https://doi.org/10.5194/sp-2023-35
Preprint. Discussion started: 15 January 2024

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. This chapter aims to provide guidance for the design and implementation of adaptation policies in European basins, and does so by, first, assessing the state-of-the-art of SLR adaptation measures in Europe, and second, presenting approaches suitable for supporting coastal adaptation decision making and addressing uncertainty. Assessment of SLR adaptation in Europe is carried out by developing a typology of measures based on the IPCC classification of *accommodate, protect, advance,* and *retreat* responses to SLR, supplemented with sub-types measures socio-economic, physical and technological, nature- and ecosystem-based characteristics. Surveying relevant literature measures being implemented in Europe are identified and characterised according to their effectiveness and location within the European sea basins. We find that adaptation strategies on 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. 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. Finally, coastal adaptation decision-making literature is then review and provides an overview of the common characteristics of coastal adaptation decisions and key aspects 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 made today, and revisiting decisions iteratively and monitoring.

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1 Introduction

By 2050, one billion people in low-lying areas will be critically exposed to natural hazards (Merkens et al., 2016). Coastlines all around the world are witnessing an increase in the intensity and frequency of coastal flooding due to extreme weather events and sea level rise, leading to significant environmental and socio-economic damages. A major socioeconomic and environmental concern for many countries is *how* to enhance coastal resilience and reduce exposure to coastal flooding. Traditional engineering solutions, here referred to as grey options, have dominated thinking and practice in coastal protection for several decades (Sancho, 2023). However, there is an increasing body of scientific evidence proving that context-adjusted nature- and ecosystem- based solutions (i.e. green and blue options) can similarly reduce the risk of coastal flooding and erosion induced by sea level rise (Kuwae & Crooks, 2021). This chapter first presents in Section 2.1 a state-of-the-art of Sea Level Rise (SLR) adaptation measures in Europe and aims to provide guidance for the design and implementation of adaptation policies in European basins encompassing grey, green, blue options as well as hybrid solutions. The chapter subsequently presents approaches suitable for supporting coastal adaptation decision making and addressing uncertainty in Section 2.2. Boxes have been inserted to highlight specific examples in more in-depth.

This overview of coastal adaptation measures is developed by reviewing the literature on coastal adaptation and categorising them through frameworks developed by the IPCC and EEA. The IPCC's framework facilitates climate action against sea level rise and guides countries in designing effective adaptation strategies by identifying four types of responses to sea level rise: *(i) accommodate, (ii) protect, (iii) advance*, and *(iv) retreat* (Oppenheimer et al., 2019). These responses aim to find ways to adapt to natural hazards by reducing risks, exposure, and vulnerability in low-lying coastal areas through climate action. The European Environment Agency (EEA) developed the Key Type of Measures for Adaptation to Climate Change which 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 combination of these two frameworks enables one to effectively categorise and specify the characteristics of each identified measure.

As for the methodology, an extensive scientific literature review was carried out, consisting of 206 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. First, using Web of Science Core Collection using 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 sea level rise. The search provided 140 articles. Second, identifying grey literature including 41 strategies, management and adaptation plans from different countries, regions, and cities as well as 25 others sectoral reports and documents.

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2.1 Adaptation measures

2.1.1 Types of responses to sea level rise

Table 1 is the main outcome of the literature review. It gathers and categorises 16 adaptation measures to sea level rise identified and discussed in over 200 published documents focusing on European sea basins and targeting four climate impacts (see 'Sea Level Rise in Europe: impacts and consequences'): *coastal flooding, saltwater intrusion, coastal erosion* and *impacts on ecosystem and estuaries.* The table lists the identified measures all of which aim at reducing exposure and vulnerability and at strengthening local adaptive capacities to build resilient coastal communities. It provides information on the adaptation measure, the type of response, the sub-key type of measure (sub-KTM), the sea basin where the measure has been implemented, the impact, and the references.

The table thus provides an overview of the current coastal adaptation measures in Europe that can inform the development of coastal adaptation policies in other contexts. It should however be noted that clear cuts in categorising measures are sometimes difficult to make, as the adaptation measures identified in the table can often be implemented at different levels of governance and different spatial scales (see 'Sea Level Rise in Europe: Governance Context and Challenges'). Further, some measures may in practice include activities across multiple sub-KTM and even combine multiple types of responses. For example, advance measures, such as urban land raising may be appropriately combined with accommodation measures, such as, improved building codes in order to effectively reduce coastal risks (e.g. see Hamburg Hafen City (Bisaro et al., 2020). The measures were classified based on the primary response and sub-KTM they addressed.

