Supplementary Information

Physical limits of sea-level rise adaptation in global river deltas

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Contents

SI1. Adaptation strategies (including examples)

We assess the physical feasibility of adaptation options for the following five adaptation strategies: advance, protect-closed, protect-open, accommodate, and retreat (Table SI1).

Table SI1: Description and examples of five adaptation strategies assessed in this study.

Adaptation strategy	Examples
Advance: involves the extension of the coastline seaward to build flood defences and is typically used to create new land for nature and recreation or urban and industrial developments. Pumps are installed to pump excess rainwater and river flows across the new coastline.	• The Flevoland polder and the Afsluitdijk pumping station in the Rhine Meuse delta, the Netherlands[1,2] • Advance strategy along the coast of the Netherlands[3,4] • The Great Garuda project for Jakarta city, Indonesia[5] • Reclaimed land to be used free up space on the mainland, Singapore[6] • Development of new coastal estates in Eko Atlantic City, Nigeria[7] • Terrebonne basin barrier island in Louisiana[8]
Protect-closed: The protect-closed strategy aims to keep flood waters away by constructing engineered structures, such as levees, along the coastline, which protects the inland areas from the sea. In addition, pumps are installed at the river mouths to pump water from the low-lying areas to the sea.	• Pumps along the IJmuiden mouth in the Rhine Meuse delta, the Netherlands[3] • A series of dikes, floodwalls and pumping stations along stretches of the coast in Louisiana[9]
Protect-open: Following protect-open, an open connection with the sea is maintained while still protecting the inland areas from SLR. This is achieved by extending sea level influences upstream by building levees along the coast and rivers. Moreover, storm surge barriers are built at the river mouths along the coast. These barriers remain open for most of the time, but close during storm surge events to mitigate the effects of elevated water levels.	• The Maeslantkering storm surge barrier in South Holland the Rhine Meuse delta, the Netherlands[10] • A series of dikes, barriers and walls along the estuary, as well as the Thames barrier in London, United Kingdom[11,12] • Floodwalls and the Inner Harbor Navigation canal (IHNC) Lake Borgne Surge Barrier in Louisiana[8] • Dikes along distributaries of the Ganges river in Dhaka, Bangladesh[13] • Seawalls, revetments and sand dunes along part of the coast in the Nile Delta, Egypt[14]

Accommodate: adopts a 'living with water' concept. This strategy implies the continued use of at-risk areas, whereby, no attempt is made to prevent flooding. Instead, land use is adjusted to reduce the vulnerability to SLR and associated floods by elevating the urban areas and surrounding land. This approach often aims to mitigate the economic and health costs associated with floods instead of preventing the flood [15]	• Building raising following SLR in the Mississippi delta, the United States of America[16] • Elevating homes in the Mekong delta, Vietnam [17] • Flood proofing houses and infrastructure in Los Angeles, USA[18] • Tidal river management in parts of the Ganges-Brahmaputra-Meghna delta, Bangladesh[19] • Flood proofing structures in the Riö-Grande delta, United States of America[20]
Retreat: focuses on a planned and permanent relocation of people, assets, and activities to reduce exposure to coastal hazards caused by SLR-induced flooding.	• Climate-driven community retreat on the Isle de Jean Charles, Gulf of Mexico[21] • Voluntary buyouts of flood-prone properties in the Mississippi river valley, United States of America[22] • Permanent retreat from damaged homes and infrastructure in the Greater Toronto Area (GTA), Canada[15] • Forced resettlement programs in the Mekong delta, Vietnam[17] • Household scale resettlement, Vietnam[17]

SI2. Delta polygon extent

The global delta dataset defines deltas as four-point deltaic extents (DN = delta node, RM = river mouth, S1 = shoreline position 1, S2 = shoreline position 2)(Fig. SI1)[23].

