



What are the implications of sea-level rise for a 1.5, 2 and 3 °C rise in global mean temperatures in the Ganges-Brahmaputra-Meghna and other vulnerable deltas?

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Abstract

Even if climate change mitigation is successful, sea levels will keep rising. With subsidence, relative sea-level rise represents a long-term threat to low-lying deltas. A large part of coastal Bangladesh was analysed using the Delta Dynamic Integrated Emulator Model to determine changes in flood depth, area and population affected given sea-level rise equivalent to global mean temperature rises of 1.5, 2.0 and 3.0 °C with respect to pre-industrial for three ensemble members of a modified A1B scenario. Annual climate variability today (with approximately 1.0 °C of warming) is potentially more important, in terms of coastal impacts, than an additional 0.5 °C warming. In coastal Bangladesh, the average depth of flooding in protected areas is projected to double to between 0.07 and 0.09 m when temperatures are projected at 3.0 °C compared with 1.5 °C. In unprotected areas, the depth of flooding is projected to increase by approximately 50% to 0.21–0.27 m, whilst the average area inundated increases 2.5 times (from 5 to 13% of the region) in the same temperature frame. The greatest area of land flooded is projected in the central and north-east regions. In contrast, lower flood depths, less land area flooded and fewer people are projected in the poldered west of the region. Over multi-centennial timescales, climate change mitigation and controlled sedimentation to maintain relative delta height are key to a delta's survival. With slow rates of sea-level rise, adaptation remains possible, but

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further support is required. Monitoring of sea-level rise and subsidence in deltas is recommended, together with improved datasets of elevation.

Keywords Sea-level rise · Flooding, delta · Ganges-Brahmaputra-Meghna · Volta · Mahanadi

Abbreviations

ΔDIEM	Delta Dynamic Integrated Emulator Model
BAU	Business-as-usual
GBM	Ganges-Brahmaputra-Meghna
GCM	Global climate model
LS	Less sustainable
MS	More sustainable
RCM	Regional climate model
RCP	Representative Concentration Pathway
SLR	Sea-level rise
SRES	Special Report on Emissions Scenarios

Introduction

The Paris Agreement (United Nations 2015) aims for temperature stabilisation to ‘well below 2 °C above pre-industrial levels’ and pursue ‘efforts to limit the temperature increase to 1.5 °C’. Climate change mitigation has many benefits; yet for the impacts of sea-level rise (SLR), this takes time to manifest as there remains a long-term commitment to SLR due to historical warming (Goodwin et al. 2018; Nicholls et al. 2018; Nicholls and Lowe 2004). Global mean rises of 0.75 to 0.80 m (with a probability of greater than 50%) are projected by 2100 (for a 1.5 and 2.0 °C scenario) with respect to 2000 (Schaeffer et al. 2012).

Presently, there is limited understanding of the impacts of SLR at 1.5 and 2.0 °C in vulnerable low-lying deltas (e.g. Zaman et al. 2017), whose problems are compounded by sediment starvation and subsidence, leading to salinisation, flooding and erosion. Deltas are subject to multiple drivers of change, as society responds to this planned and unplanned ways. Thus, this paper analyses the implications of temperature and equivalent SLR at 1.5, 2.0 and 3.0 °C in the world’s largest delta which is highly populated, the Ganges-Brahmaputra-Meghna (GBM), plus the wider implications for other deltas. This will be achieved by (i) reviewing the setting of the GBM; (ii) describing the modelling methodology used; (iii) analysing impacts at 1.5, 2.0 and 3.0 °C; and (iv) discussing the caveats and consequences of these findings in the context of other deltas, plus the potential for adaptation.

Setting

The GBM delta is a large delta occupying more than 100,000 km², depending on definition, and contains the Sundarbans mangrove forest. The impacts of SLR have been

analysed for a 18,600-km² sub-region of the delta containing 14 million people (Fig. 1). Largely rural, the study area is located less than 3 m above mean sea level. The dominant land use is agriculture, and there is a high reliance on monsoon rainfall conditions to sustain livelihoods. There is strong tidal influence in the delta (Kausher et al. 1996).

In 1975, the building of the Farakka barrage resulted in an annual decrease in sediment load of 31% (Gupta et al. 2012) and in south-west Bangladesh resulted in decreased river discharge and increased salinity (Mizra 1998). Separately, from 1989 to 2009, there was erosion along the seaward side of the Sundarbans in western Bangladesh (Sarwar and Woodroffe 2013), with erosion and accretion elsewhere along the coast-line (Brammer 2014; Sarwar and Woodroffe 2013; Shearman et al. 2013).

Polders (i.e. low-lying lands surrounded by embankments) are used for agriculture improvement and water management. One hundred twenty-six were built between 1960 and 1990 to protect farmers from tidal and saline water inundation and to regulate water levels (World Bank 2005). However, they restricted sediment deposition causing significant land subsidence of up to 20 mm/year within polders (Auerbach et al. 2015), whereas 2.6 mm/year subsidence is recorded regionally (Brown and Nicholls 2015). Relative SLR (eustatic SLR plus subsidence) is recorded as 9 mm/year (Charchanga to the south-east of the study region, from 1979 to 2000) (Holgate et al. 2013; Permanent Service for Mean Sea Level 2017), but is variable due to natural cycles, plus throughout the region due to subsidence and polders where the latter has a long-term affect on river discharge and tidal flow (Pethick and Orford 2013). Thus, relative SLR poses a major threat in coastal Bangladesh.

Determining impacts of sea-level rise

Scenarios were generated based on climate change and socio-economic development conditions and modelled numerically using the Delta Dynamic Integrated Emulator Model (ΔDIEM) (Lázár et al. 2018). These are described in the following section, with further details in the [Supplementary Material](#).

Scenarios

Climate change scenarios

Climate change scenarios for global temperature rises 1.5, 2.0 and 3.0 °C were generated from a modified version of the

