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Generic adaptation pathways for coastal archetypes under uncertain sea-level rise

Marjolijn Haasnoot*[,1,2], Sally Brown[3,4], Paolo Scussolini[5], Jose A. Jimenez[6], Athanasios. T. Vafeidis[7], Robert J. Nicholls[3]

[1] Deltares, Delft, the Netherlands
[2] Utrecht University, Utrecht, the Netherlands
[3] University of Southampton, Southampton, UK
[4] Bournemouth University, Bournemouth, UK
[5] Institute for Environmental Studies, Vrije Universiteit Amsterdam, Amsterdam, the Netherlands
[6] Universitat Politècnica de Catalunya·BarcelonaTech, Barcelona, Spain
[7] Department of Geography, Christian-Albrechts University Kiel, Kiel, Germany.

E-mail: marjolijn.haasnoot@deltares.nl

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Abstract

Adaptation to coastal flood risk is hampered by high uncertainty in the rate and magnitude of sea-level rise. Subsequently, adaptation decisions carry strong risks of under- or over-investment, and could lead to costly retrofitting or unnecessary high margins. To better allocate resources timely and effectively, and achieve long-term sustainability, planners could utilise adaptation pathways, revealing the path-dependencies of adaptation options. This helps to identify low-regret short-term decisions that preserve options in an uncertain future, while monitoring to detect signals to adapt. A major barrier to the application of adaptation pathways is limited experience. To facilitate this, here we generalize this pathways approach for six common coastal archetypes, resulting in generic pathways suitable to be adjusted to local conditions. This provides a much richer analysis of coastal adaptation than provided by any previous analysis, by assessing the solution space and options over time for a variety of coastal regions. Based on this analysis, we find that the number of adaptation options declines while sea-level rises. For some archetypes, it becomes clear that long-term thinking is needed now, about if, how and when to move to transformative options, such as planned retreat, which may presently not be considered or acceptable. Our analysis further shows that coastal adaptation needs to start earlier than anticipated, especially given time required for local debate and choice and to implement measures.

Keywords: coastal zone management, adaptation, sea-level rise, decision making, uncertainty

1. Introduction

Uncertainty about the future complicates and can even paralyze decision making on adaptation. Large uncertainty concerns the rate and magnitude of sea-level rise[1–3]. In the context of coastal adaptation, this compounds with uncertain changes in future population, economic developments and societal values, and results in deep uncertainties. Depending on climate change mitigation, by 2100, mean sea-level may further rise by 0.26 to 0.98 m[4], with a low probability that sea level rises higher due to accelerated ice sheet melting[3,5]. Even in case emissions are reduced as defined in the Paris Agreement, sea-levels will continue to rise, although more slowly[6,7].

Adapting to sea-level rise typically entails large-scale investments with long planning and implementation time, and potentially large societal impacts for current and future generations. In the face of deep uncertainty, a "wait and see" approach to adaptation is often taken, until uncertainty is reduced[8]. However, this could result in poorly planned adaptation, which may be less effective, and could limit future adaptation options[9].

To support decision making under deep uncertainty, an adaptation pathways approach was devised[9,10]. Adaptation pathways are sequences of linked (portfolios of) actions that can be implemented as conditions change. Typically, when uncertainty is high, they start with low-regret actions that maintain future options[11]. As time progresses and conditions change, this initial low-regret adaptation action may reach a threshold when it no longer performs acceptably, i.e., when an adaptation tipping point occurs[12]. Parallel to this, conditions will reach a threshold that makes an alternative adaptation option viable, i.e., an opportunity tipping point is reached. Therefore, a switch to the alternative option is needed to continue to achieve objectives, and a pathway of adaptation decisions emerges. Anticipating tipping points is important for optimal adaptation, therefore monitoring to detect early signs of change is required[13]. These signals for adaptation are then used to timely implement planned adaptation options or to adjust the plan if needed.

Adaptation pathways support decision making under uncertainty in three main ways. First, they can help overcome the policy paralysis due to uncertainty, by putting adaptation decisions into manageable steps over time, starting with low-regret actions. Second, the visualization of alternative pathways and their costs and benefits makes the path-dependency of options explicit[9], showing that past decisions can open some options and foreclose others[14]. This helps to recognize the risk of lock-in situations, minimize costly retrofitting and achieve long-term sustainability[15]. Third, adaptation pathways deal explicitly with timing and thereby help to define not only *what* decisions but also *when* decisions are needed for adaptation.

So far, adoption of pathways of adaptation to sea-level rise includes the UK Thames Estuary 2100 plan[10], the Dutch Delta Program in the Rhine-Meuse delta[16], the Bangladesh Delta Plan[17,18], the township of Lakes Entrance in Australia[11],the Hutt river[19] and national guidance[20] in New Zealand, and the Aveiro coast in Portugal[21]. In spite of their proven potential to support decision making under uncertainty, application of adaptation pathways remains uncommon[19,22]. One reason for this may be the challenge of the complexity of exploring and evaluating the wide range alternative pathways into the medium and long-term future, rather than the short-term where coastal management decisions are often focused.

Although singular adaptation options in response to sea-level rise have been analyzed widely, to date no one has considered the linkages and path-dependency of these options with an adaptation pathways framework. The pathways studies that address this path-dependency are limited and location dependent, and therefore difficult to transfer to other areas. Hence, it is often unclear how different adaptation options are compatible with each other, and what pathways for adaptation to sea level rise could look like. This paper addresses this gap, and complements the local pathways studies.

The goal of this paper is to create and describe generalized adaptation pathways applicable to a wide range of environments (referred to as archetypes) and common adaptation methods. Thus, our motivation is to provide a broad framework and method to construct pathways, thus enabling coastal managers to develop their pathways specific to their coastline and management goals. This advances the science by building upon the generic traditional 'protect-accommodate-retreat' options and considering how in reality these options can be sequenced under rising sea levels, while extending planning timescales, and considering path-dependency and uncertainty. We do not consider governance or socio-economic conditions as these can be very local in nature and determine the feasibility and preference for certain pathways.

