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The ability of societies to adapt to twenty-first-century sea-level rise

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Against the background of potentially substantial sea-level rise, one important question is to what extent are coastal societies able to adapt? This question is often answered in the negative by referring to sinking islands and submerged megacities. Although these risks are real, the picture is incomplete because it lacks consideration of adaptation. This Perspective explores societies' abilities to adapt to twenty-first-century sea-level rise by integrating perspectives from coastal engineering, economics, finance and social sciences, and provides a comparative analysis of a set of cases that vary in terms of technological limits, economic and financial barriers to adaptation and social conflicts.

Recent literature has reinforced concerns about the possibility of substantial sea-level rise (SLR) due to rapid melting of ice sheets[1] that may lead to twenty-first-century global mean SLR of 2 m or more[2–4]. Discomfortingly, the potential for high-end SLR may remain even if the ambition of the Paris Agreement to limit the temperature increase well below 2 °C above pre-industrial levels is met. This is due to the large uncertainties associated with ice-sheet responses and sea levels continuing to rise for thousands of years even if GHG concentrations are stabilized during the twenty-first-century[5,6].

In this context, an important question concerns the extent to which societies are able to adapt and maintain human settlements safe from SLR and associated extremes during the twenty-first century. In current SLR literature and the media this is often seemingly answered by referring to, for example, the "complete flooding and submergence of entire megacities"[5] or showing emblematic cities around the world submerged by the sea[7]. While these headlines illustrate that SLR may constitute a major challenge to coastal societies, they are incomplete and possibly misleading in that they neglect coastal adaptation. This is specifically true because adaptation could reduce some coastal impacts by several orders of magnitude[8,9]. Furthermore, coastal societies have a long history of adapting to environmental change and local SLR because coasts are amongst the most dynamic environments on Earth[10]. For example, a number of coastal megacities in river deltas have experienced, and adapted to, relative SLR of several metres caused by land subsidence during the twentieth century[11].

Efforts that integrate across biophysical and social dimensions of SLR impacts and adaptation are limited in the otherwise vast literature on SLR. This Perspective provides such an effort and addresses the question of societies' abilities to adapt to twenty-first-century SLR by analysing a set of diverse cases from around the world in terms of four main factors that have been empirically found to constrain societies' abilities to adapt (Fig. 1). These factors are defined in Box 1. We assess technical limits and economic barriers under twenty-first-century SLR and socio-economic development, assuming current technology. Following the empirical social science literature on adaptation barriers[12–14], we assess finance barriers and social conflict barriers under present conditions, with limited speculation on how these barriers may evolve during this century.

The purpose of this effort is not to analyse which criteria are actually used in decision-making nor to prescribe how decisions should be made. For example, the presence of an economic barrier does not mean that coastal societies actually decide using social benefit–cost analyses (BCAs), nor that societies should not adapt, because there are many other reasons for adaptation beyond monetary ones, such as human safety or nature conservation. Rather, the purpose of this analysis is to study how different factors combine in a given case, so that further research and policy attention can be aimed at those factors that are critical in that case. The combination of constraints found therefore indicates possible pathways to overcoming them. For example, the presence of both finance and economic barriers suggests that future efforts should focus on grant finance, whereas if only finance barriers are present, concessional and private finance may also be sought[15].

The case studies have been chosen to cover different coastal landforms, income groups, types of coastal impacts, and urban and rural settings (Table 1). While the cases we consider here are coastal, the framework is generic and can be applied for integrated analysis in other fields of adaptation.

Bangladesh

Bangladesh, largely situated on the delta of the Ganges–Brahmaputra–Meghna rivers, is widely recognized as one of the most hazardous large countries on Earth, having rural population densities exceeding 1,000 people per km^2, and being impacted by

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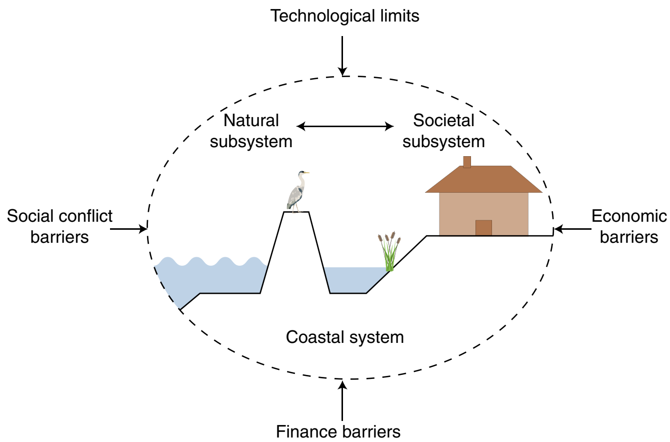

