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Impacts of sea level rise and adaptation across Asia and the Pacific

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Coastal communities worldwide face increasing risks from sea level rise (SLR) and more frequent coastal flooding, threatening densely populated areas. This study applies a Coastal Flood Risk Modelling Framework to evaluate permanent inundation from SLR and episodic flooding from extreme events across Asia and the Pacific, while also estimating the costs and benefits of adaptation. Using probabilistic projections of mean and extreme sea levels under five Shared Socio-economic Pathway (SSP) scenarios, ranging from ambitious mitigation (SSP1-1.9) to high fossil-fuel development (SSP5-8.5), the framework integrates hazard, exposure, and vulnerability data to estimate economic impacts. Current annual economic losses from coastal flooding in Asia and the Pacific amount to $26.8 billion, severely affecting Southeast Asia, South Asia, and the Pacific Islands. By 2050, expected annual economic damages are projected to rise between $143.7 and $197.8 billion just considering SLR effects (depending on the scenario), with further exacerbation by the century's end. Atoll nations, including Kiribati, Maldives, RMI and Tuvalu will face the most severe losses relative to GDP. These findings underscore the urgent need for holistic adaptation measures including, grey, green and hybrid solutions, adaptive planning, resilient infrastructure, improved governance systems, alongside mitigation policies to reduce future emissions and consequent flood risks.

Keywords Coastal flooding, Sea level rise, Climate change, Risk assessment, Socioeconomic impacts, Adaptation

Coastal communities around the world are already experiencing rising sea levels[1] and changes in extreme events[2,3] and these are expected to increasingly threaten the densely populated coastlines by floods[4]. This situation is exacerbated by a growing trend of coastal population density, which puts immense pressure on governments to develop and implement effective adaptation strategies. Such issues are particularly severe in Asia and the Pacific where 44.1 million people live below 1 m above mean sea level[5] while Asia hosts more than 1.3 billion living within 50 km from the coast, roughly 40% of the world's coastal population[6].

As global temperatures rise, polar ice melt and the thermal expansion of seawater are driving a steady increase in sea levels. Since 1900, global average sea levels have risen by approximately 21 cm, with the rate of increase accelerating in recent decades. Over the last 20 years, the rise has doubled to 3.7 mm per year[7]. Projections for future sea-level rise vary depending on the effectiveness of global mitigation efforts. In a high-emissions scenario, sea levels could increase by as much as 1 m by the end of the century. Even with successful climate neutrality efforts, the legacy of previous emissions will ensure that sea levels continue to rise for at least a century[7]. Current assessments indicate that, despite climate action, devastating consequences for low-lying coastal communities are inevitable, especially for atoll nations, which are among the most vulnerable to even slight increases in sea level[8].

For densely populated countries like Bangladesh, Vietnam and the Philippines[9–11] where a large percentage of the population resides in coastal zones, the impacts are particularly severe. The combination of sea-level rise and increasingly frequent flooding events will lead to the displacement of communities, loss of livelihoods, and

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significant damage to critical infrastructure. These nations face compounded risks due to their high population density in vulnerable coastal areas.

In addition to the gradual rise in sea levels, climate change is driving more intense and frequent tropical storms and extreme weather events[3,12,13] further worsening coastal flooding risks. Countries such as Indonesia, Thailand, and India, with vast coastlines and large coastal populations, are experiencing unprecedented levels of flood-related disasters. These disasters not only threaten lives but also stall economic growth by disrupting key sectors such as agriculture, fisheries, and tourism. Repeated flooding events erode the foundation of these economies, making long-term development more challenging.

The vulnerability of these coastal regions is further aggravated by rapid urbanization and population growth. The promise of economic opportunities, paired with limited inland land availability, has drawn increasing numbers of people to coastal areas, where many megacities are located. This demographic shift significantly increases the exposure of people and assets to flood risks. Notably, 9 out of the 10 most exposed cities to coastal flooding are located within Development Member Countries (DMCs)[14]. In countries like Malaysia[15] Sri Lanka[16] and the People's Republic of China (PRC)[17] rapid coastal development often outpaces the establishment of sufficient flood protection and adaptation measures. This gap between development and infrastructure resilience results in high susceptibility to flooding and its associated impacts.

This contribution presents a comprehensive assessment of the direct coastal flood impacts in view of climate change with specific focus on countries (with coastline) in Asia and the Pacific which are part of Asian Development Bank (ADB) Development Member Countries (DMCs) (Table 1). It employs Shared Socioeconomic Pathway (SSP) scenarios to model the rise in sea level and its subsequent impact on coastal flooding, discussing the unique challenges they face and examining potential pathways toward building a more resilient future. The extent to which projected changes in flood hazard lead to future coastal impacts will depend on local exposure, which is influenced by socioeconomic factors such as adaptation policies and coastal management strategies. Since long-term demographic and economic trends as well adaptation actions are highly uncertain[18] it is essential to isolate the effect of climate change. Therefore, in this study, we first apply flood hazard projections to the current (2020) population, economy and coastal protection. This assumption is essential to quantify the results of inaction in terms of climate policies and only in the discussion we assess the potential costs of potential adaptation actions.

Results

Present day impacts

The present-day expected annual flood damage (EAD) across Developing Member Countries (DMCs) is estimated at $26.8±[22.8 30.9] billion (Supplementary Table S1; values in brackets express the very likely range, 5th -95th percentiles), which is around one third of the global finance flows for climate adaptation in 2021/2022[19]. This figure represents about 0.1%±0.1% of the region's GDP and is compounded by additional billions in losses from damaged infrastructure, business disruptions, and agricultural impacts. The financial burden is unevenly distributed, with Southeast Asia bearing the largest share, accounting for over 42.8% of the total EAD, or $11.5±[9.8 13.2] billion. This heightened vulnerability stems from a mix of factors, including heavily populated coastlines, low-lying deltas, and frequent typhoon exposure. South Asia and East Asia follow, contributing approximately 27% and 26% of the total damage, translating to $7.3±[6.2 8.4] billion and $7.0±[5.9 8.0] billion, respectively. Although the Pacific region experiences just 2.6% of the total EAD, it faces the highest economic impact relative to GDP, with damages amounting to 1.0%±[0.9% 1.2%] of its GDP, or $0.7±[0.6 0.8]