The derived generic pathways for the coastal archetypes (described in section 3) are visualized, described with narratives and further illustrated with case studies on past and potential future pathways (Section 4). We then explore how these generic pathways can be tailored to create local pathways to support adaptation planning by coastal managers, and discuss their limitations (Section 5).

2. Methods

To derive a typology of generic adaptation pathways for coastal adaptation to sea-level rise, we created a set of common coastal archetypes through geomorphic setting and land use for which generic adaptation pathways can be developed. We then designed and visualised the potential adaptation pathways through identifying hazards, management goals, adaptation options and their tipping points.

2.1 Derivation of coastal archetypes

Physically, adaptation options principally depend on geomorphology and land use. Using existing classifications for geomorphology[23–27] and land use[28], we divide these into three sub-categorizations for geomorphology and two for land use. Our three low-lying coastal geomorphic settings are:

- Open: a coast with sediment, without river mouths;

- Delta: a deltaic coast with wetlands;
- Estuary: an estuarine coast with wetlands.

Cliffed environments are not considered as they are not low-lying or significantly threatened by sea-level rise. Small island settings are also excluded as these may contain the geomorphic features above or, depending on size, require a different approach to adaptation at island level.

The two land use types considered are:

- Urban: A densely populated coast, with substantial and/or costly building stock, and/or tourist attractions, where sea-level rise would result in significant damage and disruption. Adaptation would typically have a high benefit-to-costs ratio.
- Rural: A predominantly agricultural coast, typically of lower value than urban areas, with sparser dwellings, low population density and limited tourism. Sea-level rise could result in disruption of local livelihoods (but without regional or national implications), but not in significant infrastructure damage. Adaptation would typically have lower benefit-to-cost ratio than in urban areas.

These geomorphology and land use types were combined to form six coastal archetypes (Figure 1). Archetypes describing purely natural coastlines were not considered for the pathways analysis, as adaptation pathways are much less likely to be necessary. We have not considered socio-economic conditions as these are highly localised and cannot be conceptually modelled. However, we account for localisation of pathways with respect to these conditions. Limitations of these archetypes are discussed in Section 5.

2.2 Derivation of adaptation pathways to sea-level rise

To design adaptation pathways for the coastal archetypes, we follow the steps described in the Dynamic Adaptive Policy Pathways approach[9]. First, we specify the management aims and analyse the impacts of sea-level rise for the different archetypes. Second, adaptation options are identified to address the aims and impacts. Each adaptation option is assessed against its effectiveness to reduce the following impacts that are most relevant for coastal systems (e.g., [29–31]; see also Supplementary material):

- submergence (the permanent covering of water over the land),
- temporary flooding from extreme events (the temporary covering of the land or a wetland),
- erosion (the permanent destruction of land due to attack from sea water),
- rising groundwater levels (the raising of the water table and impeded drainage)and
- salinization (an increase in the salt content of the soil, ground water or inland water bodies).

Third, we define opportunity tipping points and adaptation tipping points for each measure. We thus considered reasons to adapt, rather than limits (e.g. [32]) or barriers (e.g.[33]) for adaptation. These reasons to adapt are defined as:

- Engineering design conditions: when design conditions are exceeded and measure effectiveness decline;
- Space and material availability: where there is insufficient space to build a defence or to allow for retreat, or where there are insufficient raw materials available;
- Cost-benefit conditions: when costs exceed benefits;
- Social (un)acceptability: when a lack of government or stakeholder support for adaptation inhibits action or generate strong opposition or social conflict with (part of the) population or stakeholders, or when support generates opportunities to implement a measure;
- Economic productivity: where the economic production or service level has insufficient yield or quality to be viable (e.g. food production).

Fourth, pathways are designed by structurally sequencing adaptation options while considering a) the relative amount of sea-level rise they are able to address as indicated through the tipping point conditions and b) the path-dependency of options. In addition, narratives were written describing sequences of adaptation options as sea-levels rise. The pathways are then visualized in a pathways map for each archetype and illustrated with pathways found in literature on historic pathways and potential future pathways in planning studies.

3. Coastal archetypes and adaptation options

The suitability of adaptation options and pathways depends on the six broad archetypes representing the combinations of dominant geomorphology (open coast, delta, and estuary) and land use (urban and rural). Figure 1 illustrates the archetypes, the direct and indirect impacts of sea-level rise they already experience or could experience in the future (see also Supplementary Material), and examples of real-world occurrence.

[FIGURE 1 HERE]

For each archetype, sea-level rise has typical physical and socio-economic impacts, depending on geomorphology and land-use respectively. For example, in terms of our archetypes, in urban areas, sea-level rise may result in erosion of open coasts with beaches (archetype 1a) and thereby a decrease in the beach recreational carrying capacity which may have economic (coastal tourism) and/or social (leisure) consequences. Conversely, along rural open coasts (archetype 1b), the loss of natural values supported by the beach may be more prominent and can be quantified in terms of affected ecosystem services. Consequently, these archetypes require separately analysis, reflecting different management aims and thus adaptation goals, measures and pathways.

Following the methodology described in Section 2.2, step 1 aims to describe the management aim. This typically depends on land use:

- In urban areas, the management aim is to reduce coastal flood, erosion and local water levels, i.e., to protect livelihoods and promote industry and tourism and reduce expected damages in coastal infrastructures.
- In rural areas, the management aim is to safeguard food production from temporary flooding, erosion, salinization and rising ground waters, and to defend smaller, local communities and industries from temporary flooding and erosion. It does not necessarily aim to address permanent flooding. In areas of high natural values, adaptation aims at ensuring accommodation space for ecosystem facing accelerated erosion (e.g., wetland migration).

