MOSE steel barriers placed at the lagoon's inlets can provide a complete closure of the lagoon from the sea, for a total length of 1,56 km divided into 4 arrays. They can guarantee a difference of 2m between the lagoon and the sea level offshore, i.e. to maintaining the level of the lagoon at the safe level of 100 cm above sea level during storm events of up to 300 cm (the maximum event ever measured is 204cm). Each of the 78 floodgates is 20m wide and varies its length according to the depth of the four inlets.

They normally lie inside big concrete caissons placed on the seabed, connected by two hinges in one end and filled with water. To close the barrier, the air is pumped into the gates by compressors, allowing them to float at the desired angle for closure. Each gate floats independently of the others to avoid the risk of stress concentration that a single, longer barrier might experience (Fig. 4).

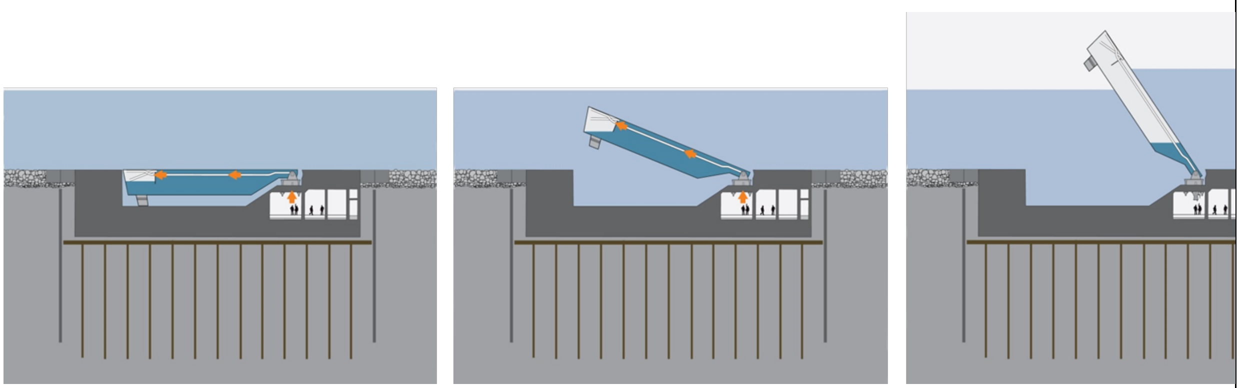
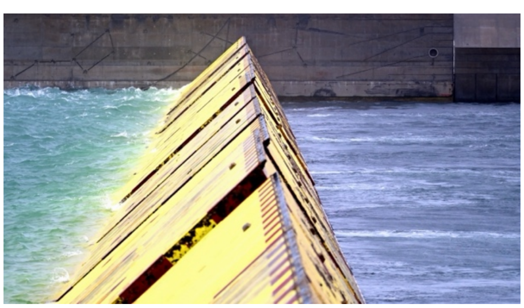


Figure 5 *MOSE barriers' functioning scheme (The original source of this figure is: Courtesy of Consorzio Venezia Nuova- Concessionary of Ministry of Infrastructure of Italy)*

After some tests (Fig. 5), the MOSE barriers became operational for the first time on 3 October 2020, and in the first three winters operated 50 times, effectively protecting Venice from floodings, including severe ones (Fig. 6 and 7).



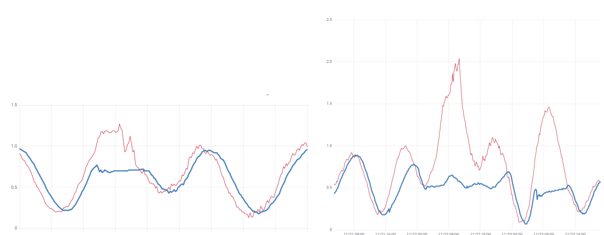


Figure 5 *The MOSE barriers in Lido, during a storm, the 15/11/2020. In the picture, the sea on the left, the lagoon on the right.* **Figure 6** *Sea level in the Adriatic (red) and inside the lagoon (blue) during the events of 3/10/2020 (left) and of 22/11/2022 (right)*

The closure of the lagoon should be kept to a minimum, for both ecological and economic reasons. The protection strategy foresees the raising of the city's pedestrian walkways to a minimum level of 110 cm above sea level. In fact, throughout its history, Venice has constantly raised the level of its buildings to cope with the relative SLR (eustacy and subsidence). In the last century, cultural heritage and landscape protection together with a faster SLR made these adaptation measures harder to implement. However, since early 2000s Venice continues to raise the level of the public pavements. Piazza S. Marco represents a special case because of the presence of relevant artefacts placed at much lower altimetric level.

In this case, an "impermeabilization" strategy has been chosen, which consists of raising the level of the entire island of S. Marco to 110 cm and in revising all the rainwater drains by installing suitable valves. These complex works are underway and will take several years to complete; in the meantime, in order to protect the most important monument, the Basilica of St. Mark, from further saltwater intrusion, a glass barrier has been erected on the front of the Basilica facing the Piazza (Fig. 7).

Figure 7 *The glass barriers in front of St. Mark's Basilica provide effective protection also from minor "acqua alta" events*

Once the main problem has been given a solution, other issues continue to challenge science and policy.
As the rise of sea level continues, the frequency of barriers closures will increase: managing a regulated lagoon requires specific observational and modelling tools to be kept up to date. Further de-pollution and morphological interventions against salt marsh erosion are also needed.
It is well known that the paradigm of mobile barriers works up to a 50-60 cm SLR; above this threshold, these gates will be permanently closed and a different protection scheme should be provided. What this new system will be has not been discussed yet. In the coming decades, however, Venice will continue to be a multi- and trans-disciplinary laboratory for testing SLR adaptation measures for the whole world.

Box 1: The MOSE system for protecting Venice and its lagoon

Soft defences for coastal management encompass different types of green, blue, and grey options**.** One major difference between hard and soft protection measures is their respective impacts on natural sedimentary dynamics and equipment reversibility (Buisson et al., 2012). Two main examples of soft defences are dominating the discourse and are being extensively used in practice. First, **the restoration and management of coastal ecosystems**, which are common green and blue options used as an alternative to traditional approaches. Coastal vegetated ecosystems and biogenic reefs can self-adapt to SLR through different mechanisms (Moraes et al., 2022). These types of measures help to reduce erosion and flooding, in addition to providing habitat for numerous species and other environmental benefits for local ecosystems (Barbier et al., 2011). Examples can be found in Spain (Estrategia de Adaptación al Cambio Climático de La Costa Española, 2016), Portugal (Programa de Ação Para a Adaptação Às Alterações Climáticas, 2019) and France (Buisson et al., 2012). This latter study shows how France successfully restored marshes and other vegetated ecosystems, protecting against wave energy and limited erosion and sediment accumulation. In the United Kingdom, the creation, restoration, and enhancement of estuarine, coastal, and marine habitats are funded through the Environmental Land Management (ELM) scheme. One initiative under this scheme is the Restoring Meadows, Marshes, and Reefs, which aims to restore at least 15% of three priority habitats by 2043 providing support to farms, to restore habitats along the coasts, and support upstream improvements (The Third National Adaptation Programme and the Fourth Strategy for Climate Adaptation Reporting, 2023).

