Integrated Assessment for the Bangladesh Delta Plan 2100

Analysis of selected interventions

Edited by:
Md. Munsur Rahman, Robert J. Nicholls, Susan E. Hanson, Mashfiqus Salehin, Shamsul Alam

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First published 2019

This book is part of ESPA Deltas Extension project and published by BUET-Southampton University-GED, Planning Commission, People's Republic of Bangladesh

This book carried out under the Extension of An assessment of the ecosystem service and livelihood implications of government development proposals in coastal Bangladesh' which, in turn, builds on a major project carried out in the coastal zone funded under the 'ESPA Deltas (Assessing Health, Livelihoods, Ecosystem Services and Poverty Alleviation in Populous Deltas)' NE-J002755-1. Project was carried out under the 'Ecosystem Services for Poverty Alleviation (ESPA)' programme funded by the UK's Department for International Development (DFID), the Economic and Social Research Council (ESRC) and the Natural Environment Research Council (NERC). The views expressed in this work are those of the authors and do not necessarily represent those of DFID, ESRC and NERC or its Board of Governance.

ISBN: 978-984-34-7513-8

Cover photo credit: Rayhanur Rahman, Research Associate, DECCMA project, Institute of Water and Flood Management, Bangladesh University of Engineering and Technology Dhaka, Bangladesh.

Design & Printed by :
turtle
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EXECUTIVE SUMMARY

The Ganges-Brahmaputra-Meghna delta covers most of Bangladesh and parts of West Bengal in India and has a population exceeding 100 million. The ESPA Deltas study area considered the seaward part of the delta in Bangladesh, south of Khulna and west of the Meghna River to the Indian border. This is a densely populated and fertile region where poverty is still significant and widespread. Rural livelihoods are inextricably linked with agriculture, fisheries and the natural ecosystems, which are exposed to long-term environmental changes including rising salinity, subsidence, sea-level rise and storm surges.

The ESPA Deltas project (www.espadeltas.net) undertook an ambitious, interdisciplinary study of coastal Bangladesh and the lives of the millions of people who benefit from them. Many of the project's findings are integrated into the Delta Dynamic Integrated Emulator Model (ΔDIEM), which is designed to analyse the present and future of the delta in a policy relevant way. It was recognised at a workshop in Dhaka in October 2016 that the ΔDIEM offered a useful tool to assess proposals within the Bangladesh Delta Plan 2100 (BDP 2100) in terms of their effects on ecosystems services and livelihoods. Hence, a pilot application of ΔDIEM was trialed based on selected proposals in the BDP 2100. The ESPA Deltas team worked with the Bangladesh Planning Commission of the Government of Bangladesh to use ΔDIEM to assess selected development options being considered as part of the BDP 2100. These options include the role of embankment maintenance, a new green belt 'buffer' zone along the coast, a strengthened coastal sea wall, and new polders in the south central region to promote agriculture.

Of these projects, the new polders in the south central district appear most beneficial both in terms of enhancing incomes and removing people from poverty. However, trade-offs with neighbouring regions due to displaced flooding need to be evaluated and suitable compensatory measures undertaken. The results also show that good maintenance of the existing polder embankments across the region is likely to maintain agriculture and associated livelihoods over the next few decades. The greenbelt and enhanced sea wall have less benefit over the next few decades, although they reduce the likelihood of embankment breaching during cyclones which is an important concern in this region.

This pilot project demonstrates how integrated assessment models of socio-ecological systems such as ΔDIEM can complement traditional project appraisal tools. They provide robust analysis to inform policy aiming to meet a range of development targets such as the Sustainable Development Goals (SDGs), and to inform long-term and complex policymaking initiatives such as the BDP 2100. Further development of tools such as ΔDIEM is recommended, with this needing to occur in the context of the national priorities.

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Foreword

I am pleased to write the foreword to this book ‘Integrated Assessment for the Bangladesh Delta Plan 2100’ prepared by a cross-national team of UK and Bangladeshi scientists and policy makers. Bangladesh is predominantly a flood plain country where water is key to maintaining both societies and ecosystems. Development and alleviation of poverty initiatives must take account of this and needs to be done in a way that is appropriate. To this end the Government of the People’s Republic of Bangladesh adopted the Bangladesh Delta Plan 2100 (BDP 2100) to plan the development of the country to achieve national goals in a way that is sensitive to the environment and robust to climate change and other challenges.

I had the pleasure of leading the preparation of the BDP 2100 over more than four years. During this time, I became aware of the ESPA Deltas project which had research objectives highly supportive of the BDP aims. As a result, we started to work together and the Planning Commission held many workshops with the ESPA Deltas team, to our mutual benefit. In particular, the ESPA Deltas team were developing and trialling tools and approaches, notably the Delta Dynamic Integrated Emulator Model (ΔDIEM), which were of strong interest to us. We were therefore very pleased that the ESPA Directorate funded a project to apply ΔDIEM to assess selected interventions within BDP 2100.

This book describes the outcome of this project and demonstrates the benefits of these two efforts being linked together: the ESPA Deltas project directly informing the Bangladesh Delta Plan 2100 and vice versa. The analysis indicates important trade-offs for these projects which need to be considered. More importantly, it shows the benefits of an integrated approach which the Planning Commission would like to take forward in the future. I would like to thank all the contributors for the efforts towards the sustainable development of Bangladesh.

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Preface

This book builds on and applies research on integrated assessment methods describing ecosystem services and rural livelihoods in coastal Bangladesh. This is based on research conducted since 2010, funded by the Ecosystem Services for Poverty Alleviation (ESPA) interdisciplinary research programme as the ESPA Deltas project. The integrated approach of the ESPA Deltas project, summarised in Figure (i) and documented in Nicholls et al. (2016, 2018), enabled bio-physical and socio-economic changes to be considered and analysed within the governance context including future scenarios.

The aim of the ESPA Deltas research was always development focussed with an emphasis on working with national government to inform high-level decision-making, i.e. link science to policy, at the landscape scale (ESPA, 2018a). In this regard, the Delta Dynamic Integrated Emulator Model (ΔDIEM), which links ecosystem services to rural livelihoods across coastal Bangladesh today and into the future, was developed.

The ESPA Deltas project and ΔDIEM model were developed as the Bangladesh Delta Plan 2100 was being prepared by the General Economic Division (GED) of the Bangladesh Planning Commission of the Government of the People's Republic of Bangladesh. The strong synergies between these two activities led to a close and fruitful cooperation. GED hosted a number of joint workshops which greatly supported the participatory development of ΔDIEM and showed its potential to inform national planning.

Following a joint national level workshop between BDP 2100 (GED) and ESPA Deltas in 30-31 October 2016, GED expressed interest in ΔDIEM being trialled to assess a small number of relevant interventions proposed in the BDP 2100. With additional funding from the ESPA programme, this research was made possible from April 2017 to March 2018. This book aims to present the assessment of four proposed management interventions within the delta and examine the utility of the approach for wider development planning in coastal Bangladesh in the context of the BDP 2100 and related planning initiatives (ESPA, 2018b).

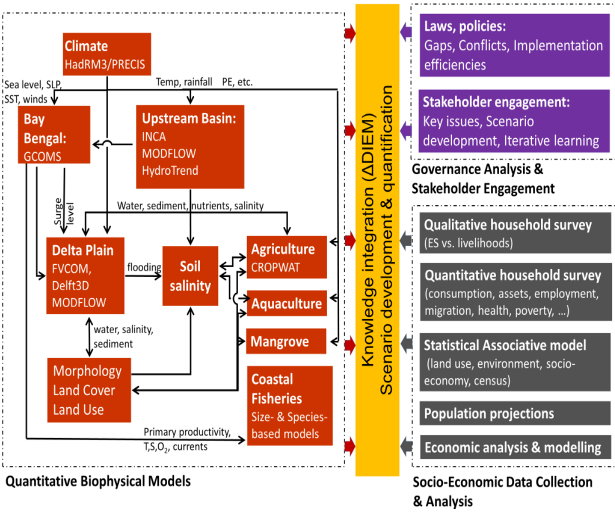

Figure (i) Components of the integrated approach used in the ESPA Deltas analysis (reprinted with permission from Nicholls et al., 2016)

Acknowledgements

The research detailed here was carried out under the 'An assessment of the ecosystem service and livelihood implications of government development proposals in coastal Bangladesh' project ROF-2017-18-01 which, in turn, builds on a major project carried out in the coastal zone of the Ganges-Brahmaputra-Meghna Delta funded under the 'ESPA Deltas (Assessing Health, Livelihoods, Ecosystem Services and Poverty Alleviation in Populous Deltas)' NE-J002755-1. Both projects were carried out under the 'Ecosystem Services for Poverty Alleviation (ESPA)' programme funded by the UK's Department for International Development (DFID), the Economic and Social Research Council (ESRC) and the Natural Environment Research Council (NERC). Publication was made possible with support from the ESRC Impact Acceleration Fund.

The authors would also like to acknowledge project and research colleagues, too numerous to mention by name, who made valuable contributions to the results discussed here and whose work is cited throughout.

Glossary

Embankment	barrier constructed to protect low lying land that, when they encircle areas, create polders
Polder	a tract of low-lying land which is hydrologically isolated from the main river system by embankments which offer protection against tidal and river floods, salinity intrusion and sedimentation and allow internal water level regulation
Coastal sea wall	an embankment specifically designed to protect against storm surge waves and anticipated sea-level rise. Can also be referred to as 'sea dyke'.
Hotspot	a board group of districts and areas facing similar risks evolved by hydrology, climate change and natural hazards

Contents

1 Introduction

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1.1 Bangladesh in the twenty-first century

Bangladesh (see Figure 1) is a country in transition with many opportunities, but also many challenges, to its future development. With a population exceeding 165 million (2018), it has been identified as one of the countries where further growth and engagement with globalisation offers the potential to develop a thriving economy (O'Neill, 2011). Since its independence in 1971, successive governments have made efforts to improve basic standards of living in the country; significant achievements in food security, infant mortality rates and standards of education have been made (GED, 2017d; Mainali et al., 2018). However, rapid economic development, urbanisation and the demographic transition combined with the physical setting of a delta means that development will continue to face challenges into the future. These are often related to the functioning of the delta system and the ecosystem services it provides.

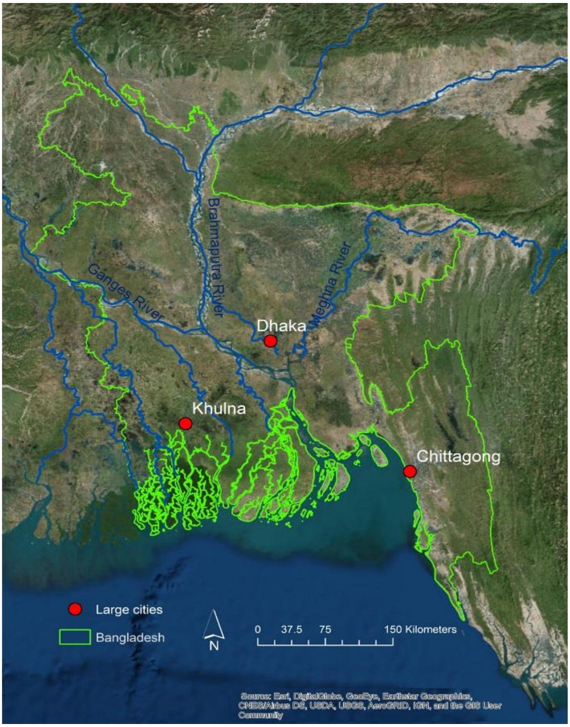

Figure 1 Satellite image of Bangladesh showing the location of major cities and rivers (World Imagery Data)

The coastal zone (see Figure 2) in particular faces intense environmental and development or anthropogenic pressures over the coming decades. The region's dense population, many of whom experience asset poverty (see Amoako Johnson and Hutton, 2018), face challenges which may be unprecedented in their scale and complexity (GED, 2017b). The coastal zone already experiences flooding, salinisation, river bank erosion, water-logging and cyclones, which the progressive nature of subsidence, climate change and sea-level rise will further exacerbate during the twenty-first century. Importantly, smallholder farmers, who are the foundation of Bangladesh's food self-sufficiency, face uncertainty as the cumulative effect of these processes can negatively affect their livelihoods. Developing a coastal zone that is resilient to future change is a long-term challenge.

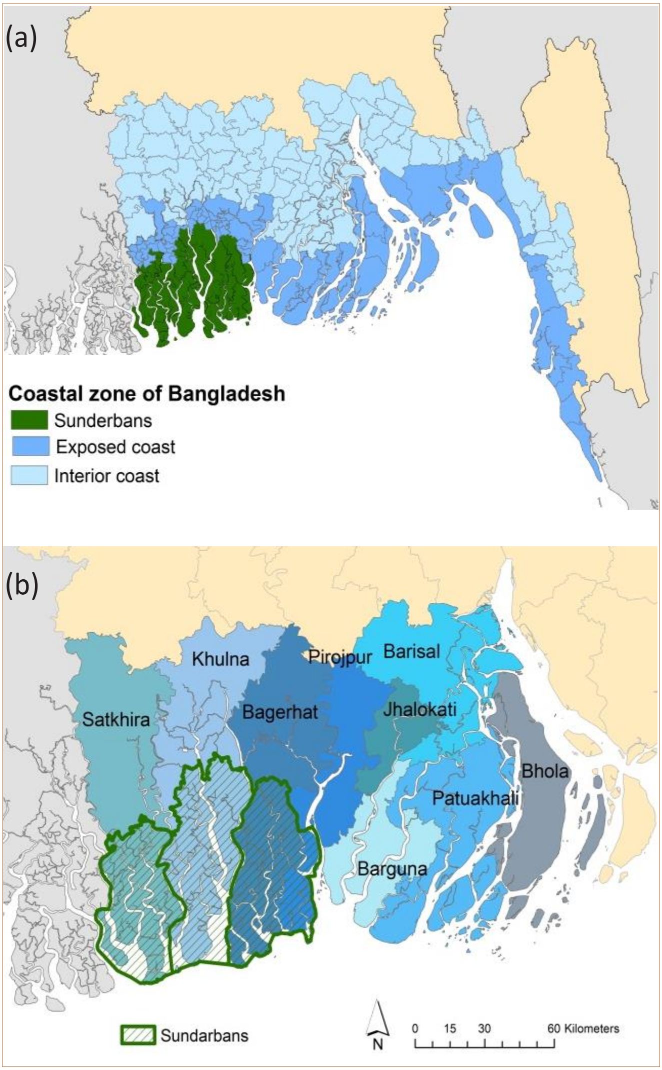

Figure 2 (a) Map of coastal Bangladesh showing the exposed and interior coastal zone and the Bangladesh Sundarbans and (b) the nine districts of the study area considered in this analysis

1.2 The Bangladesh policy environment

Food security has been and remains an important policy objective for Bangladesh. In addition, the national ambition is to transform to an upper-middle income country and eradicate extreme poverty by 2030. The Government of the People's Republic of Bangladesh has followed a planning approach which includes a series of five year plans which provide short- to mid-term strategies for health, economy, disaster management and food security. Alongside these national development goals, Bangladesh is also committed to achieve the Sustainable Development Goals (SDGs) (GED, 2017c). Meeting all 17 SDGs presents challenges as there are implicit trade-offs between the individual goals (Hutton et al., 2018). Within current parameters, SDGs such as ending hunger (Goal 2), expanding education programmes (Goal 4), and ensuring availability of water (Goal 6) are seen as dependent on sustained economic growth (Goal 8). However, economic growth does not automatically address Goal 10: "reduce inequality within and between countries". Consideration of equity and distributional effects in development is important but often not considered in detail which is a striking contrast to the headline GDP growth projections. Further there may be trade-offs between economic growth and sustaining the terrestrial and aquatic environments. It is crucial therefore that development planning and project evaluation takes a systems perspective, analysing the full spectrum of costs, benefits and trade-offs associated with different development choices and pathways.