Step 2 of the method (Section 2.2) aims to identify adaptation options to address impacts of sea-level rise. A list of thirteen common and proven adaptation options was compiled (Table 1; Supplementary Material) and divided into three categories following the International Panel on Climate Change (IPCC)[34]: protect, accommodate and retreat. We have deliberately not included 'attack' or 'advance' as a fourth option which is at times used as a method of defence or due to land claim, as it is often site-specific and a special case of protect. Attack may have similar tipping points but at different relative timings to protect.

To be consistent with the archetypes, the adaptation is considered in more generic functional terms. For instance, breakwaters and wetlands are wave dissipation structures, Their suitability depends though on the local situation, as a wetland requires accommodation space and time to growth if not already present. Also, early warning systems are appropriate across all coastal archetypes, so they are omitted.

[TABLE 1 HERE]

The third step of the method (Section 2.2) is to define adaptation and opportunity tipping points, based on literature and expert judgment of the authors. When applied to local settings (Section 5), these tipping points need to be adjusted to local conditions.

Most adaptation options address several impacts of sea-level rise, and have several reasons for opportunity and adaptation tipping points (Table 1). These tipping points were assessed in terms of a relative sea-level rise: low (e.g. less than 0.3 m), medium (e.g. 0.3-0.8 m) and high (e.g. more than 0.8 m). The boxes of figure 2 thereby present the relative amount of sea-level rise the adaptation options can address before management aims may start to fail. For example, a wave dissipation structure can prevent areas from flooding by lowering extreme water levels, and can therefore be successful for low amounts levels. As sea levels rise further, the average water level becomes too high, and additional measures, such as dikes or no-build zones, are needed. The exact values for sea-level rise are location specific. Note that this is deliberately independent of the time dimension, so as to allow analysis without assuming specific climate scenarios (or associated socio-economic conditions which typically consider up to 2100), for which rates of sea-level rise vary[4,35].

Reasons for opportunity tipping points vary. For example, constructing a storm surge barrier normally takes decades for planning and implementation (e.g[10].). The use of nature-based options such as planting mangroves or wetlands requires not only time to grow and stabilize to become effective, but also space and sufficient sediment supply[36].

4. Generic pathways for coastal archetypes

Step 4 of the methodology described in Section 2.2 involves pathway design. These pathways are described in Sections 4.1-4.4 for each archetype. The adaptation pathways for each archetype are shown in Figure 2. For some archetypes, we could not find a real-word example of an adaptation pathway, as very few exist. Hence, we also illustrate conceptual possibilities of our generic pathways from the past or other (non-pathways) plans from real case studies where they exist.

[FIGURE 2 HERE]

4.1 Urban open coast

For an 'urban open coast' archetype potential impacts of sea-level rise include erosion, temporal flooding from extreme events, submergence and rising groundwater. Adaptation options thus aim to protect from flooding and erosion and to maintain the coast for recreation and tourism. Today, the most common adaptation falls under the 'protect' category (see Table 1 and Table SM1 in Supplementary Material), but accommodation through flood proofing and, planned retreat by enforcing no-build zones are becoming more widely considered.

A common pathway for this archetype, when erosion is the main impact, starts with beach nourishment to maintain the coastline and protect the area from flooding. Nourishment volumes increase or become more frequent as sea-level rise accelerates, as expected on the Dutch coast[16]. For high-end sea-level rise, beaches may need to be almost continuously nourished, which may be unacceptable for inhabitants, tourists and nature, and thus reach an adaptation tipping point for social reasons. This could be avoided by adopting a mega-nourishment based-strategy as in the Dutch 'sand engine' approach[37]. To enable nourishment as an option in the future, more spatial reservations for sand mining are needed in the North Sea to prevent that other land use will take over (e.g. windmills or island for urban or industrial development). Still, there may be a threshold as a wide beach in front of an urban coast may not be accepted. Ultimately, a solution here must recognize the trade-off between the higher costs associated with continuous nourishments, the stronger modification of the shoreline caused by mega-nourishment[38], and the social acceptability of an option. Other reasons for adaptation tipping points for nourishments are lack of cost-effective resources (i.e. sand[35]) and high energy costs[39]. These tipping points may lead to combining nourishment with controlled retreat measures such as planned no-build zones or managed realignment in selected locations. Such a pathway was devised northern Portugal (Aveiro), where costs, effects on the ecosystem and the availability of sand determine adaptation tipping points and the switch from nourishment to planned realignment in combination with flood proofing of infrastructure[21].

A pathway addressing flooding as the main impact will consist of first using protection measures, such as wave dissipation structures or flood gates in high-risk areas to mitigate storm-induced floods under low sea-level rise, and then moving to dikes or seawalls as flood frequency becomes unacceptable.

Simultaneously, adaptation could also start with planned no-build zones / set-back line (e.g. as was proposed in Cape Town[40]) and flood proofing new infrastructure and buildings (e.g., elevating houses on piles, as common in the U.S. and Asia). This could be combined with protection for existing buildings (e.g., south east Queensland)[41], as elevation of existing parts of the city could be more expensive and socially unacceptable or not technically possible. With higher sea-levels, planned realignment and relocation are possible, although the lack of space for realigning may present a tipping point. Such pathways that start with accommodate through changes in land use and building regulations, and later switch to either protection with barriers, or planned retreat have been mapped for Lake Entrance in Australia[11,42].

4.2 Urban deltas

Historically, many 'urban deltas' were drained and pumped to remove excess water and lower groundwater levels. Subsequently dikes were built to protect against flooding. Human interventions extend beyond the deltaic coastal zone, such as upstream damming (Mississippi delta, U.S.), drainage (Rhine-Meuse delta, Netherlands), groundwater abstraction (Mekong delta, Vietnam), which may cause subsidence[43] and thus a larger relative rise of sea-level. Consequently, many deltas are already following a specific pathway, and are locked into limited future options.

