The unequal distribution of water risks and adaptation benefits in coastal Bangladesh

Emily J. Barbour[1,2], Mohammed Sarfaraz Gani Adnan[1,3], Edoardo Borgomeo[1], Kasia Paprocki[4], M. Shah Alam Khan[5], Mashfiqus Salehin[5], and Jim W. Hall[1].

[1]School of Geography and the Environment, University of Oxford, United Kingdom

[2]Commonwealth Scientific and Industrial Research Organisation, Australia

[3]Department of Urban and Regional Planning, Chittagong University of Engineering and Technology, Bangladesh

[4]London School of Economics and Political Science, United Kingdom

[5]Bangladesh University of Engineering and Technology, Bangladesh

Corresponding author: Emily J Barbour, Commonwealth Scientific and Industrial Research Organisation, Australia; emily.barbour@csiro.au; +61 (2) 6246 5992

Abstract

Increasing flood risk, salinization and waterlogging threaten the lives and livelihoods of more than 35 million people in Bangladesh's coastal zone. While planning models have long been used to inform investments in water infrastructure, they frequently overlook interacting risks, impacts on the poor, and local context. We address this gap by developing and applying a stochastic-optimisation model to simulate the impact of flood embankment investments on the distribution of agricultural incomes across income groups for six diverse polders (embanked areas) in coastal Bangladesh. Results show that increasing salinity and waterlogging negate the benefits of embankment rehabilitation in improving agricultural production, whilst improved drainage can alleviate these impacts. Outcomes vary across income groups, with risks of crop loss being greatest for the poor. We discuss the need for planning models to consider the interacting benefits and risks of infrastructure investments within a local political economy to better inform coastal adaptation decisions.

Understanding the effectiveness and equity implications of large adaptation infrastructure investment is currently paramount in Bangladesh's coastal region. As one of the world's most vulnerable and biophysically dynamic regions, coastal Bangladesh faces multiple water-related hazards including cyclones, tidal and river flooding, salinization, and waterlogging. With the potential for multiple coinciding hazards to increase in the future, the impact of hydroclimatic risks is likely to be magnified [1,2].

Flood protection embankments and drainage infrastructure were constructed to create polders (embanked areas separated from the surrounding river system) and improve agricultural production as part of the South Asia 'Green Revolution' in the 1960s to 1980s. Initial success in improving flood mitigation and food security [3,4] has been undermined by inadequate maintenance, as well as appropriation by local elites and government actors for alternative production systems such as aquaculture [5,6]. Embankments have been weakened by shrimp farmers who are supported by these elites, drilling holes to bring in saline water [7].

Flood protection goals have consequently become compromised by power imbalances and conflict, contributing to high salinity, waterlogging, wealth disparity, loss of livelihoods, and the displacement of poor and vulnerable people [7-9].

These outcomes are symptomatic of a global pattern of adoption of large water infrastructure projects in response to hydroclimatic risk [10-12], despite it being known that they do not always deliver expected outcomes [13,14]. Traditional water infrastructure planning has largely ignored distributional equity [15,16], resulting in long-term chronic environmental and social impacts [17,18]. Large-scale infrastructure projects are too often subject to control by local elites, thereby reinforcing unequal power structures [19]. Infrastructure effectiveness and the distribution of benefits are a consequence of interactions between the construction, use and operation of built infrastructure and the environmental, social and political context [16,20]. In an era of re-emerging emphasis on large infrastructure [21] combined with increasing evidence of these impacts [22,23], it is imperative for planning models to better account for who benefits and who incurs residual risks [12,24].

Whilst a number of methods exist to support the planning and management of water and flood risk infrastructure considering future uncertainty [25,26], the complex dynamics of the socio-ecological systems into which this infrastructure is introduced remains under-represented in research and practice [19]. Here, we take a novel approach linking quantitative modelling with insights from political economy literature to consider unequal socio-economic status within and across communities, and their inter-relationship with spatial variation in biophysical systems. As with any exploratory model of complex systems, its strength lies in the ability to investigate interacting dynamics to gain new insights that are not possible with sectoral-focused, detailed models. Nonetheless, there are inevitable limitations in precision compared with more detailed process-based models.

We build on earlier work [27,28] to explore the distributional effects of flood protection rehabilitation investments on flood mitigation and agricultural production in six diverse polders across coastal Bangladesh (Figure 1). First, we investigate the interrelationship between embankments, flooding, salinity, waterlogging, and agriculture in determining risk at different spatial scales both within and between polders. We use a risk-based stochastic optimisation model over a sixty-year planning horizon, drawing on contextual information from political economy literature. Second, we explore variability in sequencing and effectiveness of embankment rehabilitation investment decisions in improving crop production across the polders. We assess the role of waterlogging and salinity in limiting embankment rehabilitation effectiveness, and compare it with investment in drainage infrastructure. Third, we examine implications for agricultural income across different socio-economic groups.

We use a novel combination of datasets considering intra- and inter- polder variability in elevation, flood risk, erosion rate, salinity, cropping pattern, distribution of different land holding types, as well as investment cost (Figure 2).

Modelling impacts of water risk on farmer livelihoods

Agriculture is the most important economic activity within the region [33], supporting the livelihoods of a variety of rural classes including day labourers, sharecroppers, as well as small to large landholders. It consequently continues to play the most significant role in sustaining an economically diverse region, despite the expansion of alternative livelihoods such as aquaculture and manufacturing. Tensions in water and land management exist between agriculture and saline aquaculture, the latter of which primarily supports wealthier landholders and elites who reside outside of rural communities

[7]. Aquaculture is less labour-intensive, reducing employment opportunities and thus driving out-migration [9,34]. These tensions influence the construction, use, and operation of flood protection infrastructure.