In addition, Bangladesh has now developed its first long-term plan of action to achieve its development goals in the context of adapting to intensifying climate change. The Bangladesh Delta Plan 2100 (BDP 2100, 2018) is distinct in its long-term vision to shape the nation of Bangladesh in a co-ordinated manner over the next 80 years (e.g. GED, 2017a). This has been informed by experience in other deltas (e.g. Seijger et al., 2016), but the BDP 2100 considers one of the longest time horizons and largest spatial scales in the history of development planning. Linking such planning to the range of scientific understanding is a major challenge.

1.3 Addressing the science-policy interface

Decision makers often face difficult choices on policy development and investment choices. In addition to the environmental and socio-economic pressures, the number of commitments that each country is asked to address is increasing, including for example the Paris Agreement (United Nations, 2015) and the Sustainable Development Goals (United Nations, 2017). This leaves decision makers with a difficult task of not only balancing resources with immediate needs, but also negotiating between competing interests (e.g. economic growth versus environmental pollution). Making such choices on interventions requires a thorough understanding of benefits and dis-benefits or winners and losers, to avoid unintended negative consequences or plan compensatory measures. Such trade-offs are present in most decisions and integrated assessment frameworks and tools can support this type of analysis to enable well-informed decisions.

Integrated assessment has been applied to various issues such as acid rain (Hordijk, 1991; Hordijk and Kroeze, 1997), air quality (Schöpp et al., 1998) and climate change impacts on multiple sectors such as agriculture and the environment (e.g. Harrison et al., 2016). The integrated assessment approach has also been applied within the ESPA Deltas Project to assess and quantify ecosystem services and livelihoods in coastal Bangladesh, an area with a current population of about 14 million people (Nicholls et al., 2016; 2018). To make wise and evidence-based decisions within the context of the BDP 2100, the ESPA Deltas approach is being used to investigate the impacts of several proposed interventions Ganges-Brahmaputra-Meghna (GBM) Delta.

1.4 Why the need for an integrated and participatory approach?

Deltas are coupled systems and changes in one aspect (e.g. freshwater input) may have a cascade of impacts across the delta; this will include changes to both the natural system and livelihoods. For example, decreased freshwater input in the dry season may promote salinisation which supresses dry season agriculture which, in turn, lowers the income of farmers. It may even accelerate land use changes such as conversion from rice paddy to brackish shrimp aquaculture. To capture this complexity, natural and social scientists, policy analysts and engineers as well as those affected by any decision need to be blended into a multi-disciplinary team. This multi-expertise participation promotes a more rounded understanding of the delta, which can be elaborated and developed into firstly a conceptual model framework followed by a quantified model (see Chapter 4).

Designing the participatory approach in this way helps to enable the model team to understand the key issues and consider varying opinions and views. Repeated engagement with decision-makers and local residents ultimately promotes understanding and then acceptance of research outputs. It also ensures the analysis is relevant and addresses appropriate challenges. In this analysis, an iterative learning loop approach was utilised, involving repeated stakeholder discussions separated by analysis, model development and model application (Figure 3).

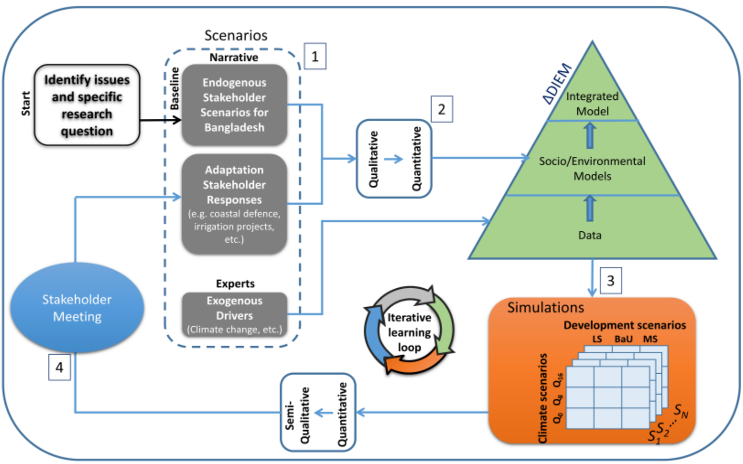

Figure 3 : The participatory approach followed in the development of ΔDIEM (reprinted with permission from Nicholls et al., 2016)

1.5 Structure of the book

Following this introduction, Chapter 2 considers the Bangladesh Delta Plan 2100 and the selection of the intervention proposals that are assessed in this book. Chapter 3 examines the future inundation in coastal Bangladesh with and without the interventions using the Delft3D modelling tool. Chapter 4 explains the integration assessment methodology used within ΔDIEM and Chapter 5 applies this model to explore the effects of the interventions on agriculture and poverty. Chapter 6 concludes the book and considers the implications of the results in the light of the BDP 2100 aims and potential future use of the integrated model. Figure 4 graphically indicates this structure.

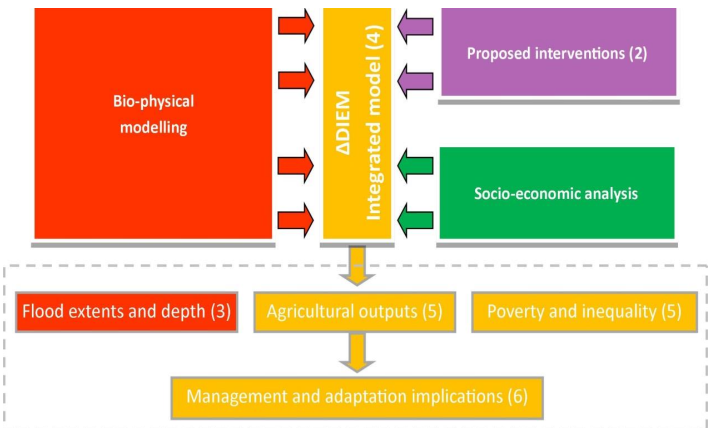

Figure 4 : Aspects of integrated analysis and selected outputs discussed in this report. Numbers correspond to the relevant chapters

2 The Bangladesh Delta Plan 2100 and intervention proposals assessed

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2.1 Background to the BDP 2100

The formulation of the Bangladesh Delta Plan 2100 (GED, 2017a) arose from the need to address a range of unique long-term challenges for development outcomes and represents a significant undertaking by General Economics Division (GED), Bangladesh Planning Commission in its ambition to protect Bangladesh's population and eradicate extreme poverty. The Government of Bangladesh also aims to avoid the consequences of some development approaches in the past that have led to ecological degradation and growing wealth inequality. Consequently, a long-term vision, looking 30 to 80 years ahead, has been developed. The Bangladesh Delta Plan 2100 (BDP 2100, 2018) is a "long-term, holistic plan for water resources management in Bangladesh". Key aspects of the plan include the outlining of a delta vision and scenarios and the selection of delta strategies. GED took a number of years to develop the holistic and integrated plan which was formally approved in 2018.

2.2 Aims of the BDP 2100

The aims of the BDP 2100 are eliminating extreme poverty by 2030, achieving upper middleincome status by 2030 and continue being a prosperous country beyond 2040. More specific goals of the BDP 2100 include ensuring safety from floods and climate change related disasters, enhancing water security and efficiency of water usages, ensuring sustainable and integrated river systems and estuaries management, conserving and preserving wetlands and ecosystems and promote their wise use, developing effective institutions and equitable governance for in-country and trans-boundary water resources management and achieving optimal and integrated use of land and water resources. BDP 2100 looks at the mid-term delta agenda until 2050, but keeps in consideration its longer-term implications to 2100. The long term goals for achieving sustainable development are based on climate-sensitive management. Both the short- and medium-term goals of this plan, associated policies, strategies and investments concentrate on adaptation.

2.3 Overview of BDP 2100 management strategies

BDP 2100 focuses on developing management strategies with a long-term perspective which aims to reduce risk whilst not negating any development opportunities. This aim underlies any short or medium strategies, recognising that these decisions will have implications in the long term for future development and the well-being of the delta's population. Both the national level (example: flood risk, fresh water supply) as well as hotspot specific strategies (example: rivers/estuaries, drought prone area, flash flood area, hilly area, urban area and coastal zone) have been addressed in the BDP 2100. The Coastal Zone of Bangladesh will remain hazardous for coastal floods for the foreseeable future. Cyclones and accompanying storm-surges will continue to develop in the Bay of Bengal, as well as high river discharges and precipitation during the monsoon placing an enormous pressure on the drainage capacity of the coastal delta. In addition, possible future changes in discharge regimes, sea-level rise or subsidence, the coastal zone will be under increasing pressure from socio-economic changes, with economic development and demographic changes as main drivers. With this backdrop, management sub-strategies for coastal areas include the effective management of existing polders, as well as new polders to safeguard people and assets through reducing risks generated by storm surge/salinity, increasing drainage capacity, reclaiming new land and conservation of the Sundarbans. Considering both time and resource constraints, this demonstrative piece of work is therefore focussed to towards flood risk (FR) management in coastal areas.

2.4 Description/selection of interventions to be analysed and their relationship to BDP aims

The interventions selected for analysis using the ESPA Deltas approach and Delta Dynamic Integrated Emulator Model (ΔDIEM) (see Chapter 4) fit within: (i) sub strategy FR 1:1 Develop and improve embankments, barriers and water control structures; and (ii) Sub strategy FR2.2: Restoration, redesign and modification of embankments and structures as illustrated in Table 1.

Table 1 Interventions selected for analysis using the ESPA Deltas integrated approach

	Selected intervention	BDP Management strategy	Rationale for selection
1	Embankment maintenance (baseline conditions)	FR 1:1	As existing embankments are unlikely to be removed, this is used to represent the baseline in the modelling. Various levels of maintenance can be considered
2	Coastal sea wall	FR 2:2	Coastal sea wall is the option of strengthening sea facing embankments to provide defence against sea-level rise, storm surges and wave action
3	Coastal greenbelt	FR 1:1	Greenbelt along coast, representing an afforested areas comprised of unspecified mangrove and terrestrial species, provides a second level of defence against storm surges to the embankments
4	New South Central polders	FR 2.2	To protect the south central region against flooding, especially monsoonal seasonal flooding, and hence enhance agriculture production

2.5 Scenarios for coastal Bangladesh

The scenarios used in the modelling for this study were developed in the ESPA Deltas project (Nicholls et al., 2018). These are presented here and compared to those used in the BDP 2100. The scenarios that were as close as possible to the BDP 2100 were selected and are outlined in Tables 2 and 3. Q8 and Q16 refer to two specific UK Metrological Office climate simulations that were analysed in the ESPA Deltas project for an A1B (high) climate forcing scenario (Ceasar et al., 2015). At the low end, the temperature rise is higher in ESPA than the BDP 2100 reflecting the forcing, but the river discharges are similar, and this is a key variable for coastal Bangladesh.

Project	Changes with 2015	2050	2100
BDP2100	“Extreme water”	2°C	4°C
ESPA	Q16	2.8°C	4.1°C
BDP2100	“Moderate water”	1°C	2°C
ESPA	Q8	2.5°C	3.7°C

Table 2 Comparison of temperature scenarios used in the analysis

Project	Changes with 2015	2050	2100
BDP2100	“Extreme water”	+40%	+70%
ESPA	Q16	+35%	+67%
BDP2100	“Moderate water”	+20%	+30%
ESPA	Q8	+18%	+31%

Table 3 Comparison of Ganges peak discharge scenarios

Following the BDP 2100, no regrets scenarios are considered in these analyses, reflecting significant climate change. Hence, adaptation responses should be sufficient even if the Paris Agreement to limit temperature rise to 2°C or less is successfully achieved.

3 Inundation due to future climate and proposed interventions

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3.1 Introduction

Flooding is a fundamental consideration when assessing the impacts of the proposed interventions described in Chapter 2, both directly and through related changes in the socio-economic life of the area. Flooding is a complex phenomenon in coastal Bangladesh, influenced by the dense channel network, flat, low-lying land, fluvial and coastal processes and existing and planned engineering interventions. To appropriately evaluate the proposed interventions, it is best to analyse and model the coastal hydrodynamics using a detailed physics-based simulation model such as Delft3D. This chapter explains these simulations and analyses them in their own right to provide more insight into the impacts of the interventions within the delta.

Flooding in coastal Bangladesh can be broadly categorised into monsoon flood and storm surge flood (Haque et al., 2018). Monsoon floods occur due to increased fluvial flows from the major rivers (the Ganges, the Brahmaputra and the Meghna) during the period July to September. This high fluvial flow interacts with the tidal regime in the Bay of Bengal, resulting in extensive flooding in the coastal zone. Storm surge flooding usually occurs during pre- and post-monsoon periods (April, May and November) due to tropical cyclones formed over the Bay of Bengal. The two types of flood driver rarely coincide and are considered separately in the Delft3D applications.

The coastal zone in Bangladesh has an existing network of coastal embankments, enclosing low-lying land to create polders, which play an important role in determining the extent and pattern of inundation in the region. Of the national total of 139 polders, 103 are located within the study area and are included in the analysis discussed here (Figure 5).