Second, **beach and shoreface nourishment** is the artificial supply of sand, and occasionally gravel or small pebbles, to increase coastal sediments. This expands the sand volume or width of the beach allowing it to counter coastal erosion and sometimes to advance seawards (de Schipper et al., 2021). Providing beach space is beneficial for tourism and recreational activities (Mendes et al., 2021). The objective of this nourishment is to compensate for the littoral imbalance caused by natural erosion and anthropogenic impacts (Buisson et al., 2012). In the literature, the difference between beach nourishment and shoreface nourishment is mainly related to the location of sand placement, which may be respectively on the subaerial beach (above-water beach) or on the subtidal beach (submerged nearshore beach profile) in the form of an underwater mound (Mendes et al., 2021). The materials are dredged from offshore and inland sources, including nearby navigation channels. For example, the Lisbon Port Authority regularly maintain the outer Tagus estuary navigation channel by dredging sand that can be used for beach nourishment (Sancho, 2023).

Beach nourishment has been applied more extensively in Europe since the 1990s. In particular in the Eastern Atlantic Ocean the increase in the number of beach nourishments has been accompanied by a reduction in the number of hard coastal structures, contributing to improvements in coastal sediment management (Pinto et al., 2020). In Portugal an extensive beach nourishment program was carried out in the framework of a coastal management master plan between 2007 and 2019 (Mendes et al., 2021; Pinto et al., 2020) . The programme placed 4.5 million m^3 of sand along 3.8 km northern shoreline (Sancho, 2023). In Spain, the Adaptation Plan envisions the regeneration of beaches and artificial dune systems to reduce erosion and revitalise coastal ecosystems. As part of the Plan, in the sandy area of Liencres, several interventions have been made to restore one of the largest dune systems of the Cantabrian Sea (Estrategia de Adaptación al Cambio Climático de La Costa Española, 2016). In the Netherlands, Tiede et al., 2023 studied the changes in shoreline and coastal developments using satellite data of a sand nourishment initiative. The study compares images from the natural evolution period (1984 - 1990) and the recent nourished period (1996-2022), where approximately half of the sandy transects were nourished regularly in combination with small groynes to support the project (see Van De Wal et al., 2023). In brief, the study showed an increase of the share of stable or accreting transects from 67% to 89%, while the share of eroding segments fell by 20% (Tiede et al., 2023). Similarly, the Wadden Delta Programme includes different operations of sand nourishment in the North Sea side of the Wadden

Islands, protecting them against flooding and also preserving ecosystem functions (Ministerie van Infrastructuur en Waterstaat, 2023).

Nourishment is a flexible and fast coastal management option that is adaptable to changing conditions, remaining relatively cheap even if nourishments have to be repeated. However, recent literature questions the sustainability of sand nourishments (Saengsupavanich et al., 2023; Staudt et al., 2021). Criticisms stress the environmental impacts both in sediment extraction and at nourishment sites, in particular in relation to the destruction of habitats, disruption of bird and other animal nesting, coverage and subsequent suffocation of benthic organisms, the increase in water turbidity and shifts in median grain size and grain-size distribution depending on the chosen material. In addition, large uncertainties in long-term ecological and geomorphological impacts of nourishment remain (Staudt et al., 2021).

Other examples of soft defence measures include the use of geotextile structures as sand containers; the creation of artificial reefs to reduce the wave energy and prevent beach erosion; plant debris cover, windbreaks, and plantations (Buisson et al., 2012). For instance, hydraulic pilings made of wooden rods vertically planted in the sediment at regular intervals, limit sedimentary transport and favour beach stability in pilot studies in France (Buisson et al., 2012). Another example of a soft measure is cliff strengthening and stabilisation which includes green and grey options that focus on reducing erosion and enhancing natural protection along coastal cliffs. It encompasses a range of techniques such as reloading littoral strips to compensate for sediment imbalances caused by marine erosion, cliff reshaping, drainage systems, and the use of anchoring elements like bolts, tie rods, polymer grids, pinned nets, and rip-rap strips (Buisson et al., 2012). This category of measure is employed in several countries such as Croatia (Omiš) (Oppenheimer et al., 2019), Italy (Marche) (ClimateAdapt, 2016a), and Portugal (Programa de Ação Para a Adaptação Às Alterações Climáticas, 2019).

iii) Advance

Raising and advancing coastal land has a long history of use to protect communities from natural hazards. Only recently *advance* has become a response to SLR on its own (Pörtner et al., 2019). Advance measures for coastal management include all those solutions that create or advance new land by expanding into the sea or ocean. Advance measures may be green or grey and mainly address coastal flooding, coastal erosion and biodiversity loss. Grey land reclamation emerges as an adaptation measure particularly in high-value urban areas in Europe and globally (Bisaro et al., 2020). **Raising and advancing coastal land** is being pursued in major coastal cities, where new ports, harbour areas, and safer urban embankments have been created in raised areas (Bisaro, 2019). At the global level, the most common land uses on reclaimed spaces are port extensions, exemplified by the two major ports in the Netherlands, Rotterdam and Amsterdam, which reclaimed 1,106 hectares and 337 hectares, respectively, between 2000 and 2020 (Sengupta et al., 2023). Advance measures can also be ecosystem-based by including measures based on conservation and restoration of sediment systems, coral barriers or coastal vegetation by applying several techniques, such as excavation of foredune notches, dune thatching, dune grass planting, dune fencing, hybrid combinations of a dyke-core in a dune (Oppenheimer et al., 2019). For instance, in southwest France the excavation of foredune notches reestablished an ecomorphological dynamic promoting landward sand transport and foredune landward translation, without threatening biodiversity. At other locations, coastal land has been advanced with the creation of a vegetated area with the specific intention to support natural accretion of land and surrounding low areas (ClimateAdapt, 2016b).

iv) Retreat

Retreat includes measures focused on reducing the level of exposure to coastal hazards by relocating human activities, infrastructure or even cities from highly exposed to less exposed areas. Retreat necessitates rethinking the entire coastal system, as well as accepting that particular assets will need to be removed entirely (Bongarts Lebbe et al., 2021). The advantage of this type of measures is their effectiveness both in low and high coastal risk areas. However, they are solely applicable in regions of low population density (Oppenheimer et al., 2019). Retreat incorporates a wide range of measures mostly categorised as management and planning. Retreat measures have been implemented in various European sea basins, for example in the Eastern Atlantic Ocean, the Baltic Sea, and the Mediterranean Sea.

