Living with sea-level rise in North-West Europe: science-policy challenges across scales

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Abstract:

Sea-level rise (SLR) confronts coastal societies and stakeholders with increasing hazards and coastal risks with large uncertainties associated to these changes. Adaptation to SLR requires societal and policy decision-making to consider these changing risks, which are in turn defined by socio-economic development objectives and the local societal context. Here, we review some of the key challenges facing governments, stakeholders and scientists in adapting to SLR, and key aspects of successful adaptation, by exploring different approaches to SLR and coastal adaptation planning in three western European countries, the Netherlands, Germany and the United Kingdom. Several common challenges of SLR adaptation emerge across the different settings, including the inherent uncertainty regarding future conditions, the significant social and socio-economic consequences, the consideration and distribution of (residual) risk over communities, and the long legacy of present-day decisions that affect future risk and management options supporting future generations. These challenges are addressed differently in the three countries, e.g. in the governance level at which adaptation is initiated, although common elements also emerge. One common emerging element is adaptive pathways planning, which entails dynamic decision-making that breaks uncertain decisions into manageable elements or steps over time, while keeping options for the future. Another common element is the development of effective local science-policy interfaces, as engagement of local decision-makers and citizens is essential to manage conflicting interests. Lastly, we find that social and communication sciences have great potential to support effective science-policy interfaces, e.g. though identifying societal tipping points. Yet, in decisions on SLR adaptation, insights from these fields are rarely used to date. We conclude that supporting science-policy interactions for adaptation decision-making at relevant (inter)national to local scales through tailored multi-disciplinary scientific assessments is an important way forward for SLR adaptation in Europe.

Introduction

Coastal settlements in Europe have been exposed to coastal flood events throughout history. Dramatic testimonials from historical archives remind us of catastrophic floods in Northwestern Europe in 1099, 1421, 1607, 1717 and many others up to more recent events (Lamb and Frydendahl 1991; Jensen and Müller-Navarra 2008). The February storm of 1953 was a game-changing event for coastal protection policies in the UK and Netherlands (Mcrobie, Spencer, and Gerritsen 2005), while the 1962 storm had a similar effect on the North Sea coast of Germany' especially in Hamburg (Mauch 2012). Today coastal settlements are much better prepared for such storms as a result of a range of improvements including better flood warnings (also through modern communication technologies) and defences (Wadey et al. 2015) which reduced flood casualties (Bouwer and Jonkman 2018). However, sea level rise (SLR) threatens these gains and is a topic of increasing concern for coastal communities. Recent assessments by IPCC (IPCC 2021; 2019) lead to the conclusion of inevitable SLR over the course of future decades and centuries even if global temperatures are stabilized, and outside the "likely" or "very likely" range of projections for the 21st century and beyond rapid rises in SLR in response to accelerated mass loss from Antarctica and Greenland are considered plausible, especially under high emissions. Increases in mean sea level have a significant impact on the return period of extreme sea level conditions, reducing the return time of present-day extreme levels by orders of magnitude in selected coastal areas depending on the local physical configuration, tides and background storm climate (Fox-Kemper et al. 2021).

While the absolute sea level at a given point in time is relevant for coastal risk management, the *rate* of SLR is also a prominent and important factor. The time needed to prepare and implement coastal adaptation policies requires sufficient lead time due to the time needed to build and maintain relationships and trust with stakeholders, and the often large-scale of protection infrastructure and cross-sectoral scope of measures involved that require time for design and implementation. Acceleration of SLR will reduce the time window available for the policy preparation and implementation process (M. Haasnoot, Kwadijk, et al. 2020). The ability of sandy coasts and coastal wetlands to keep up a dynamic sediment supply rate to keep up with a rising sea level often is constrained by the rate of SLR (e.g. Wang et al. 2018), which not only affects the environment but also sediment-based and nature-based solutions.

Given these risks, several SLR adaptation challenges (or SLR governance challenges) emerge that are common across different settings. First, SLR adaptation requires decision-making under uncertainty as an underlying principle, as scientific research is unlikely to rapidly reduce uncertainty on SLR drivers, scenarios and impacts, and many decisions are long-term with substantial planning lead times. Second, SLR requires society-wide definition of adaptation objectives that also acknowledge the interest and options for future generations. Both SLR impacts and adaptation policy may have significant societal consequences, e.g. through reduced property values, non-insurable assets, etc., while adaptation investments are largely publicly funded and thus have a redistributive dimension. As such, SLR adaptation is a public policy issue that requires grappling with the tensions between local and broader public interests. Third, SLR requires managing conflicts between perceptions of acceptable levels of risk for local communities and responsible national governments. Fourth, adaptation to SLR should not be done in isolation, and should be integrated with other societal goals and planning processes, as decisions are being made now, independent of SLR, that have a long legacy into the future and can influence both the long-term need to adapt and the available solution space for future generations.