Central and West Asia	**East Asia**
Georgia	People's Republic of China
Pakistan	**Pacific**
South Asia	Cook Islands
Bangladesh	Fiji
India	Kiribati
Maldives	Marshall Islands
Sri Lanka	Micronesia, Federated States of
Southeast Asia	Nauru
Cambodia	Niue
Indonesia	Palau
Malaysia	Papua New Guinea
Myanmar	Samoa
Philippines	Solomon Islands
Thailand	Tonga
Timor-Leste	Tuvalu
Viet Nam	Vanuatu

Table 1. List of Asian development bank (ADB) Development Member Countries (DCMs), with a coastline, divided by region (https://www.adb.org/where-we-work).

billion. Central and West Asia contribute the smallest share, at 1.6% of the total EAD, or \$0.4±[0.4 0.5] billion. In terms of regional GDP impact, Southeast Asia incurs 0.4%±[0.3% 0.4%], followed by South Asia at 0.2%±0.2%, Central and West Asia at 0.1%±0.1%, and East Asia at 0.04%±[0.03% 0.04%]. Overall, while Southeast Asia, South Asia, and East Asia face the highest monetary losses, the Pacific region suffers the most relative to its economic size, highlighting the disproportionate flood risk across DMC regions.

At the national level, People's Republic of China (PRC) and Indonesia bear the largest share of expected annual flood damage (EAD), with each country facing over \$6 billion in potential losses annually. PRC accounts for 26% of the total EAD, translating to \$7.0±[5.9 7.0] billion, while Indonesia contributes 24%, with \$6.4±[5.5 6.4] billion in damages (Fig. 1a, Supplementary Table S1). This substantial EAD reflects both countries' extensive coastlines, large populations in flood-prone areas, and critical economic infrastructure concentrated near the coast. India and Bangladesh also face significant impacts, each contributing around 13% of the total EAD, amounting to \$3.6±[3.0 3.6] billion for India and \$3.5±[3.0 3.5] billion for Bangladesh, due to their densely populated floodplains and vast deltas. Thailand follows with 6% of the total, or \$1.6±[1.4 1.6] billion in annual damage (Fig. 1a, Supplementary Table S1). In terms of EAD as a percentage of GDP, smaller island nations are the most affected. Vanuatu experiences the highest EAD relative to its economy, with 1.5%±[1.3% 1.7%] of its GDP impacted annually by flooding, followed by Papua New Guinea (1.2%±[1.0% 1.4%]), Micronesia (1.2%±[1.0% 1.4%]), Tonga (0.9%±[0.7% 1.0%]), and Bangladesh (0.75%±[0.64% 0.86%]) (Fig. 1b).

The human cost of coastal flooding is a major concern across ADB DMCs with a coastline, with nearly 6 ±[5.0 6.9] million people (Supplementary Table S2), or about 0.2% of the region's total population, at risk of flooding each year. Although this may appear to be a small percentage, it still represents millions of individuals and families whose lives and livelihoods are under constant threat. East Asia bears the largest share of this risk, accounting for 38%, followed by South Asia with 37%, and Southeast Asia with 24%. In absolute terms, this translates to 2.3 ±[1.9 2.6] million people in East Asia, 2.2 ±[1.9 2.6] million in South Asia, and 1.4 ±[1.2 1.6] million in Southeast Asia (Supplementary Table S2).

When considering population exposure as a percentage, the Pacific Islands are the most vulnerable, with 0.3% ±[0.2% 0.3%] of their population exposed to flooding due to their small landmasses and low elevations.

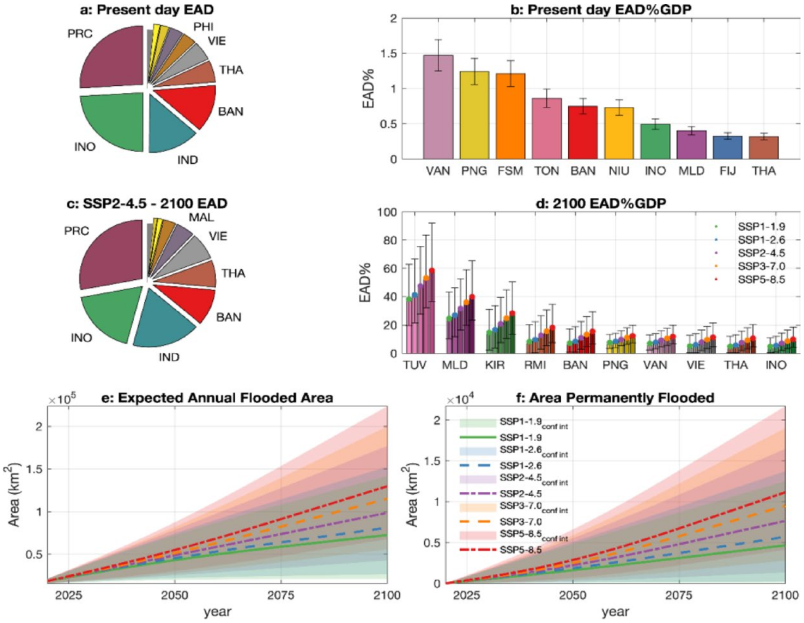


Fig. 1. Present and future coastal flood impacts along the DMC countries coastline: (**a**) The pie plot indicating the countries with the highest share of the total baseline Expected Annually Flooded Area (EAFA) - colours in a-d are unique for each country and only the countries with the 10 highest values are shown; (**b**) baseline EAFA as percentage of the country area (median values in bars with black whiskers indicating the 5th – 95th confidence interval); (**c**) Pie plot indicating the highest country contributions to the total 2100 EAFA under SSP2-4.5; (**d**) Ten countries with the highest 2100 EAFA as percentage of the country area (median values in circles with black whiskers indicating the 5th-95th quantile range; bars are grouped in stacks of 5 with one each for the 5 scenarios studied: '1.5ºC world' (SSP1-1.9; green), 'low-emissions' (SSP1-2.6; blue), 'moderate-emissions' (SSP2-4.5; purple), 'high-emissions' (SSP3-7.0; orange) and 'very-high-emissions' (SSP5-8.5; red); (**e**) evolution of EAFA and (**f**) area permanently flooded (i.e. below the high tide water level) until the year 2100 under all five scenarios (the lines express the ensemble median projections and the coloured areas the 5th -95th confidence interval). Key: BAN, Bangladesh; PRC, People's Republic of China; FIJ, Fiji; IND, India; INO, Indonesia; KIR, Kiribati; MAL, Malaysia; MLD, - Maldives; RMI, Republic of the Marshall Islands; FSM, Federated States of Micronesia; NIU, Niue; PNG, Papua New Guinea; PHI, Philippines; THA, Thailand; TON, Tonga; TUV, Tuvalu; VAN, Vanuatu; VIE, Viet Nam.