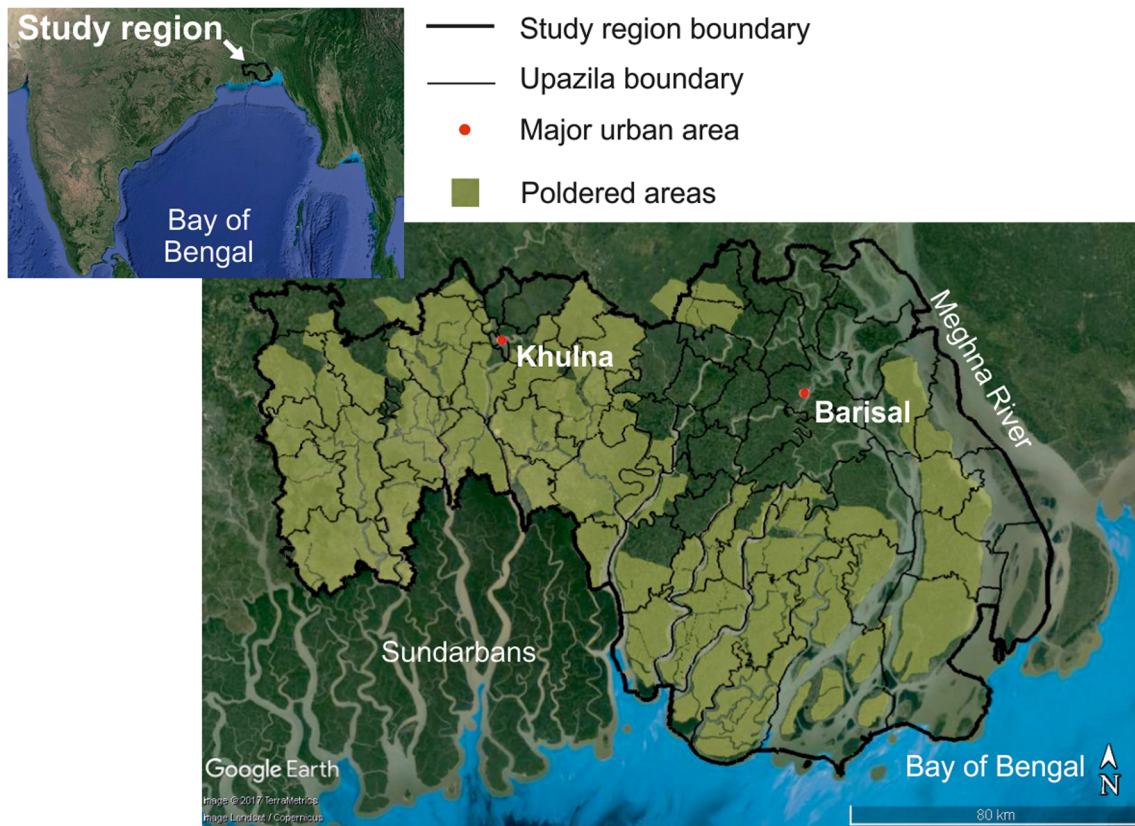


Fig. 1 Region of detailed study in the Ganges-Brahmaputra, Bangladesh

Special Report on Emissions Scenarios (SRES) A1B scenario (Caesar et al. 2015). A1B is a medium to high emissions scenario (Nakicenovic and Swart 2000) lying between Representative Concentration Pathways (RCP) 6.0 and 8.5 (Moss et al. 2010). An output from an ensemble of the global climate model (GCM) HadCM3 (Collins et al. 2006) was used to drive regional climate model (RCM) simulations at a 25-km spatial resolution over South Asia using HadRM3P (Massey et al. 2015). Three ensemble members (out of 17) were selected for detailed analysis: (i) Q0 (a moderate increase in temperature and precipitation), (ii) Q8 (a warmer but drier future around mid-century, then wetter) and (iii) Q16 (a larger increase in temperature). These members represented a wide range of possible futures as explained by Caesar et al. (2015).

Each temperature scenario was referenced by a decadal average time period (with respect to pre-industrial, i.e. 1850–1900). A single SLR scenario (of 0.24 m by 2050 and 0.54 m by 2100 with respect to 1986–2005) was applied to each ensemble member (Kay et al. 2015). This represented a median scenario, and it is recognised there is considerable uncertainty around these scenarios (as described by Kay et al. (2015)), particularly as time progresses. This could mean that impacts could occur later or earlier than anticipated. Figure 2 shows global mean temperature, SLR and the reference period (for values, see [Supplementary Material](#)). Due to different model

historical forcing factors, there were inconsistencies in defining temperature change today. For instance, Q16 indicates that 1.5 °C was reached in 2011, which is inconsistent with observations. Additionally, there is a common issue across climate science regarding defining the pre-industrial baseline (Hawkins et al. 2017). Importantly, if temperatures rise to 1.5 °C quickly (e.g. Q16), sea-level rise will be less when 1.5 °C first occurs compared with a temperature rise which happens over a longer time period (e.g. Q8). Apart from historic forcing factors, this is also due to the commitment to sea-level rise (for long-term implications of this, see discussion on ‘Commitment to sea-level rise’). Apart from SLR, high water levels took account of surges, tides, bathymetry and local river flows (Kay et al. 2015) and included an additional 2.5 mm/year of subsidence (Brown and Nicholls 2015).

Socio-economic development scenarios

Socio-economic conditions were adapted from the five Shared Socioeconomic Pathways (Moss et al. 2010; O’Neill et al. 2014) to form three new scenarios of development: business-as-usual (BAU) less sustainable (LS) and more sustainable (MS) (for definitions, see [Supplementary Material](#)). In the simulations, polder height was maintained at design height.

Methods

Δ DIEM is a modelling framework designed to analyse linkages between climatic change, environmental change, livelihoods, well-being and governance. It couples environmental, social and economic simulations by providing a novel integrated assessment platform for dynamic delta planning (Lázár et al. 2018; Nicholls et al. 2016).

Impacts were based on the decadal average mean, maximum, minimum and standard deviation of floods for the study regions and 70 *upazilas* (i.e. sub-district, mean area 270 km²). More than 90% of the *upazilas* experience some daily (tidal) flooding in the model regardless of reference temperature or ensemble member, reflecting low-lying areas outside polders. Cyclones were not considered due to modelling complexities, but these would exacerbate impacts. Three primary impact metrics were analysed:

- Depth of flooding in areas which are unprotected from flood waters, i.e. the floodplain;
- Depth of flooding in areas which are protected from flood waters;
- Area of land inundated.

A further parameter was analysed (average decadal mean only):

- Number of people affected by flooding derived as a proportion of the area affected inundated assuming a uniform population density per *upazila*.

Fig. 3 Left-hand side: impact for each reference period 1.5, 2.0 and 3.0 °C is reached under the business as usual scenario. The less sustainable and more sustainable illustrated similar results. Average decadal mean, mean \pm 1 standard deviation, maximum and minimum depth shown. **a** Depth of flooding in unprotected *upazilas* for the study region. **c** Depth of flooding in protected *upazilas* for the study region. **e** Area inundated due to flooding in protected and unprotected *upazilas* for the study region. Right-hand side: impact against time, using each year in the decade where the reference temperature is reached for the business as usual, less sustainable and more sustainable scenarios. The average annual mean, maximum and minimum depth are shown. **b** Depth of flooding in unprotected *upazilas* for the study region. **d** Depth of flooding in protected *upazilas* for the study region. **f** Area inundated due to flood in protected and unprotected *upazilas* for the study region

The model was run for the ensemble members (Q0, Q8 and Q16) and three socio-economic conditions (BAU, LS and MS) and reported for the 1.5, 2.0 and 3.0 °C decadal mean temperature intervals.

Results

Regional impacts

Impacts are shown in Fig. 3. The left-hand side illustrates for each reference period where 1.5, 2.0 and 3.0 °C are reached under the BAU scenario for the average decadal mean, mean \pm 1 standard deviation, maximum and minimum of depth without protection, depth with protection and area inundated. The LS and MS scenarios produce similar results except for Q16 at