We examine variations in crop loss within and between six polders (Figure 1) for two types of agricultural groups: subsistence farmers (land holdings of ≤ 0.04 acres); and farm holdings (small, medium, and large, 0.05 to >7.5 acres) [35] (Supplementary Table 4). The six polders are selected using published literature and a scoping visit to represent varying levels of water security risk and poverty; embankment and drainage infrastructure deterioration; institutional arrangements and effectiveness; and involvement in previous, current, or future development projects [36,37].

Flooding is a major cause of crop loss in coastal Bangladesh, resulting from the interaction of different drivers including storm surges, elevated river levels exacerbated by riverbed siltation and polder subsidence, high precipitation, embankment deterioration, poor drainage, and land use management. The relative contribution of these drivers has been examined in previous empirical studies of observed floods, which have shown the ongoing devastating impact of surge-induced flooding caused by cyclones, non-cyclonic storms, and fluvio-tidal events [37,38]. We extend this work to examine long-term risk beyond the observed record by constructing a stochastic model of extreme tidal, fluvial, and cyclonic flood events, embankment condition, and polder elevation (Figure 2).

Of our six polders, flooding is greatest in Polders 32 and 29 based on previous analysis [38], which is reflected in our model (Figure 3a,c; Supplementary Figures 1 and 6). We consider variability in flooding across the region by varying flood magnitude depending on polder location, recognising that a damaging flood event impacts the region on average just over every two years [38]. Polder embankments are damaged during flood events, whilst also being subject to ongoing deterioration due to erosion. We consequently incorporate modelled storm damage and use observed erosion data [39] to model variations in embankment deterioration, with a higher deterioration for Polder 54 in the South-Central region (Figure 3b).

Variations in flooding within each polder are modelled at the scale of the lowest administrative unit (mauza), averaging approximately 280 ha for our study area (ranging from ~11 to over 2,000 ha) [32]. Within each mauza, we estimate flood impacts on crop production comparing subsistence farmers with small to large farm holdings. Agricultural census data [40] is used to identify the number of each holding type for each mauza.

Both flooding and embankment construction influence increasing soil salinity and waterlogging. Soil salinity is influenced by inundation, saline intrusion from reduced upstream freshwater flows, application of saline irrigation water, and influx from areas under saltwater shrimp aquaculture. Salt is flushed from polders during the monsoon season through percolation [41,42]. Embankments can consequently mitigate salinity through reducing tidal and storm-surge inundation of saline water, whilst also contributing to increasing salinity due to increased waterlogging from river siltation and polder subsidence.

Salinity has become sufficiently severe to significantly impact crop production, and can disproportionately affect poorer and marginal farmers [9,43]. Increasing salinity has influenced and been influenced by transitions to saline shrimp aquaculture dominated by large-scale enterprises at the exclusion of local farmers [9]. It is thereby implicated in changing land-use, livelihoods, and local power dynamics [9].

Observed data shows soil salinity to be highest in Polders 32 and 33 within our case study area, with high river salinity levels assumed to affect four of the six polders (30, 32, 33 and 43/1) [31]. Given the pressures of sea level rise, embankment deterioration, subsidence, and drainage deterioration, we project that without action to tackle these issues salinity will exceed 16 dS/m in four of the six polders during the sixty-year simulation period, the level of salinity above which most crops cannot grow [31] (Figure 3d). A reduction in crop yields has been shown at much lower concentrations of <4 dS/m [31,41].

Waterlogging has also become widespread across the coastal zone, with areas that are inundated during intense rainfall or fluvial flooding failing to drain for prolonged periods. We predict that waterlogging will increase over time due to polder subsidence and deteriorating internal polder drainage, exacerbated by deliberate inundation for aquaculture [8,44]. We model waterlogging as a function of elevation difference between the polder and river, and drainage condition (representing infrastructure condition and sedimentation). Using river level elevations [32] enables us to capture seasonal variations, with waterlogging being greatest during the monsoon when rainfall is greatest and river levels are elevated. Modelled waterlogging is most extensive in Polder 32 (followed by Polders 33 and 30), having the lowest elevation of the six polders [30] (Figure 3e and Figure 1).

Impacts upon agricultural production vary between different socio-economic groups. Subsistence farmers primarily grow vegetables (in our model we use representative crops: water gourd and winter and summer pumpkin), whilst farm holdings primarily grow rice [40] (Supplementary Table 6). Whilst those who own less than 0.04 acres of land have been referred to as effectively landless [45], we assume here that it is of sufficient size to produce garden crops. We assume this land is evenly split between gourd, winter, and summer pumpkin across all polders in the absence of further information. We model spatial variation in cropping patterns for farm holdings using Upazila-scale (the second-lowest administrative unit) data, focusing on major crops (local, hybrid and high-yield varieties of rice as well as jute) [40].

The combined effect of flooding, salinity, waterlogging, and crop type are predicted to have a significant impact on crop production, with variations within polders, between polders, and between socio-economic groups. Crop production loss is predicted to be highest in Polders 32 (70%) and 29 (60%) (averaged over the single sixty-year simulation period shown in Figure 3f), with Polder 32 having frequent flooding as well as high salinity and waterlogging. Whilst Polder 29 has a high total crop yield due to a greater proportion of high-yield crops such as hybrid and high-yield (HYV) Boro (spring rice) [40] (Supplementary Figure 7), it also has a much lower proportion of local Aman (monsoon rice) which is grown when salinity is lower.