Fig. 1 | Coastal adaptation constraints. Coastal adaptation is situated within interacting natural and social subsystems and may be constrained by technological limits as well as economic, finance and social conflict barriers. Adapted from ref. [88], IPCC, Cambridge University Press.

river and sea floods, salinization and drought exacerbated by climate change, SLR and land subsidence[16,17]. There are extensive diked polder systems that protect agriculture against most flooding (Fig. 2), but failures during more extreme tropical storms are common, causing agricultural damage. Upgrades of these dikes are ongoing and higher reliability can be expected in the future. Experiments are also in progress with controlled sedimentation to raise land levels, termed tidal river management[18,19]. All of these measures are part of Bangladesh Delta Plan 2100[20] — a holistic, integrated and long-term plan that the government is currently developing, learning from the Dutch Delta Programme.

Technological limits. From a technological point of view, high-end SLR would be extremely challenging, but the technological measures that are needed either exist or are being developed. For example, in rural areas, tidal river management combined with sediment delivered by the rivers (on the of order 109 t yr^{-1}) offers great potential to build land elevation with sea level[21]. Changes in land use (from agriculture to aquaculture, for example) are also feasible and already occurring. Urban areas would need to be protected with more conventional methods. Rising salinity is a challenge that might be countered by a range of measures, such as salt-tolerant crops and freshwater reservoirs. While these options are available, further assessment and trials of their application are required, recognizing that this may be made more challenging by other barriers mentioned below[22].

Economic barriers. With a dense rural and urban population, adaptation provides large direct and indirect monetary benefits, such as avoided damages and reduced health effects from flood events. All

Box 1 | Adaptation limits and barriers

A growing literature has categorized factors that have been observed to constrain adaptation. This body of work distinguishes between the limits beyond which human activities cannot be maintained, and barriers, which can be overcome through adequate efforts, technology, deployment of economic and human resources, management and institutional change[14,78,89,90]. For social constraints it is preferable to use the term barrier rather than limit, because what may be considered a social limit is mutable and depends on cultural context and human values[12]. Here, we consider the following four adaptation constraints, because they (1) have been found to be most relevant in previous empirical analysis[13,78,91,92]; and (2) represent the perspectives of the main groups of actors involved in coastal adaptation.

Technological limits arise when there are no adaptation options available to effectively reduce the impacts of SLR, including the consideration of the time needed for implementing options. Asserting technical limits requires the subjective choice of an adaptation goal[12]. Here we consider the goal of maintaining human settlements safe from SLR and associated extremes through protection and accommodation measures as this viewpoint has been prominently represented in societies for centuries by coastal engineering[10]. We deliberatively exclude the coastal adaptation measure of retreat, because it is, in principle, always possible and hence never technologically limited. Asserting technical limits also entails the choice of a level of acceptable risks (or probability or consequence) as any coastal protection or accommodation measure may fail and there is no absolute or objective measure of effectiveness or safety[89].

Economic barriers arise if the implementation and maintenance of adaptation measures are more costly in monetary terms than the impacts they avoid, as assessed through social BCA. BCAs are subject to several well-known limitations that have been widely discussed in the climate change literature. First, not all costs and benefits can be adequately monetized[93]. Second, results are very sensitive to the choice of the discount rate applied[93–95]. Third, costs and benefits are aggregated across actors, which means that socially preferred options may differ from those preferred by any individual actor[96,97]. To capture this issue in a manner that is specifically relevant to adaptation, we include the barrier of social conflicts as described below. Nevertheless, BCA constitutes a prominent public decision-making perspective on coastal adaptation and is legally prescribed in countries such as the United States, the United Kingdom and The Netherlands.

Finance barriers arise if it is difficult to access financial resources for adaptation, including from public budgets, development and climate finance and private sources[78]. This angle has been included here because it is central to the adaption finance activities under the United Nations Framework Convention on Climate Change (UNFCCC), as well as to the donor and development finance organizations and public authorities involved in funding adaptation.