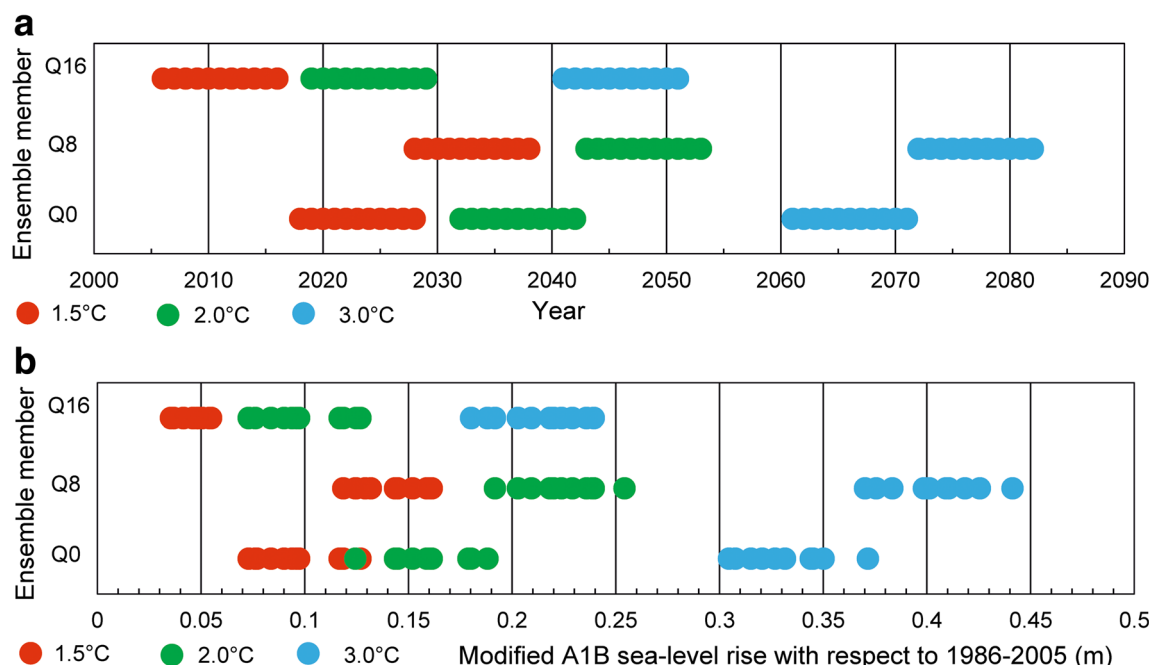
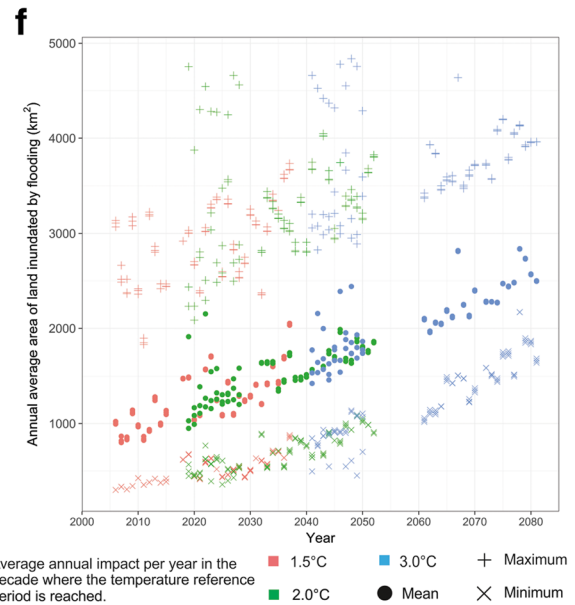
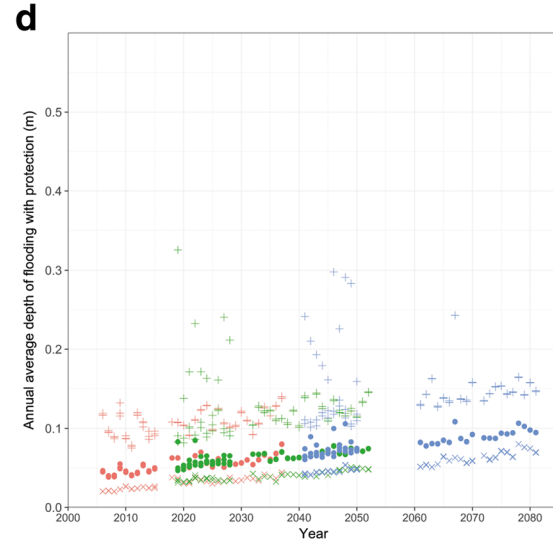
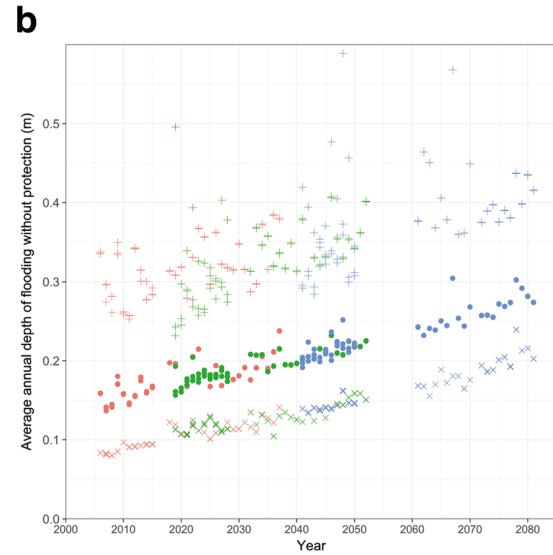
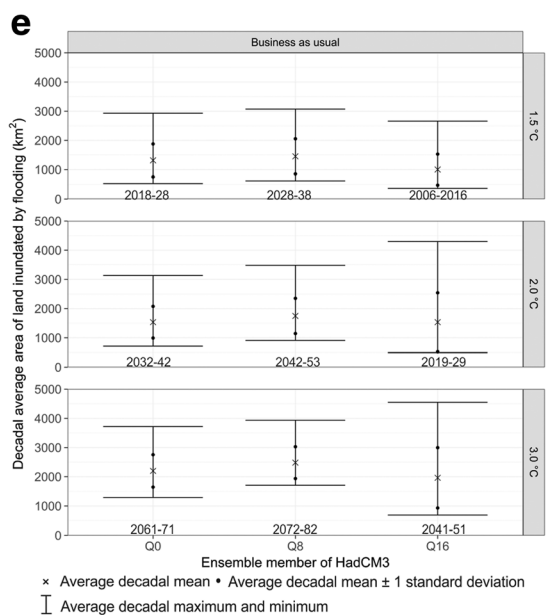
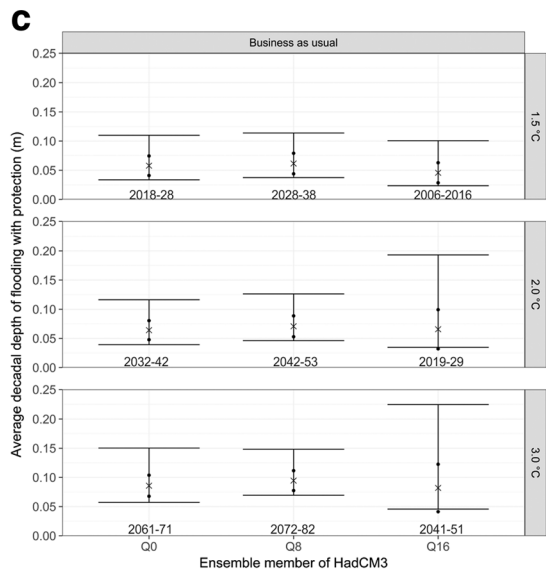
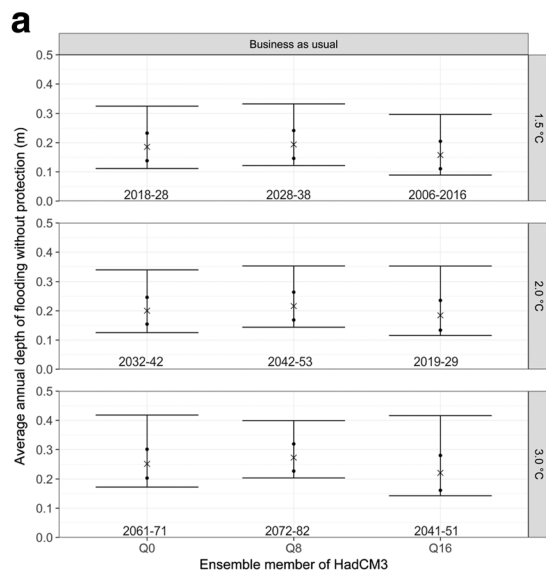