Planned relocation applies to individuals and critical assets, including the removal of existing hard infrastructure (OECD, 2019). This measure involves the governance and institutional planning behind the relocation of activities from high-risk areas, the land acquisition and the expropriation of operations. Deciding to relocate a community has complex trade-offs, on the one hand, the opportunity to reduce potential damages and meet different needs and conditions of the community and, on the other hand, the high costs and the direct impacts on people's lives, which require extensive engagement with the community and clear incentives (Sayers et al., 2022; OECD, 2019). For instance, approximately 30% of England's coastline is likely to be under increasing pressure by the 2050s, affecting more than 120,000 properties and a large but still unknown proportion of these properties will need to be relocated (Sayers et al., 2022). Another example is provided by Portugal, which has reported to the European Commission several measures that the country is implementing to manage the risk of SLR, including the progressive removal of constructions that are located in flood-critical territories along the coastline through spatial planning instruments (Government of Portugal, 2021).

Restricting new developments in flood prone areas and defining setback zones is an approach to support planned relocation. An example is the Dutch Freshwater Delta Programme that spatially restricted development based on fluctuation levels (Ministerie van Infrastructuur en Waterstaat, 2023). These flood-prone areas can be replaced with marshes, or activities like aquaculture or salt-tolerant cultivation areas (Oppenheimer et al., 2019). The governance of flood prone areas is also addressed in the Protocol on Integrated Coastal Zone Management (ICZM) of the Barcelona Convention (UNEP, 1995) – the main regional legally binding Multilateral Environmental Agreement in the Mediterranean, which entered into force in the European Union in 2011 after ratification. The article 8 of the Protocol identifies a setback zone of a minimum 100m width from the shoreline as a measure to protect coastal settlements and infrastructure from adverse impacts and is the first international legal instrument to require the use of coastal setback zones. Notably, the Protocol links setback zones with adjacent areas such as wetlands and natural forests, which allows for the restoration of biodiversity and can serve as NbS to adapt to the effects of climate change (Adriadapt, 2022).

An emerging option is **managed realignment**, a coastal adaptation strategy that entails the landward relocation of coastal defences to allow previously protected areas to restore tidal exchange and restore coastal habitats . A successful example of managed realignment in European basins, and the first large-scale example in Denmark, is the restored Gyldensteen Coastal Lagoon in the western Baltic sea where the ecological status improved and species richness increased after five years (Thorsen et al., 2021). Managed realignment as an adaptation strategy for the Ravenna coastline at 2100 can be found in 'Box 2: Ravenna Municipality Visions at 2100', in Bisaro et al., 2024).

2.2 Limits and trade-offs of adaptations measures

Adaptation measures discussed in the preceding section are generally subject to trade-offs that should be considered when planning coastal adaptation. While accommodation measures offer benefits such as cost-effectiveness and immediate relief, the financial cost of implementing these measures can be a challenge for some communities. Protection measures provide important risk reduction benefits, however, they can severely disrupt natural coastal processes and harm marine life. Even soft protection or advance measures can have similar, localised ecological effects (e.g. altering sediment transport patterns may unintentionally lead to erosion in neighbouring regions). While seawalls provide coastal protection, they can also exacerbate erosion by affecting the entire ecosystem, and thus, diminishing the ability of the system to respond naturally to different conditions (Rijn, 2011). These measures may also impact cultural heritage sites and alter coastal areas in addition to requiring high maintenance costs. Lastly, retreat measures potentially displace entire communities, and can involve the loss of assets and business activities (e.g. tourism-related activities). They therefore generally require complex governance and coordination among multiple stakeholders and are limited to regions with low population density. To accurately analyse existing trade-offs, understanding the effectiveness and feasibility of these measures is important. Currently, there is a critical literature gap in this regard. Information is lacking on the effectiveness of measures in reducing risk and the economic, technological, institutional, socio-cultural, geo-physical, and ecological feasibility of implementing them. Existing analyses of effectiveness and feasibility are typically undertaken for particular types of responses at the global level rather than for individual measures. There is thus a scientific need to evaluate the effectiveness and feasibility of individual measures and in context-specific cases. This represents a research gap that, if addressed, could advance knowledge and significantly contribute to the field of coastal adaptation.

Finally, while the identified measures can help communities and governments to adapt to the challenges posed by SLR, addressing SLR in coastal areas requires carefully considering the trade-offs associated with accommodation, protect, advance and retreat measures. In an effort to minimise the trade-offs and provide a multi-faceted, integrated, sustainable solution to rising sea levels, novel approaches combine more than one adaptation measure and develop hybrid solutions (see box 2).

Hybrid approaches combine the construction of specific grey options or built infrastructure with the simultaneous installation of restored or newly created natural infrastructure. For example, removable sea walls or flexible flood gates can be installed simultaneously with restored salt marsh and oyster reef restoration. Combining green or blue and grey protection measures is expected to be more effective and less costly under particular circumstances (Browder et al., 2019). For example, a hybrid approach can be implemented whereby natural infrastructure provides protection benefits for small to medium events, while built infrastructure is included in the measure for additional protection against larger events. Advantages of the hybrid approach include that it can be used in areas where there is little space to implement natural measures alone; it capitalises on best characteristics of build and natural measures; it allows for innovation in designing coastal protection system; and it can provide a greater level of confidence than natural approaches alone (Sutton-Grier et al., 2015).

Case study - Coastal lagoon of Aveiro, Portugal

The coastal lagoon of Aveiro, Portugal has long been studied for its peculiar configuration, high biodiversity and ecological value, and severe exposure to natural hazards (Lopes et al., 2017; Mendes et al., 2021; Pinto et al., 2020; Ribeiro et al., 2021; Stronkhorst et al., 2018). Situated along the Atlantic coast, Aveiro is extremely vulnerable to coastal erosion and SLR and thus requires integrated and sustainable management of coastal resources. Accordingly, over the last decade, Aveiro has applied a hybrid approach to coastal management by combining adaptation measures that mix traditional hydraulic engineering with green options (Stronkhorst et al., 2018), also known as 'building with nature' (Chen et al., 2022).

One of the distinguishing aspects used in Ria de Aveiro is the combination of hard defences, beach nourishment, and restoration of wetlands. Over the years, Aveiro has built approximately 10 seawalls and 20 groynes and combined these hard defences with beach nourishment along the coast to reinforce and enlarge beaches, providing natural barriers against tides and storms (Stronkhorst et al., 2018). Along with the two latter measures, Aveiro has restored previously abandoned salt pans. The latter plays a fundamental role in the mitigation of flooding and the protection of coastal communities as it increases the capacity to absorb excessive water during high tides and storm surges therefore creating a natural protection against flooding. Overall, the hybrid approach has helped to increase the resilience to climate change of coastal areas of Aveiro, protect local communities, enhance recreational use, and finally preserve coastal ecosystems.