Social conflict barriers arise whenever stakeholders' conflicting interests impede or exacerbate adaptation and may be overcome through governance, which is the effort to develop informal and formal institutions such as cultural customs, laws, policies, social norms and conventions that guide human behaviour to resolve social conflicts or realize mutual gains[98–102]. Social conflicts may arise due to diverging private interests (for example, a Catalan tourist operator favouring beach nourishment and an environmental activist opposing it), diverging public interests at different levels of administration (conflicting building codes at federal, state and city levels in NYC; also termed an institutional crowdedness barrier[13]) or between actors' interests and existing institutions (for example, populations of remote islands opposing a population centralization policy in the Maldives; also called cultural constraints[12,78] or political (economy) barriers[91,96]). Here we apply the broad concept of social conflict, because this represents the perspectives of diverse stakeholders involved and constitutes the first step in any analysis of governance issues. From there, analysis can proceed to exploring more specific questions regarding the nature of the social conflict and how this may be overcome[14,101].

Fig. 2 | Polder system in coastal Bangladesh south of Khulia. Polders are low-lying tracts of land enclosed by dikes, which are widespread in densely populated deltas with the main goal of promoting agriculture. The polder dikes and drains will require substantial upgrades to remain effective under SLR.

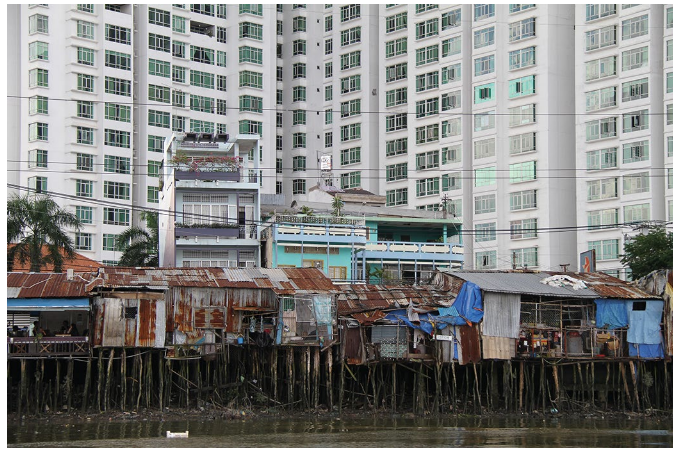

Fig. 3 | Stilt houses on a river bank in Ho Chi Minh City, Vietnam. This flood-mitigation measure is widely applied by the poorest, most exposed and most vulnerable part of the population and stands in stark contrast to the new high-rise residential apartments in the background. Credit: Stijn Koole, Bosch Slabbers Landscape + Urban Design.

the options mentioned above are expected to have benefits exceeding their costs, although it is hard to find detailed analyses demonstrating this.

Finance barriers. Bangladesh is the biggest recipient of climate adaptation funds, and is also a major recipient of donor aid, receiving US$2.6 billion in 2013[23]. Many non-governmental organizations such as the International Red Cross and Red Crescent Movement are active in the provision of cyclone shelters, for example. Significant efforts have been funded, but future funding needs are large[20] and the maintenance of existing polder systems is often constrained by a lack of funds[24].

Social conflicts. Bangladesh's dense population and intense land use means it is easy for conflict to emerge. For example, conversion of agriculture to aquaculture has given rise to conflicts associated with land grabbing, salinization impacts and reduced labour demand[25]. Tidal river management removes large areas of land from use while the land is being flooded and raised, which affects household incomes. At the same time, there are profound changes regarding major rural to urban migration and agriculture progressively diminishing relative to the national economy, so adaptation is occurring on an evolving stage[26].

Catalonia

The 600-km-long Catalan coastal zone in the Spanish Mediterranean concentrates about 62% of the population and about 65% of the gross domestic product (GDP) of Catalonia, with tourism being the main economic activity (>10% of GDP)[27]. The major SLR-induced impacts are related to enhanced shoreline erosion due to the combination of narrow beaches and lack of accommodation space[28]. The impacts of SLR due to coastal flooding and inundation are low owing to the steep coastal topography, with the exception of some lowlands[29,30]. Currently, adaptation measures are oriented towards maintaining beaches for recreation and enhancing the protection of the hinterland through artificial nourishment (that is, counteracting shoreline erosion by replacing the eroded sand).

Technological limits. There are no technological limits to these adaptation measures. Some challenges relate to the availability of adequate sand volumes for nourishment[31], because the sand used needs to have a grain size that is compatible (similar or coarser) with the eroded sand or the nourishment method needs to be combined with additional measures to reduce sediment mobility. In the past, this technique has not always been effective because it was usually carried out reactively when major erosion impacts were already observed.

Economic barriers. Generally, beach nourishment is highly beneficial in areas of tourism development as coastal tourism constitutes a substantial contribution to Catalan GDP[32]. Empirical studies have found that beaches in front of hotels raise the prices of hotel rooms by up to 17% along the Catalan coast[33]. Unit costs for sand are, however, expected to rise in the future, because the shallow near-shore sites from which most of the sand is derived today are expected to be exhausted, which will increase the distance between the sand source and nourishment sites.