Fig. 2 **a** Global mean surface temperature (with respect to pre-industrial) and **b** SLR (with respect to 1986–2005) when 1.5, 2.0 and 3.0 °C is reached for the Q0, Q8 and Q16 ensemble members. Each dot represents

the mean annual value in the decade that 1.5, 2.0 and 3.0 °C is reached. Multiple temperature reference periods even for the present day due to historical drivers in the model (see main text)



2 and 3 °C, so are not shown. Q16 is projected to experience greater flooding due to more seasonal extremes (a drier dry season and a wetter monsoon season), despite annual precipitation levels being similar between each ensemble member (see [Supplementary Material](#)). The right-hand side illustrates average annual mean, maximum and minimum depth without protection, depth with protection and area inundated against time, using each year in the decade where the reference temperature is reached for the BAU, LS and MS scenarios.

For the depth of flooding without protection (Fig. 3a) in the 1.5 °C reference period, the mean depth of flooding ranges from 0.16 m (Q16 2006–2016) to 0.19 m (Q8 2028–2038). The average maximum depth of flooding is 0.14 m across all ensemble members. At 2.0 °C, the depth ranges from 0.17 m (Q16 2019–2029) to 0.21 m (Q8 2043–2053). The average decadal maximum depth is projected as 0.10 to 0.14 m higher than the mean. At 3.0 °C, the mean depth of flooding without protection is projected to be between 0.21 m (Q16 2041–2051) and 0.27 m (Q8 2072–2082). In absolute values, the spread between the mean and the maximum is the greatest for higher rises in temperature. The standard deviation of flood depth remains similar through time and across climatic and development scenarios.

Figure 3b illustrates these changes with time, where there is an overlap between the 1.5 and the 2.0 °C scenarios. There is no clear impact signal at 1.5 °C until at least the 2040s. The average maximum depth is rising in proportion to the average mean depth, with both having a small acceleration in the rate of impacts under the 3.0 °C scenario.

For the depth of flooding with protection, the greatest uncertainty in impacts is between climate scenarios (Fig. 3c) and annual variability (Fig. 3d). For the 1.5 °C reference frame, the mean depth ranges between 0.04 m (Q16 2006–2016) and 0.06 m (Q8 2028–2038). At 2.0 °C, the mean depth ranges between 0.05 m (Q8 2043–2053) and 0.07 m (Q16 2019–2029), and at 3.0 °C, the mean depth ranges between 0.07 m (Q16 2041–2051) and 0.09 m (Q8 2072–2082). Again, similar to Fig. 3b, the implications of 1.5 °C is not clearly seen over annual mean variations until at least the 2040s. At 3.0 °C, the minimum flood depth increases with respect to the mean, and flooding is more frequent.

Figure 3e illustrates the mean area inundated from flooding. This ranges from 980 km² (Q16 in 2006–2016) to 1,470 km² (Q8 in 2028–2038) for 1.5 °C depending of the model ensemble member (5–8% of the region). The mean area inundated ranges from 1,150 km² (Q16 in 2019–2029) to 1,770 km² (Q8 2043–53) for 2.0 °C and indicates an overlap with the 1.5 °C scenario (Fig. 3f). For the 3.0 °C reference period, the mean area inundated increases to between 1,620 km² (Q16 in 2041–2051) and 2,490 km² (Q8 in 2072–2082) (9–13% of the region).

Spatial impacts

Figures 4, 5 and 6 illustrate mean impacts at *upazila* level where there is high variability in the flooding for the BAU scenario.

At 1.5 °C, the greatest depths of flooding without protection (Fig. 4), for each ensemble member, are projected for the north-east *upazilas*, adjacent to the Meghna Estuary where there are fewer polders, reflecting higher land elevations. *Upazilas* in the central region report the lowest depths, although large variations around the mean are projected. At 2.0 °C, a similar pattern emerges, with depths increasing in the southern and western *upazilas*, despite being poldered. The greatest increase in flood depths are projected at 3.0 °C, especially for the north-west, south-west *upazilas* and those north of Khulna. High variability in depths (i.e. where the decadal variability is > 4 time larger than the mean value) is limited to nine *upazilas*.

The depth of flooding with protection (Fig. 5) is lower across all *upazilas* compared with flooding without protection, but there is a greater variability in the maximum projected depth (particularly Q8). Across all scenarios, flood depth is the greatest in the west and south, which is the opposite finding of flood depth without protection. Hence, model results indicate polders are effective.

The area inundated by flooding (Fig. 6) shows much variability in area across all *upazilas*. The largest area of flooding occurs in the south (where the highest flood depth with protection was reported) despite being poldered. The area least flooded is projected away from the main river systems. Adjacent to the Meghna Estuary, the *upazilas* with the greatest flooding (in the north-east) have fewer polders than those with less flooding in the south-east. Relatively, the greatest proportion of flooding per *upazila* (> 20%) is projected to occur in the north and centre of the region, including Khulna (see [Supplementary Material](#)).

The number of people affected by flooding and the number of people affected by flooding per square kilometre was analysed (see [Supplementary Material](#)). The areas with the lowest population flooded per *upazila* and per square kilometre are in the west, south-west and east of the study region. In the west, this reflects low flood depth and area flooded, particularly in a poldered area (despite a high population density in the region). In the south-west and east, this is because of lower population densities. The greatest number of people projected to be affected by flooding per *upazila* and per square kilometre occurs around Khulna, which has partial protection. These trends remain the same regardless of ensemble member or temperature threshold.

Regional differences in the flood depth (with protection) and inundated areas under the Q16 climate and the 2.0 and