The top-level categorisation of adaptation measure presented in Table 1 is along the four main types of responses to sea level rise. First, *accommodation* measures 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. Advance measures also refer to measures that preserve sediment flow and support local ecosystems such as beach and shoreface nourishment and lagoon dredging. These approaches include nature- and ecosystem-based solutions for coastal adaptation. Lastly, *retreat* measures involve relocating human activities and infrastructure away from high-risk coastal areas to less vulnerable ones.

Table 1 further categorises adaptation measures 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 'Sea Level Rise in Europe: Governance Context and Challenges'), Economic and Finance (financing and incentive instruments; insurance and risk sharing instruments), Physical and Technological (grey options;

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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).

Although the literature examines in depth each type of response to sea level rise, accommodation measures are the most widely identified, 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.

Table 1: Adaptation measures to sea level rise.

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	Restricting new developments in flood prone areas	Management and planning	North Sea	All	(Ministerie van Infrastructuur en Waterstaat, 2023); (Oppenheimer et al., 2019)
	6	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)
	7	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);

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						(Netherlands Sovereign Green Bond, 2019)
	8	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).
	9	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)
	10	Develop a risk culture within the population	Information and awareness raising	Baltic Sea, Eastern Atlantic, Mediterranean Sea	Coastal flooding	(Zeng et al., 2020); (Xiang et al., 2019); (Stelljes et al., 2018)
Protect	11	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)
	12	Soft defence 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)
	13	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)
Advance	14	Rising and advancing coastal land	Green options	North Sea, Eastern Atlantic	Coastal flooding, coastal erosion, impacts on ecosystems and estuaries	(Van Den Hoven et al., 2022); (ClimateAdapt, 2016b); (Moraes et al., 2022); (Laporte-Fauret et al., 2021); (Bisaro, A., 2019)); (Schuerch et al., 2018); (Estrategia de Adaptación al Cambio

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						Climático de La Costa Española, 2016)
	15	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)
Retreat	16	Planned relocation	Management and planning	Eastern Atlantic, Mediterranean 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)

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 sea level rise. 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

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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. Box 9 on 'Climate change impacts and adaptation: status and challenges for the Spanish Ports system' (see 'Sea Level Rise in Europe: governance context and challenges') provides an example of government-led Ports of Spain which manages 28 ports in the country and 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. 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 can act as a natural buffer against coastal flooding and protect coastal areas (Ward et al., 2020). In turn, to increase overall adaptive capacity is important to improve the conservation of groundwater reservoirs, limit water use and optimise water reuse. In addition, adapting groundwater management must encourage the restoration and increase in the natural infiltration capacity of freshwater into the aquifer. 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). As stressed in the IPCC Special Report (Oppenheimer et al., 2019), this is of utmost importance as groundwater is an overexploited resource that is being used globally at an alarming and unsustainable rate. 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 sub-KTM management and planning also includes **sustainable fisheries and aquaculture management**. To date, future projections on sea level rise and their implications for fisheries and aquaculture are an understudied area. 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). Moreover, within studies that focus on climate-related drivers of fisheries and aquaculture, ocean warming and acidification are considered more influential than sea level rise (Oppenheimer et al., 2019). Nonetheless, in order to strengthen the adaptation capacity of coastal regions, the diversification of income sources to other economic activities could be a valuable adaptation measure (Payne et al., 2021).

Lastly, accommodation measures can be integrated in coastal zone management plans by **restricting new developments in flood prone areas** and defining setback zones to be included on territorial management documents, an example being the Dutch Freshwater Delta Programme that spatially restricts 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).

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 'Sea Level Rise in Europe: Governance Context and Challenges'). 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). For instance, Spain has identified specific insurance and reinsurance schemes as a necessity for risks specifically deriving from sea level rise in coastal areas (Estrategia de Adaptación al Cambio Climático de La Costa Española, 2016) and it developed two instruments: extraordinary risk insurance (which includes extraordinary floods and atypical cyclonic storm), which provides cover for insured goods and persons, and combined agricultural insurance. Governments are also getting to grips with the issue by funding post-disaster payments, 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).