Southeast Asia (0.2% ±0.2%), East Asia (0.2% ±[0.1% 0.2%]) and South Asia (0.1% ±[0.1% 0.2%]) also contribute significantly to the overall number of people at risk, given their large coastal populations.

At a national level, island countries like Vanuatu, the Federated States of Micronesia, and the Maldives face the most severe risks, with 1–2% of their populations threatened by flooding annually. Vanuatu leads with 2.0% ±[1.7% 2.3%] of its population at risk, followed by Micronesia with 1.5% ±[1.3% 1.8%], and the Maldives with 1.1% ±[0.9% 1.2%]. Bangladesh, with its densely populated and flood-prone delta region, also ranks highly, with 0.9% ±[0.8% 1.0%] of its population exposed to flooding each year.

Anticipated coastal flooding risks

By 2050, the Expected Annual Flooded Area (EAFA) across all ADB DMCs is projected to increase significantly compared to the baseline year of 2020, with values rising between 1.4 and 1.8 under SSP1- SSP5 climate scenarios. This translates to 44,986±[20,819 74,796] to 52,725±[28,084 83,392] km^2 of land being susceptible to annual flooding (Fig. 1e), equivalent to approximately 0.2%±[0.1% 0.4%] to 0.3%±[0.2% 0.4%] of the total land area of the region. By the end of the century, the rise in EAFA is expected to be even more pronounced under the same scenarios, increasing by 2.9 to 6.0 times, resulting in a flooded area of between 72,646±[20,819 141,864] and 129,764±[67,752 223,733] km² (Fig. 1e), or 0.4%±[0.1% 0.8%] to 0.7%±[0.4% 1.2%] of the region’s total area. It is important to note that these estimates assume no further adaptation measures are implemented throughout the century, as the primary goal is to assess the trends in coastal flood risks across DMCs under climate change scenarios. A separate section explores the costs and benefits of potential adaptation strategies.

Coastal flooding events are expected to have a substantial negative impact on the economies of ADB DMCs. By 2050, the annual economic damage (EAD) from coastal flooding across ADB DMCs is projected to increase between 4.4 and 6.4 times, depending on the scenario, reaching median values between $143.7 and $197.8 billion (Supplementary Table S1). These estimates remain below 1% of the combined GDP. The projected EAD growth is consistent with the anticipated rise in global climate finance needs, which are estimated to increase from $1 trillion today to at least $6 trillion by 2030[19]. According to current sources developing countries alone will require in average $212 billion per year in adaptation finance up to 2030 across all sectors, and the need will increase to an average of $239 billion annually between 2031 and 2050. Given that the above estimates refer to total adaptation needs among all developing countries, the activities along the DMC coastline will be only a small part and thus the costs are within the same order of magnitude and probably lower than the presently presented EAD estimates. Also, UNEP estimated that the annual cost of adaptation by 2030 will range between $140–300 billion for 76 developing countries[20] which again should be higher than the coastal adaptation needs for DMC. All the above indicate that current estimates of future climate finance needs are most likely too optimistic and more funds should be allocated.

By the end of the century, EAD is expected to rise even further, increasing between 11.6 and 26.4 times under various climate scenarios, leading to median damages ranging from $336.8 to $735.5 billion (Supplementary Table S1), which would account for 1.3–2.8% of the regional GDP. Climate policies aimed at reducing emissions could mitigate approximately one-third of these projected damages by 2050, with mitigation benefits rising to 56.3% by the end of the century.

The highest share of EAD will come from Southeast Asia, contributing between 40.80% and 41.39%, followed by South Asia (28.3–28.6%) and East Asia (27.6–28.3%). Central and West Asia and the Pacific regions will experience smaller shares, ranging from 1.0 to 1.4%. In terms of absolute values, median EAD is projected to range from $93.0 to $207.8 billion in PRC, $62.0 to $129.2 billion in Indonesia, and $58.9 to $131.7 billion in India. Bangladesh and Thailand will also face substantial EAD, ranging from $33.5 to $72.2 billion and $24.5 to $54.3 billion, respectively (Fig. 1c, Supplementary Table S1).

In contrast, smaller island nations such as Tuvalu, Maldives, and Kiribati will experience the highest EAD as a percentage of GDP, with Tuvalu facing between 38.1% and 58.5% of its GDP in damages. Other vulnerable nations include the Marshall Islands (8.2–18.2%) and Papua New Guinea (7.7–12.3%) (Fig. 1d). By 2100, the Pacific region will experience the highest EAD relative to GDP, at 6.7–10.9%, followed by Southeast Asia (4.3–9.2%) and South Asia (2.4–5.2%). These figures highlight the severe economic impact of coastal flooding, particularly for smaller and more vulnerable nations.

Rising sea levels are expected to cause significant and permanent loss of land in coastal areas, with estimates suggesting a loss of 4,652 to 11,150 km² by the end of the century, under SSP1 to SSP5 scenarios (Fig. 1f). This permanent inundation will primarily impact the Pacific and Southeast Asia, which will account for 42.4–45.7% and 27.2–30.9% of the lost land, respectively. South Asia will also be heavily affected, followed by East Asia and Central and West Asia. The loss of land will severely impact infrastructure, agriculture, and ecosystems, and is estimated to carry an annual economic cost of $34.1 to $88.0 billion, by the end of the century (Fig. 2). These estimates likely underestimate the true cost, as they only consider land use and do not account for the loss of critical infrastructure, natural resources, and cultural heritage. At the country level, PRC, Papua New Guinea, the Philippines, Bangladesh, and Vietnam will account for at least 60% of the total flooded land, with median losses ranging from 473.8 km² to 4,106.7 km². Smaller island nations such as Kiribati, Micronesia, Tuvalu, and the Maldives will experience the highest percentage of their land permanently submerged, with Kiribati losing between 9.7% and 19.8% of its total land area.

The economic damage caused by permanent land loss is also expected to be substantial, with East Asia contributing 28.3–33.9% of the total damage, followed by Southeast Asia (28.8 – 30.1%), South Asia (25.7 – 27.9%), Pacific (9.6 – 14.4%), and Central and West Asia (0.5%). The corresponding median values are $11.6–24.9, $10.0–26.5, $9.0–24.5, $3.3–11.6, and $0.2–0.4 billion, respectively (Fig. 2). PRC, Bangladesh, India, Thailand, and Vietnam will face the highest economic losses in absolute terms, while smaller island nations like Kiribati, Tuvalu, and the Maldives will experience the most severe economic impact relative to their GDP, with losses ranging from 7.3 to 50.3% of GDP.