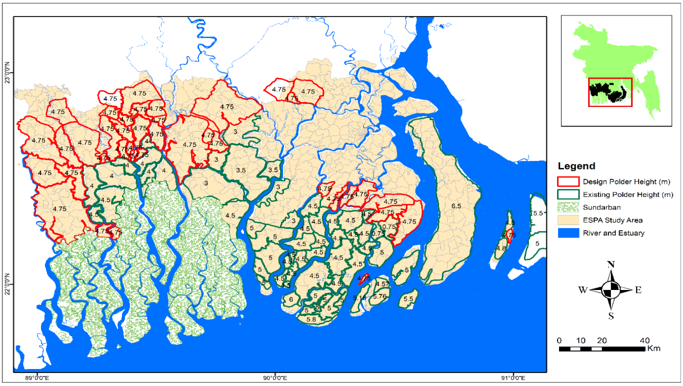


Figure 5 Location of existing polders with known (green) and assumed (red) embankment heights

In this chapter, monsoon and storm surge flood are investigated in relation to the selected interventions (see Table 1, Chapter 2) using process-based flow and storm surge models. These models are component modules of the Delft3D modelling suite (Deltares, 2011; 2014). The model domain, model setup, boundary conditions, model bathymetry and model assumptions are described in Section 3.2, followed by the scenarios considered (Section 3.3) and changes in flooding by intervention (Section 3.4). Two time periods are considered, the 2050s and end of century, coinciding with the end of the ΔDIEM runs and the end of BDP 2100, respectively.

3.2 The Delft3D model

Delft3D is a coastal hydrodynamic model. The model is process-based, and solves physics-based equations (Deltares, 2011; 2014). The calculation time step of Delft3D is ten minutes. Delft3D computes water elevation, water depth, velocity and discharge for the grid points of its study area. This study area (also termed the model domain) includes land, river and sea areas (Figure 6). The model domain is bounded in the north by the major rivers of the system, i.e., the Ganges and the west bank of Lower Meghna, and contains 896,603 grid points. A variable mesh is used with a coarse grid size in the ocean and a finer grid size covering land areas to capture the details of the river/estuary. All the rivers and estuaries of this region with a width greater than or equal to 100m are included in the model.

The upstream flows and sediment fluxes are computed with the INCA and Hydrotrend models (Darby et al., 2015; Whitehead et al., 2015a; 2015b) using an A1B climate scenario (Caesar et al., 2015). The southern boundary of the Delft3D domain is provided by the GCOMS simulation of the Bay of Bengal that provided tidal water levels (Kay et al., 2015). Land topographic input is based on the Digital Elevation Model of the National Database of Water Resources Planning Organization (WARPO), Bangladesh (50m X 50m resolution). Uniform 2.6 mm/year land subsidence is assumed for the poldered areas, whereas no subsidence is assumed for the non-protected areas (i.e. assumed to be compensated by floodplain sedimentation). For the river bathymetry, combinations of secondary (Bangladesh Water Development Board dataset) and primary data (294 locations - measured in the ESPA Deltas project) are used. Ocean bathymetry uses the open access General Bathymetric Chart of the Oceans (GEBCO) dataset. Channel planforms, channel bed level and floodplain levels of rivers/estuaries are assumed to remain constant over the model simulation period.

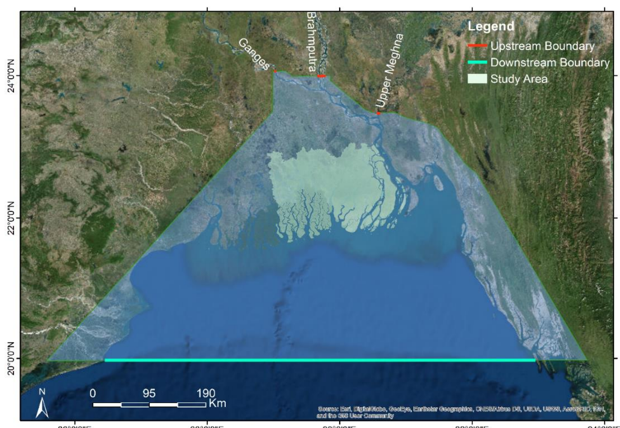


Figure 6 Model domain for Delft3D. Note the upstream boundaries of the Upper Meghna, the Brahmaputra and the Ganges Rivers

Embankment locations and design heights are available from the WARPO national database (Figure 5). Present day observations are only available for 61 polders (some of which are outside the study region). This shows that actual polder heights can considerably vary from 3m to 7m (Dasgupta et al., 2010) Where actual embankment heights are not available, an average design embankment height of 4.75m is used in the model (CEIP, 2013). Only overtopping of the polder embankments is considered, breaching of embankments is not analysed.

Land cover and land use are not directly considered in Delft3D. Instead, surface resistance parameters that describe the ground conditions and effect on flow are incorporated. These parameters are spatially variable and are determined by model calibration.

For the flood model, calibration was carried out for the monsoon flood year 2000 (considered to be an average or typical year) and validation was carried out using a monsoon flood event in 1998 (considered to be an extreme year).

The Pearson correlation coefficient (R2) of the calibration is 0.82 (Haque et al., 2016). For the storm surge model, calibration was carried out using cyclones Sidr (15 November 2007) and Mora (30 May 2017). The data for cyclones (track record, wind speed and pressure) is taken from the Indian Meteorological Department (IMD)[1] . During calibration, publicly available surge depth data (e.g. Shibayama et al., 2008) and an inundation image available from MODIS satellite images were used.

The error percentage of surge depth varies from 0.68% to 7.6% depending on the measurement location with average inundation extent accuracy of about 60% (Haque et al., 2018).

Each Delft3D run covers one calendar year for fluvial flood simulations and 5-8 days for the cyclone simulations under the baseline, mid- and end-century climate scenarios with and without the proposed BDP 2100 interventions.

[1] http://www.rsmcnewdelhi.imd.gov.in

3.3 Representation of baseline conditions and selected interventions in Delft3D

The proposed interventions are (i) coastal sea walls, (ii) coastal greenbelt and (iii) new polders in the south central region (hereafter named as SC polders). Additionally, for baseline comparison, the following conditions for embankments were also modelled within Delft3D; (i) embankments maintained in their existing condition, (ii) enhanced embankment heights, (iii) poorly maintained embankments. This results in a total of seven management options as shown in Table 4. To capture all the combinations, time slices and possible cyclone settings, 104 Delft3D runs were necessary.

Table 4 Baseline conditions and proposed interventions modelled in Delft3D

Baselines	Maintained embankments	existing embankments are maintained at either their actual (varies between 3m to 7m) or design height (4.75m) around each polder (see Figure 5), representing good maintenance
	Enhanced embankments	existing embankment heights (actual and design) are increased by 1m, representing an upgrade in protection standard
	Moderate embankment deterioration	poor maintenance of existing embankments is represented by a decrease in height of 2m modelled for mid and end-century (moderate deterioration)
	Extreme embankment deterioration	poor maintenance of existing embankments is represented by a decrease in embankment height of 3m modelled for mid and end-century (extreme deterioration)
Proposed Interventions	Coastal sea wall	proposed new coastal walls (approximately 870km) are represented as an enhanced embankment height of existing sea-facing embankments. Design and actual heights are increased by 3m height along the exposed coast. The locations of these enhanced embankments (i.e. sea walls) are shown in Figure 7a
	Coastal greenbelt	new afforested greenbelt of mangroves and other species (approximately 490km) along the exposed coast to reduce surge and storm impacts (Figure 7b)
	New polders in the South Central (SC) polders	24 new polders (total new embankment length of 1540km, height 4.75m) are implemented in the south central area where no polders currently exist (see Figure 7c)

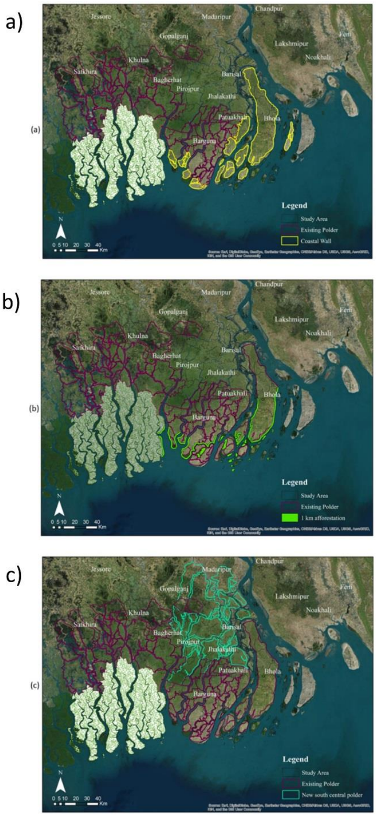


Figure 7 Representation of the proposed interventions in Delft3D. Locations of a) the coastal sea wall, b) the coastal greenbelt and c) new polders in the south central area

For the coastal greenbelt intervention, a maximum 1km wide strip of mixed species (mangrove and terrestrial species) afforestation is introduced seaward of existing embankments (CEGIS, 2016). Afforestation or plantation is represented in the model by a stronger resistance co-efficient which ranges in magnitudes from 0.08 to 0.15 suggested in the literature (Xu et al., 2010; Zhang et al., 2012). In this study, spatially variable resistance co-efficient values from 0.08 to 0.10 are used in Delft3D to represent the mangroves of the Sundarbans and a higher resistance value of 0.10 is used consistently to represent the coastal greenbelt.

3.3.1 Climate, sea level and cyclone scenario combinations

Delft3D is driven by combined climatic and sea-level scenarios (see Table 5). For each of the mid-century and end-century time periods, two climatic conditions (Q8 and Q16) are combined with a high sea-level rise scenario to represent an extreme change case. Monsoon flows increase in both cases due to higher precipitation in the delta catchment with Q16 having the higher flows. As cyclones occur during the dry season, combined cyclone/monsoon flood inundation is not considered. Out of the aforementioned 104 Delft3D model runs, 32 scenarios related to monsoon flooding and 72 scenarios relate to storm surge flooding. From these, twelve selected model outputs are presented here. The full results can be found in Haque et al. (2017).

Table 5 Combination of climatic, sea-level rise and physical interventions used in the Delft3D modelling

Period	Climatic Conditions (see Tables 2 and 3)	Sea-level rise (m)	Cyclone	Management and Interventions
Mid-century	Q16	0.61	with	• Well maintained embankments • Upgraded embankments • Poorly maintained embankments (two variants) • New polders in the south central region • Coastal sea wall • Coastal greenbelt
	Q8		without	
End-century	Q16	1.48	with	
	Q8		without	

3.4 Impacts of the interventions on flooding

3.4.1 Embankment maintenance and upgrade (baseline conditions)

Figure 8 shows the variation in monsoon flooding associated with different embankment maintenance and upgrade regimes and the Q16 climate scenario towards the end of the century. The figure shows that there is little impact on inundation depth and extent if all the embankment heights are maintained or enhanced by 1m. This implies that the existing embankment infrastructure provides sufficient protection against overtopping by fluvial floods even by the end of the century. However, there is significant increase of inundation extent and depth if the embankments are not maintained and their height falls. This indicates that the existing embankments and their maintenance play a pivotal role in the management of fluvial flooding in the coastal zone and should be an integral part of any BDP plan development.

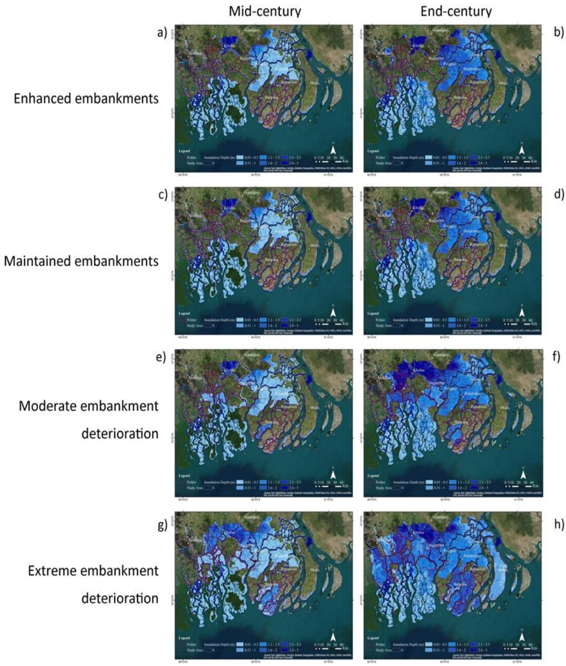


Figure 8 Impacts of embankment maintenance on monsoon flooding. The images show inundation depth and extent of monsoon flood for both mid- and end-century under the Q16 (wetter) climate scenario and high sea level.

A moderate deterioration in height produces little difference when compared to maintained embankments mid-century (2050s), but later in the century, significant areas can become flooded. Moderate deterioration (by the end of the century) and extreme deterioration of the embankments will have particular adverse consequences for some areas in north Khulna and the Unions along the north Tetulia River, west of Bhola Island, as they become increasingly flood prone. Khulna, Bagerhat, Pirojpur, Jhalokati and Barisal are particularly affected, with flood depths of up to 2.5m under the extreme deterioration scenario.

Embankment maintenance can also have significant consequences for the management of flooding associated with cyclonic storm surges (Figure 9). It shows the relative extent of inundation (white circles) in flooding associated with the different standards of maintenance under a warmer and wetter climate (Q16) and high sea-level rise by the end of the century.

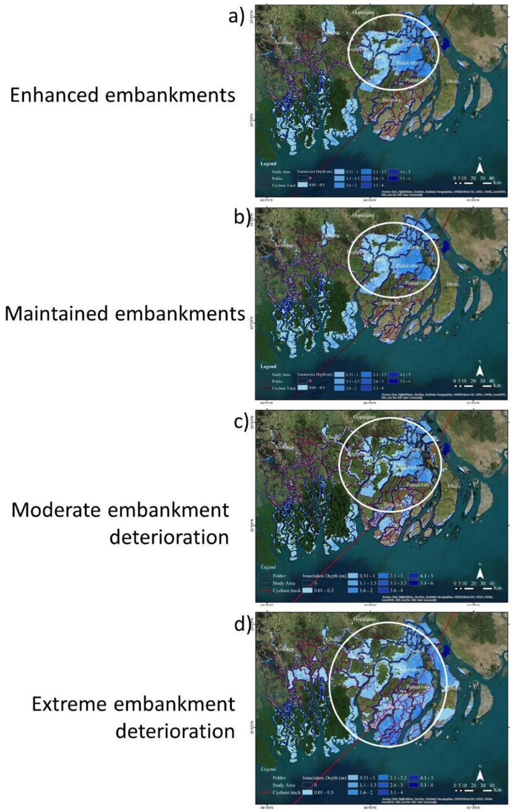


Figure 9 Impacts of embankment maintenance on storm surge flood by the end of the century with a) enhanced embankments, b) maintained embankments, c) moderate embankment deterioration and d) extreme embankment deterioration. The cyclone track is shown by the straight red line.