Finance barriers. At present there are no financial barriers as beach nourishment is publicly financed by the Spanish Government. The required annual nourishment costs will increase with SLR and it is not clear how long public finance can be maintained in the future.

Social conflicts. Increasing social activism questions the long-term sustainability of the beach nourishment strategy due to its potential negative ecological impacts on high-value coastal ecosystems such as endemic *Posidonia* sea-grass meadows[34]. In addition, the multi-level governance structure for coastal zone management generates conflicts between national, regional and local administrations, limiting the implementation of effective adaptation policy[35]. The Spanish Central Government takes beach nourishment decisions within the so-called Maritime-Terrestrial Public Domain, the Regional Government is responsible for land-use planning outside this domain and the local municipalities are responsible for urban planning adjacent to this domain[36,37]. For example, in 2016 a group of coastal municipalities north of Barcelona opposed nearshore dredging to obtain sediment for beach nourishment, claiming that this would promote unsustainable coastal management.

Ho Chi Minh City

As a fast-growing delta metropolis, Ho Chi Minh City, Vietnam, is heavily affected by frequent flooding today — a phenomenon that will exacerbate with SLR, changes in precipitation extremes

Table 1 | The coastal and social characteristics and adaptation constraints to maintaining human settlements safe from twenty-first-century sea-level rise for cases considered in this Perspective

Case	Dominant coastal characteristics				Adaptation constraints			
	Coastal landform	World Bank income group in 2017	Human settlements	Mean population density (people km^{-2})*	Technological limits	Economic barriers	Finance barriers	Social conflict barriers
Bangladesh	Delta	Lower middle income	Rural	[a]1,100	—	—	X	X
Catalonia	Beaches, deltas, cliffs	High income	Rural/urban	[a]900	—	[c]—	[c]—	X
Ho Chi Minh City	Delta	Lower middle income	Urban	[a]3,900	—	—	X	X
Maldives	Atoll islands	Higher middle income	Urban	[b]26,000	—	—	—	X
			Rural	[b]900	—	X	X	X
New York City	Estuary	High income	Urban	[a]11,000	—	—	X	X
Netherlands	Delta, beaches	High income	Rural/urban	[a]500	—	—	—	X

Dashes (–) and crosses (X) denote the absence and presence of adaptation constraints across the set of available adaptation options, respectively. [a]Mean population density values are based on the UN-adjusted GPWv4 year 2010 population density dataset[86] and the Global Administrative Areas (GADM) dataset version 2.0 (http://www.gadm.org/). For New York City and Ho Chi Minh City mean population density was calculated for the entire administrative area of the city. For Catalonia, Bangladesh and the Netherlands mean population density was calculated for the LECZ (low elevation coastal zone; areas ≤10 m and hydrologically connected to the ocean). For Bangladesh, the districts of Cox's Basar, Bandarban, Chittagong, Ramgamati and Khagrachhari were excluded as they are outside the delta. For the definition of the LECZ we used CGIAR-CSI SRTM v4.1 elevation data[87]. [b]Population counts for the Maldives are taken from the Maldives Population and Housing Census 2014 (http://statisticsmaldives.gov.mv/nbs/wp-content/uploads/2015/12/PP5.xls). We define urban as population living in the city of Malé and rural as population living on other atolls. We use GADM version 2.0 to define the administrative boundaries of the Maldives and Malé. [c]Economic and financial barriers may arise for maintaining beaches not used for tourism.

and present rates of land subsidence of about 1 cm yr^{-1} (ref. [38]). A combination of adaptation measures could be implemented to substantially reduce flood risk, including (1) building a system of ring dikes around the urban area[39], (2) elevating districts where people and assets are most concentrated, and (3) retrofitting buildings to reduce damage to households and small businesses. So far, only limited private adaptation has been carried out in the form of retrofitting existing houses and elevating land for new houses (Fig. 3).

Technological limits. Considering all measures together, there are no apparent technological limits to coastal adaptation. Elevating districts should effectively reduce flood risks even under high-end SLR. As SLR progresses, all of these measures will need to be combined and substantially upgraded over time[40].