In this study, we present a qualitative comparison between coastal risk management approaches and strategies in three western European countries to address these common SLR adaptation challenges. Our comparison is based on a survey of (sub)national coastal management domains in western Europe: the German federal state of Schleswig-Holstein, the Netherlands and the United Kingdom.

We have selected these cases for our survey in order to develop insight into elements of feasible approaches to SLR adaptation. The cases have been selected based on the following rationale. First, each of the cases are set in advanced economies with long histories of coastal flood risk management interventions, in part due to their long historical experiences of coastal flooding (Bisaro et al. 2020). This implies that they are among the most advanced countries in the world in terms of addressing coastal risks from SLR. Second, while these settings share broadly similar coastal risk and socio-economic profiles, they however employ different governance approaches to coastal risk management. Indeed, in a recent study, McEvoy, Haasnoot, and Biesbroek (2021) compared the SLR scenarios being used by coastal European countries, and documented a large variation in time horizons, climate scenarios and uncertainty representation employed across Europe. Even within a small subset of coastal zones in countries in close proximity (Germany, the Netherlands and the United Kingdom) with comparable hazard and exposure profiles, different strategies and approaches to coastal risk management are employed. Thus, surveying well-advanced, yet different coastal risk management policies and governance approaches provides a diverse sample of governance settings that enables our analysis to distill the common key elements needed for addressing SLR adaptation challenges.

We also note that our case selection also implies certain limitations regarding the transferability of the elements of approaches to SLR identified in our survey. First, due to the advanced nature of economies under investigation, the approaches identified often involve a requirement for high capacity for risk management among the responsible coastal authorities and decision-makers, as well as high financial capacity. Although this capacity is challenged by reduced risk awareness that grew during the relatively successful decades without major catastrophes, for instance in the Netherlands (OECD 2014), developing countries may face greater challenges in implementing such approaches. A key focus of development cooperation and transnational policy discussions centered on climate adaptation should be on supporting developing countries in overcoming these barriers.

Further, we note that the present paper focuses on decision-making and the science-policy interfaces that support policy and societal decisions for addressing SLR. As such, we leave aside a discussion of a number of issues that influence the implementation of SLR adaptation decisions, such as vested interests of coastal property owners and developers (Taylor et al. 2012), election cycles and the related preferences of politicians (Mullin, Smith, and McNamara 2019), and the salience of coastal flood risk in local communities faced with strained budgets (Penning-Rowsell and Johnson 2015). Further, implementation of coastal SLR adaptation requires funding, and the distribution of cost between people at risk and public financing is the outcome of a political debate on solidarity and risk sharing (Bisaro et al. 2020; Hinkel et al. 2018). Such issues also present barriers to coastal adaptation and can as such be represented in the scientific support studies discussed in the present paper. However, we consider a detailed description of these specific topics beyond the scope of the present paper..

The paper is structured as follows. First, we discuss the common SLR adaptation governance challenges. Second, we survey our three cases and discuss how these challenges are being addressed in each country. A compilation of common elements and differences rooted in the historical legacy of the respective management and policy approaches is given, and a reflection on physical, socio-economic and governance dimensions is presented. Finally, we conclude with a discussion on the different approaches and distill key elements of the approaches and lessons that can be learned from these. We note that the analysis of SLR adaptation challenges, the approaches to these challenges in the surveyed countries, and a distillation of key elements of these approaches has been inspired and informed by a dedicated conference session in the context of the 2021 European Conference on Climate Change Adaptation (ECCA21 – May and June 2021) involving key experts and policy-makers from the countries surveyed, some of who are co-authors of the present paper.

Common challenges to SLR adaptation

Important common characteristics of coastal risk management under SLR include the inherent uncertainty on future conditions, the significant social and socio-economic consequences, the distribution of (residual) risk over communities, and the long legacy of present-day decisions that affect future management options. We will briefly review each of these generic characteristics before reflecting on the national case studies.

Uncertainty as underlying principle: design of climate adaptation policies commonly has to deal with considerable uncertainty regarding future climatic, environmental and socio-economic conditions, and adaptation to SLR is no exception. Moreoever, scientific progress has resulted in an increase rather than a decreasing uncertainty level for future SLR and its impacts (Bamber et al. 2019), reflecting improved understanding of the potential physical processes undermining the stability of Greenland and Antarctic ice sheets. SLR up to ~1m /century is challenging for most of our case study regions, but evolving adaptation systems can probably cope with such change. Unlikely but plausible high-end rises above this magnitude raise more fundamental questions. The long planning and implementation lead times associated with spatial planning and infrastructure design policies make the SLR adaptation topics particularly susceptible to this large uncertainty. Adaptive or flexible policy frameworks and scientific disciplines are being developed to make this uncertainty more manageable. For instance, adaptive policy planning (M. Haasnoot et al. 2013; Ranger, Reeder, and Lowe 2013) is designed to break an uncertain decision context into manageable chunks by sketching potential decision pathways, where strategies are adjusted in response to changing boundary conditions or insights. For SLR adaptation generic response options can be classified into "protect", "accommodate", "advance" or "retreat" options (Dronkers et al. 1990; IPCC 2019), but tailored pathways should incorporate locally specific risks and adaptation options. A form of early warning at climate time scales is required to guide the definition and recognition of adaptation tipping points which if reached require adaptation policy changes (M. Haasnoot, van 't Klooster, and van Alphen 2018). This early warning system includes the continuous monitoring of precursors of (accelerated) sea-level rise, such as the indicators of the stability of large ice sheets (Wouters, Gardner, and Moholdt 2019), and climate projections at different lead times (Fox-Kemper et al. 2021).