Maintained or enhanced embankments (Figure 9 a and b) result in the same pattern and depth of flooding under storm surge, with flooding mainly occurring in the south central area where no embankments are present (see Figure 5). However, if embankments are poorly maintained (Figure 9c), a number of embankments are overtopped allowing significant flooding of previously protected areas. Extreme deterioration increases the extent of flooding and depths for Khulna and south Barisal divisions. Bhola Island is also extensively flooded. Unprotected areas experience significant increases in flood depth.

For storm surge flooding, upstream discharge due to climatic change does not play an important role. This reflects that cyclones usually occur during pre- and post- monsoon when there is hardly any change in discharge compared to today. Hence there is a spatially consistent pattern of flooding under Q8 and Q16 for comparable cyclone events climate scenarios with a few local variations (mainly Jhalokati and Barisal) in flood depth and extent. The dominant driver of flooding is the cyclone-induced storm surge.

3.4.2 Coastal sea wall

The proposed 870km coastal sea wall is designed to protect against cyclones and storm surges (see Chapter 2) and is located at the exposed edge of the Barguna, Patuakhali and Bhola districts (see Figure 7). If the existing embankments are maintained or enhanced, the sea wall provides little additional protection against storm surge flooding. Figure 9a suggests that even the existing embankments, when maintained, are sufficient against a Sidr-type cyclone. The main impact of the coastal sea wall can be seen when embankments are poorly maintained (Figure 10). In these conditions, areas directly behind the sea wall will see benefits as flooding is avoided (e.g. Bhola Island), but inland areas are still inundated due to overtopping.

a) Poorly maintained embankments

b) Poorly maintained embankments with a coastal sea wall

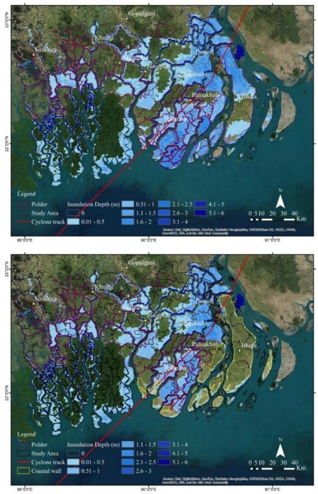


Figure 10 Impacts of the coastal sea wall on inundation due to storm surge flood under the extreme embankment deterioration scenario by the end of the century: a) without sea wall, b) with sea wall. The track of cyclone Sidr is shown by the red straight line.

3.4.3 Coastal greenbelt

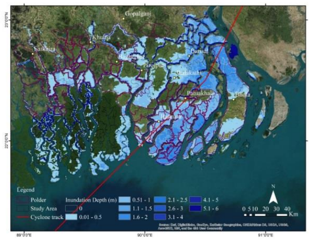
As with the coastal sea wall, the coastal greenbelt is only considered with cyclones as mangroves and other coastal afforestation are considered to be a natural buffer against storm surge (Sakib et al., 2015). In this study, the 490km coastal greenbelt is located in a similar area to the coastal sea wall (see Figure 7 b) and, in line with the recent technical study by CEGIS (2016), located seaward of any existing polder embankment.

If the existing embankment network is adequately maintained to prevent flooding, the main benefit of the greenbelt is to lower the wave energy reaching the embankment, reducing maintenance requirements and the likelihood of embankment breaching. Notably, where the width of the greenbelt reaches 1km, recent research indicates the impact of a strength of a Sidr strength storm surge can be halved (Akter, 2016). It also has benefits for preventing breaching, biodiversity, forest good collection and fisheries (Chapters 4 and 5). These benefits are not modelled in this analysis.

However, when the embankments in the region are poorly maintained, the greenbelt actively participates as a buffer against storm surge at the local level (Figure 11). Areas immediately behind the greenbelt see benefits but at the scale of the entire coastal zone the impact might be considered minimal.

a)

Poorly maintained embankments



b)

Poorly maintained embankments with a greenbelt

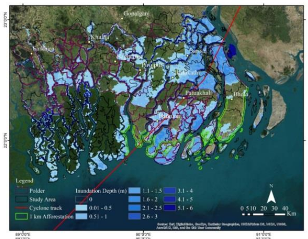


Figure 11 Impact of coastal greenbelt on inundation due to storm surge flood by the end of the century. The track of cyclone Sidr is shown by the red straight line.

3.4.4 New South Central polders

Figures 8-11 show that the south central districts (Barisal, Pirojpur, Jhalokati, Patuakhali) are subject to extensive flooding under the scenarios considered. To address this, 24 new polders (at a design height of 4.75m) are proposed to protect this south-central region of coastal zone from inundation (see Figure 7 c).

The change in flooding pattern during the monsoon with and without these new polders is shown in Figure 12. Effectively, the new South Central (SC) polders practically eliminate inundation in the region which is presently flooded during the monsoon. However, Figure 12 also shows that reduced inundation in the south-central region is associated with increased inundation in the north-central region where a number of existing embankments are overtopped due to the change in water dynamics created by the new polders. Thus, this regional modelling can capture both positive and negative effects beyond the area of the intervention.

During cyclones, the newly protected south central region also enjoys full protection against flooding, whereas the remainder of the study area floods as before.

a)

Existing embankments

b)

New polders in the South Central region, other embankments as existing

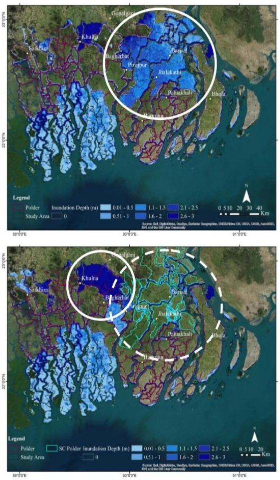


Figure 12 Impacts of new polders on inundation due to monsoon flood in extreme embankment deterioration scenario by the end of the century: a) without the new polders, b) with the new polders. The large dashed circle shows the south-central region where 24 new polders are constructed. The smaller white circle shows the north-central region where increased flooding occurs

3.5 Concluding remarks

This hydrological assessment explored the consequences of four baseline situations related to embankment upgrade and maintenance and three new interventions proposed in the BDP 2100. These were considered using the detailed, physics-based, three dimensional Delft3D coastal hydrodynamic model. The existing condition was defined as the condition where embankment heights are maintained either in their design height (4.75m) or in their actual height (3m to 7m). Only overtopping was considered as the information required to consider breaching was not available.

The simulation results showed that the existing polder embankments, if maintained properly in their current condition, effectively protect the region from inundation due to either monsoon or storm surge flooding over the coming century. A new coastal sea wall is beneficial only when embankments are poorly maintained and heights of embankments are reduced from their design or actual condition. Similarly, a coastal greenbelt has localised benefits when embankments are not maintained and only inundation extents are considered. The additional benefit of a coastal greenbelt is a reduction in the thrust on embankments reducing the risk of embankment breaching (which is not evaluated here). The new SC polders successfully eliminate inundation due to monsoon flood. But they also transfer some flood risk from the south-central region to the north-central region, where a number of embankments are overtopped. Hence this analysis suggests that if this intervention were implemented, additional interventions in the north-central area would be required to maintain current flood risk levels.

Further research could determine the financial implications of these interventions, but this analysis indicates that good maintenance of the existing embankment/polder network and the SC polders are most beneficial in terms of flood reduction over the next 50 years. The nature-based coastal greenbelt could also receive more detailed appraisal.

4 Integrated assessment for livelihoods and well-being

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4.1 Introduction

In complex systems like deltas, multiple drivers interact to produce change. Traditionally, knowledge is compartmentalised and these interactions are not considered. The ESPA Deltas project of the Ecosystem Services for Poverty Alleviation programme recognised this deficiency and developed an integrated assessment framework to investigate the status, sustainability and use of Ecosystem Services and their role in local livelihoods and poverty in the coastal zone of Bangladesh. Elements of the framework were researched on a discipline by discipline basis and then these methods and results were combined into an integrated assessment model, called the Delta Dynamic Integrated Emulator Model (ΔDIEM). The development of ΔDIEM was highly participatory and involved a number of well-attended stakeholder workshops, the knowledge and expertise from which are embedded in the model (ESPA, 2017).

Numerous detailed, technical models are available to capture the detailed behaviour of different parameters and/or sectors (e.g. coastal hydrology). However, multi-disciplinary tools cutting through traditional science boundaries are less common. A growing base of research is demonstrating the capacity of integrated assessment and systems models capable of informing decision making on trade-offs, thresholds, uncertainties and dis-benefits associated with interventions at varying scales (Anderies et al., 2007; Schlüter et al., 2012; Gies et al., 2014; Chapman and Darby, 2016). These models can be stylised and simple, or detailed and complex, to suit the local need, but all of these models cut through traditional research boundaries to provide the overarching trends and cause-effect relationships.

ΔDIEM is therefore designed to allow complex simulations and to test a large number of structural and policy interventions, thus providing a tool for policy assessment. ΔDIEM is built on the setup and results of complex process-based models (such as Delft3D) that has an important role in testing the selected BDP 2100 infrastructure projects. The following section provides a brief overview of ΔDIEM.

4.2 The Delta Dynamic Integrated Emulator Model (ΔDIEM)

ΔDIEM is an integrated assessment framework designed to analyse linkages between climatic change, environmental change, livelihoods, well-being and governance. The ΔDIEM platform fully couples environmental, social and economic simulations (Figure 13) and allows the testing of a large number of water-based structural and policy interventions, such as change to land use, embankment heights, the economy, fisheries, agricultural practices, ecosystem services, within a robust scenario framework. ΔDIEM also considers different socio-economic development trajectories (e.g. population change, economics, land use, fishing intensity, agriculture, cropping patterns) and quantifies their trade-offs. Thus, ΔDIEM has the potential to support strategic delta planning (Nicholls et al., 2016; Lázár et al., 2018).

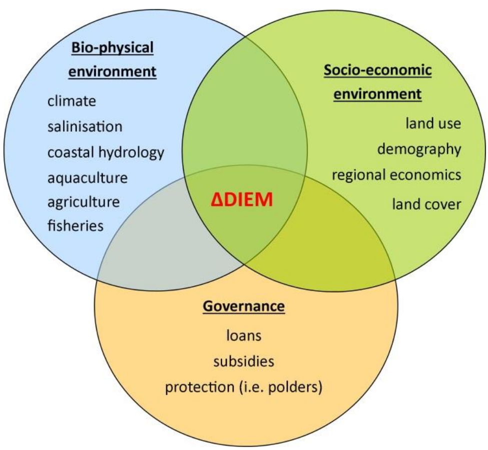

Figure 13 Main elements of the ΔDIEM framework

ΔDIEM is quantitative and process-based, and thus can easily capture the casual linkages and the cumulative effects of both bio-physical and socio-economic changes. The bio-physical aspect of ΔDIEM is built on well-established, physics-based models (e.g. Delft3D), whereas the human aspect is captured with a new and innovative household model (HEAP). The unit of analysis is the Union Parishad (from now on called Union) representing rural and local government administrative units with an average area of 26km2. Within the Unions, ΔDIEM is not spatially specific. Bio-physical changes are calculated daily, whereas socio-economic changes are calculated monthly.

4.2.1 Representation of the bio-physical environment in ΔDIEM

The bio-physical aspect of ΔDIEM is built on well-established process and physics based models. Some of these models simulated areas outside the coastal zone of Bangladesh. In these cases, the direct outputs of complex models are used in ΔDIEM as input scenarios (e.g. climate, upstream river flow and sea surface elevation including subsidence). However, in case of models applied on the coastal zone, ΔDIEM includes a dynamic, tightly coupled representation (e.g. flooding, salinisation, farm productivity – see Figure 14). The climate inputs come from the regional climate model outputs of the UK Meteorological Service (HadRM3/PRECIS, A1B scenario) (Caesar et al., 2015). The upstream river flows and nutrient inputs are calculated by the Integrated Catchment model – INCA-N (Whitehead et al., 2015a), whereas the sea surface elevation for the coastal shelf off Bangladesh is computed by the Global Coastal Ocean Modelling System - GCOMS model (Kay et al., 2015). Cyclones are also considered as input scenarios in ΔDIEM. The historical SIDR and AILA cyclones were modelled by Delft3D for the present day, mid-century and end century hydrological conditions. The user can set the occurrence of these historical cyclones for any years, and ΔDIEM adjusts the Delft3D results to the scenario in question.

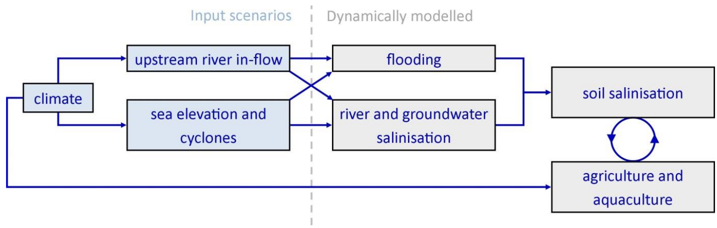

Figure 14 Conceptualisation of the bio-physical environment and interactions in ΔDIEM

ΔDIEM uses statistical models (Payo et al., 2017) for flooding (i.e. area and mean depth), groundwater processes (i.e. depth to groundwater) and salinisation in rivers and groundwater. These statistical models, or emulators, are designed to mimic the behaviour of a complex process-based model (e.g. Delft3D). This modelling technique is useful when the simulator is computationally expensive and when the focus of the analysis is on the outputs and not on the actual mechanics of change. If the complex model (e.g. Delft3D) is run multiple times for different time slices and scenarios, a library of inputs and outputs can be compiled. From this library, the 'statistical relationship' between inputs and outputs can be learnt and thus the emulators of ΔDIEM created. These emulators are very quick to run, are capable of considering spatial autocorrelation of values and allow daily continuous simulations for even a hundred year that might be impossible with a complex three dimensional model.
The key bio-physical outputs (daily for each Union) are:

- water elevation,
- inundation area/depth,
- water logging,
- soil moisture,
- depth to groundwater,
- river/groundwater/soil salinity,
- crop productivity (agriculture and aquaculture),
- fish catches,
- economics of farming and fishing (incomes / costs / net earnings).