Banking on adaptation infrastructure

Rehabilitation of Bangladesh's embankments and drainage system has been a focus of adaptation investment since the 1990's, costing in excess of $600 million USD (details provided in Supplementary Table 7). Though risks of waterlogging and salinity were recognised, the relative impacts and benefits of adapting to these threats have not been systematically quantified. To explore these interactions, we optimize an embankment investment sequence by considering flood risk reduction and investment costs, which is the economic rationale that is conventionally applied to adaptation investments [46] (optimisation parameters are described in Supplementary Table 8). We assume that during rehabilitation, embankments are returned to their as-built condition. We subsequently investigate the role of waterlogging and salinity, and compare the effectiveness of embankment rehabilitation with investment in drainage infrastructure.

We consider a maximum of three potential investments per polder over the first forty years of the sixty-year simulation period (estimated to cost over $600 million USD [47] for all polders), with investments allowed at 5-year time intervals. We use multi-objective optimisation to explore embankment investment priorities, timing, and impacts under three conditions: (1) minimise expected crop income loss with no investment cost constraint; (2) minimise expected crop income loss with an investment cost constraint of $200 million USD; and (3) minimise both crop loss and investment cost. Expected crop income loss, $\mathrm{E}(L)$, is calculated as a percentage reduction from the maximum potential crop income, $\bar{I}$, based on maximum potential yields (provided in Supplementary Table 6): $\mathrm{E}(L) = \left(\bar{I} - \mathrm{E}(I)\right) / \bar{I}$, where $\mathrm{E}(I)$ is the expected crop income calculated as an average of 100 stochastic iterations.

Under all three conditions, embankment investment is largely driven by flood risk reduction potential (Supplementary Figures 8 to 10). When costs are constrained, the greatest investment is in Polder 32 (Supplementary Figure 9 and 10). Crop income loss remains significant across polders even with all three embankment rehabilitations permitted per polder under the first condition with no cost constraint. For Polder 32, income loss with maximum investment is estimated to be 60% for small to large farm holdings and 90% for subsistence farmers, compared with 70% (farm holdings) and 90% (subsistence farmers) with no investment (averaged over 1,000 stochastic flood simulations, Figure 4). Embankment investment is found to be more effective in reducing crop loss for small to large farm holdings with little benefit for subsistence farmers. These findings are broadly consistent with observed losses from an extreme flood in 1998, noting variations in study area [48]. Observed losses are found to exceed 90% for some rice varieties.

Investment is also influenced by variation in embankment deterioration, driven by differences in erosion rates which are higher adjacent to Polder 54 [39]. As such, a greater reduction in crop loss for small to large farm holders is found with investment in Polder 54 relative to Polder 29, despite Polder 29 having a higher flood risk and greater crop loss.

Whilst embankment investment results in a substantial reduction in flooding (Supplementary Figure 6), the direct risk from large floods is relatively small in the majority of polders when compared to the impacts of waterlogging and salinity on crop production (Figure 4).

To further examine the relative impacts of waterlogging and salinity on crop production, we firstly conduct three sensitivity tests, and secondly explore an alternative intervention targeting improved drainage. We use 1,000 stochastic flood simulations to compare expected crop loss between scenarios. For the sensitivity tests, we alternately set (1) waterlogging and then (2) salinity to zero in the model, which results in a significant reduction in modelled crop loss (Figure 4). Variations are found between polders and farm holdings as to which has the biggest impact. Under a combined zero salinity and waterlogging scenario with no embankment investment, the total expected agricultural income per year for the six polders increases by >100% for small to large farm holdings, as opposed to <10% for embankment investment. This difference is even greater for subsistence farmers, where the increase in income is >200% compared with <5% for embankment investment.

Our third sensitivity test explores the influence of sediment deposition in reducing waterlogging and salinity (through increased elevation and consequently reducing flood events bringing in saline water). Sediment deposition has gained increasing attention in Bangladesh through Tidal River Management (TRM) projects with varying degrees of success [49,50]. Whilst the focus of TRM is on deposition during smaller, regular floods, we use our model of large flood events to test the sensitivity to deposition. Elevation is increased in flooded mauzas by a maximum of 37 cm [51] and scaled based on the size of each flood. This is a conservative estimate based on reported average deposition [51], which was observed to be as high as 60-70 cm in some locations.

Given that sediment deposition only occurs during large floods within our model, the overall impact is negligible with only a small improvement in Polder 32. We note that other studies have shown sediment deposition to have greater potential when considering more regular inundation events under TRM [50], and it has been adopted as a mitigation strategy in the Bangladesh Delta Plan 2100 [52]. It remains a debated topic, with studies highlighting the context-specific biophysical and socio-political setting required for its success (such as seasonality, magnitude of tidal flow, spatial distribution of sediment concentration, river salinity, and availability of land that can be inundated) [49,50].

As an alternative intervention to embankment rehabilitation, we then examine the effectiveness of investing in polder drainage by assuming no deterioration in drainage condition occurs during the simulation, thereby reducing waterlogging. Poor interior polder drainage is caused by siltation, blockages, as well as inadequate maintenance and operation, and has been reported as being a cause of waterlogging and consequently crop damage by household surveys [44]. We find a no-drainage deterioration scenario to have a greater influence in reducing crop loss for all polders relative to embankment rehabilitation, with the exception of subsistence farmers in Polder 32. The expected crop income increases by ~30% for small to large farm holdings and ~40% for subsistence farmers. Whilst our representation of drainage condition is necessarily simple due to the spatial scale of our model and hence the exact values should be treated with caution, our findings are consistent with other studies that have found drainage congestion and poor operation to be an important contributor to waterlogging and hence crop loss [44].

