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Designing coastal adaptation strategies to tackle sea level rise

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42 **ABSTRACT**

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44 Faced with sea level rise and the intensification of extreme events, human populations living
45 on the coasts are developing responses to address local situations. A synthesis of the literature
46 on responses to coastal adaptation allows us to highlight different adaptation strategies. Here,
47 we analyze these strategies according to the complexity of their implementation, both
48 institutionally and technically. First, we distinguish two opposing paradigms – fighting against
49 rising sea levels or adapting to new climatic conditions; and second, we observe the level of
50 integrated management of the strategies. This typology allows a distinction between four
51 archetypes with the most commonly associated governance modalities for each. We then
52 underline the need for hybrid approaches and adaptation trajectories over time to take into
53 account local socio-cultural, geographical, and climatic conditions as well as to integrate
54 stakeholders in the design and implementation of responses. We show that dynamic and
55 participatory policies can foster collective learning processes and enable the evolution of social
56 values and behaviors. Finally, adaptation policies rely on knowledge and participatory
57 engagement, multi-scalar governance, policy monitoring, and territorial solidarity. These
58 conditions are especially relevant for densely populated areas that will be confronted with sea
59 level rise, thus for coastal cities in particular.

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61 Keywords: Climate change, Sea level rise, Adaptation, Governance, Nature-based Solutions,
62 Multidisciplinary approach, Vulnerability, Coastal cities.

1. INTRODUCTION

Addressing sea level rise (SLR) resulting from climate change is one of the greatest societal challenges of this century. According to the IPCC *Special Report on Ocean and Cryosphere in a Changing Climate* (2019), Global Mean Sea Level (GMSL) rose by 17 cm over the 20th century and this phenomenon is accelerating (Dangendorf et al. 2019; IPCC, 2019). Thus, by 2050, one billion people living in low-lying areas will be exposed to coastal hazards (Merkens et al., 2016). SLR entails a set of risks for coastal areas, especially for coastal megacities, tropical regions, and small islands. These risks include permanent and/or short periods of submersion, disruption of coastal ecosystem functioning and destruction of these ecosystems, soil and aquifer salinization, and modification of natural drainage systems (IPCC, 2019). By 2100 extreme sea level rise events will become frequent, regardless of the selected emission scenario (IPCC, 2019) and more regions are projected to become exposed to coastal flooding and inundation (Almar et al., 2021).

Based on information and recommendations from IPCC reports as well as on locally led research, elected representatives and coastal risk managers exert their organizational efforts at different scales to better define effective adaptation strategies. But while global SLR projections are essential, they are not sufficient to support decisions for local adaptation. Indeed, sea level does not rise uniformly. Furthermore, the smaller the scale, the more sea level and exposure to coastal hazards depend on other factors than climate (IPCC, 2019). On a local scale, three factors need to be taken into account: regional GMSL variations (+/- 30% (IPCC, 2019)), small-scale coastal processes (such as shelf currents, small-scale eddies, density changes due to freshwater input in river deltas (Woodworth et al., 2019; Durand et al., 2019), and relative sea level that depends on natural and anthropogenic coastal movements of land subsidence or uplift (Herrera-García et al., 2021). In addition to the intricacy of modeling small-scale processes (Castelle & Chaumillon, 2019), elected representatives and coastal risk managers are responsible for implementing case-by-case climate action plans, which include different parameters such as vulnerability to SLR (Le Bars et al., 2020) and a wide range of sociocultural and economic factors. Their decisions also depend on the trade-offs among responses based on a protection approach and responses based on an integrated approach, including managed retreat. Ideally, decision-makers commit to co-construction of responses with the exposed populations.

We propose scientific and pragmatic elements that can accompany and support local adaptation choices. Our collective and multidisciplinary approach (from climate science to social sciences, including anthropology, sociology, ecology, geosciences, geography, law, oceanography, and economics) holds that the co-construction of knowledge and practices is a crucial prerequisite in the face of the challenges presented by SLR. Elected officials and coastal risk managers are keen for support and advice in designing, improving, and implementing their management and policy responses in a context of high uncertainty (Toimil et al., 2021) and social change.

We first establish a reference typology of governance archetypes for responding to SLR based on IPCC reports, scientific guidelines, and published literature. Integrating contexts and

106 conditions of local governance, the typology shows the diversity of responses implemented. In
107 addition, based on the presentation of *in situ* experiences and more recent research, the article
108 proposes a new model of coastal responses that engage stakeholders, facilitate social uptake,
109 and consider broader societal goals. In the second part, we argue the value of hybrid approaches
110 that integrate social solidarity at the regional level, a less common theme in the specialized
111 literature. In Part 3, we focus on the dynamic dimensions of response planning and
112 implementations. Dynamic responses are dependent on institutional and governance adaptation
113 and even transformation. Adaptive and dynamic responses further require hybridization,
114 flexibility, (Holling, 2005), and innovation (Haasnoot et al., 2021). These are essential to the
115 planning of long-term dynamic pathways and to designing the new model of coastal adaptation
116 presented here. Finally, the discussion raises the challenges and research perspectives that
117 coastal managers and stakeholders now have to consider. This study, with its analysis and
118 contextualization of coastal adaptation responses, can support decision-making when
119 developing local action plans.