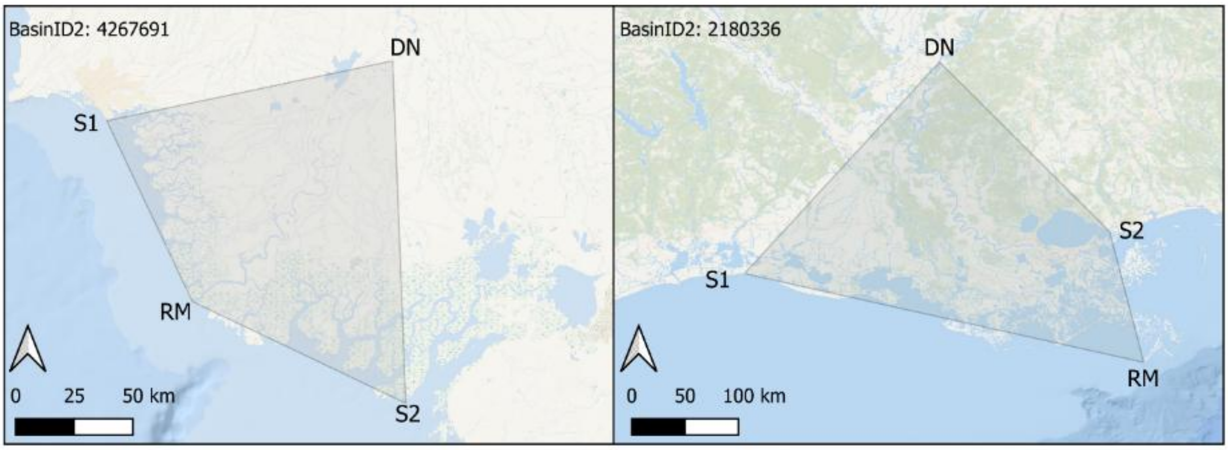


Fig. SI1: Two examples of the four deltaic points that define the delta polygon. DN represents the delta node, S1 and S2 represent the lateral shoreline positions, and RM represents the river mouth [23].

SI3. Equations and data sources of physical indicators

The physical indicators for each strategy are calculated using the following equations in a simple geometric model:

Advance

Volume of material required (m^3) to extend the coastline seaward (Fig. SI2) is calculated using:

$$V_{adv} = \left(\frac{1}{2} * D * d * c\right) + (RSLR * D * c) \quad (1)$$

where *D* is the offshore distance (m); *d* is the offshore depth (m) calculated using the bathymetric slope ($m.m^{-1}$) immediately offshore of the river mouth which is assumed to be linear[24]; and *c* is the coastline length (m). The coastline length is calculated as the distance between the coordinates which demarcate the shoreline position S1 and S2 in the delta polygon[23,25] (Fig. SI1). Finally, RSLR is calculated using the predicted SLR (m) under three climate scenarios (SSP1-2.6, SSP2-4.5 and SSP5-8.5)[26] and vertical land motion (VLM)(mm/yr)[27] for each delta by 2100. We include subsidence in this equation because omitting it from global SLR risk assessments may underestimate exposure[28].

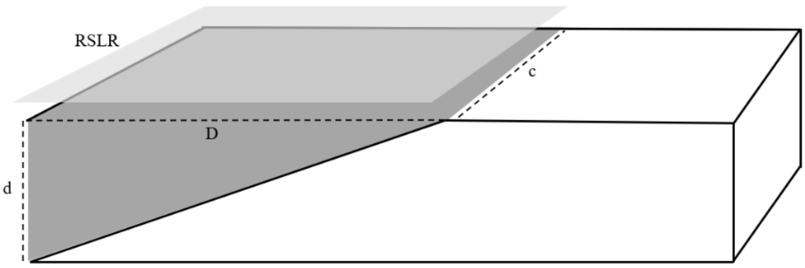


Fig. SI2: Shape of the volume of material required to extend the coastline seaward based on Eqn. 1.

The total amount of river sediment collected to advance the coastline seaward over 50 years is calculated using:

$$Q_s\,(m^3.s^{-1}) = \frac{Q_s\,(kg.s^{-1})}{\rho_b\,(kg.m^{-3})}$$

$$Sediment\ collected_{adv}\,(m^3.s^{-1}) = Q_s * R_r * T \quad (2)$$

Here, Q_s (kg/s) is the mean annual river sediment discharge (m^3/s)[29,30] which is assumed to remain unchanged until 2100 (see Supplementary Text SI6). Sediment discharge is converted to m^3/s by assuming the bulk density of the sediment (ρ_b) is 1600kg/m^3. We estimate the total volume of sediment collected over a 50-year period (T, s) and using different sediment retention rates (R_r, %)(see Methods). Since sediment retention rates vary between 2 and 100% according to existing literature (Table SI2), we consider three representative retention estimates, namely 20%, 40% and 80% which correspond to low-resource, current known and innovative thresholds, respectively. If, for example, the volume of river sediment retained at a 40%

retention rate exceeds the sediment required to aggrade the coastline seaward, then the measure is considered physically under current known conditions. However, if the volume of river sediment contained at a 20% retention rate is insufficient to meet the sediment demand for the coastline extension, the measure is considered unfeasible under low-resource conditions.

Alternatively, deltas can collect offshore sand as a material source to aggrade a new coastline instead of river sediment. The depth (m) at 10km offshore for sand minding (beach nourishment) is calculated using the offshore distance (m) and bathymetric slope[24]. Under each climate scenario, we add the SLR value to this depth calculation[26].

The pump capacity (PC)(m^3/s) is calculated using:

$$PC_{mean} = Q_r \tag{3}$$

Where the mean pump capacity (PC_{mean}) is either equal to the mean annual river discharge, Q_r (m^3/s)[29,30] or the maximum river discharge, assuming a 100% pump efficiency and that the river discharge will not change by 2100 (see Supplementary Text SI6). The maximum river discharge is the 99th percentile of discharges, which is a modelled value from the Water Balance Model (WBM) reanalysis between 1980 and 2012[31]. We base pump requirements on the mean river discharge, assuming the excess water during higher river flows can be diverted to retention areas. We also considered the maximum river discharge without assuming the availability of retention areas for excess water.