Box 3: The role of hybrid solutions: a combination of green and grey options

SLR and associated coastal hazards have been identified as a major threat to coastal world heritage, both natural and cultural (Marzeion & Levermann, 2014; Sesana, et al., 2020). Recent studies indicate that accelerating SLR is expected to exacerbate the pressure on World Heritage Sites (WHS) through, among others, more frequent flooding or increasing erosion, with the number of threatened sites increasing sharply towards the end of the century under all scenarios (Reimann et al., 2018; Vousdoukas et al., 2022). For cultural heritage, potential impacts may range from direct damages to archaeological structures, buildings and monuments, to changes in landscapes and in visitor behaviour (Phillips, 2015). For natural WHS, coastal erosion, permanent submergence and salt intrusion are examples of SLR-related processes that may alter the character and nature of the site, thus affecting their Outstanding Universal Value.

Adaptation of WHS to SLR is particularly complex due to the potentially adverse implications of adaptive measures on heritage significance (Phillips, 2015); but also because different sites, due to their nature, have very different adaptation needs and no "one-fits-all solutions" exist. Nevertheless, in some cases, natural areas may accommodate some of these disruptions and maintain ecological equilibrium by migrating landwards (Vousdoukas et al., 2022), if not constrained by coastal development, or even seawards where conditions allow. However, little information exists in the literature regarding potential adaptation options for heritage managers and policymakers (Reimann et al., 2018). Although some adaptation options such as managed retreat, ecosystem-based adaptation and relocation have been proposed in the context of WHS adaptation to SLR (e.g. (Vousdoukas et al., 2022), which mainly due to their non-intrusive nature appear to offer promising alternatives in some cases, a better understanding regarding their effectiveness and their suitability for specific sites is required for their implementation. Further adaptation barriers include the lack of institutional frameworks and policies specific for WHS as well as financial and socio-cultural barriers (Fatorić & Biesbroek, 2020).

One example of adaptation of WHS comes from the the Wadden Sea, which has been a UNESCO World Heritage Site since 2009. The Wadden Sea is located in the North Sea between the coastlines of Denmark, Germany, and the Netherlands, and is the largest unbroken system of intertidal sand and mud flats in the world and one of the last remaining large-scale, intertidal ecosystems where natural processes continue to function largely undisturbed. The site includes the Dutch Wadden Sea Conservation Area, the German Wadden Sea National Parks of Lower Saxony and Schleswig-Holstein, and a large part the Danish Wadden Sea maritime conservation area (UNESCO, 2023). It is a large coastal wetland environment with tidal channels, sandy shoals, sea-grass meadows, mussel beds, sandbars, mudflats, salt marshes, estuaries, beaches and dunes (Schuerch et al., 2014; UNESCO, 2023), the development of which is driven by diverse morpho- and hydro-dynamics (Benninghoff & Winter, 2019). SLR projections for the Dutch Wadden Sea show a significant rise for all scenarios and in particular, a rise of 0.76±0.36 cm under RCP8.5 (Vermeersen et al., 2018).

Accelerated SLR can have important implications for Wadden Sea, affecting sediment balance and potentially leading to permanent submergence in parts, despite its intertidal flats being effective sediment sinks and appearing to be quite resilient against even high rates of SLR (Hofstede et al., 2018). In fact, data from the last two decades indicate an expansion of intertidal areas but a reduction and deepening of subtidal areas and channels in some parts (Benninghoff & Winter, 2019). However, observed changes in tidal asymmetry in the German Wadden Sea suggest that sediment accretion trends may be coming to an end (Hagen et al., 2022). Further, future projections indicate a transition from a tidal-flat-dominated system toward a lagoon-like system, despite increased accumulation of sediment in the back-barrier basin as this accumulation appears to be far too weak to compensate for the rise in mean sea level (Becherer et al., 2018). Such changes can potentially have dramatic implications for the unique ecosystem of the Wadden Sea (Becherer, et al., 2018). Moreover, beyond a critical rate of SLR, major changes in ecotope distribution are projected to occur (Timmerman et al., 2021), and adaptation strategies, such as, inland migration of the shoreline can result larger impacts, including formation of a deep tidal basin with large subtidal habitats, and a shifted intertidal zone (Timmerman et al., 2021). Besides SLR, potential changes in storm activity and characteristics can further affect the development of the site, particularly its wetlands, partially exacerbating or even counteracting the effects of SLR (Schuerch et al., 2013).

Although the future of the Wadden Sea under SLR appears to be a topic of concern and the need of adaptation is well recognised (e.g. (Heron et al., 2020), little has been done in terms of developing adaptation plans for the region. This is, in part, due to complexities related to the nature of the site, existing coastal protection measures and the involvement of three countries in its management. An example of such a plan is the integrated climate change adaptation strategy established by the German state of Schleswig-Holstein with the aim to maintain, in present functions and structures as well as the integrity and dynamic nature of the Wadden Sea ecosystem over the long-term for its section of the Wadden Sea site (Hofstede & Stock, 2018). Developing such plans for the entire basin presents many challenges but is imperative for preserving the Wadden Sea and maintaining its World Heritage status.

Box 4: Sea Level Rise and World Heritage Sites: the case of Wadden Sea

3. Approaches for decision-making

This section presents approaches suitable for supporting coastal adaptation decision making. A large number of approaches (methods, tools) are available in literature and being applied in practise to support coastal adaptation decisions (i.e. to find a suitable alternative given some criteria), and it is impossible to provide a comprehensive overview. Hence, we limit ourselves here to presenting key aspects that need to be considered in coastal adaptation decision making, together with some example tools that can be used for addressing them. Towards this end, we first clarifying the decision science terminology (Sect. 2.2.1) and reviewing the common characteristics of coastal adaptation decisions (Sect. 2.2.2). Then, the section continues to present the key aspects that need to be considered in coastal adaptation decision making, which are: i) considering multiple criteria and interests (Sect. 2.2.3); ii) implementing low regret and flexible options (Sect. 2.2.4); iii) keeping future options open (Sect. 2.2.5); iv) factoring SLR into decisions that need to be made today (Sect. 2.2.6); and v) revisiting decisions iteratively and monitoring (Sect. 2.2.7).

3.1 Decision science terminology

A decision involves a predefined set of options (also called alternatives or actions) to choose from, wherein each alternative can consist of a combination of measures. For example, common coastal adaptation measures are upgrading dikes, restoring coastal wetlands and installing building-level flood shields. An adaptation option may then consist of increasing the dike height by one meter, restoring salt marshes in front of the dike and implementing flood shields to protect against floods with water depth of two meter. Typically, coastal decision are not one-shot decisions, but consist of sequences of decisions over time. Hence, the decision consists in choosing an adaptation pathway, which is a sequence of options applied over time (also called policy or strategy in some branches of decision science). Note that this general notion of adaptation pathways is independent from the method “adaptation pathway analysis” (Haasnoot et al., 2013), which is one tool that can be applied to produce adaptation pathways.

