Contrasting development trajectories for coastal Bangladesh to the end of century

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Abstract

Bangladesh is one of the most climate sensitive countries globally, creating significant challenges for future development. Here we apply an integrated assessment model -- Delta Dynamic Integrated Emulator Model (ΔDIEM) -- to the south-west coastal zone of Bangladesh to explore the outcomes of four contrasting and plausible development trajectories under different climate and socio-economic scenarios: (1) embankment rehabilitation; (2) build elevation via controlled sedimentation; (3) planned migration (managed retreat); and (4) 'do nothing' (unplanned migration and abandonment). Embankment rehabilitation reduces flood risk, but at a high economic cost and enhancing waterlogging. Planned and unplanned migration combined with limited infrastructure management and governance both result in significant abandonment. Building elevation through sedimentation has potential for increased environmental and economic sustainability, but raises equity issues. Poverty and inequality persist across all scenarios, and outmigration from the coastal zone continues, although the magnitude is sensitive to assumptions about sea-level rise, socio-economic development and development trajectory. Integrated assessment tools linking the environment, people and policy choices, such as ΔDIEM used here, highlight the complex interactions occurring in a dynamic delta environment. Such analysis supports informed management, development and adaptation.

Keywords

- integrated assessment model,
- delta,
- policy options,
- development trajectories,
- human wellbeing
- coastal adaptation

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1. Introduction

Deltas are complex systems with strong, dynamic interactions between natural and human processes requiring careful management and governance (Welch et al. 2017). They face severe multiple pressures, including reduced sediment supply due to upstream dams, subsiding land due to embankment and/or groundwater withdrawal (Adnan et al. 2019; Syvitski et al. 2009), waterlogging, salinisation (Bernier et al. 2016), flooding, cyclones, climate change and sea-level rise (SLR). These chronic and acute processes directly influence the livelihood potential and the wellbeing of delta populations and vice versa (Adnan et al. 2020). It is essential that delta development considers these processes and their interaction to minimise unintended and unexpected consequences.

The Ganges-Brahmaputra-Meghna delta, which forms most of Bangladesh's coastal region, is home to over 35 million people of whom more than 30% are poor (BBS 2011). The present and future evolution of the delta is a consequence of complex biophysical and socio-economic interactions (Nicholls et al. 2018). Whilst existing plans and policies consider multiple social-environmental processes using a combination of modelling studies and expert elicitation, for example the recently developed Bangladesh Delta Plan 2100 (BDP 2018), scientific understanding of the processes driving the delta's evolution and current capacity to examine complex interactions and trajectories remain fundamentally limited. There are profound uncertainties about future drivers, including SLR, land use change as a result of adaption to climate risks and about the links and effects of infrastructural and institutional interventions (Conway and Schipper 2011; Francesch-Huidobro et al. 2017). Thus, we regard the delta's future evolution to be a consequence of exogenous climatic and socio-economic factors, which we explore with climate scenarios and socio-economic scenarios, respectively. In addition, we wish to explore the implications of policy responses in order to inform adaptation policy and implementation (cf. Kebede et al. 2018).

Four distinct and stylised development trajectories appear possible in coastal Bangladesh: (1) embankment rehabilitation (imitate the Netherlands); (2) controlled sedimentation (build elevation – Tidal River Management, TRM); (3) planned migration (managed retreat); and (4) 'do nothing'.

This paper aims to analyse the implications of these four development trajectories for coastal Bangladesh assuming they persist to 2100. Integrated assessment of the main system elements, characteristics and interaction, provides a framework for such analysis (Anderies et al. 2007; Daw et al. 2016; Seijger et al. 2017). Here we improve and apply an integrated model of coastal Bangladesh (Lázár et al. 2017; Lazar et al. 2015; Lázár et al. 2018; Payo et al. 2017) to achieve the aim. According to our knowledge, such an integrated, transitional and process-based exploration of plausible long-term trajectories of the coastal zone of Bangladesh has not been done. In particular, the paper goes beyond a traditional scenario assessment and assesses outcomes across the range of possible long-term policy options in deltas.

2. Study area description

The study area (Figure S1) is located in the tidal-influenced south-west coastal zone of Bangladesh, within the Ganges-Brahmaputra-Meghna (GBM) delta, covering 18,850 km^2. It has low elevation of one to three meters above sea level and a tidal range of 0.5-4.5 metres. There are 105 polders (i.e. low-lying land enclosed by embankments initially built to promote agriculture). The land cover is predominantly agriculture (~45%) with two major cities (Khulna, Barisal). It includes the Sunderbans - the world's largest mangrove forest.

The total population of the study area is 14 million people with a population density of 750 person/km^2 (BBS et al. 2012). Mixed livelihoods are widespread (70% of population), where the dominant income comes from off-farm occupations such as small business enterprise and small-scale manufacturing (Adams et al. 2016b). Although agriculture only contribute 12% to the delta GDP (Arto et al. 2020), it is the biggest employment sector (85% of population), though most households (56%) are practically landless (BBS 2014). Rice is the staple food (Wright et al. 2012). Significant rural to urban (mainly Dhaka) migration is occurring across the delta, reflecting multiple economic, livelihood and environmental factors (Safra de Campos et al. 2020).

Bangladesh has rapid GDP growth of 7.3% (World Bank 2020). However, 21% of the coastal rural population is below the ‘Cost of Basic Needs’ poverty line and food expenditure is nearly 60% of total household expenditure (BBS 1991), thus accumulating savings is unlikely. Furthermore, income distribution is extremely uneven: 5,713 BDT/month for the landless and 29,673 BDT/month for large land owners (3+ hectares), with an income inequality of 43.1%.