<u>Protect-closed</u>

The volume of material required (m^3) to build a smooth, gentle-sloped (1:6) coastal levee (Fig. SI3) is calculated using:

$$h_c = 3 * (H_w + H_{ss})$$
$$b_{1c} = h_c$$
$$b_{2c} = b_{1c} * 6$$
$$V_{coast} = \left(\frac{1}{2} * (b_{1c} + b_{2c}) * h_c * c\right) + (RSLR * b_{2c} * c) \tag{4}$$

Variable definitions:

- h_c: Coastal levee height (m)
- H_w: Mean significant wave height (m)[24]
- H_{ss}: Storm surge height (m)[23,32]
- b_{1c}: Short base of the coastal levee (i.e. the top of the levee)
- b_{2c}: Long base of the coastal levee (i.e. the bottom of the levee)
- V_{coast}: Total volume of material (m^3) required to build coastal levees
- c: Coastline length
- RSLR: Relative sea-level rise (m)

The significant wave height (H_w) is the average of the largest 1/3 of wave heights using the NOAA WAVEWATCH III 30-year Hindcast Phase 2 between 1979 and 2009[33]. H_{ss} data has a 100-year return-period[23] and is calculated using the median of recorded storm surge values[32]. RSLR is the sum of the predicted SLR (m) following three climate scenarios, namely SSP1-2.6, SSP2-4.5 and SSP5-8.5[26], and the VLM (mm/yr)[27] by 2100.

The pump capacity (m^3/s) is calculated using the same equation (Eqn. 3) and data as discussed above, and the maximum river discharge is tested in this case too.

<u>Protect-open</u>

The volume of levee material required (m^3) to build levees (Fig. SI3) along the coast and both sides of the rivers is calculated using:

$$h_r = 5m = b_{1r}$$
$$b_{2r} = b_{1r} * 6$$
$$V_{river} = 2 * \left(\frac{1}{2} * (b_{1r} + b_{2r}) * h_r * L_r\right) + (RSLR * b_{2r} * L_r)$$
$$\mathrm{V}_{total} = \mathrm{V}_{coast} + \mathrm{V}_{river} \qquad (5)$$

Variable definitions:

- h_r: River levee height (m)
- b_{1r}: Short base of the river levee (i.e. the top of the levee)
- b_{2r}: Long base of the river levee (i.e. the bottom of the levee)
- V_{river}: Total volume of material (m^3) required to build river levees on both sides of the river
- L_r: Total river length (m) [34]
- RSLR: Relative sea-level rise (m)
- V_{total}: Total volume of material (m^3) required to build both coastal and river levees
- V_{coast}: Total volume of material (m3) required to build coastal levees (Eqn. 4)

Here, h_r is the river levee height (m) which we base on existing studies that show that levee heights can vary between 1m and 12m high, and can reach up to 21m[35–37]. We use an average levee height of 5m which excludes the uncommon and extreme cases. We extract the river lengths (L_r) from the Surface Water and Ocean Topography River Database (SWORD) dataset which provides high-resolution river reaches (~10km) and river nodes (200m) at a global scale[34]. Where SWORD is missing a river length (214 cases) within the polygon, we calculate the river length manually. We assume that the river length is equal to the length between the coordinates demarcating the delta node (DN) and the river mouth (RM)(Fig. SI1). DN, in this case, is the upstream-most bifurcation of the parent channel, and RM is the location of the widest river mouth along the coastline. RSLR is the sum of the predicted SLR (m) following three climate scenarios, namely SSP1-2.6, SSP2-4.5 and SSP5-8.5[26], and the VLM (mm/yr)[27] by 2100.

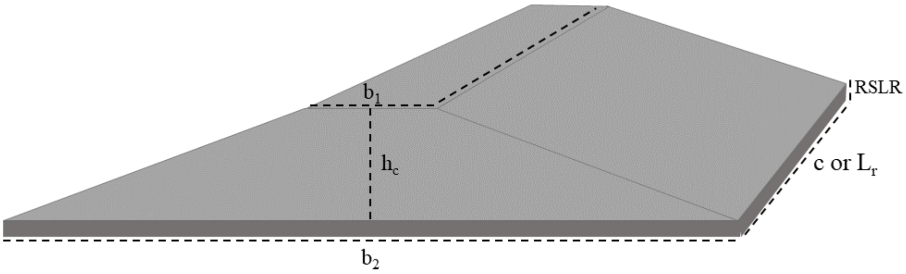


Fig. SI3: Assumed shape of the levee to calculate the volume of material required for construction, following Eqn. 4 and 5. In the equations, b_{1c} refers to the b_1 for coastal (c) levees, whereas b_{1r} refers to b_1 of river (r) levees.