4.2.2 Representation of the coastal population in ΔDIEM

The human aspect was built on a novel household survey collecting primary data from 1,500 households over three seasons on household characteristics (e.g. age, gender, economics) and use and benefits of ecosystem services (Adams et al., 2016), combined with data from the census and Household Income and Expenditure Survey (HIES).

The household module of ΔDIEM is called the Household Economy And Poverty (HEAP) trajectory model (Lázár et al., 2018). HEAP is similar to an agent-based model as it simulates 36 different household types. These types are differentiated based on the seasonality of the practiced livelihoods and their land size. The calculation is fully process-based by accounting on a monthly basis for the incomes and costs of these household types. Costs are dependent on the relative wealth level of the household. The wealth level changes over time as the household incomes change. If the household has high income levels, they attempt to increase their expenditure and thus their social status. However, if the income sources are decreasing, or if they overspend, they have to either use a coping mechanism (use savings, sell assets, get a formal or informal loan, drop expenditures or take up labour jobs) to balance their finances or move down a wealth level. There are also safety nets in the simulations such as relying on friends and neighbours, and postponement of loan repayments that the user can set. HEAP assesses the household options heuristically and optimises the household response (i.e. expenditures and coping strategies) to maintain and if possible improve the well-being of the household in question.

The income and expenditure of the households are used to calculate a number of poverty indicators such as the World Bank's $1.25 and $1.9 income and consumption headcount indicators. Based on the HIES and ESPA Deltas' observations, several expenditure levels could be established representing different 'food baskets' with distinct calorie and protein values. By knowing the food expenditure of the household, it is simple to approximate the likely calorie and protein intake as well. This allows the calculation of hunger periods and also the Bangladeshi poverty indicator (cost of basic needs method, where calorie intake is <2,122 kcal/cap/day).

The key household outputs (monthly for each Union) are:

- household economics (income, costs/expenses, savings/assets, debt),
- relative wealth-level,
- calorie/protein intake.

Key sectoral economic outputs are:

- agriculture, aquaculture and fisheries total produce and their economic value (tons, BDT),
- income inequality (GINI coefficient),
- GDP/capita,
- potential income tax revenue.

Poverty measures are:

- $1.25 and $1.9 income and consumption headcount indicator,
- Cost of Basic Needs – based temporal and extreme poverty,
- Hunger periods (i.e. number of months with < 2122 kcal/capita/day consumption),
- Multidimensional Poverty Index (heath, education and asset-based index).

4.2.3 Validation of ΔDIEM

Testing of ΔDIEM was done on each component separately, and on the full model (Lázár et al., 2018). These are briefly summarised here. The hydrological emulators (river elevation, river salinity, depth to groundwater, groundwater salinity, inundation area, mean inundation depth) show a good agreement with the high fidelity models (Delft-3D, FVCOM, MODFLOW-SEAWAT). The largest error occurs at the lower values and the smallest errors occur at the highest values. This means that, for example, large inundations are captured well, whereas small area inundations have higher emulation uncertainties. This is good, because the larger events (inundation, salinisation) are hydrologically the most important. The mean Root Mean Square Error (RMSE) of the emulators is 0.012-0.13 m for inundation depth, 1.36 ppt for river salinity and 0.35 m for river elevation. Soil salinity simulation results were evaluated against

Dasgupta et al. (2015) for 2001 and 2009. Annual median error is 2.1-2.6 dS.m, the dry season maximum salinity error is 2.6-3.6 dS/m and for the wet season it is 2.9-3.5 dS/m. The largest errors arose from the observed moderate to high dry and wet season soil salinities (4-16 and 4-12 dS/m, respectively) of the Northern part of Khulna and Bagerhat districts, where simulation models estimate low salinities for both river and groundwater (0-1 ppt). Thus ΔDIEM cannot predict high salinity values for these regions. Crop simulations were compared with observations from nine districts and nine sub-districts and the fit was good both spatially and temporally for the 2000-2010 period: 2.3-11.9% RMSE for the all major, important crops (e.g. rice varieties, chilli, grass pea). Less important crops of coastal Bangladesh, such as wheat and potato, were simulated with less accuracy (RMSE: 22-70%). The household well-being outputs were evaluated against observations on total expenditure, calorie intake, protein intake, GINI coefficient and 1.90 USD/capita/day headcount observations available from HIES2010 and World Bank datasets. The errors were not quantified because the observations were only available at national or regional level at best. However, the simulated values captured the magnitude and trend of the observations well, providing the confidence in the overall behaviour of the full ΔDIEM model.

5 Agriculture and human well-being under the interventions

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5.1 Introduction

While past development interventions have made significant contributions to growth in terms of a variety of global socio-economic indicators such as GDP, household incomes, life expectancy, and school years (United Nations, 2017), evidence is growing that there have been trade-offs, implicit or explicit, with other indicators (Hutton et al., 2018). Selection of interventions, many of which might be classed under the 'transformational' category of adaptation (Pelling et al., 2015), therefore requires considered and informed decision making to recognise and ideally avoid unintended negative consequences. Analysis using the Delta Dynamic Integrated Emulator Model (ΔDIEM) described in Chapter 4, enables the identification of trends and potential trade-offs that are implicit in the decisions more clear and more explicit to policy makers.

In this Chapter, the changes in agriculture (food security), poverty level and inequality associated with the baseline and four selected interventions are considered (see Table 1). These interventions are examples of projects in BDP 2100 with the potential to profoundly alter the provision of ecosystem services, and the potential to deliver both significant socio-economic benefits as well as unintended consequences for the well-being for the population and ecosystem health.

5.2 Agricultural productivity and value, including embankment maintenance

Agriculture is an important contributor to the health and well-being of the population of Bangladesh and the delta in particular (Nicholls et al., 2018; Arto et al., 2019). Generally, monsoon rains supply adequate water to grow a main season rice crop and if sufficient quantity and quality irrigation water is available, also a dry season crop (Clarke et al., 2018). However, cyclones generally disrupt production through flooding and salinisation of both soil and water (e.g. Spencer and Polachek, 2015). Agricultural output from the integrated ΔDIEM model shows periodic decrease in production due to cyclones. However, ΔDIEM also considers interacting factors such as crop selection, salinisation, temperature limitation, water logging and infrastructure repair time after cyclones which means that any variations in production are controlled by multiple factors, not just by flood events and the quality of embankments.

Overall the analysis indicates that income from agriculture is mainly constrained by the availability of good quality irrigation water during the dry season, access to markets and, towards the end of the simulation, increasingly flood and temperature limitations. Embankment maintenance also plays a factor (see Table 4). Maintained embankments and moderate embankment deterioration are likely to maintain crop productivity, at least until the 2050s, even under the more extreme climate scenario. This is because most agriculture goods are produced during the wet season when there is no water limitation and the existing embankments provide sufficient protection against flooding. However, extreme embankment deterioration would result in increasingly large agriculture losses. The separation of the productivity lines starts from about 2035, and by 2050, the total annual agriculture value is expected to be reduced by about 20%.

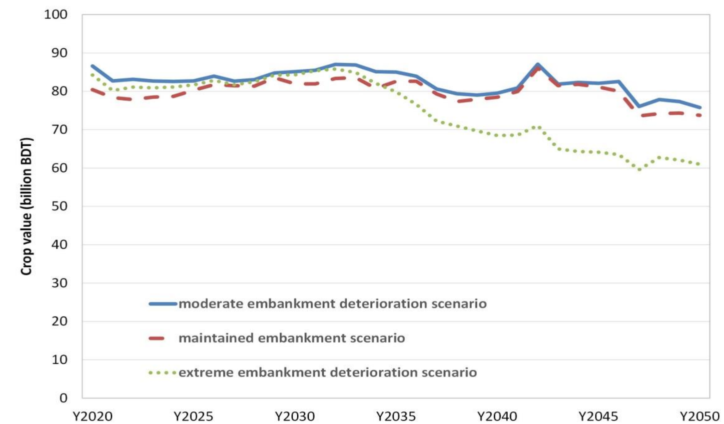

Figure 15 The importance of embankment maintenance on the annual productivity and thence value of the crops grown in Coastal Bangladesh (5yr rolling average)

5.2.1 Coastal sea wall and greenbelt

Both the coastal sea wall and coastal greenbelt proposals are aimed at reducing the impact of cyclones on the delta area. As they are confined to the coastal fringe, the physical impacts of the new sea wall and greenbelt are relatively minor at the scale of the study area, with notable effects mainly being registered when maintenance of the existing embankment network is poor (extreme deterioration).

At the local scale, the coastal sea wall serves to reduce the agricultural losses experienced during a tropical cyclone. The effects are most pronounced in Patuakhali, Barisal and are largest under scenarios where embankments experience extreme deterioration. By 2050 the agricultural output saved by the coastal sea wall in a cyclone year amounted to approximately 4% of the total output, which is significant when the area of the impacted zone is considered.

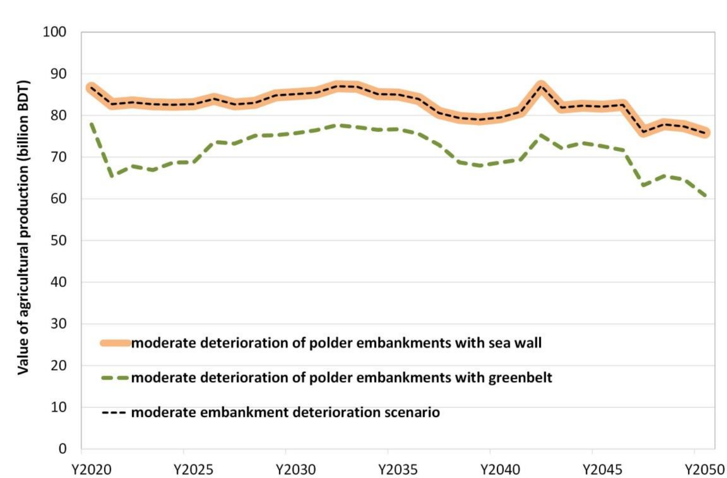

Figure 16 Comparison of agricultural outputs under the sea wall and greenbelt proposals (5yr rolling average)

The proposed greenbelt appears to reduce agricultural outputs by about 6-25% when compared to the coastal sea wall (see Figure 16). This reflects changes in land use which do not occur under the sea wall scenario (i.e. some productive lands are converted to natural vegetation). The productivity of the areas not immediately affected by the coastal greenbelt remains comparable. In addition, Figure 16 also indicates that the higher sea wall does not have any additional benefits to simply maintaining the existing embankments.

The primary benefit of the greenbelt would be assumed to be for the structural integrity of the embankments, reducing the risk of failure, especially breaching. Benefits of increased mangrove areas and other habitats for biodiversity and fisheries should also be noted. However, as breaching and these local benefits are not represented in the Chapter 3 analysis, it is not possible to assess this benefit with ΔDIEM.

5.2.2 South Central polders

The new South Central (SC) polders have the most significant impact on rice production (see Figure 17). For the study area, annual production can increase up to 20% over time if the new polders are constructed and maintained at design height. If the new polder embankments are allowed to deteriorate post construction following the moderate deterioration scenario, the increase in productivity is significantly less at up to a maximum of 10%. The influence of cyclones can significantly reduce production for the following years while salinisation levels reduce.

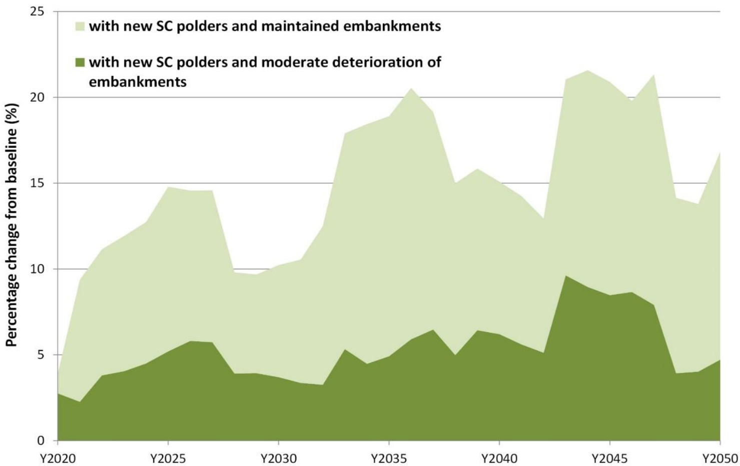

Figure 17 Percentage increase in rice outputs for the study area associated with the creation of the new South Central polders when compared to the baseline scenario (5yr rolling average)

The increase in output is not uniform across the new polder area and there can be wider changes in productivity across the delta under the interventions. For example, Figure 18 shows the area covered by the new polders experiences a large increase in productivity although this is not uniform. Conversely, the north-central area, west of the new polders, generally shows a significant decline. This is consistent with the changes in monsoon flooding associated with this intervention (see Figure 12) where these areas experience deeper and more extensive flooding.

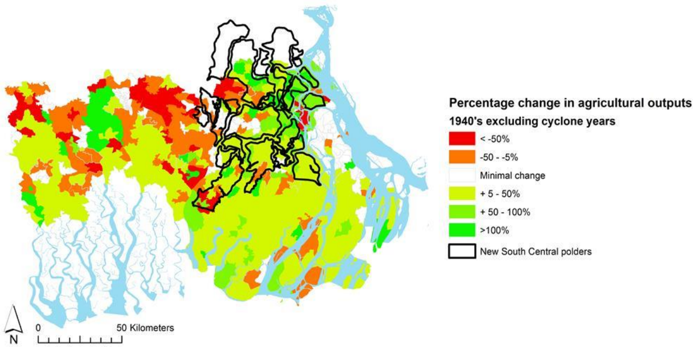

Figure 18 Percentage change in agricultural outputs averaged over the 2040s associated with the construction of new South Central polders with polders maintained at design height when compared to the baseline scenario (moderate embankment deterioration)

The change in hydrodynamics also affects other areas, but in a mainly positive manner, increasing productivity to the south and west of the new polders. The wider implications of the change in the pattern and availability of monsoon waters (for irrigation of the main crop, for example) for individual Unions may warrant further investigation, particularly due to its strong relationship with poverty and inequality (see Section 5.3).