Within polders, variations in modelled crop income between mauzas are significant, and are greatest in Polder 29 under a no-investment (190 – 390 USD/ha) and embankment investment scenario (220 – 420 USD/ha) (Figure 5). Under an embankment investment scenario with no waterlogging or salinity, the greatest variation is in Polder 43/1 (350 – 440 USD/ha). Comparing a no-investment with an embankment investment scenario, increases in area averaged income varied most in Polder 32 (30% - 50%). Whilst observed data was not available to verify these differences, these results highlight the significance of intra-polder spatial variations in investment impacts which has too often been overlooked in adaptation assessments.

Winners and losers of infrastructure investment

We compare differences in modelled crop income loss for subsistence farmers (vegetables) and small to large farm holdings (rice and jute) and find average crop income loss to be higher by up to 90% for subsistence farmers across all polders for our two interventions (Figure 4). Differences between subsistence farmers and small to large farm holdings are greatest for Polder 33, which has high salinity minimal flooding. The higher loss for subsistence farmers is primarily due to salinity having a greater impact on vegetable growth compared with other crops.

These results are consistent with empirical data for areas adjacent to the Meghna River [53], where floodplain residents below the poverty line (defined in this case as below US$105/capita/year) reported on average 42% flood damage (proportion of household income) as opposed to 17% for those above. However, this included multiple sources of damage, for which crop damage was the highest (27%) along with house property damage. In contrast, an analysis [48] of the 1998 flood for seven Upazilas (including Khulna) did not show higher production loss for smaller land holdings, although it did find a higher percentage loss of assets as well as significant impact on labour opportunities.

In our analysis, small to large farm holdings had similar crop income loss due to consistency in cropping patterns, despite variations in the number of holding types per mauza (with different susceptibility to flooding).

Distributional variations in adaptation costs and benefits also have an important gender-dimension, being influenced by access to labour and socio-economic status. We are unable to represent this in our analysis as census data does not capture the complex intra-household gender implications of agricultural income or adaptation investment. Available data does show that all farm types have a higher proportion of male-headed holdings, yet subsistence farmers have more female-headed holdings (5%) compared with small-large farm holdings (2%) (at an Upazila-scale) [40] (Supplementary Table 5). We recommend further work is undertaken to better understand the gendered implications of investment decisions.

Toward equitable flood infrastructure investment

Our findings provide important insights for the current and future management of Bangladesh’s coastal zone. The region is central to the Government of Bangladesh’s development goals, with plans including the development of a transportation hub, tourism, and additional industry [52,54]. Rehabilitation of coastal embankments is a key component of these goals, with ongoing investment through programs such as the $400 million USD Coastal Embankment Improvement Project [55].

We show that the benefits of investment in flood embankment rehabilitation can be overwhelmed by increasing salinity and waterlogging, and that these cannot be examined or mitigated in isolation. Furthermore, we show that investments in drainage rehabilitation have a greater overall influence on reducing crop loss for all polders relative to embankment rehabilitation, leading to crop income increases of ~30% for small to large farm holdings and ~40% for subsistence farmers. We demonstrate the feasibility and value of modelling distributional impacts ex-ante, supporting empirical evidence that challenges commonly held assumptions on the effectiveness of embankments.

The physically dynamic nature of the system combined with vulnerability to natural hazards, high poverty, and weakness of local institutions presents a critical need for exploratory planning tools that can accommodate multiple interacting risks and their spatial variation, limited and diverse data, and can be applied to understanding of the local political economy. Such tools provide an opportunity to further develop our capacity to represent such systems, and how they can be used to complement more detailed analyses on subsets of processes with greater accuracy and precision. Understanding these interactions can assist in identifying the right problem (or set of problems), and who defines what ‘right’ is. It can support the identification of how, where and when to invest to target areas with the highest vulnerability, which may be missed when focusing on investments with the greatest return or ease of implementation.

Larger-scale adaptations, including embankments and drainage infrastructure, continue to attract large sums of finance and development assistance. Smaller-scale adaptations, which include financial assistance such as direct cash payments after disasters, hazard forecasting and shelters, and strengthening of homes, can also help to mitigate the damage of climate-related disasters [56]. These can complement large-scale infrastructure, and can target the most vulnerable provided there is adequate geospatial poverty data.

The political economy of infrastructure management and maintenance following its initial construction can also transform impacts with significant implications to the distribution of benefits[20], and yet is frequently overlooked. Maintenance and use of embankments and drainage infrastructure influence the degree of saline water influx, sediment influx, drainage of excess ponded water, as well as vulnerability and exposure to flood risk. These environmental factors in turn influence and are influenced by land management, access to labour, access to decision making power, and ultimately capacity to build resilience against environmental risk and social poverty. Challenges in managing this political economy and chronic risks are exacerbated by donor preferences for large capital investments with insufficient attention to subsequent management and maintenance [6].

The dynamics and challenges described are by no means specific to coastal Bangladesh. Globally, the growing environmental and social impacts of existing infrastructure projects continue to motivate debate on alternative means of managing flood risk [57]. We have developed an approach that provides insights into the complex dynamics between hydroclimatic risk and social systems, and demonstrate the importance of a multi-disciplinary, systems-approach in designing adaptation strategies. We believe that such approaches are needed to provide actionable insights for effective adaptation in vulnerable coastal regions.

Methods

We develop a risk-based model that extends the work of Borgomeo et al. [27] to focus on distributional impacts considering different socio-economic groups; within and between polder heterogeneity parameterised using high resolution datasets; as well as more explicit representation of drivers influencing crop yield. We also draw on the work of Lázár et al. [33], Nicholls et al. [58], and Payo et al. [59], who integrate flood and salinity impacts on crop production for different households in coastal Bangladesh. Here, we focus instead on implications for embankment rehabilitation investment decisions.