The river width required to build a storm surge barrier (m) is extracted and summed from the SWORD dataset[34]. Where river widths are missing (369 deltas), we calculate these values using a simple river-mouth width (w_m) estimate[38]:

$$w_m = \beta * k * a * L + w_u \tag{6}$$

Here, $\beta = w/d$, where w the channel width and d is the channel depth, k is the proportionality coefficient that relates the tidal prism to the cross-sectional area to the river mouth, α is the offshore tidal amplitude (m), L is the estuarine length scale for long-wave propagation in a distributary channel (m) and w_u is the fluvial channel width (m)[38]. The calculated river-mouth widths have been compared to observed river-mouth widths and show very good agreement, with no systematic bias[38]. However, the calculated river-mouth widths tend to be lower than those from SWORD, likely because the river-mouth estimate assumes a single channel whereas values from SWORD include multiple river mouths whose combined width can be ~50% greater. However, the river-mouth width estimate is used in small deltas, typically with only one distributary mouth.

Accommodate

The 2019 Copernicus global land cover dataset is used to identify land cover within each polygon[39]. This dataset distinguishes 21 land cover types, which we categorize into 3 main groups, namely nature, cropland, urban (built-up). We isolate urban land use from this dataset, overlay it with ~1km resolution flood maps containing global inundation projections with global mean values that correspond to the climate scenario used[40], and downscale it to 100m resolution. The flood maps in our analysis were created using a static flood modelling approach with extreme sea levels from combined tide and surge levels and accounting for national estimates of flood protection standards. These maps use the Multi-Error-Removed Improved-Terrain (MERIT) digital elevation model. MERIT has previously been found to be consistently higher than the reference, specifically in areas with built-up land cover[41]. This may result in an underestimation in the flooding in the urban areas.

The flood depth of each urban land use grid cell is identified and the thresholds are applied, assuming the urban areas can be raised by of 0.5m, 1m or 2m. If the mean flood depth in the urban area, based on the flood maps[40], exceeds 0.5m, then raising by 0.5m is unfeasible. Similarly, if the mean flood depth in the urban area exceeds 1m or 2m, then raising by 1m or 2m is unfeasible. However, if the flood depth is lower than 1m, then a 1m elevation is considered to be physically feasible.

Retreat

The land availability for a retreat is calculated by dividing the urban flooded area (m^2) by three different areas where the urban flooded area can retreat to (see Methods).

$$LA_{ret} = \frac{Area\ to\ retreat\ to\ (m^2)}{Urban\ flooded\ area\ (m^2)} \quad (7)$$

Where LA_{ret} is expressed as a ratio between 0 and 1. A value greater than 1 indicates that retreat is physically feasible. Retreat to areas outside the delta is always deemed physically feasible.

Do nothing (no strategy required)

The presence or absence of flood risks in the delta polygon are identified using the flood maps[40]. Where no flood risks were predicted under each climate scenario by 2100, these deltas are assumed to do nothing.

SI4. Support for thresholds selected

The "current known" threshold is determined using existing examples of adaptation measures in literature, and refers to the largest known or most commonly used value of a measure (Table SI2). While our indicators' thresholds are based on currently implemented scales of measures, these thresholds may vary based on a delta's capabilities and resources.

Table SI2: Database of existing examples of measures within adaptation strategies. These measures represent the physical indicators in our assessment and the magnitude values are used to create the respective thresholds.

Measure	Area/ name, Country	Income level (World Bank)[42]	Magnitude	Ref
Pump capacity	New Orleans, United States of America	High income	~55m^3/s per pump (22 pumps)	43
	IJmuiden, the Netherlands	High income	~43m^3/s per pump (6 pumps)	44
	Afsluitdijk, the Netherlands	High income	~45m^3/s per pump (6 pumps)	1
	Fens, United Kingdom	High income	~16.6m^3/s per pump (6 pumps)	45
Levee heights	Mississippi, United States of America	High income	~12m high (~5.6km total extent)	46

	The Netherlands	High income	~4-7m high (~22,000km total extent)	[47]
Seawall height	Saemangeum, Korea	High income	36m (33.9km total extent)	[48]
Land reclamation	Palm Jumeirah, Dubai	High income	700ha = ~6km^2	[49]
	Hong Kong International Airport, China	Upper-middle income	250million m^3 of material was dredged for an area of 1248ha	[50]
	Maasvlaakte 2 harbour, Rotterdam, the Netherlands	High income	20km^{2,} with an offshore extension of ~3km	[51]
	Pulau Tekong, Singapore	High income	800ha polder	[6,43]
Artificial shoreline construction	Jakarta, Indonesia	Upper-middle income	18.93km^2 new coastline	[52]
	Istanbul, Turkey	Upper-middle income	9.23km^2 new coastline	[52]
Storm surge barrier	Eastern Scheldt Barrier, the Netherlands	High income	9000m	[53]
	Saint Petesburg Flood Prevention Facility Complex (FPFC), Russia	High income	25000m	[54]
	Maeslant barrier, the Netherlands	High income	400m	[53]
	Hartel Barrier, the Netherlands	High income	~150m	[55]
	Thames Barrier, United Kingdom	High income	520m	[55]
	Venice MOSE project, Italy	High income	3200m	[55]
	Ems barrier, Germany	High income	462m	[56]
	Seabrook barrier, New Orleans, United States of America	High income	130m	[55]
	IHNC Surge Barrier, New Orleans, United States of America	High income	2890m	[57]