5.3 Poverty and inequality

ΔDIEM is designed to analyse multiple socio-economic responses to an intervention, including poverty, using socio-economic models linked by process-based calculations to the environmental models (Nicholls et al., 2016; Lázár et al., 2018). It is therefore possible to assess the effects of agriculture and other environmental change factors on the poverty and inequality levels among the delta population. Importantly, it can indicate when someone cannot afford to consume 2122 kcal food per day (which is an indicator of extreme poverty).

5.3.1 Coastal sea wall and greenbelt

Change in agricultural productivity has a minimal effect on extreme poverty across the study area. Essentially, the proposed sea wall does not provide benefits to households whose livelihoods are currently largely outside the polder network; the households which are by far the largest source of extreme poverty in the study area.

Similarly, the proposed greenbelt has a limited effect at the regional scale with only 30 of the 139 polders in the study area being affected. Locally, the 2% fall in agricultural revenue detectable within Patuakhali, the district containing the largest portion of the new greenbelt, is mainly attributable to the conversion of agriculturally productive land to greenbelt. The associated change in poverty and equality reflects the assumption in ΔDIEM that the population within the Unions losing agricultural land would switch their livelihoods towards occupations that rely on labouring jobs, fishing and the collection of forest goods. This assumption for the Unions affected by the greenbelt results in a total fall in household incomes of US$2.7 million per year, an increase in extreme poverty of 10% for the 30 affected polders (i.e. the new occupations are less profitable than the previous agricultural occupations). However, crucially, the financial and other benefits a coastal greenbelt would provide through its protection of the existing embankments, potentially reducing the probability of a breach during extreme weather events and improved fisheries were not considered. Few other socio-economic changes were detectable when averaging across the study area.

5.3.2 South Central polders

Figure 19 shows ΔDIEM's extreme poverty estimates for the area covered by the new South Central (SC) polders against ambitions set out in the BDP 2100 for this riverine hotpot. In this measure of poverty only those households spending 12 months of the year below the 2122 kcal threshold are counted, thereby removing any seasonality in poverty rates.

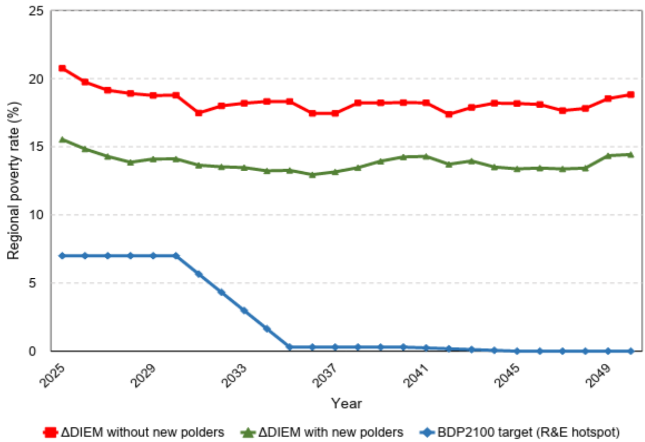

Figure 19 Long-term extreme poverty rate in the region theoretically enclosed by the proposed new polders (the south central region). The BDP2100 Rivers and Estuaries hotspot (R&E hotspot) does not cover the same geographical area as the new polders, but does provide the closest comparable poverty targets within the plan

ΔDIEM suggests that the overall extreme poverty rate in the region directly enclosed by the new polders would see a relative change of around -25% (Figure 19). With the new polders in place the extreme poverty rate in the enclosed region averages around 14% to 2050. The increase in protection against flooding in the monsoon and pre-monsoon cropping seasons means that farmers are less likely to lose crops and, where previously the likelihood of flooding led farmers to leave fields fallow, the intervention allows them to grow an additional crop. Within the newly poldered area ΔDIEM estimates a 24% increase in annual agricultural output (as measured in total economic value of the crops produced). The resulting increase in mean household incomes is slightly less, at 19%, yet still significant, especially for the poorest households (Figure 20, right).

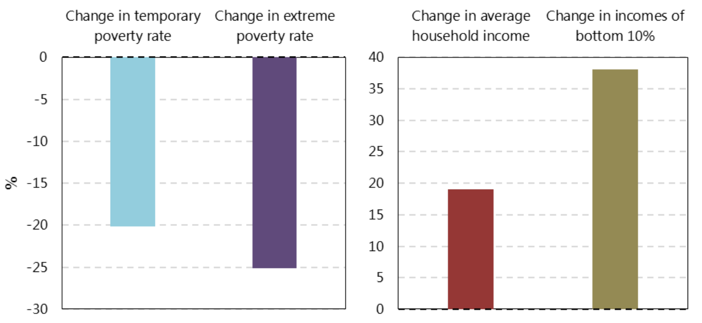

Figure 20 Annual indicator changes averaged across the simulation period (2025-2050) inside the new SC polders; (left) relative changes in two categories of poverty, extreme poverty (12 months per year) and temporary poverty (1+ months per year); (right) relative changes in household income for the average farmer and for farmers in the bottom 10% of earners

These high benefits to the poorest households reflect the assumption that the poorest remain living on the same land following the construction of the new polders. As such the very poorest receive the greatest proportional benefit (i.e. newly available and safe crop growing time) when land is upgraded to fully protected. While the benefits seen when the temporary poverty (at least one month of extreme poverty per year) rate is measured are slightly less pronounced (Figure 20, left), the absolute temporary poverty rate predicted by ΔDIEM both with and without the intervention might be considered high, at 22% and 28%, respectively.

However, this large reduction in the extreme poverty rate does not achieve the BDP 2100 targets alone and therefore could not be considered in isolation in respect of this aim. Also, whether households remain in-situ after introduction of a new polder network depends on individual decisions, and social policies introduced alongside the new infrastructure. A considerable rise in land values would likely result from the increased agricultural productivity of the land and this might be an incentive for impoverished households to sell. The BDP 2100 expects to reduce migration out of the coastal and riverine hotspots and therefore policies which encourage households to remain are realistic. However, given the demographic trends in the study area suggest significant outmigration is likely (Szabo et al., 2018), these issues are worthy of further analysis.

5.3.3 Identifying and mitigating risk transfer

A key factor in the implementation of the SC polder intervention is the existence of secondary impacts, notably the increase in flooding in the north central area as discussed in Chapter 3 and Section 5.2. ΔDIEM can apply process based simulation to translate this change into its socio-economic impacts. In doing so the integrated model also indicates the types of compensatory social policies and/or enhanced engineering measures which might be used to address any negative effects experienced in this region.

Table 6 summarises the relative changes inside and outside the newly poldered area for a number of socio-economic indicators. Overall the quantified benefits for the Unions inside the newly poldered area outweigh those for the Unions in the rest of the study area. However, these gains should also be contrasted to the very high likely cost of the intervention and the costs associated with the compensatory arrangements for those who will experience deterioration in productivity and income. Other questions are (i) what is the relative importance of the polder maintenance and upkeep for the new polders? and (ii) what is the relative importance of the future climate scenario to the performance of the intervention? A full cost-benefit analysis is not reported here due to the constraints of the modelling but should be considered.

Table 6 Changes in a variety of indicators between baseline and implementation of the South Central polder intervention (based on 2018 BDT-USD conversion)

Indicator	Within the SC polders (184 Unions)		Outside polder area (469 Unions)	
	Change (%)	Quantification of change	Change (%)	Quantification of change
Annual average household income	+19.1	$454 million	-1.4	-$125 million
Annual agricultural output	+24.5	$628 million	-3.9	-$367 million
Extreme poverty rate	-25.1	-42,800 households	+3.5	13,300 households
Temporary poverty rate	-20.1	-50,500 households	+1.9	11,700 households
Household debt	+29.8	$29 million	+0.3	$1 million
Education expenditure of the bottom 10% of households	+93.1	$3 million	-4.6	-$1 million

To investigate the effect of polder embankment maintenance on the rates of agricultural productivity and poverty, the baseline scenarios were tested as a sensitivity analysis. Figure 21 shows the deterioration rates for the two key indicators, extreme poverty and agricultural output, with and without the SC polders; both indicators move in a negative direction as embankment maintenance is reduced resulting in faster rates of height deterioration.

Figure 21 also shows the negative impacts of the introduction of new polders as household incomes outside the polders are significantly reduced when embankment deterioration is removed (i.e. there is good maintenance). This implies that embankment maintenance regimes are one way of minimising the impacts of transferred risks. These benefits, however, do not accrue to households in extreme poverty because the majority are outside of the current polder network, i.e. household in unprotected areas who experience new flood risk due to the policy intervention, but for whom polder maintenance is largely irrelevant as they experience no benefits.

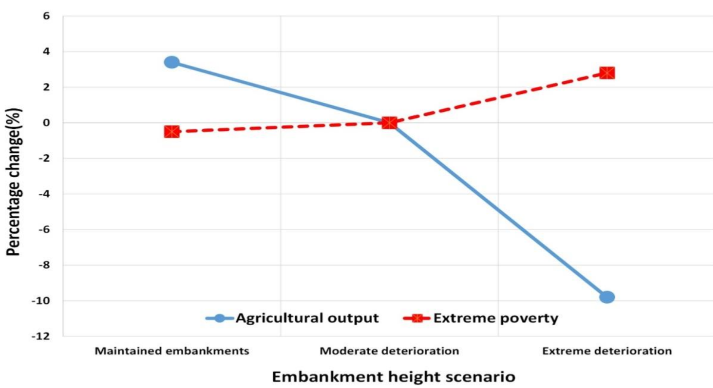

Figure 21 Comparison of average change in extreme poverty and agricultural output (2025-2050) for moderate and extreme and maintained embankment scenarios

5.3.4 Sensitivity of socio-economic changes to climate change

The sensitivity of an intervention's performance to different climate futures is also an important issue for strategic policy making. Figure 22 shows the changes in three key indicators related to future climate change as represented by the Q16 (wetter) and Q8 (drier) climate scenarios when the SC polder intervention is implemented. Across all indicators, performance is better under the Q8 scenario. A notable difference for the area outside of the proposed polders is extreme poverty reducing by 6% when the Q8 climate is compared with the Q16 scenario. This highlights that the risk transferred by the new polder network is smaller if the future climate is drier. Lower maximum river discharge peaks lower the transferred risk of flooding, both through less overtopping of downstream polders and less flooding of unprotected areas. Given that any intervention must be robust to all possible future scenarios, this information has less strategic importance. However, it shows the consequences of climate change increasing extreme discharge. Additionally and also from an academic perspective, this information gives an indication of the relative significance of climate change in the context of a country facing many disparate non-climate related risks and drivers of change.

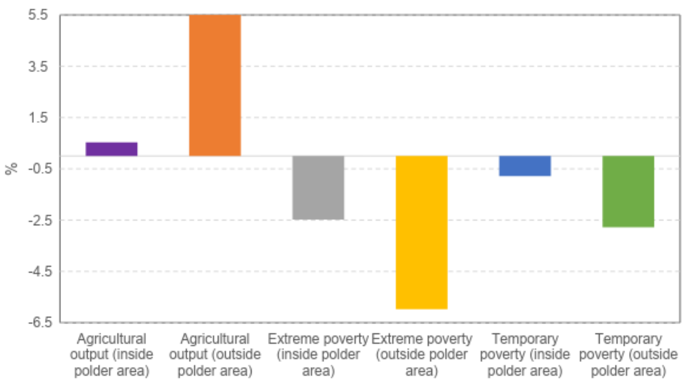

Figure 22 Changes in three indicators in- and outside the South Central polders showing the Q8 results relative to the Q16 results. Annual changes have been averaged over the period 2025-2050.

5.4 Conclusion

This analysis shows that for the study area as a whole, the most positive intervention for agriculture is the maintenance of polders and embankments at their current, or design, height. This would allow average agricultural outputs to be sustained at current levels, although extreme events of the calibre of Cyclone Sidr may introduce temporary periods of reduction and recovery. While the introduction of a coastal sea wall and/or greenbelt may generate localised non-agricultural benefits, there is no discernible advantage over simply maintaining the current embankments. The SC polders also have significant benefits, but raise questions of who will benefit and risk transfer to areas outside the new polders. Overall, the ΔDIEM framework is shown to provide important insights that can support project evaluation and analysis, and wider policy. This is explored further in Chapter 6.

6 Policy implications and recommendations

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6.1 Introduction

This chapter reviews the policy implications of the cases analysed in detail, the wider benefits of the integrated approach tested here and considers next steps. The Bangladesh Delta Plan 2100 (BDP 2100) provides the context for an integrated strategy of delta development linked to policy relevant socio-ecological and engineering interventions on the coastal zone over the next 80 years, with a focus on the next 30 years. As such the information provided in this book, whilst addressing a specific element of the coastal defence element of this plan, demonstrates the strategic value of assessing policy options using Integrated Assessment Models and their associated frameworks, including a strong participatory element (see Figure 23).

Figure 23 Stakeholder participation in the integrated framework approach. Workshop at General Economics Division, Dhaka, 16 September 2015

6.2 Summary of assessments

The approach developed in this book allows decision makers to consider firstly, if the policies they pursue are addressing the primary concerns of the BDP 2100 and secondly, if the application of an approach is inadvertently impacting on other policy approaches or having a negative impact. The simulations clearly demonstrate that it is essential to integrate sectors, disciplines, and regions to approximate the extent of their policy relevant impact across multiple dimensions. To understand the policy implications of the findings, at first it is necessary to summarise the integrated results of the hydrological and socio-economic modelling assessment.

According to the hydrological assessment, the coastal embankments in their design condition can protect the inundation due to fluvio-tidal flood and storm surge flood under increased sea-level scenarios. However, reduced polder heights, due to poor maintenance, result in increased overtopping of embankments under the same sea-level scenarios. The Delft3D outputs indicate that construction of a new coastal sea wall will not be required if embankments are effectively maintained in their design condition. Coastal greenbelts (afforestation) also do not reduce inundation depth and areal extent of inundation if embankments are maintained to their design condition. However, the afforestation approach will reduce thrust forces on the embankments during cyclones and reduce the probability of embankment breaching. Afforestation can be considered as the ‘second line of defence’ in front of the embankments. Construction of new polders in the south central region will make this area flood-free both from fluvio-tidal flooding and storm surge flooding. However, it will increase the potential for inundation in neighbouring areas during fluvio-tidal flooding (not during storm surge flooding), increasing the likelihood of overtopping for several embankments in these areas. This phenomenon can be considered as ‘transfer of risk’ from one area to another and must be considered as a key trade-off of this approach requiring increased protection and/or compensation.