The model uses crop yield as a metric for evaluating flood embankment investments given the key role it places in supporting livelihoods across coastal Bangladesh. Crop yield (Y) is calculated as a function of salinity (s_F) and waterlogging (w) for unflooded areas using a monthly time step (*t*), by proportionally reducing the maximum potential yield ($\overline{Y}$): $Y(t)=\overline{Y}(t)-\overline{Y}(t)\left[\min\left(\frac{s_F(t)+w(t)}{2}\right),1\right]$. The spatial unit of analysis is a mauza although the spatial resolution of datasets varies. Mauzas are estimated to be either completely flooded or not flooded based on their elevation using Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) data [30]. The frequency and magnitude of flood events are calibrated to observed data from 1988 to 2012 [38] for each of the six polders, and is described further in the Supplementary Information (Supplementary Figure 2 and Supplementary Table 1).

Within-polder flooding is influenced by embankment condition, modelled as a value between 0 and 1 with a starting condition of 0.6 (60% of the maximum condition) to represent initial deterioration across all polders (in the absence of further information). Condition is assumed to deteriorate at a constant rate over time due to erosion, with additional deterioration during a flood event proportional to the magnitude of the event (further described in the Supplementary Information under Embankment reliability). We model embankments as a single entity which spans the entire periphery of each polder given the lack of available information on variability within individual polders.

Soil salinity (s_L) is calculated as a combination of chronic increases (s_c) and short-term influxes (s_F) by taking the maximum of the two mechanisms for any given mauza (m) each month. Concentrations are normalised to a value between 0 and 1 using an upper limit of 16 dS/m above which there is a significant impact on crops, noting that impacts on more sensitive crops can occur at much lower concentrations [31,41]: $s_L(t,m) = \min\left(\frac{\max\left(s_c(t), s_F(t,m)\right)}{16}, 1\right)$. Mauza-scale salinity is used to reduce crop yield for each mauza, and is then summed for the entire polder.

Chronic salinity is assumed to increase at a constant rate of 0.09 dS/m per year based on average historical data [31] (Supplementary Figure 4), with the initial salinity in each polder varying between 8 and 14 dS/m (estimated using area weighted average salinity for 2009 [31], Supplementary Figure 3 and Supplementary Table 2). A monthly soil salinity profile [33] is used to represent seasonal variations at a polder scale (p): $s_c(t,p) = \left[s_c(t-1,p) + s_I\right] \cdot s_p(t)$.

During a flood event, the salinity influx for flooded mauzas is assumed to equal that of the river (s_R), and consequently varies spatially across the six polders (between 2 and 28 dS/m) [31] (Supplementary Table 3). Salinity concentrations are assumed (in the absence of available observed data) to decline over time with a ~50% reduction over a period of two years: $s_F(t,m) = s_R(p)e^{-bt'}$ (where -b controls the rate of decline, set 0.03 to reduce salinity by ~50% in two years; and t' is the time since the last flood event).

Waterlogging is assumed to be a function of drainage infrastructure condition (d), and elevation inside the polder [30] (e_L) relative to the river (e_w) (estimated from three observed gauges [32]):

$$w(t,m) = \begin{cases} 0.5 \cdot \left(e_w(t)/e_L(t,m)\right) + 0.5 \cdot (1 - d(t)) & \text{if } e_w < e_L \\ 1 & \text{otherwise} \end{cases}$$

Drainage condition is modelled as $d(t) = d(t-1) - ad(t-1)$ where a=0.005 (a decline of 50% in just over 10 years for a starting condition of 0.8).

Susceptibility to waterlogging is modelled through analysis of elevation differences between the polder and river, where drainage from the polder is restricted (precipitation also predominantly occurs during the monsoon when river levels are elevated). Land elevation is averaged over a mauza (m), and is assumed to decline over time due to subsidence (s) (caused by lack of sediment deposition due to polderisation and accelerated compaction) at a rate of 2 cm/yr [51]: $e_L(t,m) = e_L(t-1,m) - s + d_s \cdot F_F \text{ for } F > 0$ (where d_s is the sediment deposition, set to zero for all model runs except the deposition scenario where it is set to 37cm; F_F is the fraction flooded between 0 and 1, and represents the magnitude of the flood event outside the polder; and F is the start of a flood, set to 1 and at other times 0). The adopted subsidence rate is based on published literature comparing average differences in elevation between natural and poldered areas over a 50-year period [51]. There is substantial variation in published estimates of subsidence, largely due to a lack of existing understanding of subsidence processes in deltas [60]. The value we have adopted here is at the higher end of published estimates, enabling us to explore the sensitivity to changes in elevation.

Drainage infrastructure is assumed to only influence waterlogging when the polder is at a higher elevation than the river, and is assumed to influence only a proportion of runoff given percolation can occur.

Embankment rehabilitation investment timing and sequencing is evaluated using multi-objective optimisation, with the model run over a sixty-year simulation period with an initial forty-year investment period followed by a twenty-year no-investment period. A one-year spin-up period is used. The model is evaluated firstly using a single objective to minimise expected crop income loss (E(L)); secondly to minimise E(L) with an investment cost constraint of $200 million USD (half that of the Coastal Embankment Improvement Project currently being implemented); and thirdly to minimise both E(L) and total investment cost.

Embankment rehabilitation costs are estimated using existing rehabilitation project cost estimates and embankment lengths (further details are provided in Supplementary Table 7). We estimate these to sum to $204 million US for a single upgrade of the embankment in each polder, or $621 million USD for three in each.

Sensitivity to the number of Monte-Carlo simulations, optimisation results, and optimisation epsilon values (which influence the precision considered to be significant to distinguish between objective function values, Supplementary Figures 8 to 10) are evaluated. Comparing 100, 200 and 500 stochastic iterations during optimisation, it is found that objective function values vary by a similar order of magnitude between optimisation simulations as between different number of stochastic iterations. Given the model run-time constraints, 100 stochastic simulations are adopted for optimisation, noting that the stochastic generation of flood events are found to have limited impact overall on embankment investment decisions. Repeating optimisation runs influence the timing and sequencing of investments, likely to be a combined effect of lack of sensitivity to flood incidence (and hence investments) and convergence of optimisation solutions. Impact on overall crop income loss values are insignificant. Varying epsilon values did not have a significant impact on results.