The study area experiences multiple stresses including: cyclones and surges, SLR, land subsidence, river erosion, monsoonal flooding (June to September), drought (November to March) and salinization (Nicholls et al. 2018). Intense floods, such as in 2004 affecting 58,000 km^2 and resulting in 3.3% of GDP losses (Mechler and Bouwer 2015), occur once per decade on average, but monsoon and cyclone flooding occur almost annually. Based on historical data (Alam and Dominey-Howes 2015), strong cyclones (140+ km/hr wind, 4.6–6.1m surge, e.g. SIDR in 2007) occur 0.8 times per decade, while weaker cyclones (80-140 km/hr wind, 0.61-4.4 m surge, e.g. AILA in 2009) occur 4.2 times per decade. Cyclones cause wind damage and coastal floods damaging crops, housing and infrastructure, risk lives and salinize soils (Lumbroso et al. 2017; Younus 2017). For example, SIDR damaged ca. 1 million ha crops and killed about 1.8 million livestock in 2007. At the household level, the average losses due to cyclones (loss of earnings, house/crop/asset damage, healthcare cost) varies between 64,000 and 97,000 BDT (Paul and Routray 2010). Relative SLR presently averages 6 to 7 mm/year exacerbating coastal flooding, waterlogging and salinization (Becker et al. 2020; Brown and Nicholls 2015). Polders can increase tidal range via changes in tidal propagation (Pethick and Orford 2013). Saline soils have expanded at 58.75 km^2/yr between 1970 and 2009, and waterlogged areas increased by 25 km^2/yr between 1980 and 2014 (Roy et al. 2017).

3. Methods

3.1 The Delta Dynamic Integrated Emulator Model (ΔDIEM)

The Delta Dynamic Integrated Emulator Model (ΔDIEM, Figure 1) is a trans-disciplinary quantitative modelling tool developed to analyse integrated problems in delta environments (Lázár et al. 2018; Nicholls et al. 2016). ΔDIEM couples environmental change, associated livelihoods, wellbeing and poverty in a model framework considering plausible assumptions of climate-, environmental-, and socio-economic changes and governance. The spatial resolution of ΔDIEM is the ‘Union’, the lowest administrative unit in Bangladesh covering ~26km^2 area (range: 2.5-98km^2) with 21,000 people (range: 5000-65000), balancing the representation of spatial diversity and population behaviour and characteristics in ΔDIEM. The temporal resolution is daily for the bio-physical aspects and monthly for the socio-economic calculations.

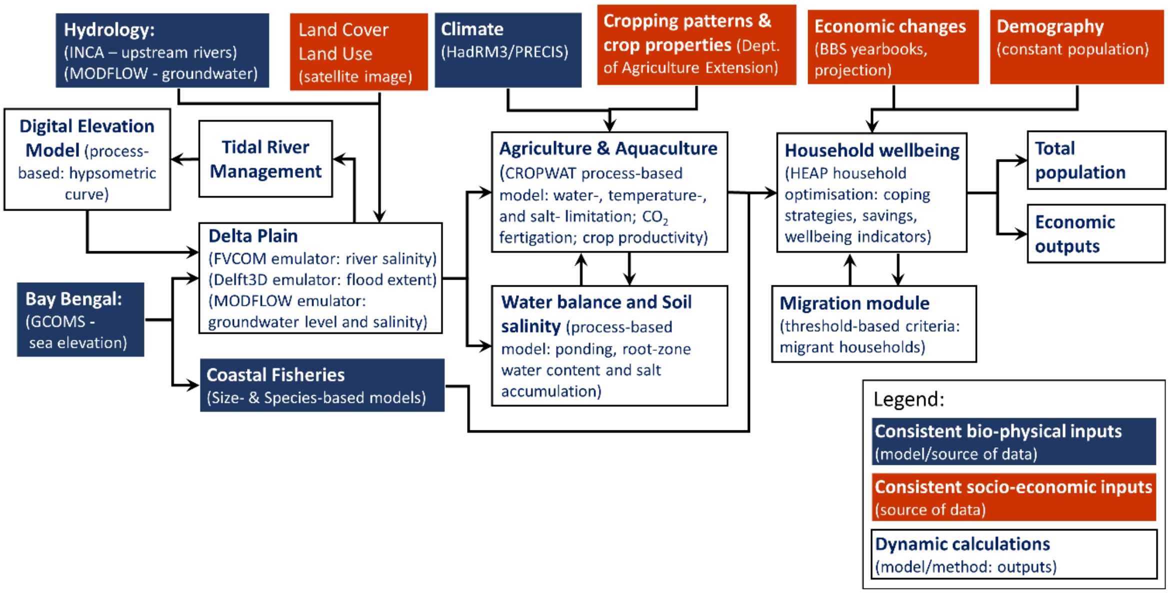

Figure 1: Schematic overview of the Delta Dynamic Integrated Emulator model (ΔDIEM)

The principles of the integrated model development was to (i) capture all important system elements of coastal Bangladesh, (ii) utilise detailed process-based models in the background studies, (iii) integrate these models on the same platform, (iv) emulate physics-based models for rapid simulation, (v) conduct calculations at the highest spatial/temporal resolution possible, and (vi) use harmonised, integrated scenarios. Detailed physics-based models included flooding (Delft-3D), channel salinity (FVCOM), and groundwater, including salinity (MODFLOW-SEAWAT) which were represented as spatial statistical emulators to effectively couple them within ΔDIEM (Payo et al. 2017). Soil, salinity and crop productivity processes were represented with coupled process-based calculations including root zone soil water and salinity balance calculations, allowing estimates of agricultural and aquaculture yields with the improved FAO CROPWAT model (Lazar et al. 2015; Payo et al. 2017). Wellbeing was estimated using an agent-based-type model following the trajectories of 36 household archetypes (Table S1). Archetypes are based on qualitative and seasonal quantitative surveys of 1586 households considering their seasonal livelihood combinations and land size (Adams and Adger 2016; Adams et al. 2016a). A coping-strategy optimisation routine balances incomes, expenditures, assets and savings to approximate the affordable expenditure of the archetypes (Lázár et al. 2017). The main limitations of ΔDIEM concern the livelihoods: land holdings are equiproportionally distributed based on aggregate demographics and land cover changes in a union; there is no household adaptation beyond coping; households react but do not make long-term predictions, service and manufacturing household incomes are input scenarios. In this application, new modules were introduced to enable stylised TRM and migration simulations (see next section). Submodules of ΔDIEM are set up, parametrised and tested against observations first in isolation, which is then refined when all components are coupled in the integrated framework. All calculations are coded in Matlab (R2017a, Lázár et al. 2019; MathWorks 2017).