Considering **climate change in credit risk and project finance assessment**s is an accommodation measure because it orients investors towards projects that enhance adaptation. Consideration of climate change in credit and finance assessments can thus mobilise financing specific projects against sea level rise 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 sea level rise 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

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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).

Another category of accommodation measures are coastal adaptation policy instruments. One example of such policy instruments is the **integration of sea level rise information in coastal adaptation strategies and plans**. Although most European national coastal adaptation plans include sea level rise they sometimes differ in the time horizons used (mid to end of the century) (Bednar-Friedl et al., 2022; McEvoy et al., 2021). Using only a single time horizon in planning, as opposed to multiple time horizons, can impact the effectiveness of adaptation strategies. For example, planning for a 0.5m versus a 2-meter increase in sea levels has significant practical consequences in terms of the area of land likely to be affected and the frequency and seriousness of the impacts (OECD, 2019). Adaptation measures at a large-scale often take a long time to implement, and if planning accounts only for the short term, they may no longer be adequate once applied (Bednar-Friedl et al., 2022). Coherent and long-term approaches are required for integrated and effective responses that involve major permeant interventions with have high investment costs (OECD, 2019). (Bednar-Friedl et al., 2022) identified a long-term gap in the case of Venice's adaptation pathways, as only the values under SSP1–2.6 and SSP5–8.5 were considered, without using intermediate scenarios. Thus 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). Spain provides an illustrative case and implements an adaptation policy since 2006. There is a single national document (Plan Nacional de Adaptacion al Cambio Climatico 2021-2030, 2020) that defines the main objectives and details 18 work areas in several lines of action, which are developed in a periodic 5-year work programme. One of the work areas is 'water resources', with lines of action on groundwater management, coordinated drought and flood management, and climate change risk monitoring (Plan Nacional de Adaptacion al Cambio Climatico 2021-2030, 2020). The PNACC is also integrated into a specific plan for coastal areas (Estrategia de Adaptación al Cambio Climático de La Costa Española, 2016).

Technological options include **early warning systems and flood preparedness**. Early warning systems can be considered as an accommodation measure as they allow people to remain in the hazard-prone area but help improve preparedness and response by providing advance warning (e.g. evacuation) in the face of imminent danger. 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

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expected sea level rise 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). On the other hand, perceived intractability of climate change hinders the desire to adopt low-carbon behaviours (Xiang et al., 2019).

ii) Protect

Protect measures in coastal management aim at reducing the risks and impacts of coastal hazards. These measures typically entail the construction of hard and soft defences (OECD, 2019). Protection measures also refer to restoration and management of coastal ecosystems. However, technical limits to protection measures are expected to be reached specifically under high emission scenarios (Oppenheimer et al., 2019).

Hard defence for coastal management includes 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. Some advantages of hard defences are that they have long-life spans, and their costs are reasonably well known and can be estimated. Moreover, hard defences are highly effective at protection, although, a recent study by Del-Rosal-Salido et al. interestingly investigates how sufficient flood defences will be throughout the 21st century. Particularly, they study when and where these are likely to fail, with a focus on Guadalete estuary, a representative case study for the coasts of southern Europe (Del-Rosal-Salido et al., 2021). In the specific case of raising dykes, there are also economic motivations linked to the cost-benefit ratio of investments. However, hard defences require a costly maintenance system, may cause severe 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 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).

One difference between hard and soft measures is their respective impacts on natural sedimentary dynamics and equipment reversibility (Buisson et al., 2012). **Soft defence for coastal management** includes different types of green, blue, and grey measures. Examples 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 (more detail in the sub-section on beach and shoreface nourishment below), cliff reshaping, drainage systems, and the use of anchoring

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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).

Restoration and management of coastal ecosystems are common green and blue options used as an alternative to traditional approaches. Coastal vegetated ecosystems and biogenic reefs can self-adapt to sea level rise 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 therefore limiting erosion and sediment accumulation.

iii) Advance

Raising and advancing coastal land has a long history of use to protect communities from natural hazards. Only recently has *advance* become a response to sea level rise 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. Often, advance measures are ecosystem-based as they frequently include 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). However, 'grey' land reclamation is also emerging 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 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). For instance, in southwest France the excavation of foredune notches re-established an ecomorphological dynamic promoting landward sand transport and foredune landward translation, without threatening biodiversity. 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). Other specific applications are dune grass planting to stabilise sand, encourage sand accretion and protect dune vegetation; dune fencing reduce wind speed on the surface and encourage foredune deposition of transported sediment, and different hybrid combinations of these (Laporte-Fauret et al., 2021).