Continuing on the pathway of protection through dikes in combination with drainage and pumping is a common pathway in urbanized deltas (e.g., deltaic part of the Netherlands[16]; Jakarta, Indonesia[44]). Nevertheless, nature-based defences to reduce waves are increasingly considered[45] to reduce flood risk, and could thus shift the pathway.

A simultaneous or complementary pathway for no to low levels of sea-level rise could start with accommodation, including flood proofing or elevating infrastructure for low levels of sea-level rise, allowing for occasional flooding. For example, in the Mekong Delta, 'accommodate' options, such as floodproofing and raising property, could postpone dike construction[46]. Additionally, accommodate measures could be combined with breakwaters to ensure reduced flood risk and/or to extend the adaptation point.

Hard defences such as dikes could occur with any level of sea-level rise, but would be increasingly necessary with low to medium levels of sea-level rise, as accommodation options reach tipping points which limit their efficiency. As tidal barriers long enough to protect deltas are expensive[46], they are not considered an option for this archetype. In practice, they are limited to parts of the delta that resemble the estuary archetype, where they aim to protect areas of particularly high exposure (e.g. Ho Chi Min City[47]) to be cost effective. Closed barriers or storm surge barriers that frequently need to close can have adverse impact on port functioning, which is a future concern for the port of Rotterdam in the Rhine–Meuse delta[12].

As floodgates, floodproofing and wave dissipation structures reach their tipping point, local land raising becomes a plausible possibility, and could be undertaken as urban areas are renewed. This renewal constitutes an opportunity tipping point. Conversely, adaptation tipping points will mainly be determined by cost-benefit conditions, space and material availability (e.g. sand) and social unacceptability of dislocation and loss of cultural value in the relinquished districts[12]. Planned retreat would be either a last resort (and could be used simultaneously with land raising), used in risk sharing across a wider area or through set-back lines to gradually relocate infrastructure to higher ground. Such pathways have been described in literature for the Netherlands and the US[48,49]. A recent study on impacts of high-end sea level rise for the Netherlands[50], has triggered discussion on the sell-by date of the current protection strategy under high sea level rise, and the need to consider transformative adaptation options including partly retreat. In coastal cities with porous ground (e.g. Miami), sea water will continue to push up flood water from underground, making relocation an option that needs to be considered.

4.3 Urban estuaries

In 'urban estuaries', such as Elbe/Hamburg, Thames/London and Hudson/New York, fluvial and coastal flooding may coincide. The management aim is to protect the city, industry and port from permanent or temporary flooding, and to a lesser extent from extreme events and rising ground waters. Thus protection and accommodate are more common adaptation types over retreat.

One pathway may involve flood retention areas for low levels of sea-level rise, thus reducing river discharge (e.g. Netherlands). With increasing sea-levels, quay walls will have to be raised (e.g., Tai O, Hong Kong[51]). Land raising is also possible, as seen in Hamburg, and was a possible solution to flooding along the Southampton, UK waterfront[52]. When a large area requires protection or sea-levels become too high so that land raising is not cost-effective along the whole estuary, a storm surge barrier or relocation to higher grounds may be more suitable (if economically viable and socially acceptable).

A storm surge barrier already exists in the Thames Estuary. To continue to protect London, the low-regret option identified was to raise existing defences, enabling the possibility of raising them further in the future, in addition to incorporating structural flexibility and reconsidering safety margins. Only with much higher sea-level will a new downstream barrier be built[10]. For rural areas of the estuary, planned retreat is considered, but this is limited due to lack of space[53].

Alternatively, a pathway set on the 'protect' trajectory, could start with no-build zones, floodproofing of infrastructure, or floodgates. With higher sea-water levels dikes and storm surge barriers are needed if retreat is not preferred. This can be illustrated with the plans for some localities around New York City. Post Hurricane Sandy in 2012 an overall policy of 'no-retreat' was defined[54]. Alternative pathways include protection through floodwalls and reclaimed natural barriers (dunes and wetlands), and accommodation through flood proofing and elevation of infrastructure[55]. Storm surge barriers are considered an option at a later stage[56]. Thus, a multi-pronged approach opens possibilities.

4.4 Rural open coast / delta / estuary

Archetypes 'rural open coast / delta / estuary' have similar and fewer adaptation options and pathways and are therefore discussed together (Figure 2). Impacts are similar to those in their urban counterparts, but preferred adaptation options are fewer and their tipping points are different due to lower socio-economic impacts on less dense population and infrastructure. Adaptation typically focuses on maintaining food productivity and the natural environment benefits. Low cost-benefit ratios may limit adaptation pathways. Differences between pathways for rural open, delta and estuarine coast are caused by land use characteristics (especially for food production or water extraction), ecological values, length of coast that may need protection and subtleties in the types of adaptation that is suitable.

Pathways for rural areas emphasise accommodate and retreat options before protect options. For example, to maintain food production as sea-level rises and salinity and groundwater levels increase, a typical short-term measure is to improve or continue to maintain field drainage, possibly complemented with pumps (in Figure 2 this is considered as part of the current situation). Productivity may be further enhanced by switching first to salt tolerant crops for low sea-level rise, then to flood tolerant crops or aquaculture for a medium sea-level rise (e.g., southwest Bangladesh[57], Mekong delta). On the long-term, if sea-level continues to rise and flooding becomes permanent, managers are left with options to relocate or raise the land. Raising land may be undertaken through river diversion, such as is being done or planned for rural parts of the Mississippi delta[35], the southwest of Bangladesh[57] and the Ebro delta[58].