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122 **2. TYPOLOGIES OF ADAPTATION RESPONSES TO SEA** 123 **LEVEL RISE**

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125 Various responses can enable densely populated coastal areas to adapt to SLR, erosion, and
126 coastal flooding. Based on different guidelines and reviews published to date (Linham and
127 Nicholls, 2010; IPCC, 2014; Hill, 2015; IPCC, 2019; Baills et al., 2020; Haasnoot et al., 2021),
128 we note a general agreement on the distinctions among three main categories of response:
129 protection (including advance), accommodation, and managed retreat. These categories differ
130 in their vision more than in their implementation. However, authors use different terminology,
131 which raises questions about how adaptation responses are grouped. For example, in Linham
132 and Nicholls (2010), coastal wetland restoration, which takes nature into account, is classified
133 as an accommodation response because it raises awareness and helps reverse maladaptive
134 trends. In contrast, the IPCC (2019) considers all ecosystem-based adaptation (EbA) responses
135 as protection responses, as they serve to fight against rising sea levels. Some responses fit in
136 more than one category: EbA responses can accompany managed retreat, as coastal ecosystems
137 can be reestablished following the destruction of dikes or depoldering. Similarly, a protection
138 response initially designed to stabilize the coastline can be used during a transitional period
139 before implementing managed retreat. Depending on the authors, EbA and nature-based
140 solutions (NbS) can have the same meaning. In our analysis, we consider NbS as ways to protect
141 or restore ecosystem services. Thus, we have considered them EbA responses.

142 Here, our intention is to analyze the different adaptation responses considering the complexity
143 of implementing them; that is, to what extent they consider whole system responses, including
144 both natural systems and socio-cultural and economic systems. Then, we propose a synthesis
145 of four governance archetypes to address coastal hazards considering two contrasting
146 paradigms and taking into account the level of integration of responses.

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1.1. Hard protection

Hard protection, or “gray infrastructure” responses, are widespread and especially concentrated in northwestern Europe, East Asia, and in deltas or densely populated areas such as coastal cities (IPCC, 2019). Although there is no technological limit that constrains a seawall’s maximum height, hard protective structures do not provide a reliable, long-term response to coastal hazards (Ballinger, 2002), as seawalls can exacerbate erosion, affect the seabed and neighboring coasts, and diminish the ability of the coastline to respond naturally to changing conditions (van Rijn, 2011). Hard protection includes dikes and static seawalls that are effective in stabilizing the shoreline but cause scour and can destabilize the beach; groynes and artificial headlands that intercept long-shore sand transport and are effective in building the beach updrift but induce scour and erosion downdrift; detached breakwaters and artificial reefs that reduce wave activity and energy along the shoreline and are effective in building beaches but can produce downdrift erosion (Gracia et al., 2018).

A new response emerged in the IPCC (2019) typology: the *advance* response. Advance response refers to the creation of artificial land above the sea and has a long history in densely populated areas as a way to create new buildable areas. Its main advantage is the high accessibility of new sites, both by sea and by land, which is an asset for ports as well as residential and recreational development (Alves et al., 2020). Coastal cities can develop their waterfront or benefit from infrastructure with direct access to the ocean by building offshore, protecting themselves from the sea behind seawalls and dikes (Donchyts et al., 2016).

Both hard and advance responses can alter overall coastal ecosystem functioning, degrade the quality of ecosystem services, and lead to habitat loss or reduced species diversity (Bilkovic & Mitchell, 2013; Sutton-Grier et al., 2015; Warner et al., 2018). These responses contribute to ‘ocean sprawl’ (Bishop et al., 2017) with large-scale ecological impacts on local and surrounding ecosystems, for instance by influencing connectivity patterns (i.e., the movement of organisms), displacing species due to the environmental changes they cause, facilitating the establishment of non-native invasive species, and/or displacing existing human uses or housing (Anguelovski et al., 2016). Finally, despite their effectiveness, these responses also remain very costly or even completely unaffordable (Hinkel et al., 2018), and while the technology exists to build enormously high sea walls, economic constraints and social acceptability will preclude their viability (Esteban et al., 2019).

The Netherlands is most emblematic in terms of implementation of hard responses, due to the country’s long experience developing gray infrastructure. However, in recent years, projected climate-driven SLR, along with the development of a stakeholder-led, integrative vision of the future coast have led some governing bodies to reconsider the Dutch national strategy, favoring adapting to rather than fighting change. The concept of ‘climate proofing’ was born in the Netherlands with the goal of making the most populated cities and ports resilient to climate change. The city of Rotterdam has the goal of being the ‘safest port city in the world’ by 2025, and the Dutch government has prioritized sustainable development of coastal areas as its strategy for the 21st century by choosing to better integrate natural systems when designing responses to SLR (Kabal et al., 2009).

1.2. Soft protection

Also originally rooted in the Netherlands (Kabal et al., 2009), the second strategy covers *soft* protection responses that still fight against marine intrusion – that is, SLR and coastal flooding – but by applying an integrated approach rather than hard protection. Awareness of the negative impacts of hard protection on erosion and sedimentation patterns (van Rijn, 2011), as well as on ecosystems and the services they provide (de Schipper et al., 2020), led to a growing recognition of the benefits of soft protection.

Dune rehabilitation and sand nourishment, including beach nourishment, allow the coast to respond dynamically to change (van Rijn, 2011). Van Slobbe et al. (2013) present these responses as part of a ‘building with Nature’ strategy that provides an effective response to protect beaches and coastal areas. For Hinkel et al. (2013), optimal beach and shore nourishment responses offer economic and social benefits and can reduce forced migration, although soft adaptation is a temporary response to SLR.

Soft adaptation is mostly focused on beach nourishment, considered as an environmentally friendly protection response for coastal ecosystems (Linham & Nicholls, 2010). A number of national reviews present examples of sites threatened by SLR where beach nourishment has been implemented. For instance, in the U.S., the volume of sand used for this purpose has increased exponentially over the last century, particularly in California (Elko et al., 2021). Pinto et al. (2020) provide an overview of beach nourishment practices since the 1950s in Portugal, while Pagán et al. (2020) analyze the evolution of beaches and beach areas over the same period and show the extent to which anthropogenic actions have affected the coastline. Karaliūnas et al. (2020) assess how the different conditions for beach nourishment transform the coastal landscape in Lithuania. Somphong et al. (2020) provide general estimates on the cost and volume of sand needed to supply all Thailand’s beaches. In China, Liu et al. (2020) present the practices, the reasons for deploying beach nourishment, and the technological advances made in recent decades.