Results of the extensive model testing and validation are reported in the above publications and summarised here briefly (see also Figures S12-S13). There is a good agreement between the results of the hydrological emulators and the high fidelity models. Larger errors occur at the lower values and smaller errors occur at the higher values that are hydrologically most important. The Root Mean Square Error (RMSE), for example for inundation depth: 0.012-0.13m, river salinity: 1.36ppt, river elevation: 0.35m. Crop simulations were compared with district and sub-district observations and the fit was good both spatially and temporally (2000-2010 period). The RMSE for crop yield was in between 2.3% and 11.9% in 2010 for Aman, Aus and Boro rice variaties, chilli and grass pea. Wheat and potato were less well simulated (RMSE: 22-70%), but account for less than 10% of the total agriculture area (rice: 95% area in 2010). The simulated household income and expenditures are used to approximate dimensions of wellbeing (calorie intake, protein intake, GINI coefficient and 1.90 USD/capita/day headcount). These followed the observed temporal patterns and magnitudes well. Errors were not quantified because the observations were only available at regional and national scales. Comparison of model outputs with literature evidence is done in Section 5. In terms of sensitivity to input parameters, this varies across the different output parameters with no single dominant driver. All inputs have potential but distinct effects on the outputs and the interaction of simulated elements defines the resulting delta characteristics (Table S8). Hence, ΔDIEM seems well suited to the analysis proposed. The current study used the calibrated model to compare environmental and socio-economic pathways.

3.2 Scenario descriptions

The Bangladesh Delta Plan 2100 (BDP2100) is a major policy initiative to enable socio-economic development under trans-boundary water sharing and an uncertain future (BDP 2018). BDP2100 uses a consistent macro-economic framework containing decoupled macro-economic, employment, poverty and environment models. BDP2100 tests four plausible future scenarios: Productive ("market driven delta": moderate water conditions, diversified economy), Resilient ("dynamic delta": extreme water conditions, diversified economy), Moderate ("delta under pressure": moderate water conditions, traditional economy) and Active ("basic needs first": extreme water conditions, traditional economy). Water conditions consider trans-boundary water sharing and climate change, and assume 60-125 cm SLR by 2100, 2-4°C temperature increase, 15-40% increase in monsoon rain, -20-0% change in dry season precipitation and 5-10% increase in cyclone intensity. BDP2100 assumes less frequent but more intense cyclones would decrease the real GDP by 45% by 2050 in the coastal zone. These snapshot scenarios cannot be used for this ΔDIEM application, because ΔDIEM requires continuous timeseries and more detailed scenarios (e.g. agriculture practices). Furthermore, losses and production are simulation-based within ΔDIEM, rather than assumption-based.

In this paper we seek to extend previous scenario exercises for the coastal zone in Bangladesh by analysing four distinct, yet plausible, contextual scenarios (Table 1, Nicholls et al. 2018) combining two bio-physical (low/high SLR) and two socio-economic (low/high development) scenarios. These deliberately represent fairly extreme points of the plausibility space. The climate scenario uses the UK MetOffice's HadRM3/PRECIS Regional Climate Model (SRES A1B, Caesar et al. 2015). The Q8 ensemble member is selected because it is the closest to the historical observations in our study area (Payo et al. 2017). The upstream river discharge is simulated with the INCA model (Whitehead et al. 2015). As already noted, strong (like SIDR) and weak cyclones historically occur 0.8 and 4.2 times per decade, and decreasing cyclone frequency and increasing intensity expected in the future. Hence, the historic SIDR cyclone is assumed to occur every 5 years: 2025, 2030, etc. with the same observed characteristics in this study: sustained winds of 215 km/h, arrival date of 15 November and landfall location in the Barguna/Patuakhali districts. The regular 'clock-like' occurrence, as opposed to stochastic representation, enables the clear distinction of fluvial and cyclone flooding.

The socio-economic assumptions are based on the less- and more-sustainable scenarios developed in the ESPA Deltas project (Nicholls et al. 2018). The only exception is population change, where a constant population of 14 million people (13 million rural population) is assumed, and only environment-induced migration can change the total population (i.e. no net births/deaths). This illustrates the impact of policy strategies on migration across development trajectories. Low/High developments are distinguished by assuming differing economic growth, crop varieties and land use (Table 1).

Table 1: Contextual scenario assumptions (by 2050 / by 2100)

We simulate four contrasting development trajectories (Table S2) within the above four contextual futures (Table 1) from 2020 to 2098. This enables the sampling of the deeply uncertain futures and providing insights into long-term benefits and disbenefits. The four development trajectories are:

1. Protect by embankment rehabilitation (imitate the Netherlands): large investments enhancing and maintaining flood embankments and drainage systems, plus water pumping ensures that waterlogging never happens.
2. Do nothing (unmanaged retreat): practically no investment in protection or adaptation to SLR in the coastal zone. It provides a baseline assessment of the potential impacts of climate change in the absence of action.
3. Managed retreat (reactive relocation): emphasis upon relocation of coastal communities to prevent the loss of life and exposure to hazard, or loss of livelihood.
4. Build elevation through controlled sedimentation (Tidal River Management, TRM): working with natural processes to deposit sediment in polders (e.g. Amir et al. 2013). Here, the maximum benefit of TRM is explored by implementing it in all polders simultaneously. Farm-based households receive some compensation during TRM years.

Migration is a complex phenomenon driven by processes from the global to individual scale (Black et al. 2011; Castles 2013; Czaika and De Haas 2014; De Haas 2010) and thus is difficult to predict. Migration decisions are made on the basis of material factors such as income and visa requirements, non-material factors such as place attachment (Adams 2016), aspirations (Carling and Collins 2018; Wiederkehr et al. 2019) and tolerance of risk (Hauer et al. 2020). As such, establishing, and being able to generalise absolute thresholds at which a person will migrate is not presently possible (Adams and Kay 2019; McLeman 2017). Simplified, stylised migration assumptions in models can however provide useful comparative insights, and thus we only consider economic and environmental push factors, and remove financial, network, cultural or family barriers to migration. Informed by the existing literature on the impacts of chronic and acute environmental change and locally-specific knowledge of coping strategies (Adger et al. 2018; Lázár et al. 2017), in this application, a household is identified as susceptible to migration, and removed from the study area, when any of the following thresholds are exceeded:

(i) the household can only afford to pay its food expenses and nothing else for 24 months (compromised quality of life);
(ii) the rice yield gap is greater than 75% (compared to potential yield) for four consecutive years (slow onset hazards); or
(iii) the household is farm-based and 75% or more of its total income is lost due to a flood/storm surge event more than four times per decade (reoccurring fast onset hazards).

