University of Southampton Research Repository

Copyright © and Moral Rights for this thesis and, where applicable, any accompanying data are retained by the author and/or other copyright owners. A copy can be downloaded for personal non-commercial research or study, without prior permission or charge. This thesis and the accompanying data cannot be reproduced or quoted extensively from without first obtaining permission in writing from the copyright holder/s. The content of the thesis and accompanying research data (where applicable) must not be changed in any way or sold commercially in any format or medium without the formal permission of the copyright holder/s.

When referring to this thesis and any accompanying data, full bibliographic details must be given, e.g.

The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

by

Balaji Angamuthu

Thesis for the degree of Doctor of Philosophy

August 2017
About 500 million people live in the world’s river deltas, which are by definition morphologically active. Hence, an understanding of the geomorphological processes affecting deltas is essential to improve our understanding of the risks that delta populations face. Unfortunately, there is little reliable data on river deltas, meaning that the task of demonstrating the links between morphodynamic and environmental change is challenging. There have been significant human impacts on the morphodynamics of deltas (e.g. reduced sediment inflows, anthropogenic subsidence, etc.) in the past century, and these impacts may intensify in the future. This research aims to answer the questions of how tidal delta morphology evolves over multi-decadal timescales under multiple drivers. A 2D idealised morphodynamic model was developed (in Delft3D) that represents the essential morphological attributes of an idealised tide-dominated delta (inspired by the contemporary GBM delta, a classic tidally dominated delta with highly vulnerable people and environment). A series of model simulations over 100 years, were then used to explore the influence of three key drivers, both individually and together, on deltaic morphodynamics: (i) varying combinations of water and sediment discharges from the upstream catchment, (ii) changes in the rate of relative sea-level rise (RSLR), and (iii) selected human interventions within the delta, such as polders, cross-dams and changing land cover.

Model simulations revealed that all of the drivers considered here influence tidal asymmetry (defined as differences in intensity and duration between ebb and flood tidal flows) over the delta. However, the relative magnitude of flood:ebb flow ratio varies between 0.10 (high fluvial discharge) and 1.0 (Cross-dams). This is important because the tidal asymmetry and rate of sediment supply together effect residual flows, patterns of erosion and accretion, aggradation and progradation of the delta and hence the overall sub-aerial delta morphodynamics. As expected, the area of the simulated sub-aerial delta increases with increasing sediment discharge, but decreases with increasing water discharge. However, delta progradation rates are more sensitive to variations in water discharge than variations in fluvial sediment supply. Human modifications are important. For example, the sub-aerial delta shrinks with increasing RSLR, but it does not when the sub-aerial delta is polderised. Indeed, the use of polders is found to lead to an increase in delta area over time, provided the polders are restricted from erosion. However, the polders are vulnerable to flooding as they lose relative elevation. Cross-dams built to steer zones of land accretion within the delta accomplish their local goal, but may not result in net land gain at the scale of the delta. When these factors were combined, the simulations revealed that the effect of human interventions in the form of cross-dams and polders dominate the pattern of erosion and accretion over the delta with the effect of environmental change such as fluvial discharge and RSLR embedded on top of that.

Lessons learnt for the contemporary GBM delta implies that the cross-dams and polders have been the main control of the morphodynamic evolution of the delta over the last 60 years. However, with likely increased fluvial water discharge and RSLR, sediment starved polders will only increase the vulnerability of the poldered area from regular flooding. But, the future trend of morphological evolution of the GBM delta vastly depends on the local human intervention to the continuing trend of RSLR and varying fluvial discharges. This methodology could be used to analyse the prognosis for other delta types. In summary, this research (i) provides guidelines to understand the drivers stimulating morphodynamic changes on large deltas, (ii) helps to evaluate the possible effects of future scenarios, and (iii) forms a basis to plan future action.
# List of Contents

List of Contents........................................................................................................ iii

List of tables ..................................................................................................................... ix

List of figures .................................................................................................................... xi

Academic Thesis: Declaration Of Authorship............................................................... xxxvii

Acknowledgements ......................................................................................................... xxxix

Definitions and Abbreviations ......................................................................................... xlii

1. The Human Pressures on Global Deltas................................................................. 1

1.1 Past, present and future state of global deltas .............................................. 1

1.1.1 Past state, the beginning .............................................................................. 1

1.1.2 Present state, on-going issues ...................................................................... 1

1.1.3 Future challenges facing the world’s deltas .............................................. 5

1.2 Knowledge of delta morphodynamics ............................................................ 6

1.3 Aims, Objectives and Scope of Research ......................................................... 7

1.4 Inspiration from the Ganges- Brahmaputra-Meghna Delta ......................... 9

1.5 Thesis layout ........................................................................................................... 11

2. Morphological Evolution of the GBM Delta......................................................... 13

2.1 GBM delta .............................................................................................................. 13

2.1.1 Past Morphological Evolution ................................................................... 16

2.1.1.1 Origin of the GBM delta ...................................................................... 16

2.1.1.2 Evolution of delta morphodynamics from the Last Glacial Maximum to the modern time .......................................................... 17

2.1.1.2.1 Influence of relative sea level rise and continental sediment flux on delta evolution .......................................................... 17

2.1.1.2.2 Avulsion and the trajectory of GBM delta building ................. 22

2.1.2 Sediment budget for the GBM delta ............................................................ 24

2.1.3 The Modern delta ........................................................................................... 26

2.1.3.1 The eastern GBM delta ...................................................................... 26

2.1.3.1.1 Morphodynamic changes in the Meghna Estuary since 1776 26

2.1.3.2 The Western GBM delta ................................................................. 37

2.1.3.3 Land cover and land use ................................................................. 39

2.1.3.4 Subsidence ......................................................................................... 40
2.1.3.5 Other human interventions ............................................ 42
2.2 GBM Catchments ............................................................... 44
  2.2.1 Ganges Catchment ....................................................... 45
  2.2.2 Brahmaputra Catchment ................................................. 50
  2.2.3 Meghna Catchment ....................................................... 54
2.3 Bay of Bengal ................................................................. 55
  2.3.1 Sea level rise and tides .................................................. 55
  2.3.2 Storm surges ............................................................... 57
2.4 Summary ........................................................................... 60