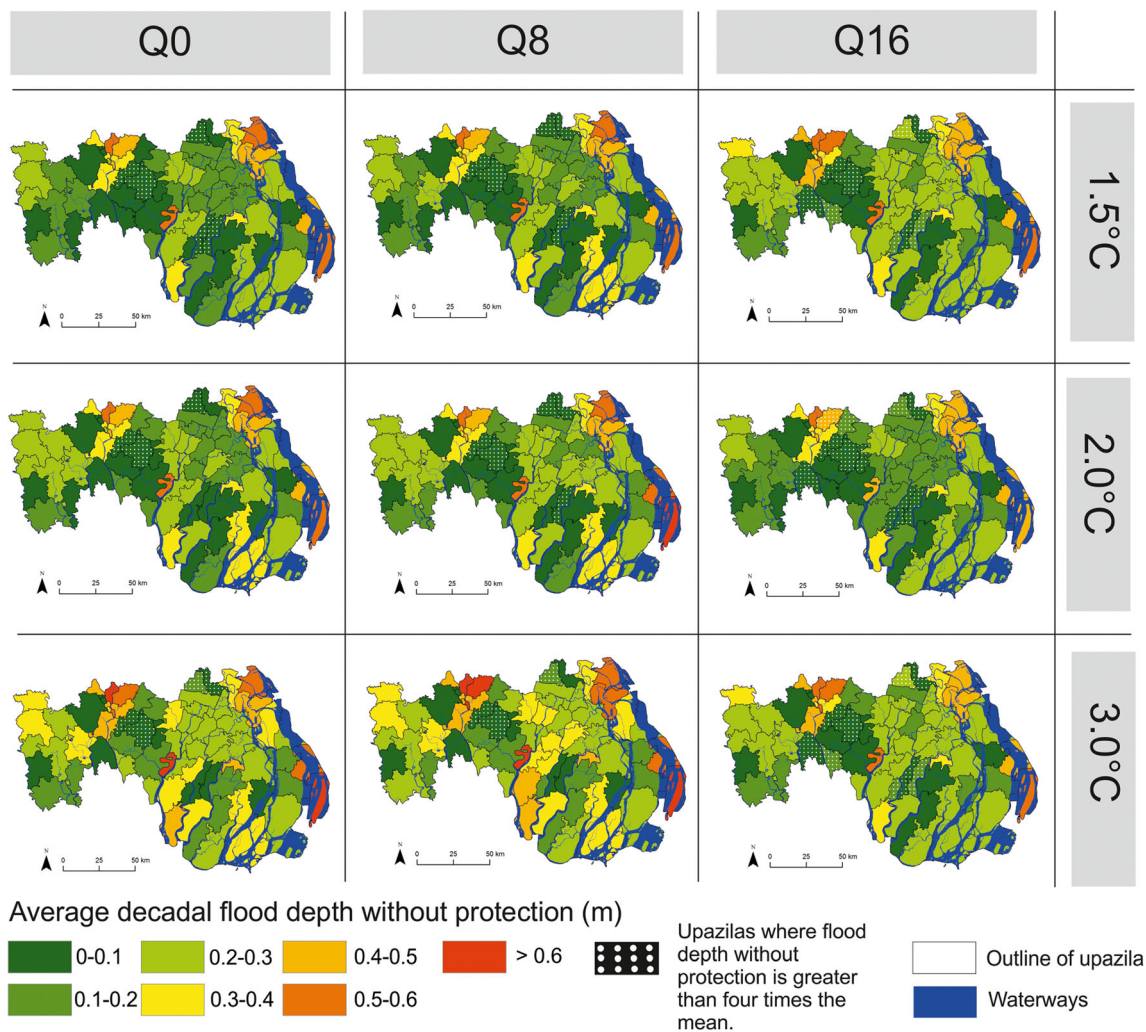


Fig. 4 Illustration of the average decadal mean depth of flooding without protection for across the 70 *upazilas*. Source base maps: National Water Resources Database

3.0 °C temperature profiles under BAU compared with LS and MS occur due to extreme flooding in six *upazilas*. Here, flood depths are projected to be four times higher under BAU than LS or MS (Fig SM3). These *upazilas* are spread throughout the study region, with the exception of south-east area. For population, there are fewer extremes in regional variations for the LS and MS scenarios compared with BAU (see [Supplementary Material](#)).

Context within the Paris Agreement

In this study, 1.5 °C is projected to occur in the decades from 2006–2016 to 2028–2038 (with respect to pre-industrial). Hence, sea level is essentially at today's level, so future impacts will not be dissimilar to today. This is particularly important given uncertainties in modelling (e.g. polder height, elevation models, river flows, see Payo et al. (2017)). Even if climate change mitigation is successful, sea levels will keep rising for decades and

longer due to the commitment to SLR (Goodwin et al. 2018; Nicholls et al. 2018; Nicholls and Lowe 2004), and there remains considerable uncertainty in the rate of rise (e.g. Goodwin et al. 2018). Therefore, a progressive increase in flooding can be expected in coastal Bangladesh unless there is adaptation. Furthermore, changes to high river flows are also worthy of consideration as there is uncertainty in precipitation and ice melt from glaciers (Kraaijenbrink et al. 2017; Mohammed et al. 2017), which contributes to flooding in the study area.

Discernible impacts of 1.5 °C are not projected until the 2040s across all impact metrics. The mean depth of flooding with and without protection is projected to increase by approximately 2-fold across the range from a 1.5 °C to 3 °C reference period. Over the same reference frame, the area flooded could increase 2.5-fold. Furthermore, local land level change, reflecting natural and anthropogenic subsidence, may have greater control on flood impacts than climate-induced SLR itself.

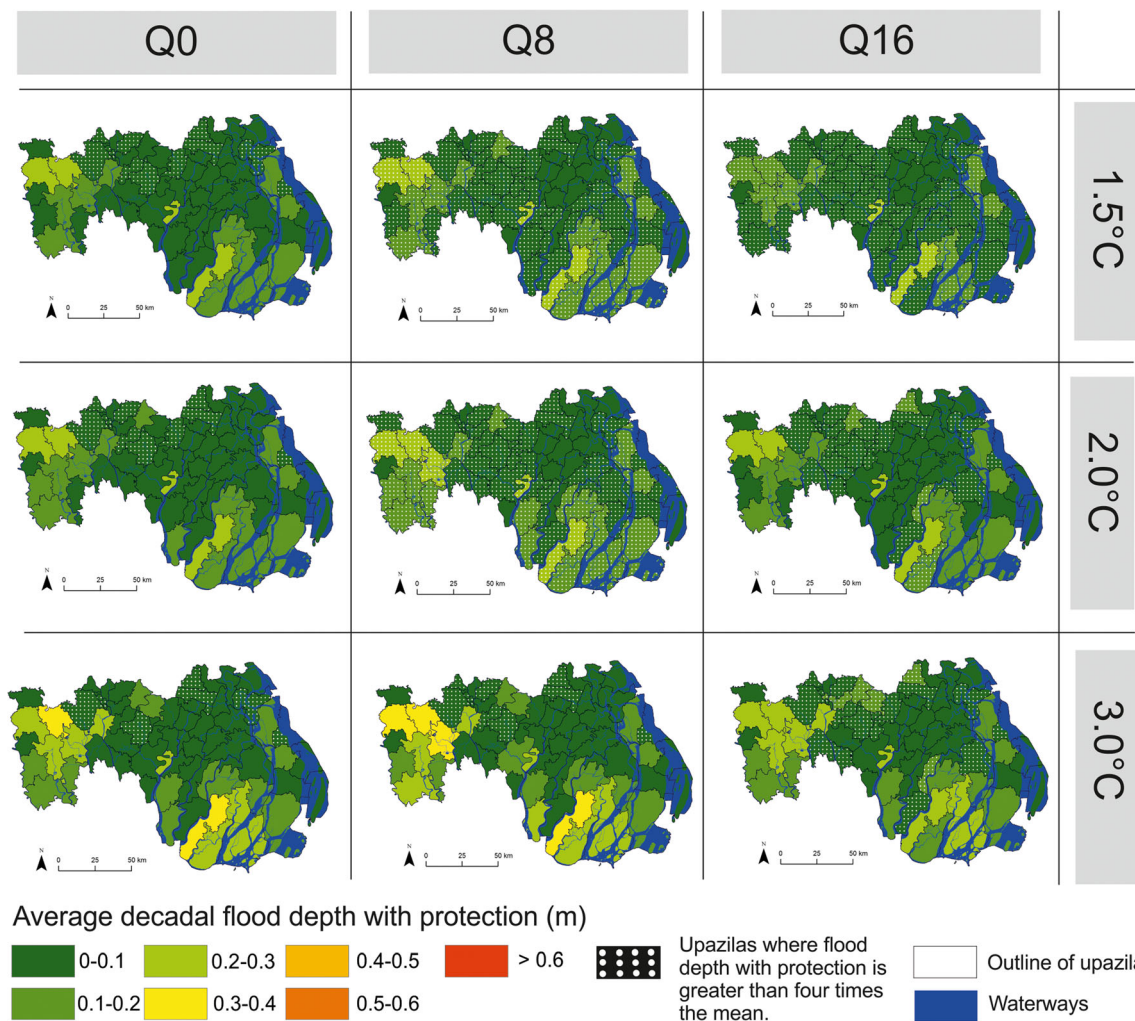


Fig. 5 Illustration of the average decadal mean depth of flooding with protection across the 70 upazilas. Source base maps: National Water Resources Database