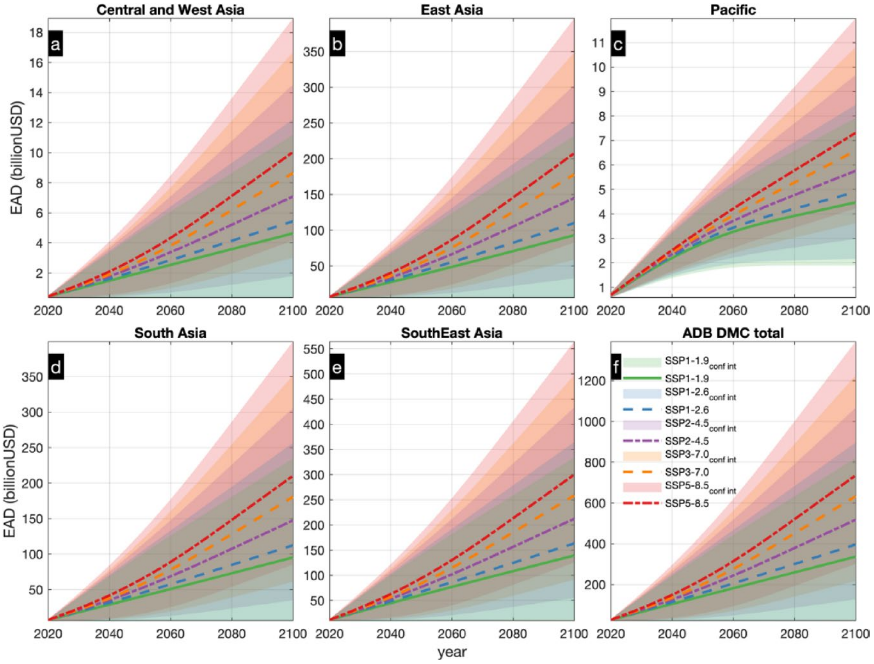


Fig. 2. Projected evolution of direct economic impacts due to coastal flooding along the DMC countries coastline. Expected Annual Damage (EAD) aggregated at regional (**a**): Central and West Asia; (**b**): East Asia; (**c**): Pacific Ocean; (**d**): South Asia; (**e**): Southeast Asia), as well as global level (**f**), under '1.5ºC world' (SSP1-1.9; green), 'low-emissions' (SSP1-2.6; blue), 'moderate-emissions' (SSP2-4.5; purple), 'high-emissions' (SSP3-7.0; orange) and 'very-high-emissions' (SSP5-8.5; red). The lines express the median projections and the coloured areas the 5th -95th confidence interval. Estimates without considering socio-economic dynamics are presented.

In terms of population, it is estimated that 2.0 to 4.5 million people in ADB DMCs are now living in areas which will be permanently flooded by the end of the century (Supplementary Table S2), representing 0.05–0.11% of the total population. The majority of these individuals are in East Asia, particularly PRC, and will account for 50.4–57.9% of the total exposed population. However, smaller island nations such as the Maldives, Tuvalu, and Kiribati will have the highest percentage of their populations affected, with 2.7–6.9% of their citizens living in areas at risk of permanent submergence. All the above highlight the need for timely adaptation, while for some low-lying small islands transformation adaptation including for example population consolidation, planning, land reclamation and possibly relocation should not be excluded.

Discussion

Our analysis focusses on the direct impacts of coastal flooding, so it is important to highlight that actual economic losses will be higher due to additional business interruption costs and other indirect effects of the economic shocks produced by the frequent floods. The estimation of such impacts require a dedicated analysis which is beyond the scope of the current contribution[21–24] but should be acknowledged. Subsidence is an important component of Relative Sea Level Rise and is a common phenomenon in Asian cities[25–27]but as it is of local character, it is possible that our global datasets underestimate current trends and consequently flood impacts. Also, along the study area are found some of the world's largest rivers and deltas which implies that compound floods from the synergy of high sea levels, precipitation and river discharge could drive even more catastrophic floods[28–33]. Again, assessing such compound risks requires dedicated analyses, but it should be acknowledged that the impact estimates reported here are probably on the conservative side, especially given the anticipated changes in river run-off and possible intensification of the monsoon driving more flooding in view of climate change[34].

Our findings are in line with other global or large-scale studies that report increasing coastal flood impacts as we advance towards the end of the century[4,35–40]. Comparisons are not straightforward since (i) there are several differences in methodology, datasets, spatial and temporal extents and scenarios, among others and (ii) such analyses come with substantial and inevitable epistemic uncertainties[36,41]. Here we focus on the isolated direct impacts of coastal flooding assuming static exposure and protection scenarios. The sections below explore the implications of our findings on coastal flood risks, focusing on the vulnerability of specific regions and the broader socioeconomic trends that exacerbate these risks. While the analysis highlights the susceptibility of small island states and in particular atoll nations, it also considers the growing challenges faced by rapidly developing coastal cities across Asia[42]. These regions, already vulnerable to rising sea levels, are further impacted by population growth and economic expansion in low-lying areas[43,44]. Additionally, this section addresses the critical need for timely adaptation measures and infrastructure improvements to mitigate the escalating risks.

Susceptibility of Small Island States

Small Island States are diverse in geography, geology, and economy, characterized by unique geological formations, from volcanic landscapes to coral reefs, which influence their biodiversity and natural resources. Economically, they range from tourism-driven economies in areas like the Maldives to more traditional fishing and agriculture like the Federated States of Micronesia. Geographically, they are dispersed, creating challenges and opportunities in connectivity, climate adaptation, and sustainable development. Despite these differences, they share a common challenge – their major economic sectors will be profoundly impacted by rising sea levels[8,45,46].

Many are volcanic islands characterized by steep landscapes (e.g. Samoa, Solomon Islands, Fiji), but there are also several low-lying atolls e.g. Tuvalu, Kiribati, Maldives, Marshall Islands which are inherently susceptible to coastal erosion and inundation[47–49] and will face the existential threat of disappearing entirely under rising sea levels. Even by the year 2050 and under low emissions, annual economic shocks from flooding are projected to exceed 3% of the GDP, a number which is not sustainable. Meanwhile, even seemingly elevated regions are not immune, with coastal infrastructure, settlements, beaches, and agricultural land all under increasing pressure. The very fabric of island life, from traditional fishing practices to tourism-dependent economies[50,51] faces an uncertain future as sea levels keep rising. Finally, the remoteness of some of the islands, poses an additional practical limitation for adaptation, related to the availability of materials, technologies and costs.