Socio-economic options and consequences: SLR may affect many aspects of the functioning of communities and ecosystems, including exposure to flooding, coastal erosion, salt water intrusion, water resource management, spatial planning, biodiversity and many more. This implies that a society-wide specification of objectives of the adaptation policy needs to be defined, where inevitable trade-offs between different interests will have to be made (Ardeshiri et al. 2019; Johnston, Makriyannis, and Whelchel 2018; Meyerhoff, Rehdanz, and Wunsch 2021; Saengsupavanich 2013). A shoreline management decision to "hold the line" will have a different stakeholder distribution of costs and benefits than decisions to "retreat" or even "advance the line". Also, "hold the line" can be implemented with very different measures, ranging from hard infrastructure, to nature based solutions or spatial planning configurations allowing intermittent flooding or "unbreachable" embankments (Pranzini, Wetzel, and Williams 2015; Gralepois et al. 2016). Even a defendable principle to "maximize societal benefit" will have both winners and losers. Enhanced safety levels by protection infrastructure will redistribute property values within the area, affect insurance policies and risk exposure, change future land use options, etc. (Landry, Keeler, and Kriesel 2003). This is a complex puzzle, particularly when the societal objectives are being defined for long time scales into the future. As such, SLR adaptation is a public policy issue which requires decision making arrangements that address the tension between the individual/local and the wider public interest.

Residual risks: The complex SLR management puzzle does not only concern the distribution of risks over different groups of stakeholders (and the resulting conflicts that may emerge), it also needs to define acceptable levels or residual risk for local communities and responsible governmental entities. Adaptation policies can increase risks for local citizens in order to avoid potentially larger damage for less protected areas. The societal response to SLR triggers new perceptions and questions of public versus private interest. Development of new urban settlements in areas that may face enhanced risk of negative SLR impacts on the long term may introduce a solidarity conflict between (private) land and house owners on the short term, versus public means that need to be mobilized to ensure safety on the long term. Similar to the implementation of measures to reduce carbon emissions by wind turbines or solar panels that have led to resistance among individuals and communities, some SLR adaptation measures can trigger reflections on the societal acceptance of risks and trade-offs with coastal amenities, which may alter over time as costs, impacts or benefits evolve. Finally, the level of public engagement into the adaptation strategy may influence the outcome of the public debate on the acceptable risk level and its management. The practice of joint fact-finding and co-creation of local solution options is shown to affect risk awareness by involved citizens, but has received little attention to date (Oppenheimer 2019).

Legacy of present-day decisions: Adaptation to SLR affects and is affected by a large variety of societal interests and dimensions. As such it should be integrated with other societal goals and planning processes (Siders, Hino, and Mach 2019). Even decisions being made now that have no apparent relationship with SLR may have a long legacy into the future and may ultimately influence the long-term need to adapt and the available solution space for future generations (M. Haasnoot, Biesbroek, et al. 2020). This applies for instance to assigning space for urban settlements, lock-ins induced by financial investments on the short-term that need to leverage a return on investment by long-term exploitation, and complex spatial planning decisions concerning large-scale infrastructure for mobility, energy or water security, which can trigger development of industry or urban settlements in future risk-prone areas. Risk assessments (and resilience metrics) underlying these complex decisions must consider long-term perspectives while appreciating the large uncertainty in the far future. Insights and tools from behavioral science may also be applicable to SLR adaptation (Anderhub and Güth 2001). They may help society to better understand how to navigate these issues over time and allow transitions towards new preferred states. Legacy of present-day decisions is also related to adaptation decisions that have a strong path-dependency and may close off some options. A typical example in flood risk management is the levee effect (e.g. Hutton, Tobin, and Montz 2019) where protected regions attract more people and developments which expect the same level of protection, leading to increasing residual risk (for future generations) under climate change. Changing the strategy such as reducing protection level, accommodate or retreat can have increasing societal and financial transfer cost.

SLR adaptation in the different countries

Coastal management in the selected case study areas Schleswig-Holstein, the Netherlands and the UK are all rooted in a long historical legacy of societal development with the sea. This includes massive reclamation for agriculture, steady erosion of many coasts, occasional major damaging storms as already mentioned, more recent industrial, port and residential/recreational developments and continuous societal debates on the protection philosophy. For example, the EU habitats directive[1] requires that the environment is now considered important together with human interests, fundamentally changing the approach relative to three or more decades ago (Lee 2001; Brady and Boda 2017). This history provides a strong context for future coastal management action, including for sea-level rise. The governing policy processes are based on a long evolution in which insights on SLR are continuously assimilated and contribute to a gradual (or shock-wise) policy transformation. To illustrate this we will elaborate on these national coastal management and policy processes, and will discuss some implications on the differences and common elements of the selection of case studies.