However, the literature points to negative physical and biological changes it can cause in beach ecosystem services (Fegley et al., 2020), as well as other ecological and socio-economic impacts (de Schipper et al., 2020). An open question for the development of beach nourishment is the accessibility of beach-compatible sand. Not all coastlines have large sand reserves. The largest sand nourishment experiment in the world was conducted on the Dutch coast, which has ample reserves (Stive et al., 2013). De Schipper et al. (2020) have shown that beach nourishment can have socio-economic impacts, particularly on recreational activities. Thus, the increased interest in the development of adaptable, sustainable, and effective soft engineering other coastal responses than beach nourishment to preserve sandy coastlines is noteworthy.

1.3. Accommodation to reduce vulnerability

A third category of response is *accommodation*, which takes projected SLR into account when adapting existing infrastructure to changing climatic conditions. Accommodation responses, also called ‘coastal planning techniques’ by Alves et al. (2020), are not homogeneous but rather

234 encompass diverse methods with a common goal: mitigating coastal hazards. Rather than
235 building infrastructure, accommodation responses comprise a variety of technological,
236 architectural, and urban planning responses. Linham & Nicholls (2010) include technologies
237 and innovations that physically modify exposed buildings or infrastructure by raising buildings,
238 protecting them individually, adapting urban drainage systems, or developing floating housing
239 (Thi Thu Trang, 2016) and exploring ‘New Urbanism’ (Smith et al., 2021). Lauterjung & Letz
240 (2017) also include information systems, flood hazard mapping, contingency plans, and
241 insurance schemes that improve understanding and awareness of coastal risks among residents
242 and elected officials and enable the development of appropriate responses.
243 These accommodation responses may also involve strengthening monitoring capacity,
244 establishing new rules and policies, producing and disseminating useful information, and
245 promoting safer behavior (Linham & Nicholls, 2010). Most accommodation responses tend to
246 be resource intensive in terms of monitoring systems, studies, communication, development of
247 new strategies for coastal protection, and management.
248 Recently, a literature review from West Africa (Alves et al., 2020) discussed accommodation,
249 noting that the continent’s accommodation responses are still insufficiently developed, with the
250 exception of early warning systems in the cities of Cotonou, Benin; Dakar, Senegal; Accra,
251 Ghana; and Lagos, Nigeria. In many countries where accommodation responses exist, the
252 review highlights that the systems fail due to a lack of maintenance.

254 **1.4. Ecosystem-based adaptation**

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256 EbA – which includes the restoration of salt marshes, mangroves, oyster beds, or coral reefs
257 (Powell et al., 2019) – consists in letting coastal ecosystems mitigate marine flooding and
258 coastal erosion (Cheong et al., 2013; Temmerman et al., 2013) and reduce risks for people
259 living in coastal areas (Barbier et al., 2011; C. Zhang et al., 2012).
260 Substantial work has been done on the efficiency of mangroves (McIvor et al., 2013; Möller et
261 al., 2014), salt marshes (Guannel et al., 2016; Leonardi et al., 2018), oyster beds (Morris et al.,
262 2019), and coral reefs (Ferrario et al., 2014; Roelvink et al. 2021) that shows how and under
263 what conditions these ecosystems can attenuate wave power, reduce erosion, and more
264 generally enhance coastal protection. However, the IPCC (2019) shows that accelerated SLR
265 and climate change may lead to significant coastal ecosystem loss by the end of the century.
266 Moreover, Gao et al. (2020) published a review on coastal dune migration, trends, and dominant
267 drivers of dune mobility and concludes that human intervention played a dominant role in
268 altering it. More globally, coastal ecosystems are threatened if they are caught between the sea
269 and the built environment, lacking the natural conditions enabling them to move.
270 Implementing EbA requires a deep understanding of the ecology of the species involved
271 (Salvador de Paiva et al., 2018), and David (2020) raises the risk of introducing new invasive
272 species, thus questioning its use as an EbA. For instance, examination of the fundamental and
273 realized niche of oysters has shown that oyster beds respond differently to a wide range of biotic
274 and abiotic factors, varying across locations, which calls for further investigation to improve
275 the services these ecosystems provide (Morris et al., 2019). Oyster restoration can introduce
276 invasive species, especially under changing climatic conditions. Rinde et al. (2017) study a

277 Pacific oyster species that has been proposed for coastal protection in several countries,
278 including the U.S. and the Netherlands, and highlight the potential of increased invasiveness
279 because of climate-change effects and the concomitant risk to native species and habitats in
280 temperate regions.

281 Mangrove restoration has the added value of providing co-benefits such as carbon sequestration
282 and habitat provision (e.g., Sierra-Correa & Cantera Kintz, 2015). Beyond adaptation to SLR,
283 coastal marshes, seagrass, and mangroves are referred to as ‘blue carbon’ due to their
284 contribution to long-term carbon storage (Mcleod et al., 2011). Salt marshes, mangroves, oyster
285 reefs, and coral reefs also provide multiple ecological functions, such as nursing grounds for
286 fish and shellfish, resting places for migratory birds, and groundwater and surface water runoff
287 filtration. Increasingly, scientists and international institutions emphasize the use of EbA to
288 connect adaptation to SLR to biodiversity conservation. For example, Alves et al. (2020) show
289 that diverse coastal ecosystem rehabilitation projects, including mangrove restoration projects
290 that cover large coastal areas, provide multiple benefits for coastal species as well as climate
291 mitigation and adaptation.