3. Deltas – Features, Evolution, Processes and Factors .................. 63
  3.1 Definition, classification and features .................................... 63
    3.1.1 Deltas ......................................................................... 63
    3.1.2 Classification of deltas .................................................. 64
    3.1.3 Features of deltas ........................................................ 66
      3.1.3.1 Distributary channels ............................................... 68
      3.1.3.2 Mouth bars ............................................................ 70
      3.1.3.3 Intertidal plains ....................................................... 71
  3.2 Evolution of deltas ............................................................. 72
    3.2.1 Response of deltas to sea level rise .................................. 72
    3.2.2 Delta growth and abandonment ....................................... 73
    3.2.3 Migration of the sediment feed point ............................... 75
  3.3 Factors and processes affecting delta evolution ....................... 76
    3.3.1 River catchment factors ................................................. 77
      3.3.1.1 River discharge ..................................................... 77
      3.3.1.2 Sediment flux ....................................................... 78
    3.3.2 Receiving basin factors ............................................... 79
      3.3.2.1 Sea level change .................................................... 79
      3.3.2.2 Waves ................................................................. 80
      3.3.2.3 Tides ................................................................. 81
      3.3.2.4 Storm surges ....................................................... 84
    3.3.3 Deltaic factors and processes ......................................... 84
      3.3.3.1 Land cover and land use ......................................... 84
      3.3.3.2 Polder dykes ....................................................... 84
      3.3.3.3 Mangroves .......................................................... 85
      3.3.3.4 Subsidence ......................................................... 86
3.3.1.3.5 Formation of river mouth bars .............................................. 88
3.3.1.3.6 Distributary switching .......................................................... 93
3.3.2 Interaction of factors and processes ........................................... 99
  3.3.2.1 Interaction of river catchment and receiving basin factors ....... 99
  3.3.2.2 Influence of receiving basin depth on delta formation ........ 101
  3.3.2.3 Control of upstream discharge on number of distributaries 102
  3.3.2.4 Control of sediment cohesion on delta shapes ................... 103
3.4 Temporal and spatial scales of delta processes ......................... 104
3.5 Delta evolution in the future ...................................................... 106
  3.5.1 Delta management ................................................................. 107
3.6 Summary ..................................................................................... 109
4. Investigating the evolution of an idealised mega-delta: A model
  based methodological design .......................................................... 113
  4.1 Overview of methodological approach ........................................ 113
  4.2 Model setup ............................................................................... 117
    4.2.1 Starting case model set-up .................................................... 117
      4.2.1.1 Model extent, bathymetry and grid .................................. 118
      4.2.1.2 Boundary conditions ...................................................... 121
      4.2.1.3 Optimising computation efficiency .................................. 125
      4.2.1.4 Model parameters .......................................................... 126
      4.2.1.5 Sensitivity analysis ......................................................... 126
      4.2.1.6 Model run ..................................................................... 127
    4.2.2 Model results ........................................................................ 129
      4.2.2.1 Hydrodynamics of the ideal model ................................. 129
      4.2.2.2 Morphodynamics of the ideal model .............................. 129
  4.3 Design of simulations ................................................................. 133
    4.3.1 Fluvial water and sediment discharge ................................. 134
    4.3.2 Relative Sea Level Rise (RSLR) ............................................ 140
    4.3.3 Human interventions ............................................................. 140
      4.3.3.1 Polders ......................................................................... 141
      4.3.3.2 Cross-dams ................................................................. 141
      4.3.3.3 Changing land cover ...................................................... 142
    4.3.4 Combined effect of environmental change and anthropogenic
        interventions ................................................................. 143
  4.4 Summary ..................................................................................... 143
5. The role of variations in fluvial water and sediment discharges
  in controlling the morphology of tidally influenced deltas ...... 149
5.1 Introduction ........................................................................................................... 149
5.2 Residual flow......................................................................................................... 149
5.3 Morphodynamic changes..................................................................................... 152
  5.3.1 Patterns of erosion and accretion on the delta .............................................. 152
  5.3.2 Progradation and aggradation of the delta ................................................... 167
  5.3.3 Sub-aerial delta area...................................................................................... 174
5.4 Summary............................................................................................................... 187

6. Role of relative sea level rise on the morphodynamics of tidally
  influenced deltas ....................................................................................................... 191
  6.1 Introduction........................................................................................................... 191
  6.2 Residual flow......................................................................................................... 191
  6.3 Morphodynamic changes..................................................................................... 204
    6.3.1 Patterns of erosion and accretion in the delta .............................................. 204
    6.3.2 Progradation and aggradation of the delta ................................................... 216
    6.3.3 Subaerial delta - area, shape and number of islands .............................. 218
  6.4 Discussions........................................................................................................... 226
  6.5 Summary............................................................................................................... 227

7. Impact of human interventions and land cover on tidally
  influenced deltas ....................................................................................................... 231
  7.1 Introduction........................................................................................................... 231
  7.2 Influence of Polders ......................................................................................... 231
    7.2.1 Residual flow.............................................................................................. 231
    7.2.2 Patterns of erosion and accretion over the delta ...................................... 238
    7.2.3 Progradation and aggradation of the delta ................................................. 241
    7.2.4 Morphodynamic changes of the sub-aerial delta .................................... 243
    7.2.5 Discussions............................................................................................... 248
  7.3 Influence of Cross-dams..................................................................................... 248
    7.3.1 Residual flow.............................................................................................. 248
    7.3.2 Patterns of erosion and accretion .............................................................. 256
    7.3.3 Progradation and aggradation of the delta ................................................. 260
    7.3.4 Morphodynamic changes of the sub-aerial delta .................................... 262
    7.3.5 Discussions............................................................................................... 264
  7.4 Influence of roughness (varying land cover)..................................................... 265
    7.4.1 Residual flow.............................................................................................. 265
    7.4.2 Patterns of erosion and accretion .............................................................. 272
    7.4.3 Progradation and aggradation of the delta ................................................. 274
    7.4.4 Morphodynamic changes of the sub-aerial delta .................................... 275
7.4.5 Discussions ................................................................................. 282
7.5 Summary ................................................................................... 283

8. The impacts of variations of multiple drivers on the
morphology of tidally influenced deltas ........................................ 287

8.1 Introduction ............................................................................... 287
8.2 Combined effect of environmental change and anthropogenic
interventions ................................................................................. 287
8.2.1 Residual flow ........................................................................ 288
8.2.2 Patterns of erosion and accretion over the delta ....................... 298
8.2.3 Progradation and aggradation of the delta ................................. 307
8.2.4 Morphodynamics of the sub-aerial delta ................................ 311
8.3 Discussions ............................................................................... 323
8.4 Summary ................................................................................... 324

9. Discussion and conclusion .......................................................... 327

9.1 Introduction ............................................................................... 327
9.2 Lessons derived from the methodological approach ................... 327
9.3 Addressing the research questions ............................................. 328
9.4 Implications for real world tidal-dominated deltas ..................... 349
9.4.1 The modern GBM delta ........................................................ 349
9.4.2 Implications for delta management ........................................ 355
9.5 Limitations and recommendations for further research .............. 357
9.5.1 Limitations of current research .............................................. 357
9.5.2 Recommendations for further research ................................. 358
9.5.2.1 Methodological Approach ............................................... 358
9.5.2.2 Simulating idealised deltas .......................................... 358
9.5.2.3 Applications to real world deltas .................................. 358
9.6 Overall conclusions .................................................................. 359

Appendices ..................................................................................... 363

10. Modelling software (Appendix) ................................................... 365

10.1 Selection of modelling software .............................................. 365
10.2 Description of the Delft3D modelling software ......................... 367
10.3 Modelled water level across varying grid sizes ......................... 370

11. Model parameter sensitivity analysis (Appendix) ......................... 371

12. Model Results (Appendix) .......................................................... 379

12.1 Fluvial discharges ................................................................... 380
12.2 Relative sea level rise ............................................................. 385
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.3</td>
<td>Human interventions</td>
<td>394</td>
</tr>
<tr>
<td>12.3.1</td>
<td>Polder embankments</td>
<td>395</td>
</tr>
<tr>
<td>12.3.2</td>
<td>Cross-dams</td>
<td>397</td>
</tr>
<tr>
<td>12.3.3</td>
<td>Change in landcover roughness</td>
<td>398</td>
</tr>
<tr>
<td>12.4</td>
<td>Conjunctive scenarios</td>
<td>399</td>
</tr>
<tr>
<td></td>
<td><strong>Glossary</strong></td>
<td><strong>409</strong></td>
</tr>
<tr>
<td></td>
<td><strong>List of References</strong></td>
<td><strong>417</strong></td>
</tr>
</tbody>
</table>
List of tables