Economic barriers. Investing in most of the aforementioned measures promises high benefit–cost ratios[41]. Using a discount rate of 5%, for example, elevating areas at high risk and retrofitting buildings would have twenty-first-century benefit–cost ratios of 8 to 11 and 15 to 16, respectively, and net present values of US$33–48 billion and US$69–73 billion, respectively, assuming SLR of between 50 cm and 180 cm. Under the same assumptions, a ring dike would have a benefit–cost-ratio of 1.2 for 50 cm SLR, but negative for 180 cm SLR.

Finance barriers. Adaptation faces deep finance challenges. So far, the city has not managed to secure funds for the highly beneficial flood protection options, even in the face of vast damage and nuisance during every monsoon season. A ring dike, for example, would require investments on the order of US$1.4–2.6 billion[42].

Social conflicts. One conflict that has been found to inhibit large-scale investment is disagreement about adaption measures between authorities at various administrative levels[39]. For example, the Ministry of Agriculture and Rural Development favours the ring dike, whereas the city government opposes it for both environmental reasons and fear of protests[43]. A ring dike would probably trigger conflict between urban and rural populations, as rural citizens outside the ring dike will suffer even greater floods. Building-scale measures would not lead to this particular conflict, but they would also not keep water out of Ho Chi Minh City's streets, hampering the transformation of the city into the modern business hub that it aspires to be.

The Maldives

The Maldives consist of 1,192 atoll islands with a mean elevation of approximately 1.5 m above mean sea level. One-third of the country's population of 400,000 lives on the urban capital island of Malé (Fig. 4), which is one of the world's most densely populated cities[44]. To relieve this population pressure, the Maldives have constructed a new island, Hulhumalé, on a reef-flat directly adjacent to Malé and incorporated adaptation by raising the island to just over 2 m above mean sea level[45].

Technological limits. Island expansion and construction by land claim is a mature and widespread technology, common in the Maldives and many other parts of the world. The elevated island Hulhumalé will be safe from flooding until SLR reaches approximately 0.6 m and thereafter it could suffer from periodic flooding due to energetic swell waves[46]. Island raising, however, can further continue even under high-end SLR, and further adaptation such as dikes, early warning systems and shelters can supplement this. The highly permeable substrate of all Maldives islands should be noted as a possible challenge.

Economic barriers. Island construction is, for densely populated atoll nations, a relatively low-cost option because the reef-flats that need to be filled with sand are shallow (1–2 m in the case of Hulhumalé), which minimizes sand requirements. The costs of reclaiming Hulhumalé were about US$30 per m². While no detailed BCA is available, adaptation through land reclamation and fill around Malé is deemed to have a high benefit–cost ratio even when raising islands by 2 m due the high real-estate prices (about US$2,000 per m²). However, in areas of low population density — which includes most of the remote islands — land raising is not economically beneficial.

Fig. 4 | Malé, the capital island of The Maldives. High and increasing population densities in Malé have led to the reclamation of the nearby island of Hulhumalé, which can be seen in the background of the photo. Credit: Shahee Ilyas.

Finance barriers. Island construction was financed by the Government of the Maldives and a concessional loan from the Saudi Fund for Development[47]. Land reclamation is generally attractive for investors, because investments can be paid back in the short term through real-estate revenues generated on the newly created land. In addition, the Maldivian economy has been attractive for investors because it has been growing at an average rate of 7.4% over the last 30 years[48].

Social conflicts. The main social conflict regarding adaptation is a distributional one between the urban elite on one hand and the peripheral islands on the other[49]. The former favour a centralization of population and services on a few well-protected islands with the dual goal of reducing the costs of services (National Population Consolidation Policy) and reducing coastal risk (Safer Island Strategy). These policies, however, meet the opposition of inhabitants of smaller and more remote islands as they are perceived to "destroy the country's 3,000-year-old cultural identity and its social fabric."[50]

The Netherlands

While a large part of The Netherlands already lies below sea level, and complex defences against sea floods are in place, SLR entails a number of challenges including (1) salt intrusion stressing agricultural production and freshwater provision in the west[51]; (2) the Maeslant barrier, protecting Rotterdam city and harbour, ceasing to be effective under 50 cm SLR; and (3) the IJssel lake system not providing necessary flood and drought relief with >30 cm SLR[52,53]. Furthermore, coastal flood impacts will be compounded by increases in peak discharge of the Rhine and Meuse rivers[54]. These challenges are currently being addressed in the context of the Delta Programme through a combination of measures including sand nourishment, dunes, dyke improvements, river widening and urban planning and adaptation.

Technological limits. The overall impression is that the Netherlands can technically cope with future SLR of 0.9 m by 2100[53], or 1.5 m per century, providing 'major improvements' are made[52]. Research also showed that with an investment of around €80 billion, it may be possible to preserve territorial integrity of the Netherlands even under 5 m of SLR, using current engineering technology[55,56].