Evaluation of model performance (described in the Supplementary Information and shown in Supplementary Figure 5) is constrained by the paucity of data and complexity of interactions represented. We acknowledge there is a significant level of uncertainty in the results presented, and emphasize the role of the analysis as providing insights and recommendations for improving systems-thinking in infrastructure modelling and planning. For this analysis, the most significant implication of uncertainty in system conceptualisation, representation, and input data is where any of the drivers of crop loss play a greater impact than shown here. In addition, we recognise there are both drivers and impacts not represented – such as changing land use, crop disease, access to employment, access to financial support such as loans and subsidies, or impacts to lives or property resulting from floods and storms.

We use R to generate Figure 3 and 4 using the libraries ggplot2, reshape, ggpubr, and egg.

Data Availability

The data generated for this study are available within the paper and Supplementary Information. Data analysed from third party sources are available, but restrictions may apply to the availability of some of these data which were accessed under specific agreements associated with the current study.

Code Availability

Code used to undertake our analysis can be found at https://github.com/EmilyWaterModelling/CoastalRisk

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Author contributions

EJB & JWH designed the study. EJB and JWH conducted most of the analysis, with input from MSGA. EJB wrote most of the manuscript, with input from all authors who helped shape the overall narrative, contributed text, provided references, and produced or contributed to figures.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information is available for this paper.

Figure Captions

Figure 1. Variation in elevation, poverty, and salinity across six case study polders in Bangladesh's coastal zone. The percent poverty shown is based on the 'upper poverty level', defined as those who are moderately poor using 2010 Bangladesh Poverty Maps[29]. Elevation is derived from digital elevation data[30], whilst soil salinity is estimated using observed data from 2009[31]. Spatial boundaries were provided by WARPO[32]. The base map was created using ArcGIS software by Esri. ArcGIS and ArcMap^{TM} are the intellectual property rights of Esri and are used herein under licence. Copyright © Esri. All rights reserved. Source: Esri, Garmin, GEBCO, NOAA NGDC, and other contributors.

Figure 2. Interacting flood hazard, vulnerability, and infrastructure interventions influence the distribution of climate impacts. We consider variations in flood risk, erosion, salinity, waterlogging, elevation, and cropping patterns across different polders, simulating impacts on different farm

holding types representing different socio-economic groups (adapted from Figure 1 in Borgomeo et al, 2018 with permission from Taylor & Francis Ltd).

Figure 3. A typical simulation of future climate hazards and impacts on crop production for six different polders assuming no embankment rehabilitation investment. Modelled variations in flood magnitude calibrated to observed events (a) are used in combination with spatial variations in elevation and embankment condition (b) to estimate the agricultural area flooded within polders (c). Flooding combined with modelled soil salinity (d) and waterlogging (e) are used to estimate crop production, shown as a fraction of the maximum potential production (f). Both salinity and waterlogging are scaled to a range of 0 to 1, where 1 represents total crop loss. Shown here is a single simulated future time series from the ensemble of 1000 stochastic model runs, which are used to estimate future risk and associated uncertainties. P29, P30, P32, P33, P43/1 and P54 are the six different polders analysed in this study (see Figure 1 for locations).

Figure 4. Differences in average crop income loss between socio-economic groups across scenarios and polders. Expected yearly crop income loss across 1000 stochastic simulations differs significantly between subsistence and small to large farm holdings in aggregate (results for small to large holdings are largely identical), as well as across polders. The role of different drivers of income loss (flood, salinity and waterlogging) as well as the effectiveness of interventions varies across both polders and socio-economic groups. Spatial boundaries were provided by WARPO[32].

Figure 5. Spatial variations in the effectiveness of embankment investment and removing waterlogging and salinity on crop income. Crop income is the area averaged income (USD/ha), averaged over the 60-year simulation period and 1,000 stochastic simulations. Left to right: no investment; embankment investment; embankment investment with no waterlogging or salinity. Spatial boundaries were provided by WARPO[32].

References

1 Mora, C. *et al.* Broad threat to humanity from cumulative climate hazards intensified by greenhouse gas emissions. *Nature Climate Change* **8**, 1062-1071, doi:10.1038/s41558-018-0315-6 (2018).

2 AghaKouchak, A. *et al.* How do natural hazards cascade to cause disasters? *Nature* **561**, 458-460, doi:10.1038/d41586-018-06783-6 (2018).

3 Brammer, H. Agriculture and Food Production in Polder Areas. *Water International* **8**, 74-81, doi:10.1080/02508068308686011 (1983).

4 *Flood Action Plan 4 (FAP 4). Southwest Area Water Resources Management Project, Final Report* (People's Republic of Bangladesh, Ministry of Irrigation, Water Development and Flood Control, 1993).

5 Afroz, S., Cramb, R. & Grünbühel, C. Exclusion and Counter-exclusion: The Struggle over Shrimp Farming in a Coastal Village in Bangladesh. *Development and Change* **48**, 692-720, doi:10.1111/dech.12310 (2017).

6 Adnan, S. in *Water, Sovereignty and Borders: Fresh and Salt in Asia and Oceania* (eds D. Ghosh, H. Goodall, & S.H. Donald) 104-124 (Routledge, 2009).