TABLE 2.1: The origin and early formation of the GBM delta based on information from (Parua, 2010, Lindsay et al., 1991) .......... 17

TABLE 2.2: Net accretion in the Meghna estuary as described in (Sarker et al., 2011) ................................................................. 31

TABLE 2.3: Time required for land development at different locations in the Meghna Estuary. Reproduced from (Sarker et al., 2011) .......... 32

TABLE 2.4: Sedimentation measurements in the Western GBM delta .......... 38

TABLE 2.5: Estimated rate of subsidence in coastal Bangladesh ................. 42

TABLE 2.6: GBM rivers- catchment size, boundaries and rainfall based on information from (Singh, 2008a, Singh, 2008b, Sarker et al., 2003) ................................................................. 45


TABLE 2.8: Observed effective sea level rise and estimated percentage contribution of each factors. Source: (Pethick and Orford, 2013) ............................................................................................................ 56

TABLE 3.1: Characteristics of deltaic depositional systems (Galloway, 1975) .. 67

TABLE 3.2: Causes of avulsion. Part of the table reproduced from (Smith and Rogers, 1999) ................................................................................................................................. 95

TABLE 3.3: A hierarchy of forcings or pulsing events affecting the formation and sustainability of deltas. Source: (Day et al., 2007) .......... 107

TABLE 4.1: Model parameters for runs in this study Note: # - model parameters identified as sensitive to produce a realistic analogue delta .. 128

TABLE 4.2: Combination of varying water and sediment discharge (Options 2b to 2j) ................................................................................................................................. 136
TABLE 4.3: List of varying fluvial discharge simulations ................................. 145

TABLE 4.4: Combination of varying water and sediment discharge (Options 2b
to 2j) .................................................................................................................. 145

TABLE 4.5: List of relative sea level rise simulations ................................. 146

TABLE 4.6: List of direct human intervention and changing land cover
simulations ........................................................................................................ 146

TABLE 4.7: Combination of scenarios of varying fluvial water discharge and
relative sea level rise with polders and cross-dams ............................. 147

TABLE 4.8: Combination of scenarios of varying fluvial sediment discharge and
relative sea level rise with polders and cross-dams ............................. 147

TABLE 8.1: Combination of scenarios of varying fluvial water discharge and
relative sea level rise with polders and cross-dams ......................... 288

TABLE 8.2: Combination of scenarios of varying fluvial sediment discharge and
relative sea level rise with polders and cross-dams ......................... 288

TABLE 10.1: Comparison of commonly used morphodynamic modelling
software. Modified from (Roelvink, 2011) and based on Chen et
al. (2011). ........................................................................................................ 366
List of figures

FIGURE 1.1: Comparison between pre-Anthropocene and modern sediment loads. 1:1 line shows no influence by humans. Other lines indicate modern sediment loads with human influences such as deforestation and/or sediment trapping in reservoirs. Insets show global sediment trapping in large reservoirs. Source: (Syvitski et al., 2005) .................................................. 4

FIGURE 1.2: Relative vulnerability of coastal deltas as shown by the indicative population potentially displaced by current sea-level trends to 2050 (Extreme =>1million; High= 1 million to 50,000; Medium = 50,000 to 5,000. Source: (Nicholls et al., 2007) ..................... 6

FIGURE 1.3: Existing reliability of coastal morphodynamic knowledge. 
Source:(de Groot, 1998) ............................................................. 7

FIGURE 2.1: Major features of the GBM delta........................................ 15

FIGURE 2.2: Coastal plain of Bangladesh. Reproduced from (Saito and Alino, 2008) .............................................................. 16

FIGURE 2.3: Plots of Eustatic sea level, South Asia Aridity index, and GB sediment storage. The hachured area shows period of high regional insolation. Reproduced from (Goodbred and Kuehl, 2000) ................................................................. 19

FIGURE 2.4: Paleo-geographic maps illustrating the Late Quarternary development of the GBM delta. Modified from (Goodbred Jr and Kuehfl, 2000). ................................................................. 21

FIGURE 2.5: Pathways and timing of the phase of late Holocene growth of the lower GBM delta plain formed by the Ganges (G1, G2, and G3), Brahmaputra (B1, B2) and combined Ganges-Brahmaputra (GB1). Modified from (Allison et al., 2003) ............................................. 23

FIGURE 2.6: Isopach map of the Ganges-Brahmaputra sediments deposited in the GBM delta since ca.11,000 yr B.P. Reproduced from (Goodbred and Kuehl, 2000). Note: Dashed lines represent modern river channel and coast. ............................................ 25
FIGURE 2.7: Modern day suspended sediment budget for the GBM Catchment and delta. Flows are $10^6$ t/y. Inset in the source region shows percentage contribution from the source region for the Ganges and its tributaries. Source: (Wasson, 2003)................................. 26

FIGURE 2.8: Maps (1776 & 1943) and satellite images (1973 & 2008) showing the Meghna Estuary. Reproduced from (Sarker et al., 2011)..... 29

FIGURE 2.9: Net accretion in the Meghna Estuary since 1776. Reproduced from (Sarker et al., 2011)................................................................. 30


FIGURE 2.11: Probability distribution function of (a) island size normalized to total island area, (b) island shape factor, (c) island aspect ratio, and (d) nearest-edge distance for the GBM delta between 1943 and 2012 .............................................................. 33


FIGURE 2.13: Coastal embankment re-built in 2014 at the actively eroding north-eastern corner of the Bhola Island. Source: Photo by author, taken during a site visit in May 2014......................... 40

FIGURE 2.14: Major structural features of the Bengal Basin and subsidence measurement sites. Modified after: (Hoque and Alam, 1997), (Sarker, 2012)and (Hanebuth et al., 2013)................................. 42

FIGURE 2.15: Map showing Cross-dams 1 and 2 and the area reclaimed by them (shaded) in the eastern part of the Meghna Estuary. Source: (Islam, 1971) ............................................................... 43

FIGURE 2.16: Map showing the course of Ganges, Brahmaputra and Meghna rivers and their major tributaries. The catchments of each river are shown in different colours. The red colour circle shows the Eastern Himalayan Syntaxis. Brahmaputra River, 2013. [online]
FIGURE 2.17: Longitudinal elevation profile of the Ganga River main stream. The sharp break in the slope indicates the river transitioning from the Himalayas to its alluvial plain. Reproduced from (Singh, 2008a).

FIGURE 2.18: (a) Ganges basin averaged rainfall and (b) discharge of the Ganges at Hardinge Bridge for two periods: pre-Farakka Barrage, 1951–1974 (solid) and post-Farakka Barrage 1975–2004 (dashed). Source: (Jian et al., 2009).

FIGURE 2.19: Pre-Farakka (before 1975) and Post-Farakka annual peak water discharge of the Ganges at Hardinge Bridge (1934-1998). Horizontal dashed line indicates mean peak water discharge of the above two periods. Source: (Mirza, 2004).

FIGURE 2.20: Suspended sediment rating curve for the Ganges River at Hardinge Bridge based on observations between 1979 and 1995. Source: (Islam et al., 1999).

FIGURE 2.21: Landuse in northern India in 1870 (lower) and 1970 (upper) based on (Richards et al., 1985).

FIGURE 2.22: Longitudinal elevation and water discharge profile of the Brahmaputra River main stream. See FIGURE 2.16 for the location of the Eastern Syntaxis. Reproduced from (Singh, 2008b).