Finally, **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 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

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and sometimes anthropogenic impact by the presence of defence structures (Buisson et al., 2012). In the literature, the difference between beach nourishment and shore surface 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). This is a widely used method in Eastern Atlantic Ocean, primarily Portugal (Mendes et al., 2021; Pinto et al., 2020; Sancho, 2023) where an extensive beach nourishment program was carried out in the framework of a coastal management master plan between 2007 and 2019. The programme placed 4.5 million m^3 of sand along 3.8 km northern shoreline (Sancho, 2023). 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 'Sea Level Rise in Europe: impacts and consequences'). In brief, the study showed that 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).

Beach nourishment has been applied more extensively in Europe since the 1990s. 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). Nourishment is a flexible and fast coastal management option that is adaptable to changing conditions. Further, the strategy remains 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 include the environmental impacts both in sediment extraction and at nourishment sites that include destruction of habitats, disruption of bird and other animal nesting, coverage and subsequent suffocation of benthic organisms, increase in water turbidity and shifts in median grain size and grain-size distribution depending on the chosen material. Further, large uncertainties in long-term ecological and geomorphological impacts of nourishment remain. As beach nourishment does not halt erosion it can be argued that beach nourishment is not sustainable as a measure to adapt sea level rise-induced coastal erosion in the long term (Staudt et al., 2021).

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

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wide range of measures. mostly categorised as management and planning (i.e. planned relocation) and information and awareness raising (i.e. development of a risk culture). Retreat measures have been implemented in various European sea basins, for example in the Eastern Atlantic Ocean, the Baltic Sea, and the Mediterranean Sea. The measures address coastal flooding, erosion and ecosystem and estuaries.

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 to re-align 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 sea-level rise, including the progressive removal of constructions that are located in flood-critical territories along the coastline through spatial planning instruments (Government of Portugal, 2021). 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 (Schuerch et al., 2018; Van Den Hoven et al., 2022). 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 five years into the project the ecological status improved and species richness increased (Thorsen et al., 2021).

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

On the 4th of November 1966, an extreme and unexpected meteorological event caused disasters in Venice, where the level of water touched 194 cm over the "historical" mean sea level and remained above 110 cm for 22 hours. The world felt the fear of losing Venice forever. A few years later, the 16/4/1973 the Italian Parliament promulgated the first Special Law for Venice, which declared the protection of Venice and its lagoon of "primary national interest".

From that date, the frequency of city flooding increased, passing from 30 per decade up to 95, which occurred between 2010 and 2019 (Fig. 1).

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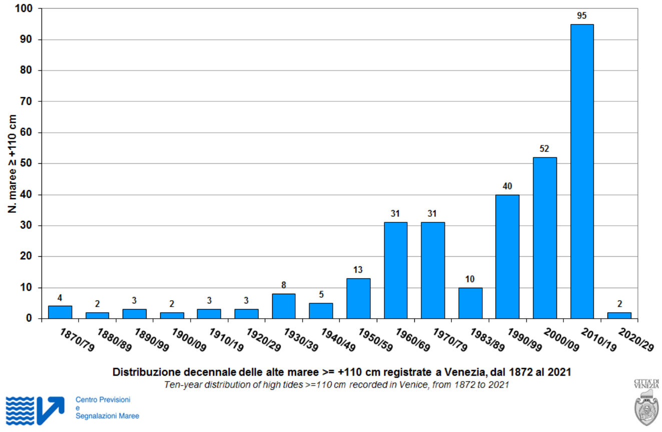

Figure 1 Number of city flooding events in Venice per decade. The distribution indicates the number of events with a sea level higher than 110 cm (The original source of this figure is Municipality of Venice- *Centro Previsioni e Segnalazioni maree).*

After a long period of discussions, prototype testing, and design revisions, the construction of the MOSE barriers started in 2003 and the MOSE was operational for the first time on the 3rd of October 2020, effectively protecting the Venice centre and all the lagoon settlements.