Another pathway could start with low-cost green protection measures with for example reed beds or mangroves, to dissipate waves and reduce erosion and flooding. For example, pathways for the Danube and Ebro deltas first consider green protection with reeds combined with raising the land via strategic sediment measures, with a later option of set-back lines within a planned realignment of the coastline[58]. Along parts of the coast in the UK (e.g., The Wash estuary), Germany (e.g., Langeoog Island with sandy coast), and the Netherlands (e.g., Westerschelde estuary), managed realignment is implemented to restore saltmarshes and to aid coastal defence[59–61].

Selecting preferred pathways is based on trade-offs between different criteria reflecting management aims such as food production or mitigation of potential infrastructural damage. At the same time decisions on adaptation are also driven by other incentives, such as economic development. In rural south west of Bangladesh, this triggers the implementation and development of pathways with dykes, drainage and pumps[17]. For the Mekong Delta, accommodate/retreat pathways have been explored, consisting of adapting agriculture to enhance yield, diversifying livelihoods to ensure other sources of income, and migrating to less hazardous areas[62]. However, current governance focuses on protection options, like raising dikes, to enable socio-economic development, which benefits triple-cropping agriculture on the short-term, but may lead to reduced productivity in the long-term without costly fertilization, thus penalising poorer farmers[63]. In the end, opting for protection through dikes may lead to path-dependencies that could result in non-inclusive outcomes[63] and ultimately reduce the possibility to pursue accommodate and retreat[62].

Considering the above, it is thus noted that decision makers may still favour urban options over rural options, when for example the agriculture land is of high value. Similarly, to enable socio-economic development, urban options may be preferred to ensure a water secure environment[14]. Subsequently dikes or seawalls may be present today or start earlier in time than in the generic example in Figure 2.

4.5 Meta-pathways for archetypes

Based on our analysis (Figure 2), common traits of coastal adaptation pathways emerge (Figure 3) which are more dominated by land use rather than the morphological setting. In urban environments, the immediate priority is to protect, by either soft or hard measures. Aside from a few variations (storm surge barrier across an estuary, nourishment on open coasts, wave dissipation in deltas and open coast, and flood retention in estuaries), urban environments have a similar range of adaptation options open to them (Table 1, Figure 2), which is focused on protection. However, the precise timing of these options may vary depending on morphology (e.g. deltas are low and flat so would require protection against sea-level rise earlier than an open coast or estuary at a slightly higher elevation). The path of protection tends to be self-reinforcing, because by virtue of the 'levee effect'; people and assets tend to accumulate in protected areas, in turn requiring higher protection, in a feedback loop[64,65]. Accommodation could extend the effectiveness of protective measures, but in the end stronger protection may be needed, and retreat remains the last option if protection is not possible or preferred anymore. In rural land hard protection is difficult to motivate: present interventions are minimal and mostly in the direction of accommodate, with a possibility to delay the tipping point through the combination with protection measures (of relatively small investment). However, with medium to high sea-levels retreat remains the last option, unless new technologies delay the tipping point and extend the lifetime of accommodate measures.

[FIGURE 3 HERE]

Figure 3 indicates that adaptation tipping points will occur sooner in rural than in urban areas, as different resources are available, which limits the amount on sea-level rise an action can accommodate. Social acceptability is a major barrier to switching adaptation types[32] as can be finance of adaptation where a cost-benefit ratio cannot be met. Barriers that may result in tipping points vary in the understanding, planning and managing stages of adaptation[33] which unless overcome could result in less investment in protect and accommodation options or planned managed realignment. Subsequently, with time (and thus higher sea-levels), retreat (whether planned or not) is a realistic outcome for both urban and rural areas, but may come earlier for rural and for different reasons. For example, we acknowledge that retreat may be the only viable option after an extremely severe extreme event where transformational change is required. Thus it is important to consider each pathway to a local setting and the conditions that occurred in the past and are foreseen in the future.

5. Generation of local pathways

Our generic pathways (Figure 2) provide a framework to develop site-specific adaptation plans to sea-level rise. First a coastal manager needs to identify their coastal archetype from the six options. In practice, hybrid and nested archetypes exist besides our six archetypes. Many morphological classifications have a hierarchical structure, where one morphological type or land use may be embedded in another[27]. For example, a delta system could comprise a sandy beach at the delta front (e.g., Ebro delta). This is representative of 'open coast' geomorphology, nested within a 'delta' geomorphology. While these complexities cannot be considered in the scope of our archetypal analysis, we recommend that, upon applying our archetypes for the design of localised adaptation pathways, any subareas within a larger coastal archetype should be considered as a coastal archetype in their own, depending on size and relevance and on the management scopes. Thus, options from multiple archetypes may need to be considered in real world cases.

Similar land use types nest within another. For example, if a nuclear power station was situated on a rural coast (e.g., Sizewell in Suffolk, UK), coastal adaptation there might follow the path of urban coast, as high protection standards are required. Another example is low-lying farmland which maybe a valuable asset and therefore protected. Hence, each feature of morphology and land use must be considered in a wider context.

We acknowledge that even in rural settings sea-level rise and actions that result in planned retreat may have significant impacts locally, in addition to societal ramifications in a wider region. This is especially so for early-onset events such as salinization, which may cause population displacement if those living by the coast rely on groundwater for their livelihoods[66]. These important issues warrant a separate debate as there are significant cultural and social sensitivities, as potentially secondary impacts. We do not undertake this here as our scope is confined to the immediate physical and engineering adaptation actions.

Then following the methodology described in Section 2.2, local managers must clearly define their management goal (step 1). Next, the full range of adaptation options need to be explored (step 2), using table1 and taking account of local perspectives. Local adaptation pathways require specific information to select and complement the adaptation measures that most align with the case context, and to define their adaptation and opportunity tipping points (step 3) (similar to table 1), as seen for the local pathway of Lakes Entrance[11] (their Table 1). These tipping points should take account of the possible rate of regional sea-level rise and its effects (e.g. number of days inundated), as well as other processes and criteria which influence decision making. Next, the pathways from Figure 2 can be adjusted to local conditions (step 4), first at a generic level by selecting the relevant pathways and adjusting the tipping point conditions; and then towards more detailed levels, possibly with site specific adaptation measures (e.g. split the adaptation step 'protection through dikes' into dikes up to 0.5 m of sea-level rise, followed by dikes up to 1 m of sea-level rise). The result is a set of nested pathways that describe different levels of detail.