Home raising	Vietnam	Lower-middle income	0.3-0.8m (39 homes)	17
	Genuk, Indonesia	Upper-middle income	0.5m (170 homes)	58
	Philippines Islands	Lower-middle income	0.3m (169 homes)	59
	Mississippi, United States of America	High income	3.6m (1 gymnasium)	16
	Mississippi, United States of America	High income	1.8m	60
Retreat	Mozambique	Low income	43,400 families	61
	Vietnam	Lower-middle income	Household scale	17
	Vietnam	Lower-middle income	Neighbourhood scale	17
	Isle de Jean Charles, Gulf of Mexico	Upper-middle income	Community retreat	21

Table SI3: Examples of published natural sediment retention rate estimates in delta plains.

Delta, Country	**Sediment retention rate (%)**	**Source**
Amazon, Brazil	41 (over 15 years)	62–66
Guadiana, Portugal	2	67
Burdekin, Australia	2	68,69
Mekong, Vietnam	102	70–72
Rhine, the Netherlands	13 to 67	73,74
Ob, Russia	43 (over 30 years)	75
Yangtze, China	37	76,77

The "innovative" threshold is defined as twice the value of the "current known" threshold (Table 2 in manuscript). This threshold reflects the importance of scaling-up measures for long term sustainability[78]. While there are currently no projections for how adaptation technologies will evolve by 2100, there have been significant increases in technological and infrastructural capabilities over the last 100 years. For example, between 1970 and the late 20th century, there was a shift from manual data collection to modern, high-technology digital modelling methods[79], and nowadays, artificial intelligence (AI) and machine learning (ML) offer even more opportunities for flood risk assessments[79,80]. Beyond technological modelling advancements, flood management practices have advanced between 2000 and 2017, from costly and basic structural flood control measures that impact biodiversity, to environmentally friendly adaptation strategies that build resilience and enable rapid recovery[81]. More specifically, in the Netherlands, flood defences have evolved from the Afsluitdijk (1932) and the Delta Works with storm surge barriers like the Eastern Scheldt (1986) and Maeslant Barrier (1997) to recent adaptive and nature-based projects such as the Room for the River and the Sand Motor[82]. This reflects the innovation in scale, technology, and sustainability over the last century. As such, assuming a twofold increase in technological capabilities by 2100 is perhaps conservative, but also more realistic than an extrapolation based on the past.

For other strategies, including accommodate where homes are raised by more than 1m, or retreat where people and assets are relocated outside of the delta, such technologies to implement these measures at "innovative" scales already exist (Table SI2) but have not been implemented delta-wide, which would require innovation. Similarly, while one storm-surge barrier of 9km has already been constructed (Table SI2), constructing multiple barriers of similar scale would also require innovation in terms of resources, space and planning. Thus, the innovative threshold not only represents possible physical limits of technology (in the case of pump capacity), but also the application of measures at a larger scale (accommodate or protect-open) and the coordination required for their implementation.

SI5. Flood risks for global deltas and differences between climate scenarios

Our data shows that all 769 global deltas will experience sea-level rise following each climate scenario (Mean = 0.48m under SSP1-2.6; Mean = 0.6m under SSP2-4.5; Mean = 0.94m under SSP5-8.5). Additionally, at least 79% of global deltas will experience flooding under a 100-year return storm surge event. This increases to 82% and 86% under higher climate scenarios (SSP2-4.5 and SSP5-8.5), respectively.