Our findings are in agreement to previous studies, which has already raised awareness of the challenges along SIDS[52–55] as the international community has also a crucial role to play in ensuring that these unique island ecosystems and their vibrant cultures survive and thrive in the face of a changing climate. Such support involves access to climate financing to mitigate the impacts of climate change and loss and damages, but also technical expertise to deal with still open challenges.

Coupling with socioeconomic trends

The coastal flood impact trends discussed here assume static socioeconomic conditions and only consider the effects of changing climate and rising seas. However, many DMC countries have vibrant economies and are experiencing significant increases in population. As a great part of such development takes place in coastal areas, the present projections are on the conservative side, since the constant economic and population growth on the coast will translate to even higher flood risks. India and Bangladesh, with their vast and growing populations, are prime examples where coastal cities like Mumbai, Kolkata and Chattogram are expanding rapidly. These urban centres attract million people due to economic opportunities, leading to increased population densities in low-lying coastal zones. Similarly, Indonesia, the world's fourth most populous country, sees rapid population growth in coastal regions such as Jakarta and Surabaya, intensifying the strain on infrastructure and heightening flood risks. The Philippines, with its archipelagic nature, also faces considerable population growth in coastal areas, particularly in Metro Manila and Cebu, which are already prone to flooding and storm surges. Viet Nam, with its burgeoning population in the Mekong Delta and Ho Chi Minh City, experiences significant challenges as these regions are highly susceptible to sea-level rise and frequent flooding. The PRC, while experiencing slower population growth overall, still sees substantial increases in coastal megacities like Shenzhen and Shanghai, where the risks of flooding are magnified by dense populations and extensive economic activities. In addition, land subsidence is aggravating the situation in many cities across Asia such as Jakarta, Ho Chi Minh City, Dhaka, Bangkok and Manila. Also, salinity intrusion in delta areas such as in Bangladesh, Vietnam and in the Pacific islands is posing a severe threat to the availability of drinking water and to agricultural activities.

The way forward

The findings highlight the need for climate action as the impacts of coastal flooding in the decades to come will be too disruptive. They also imply that timely adaptation measures will be necessary. Even under low emissions and by the year 2050, several DMC countries are projected to experience direct EAD exceeding 1% of the GDP; which constitute substantial economic shocks for any economy, without even considering indirect impacts such as business interruption and other spill-over effects.

A critical issue is the resilience of ports and airports and critical infrastructure which tend to be in flat, low-lying areas and constitute the lifelines of several communities, either by supporting economic activity or by ensuring access to critical supplies, among others. Sea ports are located on the coast and will need to be upgraded to ensure their smooth operation under higher sea levels. Airports require extended flat areas, which are often found near the sea and below 10 m of elevation and will experience increasing flood risk, even under moderate sea level rise scenarios. Such examples are the Funafuti International Airport in Tuvalu and the Velana International Airport in the Maldives, but also in larger countries like the Shah Amanat International Airport in Chittagong, the Penang International Airport in Thailand and the Hong Kong International Airport.

The analysis shows that by the end of this century, without adaptation, climate change would amplify present direct economic damages from coastal flooding by more than 20 times under high emissions scenarios. Keeping global warming below 1.5 °C could avoid more than half of unmitigated damage, depending on the region. Achieving this climate target, however, would still not prevent several countries and especially SIDS from suffering economic losses that correspond to considerable shares of their GDP, possibly leading to forced migration from low-lying coastal zones. Our results underline that investments in adaptation and sustainable development are urgently needed, as well as dedicated support to assisting developing countries in responding to loss and damages.

These enormous challenges call for a different and transformative approach to coastal resilience, based on system understanding and combining different forms of coastal adaptation (nature-based, hybrid and grey) depending on coastal characteristics and land-use, and associated to other forms of adaptation as, for example, improved land use and settlement planning, resilient infrastructure systems, governance, policy integration, disaster preparedness, and community resilience. For simplicity, in this study we have assessed the costs associated with rising protection levels to keep economic damages in 2100 at today's levels. This would imply rising existing natural and artificial protection by more than a meter in several countries, under the high emission scenarios. The estimated at country level mean additional protection height needed to maintain annual damage from coastal floods by the end of the century to baseline levels ranges from 0.16 to 1.04 m under SSP1 and from 0.67 to 1.67 m under SSP5 (Fig. 3a). The corresponding mean costs per coastline length are 1.4–8.9 and 5.1–14.8 million USD/km respectively (Fig. 3a). Countries with the highest estimates of additional protection (in meters compared to current protection levels) are Tuvalu, Republic of Maldives, Kiribati, Bangladesh, Marshall Islands, Vanuatu, Papua New Guinea, Viet Nam, Indonesia, Thailand and Malaysia (Fig. 3a). The above countries come also with the highest estimates of cost of adaptation per length of coastline (Fig. 3b), while obviously the total country cost is a function of the coastline length and countries like Indonesia, Philippines and PRC rank higher.

The above values are first-pass estimates and not a detailed cost/benefit analysis of adaptation options, which would require additional local scale data, especially for the most vulnerable areas, such as remote, low-lying islands. However, the above values indicate very high rate of return on such investments as for each dollar invested in coastal protection at least $10 of net economic benefits are expected, values which are in line with previous estimates[5]. The annual costs of coastal adaptation for all DMC countries are between $9 and $18 billion and the benefits are one order of magnitude, $157–311 billion, depending on the scenario. The benefit to cost ratio depends on factors like the discount rates and the priorities of the adaptation planning, but overall the economic incentives for adapting are strong.