FIGURE 2.24: Suspended sediment rating curves for the Brahmaputra River at Bahadurabad (left) and for the Ganges-Brahmaputra Rivers at Mawa (right) based on observations taken between 1979 and 1995. Source: (Islam et al., 1999).
FIGURE 2.25: Erosion rates of the different parts of the Brahmaputra River Catchment. See FIGURE 2.16 for the location of Eastern Syntaxis. Reproduced from (Singh, 2008b) ........................................ 54

FIGURE 2.26: Different types of cyclonic storm that hit the GBM Delta between 1890 and 2009. Source: (Hossain, 2012) ...................... 59

FIGURE 2.27: Frequency of cyclonic storm in the GBM Delta in 10 year period between 1890 and 2009. Source: (Hossain, 2012) .............. 59

FIGURE 2.28: Yearly time series of Accumulated Cyclone Energy (ACE) of cyclones hitting the GBM delta since 1877 based on (Knapp and Kruk, 2009) ................................................................. 59

FIGURE 2.29: Monthly distribution of recorded cyclonic storm in the GBM Delta between 1584 and 2009. Source: (Hossain, 2012) ............ 60

FIGURE 3.1: Triangular classification of deltas based on relative amounts of fluvial, wave and tidal influence. Source: (Syvitski and Saito, 2007) modified after Galloway (1975) ................................................. 65

FIGURE 3.2: Orton and Reading’s delta classification scheme based on the Galloway diagram with consideration of prevailing grain size. Source: (Orton and Reading, 1993) ................................................. 66

FIGURE 3.3: Basic environments of fluvial, tide and wave-dominated deltas. Source: (Gupta, 2011) ................................................................. 67

FIGURE 3.4: The major physiographic and morphologic features of tide-dominated delta systems in cross-section. The scope of this research is limited to the lower delta plain (shown in red dashed line). Source: (Goodbred and Saito, 2012) ...................... 68

FIGURE 3.5: Types of end-member distributary channel patterns. Source: (Coleman and Wright, 1975) ................................................................. 69

FIGURE 3.6: Major types of river mouth bars. Source: (Coleman and Wright, 1975) ................................................................. 70

FIGURE 3.7: A schematic cross-section of the reconstruction of the response of Asian megadeltas to sea-level change during the Holocene and
hypothetical prediction of their response to future sea level rise. Source: (Woodroffe et al., 2006)

FIGURE 3.8: Longitudinal section of deltas showing response to sea level rise: (a) stable sea level; and (b) steadily rising sea level. Source: (Hori and Saito, 2008)

FIGURE 3.9: A graphic representation of the delta cycle stressing processes and responses in the river-dominated regressive and marine-dominated transgressive phases of development. Source: (Roberts, 1997)

FIGURE 3.10: Plan view of the evolution of fluvial, wave and tide dominated deltas. Source: (Hori and Saito, 2008)

FIGURE 3.11: Schematisation of two types of delta in plan view: (a) With a fixed sediment feed point and (b) with a downstream-migrating sediment feed point. Source: (Kim et al., 2009)


FIGURE 3.13: Contrasting relative sea level change observations from the 19th to the early 21st centuries. Source: (Nicholls et al., 2014)

FIGURE 3.14: Mean wave height versus mean tidal range for major large river deltas. Source: (Goodbred and Saito, 2012)

FIGURE 3.15: Modeled bathymetric and velocity field evolution during river mouth bar formation (Edmonds and Slingerland, 2007). In the figure, A - river mouth bar progrades, B - river mouth bar stops prograding and levees grows basinward and C - river mouth bar aggrades and widens and cause the levees to spread.

FIGURE 3.16: Conceptual formation and evolution of mouth bars and terminal distributary channels. Source: (Olariu and Bhattacharya, 2006b)

FIGURE 3.17: Initiation of deltaic avulsion due to river mouth bar stagnation, bed and water surface aggradation (Edmonds et al., 2009).
Circled numbers 1, 2, and 3 are three locations shown in the location plan.

FIGURE 3.18: Numerical modelling of delta morphology after 7.5 simulated years for various hydraulic and sedimentary forcing types. Source: (Geleynse et al., 2011) Symbols shown in the figure are: $\alpha$ mean distributary depth, $\beta$ sinuosity, $\gamma$ shoreline roughness, $\delta$ subaerial delta volume, $\epsilon$ river valley width, $\zeta$ longitudinal slope.

FIGURE 3.19: Numerical simulation of initial delta formation. SIM A – simulation with shallow receiving basin and SIM B – simulation with deep receiving basin. Source: (Storms, 2007)

FIGURE 3.20: Shoreline traces of simulated deltas. The relative positions of the tracings reflect their position in the parameter space where total cohesion increases from bottom right to upper left. Source: (Edmonds and Slingerland, 2010)

FIGURE 3.21: Spatial and temporal variability in natural and socio-economic processes. Source: (Woodroffe et al., 2006)

FIGURE 3.22: Coastal tract cascade. Source: (Brommer and Bochev-van der Burgh, 2009) after (Cowell et al., 2003)

FIGURE 3.23: Influencing factors and processes on delta morphodynamics. The factors and processes highlighted in bold text will be considered in this thesis.

FIGURE 4.1: Diagrammatic overview of the methodology.

FIGURE 4.2: 1943 map of the GBM delta. Brown lines are land boundaries and blue shades are watercourses.

FIGURE 4.3: A sketch of the schematised 2D model (not to scale): (a) geometry (top view) see FIGURE 4.2 for the basis of selection, and (b) initial bathymetry (longitudinal view) based on BWDB 2000s bathymetric survey of lower Meghna River and Meghna Estuary.
FIGURE 4.4: Best fit regression plot for the observed daily water discharge vs sand sediment in the Padma River at Baruria Transit .......... 122

FIGURE 4.5: Best fit regression plot for the observed daily water discharge vs silt and clay sediment in the Padma River at Baruria Transit .. 122

FIGURE 4.6: Dominant discharge plot for the Padma River at Baruria Transit 124

FIGURE 4.7: Cumulative sediment load curves for the Padma River at Baruria Transit ................................................................. 124

FIGURE 4.8: Flow duration curve for Padma River at Baruria Transit 1968-2012 ................................................................................. 125

FIGURE 4.9: Location plan of longitudinal section of the idealised delta...... 130

FIGURE 4.10: Longitudinal section of modelled delta bed level through its centre (x-x) during the starting case simulation. Figure shows delta evolution reaching equilibrium. See FIGURE 4.9 for location X-X ........................................................................................................ 130

FIGURE 4.11: Probability distribution function of island size normalised to total island area for the GBM delta in 1943 and modelled idealised tidal delta ................................................................. 132

FIGURE 4.12: Probability distribution function of island shape factor for the GBM delta in 1943 and modelled idealised tidal delta .......... 132

FIGURE 4.13: Probability distribution function of island aspect ratio for the GBM delta in 1943 and modelled idealised tidal delta ............ 133

FIGURE 4.14: Probability distribution function of nearest-edge distance for the GBM delta in 1943 and modelled idealised tidal delta .......... 133

FIGURE 4.15: Fluvial water and sediment discharge constant over time....... 136

FIGURE 4.16: A schematic representation of the typical trajectory of change in sediment discharge in response to various catchment influencing factors. Modified from (Walling, 2011) ............... 137

FIGURE 4.17: Sediment concentration of sand for the experimental 100 years. ..................................................................................... 138
FIGURE 4.18: Sediment concentration of silt for the experimental 100 years.