Schleswig Holstein, Germany

Almost a quarter of the German federal state of Schleswig-Holstein, around 4,000 km^2, located in the coastal lowlands is at risk of flooding (Figure 1). More than 350,000 people live in this area. With its approximately 1,100 km of sandy coastline, numerous islands and Halligen, and coastal lowlands it is particularly exposed to the threats posed by the sea.

For over two millennia, the inhabitants of the North Sea coast of Schleswig-Holstein have protected themselves from storm surges. Recurrent severe storm surges (e.g. in 1362, 1634, 1717, 1825 and 1962) repeatedly led to dike breaches, whereupon the dikes were constantly repaired, raised and reinforced. The Baltic coast of Schleswig-Holstein is far less exposed to storm surges. The first dikes have existed since 1581. For this coast, the severe storm surge in 1872 represents the turning point for coastal protection. Today the coastline of Schleswig-Holstein is protected by a combination of primary

[1] https://ec.europa.eu/environment/nature/legislation/habitatsdirective/index_en.htm

and secondary dikes, regional embankments, stretches of sand nourishment and engineering structures such as sluices (Hofstede 2019).

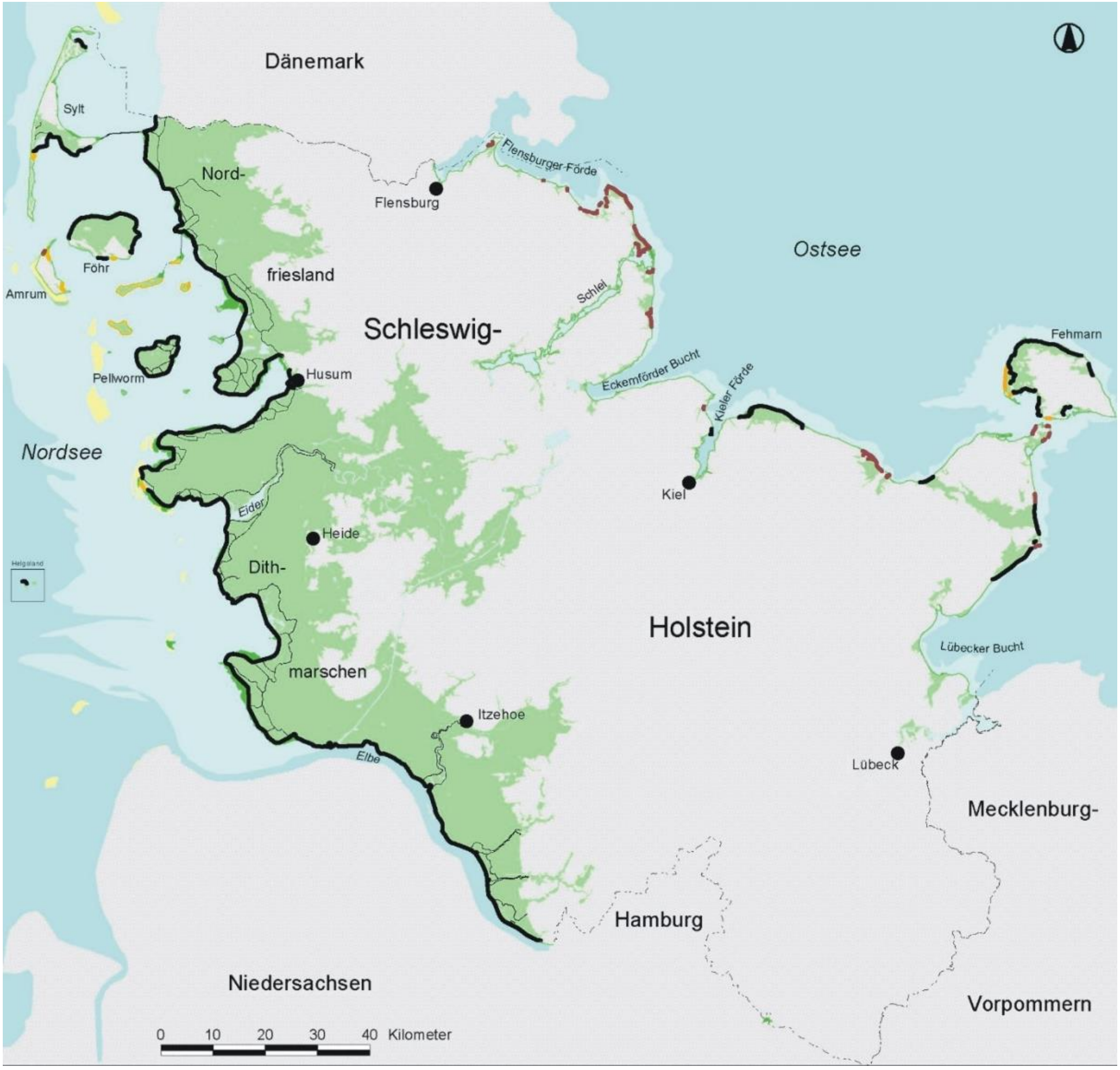

Figure 1: Overview of Schleswig-Holstein with its state dykes (bold black lines), regional dikes (brown lines), middle dikes (thin black lines) and coastal lowlands (green areas) (Hofstede 2019)