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293 **1.5. Managed Retreat**

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295 While SLR will reshape coastal ecosystems and population distribution (see, for the U.S.,
296 Hauer, 2017; and globally, see IPCC, 2019) *managed retreat* involves rethinking living on the
297 coast by accepting that certain coastal infrastructure, neighborhoods, or even cities will need to
298 relocate entirely. This response can take place at different scales and levels of complexity –
299 resettling a few particularly exposed houses, relocating entire neighborhoods, moving large
300 cities, or moving entire island populations to new host countries. The larger the geographic
301 scale at which managed retreat is implemented, the more anticipatory planning and cooperation
302 are needed. Furthermore, if this response appears to be the most effective way to protect people
303 and assets from coastal risks (Haasnoot et al., 2021), Barnett et al. (2012) have shown that its
304 implementation is complex and often highly controversial, both politically and socially.
305 Managed retreat raises indeed a range of social, cultural, psychological, and economic
306 considerations (Abel et al., 2011). Consequently, retreat has generally been carried out after
307 extreme events, without planning ahead; Hino et al., (2017) report 27 cases of post-event,
308 unmanaged relocation worldwide. However, there are currently communities planning for
309 managed retreat strategies and working at defining pathways to get there (Lawrence et al.,
310 2020).

311 Managed retreat is approached and deployed differently around the world. Apart from a few
312 emblematic examples such as Jakarta, where the Indonesian government decided to relocate
313 part of the city of Borneo (Van de Vuurst & Escobar, 2020), or the ongoing relocation of the
314 densely populated fishermen's district of Guet'Ndar in Saint-Louis, Senegal (World Bank,
315 2018), managed retreat responses with public support have primarily been carried out in
316 developed countries (North America and Western and Northern Europe).

317 In the U.S., managed retreat is constrained by psychological, institutional, and practical limits
318 (Siders, 2019). In Europe, although managing flooding risk through depoldering conveys
319 ecosystem benefits, many countries still favor the reinforcement of dikes (Goeldner-Gianella et

320 al., 2015). People are deeply attached to local polders and their uses, which explains optimism
321 and *status quo* biases, and hinders thinking about managed retreat. Elected officials coastal
322 managers can also be reluctant to implement managed retreat. Bragg et al. (2021) underline that
323 the use of the term ‘managed retreat’ can create anxiety amongst those least able to move, lead
324 to resistance from those affected and to the abandonment of the policy. They note that the use
325 of appropriate terminology and communication strategies remains crucial to increase
326 acceptance of managed retreat.

327 French attempts and polices experiments are notable for their anticipatory and learning
328 approach of managed retreat. As part of a national integrated coastline management strategy,
329 pilot projects were implemented to identify legal, economic and operational constraints and
330 psychological or political opposition. Rocle & Salles (2018) and Rocle et al (2021) show that
331 the pilot programs led by French government together with local institutions were successful in
332 delivering innovative and actionable knowledge and tools (depending on scale and density of
333 coastal development) through multi-level exchanges and multijurisdictional governance. Such
334 an integrated approach leads to a better understanding of erosion management and coastal land
335 use planning (Robert & Schleyer-Lindenmann, 2021), while emphasizing the need for
336 observations and information or warnings for future owners. For instance, in order to prevent
337 current economic losses, regulations can allow temporary construction in exposed areas for
338 periods spanning over 30 years. Innovative planning concepts include buy-out programs to
339 avoid future loss of value (André et al., 2016), and other scientific work explores innovations
340 in compensation arrangements to reduce the expense of compensation (André et al., 2016;
341 Henderson, 2018), although this can’t be the only sufficient source of funding for relocation
342 strategies.

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344 **1.6. Governance archetypes for responding to sea level rise**

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346 Based on this typology of responses, we propose four governance archetypes for responding to
347 SLR that allow us to rank the degree of complexity of implementing the different approaches
348 to coastal adaptation.

349 In the synthesis table (Figure 1), archetypes are classified according to two contrasting
350 paradigms positioned on the vertical axis. The first paradigm is to ‘*Protect from coastal*
351 *hazards*’. It consists of fighting against advance of the sea in order to protect threatened
352 population and infrastructure. By accepting coastline mobility, the second paradigm is to ‘*Adapt*
353 *to coastal hazards*’. Through this paradigm, if certain areas must be ceded to the sea, it
354 recommends planning ahead for the relocation of communities and activities to safe spaces.
355 Regarding governance modalities, we postulate that the ‘*Level of stakeholder engagement in*
356 *the decision-making process*’ is low for responses that fit into the first paradigm, and high for
357 responses that fit into the second paradigm.

358 The synthesis table also refers on the horizontal axis to how adaptation responses are planned
359 and implemented, depending on whether they favor an ‘*Infrastructure-based approach*’, that
360 is, technological or technical solutions, or an ‘*Integrated approach*’ that considers broader
361 societal goals. In terms of governance, we postulate that the more a response to coastal hazards
362 is integrated, the bigger ‘*Spatial implementation scale*’ needs to be.

363 *Designing a new coastal model* archetype promotes adaptation to new climatic conditions by
364 adopting an integrated, systems-based approach. Thus, overcoming the complexity of
365 implementing responses that correspond to this archetype requires a high level of stakeholder
366 engagement in the decision-making process, as well as planning on a large spatial scale.
367 Because it is difficult to account for the diversity of governance arrangements, which are highly
368 dependent on national political organization and capacities, the elements of governance
369 represented do not always correspond to specific cases. Finally, a single response can fall into
370 different governance archetypes. Indeed, responses are often connected and can be executed
371 together (see Part 3) in differing time frames (see Part 4).