Regionally, without protection, the greatest flood depths and area flooded are projected in the north-east of the region, whilst the lowest is projected in the west away from the main river. In terms of people affected by flooding, the upazilas with the higher population density to the west experience the least number of people affected. Large numbers are projected to be flooded in the urban areas of Khulna and Barisal. These areas could be targets for adaptation, and new polders are under consideration for these areas.

Caveats

As demonstrated in Fig. 3, natural annual variability is a major source of uncertainty in the magnitude of flooding. The results presented are internally consistent with each other and present day observations, although the absolute differences in the model are hard to validate as the uncertainty surrounding the data is poorly defined (see [Supplementary Material](#)). Uncertainties include

- subsidence (which locally under human influence, could be two or three times the average value used here of 2.5 mm/year, see Brown and Nicholls (2015));
- sea-level rise (particularly high ice melt, which could lead to a sea-level rise of 1.14 m in 2100 for an unmitigated climate change scenario, see Goodwin et al. 2018);
- socio-economic change (population is declining in the study area, and Szabo et al. (2015) estimated a population of between 11.4 and 14.1 million people by 2050 for the three scenarios compared with a population of 14.1 million people in 2011);
- polder design and maintenance (variation of polder height to design height is on average ± 0.4 m if extreme events are considered, see [Supplementary Material](#));
- added ‘internal’ uncertainties of Δ DIEM (Lázár et al. 2018; Payo et al. 2017).

These uncertainties indicate potentially large variations in the timing and magnitude of flooding. In agreement with

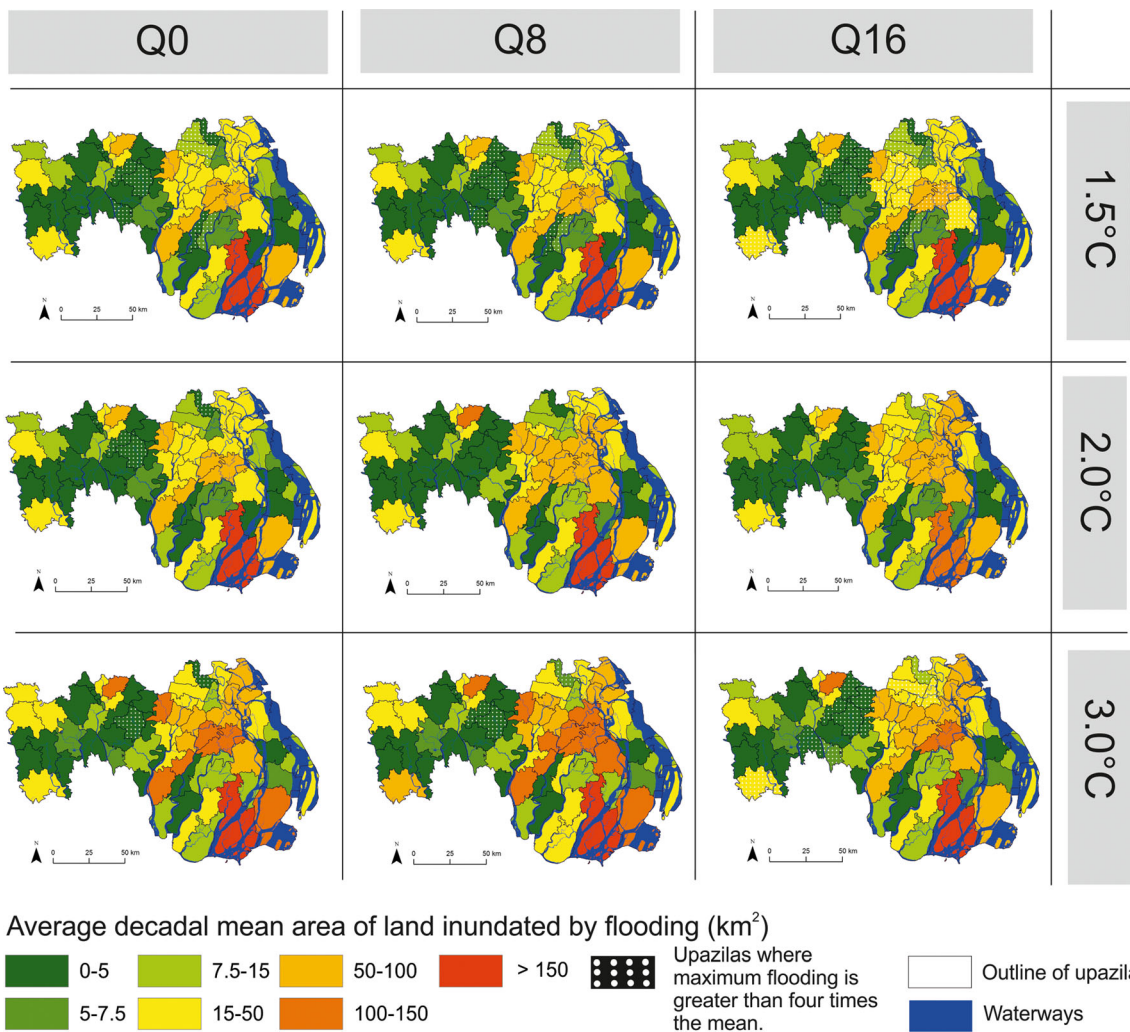


Fig. 6 Illustration of the average decadal mean area inundated due to flooding without protection across the 70 upazilas. Source base maps: National Water Resources Database

previous research (e.g. Lewis et al. 2012), further knowledge and data are required of the topography, particularly as the area is relatively flat and low-lying. Furthermore, it is human actions that may affect impacts the greatest, such as maintenance of poldered areas or human induced subsidence. Additional research is required to better quantify these affects, including better estimates of land elevation and embankment breaching (Krien et al. 2017) and appropriate scenarios for the future.