The Coastal Flood and Erosion Risk Management (CFERM) is mandated by the federal authorities to the state, and prescribes the management strategies and (nationally uniform) safety standards. Master plans are defined at the state level, and assign public responsibility to safeguarding sea embankments that are in public interest (MELUR 2013).

The safety standards do not take a risk based approach, but impose a design margin of structural flood defense measures to accommodate for future (highly uncertain) SLR. These structural flood defenses cover approximately one third of the total coastline (see Figure 1). The design margin of 0.5 m per century from the 2001 Masterplan was recently raised to 1 m per century after the release of the IPCC Special Report SROCC (IPCC 2019). However, an adaptive adaptation policy principle is implemented to accommodate SLR exceeding 1 m/century, by application of a flexible flood defense elevation. For the remaining (sandy) coastline nature-based protection measures are applied, including beach nourishment, salt marshes and natural (sandy) dune cliffs. Some of these do not reduce risk of defense breaches but strongly reduce negative impacts of such a breach, by wave breaking and dissipation.

The Masterplan and regional coastline management measures are primarily designed by experts and state authorities. A public consultation involving direct stakeholders and NGOs is applied prior to formal approval, but a strong stakeholder engagement via co-design principles is generally not intended. However, informal stakeholder engagement is arranged by means of advisory councils addressing the formulation of the CFERM regulations and accompanying large infrastructure research and design programs. For instance, the advisory council for Integrated Coastal Protection Management (BIK) brings together private and public stakeholders. This includes municipal associations, water and soil associations, nature conservation associations, nature conservation administration, coastal protection administration (MELUR 2001).

The Netherlands

A large fraction of the Netherlands area, and more than half of the national GDP and population is situated below mean sea level (Figure 2). Since the early 20th century a number of storm disasters triggered the construction of (hard) infrastructure reducing the coastline extent to the current length of approximately 450 km.

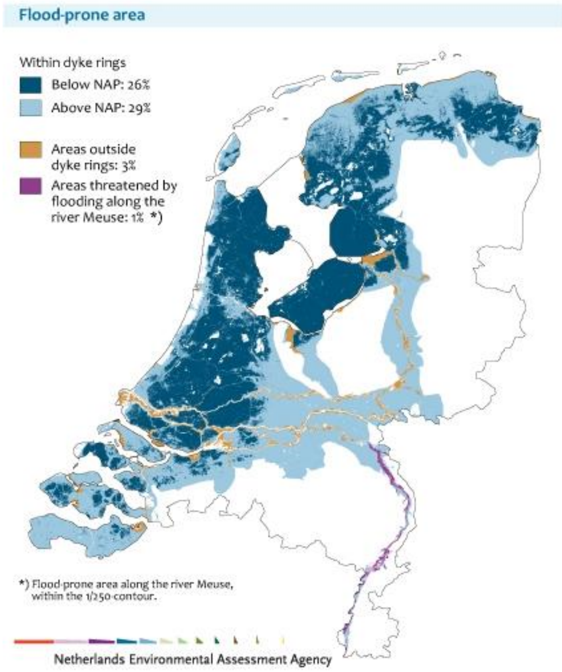

Figure 2 Flood prone areas in the Netherlands, distinguishing between levels below and above mean sea level (NAP)

Coastal protection standards are based on a risk assessment addressing individual probability to become victim of a coastal surge. This translates to design storm surges that have a probability of occurrence as low as once per 10,000 years for most coastal areas. Similar to Schleswig-Holstein protection infrastructure consists of a mixture of structural flood defense measures and sand nourishment programs aimed at holding the coastline in its current position, including storm surge barriers at five estuary locations (Van Alphen 2016). Apart from storm surge risks, SLR also increases salt intrusion into surface and ground water reservoirs, and imposes a risk for permanent flooding of the Wadden tidal floodplains.

The present-day defense infrastructure is largely generated by a national scale Delta program which was invoked after a devastating storm surge in 1953 (Kabat et al. 2005). In the Netherlands a Delta Act is in force since 2008 (Bloemen et al. 2019). It operates a (second) Delta program, and ensures long-term policy and financial planning, including periodic strategic renewals, extensive collaboration between local to national authorities and stakeholder organizations, and a program for scientific research and monitoring external pressures and internal policy progress. The Delta program essentially follows an adaptive policy strategy development process addressing the associated fields of flood safety, fresh water management and spatial planning (Bloemen et al. 2019; Klijn et al. 2012). It performs periodic updates of preferred strategies informed by signal monitoring, and construction of long-term outlooks with solution options and policy pathways (M. Haasnoot et al. 2013). A multi-level governance structure is inherent to the Dutch water and risk management (OECD 2014). It distributes responsibilities between national and regional levels, where flood risk management of the coastal and main river systems is executed by the federal government, while flood risk from pluvial extremes or smaller fluvial systems are regionally managed by water management organizations and municipalities.