FIGURE 4.19: Scenarios of relative sea rise for the experimental 100 years.

FIGURE 4.20: Initial condition of the model for the scenario with polders.

FIGURE 4.21: Initial condition of the model for the scenario with cross-dams.

FIGURE 4.22: Initial condition of the model for the scenario with land cover.

FIGURE 5.1: Time series of modelled water level (A), velocity (B), water discharge (C), bed level (D), bed (E) and suspended load transport (F) at the delta apex for the initial condition and after 100 years of simulation for: water discharge scenarios: 2e (1Qw:2Qs), 2f-basecase (2Qw:2Qs), 2g (3Qw:2Qs) and sediment discharge scenarios: 2c (2Qw:1Qs), 2i (1Qw:3Qs) Note: Water discharge, Qw = 32,500m^3/s; sediment discharge, Qs = 0.74m^3/s.

FIGURE 5.2: Ratio of flood to ebb flow in a tidal cycle at the delta apex during the initial condition and after 100 years of simulation for varying water and sediment discharge scenarios: 2b(1Qw:1Qs), 2c(2Qw:1Qs), 2d(3Qw:1Qs), 2e(1Qw:2Qs), 2f(2Qw:2Qs), 2g(3Qw:2Qs), 2h(1Qw:3Qs), 2i(2Qw:3Qs), 2j(3Qw:3Qs).

FIGURE 5.3: Location of tidal flow observation points (brown colour) and spatial distribution of tidal flood to ebb flow ratio (blue colour) in the delta after 100 years of simulation.

FIGURE 5.4: Ratio of flood to ebb flow in a tidal cycle for varying water discharge scenarios after 100 years of simulation: 2g(3Qw:2Qs), 2f(2Qw:2Qs) and 2e(1Qw:2Qs). See FIGURE 5.3 for the location of observation points.

FIGURE 5.5: Ratio of water to sediment discharge for scenarios after 100 years of simulation: 2c(2Qw:1Qs), 2g(3Qw:2Qs), 2f(2Qw:2Qs), 2i(2Qw:3Qs), 2e(1Qw:2Qs) at observation points 1 (A), 14 (B),
16(C), 6(D), 7(E), 10(F), 13(G). See FIGURE 5.3 for the location of observation points ................................................................. 159

FIGURE 5.6: Water discharge through eroding channel at its top end after 25 years for scenarios: 2c (2Qw:1Qs), 2e (1Qw:2Qs), 2f (base case-2Qw:2Qs), 2g (3Qw:2Qs) and 2i (2Qw:3Qs). ............................................ 162

FIGURE 5.7: Water discharge through eroding channel at its top end for scenario: 2f-base case (2Qw:2Qs) ................................................................. 163

FIGURE 5.8: Water discharge through eroding channel at its bottom end for scenario: 2f-base case (2Qw:2Qs) ................................................................. 163

FIGURE 5.9: Net volume of accretion and erosion against the depth of accretion and erosion after 100 years for scenarios: 2c(A1&A2), 2f(B1&B2), 2i(C1&C2), 2e(D1&D2), 2g(E1&E2) Note: Water discharge, Qw= 32,500m³/s; sediment discharge, Qs = 0.74m³/s ....................... 164

FIGURE 5.10: Total volume change in the delta area for “2” scenarios after 100 years ...................................................................................... 166

FIGURE 5.11: Net volume change in the delta for “2” scenarios after 100 years ...................................................................................... 166

FIGURE 5.12: Location plan of longitudinal and cross sections of the idealised delta ................................................................................. 167

FIGURE 5.13: Longitudinal section of the delta through its centre (x-x) for varying water discharge scenarios: 2e (1Qw:2Qs), 2f-base case (2Qw:2Qs) and 2g (3Qw:2Qs). See FIGURE 5.12 for location . 169

FIGURE 5.14: Time-series plot of clinoform slope angle for the experimental scenarios of varying fluvial sediment discharge ....................... 169

FIGURE 5.15: Longitudinal section of the delta through its centre (x-x) for varying sediment discharge scenarios: 2c (2Qw:1Qs), 2f-base case (2Qw:2Qs) and 2i (2Qw:3Qs). See FIGURE 5.12 for location ................................................................................................. 170

FIGURE 5.16: Cross section of the delta at location1-1 for initial condition and after 100 years of simulation. See FIGURE 5.12 for location . 171
FIGURE 5.17: Cross section of the delta at location 2-2 for initial condition and after 100 years of simulation. See FIGURE 5.12 for location... 172

FIGURE 5.18: Cross section of the delta at location 3-3 for initial condition and after 100 years of simulation. See FIGURE 5.12 for location... 173

FIGURE 5.19: Time-series of sediment discharge at location 10 (A, B) and 15 (C, D) after 100 years. See FIGURE 5.3 for the location of observation points 10 and 15... 176

FIGURE 5.20: Area and rate of accretion and erosion over delta land area for scenarios of varying water discharge: 2e(1Qw:2Qs), 2f- base case(2Qw:2Qs) 2g (3Qw:2Qs) (Water discharge, Qw= 32,500m$^3$/s: sediment discharge = 0.74m$^3$/s)... 177

FIGURE 5.21: Area and rate of accretion and erosion over delta land area for scenarios of varying sediment discharge: 2a(2Qw:0Qs), 2c(2Qw:1Qs), 2f-base case (2Qw:2Qs), 2i(2Qw:3Qs) (Water discharge, Qw= 32,500m$^3$/s: sediment discharge = 0.74m$^3$/s)... 178

FIGURE 5.22: Comparison of sub-aerial delta land constructed between the initial state and after 100 years of the simulation for the base case (2f; 2Qw:2Qs) scenario. The net change in sub-aerial delta extent over this time period for this base case scenario is +21 km$^2$, compared to the initial delta extent of 694 km$^2$... 179

FIGURE 5.23: Time series of absolute change and percentage variation of modelled delta land area over 100 years from the total initial land area for 2 series experiments ... 181

FIGURE 5.24: Net change in sub-aerial delta area after 100 years as a function of Q varying water and sediment discharges ... 182

FIGURE 5.25: Probability distribution function of island size normalised to total island area for the experimental scenarios of varying fluvial water discharge... 183
FIGURE 5.26: Probability distribution function of island size normalised to total island area for the experimental scenarios of varying fluvial sediment discharge ................................................................. 183

FIGURE 5.27: Probability distribution function of island aspect ratio for the experimental scenarios of varying fluvial water discharge ..... 184

FIGURE 5.28: Probability distribution function of island aspect ratio for the experimental scenarios of varying fluvial sediment discharge 184

FIGURE 5.29: Probability distribution function of island shape factor for the experimental scenarios of varying fluvial water discharge ..... 185

FIGURE 5.30: Probability distribution function of island shape factor for the experimental scenarios of varying fluvial sediment discharge 185

FIGURE 5.31: Probability distribution function of nearest-edge distance for the experimental scenarios of varying fluvial water discharge ..... 186

FIGURE 6.1: Time series of modelled water level (A), velocity (B), water discharge (C), bed level (D), bed (E) and suspended load transport (F) at the delta apex for initial and after 100 years of simulation for relative sea level rise (RSLR) scenarios: Base case- 2f(RSLR=0mm/y), 3a(RSLR=5mm/y), 3b(RSLR=10mm/y), 3c(RSLR=15mm/y), and 3d(RSLR=20mm/y) ......................... 193