Approaches (methods, tools) to decision making involve both participatory and analytical methods, which fulfil complementary roles in supporting adaptation decisions. Participatory methods (also called transdisciplinary, co-production or co-creation methods) target the social processes of learning and cooperating among stakeholders and possibly researchers (Anderson & McLachlan, 2016; Cornwall, 2008; Watson, 2014). Analytical methods, in turn, support the identification of suitable options or adaptation pathways in those situations in which it is not obvious what to do. They do so by helping to identify options that perform best or well with regards to the preferences of the stakeholders. Towards this end, each option is characterized by one or several criteria, which measure any relevant social, ecological, or economic value associated with choosing and implementing the alternative (Kleindorfer et al., 1993). Criteria commonly used in the coastal adaptation domain include cost of options, avoided damages, longevity of options, robustness of options, flexibility of options, social acceptance, etc.

3.2 Common characteristics of coastal adaptation decisions

Coast adaptation decision making is challenging due to the following characteristics:

Diversity of fundamentally different measures. Section 2.1 highlighted that there are four fundamentally different ways to respond to SLR (protect, accommodate, advance and retreat), with each way having advantages and disadvantages. In addition, each of these categories entails many measures, which again come with their own advantages and disadvantages.

Multiple objectives and trade-offs. Whatever approach to coastal adaptation is taken, the choice and planning of adaptation pathways generally needs to consider multiple objectives. Adaptation policy is not only about SLR and flood risk but also needs to consider many other policy objectives such as socioeconomic development, human safety, biodiversity, water quality, etc., as well as the numerous human activities that coastal systems support including shipping, agriculture, aquaculture, tourism, fishing, etc. Therefore, there is generally no single "best" solution that satisfies all objectives. Instead, coastal adaptation decisions are characterized by trade-offs. For example, restoring wetlands for coastal protection and biodiversity reduces space available for industrial or urban land use.

Diverse interests and social conflict. Coastal decisions are generally not only characterized by multiple objectives, but also by diverse and often conflicting interests of stakeholders involved in, and affected by the decision, which gives rise to social conflicts (Hinkel et al., 2018; Oppenheimer et al., 2019). For example, home owners or tourism operators may prefer not to have dikes in front of their homes if these jeopardize the view on the beach. As a consequence, stakeholders generally disagree on how to rank objectives or on which criteria to apply for measuring progress towards objectives (see Bisaro et al., 2024 for governance arrangements, e.g. Marine Spatial Planning, to addresses diverse interests in coastal adaptation).

Long-time horizons. Many coastal decisions involve adaptation measures with long lead and life times (Haasnoot et al., 2020). For example, coastal protection infrastructure such as dikes, seawalls and breakwaters usually involve decision horizons of 30 to 100 years and more (Burcharth et al., 2014) and major protection infrastructure such as storm surge barriers generally take decades to plan and implement and hence may be built for even longer lifetimes (Gilbert & Horner, 1986). Similarly, land-use planning, coastal risk zoning and coastal realignment decisions (Hino et al., 2017) may have effects that last several decades extending to over a century.

Large and deep uncertainties. The long-time horizons involved in some coastal adaptation decisions are specifically challenging due to the large and deep uncertainties involved in long-term projections (i.e. 50 years and more) of SLR. Deep uncertainty means that SLR experts cannot attach a single unambiguous probability distribution to future SLR, because they can't agree on an unambiguous method for deriving probabilities, or their subjective probability judgments differ (Kwakkel et al., 2010; Lempert and Schlesinger, 2001; Weaver et al., 2013). Projections of long-term SLR and other climate change variables are generally deep, because these depend on emissions scenarios. But also within a given emission scenario, uncertainty is large. For example, according to the latest IPCC Report, there is a 65% chance that sea-levels will rise by 0.6 to 1.0 m until 2100 under all emissions scenarios considered, with rises of up to 1.6 meters or more also being possible (Fox-Kemper et al., 2021).

3.3 Considering multiple criteria and interests

Given the multi-objective and social conflict nature of coastal decisions described above, participatory methods and multi-criteria decision analysis methods (MCA) can support most coastal decisions. MCA methods are standard methods for addressing multiple-objective problems. These methods help stakeholders to structure the process of decision making into a series of steps, to identify their preferences, and to choose an option that is consistent with those preferences (Cinelli et al., 2020; Greco et al., 2016). For example, the MCA method called Analytical Hierarchy Process guides stakeholders through a pairwise comparisons of criteria in order to transform their preferences into weights for aggregating criteria into a single score for each option (Saaty, 1980). MCA methods have been applied widely in a coastal context (Townend et al., 2021; Le Cozannet et al., 2013; Hinkel et al., 2023). These methods are also an integral part of many decision making tools such as dynamic adaptation policy pathway (DAPP) analysis (Haasnoot et al., 2013), to which we will return later below.

MCA methods can, to some extent, also contribute to addressing social conflicts, for example, by supporting the analytic search for compromises between stakeholders' divergent preferences (Munda, G., 2008), but the suite of available participatory methods entails much more, also beyond those methods that have a more analytical focus. Examples of such approaches include climate risk narratives (Jack et al., 2020), anticipatory learning (Tschakert and Dietrich, 2010), Living labs (Bergvall-Kåreborn and Ståhlbröst, 2009), citizens' juries, planning cells and consensus conferences (Escobar and Elstub, 2017). Generally, the normative literature on adaptation suggests that any analytical method for supporting adaptation should be embedded in a participatory process that includes all stakeholders in order to build trust, enhance legitimacy, reduce social conflicts, and advances fairness and justice (Michels and De Graaf, 2010; Callahan, 2007; Irvin and Stansbury, 2004).

It is important to note that participation is not an automatic automatically a key to success. A growing empirical literature that describes how adaptation processes play out in practice, shows that participatory processes often fail to deliver, either because they are poorly designed and implemented, conflicts cannot be overcome or interests of powerful actors dominate outcomes (Harman et al., 2013; Hinkel et al., 2018; Oppenheimer et al., 2019). This resonates with a larger empirical literature in the field of public participation, which has found that many participatory processes are tokenisms, in which the have-nots are informed or heard but the power-holders retain the right to decide (Hoppe, 2011; White, 1996; Arnstein, 1969).

Two conclusions can be drawn from this discrepancy between the normative and descriptive literature. First, more empirical work is needed for understanding under which conditions participatory adaptation processes deliver. Second, it needs to be acknowledged that participation cannot solve all problems, in particular not those related to power asymmetries rooted deeply in social structure.