Economic barriers. For the Netherlands as a whole, coastal adaptation to 0.8 m SLR was deemed highly beneficial in economic terms, with an overall benefit–cost ratio of 5 using a discount rate of 4%[57]. Adaptation costs are estimated as €1.6 to 3.1 billion per year up to 2050 (about 0.5% of the current Dutch GDP), whereas the costs of doing nothing are much higher[58]. BCAs are not available for greater SLR, but ballpark estimates suggest that for 5 m of SLR, protection costs may exceed the cost of evacuation[55].

Finance barriers. The Delta Programme 2015 has already allocated €1.2 billion per year for adaptation through the Delta Fund until 2028. State funding is assumed to continue afterwards, and it is foreseen that regional (the Water Boards) and local entities (municipalities) will supplement these resources. Water Boards are autonomous governmental bodies that have their own independent tax revenue system to maintain water infrastructure.

Social conflicts. The Netherlands has a long history of developing institutional arrangements (such as the Water Boards) for dealing with saline water, freshwater and flooding conflicts, and these are likely to be effective in the future — at least under moderate levels of SLR[59]. Current conflicts relate to areas where dikes have been relocated to allow for larger peak river flows. For some river-widening projects, a dozen or so farms have either been rebuilt on elevated hills or relocated, which has triggered huge debates[60]. Under high-end SLR, large investments to protect the west of the country may spark a debate over the distribution of resources with the population in the safe eastern parts, which already feels neglected by the population in low-lying cities in the west[61].

New York City

Historical flood events have shown that hurricanes and winter storms can have considerable impacts on New York City (NYC), as illustrated by Hurricane Sandy (also called Superstorm Sandy) in 2012 causing more than US$20 billion of damage[62]. SLR and population growth will further increase the potential consequences of flooding. In the aftermath of Hurricane Sandy, NYC has been formulating flood adaptation strategies that include a wealth of potential measures such as enhancing building codes, building dikes ('the big U'), installing large-scale storm surge barriers and 'green' engineering measures to enhance the resilience of wetlands against storm surges[63].

Technological limits. Theoretically, there are no technological limits in this case. The main technological challenge involved in implementing adaptation measures is that they must fit into the existing high-density building stock, which increases costs[64]. Furthermore, a change of building codes will effectively only pertain to new buildings.

Economic barriers. The investment costs for different combinations of adaptation measures vary from US$14.7–23.8 billion for strategies involving large-scale levees, to US$11.6 billion for a 'hybrid' strategy targeting the protection of critical infrastructure and enhancing building codes[65]. When only considering current climate conditions, benefit–cost ratios for all combinations of measures are below 1 (using a discount rate of 4%). However, when also considering twenty-first-century SLR of up to 1 m, all benefit–cost ratios are above 1, with the highest being 2.5 for the hybrid strategy.

Finance barriers. After Hurricane Sandy, the Federal Government made US$16 billion available for disaster recovery and adaptation through the Disaster Relief Appropriations Act in 2013, but the allocation of this money is proceeding slowly. So far US$4 billion have been allocated by NYC, mostly to recovery[66]. About US$1 billion have been spent on adaptation projects in NYC and New Jersey under the Rebuild by Design programme (http://www.rebuildbydesign.org). The novel aspect of this programme is the bottom-up approach, developing projects as joint efforts between the public, research, private sector and government.

Social conflicts. One main distributional conflict in the context of coastal flood risk management in the United States relates to the National Flood Insurance Program subsidizing flood insurance for homeowners to stimulate them to enrol into the programme. This also creates disincentives for households to implement disaster risk reduction measures such as flood-proofing their homes[67,68]. Another issue has been conflicting and fragmented policies issued by federal-, state- and city-level authorities regarding building codes. The federal National Flood Insurance Program assigns building codes to be implemented in 1-in-100 year flood zones, whereas state and city authorities have added additional and conflicting requirements as to how much to elevate new buildings (called freeboard)[68]. State- and city-level policies are now under revision to address this issue.

Lessons learned across cases

A limited number of cases, as analysed here, can only give a partial answer to the question of the extent to which coastal societies are able to adapt to twenty-first-century SLR. Nevertheless, across the cases it is consistently found that economic barriers, and specifically finance and social conflict barriers, are reached before technological limits to coastal adaptation arise. Given the maturity and widespread use of coastal protection technology, this is likely to be true beyond the cases studied here. The core questions concerning adaptation technology are how much this will cost and whether societies will be able to access sufficient finance and resolve the distributional conflicts associated with spending large amounts of public money on coastal protection rather than on other policy domains. Unfavourable side effects of coastal protection, such as the loss of tourism due to a decline in beach attractiveness and the loss of coastal ecosystems through coastal squeeze, lead to additional economic costs, finance constraints and associated social conflicts — as elaborated below.