The possibility of extreme SLR, and in particular the notion of a rapid SLR acceleration that may reduce the available implementation time for large-scale defense measures, was recently recognized as a potential game changer for strategic policy making (M. Haasnoot, Kwadijk, et al. 2020). An ongoing research program is currently exploring adaptation pathways and local implementation options of an alternative form of the "protect/accommodate/retreat" framework comprised in four anchoring narratives for nation-wide adaptation strategies (Marjolijn Haasnoot et al. 2019). Time is a key dimension in this framework, addressing time scales associated with early warning, implementation lead times, cost/benefits of adaptation measures, and path-dependencies of solution options.

England, United Kingdom

England is one of four devolved coastal administrations in the UK. The English coastal defense system of the 5000 km long coastline has also been shaped by extreme storm conditions over the course of many centuries. Since the 1953 North Sea storm, there has been a progressive evolution of management which continues (e.g., (Nicholls et al. 2013; Haigh et al. 2020)). This includes the development of a system of forecasts and warnings together with improved and more extensive defenses and use of economic risk and benefit-cost assessments. In the 1990s there was a coastal policy paradigm shift towards a "systemic risk" perspective, which recognizes that risk is influenced by multiple factors (e.g., sources such as surges, waves and sea-level rise, or receptors such as increasing coastal development, as well as adaptation). The policy response has also become more stratified comprising three layers; (1) Shoreline Management Plans (SMPs) set the strategic aspirations (Figure 3), (2) more detailed Strategy Studies which set the conditions for (3) Projects where implementation occurs. This allows for more dynamic adaptation approaches of managed realignment and no active intervention as well as defense (hold the line) alone. These approaches are being reviewed at the present time in the SMP Refresh, and as noted later in the paper, the use of resilience in coastal management is attracting increased attention.

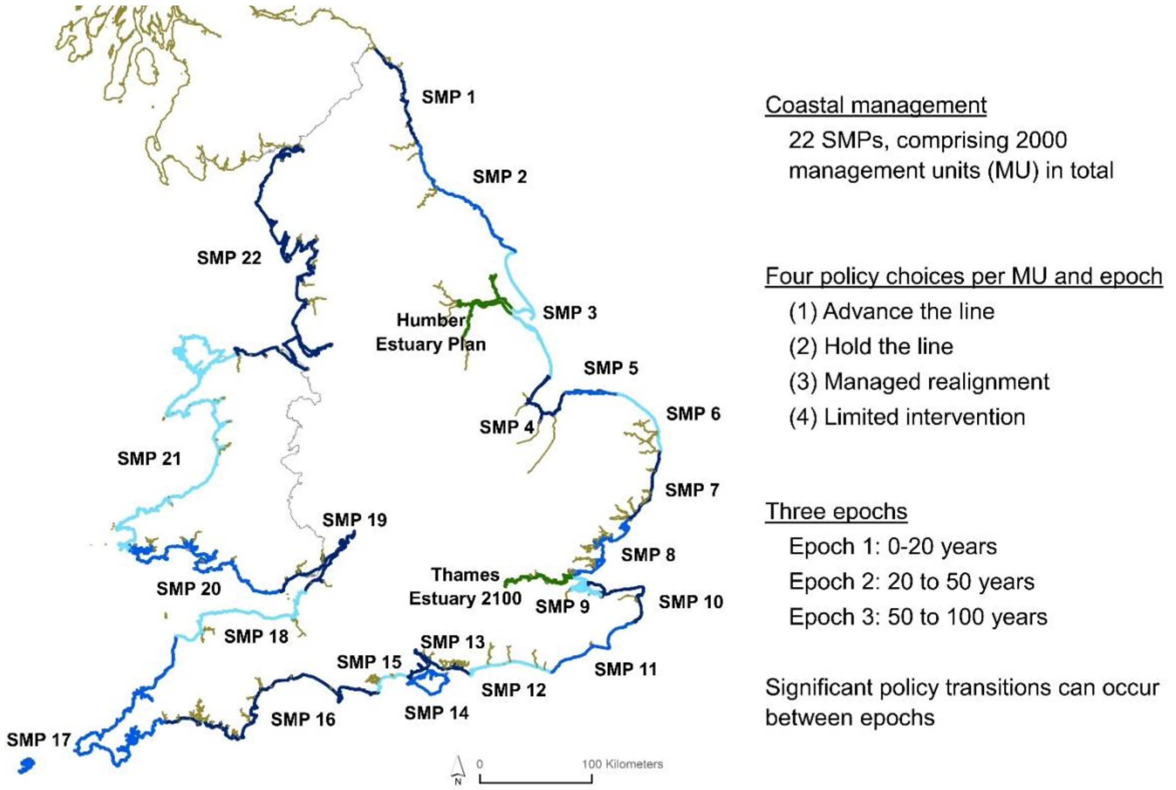

Figure 3: The 22 Second Generation Shoreline Management Plans (SMPs) around England and Wales and two Estuary Management Plans (Humber and Thames). The extent of each SMP is coloured for visualisation purposes