FIGURE 6.2: Modelled ratio of flood to ebb flow of water and sediment for the initial condition and after 100 years for the base case (2f;RSLR=0mm/y) and relative sea level rise scenarios (3a:5mm/y, 3b:100mm/y, 3c:15mm/y, 3d:20mm/y)................. 194

FIGURE 6.3: Sediment accommodation space and its relationship to relative sea level rise (Source: (Coe, 2003)).......................... 195

FIGURE 6.4: Morphodynamic response of shorelines to varying relative sea level rise and rate of sediment supply after (Posamentier, 1999) ... 195

FIGURE 6.5: Maximum flow velocity in the delta area during high and low tide of initial condition and after 100 years for base case- 2f(RSLR=0mm/y) and sea level rise scenarios: (3a:5mm/y, 3b:100mm/y, 3c:15mm/y, 3d:20mm/y)................................. 196

xxi
FIGURE 6.6: Spatial distribution of flow velocity over the delta during high tides for scenarios: Initial (A), 3a at 25y (RSLR=0.125m) (B), 3a at 50y (RSLR=0.25m) (C), 3a at 75y (RSLR=0.375m) (D), 3a at 100y (RSLR=0.5m) (E) and base case 2f at 100y (RSLR=0m) (F) ...... 198

FIGURE 6.7: Spatial distribution of flow velocity over the delta during high tides for scenarios: Initial (A), 3d at 25y (RSLR=0.5m) (B), 3d at 50y (RSLR=1m) (C), 3d at 75y (RSLR=1.5m) (D), 3d at 100y (RSLR=2m) (E) and base case 2f at 100y (RSLR=0mm) (F) ...... 199

FIGURE 6.8: Spatial distribution of flow velocity over the delta during high tides for scenarios: Initial (A), 3a at 100y (RSLR=0.5m) (B), 3b at 100y (RSLR=1m) (C), 3c at 75y (RSLR=1.5m) (D), 3d at 100y (RSLR=2m) (E) and base case 2f at 100y (RSLR=0mm) (F) ..... 200

FIGURE 6.9: Spatial distribution of water depth over the sub-aerial delta during high tides for scenarios: Initial (A), 3a at 25y (RSLR=0.125m) (B), 3a at 50y (RSLR=0.25m) (C), 3a at 75y (RSLR=0.375m) (D), 3a at 100y (RSLR=0.5m) (E) and base case 2f at 100y (RSLR=0m) (F) .......................................................... 201

FIGURE 6.10: Spatial distribution of water depth over the sub-aerial delta during high tides for scenarios: Initial (A), 3d at 25y (RSLR=0.5m) (B), 3d at 50y (RSLR=1m) (C), 3d at 75y (RSLR=1.5m) (D), 3d at 100y (RSLR=2m) (E) and base case 2f at 100y (RSLR=0mm) (F) .......................................................... 202

FIGURE 6.11: Spatial distribution of water depth over the sub-aerial delta during high tides for scenarios: Initial (A), 3a at 100y (RSLR=0.5m) (B), 3b at 100y (RSLR=1m) (C), 3c at 75y (RSLR=1.5m) (D), 3d at 100y (RSLR=2m) (E) and base case 2f at 100y (RSLR=0mm) (F) .......................................................... 203

FIGURE 6.12: Elevation of the delta for scenarios: Initial (A), 3a at 25y (RSLR=0.125m) (B), 3a at 50y (RSLR=0.25m) (C), 3a at 75y (RSLR=0.375m) (D), 3a at 100y (RSLR=0.5m) and base case 2f at 100y (RSLR=0m) (F) .......................................................... 207
FIGURE 6.13: Elevation of the delta for scenarios: Initial (A), 3d at 25y (RSLR=0.5m) (B), 3d at 50y (RSLR=1m) (C), 3d at 75y (RSLR=1.5m) (D), 3d at 100y (RSLR=2m) and base case-2f at 100y (RSLR=0mm) (F) ................................................................. 208

FIGURE 6.14: Elevation of the delta for scenarios: Initial (A), 3a at 100y (RSLR=0.5m) (B), 3b at 100y (RSLR=1m) (C), 3c at 75y (RSLR=1.5m) (D), 3d at 100y (RSLR=2m) and base case-2f at 100y (RSLR=0mm) (F) ................................................................. 209

FIGURE 6.15: Net volume of accretion and erosion against the depth of accretion and erosion after 100 years for scenarios: Base case-2f(SLR=0mm/y), 3a(SLR=5mm/y), 3b(SLR=10mm/y), 3c(SLR=15mm/y), 3d(SLR=20mm/y) ................................................................. 210

FIGURE 6.16: Cumulative volume of accretion (A), erosion (B) and net change (C) in the delta for scenarios (Basecase (0mm/y), 3a:5mm/y, 3b:100mm/y, 3c:15mm/y, 3d:20mm/y) ................................................................. 213

FIGURE 6.17: Hypsometric curve showing area vs elevation of the delta for scenarios: Initial and after 100 years for Base case-2f (RSLR=0mm/y), 3a (RSLR=5mm/y) and 3d (RSLR=20mm/y) (A) over sub-aerial and sub-aqueous delta,(B) over and near sub-aerial delta, (C) time series of delta land building trajectory as a function of rate of sea level rise .................................................. 215

FIGURE 6.18: Ground elevation and bathymetry for the base case scenario (2f;RSLR=0mm/y) after 100 years of simulation. Location plan of longitudinal and cross sections of delta ........................................... 216

FIGURE 6.19: Longitudinal section of the delta through its centre (x-x) for various sea level rise scenarios after 100 years: 3a (RSLR=0.5m @ 5mm/y), 3b (RSLR=1m @ 10mm/y), 3c RSLR=1.5m @15mm/y), 3d (RSLR=2m, 20mm/y) 2f-basecase (RSLR=0). See FIGURE 6.18 for the location of longitudinal section line x-x. 217

FIGURE 6.20: Cross section of the delta at location1-1 See FIGURE 6.18 for location ............................................................................................................ 218
FIGURE 6.21: Cross section of the delta at location 3. See FIGURE 6.18 for location .............................................................. 218

FIGURE 6.22: Area and mean rate of accretion and erosion over sub-aerial delta
Note: Base case-2f (RSLR= 0mm/y), 3a (RSLR=5mm/y), 3b (RSLR=10mm/y), 3c (RSLR=15mm/y) and 3d (RSLR=20mm/y) 220

FIGURE 6.23: Time series of simulated sub-aerial delta area for sea level rise scenarios Base case-2f (RSLR= 0mm/y), 3a (RSLR=5mm/y), 3b (RSLR=10mm/y), 3c (RSLR=15mm/y) and 3d (RSLR=20mm/y) 221

FIGURE 6.24: Percentage change in initial sub-aerial delta area after 100 years as a function of relative sea level rise for scenarios: Base case-2f (RSLR= 0mm/y), 3a (RSLR=5mm/y), 3b (RSLR=10mm/y), 3c (RSLR=15mm/y) and 3d (RSLR=20mm/y) .......................... 222

FIGURE 6.25: Elevation vs sub-aerial delta area relationship for base case (2f; RSLR=0mm/y) after 100 years .......................................................... 222

FIGURE 6.26: Probability distribution function of island size normalised to total island area for the experimental scenarios of varying rates of sea level rise ................................................................. 223

FIGURE 6.27: Probability distribution function of island shape factor for the experimental scenarios of varying rates of sea level rise........ 223