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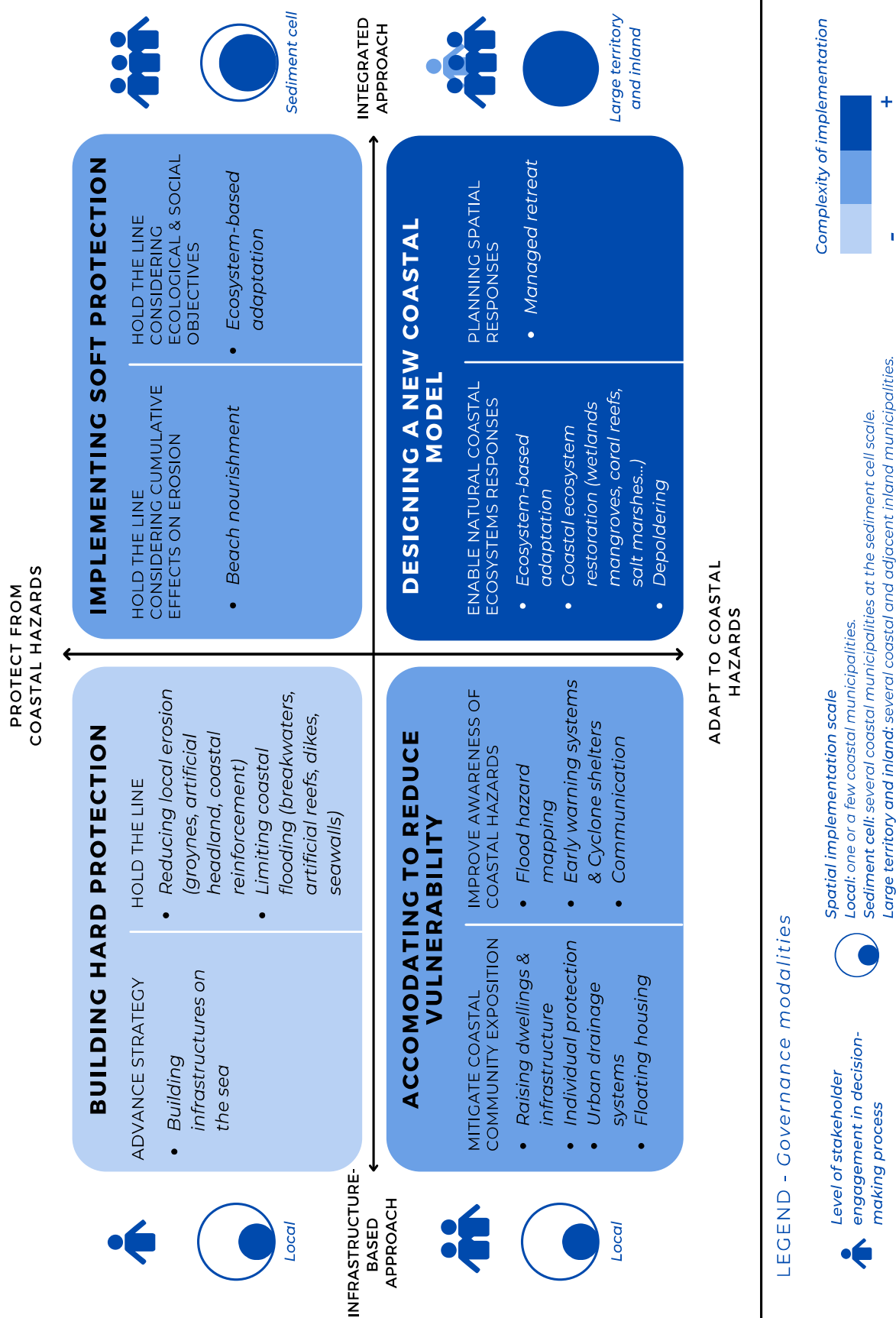


Figure 1 – Governance archetypes of adaptation strategies to sea level rise, by authors 2021

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3. GOVERNANCE OF HYBRID RESPONSES

Responding to several technical, social, and ecological constraints, there is no one-size-fits-all solution for SLR. Here, we focus on strategies that consist in adapting to SLR through an integrated approach. Planning and implementation processes and constraints depend on social, geographical, ecosystem, and institutional contexts. We therefore emphasize the need to adopt hybrid responses and processes (3.1). We identify social, economic, and environmental issues that require attention but that may also facilitate individual and community responses and improve governance (3.2).

3.1. Designing hybrid approaches to meet context-specific challenges

Hybrid responses are increasingly numerous and diverse, providing coastal cities and territories with new effective opportunities to adapt to SLR by mixing strategies (Sutton-Grier et al. 2015; Hill, 2015). The IPCC (2019) acknowledges that hybrid responses are often a combination of protection, retreat, accommodation, advance, and ecosystem-based adaptation responses.

Sutton-Grier et al. (2015) define hybrid approaches as the combination of natural and built infrastructure to protect coastlines from erosion and flooding, aiming to be more cost-effective in the long term than built infrastructure alone. They mention examples of hybrid approaches developed in the U.S. after Hurricane Sandy that combine many natural options (salt marsh restoration, rock groynes, and oyster restoration) with infrastructure-based approaches, such as removable floodwalls or mobile floodgates that are only used when a storm is approaching. Seeking to capitalize on the best features of both built and natural infrastructures, hybrid approaches can provide a greater level of confidence than just EbA. They can also provide co-benefits, including enhancing social, economic, and ecological resilience of coasts and coastal communities, maintaining coastal ecosystem services, and preventing the loss of human life and property (Sutton-Grier et al., 2015).

While cost-benefit analyses generally result in a preference for hard responses over managed retreat and EbA— assuming high initial costs for future benefits (André et al., 2016) – limited evidence exists on the economic value of hybrid approaches (Sutton-Grier et al., 2015) more recent data demonstrates hybrid systems’ effectiveness and provision of ecosystem services (Bilkovic & Mitchell, 2013). Du et al. (2020) conducted an economic assessment of hard, soft, and natural strategies, as well as hybrid strategies that combine the three, to face major floods in Shanghai and concluded that hybrid approaches can serve as a robust flood adaptation strategy.

However, while no single response can satisfy the diversity of local issues related to adaptation to SLR, the implementation of hybrid approaches may pose more governance challenges than hard protection responses do (Sutton-Grier et al., 2015). The section below considers these governance responses and challenges.

488 3.2. Planning spatial hybridization of responses to foster 489 territorial solidarity 490

491 IPCC experts (2019) underline that the implementation of coastal SLR adaptation responses
492 poses a profound governance challenge due to difficult social and political choices. Here,
493 governance challenges refer to institutional and organizational factors hindering the effective,
494 efficient, and equitable implementation of responses (as defined in IPCC, 2019).