Adequate maintenance of embankment heights and their structural integrity may be a cost-effective way to help Bangladesh reach the poverty alleviation targets and economic growth targets. Although the proposed new polders contribute to a reduction in the extreme poverty rate, the declining poverty rates forecast by the BDP 2100 rely upon 19 other interventions of varying scale and spatial coverage. Therefore, a further more holistic assessment and detailed study of the interventions and their interactions is essential.

After assessment of polderisation options through Delta Dynamic Integrated Emulator Model (ΔDIEM), the overall extreme poverty rate in the new polders would show a significant reduction. These improvements are generally driven by the agriculture sector; farmers become less vulnerable due to reduced flood risks and annual agricultural output increases considerably. However, the benefits of the new protection are unlikely to be retained by the poorer population, unless other support is provided (Chapman and Darby, 2016; Chapman et al., 2016). With protection, the value of the land will increase and there is a high likelihood of a transfer of land from the vulnerable poor towards richer farmers and land developers (Reddy and Reddy, 2007). If poorer people are displaced by increased land prices, this may increase outward migration, a process which appears to be longstanding in this region.

The two other policy interventions (coastal greenbelt and sea wall) simulated can be summarised as being considerably more modest in their impacts on agriculture and poverty rates. Greenbelts are useful to reduce the risk of embankment or sea wall failure by reducing the thrust of moving surge and further work in this field is required. As a result, such implementation can reduce embankment damage and will also enhance local biodiversity and possibly eco-tourism (e.g. Nguyen 1998). However, such a project would require space that is already limited in coastal Bangladesh, notably conversion of valuable farm lands to mixed-species greenbelts. This has likely consequences for food security and potential compensation and relocation of communities. The remaining policy intervention, a new sea wall, only has an impact during significant cyclone events. Current polders, if maintained properly, withstand the average storm events already. Looking beyond 2050, the coastal greenbelt and sea wall may have larger benefits and be necessary to respond to sea-level rise.

6.3 Wider policy considerations

The results of the ΔDIEM simulations have important policy implications. By testing embankment maintenance and climate scenarios, the simulations demonstrate some important issues that can be easily forgotten. A sufficient annual budget for embankment and polder maintenance is essential to ensure that the likely benefits of the new polders are maximised and sustained into the future (Tuong et al., 2014) and in BDP 2100 this has been duly emphasised. The governance of these assets must also be considered as centralised maintenance may not be sufficient. Education, training and conflict resolution with the local population is similarly essential to ensure that the polders and their embankments are used and maintained appropriately.

The development of the polders and embankments will see a substantial change in land use and access rights to common resources, such as the river, which will specifically impact the poor. The intensification of farming on high value land can encourage mechanisation and reduce labour demand and employment for the most vulnerable members of society. This in turn may drive migration to areas with employment opportunities, which are likely to be urban areas.

6.3.1 Sustainable Development Goals

In order to contribute to the successful fulfilment of the SDGs within Bangladesh through the implementation of BDP 2100, a number of key areas of policy need to be addressed including transfer of risk, ecosystem degradation and diverse poverty dimensions. The ΔDIEM assessment of the selected BDP 2100 interventions reveals the need for policies to integrate thematic sectors for both short and long-term targets. Historically, there is a strong chance that the benefits provided by these interventions will be mostly retained by the wealthier sectors of the population who are able to buy up land during times of difficulty or oppress the poor, deviating from the original goal of eliminating extreme poverty and addressing Inequity (SDG 10). Policies addressing such issues should concentrate on a strategy for protecting and enhancing livelihoods of the poor and facilitating new ones. In addition, whilst net incomes may rise due to the polders, the distribution of that wealth and the significant rise in poverty levels in areas removed from the polders themselves due to flood displacement must still be addressed. Policies must be in place to offset these damages and drawbacks. Sustainable development requires sufficient annual budget targeted towards efforts on education and training of local population which will both enhance current livelihoods and provide greater access to the growing service sector in the delta.

6.3.2 Potential barriers in achieving successful policy

The key barriers to effective policy implementation are poor policy design at the initial stage, inter-ministerial and remit confusion and low financial efficiency of implementation. Within the context of confused messages from multiple sources and poorly constructed maintenance strategies, engineering infrastructure can rapidly fall into disrepair as well as become subject to informal alteration. That is to say altered without formal authorisation, which itself can lead to an increased risk of failures, damaging agriculture production and generating conflict. The proposed modelling approach aims to provide a platform by which diverse outcomes can be assessed. However, the model approach is yet to include an efficiency characterisation which identifies the compounding issues associated with poor governance. This might well be a valuable activity for future work. The outputs of the model do identify the need for cross-ministry co-operation, which offers a starting point for such an activity.

A further barrier to the implementation of policy as linked to the work of ΔDIEM is the maintenance and effective use of the model itself. There is a requirement that the model is (i) maintained with up to date data and models; (ii) effectively interpreted with the appropriate expertise; and (iii) further developed to reflect ever diversifying policy requirements. In order to achieve this, there needs to be a development team working within Bangladesh that can work with the government to this end.

6.4 The benefits of an integrated model approach and the BDP 2100

Given the experience analysing the four interventions here and their policy implications (see also ESPA, 2018a; 2018b), this section considers the wider implications of an integrated model approach to support the BDP 2100 and delta management in general. There are a number of benefits for delta management including (i) promoting participation and learning; (ii) recognising indirect linkages and consequences; and (iii) exploring a range of futures so that choices are more informed.

In terms of promoting participation and learning, it is important to recognise the benefits of the process of integration as well as the end point. Integration encourages people from different disciplines, agencies and perspectives to work together and share their views and perspectives. Integrated assessment as exemplified by the ΔDIEM is highly participatory and both the model users and the stakeholders learn in the process of application. The questions being posed often evolve through the assessment as understanding increases, making the final outcomes more relevant and insightful. An important point to recognise is that these integrated assessment frameworks and models are flexible and can easily evolve as our understanding improves and the questions change. As the understanding of the stakeholders improve with their growing confidence in the method, they may pose more sophisticated questions. This encourages model development and improvement over time, although the scale of this obviously depends on the resources and time available.

In terms of recognising indirect linkages and consequences, the integrated framework shows the cascade of effects of a change, such as the increase in flooding to the west of the new South Central (SC) polders. The ΔDIEM integrated assessment framework has been developed and designed to analyse linkages between climatic change, environmental change, livelihoods, well-being and governance. Traditional assessment approaches fail to capture such effects, while here these indirect effects and their magnitudes are evaluated and the resulting trade-offs can be considered. Further additional mitigation measures can be evaluated as needed.

Exploring a range of futures rather than a single scenario means that insights and resulting choices are more informed. Traditional analysis has often focussed on single future cases or simply a with or without change approach. Here, a number of cases have been examined as exemplified by varying multiple parameters. By following this approach, it is apparent that the future is not certain and the analysis helps to understand these uncertainties and inform the decision maker.

The major constraints of ΔDIEM should also be noted in relation to the BDP 2100. Firstly, the BDP 2100 is national. While ΔDIEM covers an area of 14 million people, which is essentially coastal Bangladesh, west of the Padma (Coastal Hotspot within BDP 2100), there is a need to harmonise the spatial domains of ΔDIEM to cover all of coastal Bangladesh as defined by the Government of Bangladesh. The DECCMA project has progressed our understanding at this larger spatial scale, and extension of ΔDIEM to all of coastal Bangladesh is easily achievable (e.g. DECCMA, 2018). Looking nationally, ΔDIEM could be extended to other inland hotspots and become a truly national resource for the BDP 2100. Secondly and importantly, ΔDIEM is not designed to replace models like Delft3D, but rather to integrate these more sectoral models and link bio-physical futures and, importantly, socio-economic futures. Hence it is important to design a realistic method that extracts the maximum information for the least effort.

Hence, the potential benefits of an integrated model approach to the BDP 2100 are significant. Further development is required to provide more seamless integration with the BDP 2100. A distinct difference of the work considered in Bangladesh, compared to the Dutch perspective, is the explicit consideration of the socio-economic situation in ΔDIEM, as this is so strongly coupled to the bio-physical setting of the delta.

6.5 Next steps

ΔDIEM integrated assessment framework has been developed and designed to analyse linkages between climatic change, environmental change, livelihoods, well-being and governance. ΔDIEM is quantitative and process-based, thus can capture the casual linkages and the cumulative effects of both bio-physical and socio-economic changes. Indeed, the analysis shows that the GBM Delta is both a hotspot of socio-economic activities and environmental change which, along with deterioration in the environment, such as salinity intrusion and flooding is leading to increased risks and hazards. Further application will be useful to explore these and other inter-relationships. For example, a project has been funded to use ΔDIEM to analyse changes in waterlogging.

The results reported here have demonstrated the potential for an integrated assessment model such as ΔDIEM, grounded in an ecosystem services perspective of a social-ecological system, to highlight and provide quantification of trade-offs and secondary impacts. ΔDIEM does not aim to replace the technical sectoral models which will inform the specifics of intervention design, but to provide information at the strategic and regional level. The power of ΔDIEM to answer questions posed of this system has been demonstrated and questions posed during the project which ΔDIEM is not currently equipped to answer are well within reach of future development: the model has a modular design which allows for ease of modification and development.

In order to maintain the effectiveness and application of ΔDIEM to policy support the following strategies might be considered:

(i) extend the ΔDIEM model framework to cover the full coastal hotspot as a first step to whole (national) BDP 2100 coverage.

(ii) continue the model development using the existing modules to address key BDP 2100 issues, such as improving representation of aquaculture.

(iii) review the model components and consider adding other functionality such as a demographic and economic module from the DECCMA Project. This might include gender dimensions and micro-economics of communities.

(iv) consider the interventions that are required to address the range of BDP 2100 interventions, recognising that these will vary from soft to hard measures and will be applied as portfolios of measures i.e. the measures will interact and this should be assessed.

(v) develop training and capacity building on these approaches to build a in-country national capacity to develop, maintain and apply these methods with the BDP 2100 and other relevant policy processes, such as the Five Year Plans.

ΔDIEM can be best developed in use, learning from policy questions in a participatory way across scales and levels of analysis from scoping to detailed. This can shape its design towards relevant application and investigation of policy decisions. A full coastal hotspot or national model coverage would seem to be required to maximise the benefits.

7 References

Adams, H.; Adger, W. N.; Ahmad, S.; Ahmed, A.; Begum, D.; Matthews, Z.; Rahman, M. M. & Streatfield, P. K. (2016) Spatial and temporal dynamics of multidimensional well-being, livelihoods and ecosystem services in coastal Bangladesh. Data Archive. 10.5255/UKDA-SN-852179. http://reshare.ukdataservice.ac.uk/852179/ Last accessed 06 February 2019

Akter, M. (2016) Analytical solution of the distributive thrust force due to storm surge in coastal area. M.Sc Thesis. Department of Mathematics, Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh

Amoako Johnson, F. & Hutton, C. W. (2018) A geospatial analysis of the social, economic and environmental dimensions and drivers of poverty in South-West Coastal Bangladesh. in Nicholls, R. J., Hutton, C. W., Adger, W. N., Hanson, S. E., Rahman, M. M. & Salehin, M. (eds.) Ecosystem Services for Well-Being in Deltas: Integrated Assessment for Policy Analysis. Springer International Publishing, Cham pp383-403 http://dx.doi.org/10.1007/978-3-319-71093-8_21

Anderies, J. M.; Rodriguez, A. A.; Janssen, M. A. & Cifdaloz, O. (2007) Panaceas, uncertainty, and the robust control framework in sustainability science. Proceedings of the National Academy of Sciences, 104, 39 pp15194-15199 http://dx.doi.org/10.1073/pnas.0702655104

Arto, I.; García-Muros, X.; Cazcarro, I.; González-Eguino, M.; Markandya, A. & Hazra, S. (2019) The socioeconomic future of deltas in a changing environment. Science of The Total Environment, 648, pp1284-1296 http://dx.doi.org/10.1016/j.scitotenv.2018.08.139

BDP 2100 (2018) Bangladesh Delta Plan 2100. Dhaka, Bangladesh, General Economics Division (GED), Bangladesh Planning Commission, Government of the People's Republic of Bangladesh https://www.bangladeshdeltaplan2100.org/ Last accessed 28 April 2019

Caesar, J.; Janes, T.; Lindsay, A. & Bhaskaran, B. (2015) Temperature and precipitation projections over Bangladesh and the upstream Ganges, Brahmaputra and Meghna systems. Environmental Science: Processes & Impacts, 17, 6 pp1047-1056 http://dx.doi.org/10.1039/C4EM00650J

CEGIS (2016) Technical study for mapping of potential green belt zone in the coastal regions of Bangladesh. Final report on climate resilient participatory afforestation and reforestation project for the Bangladesh Forest Department. Dhaka, Bangladesh, Center for Environmental and Geographic Information Services (CEGIS)

CEIP (2013) Technical feasibility studies and detailed design for Coastal Embankment Improvement Programme (CEIP). Ministry of Water Resources, Government of the People's Republic of Bangladesh

Chapman, A. & Darby, S. (2016) Evaluating sustainable adaptation strategies for vulnerable mega-deltas using system dynamics modelling: Rice agriculture in the Mekong Delta's An Giang Province, Vietnam. Science of The Total Environment, 559, pp326-338 http://dx.doi.org/10.1016/j.scitotenv.2016.02.162

Chapman, A. D.; Darby, S. E.; Hồng, H. M.; Tompkins, E. L. & Van, T. P. D. (2016) Adaptation and development trade-offs: fluvial sediment deposition and the sustainability of rice-cropping in An Giang Province, Mekong Delta. Climatic Change, 137, 3 pp593-608 http://dx.doi.org/10.1007/s10584-016-1684-3

Clarke, D.; Lázár, A. N.; Saleh, A. F. M. & Jahiruddin, M. (2018) Prospects for agriculture under climate change and soil salinisation. in Nicholls, R. J., Hutton, C. W., Adger, W. N., Hanson, S. E., Rahman, M. M. & Salehin, M. (eds.) Ecosystem Services for Well-Being in Deltas: Integrated Assessment for Policy Analysis. Springer International Publishing, Cham pp447-467 http://dx.doi.org/10.1007/978-3-319-71093-8_24

Darby, S. E.; Dunn, F. E.; Nicholls, R. J.; Rahman, M. & Riddy, L. (2015) A first look at the influence of anthropogenic climate change on the future delivery of fluvial sediment to the Ganges-Brahmaputra-Meghna delta. Environmental Science: Processes & Impacts, 17, 9 pp1587-1600 http://dx.doi.org/10.1039/C5EM00252D