Flooding alone does not consistently increase mobility (Gray and Bilsborrow 2013). But, there is consistent evidence that agro-climatic conditions and crop failures have an important role in urbanization and rural mobility (Chen and Mueller 2018; Gray and Mueller 2012; Henderson et al. 2017) and repeated stress over a longer period has the potential to trigger migration (Kartiki 2011; Mallick and Vogt 2014). Further, a universally common motivation for migration is increasing living standards through better work and/or remittance inflows (Liu 1975; Lokshin et al. 2010).

Finally, we constrain the migration decision to ensure a parsimonious model. While recognising that migration generally involves the movement of one household member resulting in a remittance economy (Call et al. 2017), in this analysis the entire household migrates. This eliminates the need to consider intra-household decision-making, remittances, and the receiving area. This is a partial representation of reality – most migrants go to the capital (Dhaka, outside the study area) but some people do migrate to the regional centre (Khulna, inside the study area) (Safra de Campos et al. 2020). Finally, the land size of remaining farming households does not increase, because those who migrate hold onto land assets as a financial safety net (Toufique and Turton 2002). Hazard-prone and unproductive lands are unlikely to attract farmers or investors.

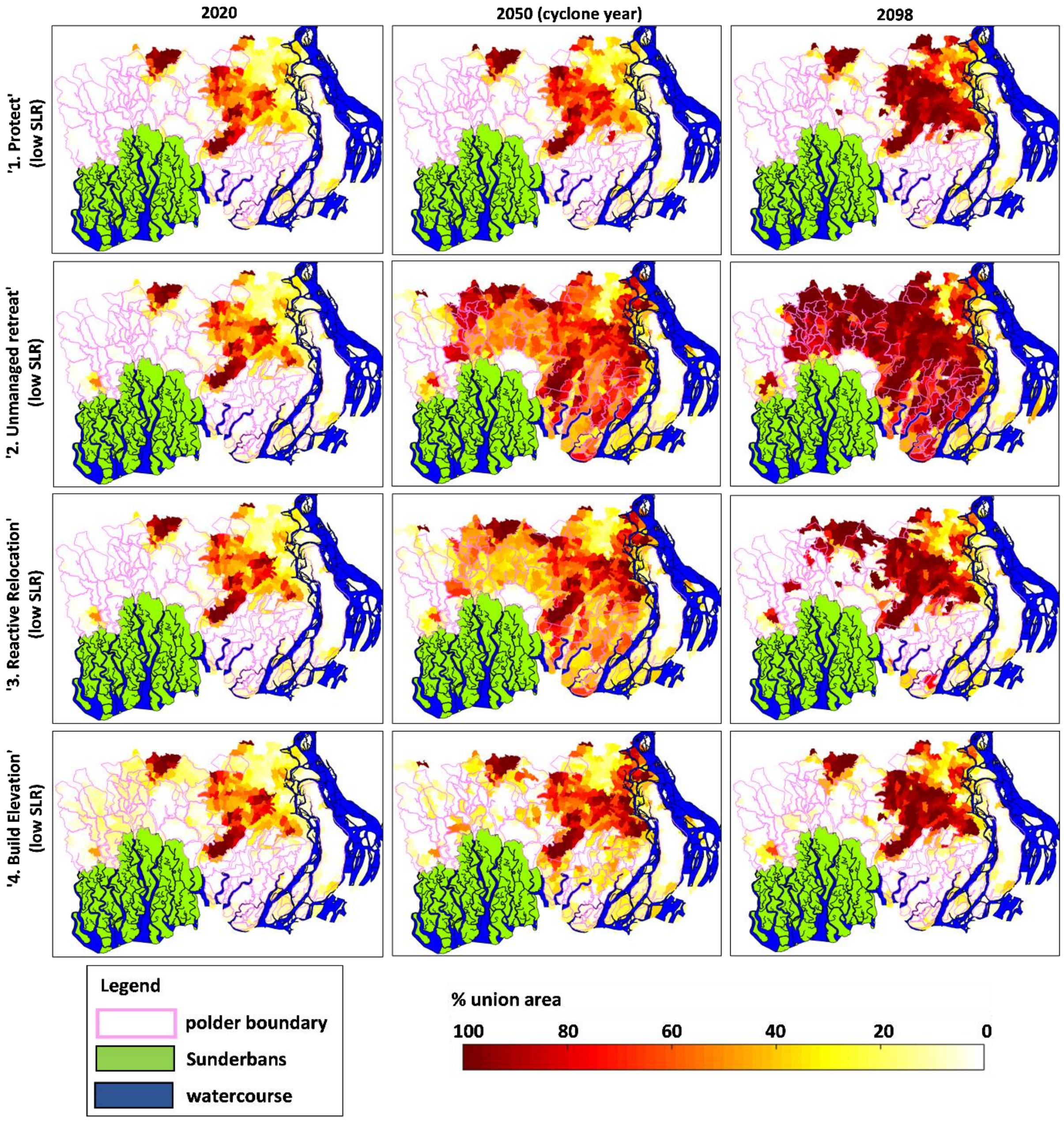

Figure 2: Maximum union inundation area (percent) in three time slices under low sea-level rise trajectories

4. Results

4.1 Flood inundation

The north-west and south-east parts of the study area are protected by embankments, thus compared to other policy trajectories, polder enhancement significantly reduces flooding under the 'Protect' trajectory, although flooding increases by 87 km^2 and 179 km^2 in the high SLR assumption in 2050 and 2100, respectively (Figure 2 and Figure S2 in the Supplementary document). On the other hand, the north-east areas are largely unprotected, and hence flooding remains unchanged with the elevation of existing embankments. In cyclone years, the enhanced (+3m) polders provide sufficient protection against the storm surges.