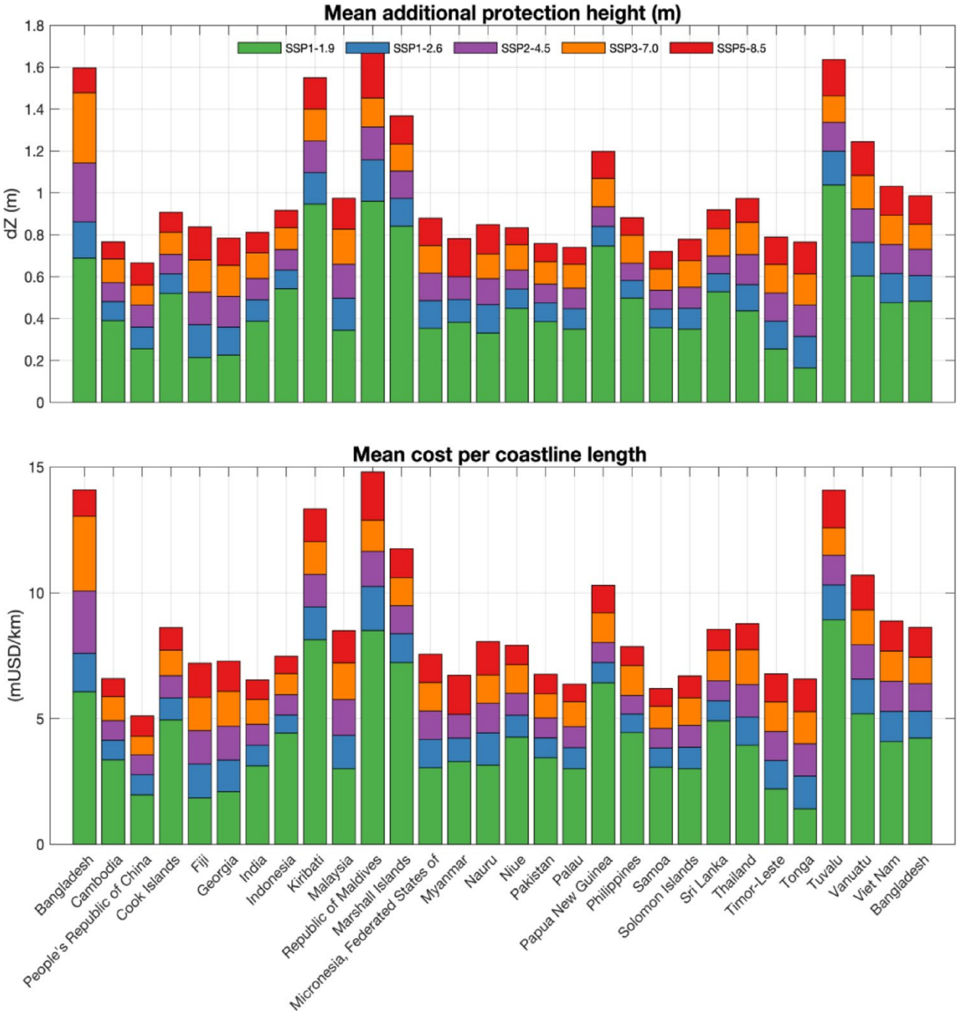


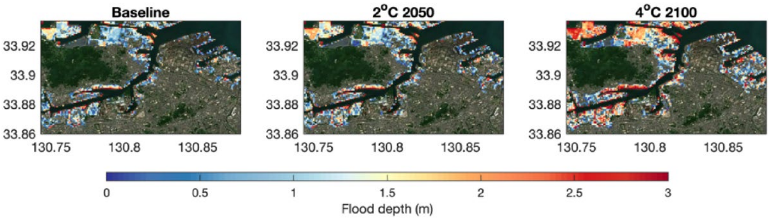
Fig. 3. Country level expected mean additional protection height and corresponding mean cost per coastline length needed to maintain annual damage from coastal floods by the end of the century to baseline levels, under all scenarios ('1.5°C world' (SSP1-1.9; green), 'low-emissions' (SSP1-2.6; blue), 'moderate-emissions' (SSP2-4.5; purple), 'high-emissions' (SSP3-7.0; orange) and 'very-high-emissions' (SSP5-8.5; red)). The bars for each region are grouped at four stacks corresponding to median values for the baseline, 2050, 2100 and 2150 and the colours express the four scenarios.

Conclusions

Coastal flooding poses significant and growing risks for Developing Member Countries (DMCs) across Asia and the Pacific. Present-day impacts equal to an annual economic loss of $26.8 billion, severely affecting Southeast Asia, South Asia, and East Asia. Despite representing 0.1% of the region's GDP, the economic strain is substantial, with small island nations such as Vanuatu and Micronesia experiencing the highest relative impacts. Nearly 6 million people are exposed to coastal flooding annually, with atoll nations showing the highest vulnerability in terms of population percentage of people impacted.

By 2050, under various climate scenarios, the Expected Annual Flooded Area (EAFA) is projected to increase between 1.4 and 1.8 times, and economic damages will rise between 4.4 and 6.4 times, reaching $143.7 to $197.8 billion annually. The trend will continue, with the EAD expected to increase between 11.6 and 26.4 times by the century's end. Atoll nations, such as Tuvalu and Kiribati, will experience the most significant economic losses relative to GDP, and rising sea levels will permanently flood thousands of square kilometres of land, impacting millions of people.

These findings highlight the urgent need for adaptation measures, particularly for the most vulnerable regions. Without significant action, the impacts of coastal flooding will intensify, causing devastating economic, environmental, and social consequences. Investments in both nature-based and engineered solutions, associated to other forms of adaptation as, for example, improved land use and settlement planning, resilient infrastructure systems, governance, policy integration, disaster preparedness, and community resilience. as well as climate mitigation policies, will be essential to reduce the risks and the future burden of coastal flooding on DMCs.



Extended Figure 1. Example of flood maps for the port city of Kitakyusu, Japan for the baseline, and the years 2050 and 2100, under 2ºC and 4ºC warming respectively. Colors indicate flood depths for the 100-year event. The maps were generated using MATLAB® R2024a (https://www.mathworks.com/products/matlab.html) and a Sentinel-2 satellite image as the basemap.

Methods

Coastal flood risk modelling framework

The framework assesses the impacts of sea level rise (SLR) and episodic coastal flooding throughout the 21st century. This analysis accounts for both permanent inundation from SLR and tidal effects, as well as temporary flooding caused by extreme coastal events. The framework is based on the Large-scale Integrated Sea-level and Coastal Assessment Tool (LISCOAST) and incorporates advanced large-scale models and datasets to assess hazards, exposure, and vulnerability in coastal areas, leading to an estimate of consequent risks[8,56].

The study considers five key Shared Socio-economic Pathway (SSP) scenarios that reflect varying degrees of climate action, ranging from ambitious mitigation to no emission policies: SSP1-1.9 that aligns with the Paris Agreement's goal of limiting global temperature increase to below 1.5 °C relative to pre-industrial levels; SSP1-2.6, a low-emission scenario achieving net-zero emissions after 2050, consistent with the 2 °C target; SSP2-4.5, a moderate-emissions scenario characterized by stable emissions until mid-century, followed by reductions that do not reach net-zero; SSP3-7.0, a high-emission scenario in which emissions nearly double from current levels by the end of the century; and SSP5-8.5, that depicts a trajectory of high fossil fuel reliance throughout the 21st century[57] (similar to[8]). For each pathway, the study generates probabilistic projections of both mean and extreme sea levels, which are then integrated with data on exposure and vulnerability to estimate the economic impacts of flooding. Further details on the methodological steps involved in this analysis are elaborated in subsequent sections.