495 Meur-Ferec & Guillou (2020) highlight a governance constraint based on risk perceptions that
496 can underestimate the effects of climate change. Drawing on Beck's (1997) 'risk society',
497 Michelot (2015) defined the concept of 'risk culture' as a set of perceptions and behaviors
498 adopted by a society in the face of risk to show that developing a new risk culture could be a
499 solution to these constraints. For instance, the *Building hard responses* strategy can comfort
500 and reassure people. But these behaviours can also be counterproductive and alter the risk
501 perception, inducing a fear of disasters that can lead to subsequent difficulties dealing with
502 danger. Focusing on disaster risk reduction measures, Martinez et al. (2020) identify a 'culture
503 of risk memory' as one of the prerequisites for successful collaboration and policy
504 implementation. Public awareness of risk can be improved by building on local observation
505 systems and scientific knowledge systems, involving local communities in planning, and
506 promoting social learning about risks and potential local responses (Baird et al., 2014; Martinez
507 et al., 2020; Bragg et al., 2021). Communication (Bragg et al., 2021) and, even more, involving
508 stakeholders and the public are particularly important (Hügel and Davies, 2020).

509 More generally, a combination of decision analysis, coastal land use planning, civil society
510 participation, scenario development, and conflict resolution can help address the complexity of
511 implementing responses. For instance, Scyphers et al. (2020) recommend investigating
512 potential pathways to navigate social, economic, and environmental influences on landowner
513 decisions for coastal habitat conservation. Their study reveals opportunities for incentivizing
514 living shorelines as a tool for coastal habitat conservation.

515 Finance, insurance, and management capacity are key governance issues for implementing
516 hybrid responses. Airoldi et al. (2021) identify economic incentives that can be used to support
517 sustainable development and reduce coastal risks. They discuss the rise of new financing
518 avenues for natural infrastructure for flood risk reduction and climate adaptation, including
519 green bonds and impact investments, blue bonds, incentives and funding for pre-disaster
520 mitigation, post-disaster recovery funds, and insurance instruments.

521 The appropriate governance scale has been addressed through the notion of sediment cell, based
522 on the scale of the physical phenomenon of sediment transport (Cooper & Pontee, 2006),
523 considering that human interventions in each jurisdiction will affect neighboring jurisdictions;
524 for example, sediment reduction from dams will impact the sediment cell they are part of, and
525 deep-water ports will block sediment drift downstream (Almar et al., 2015; Guerrero et al.,
526 2021). This issue has prompted several communities to cooperate in order to avoid the transfer
527 of impact caused by gray infrastructure. It has also led communities to share certain costs,
528 including for research or jointly paying for barge displacement for recharging operations. Thus,
529 hybrid approaches involve financing arrangements that go beyond the communities or countries
530 directly affected and broaden dialogue.

531 When addressing coastal risks through land use planning, often only small groups of affected
532 citizens become involved, rather than the wider affected community that may also contribute
533 to the funding of coastal adaptation (Clément et al., 2015; Anguelovski et al., 2016). For
534 instance, inland communities, which also use beaches and protected coastal ecosystems, should
535 be concerned by financing coastal adaptation. In addition, they may be affected by migrants
536 retreating from coastal areas. Depending on the case, it is necessary to consider the appropriate
537 fiscal scale to raise public funding or to access national and international funding sources. Yet
538 for both developing and developed countries, inland populations are generally not consulted,
539 nor are part-time residents and tourists (Rey-Valette et al., 2015). More generally, improving
540 the coordination of responses at all levels of governance and across all sectors and policy
541 domains, which has proven to be an effective response (IPCC, 2019), remains a major
542 challenge.

543 Finally and importantly, coastal adaptation raises equity concerns, and requires ensuring that
544 responses do not further marginalize the most vulnerable populations, especially in fast-
545 growing cities in developing countries (See & Wilmsen, 2020) and also in areas with large
546 existing wealth and resource gaps, and do not trigger or aggravate social conflicts (McGinlay
547 et al., 2021). Efforts to promote climate resilience should be undertaken alongside sustainable,
548 just, and equitable development. Otherwise SLR is likely to cause or exacerbate social conflicts
549 over time to the point of their becoming even more difficult to resolve; this is why we highlight
550 the importance of considering larger scales and neighboring jurisdictions. We now focus on the
551 key importance of considering multiple temporal scales.

552
553

554 **4. TOWARDS DYNAMIC COASTAL MANAGEMENT**

555

556 The evolution of the world's coastlines presents uncertainties for the future (Le Cozannet et al.,
557 2019; Le Bars et al., 2020), limiting our ability to anticipate risks and develop sustainable
558 strategies. We emphasize the importance of planning dynamic coastal management to
559 implement responses to SLR over time and to manage adaptively for uncertainty. By testing
560 different pathways against different scenarios, the following approaches enables to identify
561 signals and decision triggers for taking anticipatory action and articulate temporal scales to
562 move towards desirable futures.

563

564 Reactive adaptation could be defined as 'one shock, one reaction', whereas preventive
565 adaptation is more about 'building better for the future' (Nicholls, 2011). Reactive adaptation
566 is notoriously costly and only moderately efficient (Nicholls, 2011). On the other hand, adaptive
567 coastal management also entails certain constraints, notably regarding information on the
568 evolution of physical processes and biases in the perception of future risks (Coquet et al., 2019).
569 However, distant timeframes (2050 or, even more, 2100) make it very difficult to anticipate
570 societal evolution (social and institutional) despite forward-looking approaches. It will be
571 necessary to be able to adapt under large uncertainty and over time frames beyond 2050, thus
572 calling into question planning and decision-making practices as they are conceived today

573 (Haasnoot et al., 2013; Bloemen et al., 2019; Kool et al., 2020; Rocle et al., 2020; Werners et
574 al., 2021).