3.4 Implementation of low regret measures

One immediate and generally recognized priority in coastal adaptation is the implementation of no or low regret measures. What this means in practice depends on the context, but generally this includes generic accommodation measures such as awareness raising, emergency planning and early warning systems (Lumbroso et al., 2017). The strength of these measures is that they have high benefit-cost ratios over short time horizons, which means that implementing them today produces almost immediate net benefits (Oppenheimer et al., 2019). Early warning systems have one of the highest benefit-cost ratios and should be a universal response (Rogers and Tsirkunov, 2010). However, these measures alone are only effective for current conditions, and small rises in sea level and therefore need to be combined and/or replaced with other approaches if SLRs substantially.

Other low regret measures can be found in addressing the local drivers of relative SLR and coastal hazards. These may include: (1) the preservation of coastal wetlands to reduce both surge and wave impacts, as well as the maintenance of sufficient accommodation space for these to migrate inland with SLR; (2) the maintenance of natural sediment supply by reducing dam building in rivers, which in turn reduces the risk of wetland loss and erosion; and (3) reducing anthropogenic drivers of subsidence and building land elevation with natural processes (Nicholls et al., 2021).

Retreat is generally not a low regret measure for densely populated and heavily used coastal areas, but it may be for rural areas if sufficient space is available to convert dry land into coastal wetlands that contributes to coastal protection. In the aftermath of disaster, retreat may also become low regret for more densely populated zones when reconstructing livelihoods in situ may be as costly as relocating. After Superstorm Sandy, for example, a number of flooded formerly developed areas around New York were purchased and not rebuilt, although this was a reactive rather than proactive response (Braamskamp & Penning-Rowsell, 2018). In Europe, one example of retreat happening after a disaster is the the storm Xynthia, which hit the French Atlantic Coast in February 2010, killing 47 people and causing a total damage of about 1.5 billion Euros, which lead to the decision to relocate some houses and neighbourhoods (Rouhaud, & Vanderlinden, 2022). It must, however, be noted that part of this decision was later taken back due to strong civil opposition, which illustrates the difficult and socially contested nature of coastal retreat in general (Hino, et al., 2017).

3.5 Keeping future options open

Given the large uncertainty about by how much sea levels will rise in the coming decades, an important policy priority is to keep future options open (Hinkel et al., 2019; Hallegatte, 2009). One way to do this is to postpone long-term decisions that do not need to be made today. Many decisions about retreating from the shoreline, in particular for urban areas, fall under this category (Oppenheimer et al., 2019). While SLR may rise by multiple meters, posing existential threats to coastal zones, there is also a substantial chance that SLR may stay below 30 cm by 2100 (50^{th} percentile of SPP1-1.9) if the Paris Goals are reached. Protecting coasts to the latter amount of SLR is economically efficient and relatively cheap for about 90% of the global population, as coastal population tends to be concentrated in coastal urban areas making up about 10% of the global coastline (Hinkel et al., 2018; Lincke & Hinkel, 2018; Tiggeloven et al., 2020; Vousdoukas et al., 2020). Hence, a practical strategy for urban areas is to wait and observe how SLR observations and projections develop over the next decades, providing a robust basis for retreat versus protect decisions (Hinkel et al., 2019).

Another way of keeping future options open is by implementing flexible options that can be upgraded or changed over time once more is known about future SLR. This is generally an argument in favour of implementing soft and sediment-based measures such as NbS instead of hard measures, because the former can either self-adjust to relative SLR (in the case of coastal wetlands, see Box 2) or can easily be adjusted (in the case of sediment nourishment). However, flexibility can also be built into hard infrastructure. For example, in Germany's new coastal dikes are built with a wider crest than necessary today, which allows further raising at low costs if SLR turns out to be higher than originally anticipated (MELUR-SH, 2012).

Both postponing the decision and building flexibility into current options, raise questions of timing: By how much shall a decision be postponed or how much flexibility should be built in. These questions can be addressed from an economic point of view by a class of methods termed real-option analysis (ROA), which are covered in the next subsection.

3.6 Factoring SLR into decisions that need to be made today

Some long-term decisions cannot be postponed and need to be made today. This may include decisions related to critical infrastructure, urban renewal, inadequate coastal protection, land use planning and land reclamation. As these and similar decisions have time horizons of decades to over a century (Azevedo de Almeida and Mostafavi, 2016; Haasnoot et al., 2020), factoring SLR into such decisions is beneficial. A range of analytical methods for supporting these kinds of decisions exists.

One classical set of methods for decision making under deep uncertainty (i.e. without probabilities) is ***robust decision-making***, which refers to a range of methods that identify adaptation measures that are effective under a wide range of scenarios (Heal and Millner, 2014; Lempert and Schlesinger, 2001; Wilby and Dessai, 2010). This includes so-called exploratory modeling, which uses models to create large ensemble of plausible future scenarios, and then search and visualization techniques to identify robust options (Lempert and Schlesinger, 2000). RDM also includes methods that follow similar ideas such as robust optimization (Ben-Tal et al., 2009), info gap theory (Ben-Haim, 2006), and classical approaches such as minimax and minimax regret (Savage, 1951). The latter approaches (i.e., minimax or minimax regret) are simple and low burden to apply and constitute a useful addition to, e.g., standard cost-benefit analysis carried out for different sea-level rise scenarios (van der Pol et al., 2021). The more complex approaches such as exploratory modelling and robust optimisation are generally applied in the context of expensive coastal infrastructure project, such as upgrading the Port of LA (Sriver et al., 2018).

Another set of analytical methods for long-term decision making under SLR is found in the so-called ***adaptative decision making*** methods. These methods are suitable if adaptation decisions are not taken as single-shot decision today, but as sequences of decisions at several moments in time, a situation frequently found in the coastal adaptation context. These methods aim at finding adaptation measures that are robust against a wide range of futures in that they are flexible to allow adjustments over time once more about SLR is known (New et. al, 2022; Marchau et al., 2019).

Broadly, two categories of analytical ADM approaches exist (Völz, & Hinkel, 2023b). A first category of these methods starts with a user-defined a set of adaptation options and then analysis how these options can be sequenced over time under different scenarios (e.g. SLR) in order to achieve the desired objectives (Walker et al., 2001). A widely used tool for such adaptive planning is adaptation pathway analysis (Haasnoot et al., 2013; 2012), which graphically explores how available adaptation measures can be sequenced over time, in order to reach adaptation goals. This analysis also considers the lead times of adaptation measures (i.e. the time needed for planning and implementing adaptation measures), because rapid SLR may lead to insufficient time being left to plan and implement measurers with long lead times, such as surge barriers, as these usually take decades to plan and implement (Haasnoot et al., 2020). A prominent example for which this approach has been applied is the Thames Barrier in the UK, which protects the city of London. Within the Thames Estuary 2100 project, adaptation pathway analysis has been applied, next to other approaches, in order to find out if there is sufficient time to upgrade or replace the Thames Barrier under a rapid acceleration of SLR (Ranger et al., 2013).