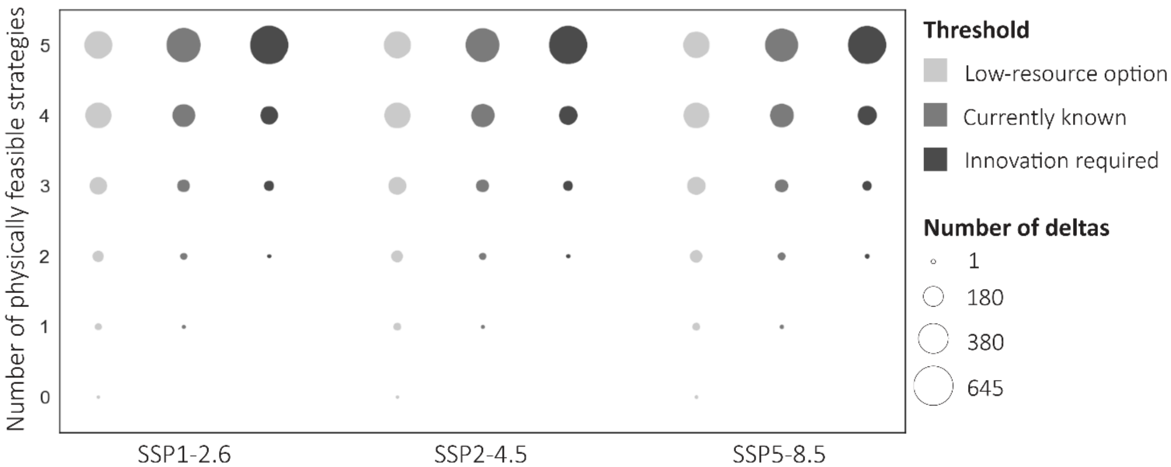


Fig. SI4: The number of physically feasible adaptation strategies (between 0 and 5) for global deltas following three climate scenarios. The size of the bubbles represent the number of deltas that can choose between each range of adaptation options. The coloured thresholds represent different scales of adaptation measures, namely low-resource measures that are physically feasible under limited resource conditions, current known measures that are the largest known examples of measures or commonly used scales of measures, and innovative measures which are only physically feasible with technological advancements.

However, when comparing the number of physically feasible adaptation strategies for deltas across climate scenarios, we find that the differences between scenarios are minor (1.62% decrease; Fig. SI4). Instead, the thresholds applied to the adaptation measures have a greater influence on the number of strategies that are physically feasible (35% increase; Fig. SI4). For only one delta, namely the Rhine-Meuse delta in the Netherlands, there are no physically feasible low-resource strategies across all three climate scenarios (Fig. SI4). In this delta, only current known scales of measures or innovative solutions are physically feasible given the deltas large physical characteristics, large urban area, and large flooded extent.

SI6. Model output comparison

SI6.1. Sensitivity analysis and model stress-testing

To validate the model performance under extreme conditions, we perform a sensitivity test by increasing or decreasing parameters by an order of magnitude well beyond plausible ranges (± 10 or ×/÷ 10)(Fig. SI5). This confirms the expected expansion of the PSS when the delta's physical characteristics are small, and the contraction of the PSS when the delta's physical characteristics are large. This stress test serves as a boundary check which illustrates model reliability rather than reflecting parameter uncertainty.

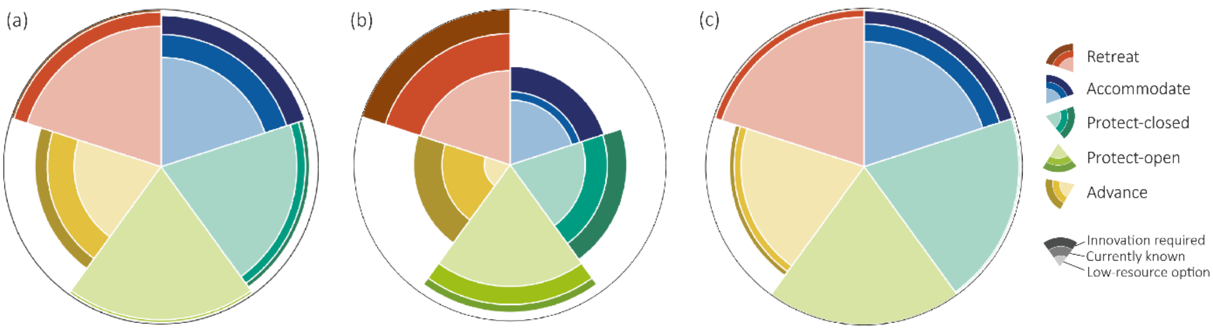


Fig SI5: Radar plots comparing (a) the physical solution space (PSS) of global deltas under an SSP2-4.5 scenario, with the outcomes from a stress-test of the model by (b) increasing or (c) decreasing input parameters well beyond plausible ranges to assess how the PSS contracts or expands, respectively.

However, we also assess parameter uncertainty by performing a sensitivity analysis. Based on projected changes in river discharge, mean flow is expected to vary between approximately a decrease of 23% and increase of 65% across river basins[83], while global mean river discharge is projected to increase by 2%, 6%, 7.5%, and 11% under RCP2.6, 4.5, 6.0, and 8.5 scenarios, respectively, by the end of this century[84]. In contrast, projected sediment discharge for many deltas around the world shows a reduction in sediment flux, with mean declines of approximately 38% by 2100[85], while the mean global sediment flux is projected to increase by 11%, 15%, 14%, and 16.4% across the four emission scenarios[84]. We use these projections to test the sensitivity of our input parameters on the physical feasibility of strategies. Specifically, we vary river discharge between −23% and +65% and sediment flux between −38% and +16% to consider the full range of variability from both basin and global scale projections. Under decreased river discharge projections, we find that 13 additional deltas can adopt the protect-closed strategy under current known conditions given lower pump capacity requirements. However, under increased river discharge projections, 28 fewer deltas can adopt this strategy due to pump capacity constraints under current known conditions. We assume that projected increases in maximum river discharge would also decrease the number of deltas that can adopt this strategy. Under decreased river and sediment discharge projections, the advance strategy becomes physically feasible for an additional 12 deltas given the lower pump capacity requirements. However, under increased river and sediment discharge projections, the number of deltas that can adopt advance decreases by 25 deltas, since installing larger river pumps become less physically feasible despite increased sediment to aggrade the coastline. This reveals that some input parameters, such as river discharge, have a greater influence on the physical feasibility of certain strategies, like advance. Moreover, while individual deltas are impacted by changes in these parameters which has implications for local scale decision-making, the general adaptation trends remain mostly consistent across the global scale.