7 Paprocki, K. & Cons, J. Life in a shrimp zone: aqua- and other cultures of Bangladesh's coastal landscape. *The Journal of Peasant Studies* **41**, 1109-1130, doi:10.1080/03066150.2014.937709 (2014).

8 Nowreen, S., Jalal, M. R. & Shah Alam Khan, M. Historical analysis of rationalizing South West coastal polders of Bangladesh. *Water Policy* **16**, 264-279, doi:10.2166/wp.2013.172 (2013).

9 Swapan, M. S. H. & Gavin, M. A desert in the delta: Participatory assessment of changing livelihoods induced by commercial shrimp farming in Southwest Bangladesh. *Ocean & Coastal Management* **54**, 45-54, doi:https://doi.org/10.1016/j.ocecoaman.2010.10.011 (2011).

10 Grey, D. & Sadoff, C. W. Sink or Swim? Water security for growth and development. *Water Policy* **9**, 545-571, doi:10.2166/wp.2007.021 (2007).

11 Dadson, S. *et al.* Water security, risk, and economic growth: Insights from a dynamical systems model. *Water Resources Research* **53**, 6425-6438, doi:10.1002/2017wr020640 (2017).

12 Hall, J. W. *et al.* Coping with the curse of freshwater variability. *Science* **346**, 429-430, doi:10.1126/science.1257890 (2014).

13 Di Baldassarre, G. *et al.* Water shortages worsened by reservoir effects. *Nature Sustainability* **1**, 617-622, doi:10.1038/s41893-018-0159-0 (2018).

14 Palmer, M. A., Liu, J., Matthews, J. H., Mumba, M. & D'Odorico, P. Manage water in a green way. *Science* **349**, 584-585, doi:10.1126/science.aac7778 (2015).

15 Tortajada, C. Water infrastructure as an essential element for human development. *International Journal of Water Resources Development* **30**, 8-19, doi:10.1080/07900627.2014.888636 (2014).

16 Zeitoun, M. *et al.* Reductionist and integrative research approaches to complex water security policy challenges. *Global Environmental Change* **39**, 143-154, doi:https://doi.org/10.1016/j.gloenvcha.2016.04.010 (2016).

17 Howe, C. *et al.* Paradoxical Infrastructures:Ruins, Retrofit, and Risk. *Science, Technology, & Human Values* **41**, 547-565, doi:10.1177/0162243915620017 (2016).

18 Gleick, P. H. Global Freshwater Resources: Soft-Path Solutions for the 21st Century. *Science* **302**, 1524-1528, doi:10.1126/science.1089967 (2003).

19 Eriksen, S. *et al.* Adaptation interventions and their effect on vulnerability in developing countries: Help, hindrance or irrelevance? *World Development* **141**, 105383, doi:https://doi.org/10.1016/j.worlddev.2020.105383 (2021).

20 Anand, N., Gupta, A. & Appel, H. e. *The Promise of Infrastructure*. (Duke University Press, 2018).

21 Thacker, S. *et al.* Infrastructure for sustainable development. *Nature Sustainability* **2**, 324-331, doi:10.1038/s41893-019-0256-8 (2019).

22 Poff, N. L. *et al.* Sustainable water management under future uncertainty with eco-engineering decision scaling. *Nature Climate Change* **6**, 25-34, doi:10.1038/nclimate2765 (2016).

23 Winemiller, K. O. *et al.* Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong. *Science* **351**, 128-129, doi:10.1126/science.aac7082 (2016).

24 Loftus, A. Water (in)security: securing the right to water. *The Geographical Journal* **181**, 350-356, doi:10.1111/geoj.12079 (2015).

25 Haasnoot, M. *et al.* Investments under non-stationarity: economic evaluation of adaptation pathways. *Climatic Change*, doi:10.1007/s10584-019-02409-6 (2019).

26 Hino, M. & Hall, J. W. Real Options Analysis of Adaptation to Changing Flood Risk: Structural and Nonstructural Measures. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering* **3**, 04017005, doi:doi:10.1061/AJRUA6.0000905 (2017).

27 Borgomeo, E., Hall, J. W. & Salehin, M. Avoiding the water-poverty trap: insights from a conceptual human-water dynamical model for coastal Bangladesh. *International Journal of Water Resources Development* **34**, 900-922, doi:10.1080/07900627.2017.1331842 (2018).

28 Verschuur, J., Koks, E. E., Haque, A. & Hall, J. W. Prioritising resilience policies to reduce welfare losses from natural disasters: A case study for coastal Bangladesh. *Global Environmental Change* **65**, 102179, doi:https://doi.org/10.1016/j.gloenvcha.2020.102179 (2020).

29 *Bangladesh Poverty Maps (Zila Upazila)* (The World Bank, Bangladesh Bureau of Statistics, and World Food Programme, 2010).

30 Farr, T. G. *et al.* The Shuttle Radar Topography Mission. *Reviews of Geophysics* **45**, doi:10.1029/2005rg000183 (2007).

31 *Saline Soils of Bangladesh* (Soil Resource Development Institute, SRMAF Project, Ministry of Agriculture, 2010).

32 *National Water Resources Database (NWRD)* (Bangladesh Water Resources Planning Organization, 2018).

33 Lázár, A. N. *et al.* Agricultural livelihoods in coastal Bangladesh under climate and environmental change – a model framework. *Environmental Science: Processes & Impacts* **17**, 1018-1031, doi:10.1039/C4EM00600C (2015).

34 Paprocki, K. Threatening Dystopias: Development and Adaptation Regimes in Bangladesh. *Annals of the American Association of Geographers* **108**, 955-973, doi:10.1080/24694452.2017.1406330 (2018).

35 *Yearbook of Agricultural Statistics-2016* (Bangladesh Bureau of Statistics, Statistics and Information Division, Ministry of Planning, Government of the People's Republic of Bangladesh, 2017).