Existing dike heights (‘Build elevation’ and ‘Reactive relocation’) are also sufficient against normal fluvial flooding, but breaching can occur during cyclone events (see 2050 on the figures). Polder deterioration (‘Unmanaged retreat’) on the other hand would result in large scale flooding even by mid-century (2050/2098: +181%/+153% and +168%/+162% area compared to ‘Protect’ in low and high SLR). An interesting pattern is shown on the ‘Unmanaged retreat’ inundation maps. Under the low SLR scenario, the flood extent in 2050 and 2098 is similar except for a slightly larger inundation extent (Figure 2). Under high SLR, however, the spatial pattern changes (Figure S2). Bhola island (the big island in the east) becomes inundated relieving the adjacent lands from flooding, and many Khulna division unions (north of the Sunderbans) become inundated by 2098. The scattered unions with large inundations under ‘Reactive relocation’ are abandoned with no population. Finally, the ‘Build elevation’ flood maps show the benefit of higher ground elevation: the inundation extent is the same as under ‘Protect’ (-1% and +22% in 2098, under low and high SLR).

The peaks on the daily flooded area time series (Figures S3a,b) correspond to the reoccurring cyclones every five years. High levels of protection (‘Protect’) is efficient even under high SLR with marginal flooding, but significant non-protected areas are still annually flooded. TRM effectively reduces both the flood peaks and the extent of flooding. The importance of coastal infrastructure repair time is also apparent in ‘Unmanaged retreat’ trajectory: the 60 months repair time make flooding almost permanent. High SLR causes somewhat larger flood events throughout the simulations. The flooded area gradually increases over time under all trajectories, but grows less rapidly after 2080 indicating that the total inundation area relates more to fluvial flooding than SLR.

4.2 Waterlogging and pumping requirement

Waterlogging is prolonged inundation of land, often caused by localised rainfall, which cannot drain out of the polder due to elevated water levels in the river channels outside the polder. In the case of Bangladesh, waterlogging is defined as six months of ponding water.

The ‘Protect’ trajectory assumes pumping that eliminates all drainage reductions and the unions are never waterlogged (Figure S4a). Non-protected areas require significantly more pumping under this trajectory (Figures S5a,b), with infrequent extremes in a few unions (>500 mm/day). High SLR increases the mean annual pumping requirement by 45% (mainly non-protected areas) by 2100.

The other development trajectories do not consider pumping. The ‘Build elevation’ trajectory results in significantly better drainage characteristics. The number of ‘never waterlogged’ unions more than doubles compared to ‘Unmanaged retreat’ and ‘Reactive relocation’. However, moderately rising sea levels gradually increase the incidence of water ponding and drainage reduction. ‘Unmanaged retreat’ and ‘Reactive relocation’ show similar drainage reduction patters because land height is not modified and the only difference is the extent of flooded area due to embankment maintenance assumptions. In both cases, the severely waterlogged areas continuously increase, though beyond 2080, this becomes dramatic under ‘Unmanaged retreat’. Only ‘Reactive relocation’ results in union abandonment under the low SLR scenarios.

Under high SLR conditions (Figure S4b), the waterlogged and abandoned unions more than doubled, though the simulated patterns are the same. But, for ‘Unmanaged retreat’, the deteriorating polders result in changing waterlogging patterns beyond 2050 and some unions become abandoned (Figure S2b).

4.3 Soil salinization and rice production

The study area is dominated by two extremes during the dry season, under low SLR (Figure S6a and S7a). A significant portion has very low salinities (0-4 dSm^{-1}), and another significant portion is very saline (16+ dSm^{-1}). This pattern is different from the annual mean soil salinity results (not shown), where the lowest salinity class is most extensive and the very saline class is least extensive (hyperbolic pattern). Thus, some areas experience significant annual variation in salinity with increases in the dry season, and monsoon leaching in the wet season. Protected areas are more saline than non-protected areas, because more frequent freshwater flooding enhances the flushing of salt. For example on Figure S6a, the protected 'very high' salinity areas increases under 'Protect', but decreases under 'Unmanaged retreat'. This indicates the importance of land-river connectivity that is disrupted by the dikes.

ΔDIEM calculates water content and soil salinity as the balance of inputs (precipitation, floods, irrigation, capillary rise) and reductions (evapotranspiration, surface runoff, deep percolation) (Payo et al. 2017). Protected lands experience much less flooding in the 'Protect' trajectory than in the other policy strategies (Figures S3a,b), yet, the soil salinity levels are similar indicating that the main source of salinity is not flooding, and is either due to capillary rise (i.e. groundwater), or irrigation (i.e. farm management). The groundwater processes are the same under all development trajectories, so soil salinity is defined by agriculture practices. The 'More development' scenario grows more rice during the dry season than the 'Less development' scenario. Rice uses a large amount of irrigation water (nursery and development stages) that pushes down the water table and salt from the top soil into deeper layers, thus reducing the salt content of the root zone if the irrigation water has low salinities.