We test the sensitivity of assuming 5m high river levees following the protect-open strategy by changing this height and recalculating the material requirements (2m = 8.4km^3; 5m = 14.56km^3; 10m = 33.64km^3). We find that the overall message remains the same whereby the protect-open strategy has higher material requirements than protect-closed strategy, even when considering lower-end levee heights.

Finally, we explore the influence of the chosen innovative threshold on the PSS. We increase the threshold by an order of magnitude, as opposed to a twofold increase, and find that substantial innovation in technological capabilities does not necessarily imply more strategies are physically feasible. While certain adaptation measures, such as 10m stilts following accommodate or 12,000m^3/s pumps following protect-closed, increase the PSS for some deltas, the PSS of other deltas remain unchanged due to fundamental physical characteristics. This highlights that innovation alone does not provide more adaptation opportunities. Given these findings, we maintain the assumption of a twofold increase in innovation capabilities for our analysis since it is more realistic by 2100, and avoids overestimating adaptation opportunities.

SI6.2. Literature assessment and model output comparison for 10 deltas

The model is tested by first applying the equations and thresholds to 10 field deltas, which vary in size, degree of urbanization and flood extent (Fig. SI5; Table SI3).

Fig. SI6: Names and locations of 10 deltas for model testing.

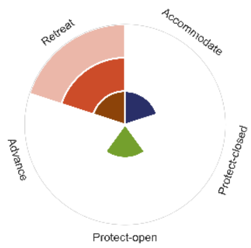
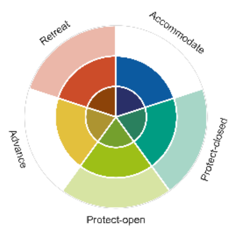
Table SI3: Delta names and country of 10 deltas for model testing.

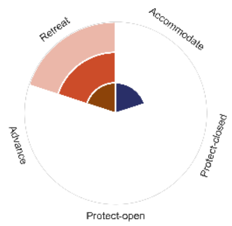
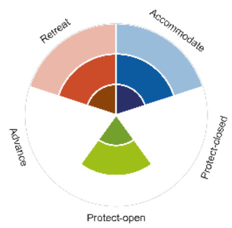
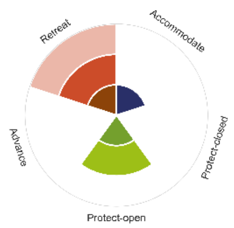
Number	Delta name	Country
1	Amazon	South America
2	Ebro	Spain
3	Ganges-Brahmaputra-Meghna	Bangladesh
4	Mekong	Vietnam
5	MacKenzie	Canada
6	Mississippi	United States of America
7	Niger	Nigeria
8	Nile	Egypt
9	Rhine-Meuse	The Netherlands
10	Riö Grande- Bravo	United States of America

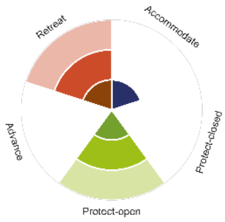
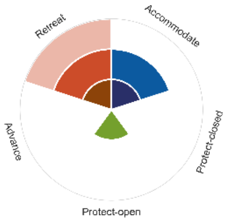
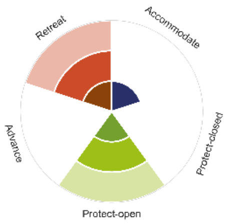
We compare our model outputs with literature that focusses on current implemented adaptation measures and potential future strategies in these deltas. The model outcomes are mostly consistent with measures used in practice (Table SI4). For example, in the Ebro delta, future strategies based on literature include protect, advance, or accommodate, which we find to be physically feasible based on our model (Table SI4). Additionally, in the Mississippi delta, future measures to address flood risks include relocations within the delta, land raising or elevations of urban areas, and protective measures, which we also find to be physically feasible strategies in 2100 (Table SI4).