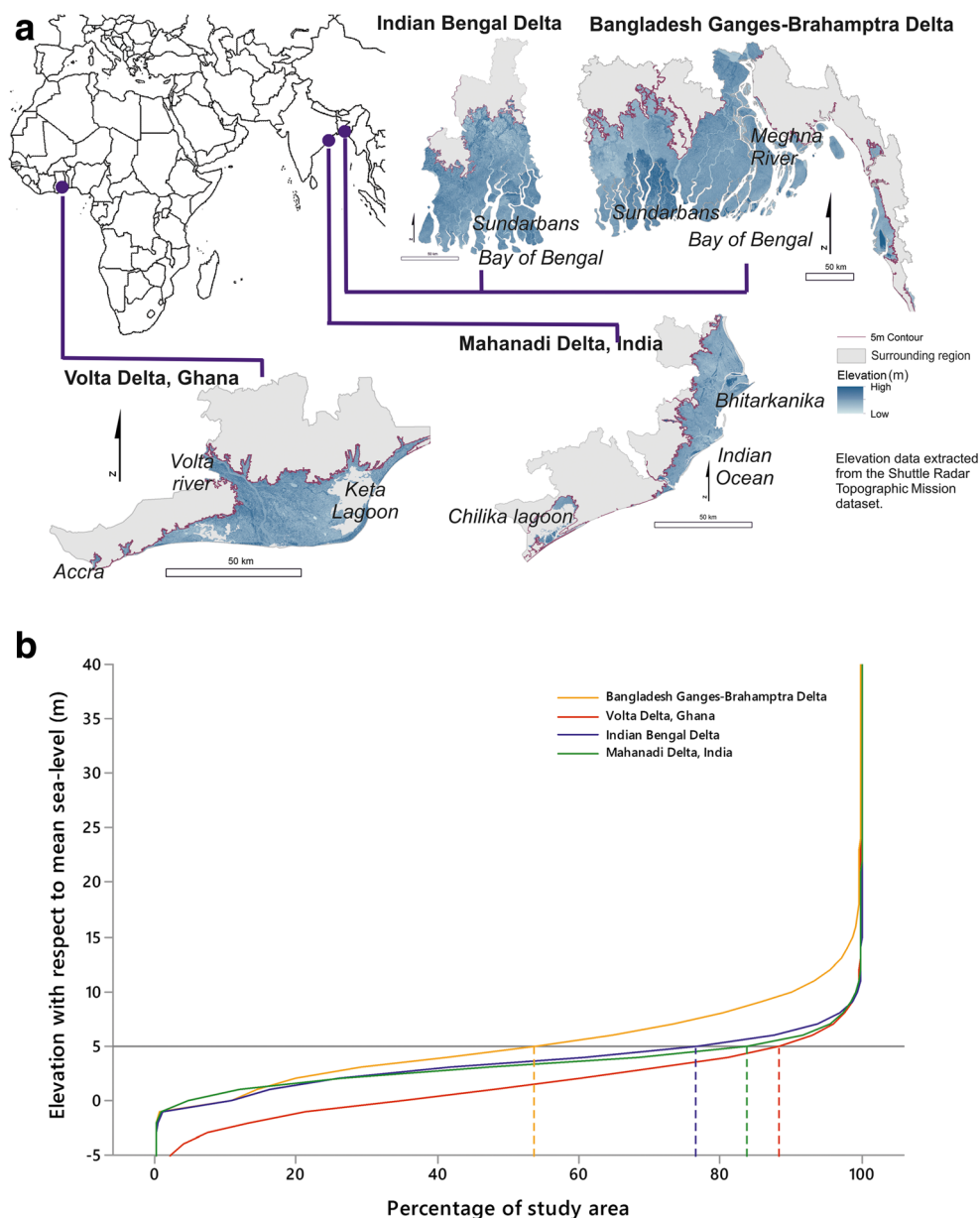
Cyclones have not been considered in this analysis due to their unpredictable nature and the need for thousands of simulations to provide a full explanation on impacts. They could potentially cause significant damage, and further research is required to determine impacts or potential breaching of embankments based on cyclone strength, landfall location, timing and stage in the tidal cycle. The latter is particularly important as if a cyclone coincides with the highest tides, impacts are most severe.

Implications of a 1.5 °C+ world

Past human changes are significant

Humans have endeavoured to control rivers through the building of dams, barrages and embankments affecting flow and sediment yield which can adversely affect drainage land use, livelihoods, socio-ecological systems and flood risk (Roy et al. 2017). This can have a greater affect than climate change. For instance, Pethick and Orford (2013) and Wilson et al. (2017) found tidal and morphodynamic changes due to polderisation. Auerbach et al. (2015) found the height difference between natural and polderised land differed by an average of 0.02 m for each year a polder was present. This reflects restricted sedimentation and enhanced subsidence within polders. In contrast, global mean SLR was one tenth of this value. Human factors will to continue to operate in the coming decades, interacting with any climate change that occurs.

Fig. 7 **a** Location and elevation of the four vulnerable deltas. **b** Hypsometric curve illustrating the elevation as a percentage of the study area for each delta. The vertical lines indicate the 5-m elevation levels

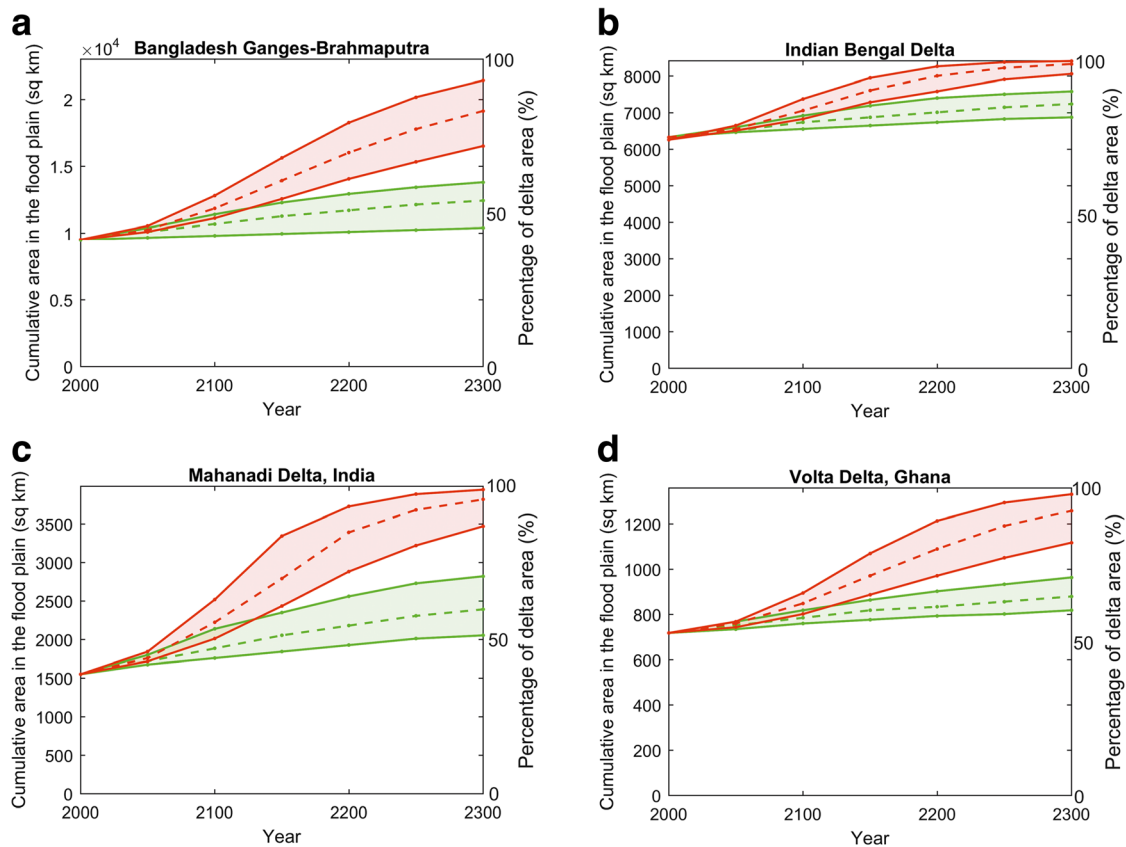


Commitment to sea-level rise

The threat of long-term flooding does not stop even if temperatures are stabilised, threatening deltas world-wide. Figure 7a illustrates land below the 5-m contour line for four deltas (a) Bangladeshi Ganges-Brahmaputra, (b) Indian Bengal (note these two are a wider region that the sub-section previously described), (c) Indian Mahanadi and (d) Ghanaian Volta deltas extracted from the Shuttle Radar Topographic Mission dataset (USGS 2017) (for methodology, see [Supplementary Material](#)). These deltas in developing nations were selected as they are low lying, containing significant populations vulnerable to SLR. The elevation of each delta with respect to mean sea level is shown in Fig. 7b. For the Bangladesh Ganges-Brahmaputra delta and the Indian Bengal delta, 53 and 77%

of the land is located below the 5-m contour, respectively. In the Mahanadi and Volta deltas, 83 and 88% of the deltas are below 5 m in elevation. Although errors in data elevation are expected (see [Supplementary Material](#)), it indicates that all deltas are threatened by long-term SLR and subsidence.