The second category consists of ***economic ADM approaches****,* which that identify optimal adaptation decision rules taking into account information about what will be learned in the future about the development of key climate variables. These methods are often found under the labels of real-option analysis (Wreford et al., 2020)) and optimal control studies (Hermans et al., 2020). Importantly, these methods consider future learning about relevant variables (e.g., mean and extreme sea levels) in the economic valuation of adaptation measures in order to find optimal trade-offs between investing today, including the cost of flexible design, versus postponing investment decisions until additional information is available (Dixit and Pindyck, 1994). Hence, these methods can provide justifications whether implementing flexible adaptation measures today are worth the extra costs. This is specifically relevant for public decisions that involve expensive and long-lasting infrastructure, as found in coasts, because the public sector needs to justify that public money is spent wisely. While ROA applications of adaptation to coastal and river floods are growing (Dawson et al., 2018; Kim et al., 2019; Hino and Hall, 2017; Linquiti and Vonortas, 2012; Woodward et al., 2011, 2014; Ryu et al., 2018) to date they are poorly connected to state-of-the-art SLR science. First steps towards closing this gap have been taken by Völz and Hinkel (Völz & Hinkel, 2023b), who developed SLR learning scenarios based on the SLR scenarios of IPCC AR6.

A critical and difficult decision that needs to be taken in the application of all of the above-mentioned decision analysis methods is how much SLR should be considered in a particular decision. Importantly, sea-level science can only give a partial answer to this question, because the other part of the answer depends on the uncertainty preferences of the stakeholders involved and affected by the decisions. When stakeholders are uncertainty tolerant and the value at risk is relatively low, then the "standard" IPCC scenarios, which provide a so-called *likely* range of possible future

SLR, are a good basis for decision making (Oppenheimer et al., 2019). If stakeholders are less tolerant of uncertainties, which is often the case in urban contexts, then higher SLR scenarios should also be considered. This is because the IPCC *likely* range is the 66% central interval of future SLR, which means there is a 17% chance of SLR exceeding the likely range, which may be too large a chance for uncertainty-averse stakeholders (J. Hinkel et al., 2015; Nicholls et al., 2021a). In this case, more unlikely SLR scenarios should be considered, with the exact choice depending on the stakeholders in the specific case. IPCC AR6, for example, states that in the case of unlikely, but rapid melting of the ice sheets, a 2 m rise in sea level by 2100 cannot be excluded under an unabated emissions scenario (SPP5-8.5) (Fox-Kemper et al., 2021).

3.7 Revisiting decisions iteratively and monitoring

No matter which decision analytical method applied, a final and critical priority is to set up an iterative policy/decision making process that regular revisits decisions and includes a monitoring framework, through which SLR and other relevant variables are monitored and appropriate action can be triggered if a relevant threshold is crossed (Walker et al., 2001, 2013). The concept is to implement no/low regret options and flexible measures today and then monitor SLR, ESL and other decision relevant variables in order to be able to identify when decisions and new policies are required. Importantly, a monitoring system is essential to identify the need for action in sufficiently early time to allow planning and implementation before negative impacts occur (Hermans et al., 2017). One well known framework that entails this idea (and combines it with adaptation pathway analysis covered in the last subsection) is Dynamic Adaptive Policy Pathways (Haasnoot et al., 2013). This method has been widely applied in various context and has, for example, been integrated into the national guidance for coastal hazard and climate change decision making in New Zealand (Lawrence et al., 2018).

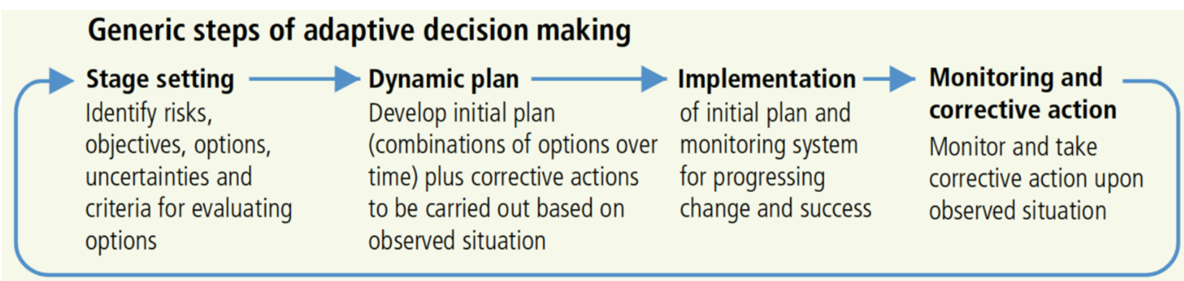


Figure 6: The adaptative decision making cycle
Source: Original figure SPM.5 in Pörtner, H. O. (Ed). 2019. Summary for Policymakers, in: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. (Pörtner et al., 2019)

4. Summary: key developments per basin

Adaptation to SLR in Europe has been approached through various types of measures to accommodate, protect, advance and retreat. Adaptation strategies on Europe's coasts thus constitute a mix of hard and soft measures, planning measures, policy developments, and stakeholder and community engagements. Below, we summarise the main developments organized by the different sea basins.

In the Baltic Sea Basin, for accommodation measures, progress has been made with several Baltic nations incorporating SLR projections into their spatial planning and land-use regulations. Notably, Estonia has implemented a Maritime Spatial Plan for 2022 that integrates SLR information. In terms of protection measures, upgrading coastal defences, e.g. with sea walls, embankments, and dykes has been implemented, while nature-based solutions initiatives to restore and create wetlands and coastal marshes that can act as buffer zones and reduce wave energy are also underway. For instance, the Danish Baltic coast provides the first large-scale example of successful managed realignment with the restored Gyldensteen Coastal Lagoon, which has to date enhanced ecological status and species richness in the project area (Thorsen et al., 2021). The Baltic Sea Basin as also seen progress on marine environment conservation, which can potential enhance living marine resources, and related fishing activities. Key to furthering coastal adaptation in the basin is ensure that solutions are also linked to financing mechanisms that can mobilise co-finance, e.g. from the private sector, that can supplement national public funding.