FIGURE 6.28: Probability distribution function of island aspect ratio for the experimental scenarios of varying rates of sea level rise....... 224

FIGURE 6.29: Probability distribution function of nearest-edge distance for the experimental scenarios of varying rates of sea level rise....... 224

FIGURE 6.30: Time series of number of deltaic islands in sub-aerial delta for sea level rise scenarios: Base case-2f (RSLR= 0mm/y), 3a (RSLR=5mm/y), 3b (RSLR=10mm/y), 3c (RSLR=15mm/y) and 3d (RSLR=20mm/y) ......................................................... 225

FIGURE 6.31: Plot of island shape factor in sub-aerial delta for sea level rise scenarios: Base case-2f (RSLR= 0mm/y), 3a (RSLR=5mm/y), 3b (RSLR=10mm/y), 3c (RSLR=15mm/y) and 3d (RSLR=20mm/y) 226
FIGURE 7.1: Location of tidal flow observation points (brown colour) and spatial distribution of tidal flood to ebb flow ratio (blue colour) in the delta after 100 years for scenarios: (X) – basecase (2f- no interventions) and (Y) – 4a (With polders) ............................... 233

FIGURE 7.2: Spatial distribution of flow velocity over the delta during low tides for scenarios: Initial (A), 4a (with polders) at 100y (B), and base case-2f (no interventions) at 100y (C) and during high tides for scenarios: Initial (D), 4a (with polders) at 100y (E), and base case-2f (no interventions) at 100y (F) ................................................................. 234

FIGURE 7.3: Spatial distribution of water depth over the sub-aerial delta during high tides for scenarios: Initial (A), 4a (with polders) at 25y (B), at 50y(C), at 75y (D), at 100y (E), and base case-2f (no interventions) at 100y (F) ............................................................................. 235

FIGURE 7.4: Ratio of water to sediment discharge for scenarios: basecase (2f- no interventions) and 4a (with polders) at observation points 2 (A), 15 (B), 6(C). See FIGURE 7.1 for the locations of the identified observation points ................................................................. 236

FIGURE 7.5: Ratio of water to sediment discharge for scenarios: basecase (2f- no interventions) and 4a (with polders) at observation points 8 (A), 9 (B), 12(C). See FIGURE 7.1 for the locations of the identified observation points ................................................................. 237

FIGURE 7.6: Net volume of accretion and erosion against the depth of accretion and erosion after 100 years for scenarios: Base case-2f(no human interventions), and 4a (with polders) ........................................ 239

FIGURE 7.7: Elevation of the delta for scenarios: Initial (A), 4a (with polders) at 25y (B), at 50y (C), 75y (D), at 100y (E) and base case-2f (no human interventions) at 100y (F)............................................................ 240

FIGURE 7.8: Ground elevation and bathymetry for the base case scenario (2f; no human interventions) after 100 years of simulation. Location plan of longitudinal and cross sections of delta ....................... 241
FIGURE 7.9: Longitudinal section of the delta through its centre (x-x) for scenarios: Initial, base case (2f- no human interventions) and with polders (4a). FIGURE 7.8 for location X-X.......................... 241

FIGURE 7.10: Cross section of the delta at locations 1-1 (A), 2-2 (B) and 3-3 (C) for scenarios: Initial, base case (2f- no human interventions) and with polders (4a). See FIGURE 7.8 for location of cross-sections ............................................................... 242

FIGURE 7.11: Area and mean rate of accretion and erosion over sub-aerial delta for scenarios: 4a (polder), 4b (cross-dam), 4c (higher roughness land cover) and base case (2f-no interventions) ...................... 245

FIGURE 7.12: Comparison of sub-aerial delta land constructed between the initial state and after 100 years of the simulation for the polders (4a) scenario. The net change in sub-aerial delta extent over this time period for this polders scenario is +92 km², compared to the initial delta extent of 694 km². ......................................................... 246

FIGURE 7.13: Time-series of simulated sub-aerial delta area for scenarios with human interventions: 4a (with polders) and 4b (with cross-dams) and 4c (higher roughness land cover) compared with base case scenario (2f-no interventions)......................................................... 247

FIGURE 7.14: Time-series of sum of sub-aerial delta islands perimeter for scenarios with human interventions: 4a (with polders) and 4b (with cross-dams) and 4c (higher roughness land cover) compared with base case scenario (2f-no interventions)...... 247

FIGURE 7.15: Location of tidal flow observation points (brown colour) and spatial distribution of tidal flood to ebb flow ratio (blue colour) in the delta after 100 years for scenarios: (X) – basecase (2f- no interventions) and (Y) – 4b (With cross-dams) ......................... 250

FIGURE 7.16: Ratio of water to sediment discharge for scenarios: basecase (2f-no interventions) and 4b (with cross-dams) at observation points 1 (A), 5 (B), 14(C). See FIGURE 7.15 for the location of observation points ................................................................. 251
FIGURE 7.17: Ratio of water to sediment discharge for scenarios: basecase (2f-no interventions) and 4b (with cross-dams) at observation points 16 (A), 7 (B), 11(C). See FIGURE 7.15 for the location of observation points .......................................................... 252

FIGURE 7.18: Spatial distribution of flow velocity over the delta during low tides for scenarios: Initial (A), 4b (with cross-dams) at 25y (B), at 50y (C), at 75y (D), at 100y (E), and base case-2f (no interventions) at 100y (F). Dashed black oval lines indicates the evolution of channel over time for 4b (with cross-dams) scenario. .......... 253

FIGURE 7.19: Spatial distribution of flow velocity over the delta during high tides for scenarios: Initial (A), 4b (with cross-dams) at 25y (B), at 50y (C), at 75y (D), at 100y (E), and base case-2f (no interventions) at 100y (F) .......................................................... 254

FIGURE 7.20: Spatial distribution of water depth over the sub-aerial delta during high tides for scenarios: Initial (A), 4a (with cross-dams) at 25y (B), at 50y(C), at 75y (D), at 100y (E), and base case-2f (no interventions) at 100y (F) .................................................................................. 255

FIGURE 7.21: Water discharges for scenarios: basecase (2f- no interventions) and 4b (with cross-dams) at observation points 4 (A), 5 (B), 15(C). See FIGURE 7.15 for the location of observation points 258

FIGURE 7.22: Net volume of accretion and erosion against the depth of accretion and erosion after 100 years for scenarios: Base case (2f-no interventions) (A1 &A2) and 4b (with cross-dams) (B1 &B2) .......................................................................................... 259

FIGURE 7.23: Longitudinal section of the delta through its centre (x-x) for cross-dams (4b) scenario. See FIGURE 7.8 for location X-X..... 260

FIGURE 7.24: Cross section of the delta at locations 1-1, 2-2 and 3-3 See FIGURE 7.8 for location of cross-sections. Dashed green circle indicates deposition and purple box indicates erosion .......... 261

FIGURE 7.25: Comparison of sub-aerial delta land constructed between the initial state and after 100 years of the simulation for the cross-dams (4b) scenario. The net change in sub-aerial delta extent xxvii
over this time period for this cross-dams scenario is -21 km², compared to the initial delta extent of 694 km².

FIGURE 7.26: Water discharges for scenarios: basecase (2f- lower roughness land cover) and 4c (higher roughness land cover) at observation points 4 (A), 8 (B) and 15(C). See FIGURE 7.27 for the locations.