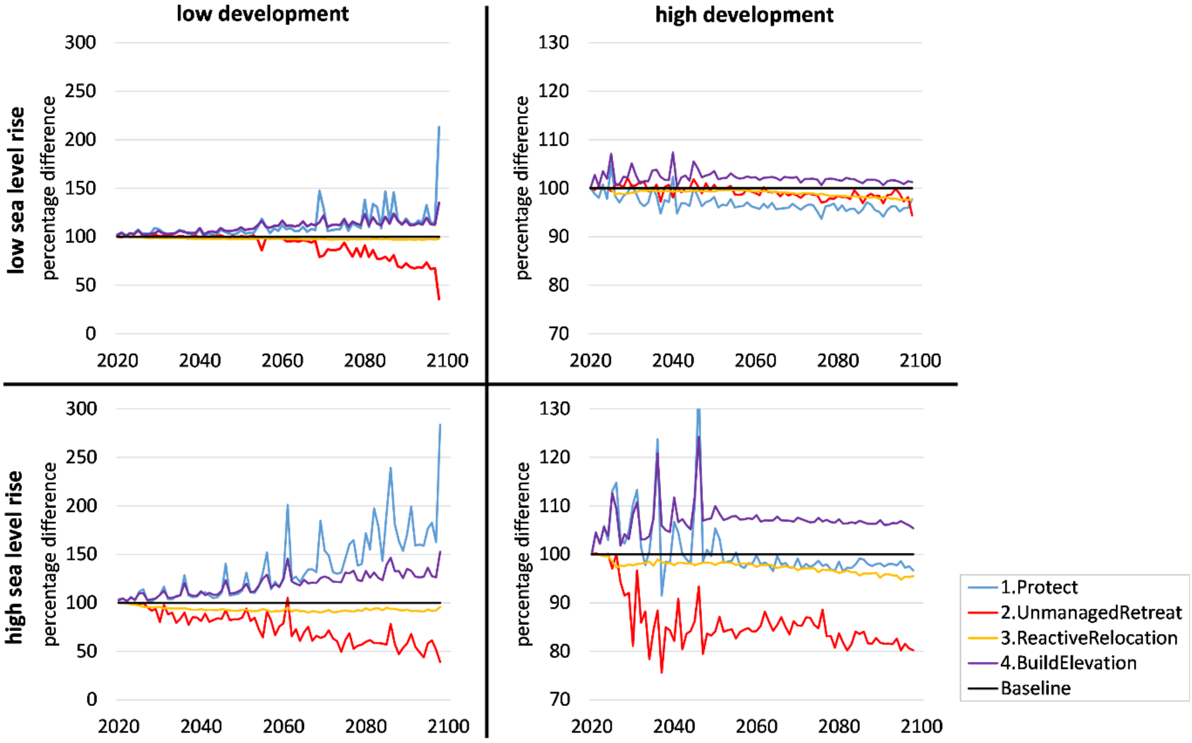

Figure 3: Total rice produced (tons) under the development trajectories (difference compared to specific contextual scenario)

There is about a 2 million tons difference in annual rice production between the low and high development scenarios in the 2020s, and this increases to ca. 8 million tons per year difference at the end of century (Table S4). This difference reflects assumed higher yields and more salt tolerant crop varieties under 'High development'. Further, the low development scenarios are more sensitive to policy directions (i.e. significant separation of results) than the high development scenarios. As expected, the worst simulated future is the 'high SLR - low development' scenario, whereas the best future is the 'low SLR - high development' scenario. Development trajectories also influence success rates. In the case of the low development scenarios, the 'Protect' and 'Build elevation' trajectories are the most successful strategies (Figure 3). 'Protect' constantly outperforms 'Build elevation', but 'Build elevation' leads to more stable rice production. Deviation between these policy strategies amplifies beyond 2050 under high SLR, due to the more efficient protection against flood damage. 'Reactive relocation' does not offer any benefit for agriculture, and 'Unmanaged retreat' is disastrous with a 300,000 tons of rice deficit (~350 million BDT = ~4 million USD) compared to the Baseline simulation. Under the 'high development' scenarios, with the exception of 'Build elevation', all policy trajectories are worse than the Baseline (up to -6% under low SLR, up to -20% under high SLR). Even 'Protect' is ineffective under these conditions, due to the increase in high soil salinity impacted areas (see 'high' + 'very high' categories in Fig S6-7). Thus, the 'Build elevation' trajectory offers the best possible outcome for agriculture under the tested futures.

4.4 Migration, income and inequality

The total population of the study area falls under all development trajectories (Figure S8). Susceptible outmigration is highest for the 'high SLR - low development' and smallest for the 'low SLR - high development' scenarios. SLR accelerates forced out-migration, whereas 'Protect' and 'Build elevation' strategies reduce it. The 'Reactive relocation' trajectory always has more outmigration, because entire communities are relocated. Migration is universal, not region specific, though areas along the Lower Meghna and North of Khulna district are more vulnerable. In general, the poorest simulated households leave first (due to low expenditure levels), followed by a second wave of forced migrants when farm-based livelihoods become increasingly unsustainable after 2060 (due to environmental change).

Household income consists of natural resources and 'off-farm' (e.g. manufacturing) components. (N.B. 'off-farm' livelihood incomes are based on extrapolated observations). Simulated total household income levels (Figure S10) increase similarly across the four development trajectories (except 'high SLR, low economic growth' - 'Unmanaged retreat'). The rate of increase is defined primarily by the development trajectory, and secondarily by the SLR scenario. The mean simulated income significantly increases after 2050 accelerated by both market price increases and improved crop properties re-iterating the importance of R&D and market management.

Inequality is measured with the GINI coefficient that scales from 0 to 100, where 0 means everyone has an equal amount of income and 100 means a single household receives everything. Income inequality has high inter-annual variability, but when the decadal means are assessed (Figure S9), inequality is worse under the high economic growth scenarios (+35-45%). The majority of the population is getting better-off, but the poorest is left behind. On the other hand, the income gap narrows in the low development scenarios.

The 'Protect' trajectory under the low economic development scenarios, reduces inequality because the off-farm sector growth is not significantly higher than the farm sector growth (rice is protected from flood damage), thus the different household archetypes are not separated greatly. 'Reactive relocation' has a similar inequality trend due to the continuous relocation of the most vulnerable communities resulting in a more resilient, better-off population. The 'Build elevation' trajectory has the highest inequalities, because farmers living outside the polders do not benefit from the intervention.

The high development scenarios are different. In all trajectories (except 'Reactive relocation'), inequality increases up to mid-century, and then stabilises or decreases because the assumed continuous growth in the off-farm sector exceeds greatly the growth of the farm sector which counteracts that negative effect of environmental change after 2050. 'Reactive relocation' is different, where inequality decreases due to relocation of the most vulnerable (entire) communities. Under high SLR, however, inequality stagnates because in areas where relocation is not simulated, the income gap significantly widens due to environmental stress.