575 Pathway analysis is a low-cost tool to define long-term adaptation responses that Haasnoot et
576 al. (2021) present as a positive approach to reduce coastal risks and minimize ineffective
577 investments and social inequities. It enables adaptation to SLR over time and allows for
578 alternative pathways. Some studies have presented different approaches to pathway
579 development in different decision-making contexts (Bloemen et al., 2018; Bosomworth and
580 Gaillard, 2019; Lawrence et al., 2019). For example, Haasnoot et al. (2019) investigated how
581 uncertainty related to Antarctic melting could impact the coastal adaptation strategy of the
582 Netherlands. These authors and Le Bars et al. (2020) identified key variables and processes for
583 the adaptation of different coastal areas with a long-term vision to assist decision-making under
584 high uncertainty. They propose a dynamic approach that leads to the identification of several
585 trajectories based on previously identified tipping points.

586 This approach aims at defining the solution space to accelerate climate change adaptation,
587 defined by Haasnoot et al. (2020) as the space within which opportunities and constraints
588 determine why, how, when, and who adapts to climate risks. The solution space is shaped in an
589 integrative approach, taking into account biophysical, cultural, socio-economic, and political-
590 institutional dimensions at a given moment in time. In a recent article, Haasnoot et al. (2021)
591 show that the space for available solutions is shrinking and that managed retreat is emerging as
592 the main remaining response.

593 Based on this methodology and building upon archetypes of French coastal territories, Rocle et
594 al. (2020) highlight several key social and institutional variables and processes leading to
595 different adaptation pathways, which themselves depend on local contexts and how different
596 stakeholders respond to climatic and socioeconomic parameters. Pathways planning implies
597 holistic approaches and a new generation of coastline models as proposed by Ranasinghe (2020)
598 and Bamunawala et al. (2020). If participatory, pathways planning enables engagement and
599 governance, thus reinforcing the acceptance and implementation of responses by affected
600 communities.

601

602

603 **5. DISCUSSION**

604

605 Policy makers' and coastal risk managers' understanding of coastal adaptation has evolved over
606 the last two decades, as have the approaches, policy processes, and the responses developed in
607 order to address coastal hazards. Analyzing the various adaptation responses mentioned in
608 IPCC reports and in other scientific literature led us to define four governance archetypes for
609 responding to SLR. Each offers feasible and actionable adaptation approaches. We note that
610 adaptation is itself an adaptive process that responds to new climate conditions. Adaptation
611 strategies need to consider an integrated approach that encompasses broader societal goals.

612 In the case of densely populated areas exposed to SLR, this consists in designing new coastal
613 models that take into account local issues and address the complex governance context for
614 implementation. To do so, coastal adaptation must be planned on large scales with broad
615 stakeholder involvement regarding responses to SLR. This will allow the new coastal model to
616 facilitate the effectiveness and acceptability of the selected adaptation responses. Finally, two

617 frameworks for action are suggested: encourage hybrid responses to better take into account
618 local contexts specificities and reinforcing territorial solidarity; and plan for long-term,
619 dynamic pathways.

620
621 These frameworks need to encompass different types of interaction among the cities' or
622 territories' stakeholders. This in turn requires new forms of *actionable* and *institutionalized*
623 knowledge. This goes along with expanding the research fields and disciplines involved and
624 improving monitoring. Actionable knowledge and data are needed at different scales that are
625 targeted to coastal risk managers, which also implies the evolution of how decision-makers and
626 researchers interact (Kopp et al., 2019; Lawrence et al., 2021). Rocle et al. (2021) emphasize
627 the value of actionable knowledge (Cash et al., 2003; Kirchhoff et al., 2013) for managed retreat
628 through a framework that takes into consideration the credibility, legitimacy, salience, and
629 applicability of knowledge. Their analysis of managed retreat governance in France shows the
630 importance of organizational learning processes through multi-level construction of actionable
631 knowledge, policy guidelines and practical tools.

632
633 There are still relatively few concrete examples of sustainable and effective solutions
634 implemented on the ground to adapt to SLR. Despite the crucial role of coastal cities' adaptation
635 to SLR included in both SDGs 9 and 11, a recent systematic review of the literature on
636 adaptation policies (Berrang-Ford et al., 2021) highlights the lack of attention to this topic.
637 Indeed, only 6% of the publications reviewed focus on cities and only 4% focus on the ocean
638 and coastal areas. The same publication underlines the weakness of actions and monitoring
639 tools for transformational adaptation, especially for risk reduction (Magnan et al., 2020). The
640 authors reveal the preponderance of individual adaptations – which are most often
641 uncoordinated and small-scale – and they recognize that the scope and the speed of
642 implementation are inversely related

643 We have two other further observations. First, the low mobilization of scientific knowledge and
644 second, the need for multi-scalar knowledge (in terms of both time and space) that would help
645 defining dynamic and adaptive schedules for action, which in turn imply specific monitoring
646 needs. Magnan et al. (2020) concur in their *Adaptation Gap Report 2020* - United Nations
647 Environment Programme. They highlight that “*Actionable policies refer to the extent to which*
648 *multi- and bilateral cooperation and national policies provide clear guidance on how to*
649 *operationalize adaptation on the ground (i.e. beyond only providing strategic guidance)”*
650 (p.29).

651
652 We suggest several key considerations related to knowledge, participation, societal parameters
653 of adaptation, and monitoring of policies, in order to reinforce actionability, hybridization of
654 responses, and long-term dynamic pathways.