Technological limits. In the cases considered here a number of technological challenges (such as the lack of space for building protection infrastructure in densely populated cities) are observed, but these do not constitute technological limits but rather raise costs. Although the cases chosen represent a wide variety of contexts and SLR-related coastal challenges, this does not mean that no technological limits exist. For example, coastal protection is technologically extremely challenging for Miami, because protected areas can be flooded from below due to the underlying porous limestone. Pumps can be implemented to deal with the flooding issue, but this reduces groundwater storage and limits the effects of infiltration pumps to reduce salinity intrusion into the aquifers[69].

In principle, technological limits could also arise in the case of adaptation options not offering a low enough level of residual risk for societies to accept (see Box 1). In our cases and beyond we do not find evidence supporting this point and also expect that this will not be the case under twenty-first-century SLR. Currently, at least 20 million people accept the risk of living up to several metres below normal high tides in countries such as Belgium, Canada, China, Germany, Italy, Japan, the Netherlands, Poland, Thailand, the United Kingdom and the United States[70]. In principle there is no technical obstacle to engineering coastal protection to very high standards, as for example the discussion on so-called ‘unbreakable dikes’ illustrates[71]. Hence residual risks can be managed, but should never be forgotten or taken for granted.

Economic barriers. Few economic barriers are found in the six cases considered here. On the one hand this is due to coastal adaptation research generally focusing on the hotspots of social impacts. In those low-lying areas with high population and asset densities it is generally highly beneficial in economic terms to protect against even high-end SLR. Hence, it is very unlikely that we will see megacities submerged by SLR during the twenty-first century. On the other hand, the high benefit–cost ratios found here, as well as in earlier global analyses[9], illustrate why massive coastal protection is widespread today — and will probably continue to be so during the twenty-first century, even if prices for sand and other materials rise.

Conversely, protecting rural coastal areas and agricultural land will generally have benefit–cost ratios that are below one, at least when only considering market values of benefits. When also considering non-market values of coastal wetlands (for example, mangroves and marshes), hard protection may lead to negative net-benefits through a loss of wetlands and their ecosystem services, because hard structures prohibit the inland migration of coastal wetlands, which would allow them to keep up with rising sea-levels[72]. A solution may be offered by so-called nature-based adaptation measures, which provide coastal protection together with additional ecosystem service benefits; there are still large uncertainties about the effectiveness of these solutions, however[73,74].

Finance barriers. Coastal adaptation seems to be frequently constrained by inaccessible finance, even if benefit–cost ratios are high. One reason for this is that it is difficult to convert the benefits of coastal adaptation into revenue streams for financing the investment upfront, because benefits (such as the avoided damage of extreme sea-level events) occur stochastically over a long time horizon, and are distributed across stakeholders. An interesting exception occurs when adaptation is combined with the creation of short-term revenue streams via real-estate development on land that is either newly created or made more valuable through coastal protection. This is illustrated in the case of the Hulhumalé, Maldives, as well as through urban land-reclamation projects in other parts of the world[75].

Social conflicts. Social conflicts are present in all the cases investigated here, and are very likely to occur elsewhere. Two types of conflicts were observed. The first relates to actors who are negatively affected by adaptation measures. In Catalonia, for example, the tourism sector welcomes beach nourishment as the sector directly benefits, whereas those making a living from natural resources (such as fishermen) show growing opposition. This type of conflict can generally be expected with coastal adaptation, because SLR and coastal adaptation redistribute risks and benefits amongst stakeholders, creating winners who favour adaptation and losers who object to it. The second type of conflict relates to the distribution of public money between the coastal actors receiving public support for adaptation and non-coastal actors paying for this through taxes, as found in the cases of The Netherlands, NYC and Catalonia.

In many parts of the world, coastal adaptation is further complicated by existing conflicts over resources. For example, illegal coastal sand mining is currently a major driver of coastal erosion in many parts of the developing world[76]. In Ghana, for example, lack of law enforcement, lack of employment opportunities for the youth and high demand for sand from the construction industry continue to make this practice attractive[77].