At local level, system-specific information (e.g. physical,, institutional and socio-economic conditions) and stakeholder participation are vital in debating and selecting adaptation measures (e.g. in Lakes Entrance this was achieved through a telephone survey to identify the important features on the local environment[11] – see their Figure 2), and to define their tipping points with respect to future sea-levels, other drivers of change and other criteria which influence decision making. With this local information in combination with the typology of pathways, local adaptation pathways can be designed and evaluated on their cost and benefits.

For successful implementation, pathways need to be complemented by good, continuous governance[22,67,68], where all stakeholders work towards the overall management goal, rather than their own narrow objectives, a monitoring plan to timely detect signals of change[13,69,70], and preparatory actions to keep options open (e.g. spatial planning or institutional changes) or to generate future options (e.g. research and innovation). Such preparatory actions are especially needed for high sea-level rise, as several options become insufficient (table 1, figure 2). The options and pathways that are left are either transformative (e.g. retreat) and/or require lot of space and time to implement (land raising or large flood defences). Also, if such actions are needed in the end, decision makers may want to skip some intermediate actions, as the functional lifetime of those investments may become too short.

6. Conclusions

Adaptation pathways boost flexibility and sustainability in decision making for coastal adaptation, yet they are limited in application due in part to lack of experience and the complexity involved in their generation. To aid take up at local level, pathways have been generated generically for six coastal archetypes, and illustrated with examples at local settings.

We illustrate that presently adaptation options decrease with rising sea-levels, unless we radically change our approach to coastal adaptation by considering adaptation pathways and making the necessary preparations to timely adapt. The pathways analysis also shows that, for high sea-levels, options will need to be considered that are not presently acceptable, but may be needed in the end. This helps to avoid unsustainable investments with potential for lock-in. In urban areas, there is a greater motivation to protect and accommodate rather than retreat. However, accommodation cannot continue forever, and in the long-term, protect, or planned retreat are options that could become more common[71]. Inaction could lead to unplanned retreat[66] or lack of adaptation options in the end.

Exploring adaptation pathways to sea-level rise can help coastal planners to evaluate the sustainability of their investments for coastal adaptation under uncertainty. We show that this approach allows for a richer analysis of the operation space for coastal adaptation than has be done with static assessments, and takes into account the uncertainty and timing of adaptation needs.

Rarely do people adapt to sea-level rise alone, with many factors influencing the need to change. Additional criteria, such as higher economic development or the effects on the natural environment are also considered, and will influence how the pathways result in practice. Our generic adaptation pathways serve as inspiration as to what is physically possible, but local decision making and stakeholder engagement is key to determine what is acceptable.

By just taking account of physical constraints, the lead time of measures and adaptation planning frequently needs to start earlier than anticipated, especially as rapid sea-level rise is a risk and may require larger time consuming adaptation efforts. Local stakeholder engagement to enable effective decisions making would further extend this time. Therefore, with potential accelerated sea-level rise[3], exploring pathways and monitoring to detect signals for adaptation becomes more urgent as then time available for planning and implementation will be less.

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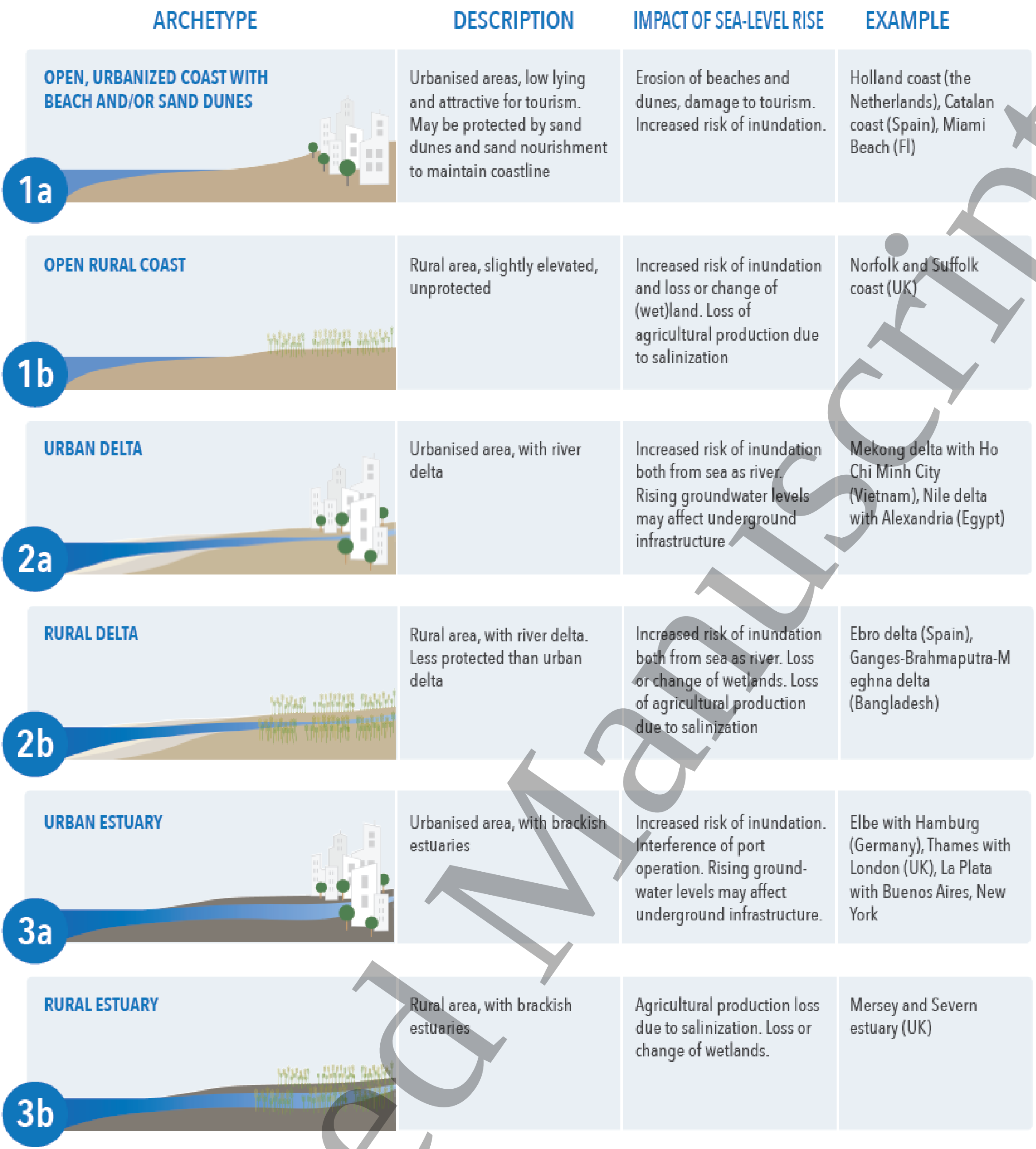