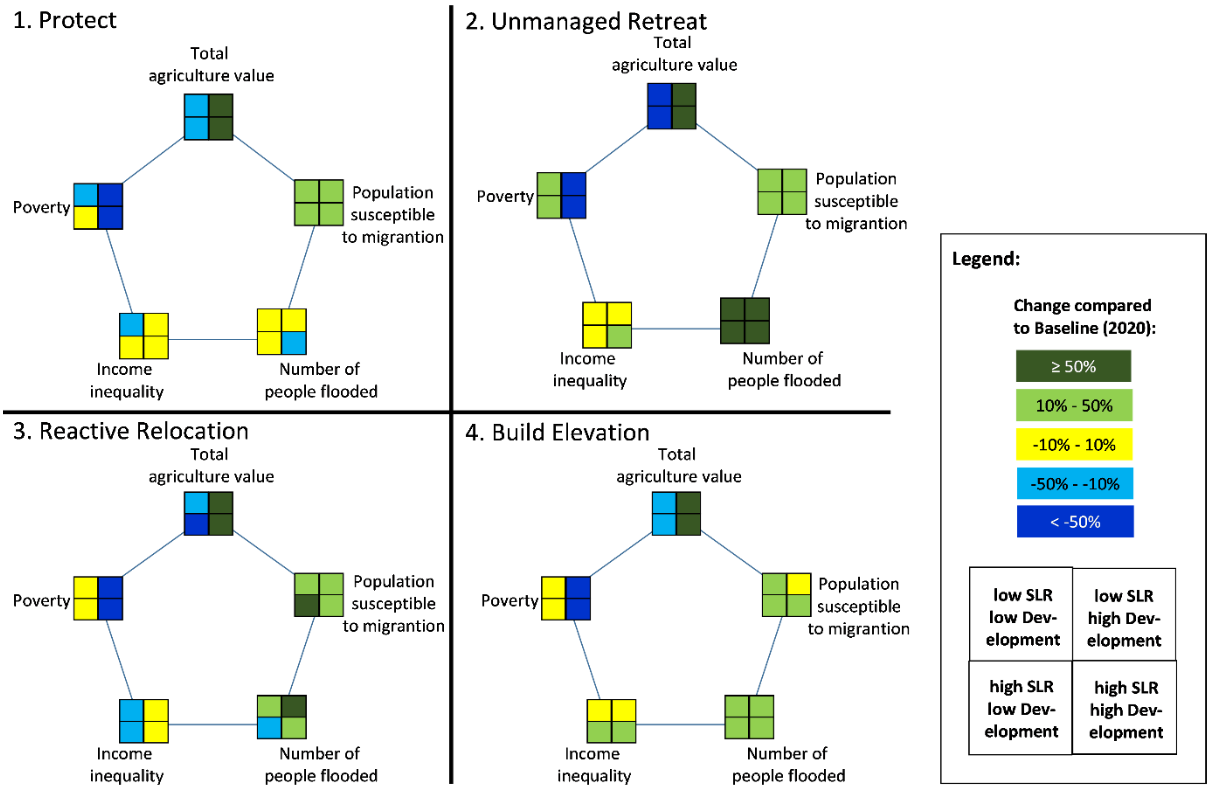

Figure 4: Overview of changes (2020-2098) in key outputs under all climate and development scenarios and development trajectories (SLR: Sea Level Rise)

4.5 Comparison of development trajectories

This section presents the robustness of development trajectories at mid- and end century. Overall, no significant change can be expected by 2050 (Figure S11), although the population susceptible to migration increases, and poverty rate changes can be positive or negative depending on the plausible future. By the end of century (Figure 4), migration and flooding impacts are projected to intensify. Inequality and poverty rates are very uncertain. Below, we assess the performance of the development trajectories.

The 'Protect' trajectory has multiple benefits. It reduces the agriculture losses under the low development scenarios, maintains or reduces the number of people flooded, and reduces the outmigration rates. Although mean income levels increase in all cases and general wellbeing maintained or increased, inequality depends on economic development and level of environmental stress. However, this policy intervention is costly (Table S6). The 5000 km long embankments of the study area would require an initial 1000-2000 billion BDT investment to raise the embankments, plus about 80 billion BDT to maintain the embankments between 2020 and 2100 (unit costs based on Jonkman et al. 2013). This trajectory provides +200 and +1800 billion BDT agriculture produce compared to contextual scenario (cumulative value to end-century) under low and high development.

The opposite trajectory is if the coastal defences are not maintained ('Unmanaged retreat'). The total cumulative agriculture value would sharply fall under the low development scenarios (between -140 and -2700 billion BDT), but the negative environmental impacts can to some extent be ameliorated by coping strategies such as better crop varieties (i.e. high development scenarios). In all cases, significant outmigration can be expected and flood impact increases. The current inequality level is likely to be maintained, but poverty rates can increase or decrease depending on the economic development. We note that the analysis is partial as the fate of the migrants outside of the study area is not considered.

The 'Reactive relocation' trajectory has mixed benefits. The number of people susceptible to migration is expected to significantly increase under extreme environmental or economic conditions. Dikes maintain the agriculture productivity, but the total agriculture produce is reduced due to outmigration and relocation, potentially causing food supply issues for the cities. For the same reasons, however, the mean income increases, inequality decreases resulting in a better off, more resilient and equal population, but poverty rates can still increase. The large scale relocation program, however, could be very costly (458-1194 billion BDT – Table S6) (unit cost based on Hino et al. 2017). As with Unmanaged Retreat, the analysis is partial.

The 'Build elevation' trajectory is most promising. It ensures a steady farm production above the contextual scenario, thus maintaining rural natural resource-based livelihoods. However, due to environmental change, the overall production value will likely decrease if crop varieties and economic conditions are not improved. Flood and waterlogging damage are reduced, susceptible outmigration rates are low and poverty rates are likely to fall. But the number of people flooded and inequality still slightly increase, because only farmers living inside the polders benefit from the intervention. The cost of this development trajectory is the lowest totalling of ca. 219 billion BDT that also includes the 80 billion BDT embankment maintenance cost and the assumed 1000 BDTha^{-1}year^{-1} compensation (Table S6).

In summary, 'Protect' gives the most benefits, but it is costly and locks the system into a dependence on defences and associated problems (drainage, salinisation, inequality) irrespective of the rate of SLR. 'Reactive relocation' has benefits, but is costly and socially difficult to implement. It transfers 'inequality' elsewhere where lives and livelihoods have to be rebuilt. 'Build elevation' promises a sustainable, more natural river-sea-land interaction in coastal Bangladesh at a reasonable cost.

5. Discussion

The aim of this paper was to investigate the likely implications of stylised consistent development trajectories on coastal Bangladesh under uncertain climate and socio-economics. ΔDIEM is designed to analyse the human-natural system dynamics, and to inform policy at the scale of analysis. We used stylised policy strategies without spatial/temporal optimisation of the strategies. These provide important insights, but should not be used directly in planning.