The MOSE barriers are essential parts of a much wider safeguarding approach, that includes littoral island defence, adaptation measures in urban settlements, ecological end morphological restoration in the lagoon (the largest in the Mediterranean Sea, approximately 550 km^2), de-pollution and defence measures in the lagoon drainage basin (2.068 km^2).

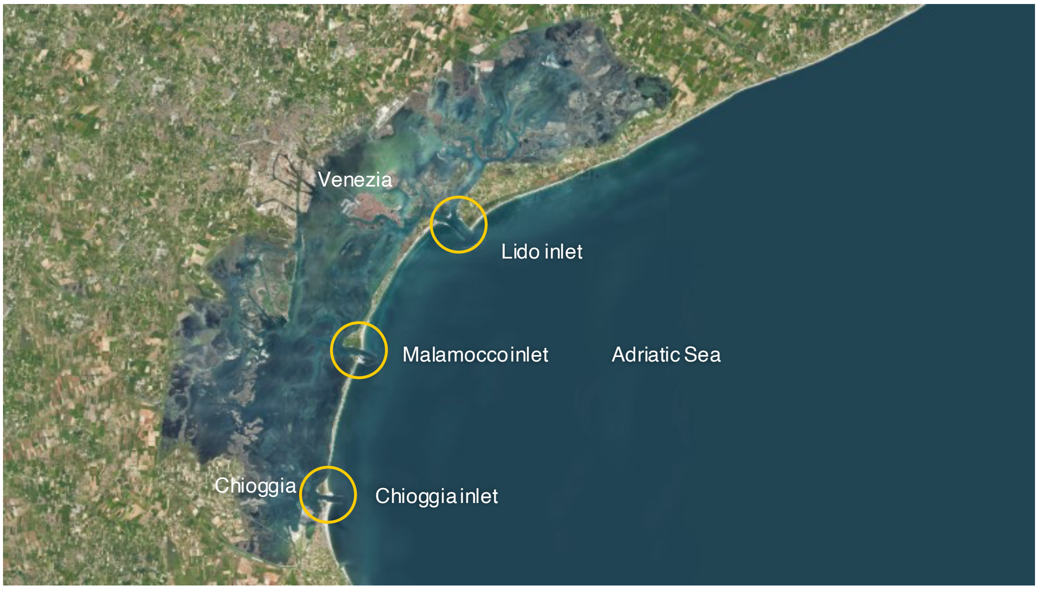

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Figure 2 The lagoon of Venice and its three inlets (The original source of this figure is: Courtesy of Consorzio Venezia Nuova- Concessionary of Ministry of Infrastructure of Italy)

Indeed, 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 limit the Venice lagoon from the Adriatic Sea, when the lagoon was formed around 6.000 years ago, were made of sand banks. But already seven centuries ago, the necessity of protecting the littoral settlements from the sea storms urged the Venice Republic to organize a complex system of defence made of wood poles ("palade"), coming from the forest of the Dolomites floating on the rivers, that was constantly (and costly) renovated. In the XVIII century, this defence was substituted by massive stone seawalls placed on the shore in front of the sea ("murazzi").
In recent years, from 2000 onwards, the ancient seawalls were repaired and reinforced by a new shore, in gyrons, realized in front of them, with the sand taken from the Adriatic. It is the largest "confined" sand nourishment that occurs in Europe (Fig. 3).

Figure 3 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 inlets can provide a complete closure of the lagoon from the sea, for a total of 1,56 km length, divided into 4 arrows. They can guarantee a 2m difference between the lagoon and the sea level offshore, i.e. to maintain the level of the lagoon at the safe quote of 100 cm on the m.s.l., with storms events up to 300 cm (the maximum measured event ever is 204cm).
Each of the 78 floodgates is 20m wide and its lengths vary in dependence on the depths of the four inlets.
They normally lie inside big concrete caissons placed on the bottom of the sea, connected to them at two hinges in one extremity, and are filled by water. For closing the barrier, the air is pushed inside the gates using compressors, so they can float at the desired angle, for realizing the closure. Each gate floats independently from the others, to avoid the risk of stress concentration that a single, longer barrier might have experienced (Fig. 4).