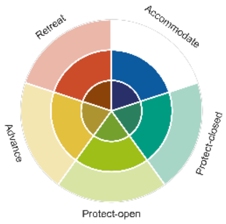
However, there are also measures in the literature that are not consistent in the PSS that we modelled. This may be primarily because we assessed the PSS assuming the strategy will be adopted across the entire delta, however, small scale, localized strategies may also be implemented in these deltas. For example, in the Ganges-Brahmaputra-Meghna delta, the modelled PSS is small, but according to literature, many other measures are already implemented in this delta at a smaller scale (Table SI4). Additionally, in some cases, the hazards that measures protect against, or the currently implemented measures based on literature are not measures that we assess within the adaptation strategy, as seen for the Ganges-Brahmaputra-Meghna and the Amazon delta, respectively (Table SI4).

Table SI4: Comparison between the calculated physical solution space, and the existing implemented or future strategies in the 10 deltas based on existing literature.

Delta Name	PSS found in this study	Existing implemented strategies and future strategies
Amazon		• Sediment deposition along the coast [64] • Early warning systems[86] • Forecasting and alert system for floods[87] • River and rainwater drainage infrastructure[88] • Raise the level of properties (25cm between road and flood level)[88] • Flood resistant crops[89] • Artificial islands and terraces built on flooded areas[89] • Social organization and the process of awareness and training of the community[88]
Ebro		• Large dams and marshes in the area[90] • Wetlands[91] **Future:** • Sand dunes, natural beach barriers, artificial barriers, accretion of sediment supply, shift rice fields to wetlands to retain more sediment[92] • Use sediment to naturally raise the land to compensate flooding[93] • Wetland restoration, engineered structures (dikes, canals), sediment accretion to stop coastal retreats[94]

Ganges-Brahmaputra-Meghna		• Diked polder system that protect agriculture[95] • Controlled flooding to allow sediment deposition (Sedimentation following dike breaches)[96] • Cyclone shelters, dike construction, aquaculture, salt tolerant rice, floating infrastructure[97] • Dikes and early warning systems[98] **Future:** • Promote nature-based solutions to protect and restore natural or modified ecosystems, construction and rehabilitation of flood and drainage management measures, protection against flash floods and waves, reclamation and development of lands for expansion [99] • Future migration from hazard-prone areas. Specifically, overseas migration over urban migration[97]
MacKenzie		• Home to a very small population, so there are no protect adaptation measures. **Future:** • Promote emergency preparedness in schools, avoid building in areas vulnerable to erosion and slumping[100]
Mekong		• Sedimentation basins created by permeable bamboo dams[101] • Earth dike and floodplain (mangrove) restoration using T-groins/fences[102] • Dike rings to protect agricultural crops and reduce local natural hazards[103] • Mangrove restoration and national sea dike along entire coast[104] **Future:** • Implement integrated flood impacts assessment, improve communication, and build capacity for flood management staffs, and infrastructural measures such as optimize the existing flood control infrastructures[105] • Develop new technical measures for flood management and address the unwanted impacts of existing flood management infrastructures[105]

		• Enhance early forecast and warning of extreme events, enhance monitoring, data collection and sharing, strengthen capacity on development of climate change adaptation strategies[106]
Mississippi		• Community relocation from areas at risk[22] • Wetlands and levees[107] • Inner Harbor Navigation Canal-Lake (IHNC) Borgne Surge Barrier[55] • Home raising 5-6ft (1.5-1.8m)[60] • Forced relocation (involuntary relocation)[108] • Terrebonne Basin Barrier island restoration[109] **Future:** • Elevating the city of New Orleans[16] • Land raising in New Orleans[60] • Ring levee systems to protect specific areas[110] • Relocate within the delta if necessary[108]
Niger		• Construction of foot bridges with wood, stones and sand bags[111] • Raising walls with sand bags and/or blocks to divert flood water[111] • Use of mulching materials for crops and shades for animals[111] • Agricultural adaptation, such as crop diversification and altering the timing of operations[112] • Migration from climate risk areas[112] • Reclamation of wetlands/ river valleys[112] **Future:** • Need government, NGO, donor agencies and other stakeholders to come together to implement strategies (accommodate, protect, retreat)[113]
Nile		• Seawalls, revetments, sand dunes, nourishment, and artificial sand dunes based on a geotextile sand-tube core, fish farming, regular dredging for coastal lakes and lagoons, and enforcing the coastal road were observed[14] **Future:** • Restoration and maintenance of sand dunes, maintaining coastal protection structures,

		preserving existing wetlands, setting up regulations to restrict development in vulnerable areas, change of land use, development of comprehensive monitoring program[114]
Rhine-Meuse		• Zuiderzee closure, groynes, river training (canalisation), Delta Works (dams, sluices, storm surge barriers), dikes, pumps, land reclamation[115,116] • Floating homes[117] **Future:** • Upgrading of current flood defense system[118] • Permanent closure of estuaries, pumping high river discharges, maintenance of coastlines by beach nourishments[3,119] • Frequent closure of storm surge barriers[119]
Riö Grande-Bravo		• Levee system[118] • Diversion dams[118] • Pumping plant and conveyance channel used to reduce salinity of the river[118] • Flood warning systems, flood proofing structures, land use regulations, development restrictions in flood[20]

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