The bio-physical model results are in broad agreement with published literature (Table S7). Simulated flood extent agrees well with other studies (CCC 2009a; CCC 2009b; Mohal and Hossain 2007; WARPO 2005). Soil salinity results are comparable for 2020 with SRDI (2012), but other studies suggest twice as much future soil salinisation (Dasgupta et al. 2015; Mohal and Hossain 2007). The monsoon representation and the integrated, process-based soil salinity calculation of ΔDIEM might cause this discrepancy. Rice production for 2020 is in good agreement with the 2012 agriculture statistics (BBS 2012).

The current 166 million population of Bangladesh is expected to increase to 200 million by 2050, and subsequently decline to 170 million by 2100 (UN 2015). Our study area is a marginal area, where outmigration (mostly to Dhaka) is significant. Approximately 30% of coastal households today have migrant members and 50% of these migrants left the coastal zone (unpublished dataset, DECCMA project, www.deccma.com). Our results suggest that 12-58% of the population are susceptible to migration.

Most coastal households have mixed farm and off-farm livelihoods, and the simulated income levels steadily rise across all scenarios. (N.B. ΔDIEM only calculates agriculture and fisheries income variations, and off-farm incomes are projections.) Our trend is consistent with the observed five-yearly increase (50-60%) of household income (BBS 2011). Income however is a poor indicator of welfare. In 2010, consumption was 97% of total income in Khulna and 107% in Barisal divisions (BBS 2011). Our results show comparable levels. The Government of Bangladesh aims to eradicate most poverty by 2033 and completely by 2050 (BDP 2018). The latest reported (2016) $1.9/capita/day headcount poverty indicator of Bangladesh is 14.8% (World Bank 2017). We estimate that the simulated 44% (consumption-based) poverty rate in 2020 could be reduced to about 24% by 2050 and 7% by 2100 under the most optimistic scenarios, but can also increase to 70% under scenarios of environmental stress and a poor economy. Our 2020 poverty rate is much higher than the World Bank's revised, national figure, but this is thought to be realistic, as ΔDIEM only simulates the rural population of the marginal coastal zone.

The policy trajectory evaluation indicated that 'Protect' and 'Build elevation' strategies are the most robust options, but both raise issues. Embankments prevent sedimentation and results in subsidence due to sediment compaction and potentially groundwater abstraction (Syvitski et al. 2009). Auerbach et al. (2015) reported that coastal Bangladesh have lost 1-1.5 m land elevation within the polders since the 1960s. Embankments also cause a loss of soil fertility unless replenished by fertiliser application. To ensure long-term geomorphic and ecological sustainability in the presence of embankments, small-scale controlled flooding and sedimentation (i.e. TRM) is being applied in Bangladesh. Even though TRM provides long-term benefits reducing flooding and waterlogging, without addressing institutional limitations and compensation, many communities are reluctant to agree (Gain et al. 2017). TRM is not applicable everywhere and sediment supply is reducing in the GBM delta (Dunn et al. 2019; Rahman et al. 2018). It is noteworthy that while the Bangladesh Delta Plan 2100 supports TRM as a concept, it contains no specific further TRM projects beyond the current portfolio (Nicholls et al. 2020). Despite the difficulties outlined here, these results suggest more urgency could provide benefits. New embankments would not benefit the poorest as the increase in land value would encourage investors to push the marginalised off their land causing social disparities. The combination of these two policy strategies would enable sustainable farming, good economic return and economic sustainability. Further detailed analysis are recommended to assess their benefits and if the side-effects could be mitigated with other means. Other promising land use strategies such as agriculture to aquaculture conversion might also be considered, but environmental, wellbeing, gender and inequality trade-offs remain (Gurung et al. 2016; Paul and Vogl 2011; Sohel and Ullah 2012).

The results clearly show that climate and environmental change are important, but not as important as the socio-economic development and coastal management policy in Bangladesh. Continuous adaptation through research and technologies can overcome many of the adverse effect of climate change on the natural-resource-based livelihoods. Off-farm sectors are also dominant income sources in coastal Bangladesh and their significance will increase as environmental pressure increases. Thus, a healthy off-farm economy is fundamental in future development.

The GBM delta is highly dynamic, highly modified and highly populated. Representation of processes and feedbacks of such as complex system is a major challenge. Model developers always face a trade-off between comprehensiveness, process detail and data requirements. ΔDIEM is no different with many current limitations. Field and modelling studies are especially needed to better understand the link between economy, institutions, demography and environmental change, and household adaptations.

Delta management today is moving towards a more holistic, adaptive management approach (Seijger et al. 2017; Zevenbergen et al. 2018). Indeed, the Bangladesh Delta Plan 2100 (BDP 2018) designs long-term “living plans” that will be regularly updated with new evidence. Currently it is based on extensive bio-physical modelling, but lacks the dynamic capturing of the human-nature interaction. The ΔDIEM method is a first level approximation of this complexity providing high level insights by simulating the impact of environmental, socio-economic and policy changes on the welfare of the coastal population of Bangladesh. By providing new perspectives on delta futures it serves a fundamental and growing need in delta planning.

6. Conclusion

In this paper, we extended the ΔDIEM integrated model with new tidal river management and migration modules, and explored the long-term effects of stylised policy choices on development trajectories in coastal Bangladesh. The results indicate that significant changes in flooding and productivity are only expected to occur after 2060. The level of change is strongly dependent on the selected scenario. Significant outmigration and the persistence of poverty is expected under all scenarios. With good management approaches (protection or building elevation) the coastal zone can remain habitable and agriculturally productive until 2100 at least. The ‘Build elevation’ trajectory raises equity questions – a compensation mechanism is needed to address the short-term losses due to temporary flooding, but it holds potential for a more sustainable coastal zone (geomorphic and livelihood) in Bangladesh. The economic benefits of maintaining the existing embankments is demonstrated, but the side-effects are also highlighted. The ΔDIEM integrated approach captures the complexity of the human-natural system and provides new perspectives and insights on delta futures that is essential to support robust delta planning of the 21st century.

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