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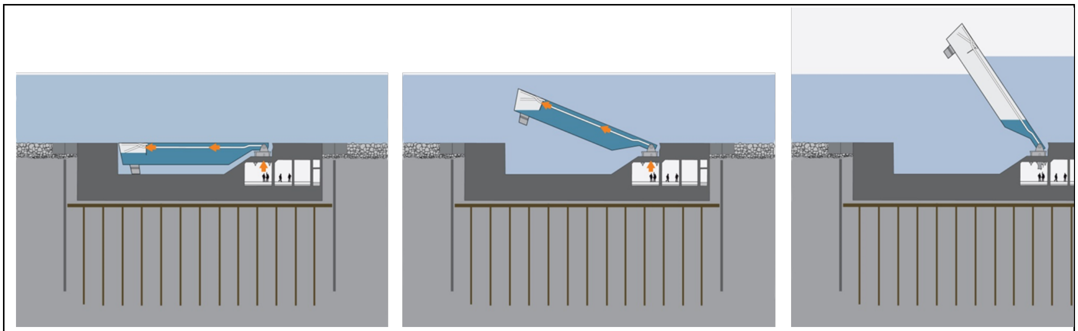

Figure 4 MOSE barriers' functioning scheme (The original source of this figure is: Courtesy of Consorzio Venezia Nuova- Concessionary of Ministry of Infrastructure of Italy)

Figure 5 MOSE barrier closes the Lido inlet (S.Nicolò side), during a test (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 the 3rd of October 2020, and in the first three winters operated 50 times, effectively saving Venice from floodings, including some severe ones (Fig. 6 and 7).

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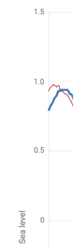

Figure 6 The MOSE barriers in Lido, during a storm, the 15/11/2020. In the picture, the sea on the left, the lagoon on the right

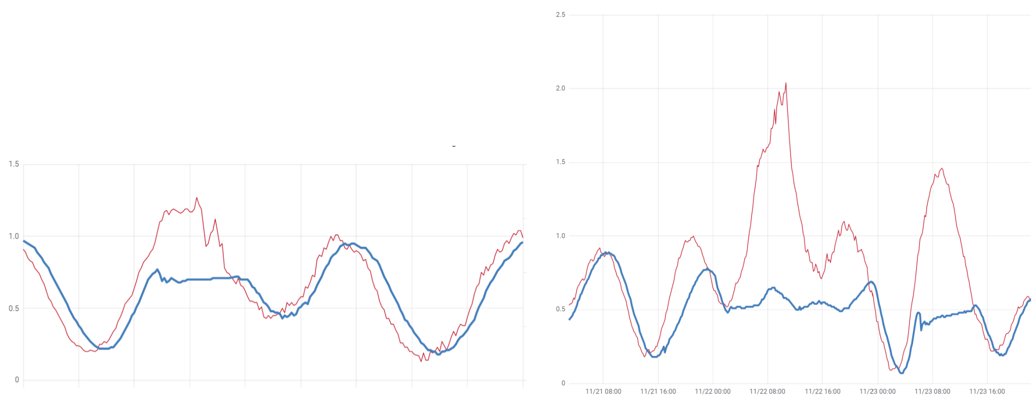

Figure 7 Sea level in the Adriatic (red) and inside the lagoon (blue) during the events of 3/10/2020 (left) and of 22/11/2022 (right)

The closures of the lagoon should be minimised, for both ecological and economic reasons. The protection strategy foresees the rising of the city pedestrian pavements at the minimum quote of 110 cm on the m.s.l. Indeed, in its history, Venice constantly raised the building construction levels, to cope with SLR. In the last century, cultural constraints (we feel important to conserve the architecture of the past), together with a faster SLR (due to several reasons, elsewhere in this document discussed) made these interventions much more complicated and somewhere

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impossible. However, the modern accommodation diffused works in the city for rising the public pavement level took place since the first years of 2000 and today need to be completed only in some minor parts.

The Piazza S.Marco constitutes a special case, for the presence of relevant artifacts placed at a significantly lower altimetric level. In this case, an “impermeabilization” strategy was chosen, consisting of raising the border of the whole of S.Marco island to 110 cm and revising all the rain drains, inserting opportune valves. These complex works are underway and will take some years to be finished; in the meanwhile, to protect from any further saltwater intrusion the most important monument, the Basilica of S.Marco, a glass barrier was placed in the front of the Basilica facing the Piazza (Fig. 8).