Dasgupta, S.; Hossain, M. M.; Huq, M. & Wheeler, D. (2015) Climate change and soil salinity: The case of coastal Bangladesh. Ambio, 44, 8 pp815-826 http://dx.doi.org/10.1007/s13280-015-0681-5

Dasgupta, S.; Huq, M.; Khan, Z. H.; Ahmed, M. M. Z.; Mukherjee, N.; Khan, M. F. & Pandey, K. D. (2010) Vulnerability of Bangladesh to cyclones in a changing climate: Potential damages and adaptation cost. Washington DC, USA, World Bank https://openknowledge.worldbank.org/handle/10986/3767

DECCMA (2018) Climate change, migration and adaptation in deltas: Key findings from the DECCMA project. Deltas, Vulnerability and Climate Change: Migration and Adaptation (DECCMA) report. Southampton, UK, DECCMA Consortium https://www.preventionweb.net/publications/view/61576 Last accessed 27 November 2018

Deltares (2011) Simulation of multi-dimensional hydrodynamic flows and transport phenomena, including sediments. User Manual of Delft 3D flow. Deltares, The Netharlands

Deltares (2014) Delft3D-Flow, Simulation of multi-dimensional hydrodynamic flows and transport phenomena, including sediments. User Manual, Version 3.15.34158. Delft, The Netherlands, Deltares

ESPA (2017) Interdisciplinary modelling for pro-poor policy-making: experience from Bangladesh. Ecosystem Services for Poverty Alleviation (ESPA) research brief. Edinburgh, UK, ESPA Directorate https://www.espa.ac.uk/publications Last accessed 30 January 2019

ESPA (2018a) Integrated environment and development modelling to benefit the poorest in coastal Bangladesh. Ecosystem Services for Poverty Alleviation (ESPA) research brief. Edinburgh, UK, ESPA Directorate https://www.espa.ac.uk/publications Last accessed 30 January 2019

ESPA (2018b) ΔDIEM: Using scenarios to inform pro-poor policy making. Ecosystem Services for Poverty Alleviation (ESPA) research brief. Edinburgh, UK, ESPA Directorate https://www.espa.ac.uk/publications Last accessed 30 January 2019

GED (2017a) The Bangladesh Delta Plan 2100. Draft circulated for expert comments. General Economics Division (GED), Planning Commission, Government of the People's Republic of Bangladesh http://www.bangladeshdeltaplan2100.org/bangladesh-delta-plan-2100-draft/ Last accessed 02 July 2018

GED (2017b) Bangladesh state of the economy by August 2017. Dhaka, Bangladesh, General Economics Division (GED), Government of the People's Republic of Bangladesh

GED (2017c) Data gap analysis of Sustainable Development Goals (SDGs): Bangladesh perspective. SDGs Publication #2. Dhaka, Bangladesh, General Economics Division (GED), Planning Commission, Government of the People's Republic of Bangladesh http://plancomm.gov.bd/wp-content/uploads/2017/01/SDG-DATA-Gap-Final-Draft.pdf Last accessed 20 March 2018

GED (2017d) Eradicating poverty and promoting prosperity in a changing world. Voluntary National Review (VNR). General Ecnomics Division (GED), Planning Commission, Government of the People's Republic of Bangladesh https://sustainabledevelopment.un.org/content/documents/15826Bangladesh.pdf Last accessed 02 July 2018

Gies, L.; Agusdinata, D. B. & Merwade, V. (2014) Drought adaptation policy development and assessment in East Africa using hydrologic and system dynamics modeling. Natural Hazards, 74, 2 pp789-813 http://dx.doi.org/10.1007/s11069-014-1216-2

Haque, A.; Hossain, D.; Al Azad, A.; Mita, K. S.; Ahmed, T.; Zaman, W. & Sakib, M. N. (2017) Delft3D model documentation for ESPA-Extension project model setup and scenario description. Dhaka, Bangladesh, Bangladesh University of Engineering and Technology

Haque, A.; Kay, S. & Nicholls, R. J. (2018) Present and future fluvial, tidal and storm surge flooding in Coastal Bangladesh. in Nicholls, R. J., Hutton, C. W., Adger, W. N., Hanson, S. E., Rahman, M. M. & Salehin, M. (eds.) Ecosystem Services for Well-Being in Deltas: Integrated Assessment for Policy Analysis. Springer International Publishing, Cham pp293-314 http://dx.doi.org/10.1007/978-3-319-71093-8_16

Haque, A.; Sumaiya, S. & Rahman, M. (2016) Flow distribution and sediment transport mechanism in the estuarine systems of Ganges-Brahmaputra-Meghna delta. International Journal of Environmental Science and Development, 7, 1 pp22-30 http://dx.doi.org/10.7763/IJESD.2016.V7.735

Harrison, P. A.; Dunford, R. W.; Holman, I. P. & Rounsevell, M. D. A. (2016) Climate change impact modelling needs to include cross-sectoral interactions. Nature Climate Change, 6, pp885 http://dx.doi.org/10.1038/nclimate3039

Hordijk, L. (1991) Use of the RAINS model in acid rain negotiations in Europe. Environmental Science and Technology, 25, pp596 - 603 596 http://dx.doi.org/urn:nbn:nl:ui:32-109190

Hordijk, L. & Kroeze, C. (1997) Integrated assessment models for acid rain. European Journal of Operational Research, 102, 3 pp405-417 http://dx.doi.org/10.1016/S0377-2217(97)00229-4

Hutton, C. W.; Nicholls, R. J.; Lázár, A. N.; Chapman, A.; Schaafsma, M. & Salehin, M. (2018) Potential trade-offs between the Sustainable Development Goals in Coastal Bangladesh. Sustainability Science 10, 4 pp1008 http://dx.doi.org/10.3390/su10041108

Kay, S.; Caesar, J.; Wolf, J.; Bricheno, L.; Nicholls, R. J.; Saiful Islam, A. K. M.; Haque, A.; Pardaens, A. & Lowe, J. A. (2015) Modelling the increased frequency of extreme sea levels in the Ganges-Brahmaputra-Meghna delta due to sea level rise and other effects of climate change. Environmental Science: Processes & Impacts, 17, 7 pp1311-1322 http://dx.doi.org/10.1039/C4EM00683F

Lázár, A. N.; Payo, A.; Adams, H.; Ahmed, A.; Allan, A.; Akanda, A. R.; Amoako Johnson, F.; Barbour, E. J.; Biswas, S. K.; Caesar, J.; Chapman, A.; Clarke, D.; Fernandes, J. A.; Haque, A.; Hossain, M. A. R.; Hunt, A.; Hutton, C. W.; Kay, S.; Mukhopadhyay, A.; Nicholls, R. J.; Saleh, A. F. M.; Salehin, M.; Szabo, S. & Whitehead, P. G. (2018) Integrative analysis applying the Delta Dynamic Integrated Emulator Model in South-West Coastal Bangladesh. in Nicholls, R. J., Hutton, C. W., Adger,

W. N., Hanson, S. E., Rahman, M. M. & Salehin, M. (eds.) Ecosystem Services for Well-Being in Deltas: Integrated Assessment for Policy Analysis. Springer International Publishing, Cham pp525-574 http://dx.doi.org/10.1007/978-3-319-71093-8_28

Mainali, B.; Luukkanen, J.; Silveira, S. & Kaivo-oja, J. (2018) Evaluating synergies and trade-offs among Sustainable Development Goals (SDGs): Explorative analyses of development paths in South Asia and Sub-Saharan Africa. Sustainability, 10, 3 http://dx.doi.org/10.3390/su10030815

Nguyen, T. H. (1998) Ecotourism development in Vietnam: A sustainable perspective. Workshop on the Role of ecotourism in sustainable tourism development in Vietnam. April, Hanoi, Vietnam. http://www.mekonginfo.org/

Nicholls, R. J.; Hutton, C. W.; Adger, W. N.; Hanson, S. E.; Rahman, M. M. & Salehin, M. (Eds.) (2018) Ecosystem services for well-being in deltas: Integrated assessment for policy analysis, Palgrave Macmillan, London, UK http://dx.doi.org/10.1007/978-3-319-71093-8

Nicholls, R. J.; Hutton, C. W.; Lázár, A. N.; Allan, A.; Adger, W. N.; Adams, H.; Wolf, J.; Rahman, M. & Salehin, M. (2016) Integrated assessment of social and environmental sustainability dynamics in the Ganges-Brahmaputra-Meghna delta, Bangladesh. Estuarine, Coastal and Shelf Science, 183, Part B, pp370-381 http://dx.doi.org/10.1016/j.ecss.2016.08.017

O'Neill, J. (2011) The growth map: Economic opportunity in the BRICs and beyond, Penguin, London, UK

Payo, A.; Lázár, A. N.; Clarke, D.; Nicholls, R. J.; Bricheno, L.; Mashfiqus, S. & Haque, A. (2017) Modeling daily soil salinity dynamics in response to agricultural and environmental changes in coastal Bangladesh. Earth's Future, 5, pp495–514 http://dx.doi.org/10.1002/2016EF000530

Pelling, M.; O'Brien, K. & Matyas, D. (2015) Adaptation and transformation. Climatic Change, 133, 1 pp113-127 http://dx.doi.org/10.1007/s10584-014-1303-0

Reddy, V. R. & Reddy, B. S. (2007) Land alienation and local communities: Case studies in Hyderabad-Secunderabad. Economic and Political Weekly, 42, 31 pp3233-3240

Sakib, M.; Nihal, F.; Haque, A.; Rahman, M. & Ali, M. (2015) Sundarban as a buffer against storm surge flooding. World Journal of Engineering and Technology, 30, 3 pp59-64 http://dx.doi.org/10.4236/wjet.2015.33C009

Schlüter, M.; McAllister, R. R. J.; Arlinghaus, R.; Bunnefeld, N.; Eisenack, K.; HÖLker, F.; Milner-Gulland, E. J.; MÜLler, B.; Nicholson, E.; Quaas, M. & StÖVen, M. (2012) New horizons for managing the environment: a review of coupled social-ecological systems modeling. Natural Resource Modeling, 25, 1 pp219-272 http://dx.doi.org/10.1111/j.1939-7445.2011.00108.x

Schöpp, W.; Amann, M.; Cofala, J.; Heyes, C. & Klimont, Z. (1998) Integrated assessment of European air pollution emission control strategies. Environmental Modelling & Software, 14, 1 pp1-9 http://dx.doi.org/10.1016/S1364-8152(98)00034-6

Seijger, C.; Douven, W.; Hermans, L. M.; Evers, J.; Phi, H. L.; Brunner, J.; Pols, L.; Ligtvoet, W.; Koole, S.; Slager, K.; Vermoolen, M. S.; Hasan, S.; Hoang, V. T. M. & van Halsema, G. (2016) An analytical framework for strategic delta planning. Journal of Environmental Planning and Management, http://dx.doi.org/urn:NBN:nl:ui:24-uuid:e3b68127-2f3b-4fed-b933-82e0cb2f5fda

Shibayama, T., Tajima, Y., Kakinuma, T., Nobuoka, H., Yasuda, T., Ahsan, R., Rahman, M. & Islam, M. S. (2008) Field survey of storm surge disaster due to Cyclone Sidr in Bangladesh. Proceedings of Coastal Engineering, JSCE, 55, pp1396-1400 http://dx.doi.org/10.2208/proce1989.55.1396

Spencer, N. & Polachek, S. (2015) Hurricane watch: Battening down the effects of the storm on local crop production. Ecological Economics, 120, pp234-240 http://dx.doi.org/10.1016/j.ecolecon.2015.10.006

Szabo, S.; Ahmad, S. & Adger, W. N. (2018) Population dynamics in the south-west of Bangladesh. in Nicholls, R. J., Hutton, C. W., Adger, W. N., Hanson, S. E., Rahman, M. M. & Salehin,

M. (eds.) Ecosystem Services for Well-Being in Deltas: Integrated Assessment for Policy Analysis. Springer International Publishing, Cham pp349-365 http://dx.doi.org/10.1007/978-3-319-71093-8_19

Tuong, T. P.; Humphreys, E.; Khan, Z. H.; Nelson, A.; Mondal, M.; Buisson, M. & George, P. (2014) Messages from the Ganges Basin Development Challenge: Unlocking the production potential of the polders of the Coastal Zone of Bangladesh through water management investment and reform. CPWF Research for Development Series,Paper 9. Dhaka, Bangladesh, http://hdl.handle.net/10568/41708 Last accessed 05 June 2018

United Nations (2015) Paris Agreement. http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf Last accessed March 2018

United Nations (2017) Sustainable Development Goals. 17 goals to transform our world. http://www.un.org/sustainabledevelopment/sustainable-development-goals/

Whitehead, P. G.; Barbour, E.; Futter, M. N.; Sarkar, S.; Rodda, H.; Caesar, J.; Butterfield, D.; Jin, L.; Sinha, R.; Nicholls, R. & Salehin, M. (2015a) Impacts of climate change and socio-economic scenarios on flow and water quality of the Ganges, Brahmaputra and Meghna (GBM) river systems: low flow and flood statistics. Environmental Science: Processes & Impacts, 17, 6 pp1057-1069 http://dx.doi.org/10.1039/C4EM00619D

Whitehead, P. G.; Sarkar, S.; Jin, L.; Futter, M. N.; Caesar, J.; Barbour, E.; Butterfield, D.; Sinha, R.; Nicholls, R.; Hutton, C. & Leckie, H. D. (2015b) Dynamic modeling of the Ganga river system: impacts of future climate and socio-economic change on flows and nitrogen fluxes in India and Bangladesh. Environmental Science: Processes & Impacts, 17, 6 pp1082-1097 http://dx.doi.org/10.1039/C4EM00616J

Xu, H.; Zhang, K.; Shen, J. & Li, Y. (2010) Storm surge simulation along the U.S. East and Gulf Coasts using a multi-scale numerical model approach. Ocean Dynamics, 60, 6 pp1597-1619 http://dx.doi.org/10.1007/s10236-010-0321-3

Zhang, K.; Liu, H.; Li, Y.; Xu, H.; Shen, J.; Rhome, J. & Smith, T. J. (2012) The role of mangroves in attenuating storm surges. Estuarine, Coastal and Shelf Science, 102-103, pp11-23 http://dx.doi.org/10.1016/j.ecss.2012.02.021

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Bangladesh Delta Plan 2100
Analysis of selected interventions

ISBN : 978-984-34-7513-8

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