Other social barriers. Although the four types of limits and barriers considered here cover major societal perspectives on coastal adaptation, they are not exhaustive. Even when no conflict of interest is present, a lack of capacity of governance structures to plan, implement, enforce, monitor and maintain coastal adaptation measures may constrain adaptation[78,79]. In Ho Chi Minh City, for example, the limited experience in dealing with large projects has been reported as a barrier to adaptation[39]. A lack of capacity is particularly problematic when it comes to the maintenance of coastal protection infrastructure as this has caused many coastal disasters in the past — such as in New Orleans[80], just to mention one prominent example. In other countries where coastal defence systems have existed for a long period, effective governance arrangements for maintenance (such as the Water Boards in the Netherlands) have emerged. Mixed experiences with both bottom-up and top-down governance structures have been gained in Bangladesh since the introduction of the Dutch-like polders in the 1960s[24]. We have left this dimension aside, because it is difficult to make the concept of governance capacity operational for a high-level comparison of diverse cases[81] as done in this paper.

Evolution of limits and barriers. Adaptation constraints will evolve over time. Technological change may help to overcome technological limits and economic barriers (by reducing adaptation costs, for example). The effect of this is likely to be small for classical 'hard' coastal engineering measures as these are mature technologies, but potentially larger for emerging nature-based solutions. For finance and social conflict barriers it is more difficult to speculate how these will evolve during the twenty-first century. On the one hand, economic growth and better institutions may help to overcome these barriers. On the other hand, these barriers may be exacerbated as the overall expenditure for adaptation rises with sea level, and this will have to compete for public expenditure with other needs, such as pensions and unemployment. In any case, finance barriers are likely to persist in the near future, because in the developed world austerity policy generally reduces public investment levels[82], and in the developing world, where many countries rely on donor funding, the adaptation finance gap is large[83].

Outlook and future research

Taken together, our results suggest bifurcating coastal futures during the twenty-first century. Urban and richer areas will continue to have engineered coasts with higher and higher defences, radically altered landscapes and possible catastrophic consequences in the case of defence failure. Whereas rural and poorer areas will struggle to maintain safe human settlements and will eventually retreat from the coast. Such retreat is likely to involve massive social conflict, forcing societies to address difficult questions concerning transfer payments, compensation and liability for loss and damage[84].

Looking beyond 2100, this picture may or may not change. As sea levels will continue to rise for millennia, the world is already committed to long-term SLR in the range of 1.2 to 2.2 m under present levels of global warming, and this commitment could increase to 25–52 m within the next 10,000 years under cumulate emissions[5] of 1,280 and 5,120 PgC. This means that our heirs could either see a world similar to the one described in here or a radically different world, with sea levels tens of metres higher. Irrespective of the deep uncertainties in future sea levels, strong mitigation efforts can, and are needed to, reduce the risks of high-end SLR.

In addition to mitigation efforts, research is needed to advance coastal adaptation by finding ways to overcome prevailing barriers. To this end, we advance two avenues of research. One avenue concerns research and experimentation for overcoming technological challenges and economic barriers. So-called green or nature-based options[73] seem to promise multiple co-benefits, amongst them the capacity to self-adjust to SLR[85]. But research is needed to better understand effectiveness, optimal timing and benefit–cost ratios together with other socially relevant criteria — such as risk tolerance and social desirability associated with both traditional and novel adaptation options across the full ranges of SLR and socio-economic uncertainties.

A second, much less developed direction of study concerns understanding and designing governance arrangements for overcoming finance barriers and social conflicts. This needs to be a priority, as these are today clearly the most critical barriers to adaptation. Research should therefore target both international arrangements for enhancing the scale and effectiveness of adaptation finance mechanisms under the UNFCCC and beyond, as well as project-based financial arrangements for leveraging public funds and the involvement of private investors and project developers[15]. Owing to the potentially severe distributional consequences of SLR and adaptation, specific attention needs to be paid to distributional justice, compensation and transfer payments to poorer and rural areas for which the economics of adaptation is less favourable.

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Author contributions
J.H. conceived this study, drafted the general sections of the paper and contributed to drafting each case study. J.C.J.H.A. carried out and drafted the New York case study. S.B., D.L., R.J.N. and J.H. carried out and drafted the Maldives case study. R.J.N. and S.B. carried out and drafted the Bangladesh case study. J.A.J. and A.S.A. carried out and drafted the Catalonia case study. P.S. carried out and drafted the Ho Chi Minh City case study. P.S. and J.C.J.H.A. carried out and drafted the Netherlands case study. K.A.A. and N.V. contributed to the drafting the discussion.

Competing interests
The authors declare no competing interests.

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