In the North Sea Basin, SLR information has been integrated into coastal planning at national and sub-national levels in most countries, while North Sea Basin countries are implementing different mixes of hard and soft protection measures. In the Netherlands, the Delta Programme includes a comprehensive mix of measures to maintain a healthy groundwater system, using spatial planning and other context-specific strategies, while providing more space for water and enhancing urban and ecological values. Sand nourishment is also growing in importance as a coastal protection measure in the Netherlands, alongside dike upgrading and reinforcement. In Germany, there is an emphasis on integrated coastal zone management and dike upgrading and widening that incorporates flexibility for future SLR. In the UK, a mix of protection, beach nourishment and managed retreat, are being considered for different portions of the coastline. These countries each reflect different approaches to addressing uncertainty that should be iterated and revisited as more information on SLR becomes available in future.

In the Mediterranean Sea Basin, key developments include the mainstreaming of SLR information into planning through the development of national adaptation plans, e.g. in Spain and Italy. Further, insurance is emerging as an accommodation measure to address SLR-related risks, e.g., in Spain and France. Soft protection measures, such as, sand nourishment and nature-based solutions more broadly are important in the Mediterranean Sea Basin, with coastal reforestation and the restoration of dunes and marshes implemented in various regions to act as natural barriers. Another example is cliff strengthening and stabilisation measures that include green and grey options focussing on reducing erosion and enhancing natural protection along coastal cliffs, e.g. in Croatia and Italy. Several major urban areas in the basin have initiated large-scale adaptation measures. For example, the Venice MOSE project is a system of mobile barriers constructed to protect Venice from high tides and flooding, while the city of Barcelona has introduced green infrastructure projects that focus on permeability and water retention to combat both SLR and increased rainfall. Such differentiated measures appropriate to the specific biophysical and socio-economic context at issue should be further supported through participatory co-development approaches to coastal decision-making (Bisaro et al., 2024).

In the Black Sea Basin, there is an increased emphasis on developing monitoring and early warning systems to help manage SLR and associated flood risks. Further, efforts have focused on upgrading and modernizing existing coastal infrastructure to enhance resilience to rising sea levels. For example, in Romania, a major initiative combining sand nourishment and cliff stabilisation with marine measures including artificial reef building is being implemented to reduce coastal erosion risks exacerbated by SLR and enhance resilience in the tourism sector. Further, implementation of such nature-based solutions that also benefit local economies are promising and should be explored for scaling-up coastal adaptation in the basin.

In the Atlantic Ocean Basin, countries are implementing a range of adaptation measures, with an emerging focus on nature-based solutions and improved spatial planning to reduce risks to coastal development across the entire basin. Soft protection measures, such as cliff strengthening and sand nourishment, are being implemented in Portugal, while restoration measures, protecting against wave energy and therefore limiting erosion and sediment accumulation, are being implemented in Spain, Portugal, and France. Advance strategies are also being implemented through nature-based solution approaches, as in Spain, the national adaptation plan envisions the regeneration of beaches and artificial dune systems to reduce erosion and revitalise coastal ecosystems, e.g. in the restoration one of the largest dune systems of the Cantabrian Sea. Further, in France, coastal land in the southwest of the country has been advanced with the creation of a vegetated area with the specific intention to support natural accretion of land and surrounding low areas. Finally, retreat measures are also being implemented, as in Portugal, the progressive removal of constructions located in flood-critical territories along the coastline is being implemented through spatial planning instruments to manage the risk of SLR.

Across all basins, a common theme is the shift towards a combination of traditional engineering solutions with soft measures, including nature-based solutions. Integrating local communities into decision-making processes and emphasizing the importance of continuous monitoring and flexible management strategies, e.g., through the coastal planning instruments, such as Marine Spatial Plans (see 'Sea Level Rise in Europe: Governance Context and Challenges') and other adaptation decision-making methods discussed above, are also notable trends. To ensure that these trends lead to finding appropriate mixes of coastal adaptation measures depends on continued support and involvement of public and private sector stakeholders for effective multilevel governance.

Conclusions

This paper has conducted a review of literature on coastal adaptation and analysed seventeen adaptation measures targeting climate impacts, such as coastal flooding, saltwater intrusion, coastal erosion, and impacts on ecosystems and estuaries. Some examples of coastal adaptation measures that have been discussed are: early warning systems, insurance and policy instruments, hard and soft defences, nature-based adaptation measures, new raised ports, and planned relocation. At the sea basin level, Baltic countries are incorporating SLR projections into their spatial planning and land-use regulations, and progress has also been made on marine environment conservation. In the North Sea Basin, SLR information has been integrated into coastal planning at national and sub-national levels in most countries, and countries are implementing different mixes of hard and soft protection measures. In the Mediterranean Sea Basin, SLR information is being mainstreamed through the development of national adaptation plans. Prominent protection measures are coastal reforestation and dunes and marsh restoration, while insurance is emerging as an accommodation measure. In the Black Sea Basin, emphasis is on early warning systems, and upgrading and modernizing existing coastal infrastructure to enhance resilience. In the Atlantic Ocean Basin, an emerging focus of adaptation measures is on nature-based solutions and improved spatial planning. In addition, the measures discussed in this paper are generally subject to trade-offs that should be considered when planning for coastal adaptation. In order to accurately analyse existing trade-offs, it is important to understand the effectiveness and feasibility of these measures. Future research can expand the literature review to include more studies, and more research is needed to learn about the trade-offs of implementing each of these measures as well.

The approaches for decision-making uncovered that coastal adaptation is a complex undertaking, given the large amount of possible and diverse adaptation measures available, as well as the equally large set of participatory and analytical methods available for supporting this process. Furthermore, context and decisions to be taken, as well as experience in coastal adaptation, differ significantly from place to place and region to region across Europe. Whereas Northern Europe, and also some parts of Southern Europe such as the Po Delta, have been protected against the sea for decades to century and have a long experience adapting to relative SLR, for most of Southern Europe, coastal adaptation is a new necessity. Across both context, decisions differ in terms of the time horizons considered, the size of investments involved, as well as the preferences decision makers and their constituencies have towards accepting risk. For all of these diverse situations, analytical tools are available to support decision making, ranging from relatively low burden tools such as adaptation pathway analysis and multi-criteria analysis to technically sophisticated methods such as robust decision making and real-options analysis.

Regarding the participatory approaches for supporting decisions, which were not the focus of this paper, it can nevertheless be concluded that there is a large discrepancy between the normative and descriptive literature: While there are many papers and guidelines available recommending what there is to do, the empirical evidence on whether this works in practise is relatively thin. Hence, more empirical work is needed for understanding under which conditions participatory adaptation processes deliver. But even if we learn more about what works and what does not work in practise, it needs to be acknowledged that participative methods cannot solve all problems, in particular not those related to power asymmetries rooted deeply in society.

Author contributions

GG, JH, EFB, SB and RBA wrote the paper with text contributions from OE, and MFC. ATV wrote the box of the Wadden Sea and PC the box of the MOSE system in Venice. All authors participated in the iterations and revisions of the paper. BvdH was the handling Editor.

Competing interest

The contact author has declared that none of the authors has any competing interests.

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