Figure 1 Common coastal archetypes that are subject to the impacts of sea-level rise (SLR) and for which adaptation actions will be taken.

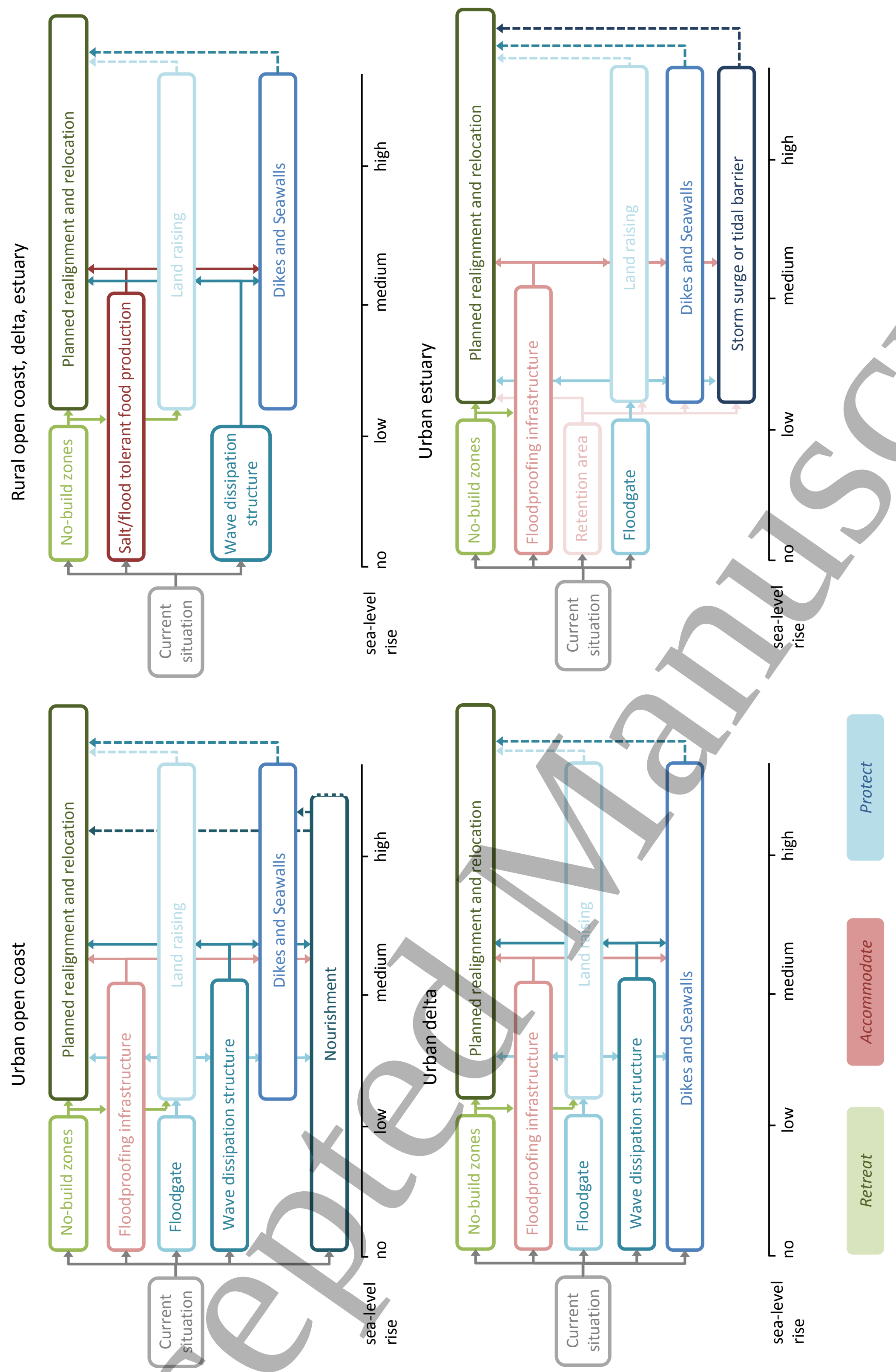

Figure 2 Adaptation pathways for the coastal archetypes, consisting of sequences of (portfolio) of) adaptation actions (coloured boxes). The length of the boxes represents the interval of sea-level rise for which the adaptation measure is effective, i.e. before it reaches its adaptation or opportunity tipping points. Combining measures could extend the design life of a measure. (Light/dark) green: retreat actions, (light/dark) pink: accommodate actions, (light/dark) blue: protect actions.