Present day extreme sea levels

Coastal areas face increasing risks from rising mean sea levels (MSL) and episodic extreme sea levels (ESLs), driven by extreme atmospheric conditions. Extreme sea levels (ESLs) result from the interplay of MSL, tides, and water level variations caused by storm surges and waves. Using state-of-the-art models, ESLs are calculated at 1 km intervals along coastlines. For the baseline period (1980–2020), a reanalysis of wave and storm surges is performed using a two-way coupled ocean model with an unstructured grid (resolution ranging from ~50 km offshore to ~2 km nearshore). The model integrates the Semi-implicit Cross-scale Hydroscience Integrated System Model (SCHISM)[58] and the 3rd-generation spectral wave model (WWM-V)[59]accounting for wind, atmospheric pressure, and tides[60]. Further details about the model setup and the validation can be found in Mentaschi et al.[61]. Tropical cyclone-induced sea-level anomalies are further refined through the Delft3D-FM model, corrected by the IBTrACS best-track archive[62]. This methodology builds on the framework established by Vousdoukas et al.[63] and related studies (e.g. Vousdoukas et al.[8]).

Wave parameters (height, direction, and period) along the shoreline are derived using spectral peaks from the WWM-V model and propagated along a global 1 km resolution transect dataset, which includes key coastal characteristics such as shoreline position and slope. Comprehensive details on the data and methods used to create these transects can be found in Athanasiou et al.[64]. The complete spectral data from the wave model is utilized to propagate each peak at each time stamp along its corresponding transect, applying Snell's law[65]. The wave characteristics and the profile slope are then used to estimate wave run-up heights based on the Stockdon empirical formula[66]. The combined wave run-up and storm surge data are used to calculate meteorological tides for various return periods using non-stationary extreme value analysis[67]. Present-day ESLs are produced by combining the final meteorological tide time series with tidal elevations obtained from the FES2014 model[68]following the approach of Vousdoukas et al.[63] and related studies (e.g. Vousdoukas et al.[8]).

Projections of future ESLs

Future ESLs up to 2100 are projected by incorporating relative SLR estimates from the latest IPCC (AR6) report[1,69–71] with the effects of the various components of future SLR, as simulated by climate models from the Coupled Model Intercomparison Project phase 6 (CMIP6 - the medium confidence dataset is being used). All components (Relative Sea Level Rise-RSLR, tides, surges, and wave run-up exceeded by only 2% of te waves R_2) are represented as probability density functions (PDFs) to account for uncertainties. These PDFs are combined using Monte Carlo simulations to generate probabilistic estimates of ESLs for each coastal segment. Non-stationary extreme value analysis[67] is subsequently applied to derive PDFs for the return values of ESL over a range of return periods, including 1, 2, 5, 10, 20, 50, 100, 200, 500, 1000, and 5000 years, throughout the century (similar to Vousdoukas et al.[8]).

Coastal flooding

Previous studies have relied on static methods to create inundation maps, which tend to overestimate coastal flooding, particularly in flat areas[72]. A major advancement in this study is the introduction of two-dimensional hydraulic simulations along the entire coastline, providing a more accurate estimation of flood extent and depth. Following the methodology of Vousdoukas et al.[72] the Lisflood-ACC (LFP)[73] model is implemented at a 30 m spatial resolution, using the estimated ESLs as input and incorporating hydraulic roughness based on land-use maps[74] (see also Vousdoukas et al.[8]). For areas below the combination of mean sea level and high tide, the bathtub approach is employed to assess permanent inundation caused by sea level rise.

In the case of episodic flooding, Lisflood-ACC is applied to coastal segments, each including in average 10 km of coastline, along with the nearest hydrologically connected inland areas extending up to 200 km inland Extended Fig. 1. The segments are continuous and are defined along the GSHHG shoreline[75]subsampled every 10 km, as a result they rely only on land masses and neglect national boundaries and exposure information. The flood simulation of each segment includes also the adjacent ones to ensure sufficient overlap and no obstruction of flooding from local obstacles. More details on the methods and the validation of the approach can be found in Vousdoukas et al.[72].

A key improvement over previous studies lies in the Digital Elevation Model (DEM) employed in this analysis, as DEM accuracy has been a major source of uncertainty in flood inundation modelling[72]. In this study, the recently released GLO-30 DEM[76] derived from Synthetic Aperture Radar data, is used to reduce vertical bias of SRTM-based products. Additionally, post-processing is applied using global LIDAR data to further correct vertical inaccuracies, particularly those caused by buildings and vegetation (e.g. Vousdoukas et al.[8]). The detailed development of the DEM is documented in Pronk et al.[76]and the dataset is publicly accessible.

Another common limitation in large-scale flood risk assessments is the lack of data on coastal flood protection measures. Earlier studies often ignored protection standards, relying instead on proxies such as per capita wealth or population density and expert judgment. In this study, following Vousdoukas et al.[8] a broader range of indicators is employed as proxy to define current flood protection levels for each coastal segment. These indicators include wealth measured by GDP per capita based on World Bank classifications (https://blogs.worldbank.org/opendata/new-world-bank-country-classifications-income-level-2020-2021), the presence of critical infrastructure such as ports (https://data.amerigeoss.org/tr/dataset/global-ports1/resource/7ad834dc-a836-4dec-9cce-007da79b3adf) and airports (https://datacatalog.worldbank.org/dataset/global-airports, https://www.partow.net/miscellaneous/airportdatabase), as well as urbanization and artificial surface coverage derived from land-use and population density data (see following section for the datasets http://www.worldpop.org/).

For each coastal segment, the analysis considers the population, urbanization, critical infrastructure, and economic capacity within the present 1-in-500 year flood area[77]. A positive correlation is assumed between coastal protection levels and the concentration of people, assets, and economic activity. Protection levels are defined based on a set of criteria, where GDP per capita reflects the average gridded value for the coastal segment rather than the national average. The minimum protection level is assumed to guard against a 1-in-1 year sea level, and when multiple conditions are met, the higher protection level is selected (see also Table 2). It is important to highlight that protection standards defined as return periods are all defined according to the baseline conditions. This means that as sea levels rise the protection standard is decreasing over time.