36 Uddin, M. S., Rahman, M. M., Sarkar, M. & Khan, M. B. U. Scoping Visit: Polder 29, 30, 32, 33, 35/3. Draft Report (Unpublished). (2016).

37 Haque, A., Kay, S. & Nicholls, R. J. in *Ecosystem Services for Well-Being in Deltas: Integrated Assessment for Policy Analysis* (eds Robert J. Nicholls *et al.*) 293-314 (Springer International Publishing, 2018).

38 Adnan, M. S. G., Haque, A. & Hall, J. W. Have coastal embankments reduced flooding in Bangladesh? *Science of The Total Environment* **682**, 405-416, doi:https://doi.org/10.1016/j.scitotenv.2019.05.048 (2019).

39 *Erosion data for coastal Bangladesh* (DEltas, vulnerability and Climate Change: Migration and Adaptation (DECCMA), 2017).

40 *Census of Agriculture 2008* (Bangladesh Bureau of Statistics, Planning Division, Ministry of Planning, Government of the People's Republic of Bangladesh, 2011).41 Dasgupta, S., Hossain, M. M., Huq, M. & Wheeler, D. Climate change and soil salinity: The case of coastal Bangladesh. *Ambio* **44**, 815-826, doi:10.1007/s13280-015-0681-5 (2015).

42 Salehin, M. *et al.* in *Ecosystem Services for Well-Being in Deltas: Integrated Assessment for Policy Analysis* (eds Robert J. Nicholls *et al.*) 333-347 (Springer International Publishing, 2018).

43 Rabbani, G., Rahman, A. & Mainuddin, K. Salinity-induced loss and damage to farming households in coastal Bangladesh. *International Journal of Global Warming* **5**, 400-415, doi:10.1504/ijgw.2013.057284 (2013).

44 Alam, M. S., Sasaki, N. & Datta, A. Waterlogging, crop damage and adaptation interventions in the coastal region of Bangladesh: A perception analysis of local people. *Environmental Development* **23**, 22-32, doi:https://doi.org/10.1016/j.envdev.2017.02.009 (2017).

45 *Poverty in Bangladesh: Building on Progress* (World Bank and Asian Development Bank, 2002).

46 Hall, J. W., Brown, S., Nicholls, R. J., Pidgeon, N. F. & Watson, R. T. Proportionate adaptation. *Nature Climate Change* **2**, 833-834, doi:10.1038/nclimate1749 (2012).

47 *Development Project Proforma/Proposal (DPP) for Blue Gold Program (BWDB Component)* (Government of the People's Republic of Bangladesh, Ministry of Water Resources, Bangladesh Water Development Board, 2013).

48 del Ninno, C., Dorosh, P., Smith, L. & Roy, D. The 1998 Floods in Bangladesh Disaster Impacts, Household Coping Strategies, and Response. *Research Report of the International Food Policy Research Institute*, 1-114 (2001).

49 van Staveren, M. F., Warner, J. F. & Shah Alam Khan, M. Bringing in the tides. From closing down to opening up delta polders via Tidal River Management in the southwest delta of Bangladesh. *Water Policy* **19**, 147-164, doi:10.2166/wp.2016.029 (2016).

50 Adnan, M. S. G., Talchabhadel, R., Nakagawa, H. & Hall, J. W. The potential of Tidal River Management for flood alleviation in South Western Bangladesh. *Science of The Total Environment* **731**, 138747, doi:https://doi.org/10.1016/j.scitotenv.2020.138747 (2020).

51 Auerbach, L. W. *et al.* Flood risk of natural and embanked landscapes on the Ganges–Brahmaputra tidal delta plain. *Nature Climate Change* **5**, 153-157, doi:10.1038/nclimate2472 (2015).

52 *Bangladesh Delta Plan 2100 – Draft* (Government of the People's Republic of Bangladesh, 2017).

53 Brouwer, R., Akter, S., Brander, L. & Haque, E. Socioeconomic Vulnerability and Adaptation to Environmental Risk: A Case Study of Climate Change and Flooding in Bangladesh. *Risk Analysis* **27**, 313-326, doi:10.1111/j.1539-6924.2007.00884.x (2007).

54 *Bangladesh Vision 2021* (Centre for Policy Dialogue, 2007).

55 *Project Information Document (PID) Appraisal Stage: Coastal Embankment Improvement Project - Phase 1 (CEIP-1)* (The World Bank, 2013).

56 Hallegatte, S., Vogt-Schilb, A., Bangalore, M. & Rozenberg, J. Unbreakable: Building the Resilience of the Poor in the Face of Natural Disasters. (World Bank, Washington, DC, 2017).

57 Di Baldassarre, G. *et al.* Sociohydrology: Scientific Challenges in Addressing the Sustainable Development Goals. *Water Resources Research* **55**, 6327-6355, doi:10.1029/2018wr023901 (2019).

58 Nicholls, R. J. *et al.* Integrated assessment of social and environmental sustainability dynamics in the Ganges-Brahmaputra-Meghna delta, Bangladesh. *Estuarine, Coastal and Shelf Science* **183**, 370-381, doi:https://doi.org/10.1016/j.ecss.2016.08.017 (2016).

59 Payo, A. *et al.* Modeling daily soil salinity dynamics in response to agricultural and environmental changes in coastal Bangladesh. *Earth's Future* **5**, 495-514, doi:10.1002/2016ef000530 (2017).

60 Brown, S. & Nicholls, R. J. Subsidence and human influences in mega deltas: The case of the Ganges–Brahmaputra–Meghna. *Science of The Total Environment* **527-528**, 362-374, doi:https://doi.org/10.1016/j.scitotenv.2015.04.124 (2015).