Since 2008 a national Climate Act formalizes frequent (every five years) assessments of coastal adaptation via the Climate Change Risk Assessment. For the Thames Estuary an adaptive approach has been developed sketching potential policy development pathways triggered by SLR and socio-economic developments (Ranger, Reeder, and Lowe 2013).

An agreed procedure to assess costs and benefits of flood alleviation measures is applied, prescribing that public funding support of measures requires long-term benefits to exceed the investments. This principle explicitly acknowledges that there are many discrete coastline segments that cannot be cost-effectively protected from or adapted to flood and/or erosion risk, or runs the risk of falling below the cost-effectivity threshold as SLR proceeds, and the (CCC 2018) argued that widespread retreat looked likely unless coastal investment is substantially increased. At the same time, the objectives of coastal management are broadening from "hazard protection" to "increasing societal resilience", which leads to explicitly addressing nature-based adaptation, adaptive coastal management strategies, and acknowledging the need to address handling residual risks. An illustrative Coastal Resilience Model (Townend et al. 2021) has been developed to explore the resilience of coastal management units which includes stakeholder perspectives and has the potential to inform resource allocation and policy making. Metrics for community resilience (including non-monetary topics), and accounting for cost/benefit terms of (far) future generations need to be developed in this trade-off process.

Discussion: Elements of feasible approaches to SLR adaptation

The description of the national perspectives above illustrates the multiple dimensions of societal adaptation to SLR. Adaptive approaches are utilized in every case study to address the considerable uncertainty in future SLR and societal impacts. Formal management planning cycles are defined at national/federal level and implemented at local community scales, adopting generic principles of cost effectiveness, solidarity and stakeholder representation in the associated planning and decision processes. The level of stakeholder engagement varies between (informal) consultation to (formalized) co-design of solutions at community level, but a trade-off process between distributed interests, monetary versus non-monetary topics, solidarity between generations, and management of residual risks is usually embedded in the adopted adaptation policy making process.

This comparative survey generates a number of relevant observations and recommendations. We discuss these from the perspective of key elements of *scientific support*, *collaborative efforts* between regions and disciplines, and the need to define *societal objectives*.

Scientific support

With the gradual shifts in paradigms to address coastal adaptation, the science agenda and its role in supporting societal decision taking is also shifting. The multi-dimensional scope of societal transitions requires a scientific analysis framework that can quantify, visualize and evaluate multi-criteria problems in a way that is consistent with the societal decision contexts, and can enable transparent and explicit deliberations by societal stakeholders. Formal multi-criteria analysis in order to identify preferred solution explicitly involves societal and personal values that play a dominant role in assigning weights to different topics. A scientific analysis can assist in expressing explicitly and transparently. Scientific assessment thus plays a supporting role here, as nearly every outcome of a collective decision problem is the result of a trade-off between winners and losers. Win-win solutions are rare, and claims for these need to be carefully scrutinized by scientific analysis. Indeed, for complex decision problems, it may be difficult for individuals, even experts, to form consistent preferences over different options and criteria, and scientific tools can help elucidate these (Saaty 1987).

There are quite a few emerging new scientific "kids on the block": (1) enhanced attention for compound flood risks (Zscheischler et al. 2018), (2) quantifying societal/ecological damage functions or benefits of solution options (Johnston, Makriyannis, and Whelchel 2018; Meyerhoff, Rehdanz, and Wunsch 2021), (3) defining metrics for community or coastal resilience (Masselink and Lazarus 2019; Townend et al. 2021), (4) distillation of early warning signals at climate time scales (M. Haasnoot, van 't Klooster, and van Alphen 2018), and (5) mapping environmental constraints on spatial planning (Wannewitz and Garschagen 2021). This short list of topics is of great relevance for the societal discussions and indicate where deepening scientific understanding is required.

The science/policy interaction is also a topic of importance. Scientific evidence needs to be assessed and presented in a context-relevant format, appreciating the appropriate scale, domains, time frames and options. In short, scientific evidence to address societal decision-making needs to be salient (Cash et al. 2003). Salient scientific knowledge is generally developed through effective co-development process that involve both stakeholders and scientists in an assessment process that successfully integrates generic scientific principles, models and data, with locally specific preferences, knowledge and experiences. It also requires a format that allows joint problem definition, fact-finding of regional challenges and co-design of regional solutions. The art of "designer science" is maturing (Winter 2008; Christel et al. 2018; Le Cozannet et al. 2017), where localized visualization of impacts (floods, salinization, erosion), and spatial solutions are rapidly developing in order to improve both problem-definition and identify the solution space by incorporating the perspectives of stakeholders at various scales. Design-oriented research principles with tailored interaction between scientists and citizens can enlarge mutual engagement and education, which is required to meet to local scale perspective. Social science and communication science can help map societal trade-offs and tipping points. A successful societal transformation requires co-production processes that involve stakeholders along the entire assessment process in order to define problems and solutions, and a scientific guidance to the proposed approaches and methods.