If at least 10% of the 1-in-500 year flood area comprises artificial surfaces or the population density exceeds 500 people/km², low-income communities (GDP per capita below $1,036) are assumed to be protected against a 1-in-1 year event, lower-middle-income communities ($1,036–$4,045) against a 1-in-2 year event, upper-middle-income communities ($4,045–$12,535) against a 1-in-5 year event, and high-income communities (above $12,535) against a 1-in-30 year event. If a large port is present, high-income communities are protected against a 1-in-50 year event, while other income groups are protected against a 1-in-10 year event. For segments with a small port, protection is assumed up to a 1-in-2 year event for low- and lower-middle-income communities and up to a 1-in-10 year event for upper-middle- and high-income communities. Similarly, the presence of an

		Income Level			
		Low	Lower-middle	Upper-middle	High
Exposure criterion	At least 10% artificial areas	1	2	5	30
	Population density exceeds 500 people/km^2	1	2	5	30
	Large port	10	10	10	50
	Small port	2	10	10	10
	Airport	2	5	10	30

Table 2. Criteria for coastal protection standards (expressed as return periods) for the areas in which no information is available. Income levels are considered according to the world bank and the minimum protection standard is 1 year.

airport increases protection levels: low-income communities are protected against a 1-in-2 year event, lower-middle-income communities against a 1-in-5 year event, upper-middle-income communities against a 1-in-10 year event, and high-income communities against a 1-in-30 year event.

These estimated protection levels are incorporated into flood inundation modeling, with flooding assumed to occur only when coastal water levels exceed the protection thresholds. In instances where results appear unrealistic, the methodology of Vousdoukas et al.[63] is applied, using reverse calibration of coastal protection standards informed by data from the PCRAFI dataset (https://pacificdata.org/), local studies[47,78,79] and expert judgment to refine the estimates.

Exposure and vulnerability

The flood inundation maps generated from ESL projections are combined with exposure and vulnerability data to estimate population exposure and direct flood damages. Population exposure is estimated by overlaying the present flood maps with the WorldPop 2020 dataset (www.worldpop.org), while vulnerability is assessed using depth-damage functions (DDFs)[80] specific to different land use classes. Asset values, based on data from the European Space Agency's WorldCover 2020 dataset (https://worldcover2020.esa.int/; reference year 2020), are scaled according to GDP per capita at a 5 arc-minute resolution to reflect intra-national wealth distribution[81]. The baseline global land cover is derived from the European Space Agency's dataset[82] at 10-meter resolution. Built-up areas, which contribute to the vast majority of damages (approximately 95%), are further refined using the Global Human Built-up and Settlement Extent dataset, providing 30-meter resolution data on global human settlements (reference year 2010)[83]. The land-cover dataset is detailed in terms of spatial resolution, but reports only a limited number of classes, which come as an inevitable limitation of our study. The maximum detail possible in assessing impacts of floods on different kinds of exposure is limited in the land-cover classes accessible and cannot assess the spatial variability of the density or other characteristics of the built-up area. Additional details are provided in Vousdoukas et al.[63].

In this work, the DDFs were derived by combining the simulated inundation extent and depth for each flood event with country-specific stage-damage functions for five sectors: residential, commercial, industrial, infrastructure, and agriculture. The extent of urban land use was estimated by assuming continentally uniform percentages of sectoral occupation in cells classified as urban areas. These uniform percentages were based on a set of studies conducted in cities across different continents, which reported similar average sectoral distributions worldwide. For each land use class in the ESA WorldCover dataset, we assigned DDFs corresponding to the weighted combination of the sector-specific DDFs, according to these continentally uniform percentages. This mapping approach aligns with methods previously used in the literature[80,84] and enables the application of structure-based DDFs to coarser land use classes.

Risk assessment

Flood risk is assessed by estimating the flooded area, affected population, and direct economic losses for each coastal segment (at ~ 100 m resolution) by combining flood inundation projections with population and land use data, as well as vulnerability functions. In regions regularly submerged due to sea-level rise (SLR), defined as being below the current high-tide level, assets are assumed to be fully damaged, with maximum losses applied based on depth-damage functions (DDFs). For areas affected only by extreme flooding events, damages are calculated by applying the DDFs in conjunction with the estimated flood depth and land use characteristics[8].

From the MSLs and ESLs and the corresponding flood depths expressed as PDFs for return periods ranging from 1 to 5,000 years, we can obtain probabilistic estimates of flooded areas (FA), population exposure (PE), and economic damages (D) from 1981 to 2100[8]. By integrating these factors across return periods, the analysis produces estimates of the Expected Annual Flooded Area (EAFA), Expected Annual Population Exposed (EAPE), and Expected Annual Damage (EAD). Results are presented and analysed at global, regional, and national levels, with a focus on median values as well as 5th and 95th percentiles to account for uncertainty[8].

Costs of adaptation

The costs of adaptation are evaluated by considering additional protection measures that maintain the 2100 EAD at current levels. Following the approach of Vousdoukas et al.[56] the analysis estimates the costs of rising protection levels over the course of the century. To determine the final protection design for a coastal area, additional protection heights were considered ranging from the current height to a maximum height which is way beyond the 1000 year ESL by the end of the century and under the high emissions scenario. The height range is divided into 40 steps. The protection height is assumed to increase gradually from 2020 to 2050 to reach the desired design level and then stay constant until the end of the century. Investment costs are expressed as a linear function of the protection heightening; which has been shown to be a good approximation[85]. Maintenance costs are assumed to be 1% of the initial construction investment and the analysis is performed with and without an 8% discount rate. After discretizing the costs of additional protection, we discuss the scenario which maintains the 2100 EAD to present-day standards. While the primary focus is at the segment level, results are aggregated to provide a comprehensive overview at the country level, facilitating broader regional discussions of adaptation strategies.

Data availability

The analysis is carried out using the integrated risk assessment tool LISCoAsT (Large-scale Integrated Sea-level and Coastal Assessment Tool) developed by the Joint Research Centre of the European Commission. The framework uses open source data for which links and detailed description are provided in the methods. The output data are provided in the supplementary material. Any additional information is available from the corresponding author upon request.

Code availability

Most of the code that supported the findings of this study is already open access with references provided in the manuscript; specific tools which are not available in public repositories will be available on reasonable request from the corresponding authors.

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Author contributions

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Declarations

Competing interests

The authors declare no competing interests.

Ethics and inclusion statement

The authors declare no ethics issues such as research on race, sex, ethnicity, clinical trials or humans or animals. The list of authors is broad while local and regional studies have been considered.

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