655
656 i. Hybridization refers not just to the contextualization of responses but also to the
657 reinforcement of scientific knowledge-sharing. It is linked to a greater disciplinary openness
658 and to a transformation of knowledge production processes through in partnership with
659 stakeholders and civil society, who must be fully integrated in the collective learning
660 entailed by adaptation policies. Knowledge should not be limited to scientific engineering

661 and natural science, but must include local knowledge, contributing to greater awareness
662 and collective learning (Iorns Magallanes & Watts, 2019; Werners et al., 2021). Different
663 tools to gain an effective, collective commitment of citizens at all scales include a diversity
664 of media, such as virtual reality or serious games (den Haan & van der Voort, 2018,
665 Blanckett, 2019). In this regard, the New Zealand case study analyzed by Lawrence et al.
666 (2021) highlights both the information constraints of citizens and the need for a deep change
667 in the knowledge production process. They emphasize the contribution of warning systems
668 and different types of serious games, but also more generally the importance of institutional
669 adaptations to facilitate the uptake of these tools. Because the consideration of local issues
670 depends on communities' participation, collective learning could facilitate the
671 understanding of risk, help develop capacity for action (Lawrence & Haasnoot, 2017), and
672 allow for adoption of adaptation responses (Reed, 2008; Baird et al., 2014). It is thus
673 important to go beyond the notion of awareness-raising to strengthen the medium-term
674 commitment of stakeholders by mobilizing their knowledge and perceptions. Although
675 scientific mediation initiatives tend to develop, the reality of coastline management is that
676 this interaction is usually mediated by a single type of actor – engineering offices, which
677 are then in charge of scientific knowledge transfer. Thus, despite their efforts to develop
678 forward-looking and participatory approaches, natural and social scientists, as well as the
679 public, often remain on the fringes of these initiatives.

680 ii. At the institutional level, it is crucial to coordinate and articulate the geographic scales
681 covered by multi-level governance (Abel et al., 2011; Piggott-McKellar et al., 2019;
682 Schneider et al., 2020; Robert & Schleyer-Lindenmann, 2021; McGinlay et al., 2021). We
683 have shown the relevance of comparing shared experiences and the positive role of multi-
684 level governance (Rocle & Salles, 2018; Rocle et al., 2021). Efficacy and implementability
685 depends on the policy construction process and on the institutional context. Coordination
686 of initiatives and financial experiments usually occurs at the national level, with on-the-
687 ground implementation at the local level (Shi, 2019; Berrang-Ford et al., 2021). Ensuring
688 the continuity of strategies and implementation requires sustained funding and ongoing
689 governance agreements. For several countries, these conditions depend internally on
690 political stability and externally on the programmatic priorities of international donors. Our
691 analysis shows the role of proactive governance capacities of institutions, which partly
692 explains the difficulties in implementing adaptive strategies for several countries. This is
693 particularly true in colonized countries that recently became independent, where the
694 legacy of extraction of wealth and a system of post-colonial Western administrative and
695 legal tools dominate local and customary ways of conceiving adaptation (Bambridge, 2016).
696 The struggle between endogenous and exogenous strategies often opens breaches and
697 weakens political decisions for coastal adaptation.

698 iii. The implementation of collaborative approaches leads to the diversification of questions.
699 This requires a transdisciplinary approach with a focus on social impact and a connection
700 with the needs and concerns of affected communities. As an example, Magnan et al. (2021)
701 raised gender as an insufficiently addressed parameter. More generally, adaptation to
702 climate change can have a negative impact on some social groups and localities by
703 increasing poverty, vulnerability, and inequity. Coastal adaptation studies thus need to
704 consider territorial inequalities from an environmental and social justice perspective (King

705 et al., 2014; Clement et al., 2015; Anguelovski et al., 2016). Climate migration is also
706 incompletely explored (Gioli et al., 2016; Hauer, 2017; Hino et al., 2017), because it usually
707 focuses more on the resistance of migrating populations to leave their homes or
708 neighborhoods, while the issue of new inhabitants' acceptance by inland populations is little
709 addressed. And as shown by the modeling of population flows carried out for Florida by
710 Treuer et al. (2018), out-migration can produce negative effects on tax revenues when
711 homeowners decide to move out of the region. Migration also involves very large scales,
712 especially for island countries.

713 iv. From the perspective of sustainable adaptation, effective implementation of transformative
714 actions, such as new coastal models (See Figure 1), involves a gradual implementation.
715 Longevity of responses requires adaptive approaches over time with improved monitoring
716 (Bloemen et al., 2018; Bosomworth & Gaillard, 2019; Carstens et al., 2019; Haasnoot et
717 al., 2019). Lawrence et al. (2021) suggest a logical chain of action (monitor, review, update,
718 anticipate) that focuses on the role of information and continuity of follow-up. Since the
719 elaboration of adaptive approaches over time depends on countries' institutional
720 characteristics (Bloemen et al., 2018; Bosomworth & Gaillard, 2019; Carstens et al., 2019;
721 Haasnoot et al., 2019), many policy practices and information and monitoring systems are
722 not standardized or static (Magnan et al. 2021; Magnan et al., 2020; Berrang-Ford et al.,
723 2021). Local and multidisciplinary coastal data are far from being widely available (Rocle
724 et al., 2020; Le Bars et al., 2020), so there is also a need for new generation of multi-scale,
725 probabilistic coastal change models to adapt in conditions of great uncertainty (Ranasinghe,
726 2020).

727
728 In line with the studies on adaptation to climate change generally, our findings for coastal
729 adaptation advocate for improving anticipation proposing trajectories based on different
730 greenhouse gas emission scenarios (Berrang-Ford et al., 2021). This implies more regular
731 monitoring processes to facilitate the anticipation and management of adaptation and to identify
732 in real time the subtle signals of changing trends. It is necessary to reinforce the temporal
733 frequency and the geographical resolution of data through multi-source observation systems or
734 big data mining processes. Moreover, the improvement of information and monitoring systems
735 would offer a better evaluation of the effects of different adaptation responses. This is especially
736 true in terms of damage costs and vulnerability reduction for ecosystems, economies, and
737 communities (Berrang-Ford et al., 2021). Then, to implement and facilitate the governance of
738 adaptation policies, making a better use of multidisciplinary knowledge will be a key to success.
739 These conditions are necessary for the deployment of effective actions, involving and raising
740 the awareness of all stakeholders, from coastal managers to citizens, for an adaptation that is
741 equal to the great challenges of the future.

742
743

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745

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