Multilevel interaction and collaboration

In the case studies discussed above an explicit interaction between the national/federal level on one hand, and the local/community level on the other is occurring. Generic policy principles, and (fractions of) required funding are provided from national/federal levels, while mapping challenges and solutions is taking place at the local/community level. In addition explicit collaboration between individuals from different disciplines (multi-disciplinary) and with different responsibilities (trans-disciplinary) is occurring, which is required in order to ensure adequate engagement and support for the tough decisions that are required.

Similar to the common practice of scientists sharing their results and findings, an enhanced system of sharing experiences in policy definition and implementation (both between regions and at international levels) may lead to additional cross-fertilization of ideas and opinions, promoting the search for effective adaptation solutions. This includes sharing experience of the societal response to sea level rise: scenarios used, concrete adaptation solutions, sharing expertise on stakeholder intervention, comparison of legal structures, etc.

The long-term scope of the topic of SLR adaptation also requires a long-term collaboration arrangement between the various actors. National and federal climate adaptation acts provide a legal reference for sustained monitoring and planning of the adaptation implementation process. The supporting process of (scientific) knowledge assessment and dissemination also needs to have a long-term perspective. Insights into the climate system (and the corresponding climate change scenarios), societal dynamics and the preferred solution directions are developing rapidly and continuously. A progressive shift in the management of the science/policy interface, from short-term, project-oriented approaches to (long-term) more strategic and structured approaches is apparent in our three case studies, enabling more sustained knowledge management, including sharing the state-of-the-art.

Definition of societal objectives

The complex interplay between long- and short-term goals, distributed interests and risks, explicit and hidden consequences and time-varying societal values calls for an integrated assessment of drivers and solutions, but this integration is not a trivial task as shown by the Future Flooding and Coastal Defence Foresight study in the UK (Thorne, Evans, and Penning-Rowsell 2007). In practice it is necessary to delineate sub-topics and define partial decisions and corresponding responsibilities and knowledge requirements.

A transparent legal framework is a prerequisite for policy directions that can count on sustained societal acceptance. Further, within this framework societal objectives need to be defined in order to support focused and effective decision making. But these objectives are preferably to be translated into local context-specific measures that comply with community resilience targets. This requires legal space for local redistribution of risks and benefits, non-monetary targets (such as ecological quality and individual wellbeing) and secured attention for long-term perspectives that avoid negative lock-ins (Mach and Siders 2021).

To these ends, the scientific support can contribute to a transparent picture of long-term risks, benefits, options and tipping points. Co-designing context-specific solution pathways that makes uncertainty manageable by accommodating future changes in external conditions or societal preferences is a powerful strategy to create societal awareness, engagement and buy-in.

Summary and conclusions

Sea level rise (SLR) is a topic that is associated with large uncertainty, and also cuts across a wide range of societal issues and decisions around the need to secure community resilience against changing environmental conditions. As a result, SLR management policies have significant potential consequences for the (re)distribution of risks and benefits in coastal areas. To avoid lock-ins of negative future risk profiles or solidarity pressures it is important to consider long-term pathways and how they are shaped by near-term decisions: this mandates a more proactive and long-term view that has been typical in the past. Further, measures to protect against negative SLR impacts are associated with residual risks and trade-offs between societal costs and benefits, including their ecosystem consequences.

As part of the broader climate adaptation challenge, coastal management to address SLR impacts on coastal flood risk is included in national adaptation frameworks in most European countries, including the three countries explored in this paper. In many ways these countries are leaders in this regard. From this brief analysis, we extracted a few generic conclusions. The science required to support SLR management needs to embrace new topics and collaboration protocols. Impacts of SLR are society-wide and long-term nature of SLR impacts which requires transformative adaptation and climate resilient development. It therefore is more than a natural science and engineering domain and requires intensive collaboration between a range of expert disciplines in social and communication sciences, as well as across the different levels of government and society. This implies a more collaborative and multidisciplinary/transdisciplinary approach which may encourage the development of new scientific structures and ways of scientific working. Our societal goals are evolving as exemplified by initiatives such as the EU Adaptation Strategy and the EU Green Deal and this may have major effects on what we aspire to in the future. We already see evidence of such transformations in the three countries as coastal management involves the input from multiple disciplines and stronger citizen engagement, albeit there is still room for improvement on the topic of long-term transformative adaptation and climate resilient development. Learning by doing is an important approach and sharing local experience with development of solution strategies and collaboration networks can help the formulation of new methods and transparent societal objectives. This can provide the effective scientific support that the major societal transformations that lie ahead of us require.

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