Figure 8 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 SLR continues to rise, the frequency of the barriers closing will increase: the management of a “regulated lagoon” needs specific observational and modelling tools, to be maintained at the state-of-the-art. Further de-pollution and morphological interventions against salt marsh erosion are needed, too.

It is perfectly known that the paradigm of “mobile” barriers works up to a 50-60 cm SLR; over this threshold, these gates will be permanently closed, and a different protection scheme should be provided. Which would be this new scheme has not been discussed yet.

However, in the next decades, a safe Venice will continue to be a multi and trans-disciplinary laboratory for the confrontation of SLR adaptation measures for the whole world.

2.1.2 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

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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 sea level rise, addressing sea level rise 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).

Box 2: The role of hybrid solutions: a combination of green and grey options

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.,

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2020; Ribeiro et al., 2021; Stronkhorst et al., 2018). Situated along the Atlantic coast, Aveiro is extremely vulnerable to coastal erosion and sea level rise 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: Sea Level Rise and World Heritage Sites: the case of Wadden Sea

Sea-level rise 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 sea-level rise 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 sea-level rise-related processes that may alter the character and nature of the site, thus affecting their Outstanding Universal Value.

Adaptation of WHS to sea-level rise 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 sea-level rise (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).

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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). Sea-level rise 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 sea-level rise 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 sea-level rise (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 sea-level rise, 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 sea-level rise (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.

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2.2 Approaches for decision-making

This section presents approaches suitable for supporting coastal adaptation decision making. It does so by 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).

2.2.1 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.

2.2.2 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.

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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 'Sea Level Rise in Europe: Governance Context and Challenges' 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 sea-level rise 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).

2.2.3 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

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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, J. 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 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.

2.2.4 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 sea level rises 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

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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)

2.2.5 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 (50th 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.

2.2.6 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.

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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*** (Van der Pol et al., 2019), 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).

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 and flexible to allow adjustments over time once future information about climate change emerges.(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 are ***adaptive planning methods*** (Walker et al., 2001), which start with a set of pre-defined adaptation options and then analyse under which future climatic developments desired objectives can be achieved. 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 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).

The second category consists of ***economic ADM approaches*** that identify optimal adaptation decision rules taking into account information about what will be learned in the future about 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

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this gap have been taken by Völz and Hinkel (Völz & Hinkel., 2023b), who developed sea-level rise learning scenarios based on the sea-level rise 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 (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).

2.2.7 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 sea-level rise 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 strategy is essential to identify the need for action in sufficient 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), which has, for example, been integrated into the national guidance for coastal hazard and climate change decision making in New Zealand (Lawrence et al., 2018).

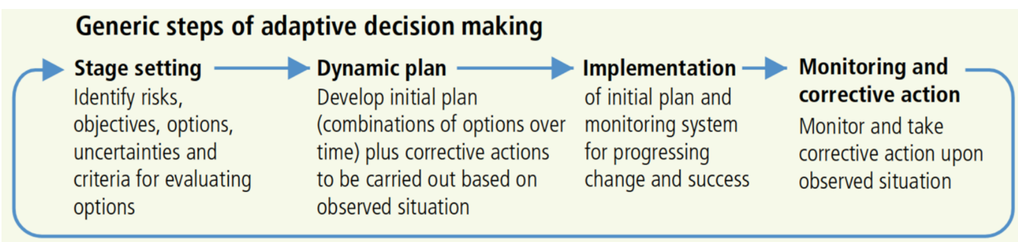

Figure 9: The adaptative decision making cycle
Source: Original figure SPM.5 in Pörtner, H. O. (Ed). 2019. Summary for Policymakers, in: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. (Pörtner et al., 2019)

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2.3 Summary: key developments per basin

Adaptation to sea-level rise 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 sea-level rise 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.

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.

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 sea-level rise and increased rainfall.

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In the Black Sea Basin, there is an increased emphasis on developing monitoring and early warning systems to help manage sea-level rise 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.

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 sea-level rise.

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.

Author contributions

GG, SB, and EFB wrote the paper with text contributions from RBA, JH, MFC, and OE. 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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