Using multi-centennial stringent climate change mitigation (at 1.5 °C) and high emission scenarios (Goodwin et al. 2018), together with extreme sea levels (Muis et al. 2016), the area of each delta potential inundated by SLR and a 100-year event is plotted in Fig. 8. SLR in 2300 is projected to be between 0.59 and 1.55 m (climate change mitigation scenario) and 2.76 and 6.86 m (high emission scenario) (for further details, see [Supplementary Material](#)). These unmitigated scenarios are lower than projections of multi-centennial or millennium sea-level change, such as



High emissions scenario (red). Climate change mitigation scenario (green). 5th, 95th (solid) 50th (dashed) percentile of SLR

Fig. 8 Area exposed to flooding with SLR and a 1-in-100-year extreme sea level over time for a high emissions and climate change mitigation scenario for **a** Bangladesh Ganges-Brahmaputra; **b** Indian Bengal Delta; **c** Mahanadi Delta, India and **d** Volta Delta, Ghana

Clark et al. (2016) who suggest 2–4 m per century. Reinforcing Fig. 7b, today, a large proportion of each delta is at risk from being flooded. By 2200, 95% of the Indian Bengal delta is projected to be exposed and 99% in 2300 (reducing to 83 and 86% with climate change mitigation, respectively). In the Indian Bengal, Mahanadi and Volta deltas nearly 100% of their deltas will be exposed by 2300, with substantial reductions under climate change mitigation. Hence, climate change mitigation reduces exposure over multi-centennial timescales.

Promoting sedimentation in deltas is a good long-term strategy against SLR. In the deltas that are presented in Fig. 8, sediment reduction and dispersion have been influenced through dams (Bastia and Equeenuddin 2016; Gupta et al. 2012; Gyau-Boakye 2001) and embankment building (Auerbach et al. 2015) plus localised beach mining (Appeaning Addo 2015; Mensah 1997). This has improved livelihoods and development but also enhanced flood and erosion risk, as each delta reports land loss today (Akhand et al. 2017; Armah and Amlalo 1998; Sarwar and Woodroffe 2013) and growing flood plains (Syvitski et al. 2009). The ability to raise land with controlled sedimentation to combat SLR and subsidence in

populated deltas is challenging, but deserves more investigation. At centennial timescales, and given the impacts that are projected in Fig. 7, the strategy of damming may need to be rethought, as witnessed in the removal of the Marmot Dam, Oregon, USA (Major et al. 2012).

Delta populations have a history of adaptation. For example, surges during cyclones can have significant effects on livelihoods, but improved warning and disaster risk management in recent years have reduced risk (Iwasaki 2016). Adaptation in large deltas represents significant challenges given the geographic scale. Autonomous adaptation (at household or community levels) to SLR and other environmental change, e.g. sale of assets, switching livelihoods or accessing financial support will continue, provided the environment changes slowly (Duncan et al. 2017). Appropriate adaptation buys time, but will not ultimately solve the problem of multi-millennium climate-induced SLR without further mitigation. Planned adaptations in deltas, guided by the government and other national or international organisations, are already documented, such as flood risk management plans and disaster risk reducing infrastructure (Tompkins et al. 2017). Planned adaptation at the national level could support autonomous action at a local level at a larger geographical scale.

Planning for 1.5 °C

For coastal impacts, a 1.5 °C world when the temperature is first reached will not be too dissimilar to conditions seen today. Greater climate stabilisation appears to reduce impacts slightly in coastal Bangladesh. The benefits of climate change mitigation will have significant advantages on centennial scale (e.g. by allowing time for humans and natural systems to respond), particularly if sediment availability does not further decline or is maintained at present day levels. However, ongoing sea-level rise and subsidence means that whatever the stabilisation level, a growing requirement to adapt remains extending beyond 2100. A response will require more focussed and planned adaptation than is current. As an example, the Bangladesh Delta Plan 2100 provides an institutional mechanism that has the potential to address this challenge.

Developing nations will feel the impacts of climate change first, in part due to their geographic location (e.g. Harrington et al. 2016), but also due to their reliance on the environment for their livelihoods and the challenges of adaptation. The Paris Agreement fails to recognise regional differences in climatic parameters. Adaptation funding needs to take account of these regional differences in the context of sustainable development and ‘different national circumstances’ (United Nations 2015). Adaptation planning is challenging due to multiple levels of co-ordination and integration into existing policies and development (e.g. Stanturf et al. 2011). The greatest threat is the long-term commitment to SLR where additional adaptation is encouraged both nationally and locally. Monitoring of SLR and subsidence remains important, as it provides evidence of change and informs when to act.

Conclusions

This study has assessed the impacts of SLR at temperatures equivalent to 1.5, 2.0 and 3.0 °C in coastal Bangladesh and the wider implications for other vulnerable deltas. The immediate effects of a 1.5 °C rise in temperature on the sea level may be relatively small, but sea-level rise will have an important legacy in delta regions. The following conclusions were drawn:

- In the GBM, the effects of a 1.5 °C world compared with a 2.0 °C world may not be discernible until at least the 2040s due to annual variability.
- Flooding will be more intense and widespread. Comparing a 1.5 °C world with a 3.0 °C world, the average decadal mean depth of flooding in protected and unprotected areas may increase 2-fold. The average decadal mean area of land inundated is projected to increase 2.5 times.
- Regionally, to the west of the GBM study region, impacts are less despite having higher population density, as it is

further from the main river channel and is poldered. The *upazilas* with the greatest projected flood depths are in the north-west near the river where the land is unprotected. The greatest number of people affected by flooding are projected to be in the major population centres. Thus, planned adaptation resources and skill building to create adaptive capacity need to be targeted appropriately.

- Climate change mitigation has significant benefits over centennial scales, to reduce both the rate and the magnitude of SLR. Numerous deltas world-wide are under threat from SLR and sediment starvation. Under a high emissions scenario, and without sufficient sedimentation or adaptation, nearly all deltaic land in the regions analysed will be exposed to significant flooding by 2200 unless adaptation occurs. Over multi-centennial timescales, climate change mitigation to reduce SLR and sedimentation in response to residual SLR and subsidence is key to the deltas’ survival.
- Planned adaptation today changes the physical landscape in the delta, and it is in this context that people will continue to adapt. SLR is likely to make sustainable development more challenging particularly as assets and people living in risky areas are likely to increase.

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