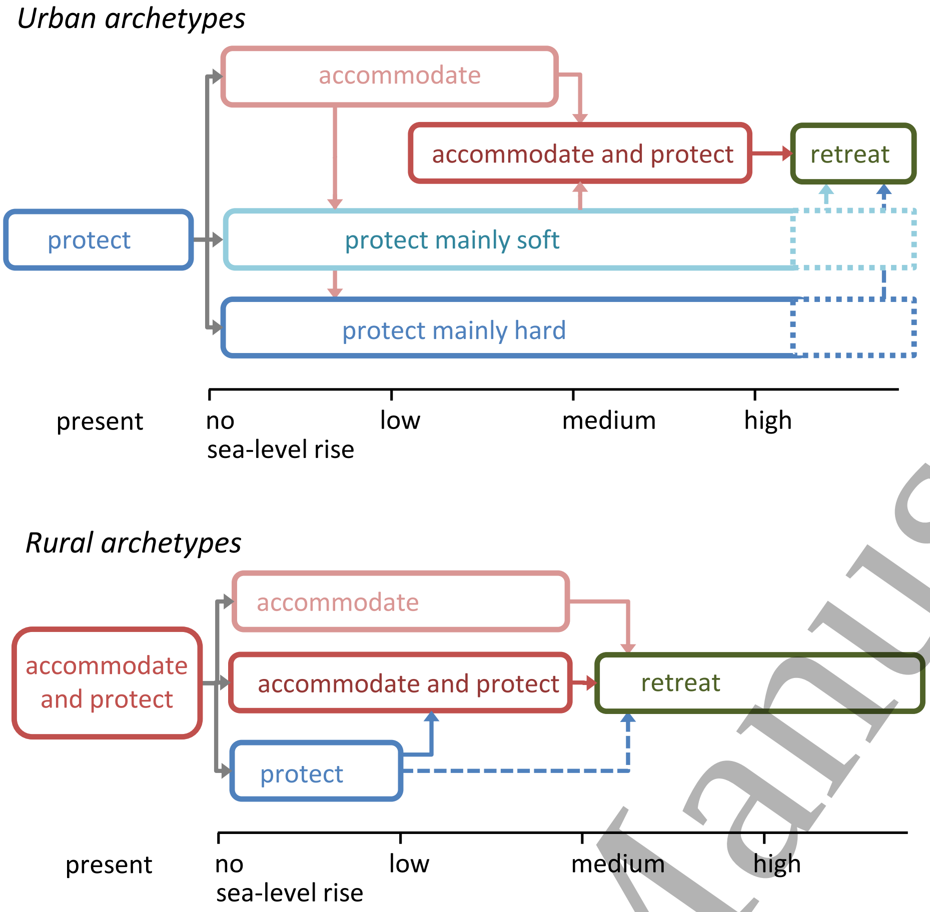

Figure 3. Generic traits in adaptation options and pathways per land use. Dashed lines present uncertain or less likely pathways.

Table 1 Possible adaptation options, the impacts they address and their opportunity and adaptation tipping points across the six coastal archetypes studied. Impacts: P=permanent flooding (submergence); T=temporal flooding due to extreme event; E=erosion, G=rising groundwater levels; S=salt water intrusion. Reasons for opportunity and adaptation tipping points: D=engineering design; $=cost-benefit considerations; M=space and material availability; A=social acceptability; Y=economic productivity. X indicate that the adaptation option is more or less common for a given archetype, respectively. o indicates a less common adaptation for an archetype. Uncertainty in the sea-level rise conditions or timing of a tipping point is indicated with a dotted line. * Like early warning systems, drainage systems and in a later stages pumping would become ubiquitous with sea-level rise so are not considered in pathways.

Adaptation options	Impact of sea-level rise	Reasons for opportunity and adaptation tipping points		1a. Urban open coast	1b. Rural open coast	2a. Urban delta	2b. Rural delta	3a. Urban estuary	3b. Rural estuary
ACCOMMODATE									
Flood retention areas	T	A, M	Space limitation, social acceptance.					X	
Drainage systems and pumps*	T, G, S	$, D, M	Design. Resourcse (power supply, finances).	X		X	X	X	X
Floodproofing of infrastracture	P, T	D, $	Too frequent flooding. Too expensive. Design limitations. Lead-in time.	X		X		X	
Salt-tolerant food production	G, S	Y	Decrease in crop yield due to salinity.		X		X		X
Flood tolerant food production	P, T, S, G	Y	Decrease in crop yield due to flooding.		X		X		X
PROTECT									
Flood gate	P, T	D, $, A	Design limitations, if frequency of flooding is too high.	X		X		X	
Wave dissipation structure (e.g. break waters or wetlands)	T, E	D, $, M, A	Design limitations, ecomomic, space, environmental conditions. Lead-in time for new wetlands.	o	o	X	X		o
Nourishments for beach and dunes	P, T, E	D, $, M, A	Finances, sediment resources, possibly energy cost, unaccepted frequency.	X					
Dikes and sea walls	P, T	D, $, R, A	Design limitations, finances, social acceptance e.g. too high, lack of space.	X	X	X	X	X	X
Storm surge or tidal barriers	P, T	D, $, A	Design limitations. Finance. If too often used, too risky if fails.					X	
Land raising	P, G, S	M, $	Lack of resources (sand) and finances. Lack of space to temporarly retreat to. Long lead-in time.	o		X	X	X	
RETREAT									
Planned no-build zones (setback)	T, E	A, $	Setback consumed by flooding or developments, social acceptability, missed opportunity cost.	X		X		X	
Planned realignment and relocation of key infrastructure and assets	P, E	A, $	No space for retreat. Social acceptability, Long lead time.	o	X	o	X	o	X