FIGURE 7.27: Location of tidal flow observation points (brown colour) and spatial distribution of tidal flood to ebb flow ratio (blue colour) in the delta after 100 years for scenarios: (X) – basecase (2f- lower roughness land cover) and (Y) – 4c (higher roughness land cover).

FIGURE 7.28: Ratio of water to sediment discharge for scenarios: basecase (2f- lower roughness land cover) and 4c (higher roughness land cover) at observation points 1 (A), 3 (B), 15(C). See FIGURE 7.27 for the location of observation points.

FIGURE 7.29: Ratio of water to sediment discharge for scenarios: basecase (2f- lower roughness land cover) and 4c (higher roughness land cover) at observation points 6 (A), 8 (B), 13(C). See FIGURE 7.27 for the location of observation points.

FIGURE 7.30: Spatial distribution of flow velocity over the delta during low tides for scenarios: Initial (A), 4c (higher roughness land cover) at 100y (B), and base case-2f (lower roughness land cover) at 100y (C) and during high tides for scenarios: Initial (D), 4c (higher roughness land cover) at 100y (E), and base case-2f (lower roughness land cover) at 100y (F).

FIGURE 7.31: Net volume of accretion and erosion against the depth of accretion and erosion after 100 years for scenarios: Base case (2f-lower roughness land cover) (A1&A2) and 4c (higher roughness land cover) (B1 &B2).

FIGURE 7.32: Longitudinal section of the delta through its centre (x-x) for higher roughness land cover (4c) scenario. See FIGURE 7.8 for location X-X.
FIGURE 7.33: Cross section of the delta at locations 1-1, 2-2 and 3-3 See FIGURE 7.8 for cross-section locations. Dashed green circle indicates greater channel erosion ........................................ 275

FIGURE 7.34: Comparison of sub-aerial delta land constructed between the initial state and after 100 years of the simulation for the higher roughness land cover (4c) scenario. The net change in sub-aerial delta extent over this time period for this land cover scenario is \(-36 \text{ km}^2\), compared to the initial delta extent of \(694 \text{ km}^2\).................. 276

FIGURE 7.35: Probability distribution function of island size normalised to total island area for the modelled delta with polders.................. 278

FIGURE 7.36: Probability distribution function of island size normalised to total island area for the modelled delta with cross-dams............. 278

FIGURE 7.37: Probability distribution function of island size normalised to total island area for the modelled delta with changing landcover roughness (LC)~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~ 279

FIGURE 7.38: Probability distribution function of island shape factor for the modelled delta with and without human interventions .......... 280

FIGURE 7.39: Probability distribution function of island aspect ratio for the modelled delta with and without human interventions .......... 280

FIGURE 7.40: Probability distribution function of nearest-edge distance for the modelled delta with polders, and cross-dams.................. 281

FIGURE 7.41: Probability distribution function of nearest-edge distance for the modelled delta with changing landcover roughness .......... 282

FIGURE 8.1: Location of tidal flow observation points (brown colour) and spatial distribution of tidal flood to ebb flow ratio (blue colour) in the delta after 100 years for scenarios: (X) – basecase (2f- no interventions within the delta) and (Y) – 5a(With polders and cross-dams)................................................................. 291

FIGURE 8.2: Location of tidal flow observation points (brown colour) and spatial distribution of tidal flood to ebb flow ratio (blue colour) in the delta after 100 years for scenarios: (X) – basecase (2f- no
interactions within the delta, RSLR=0m, 2Qw=65,000m³/s) and
(Y) With polders and cross-dams: 6b(2Qs:1Qw;10rslr),
5b(2Qs:2Qw;10rslr), 6e (2Qs:3Qw;10rslr).............................. 292

FIGURE 8.3: Ratio of water to sediment discharge after 100 years at
observation location 2. See FIGURE 8.2 for the location of
observation point.............................................................. 294

FIGURE 8.4: Ratio of water to sediment discharge after 100 years at
observation location 6 See FIGURE 8.2 for the location of
observation point.............................................................. 296

FIGURE 8.5: Ratio of water to sediment discharge after 100 years at
observation location 10. See FIGURE 8.2 for the location of
observation point.............................................................. 298

FIGURE 8.6: Net volume of accretion and erosion against the depth of accretion
and erosion after 100 years for scenarios: Base case (2f-no
interventions) (A1 &A2) and with interventions 5a
(2Qs:2Qw;0rslr) (B1 &B2), 5b (2Qs:2Qw;10rslr) (C1 &C2),
5f(2Qs:2Qw;20rslr) (D1 &D2)................................................. 302

FIGURE 8.7: Net volume of accretion and erosion against the depth of accretion
and erosion after 100 years for scenarios: 5e (1Qs:2Qw;10rslr)
(E1 &E2) and 5c (2Qs+45% over 100 years:2Qw;10rslr) (F1 &F2),
5d (6Qs:2Qw;10rslr) (G1 &G2)................................................ 303

FIGURE 8.8: Net volume of accretion and erosion against the depth of accretion
and erosion after 100 years for scenarios: 6b (2Qs:1Qw;10rslr)
(H1 &H2) and 6e (2Qs:3Qw;10rslr) (I1 &I2).............................. 304

FIGURE 8.9: Volume of accretion and erosion in delta area after 100 years for
varying relative sea level rise and sediment discharges with
polders and cross-dams ...................................................... 305

FIGURE 8.10: Ratio of volume of accretion to erosion in delta after 100 years
for base case and scenarios of relative sea level rise and water
discharges with polders and cross-dams ............................ 306
FIGURE 8.11: Ground elevation and bathymetry for the base case scenario (2f;SLR=0mm/y) after 100 years of simulation. Location plan of longitudinal and cross sections of delta ............................. 307

FIGURE 8.12: Longitudinal section of the delta through its centre (x-x) for initial condition and after 100 years for base case and scenarios with polders and cross-dams, 5e (1Qs:2Qw;10rslr), 5b (2Qs:2Qw;10rslr), 5c (2Qs+45%;2Qw;10rslr), and 5d (6Qs:2Qw;10rslr) See FIGURE 8.11 for location.............................. 307

FIGURE 8.13: Cross section of the delta at location1 for initial condition and after 100 years for base case and scenarios with polders and cross-dams, 5e (1Qs:2Qw;10rslr), 5b (2Qs:2Qw;10rslr), 5c (2Qs+45%;2Qw;10rslr), and 5d (6Qs:2Qw;10rslr) See FIGURE 8.11 for location. Green dashed lines indicate the effect due to cross-dams. ........................................................................................................ 308

FIGURE 8.14: Longitudinal section of the delta through its centre (x-x) for initial condition and after 100 years for base case and scenarios with polders and cross-dams; 6c (2Qs:1Qw;20rslr), 5f (2Qs:2Qw;20rslr), and 6f (2Qs:3Qw;20rslr). See FIGURE 8.11 for location .................................................................................................................. 309

FIGURE 8.15: Time-series plot of modelled clinoform angle for the varying rates of fluvial discharges, and sea level under combined scenarios ................................................................................................................. 310

FIGURE 8.16: Cross section of the delta at location1 for initial condition and after 100 years for base case and scenarios with polders and cross-dams, 6c (2Qs:1Qw;20rslr), 5f (2Qs:2Qw;20rslr), and 6f (2Qs:3Qw;20rslr). See FIGURE 8.11 for location. Green dashed lines indicate the effect due to cross-dams. .................... 310

FIGURE 8.17: Area and rate of accretion and erosion over sub-aerial delta for scenarios of varying water discharge and relative sea level rise with polders and cross-dams. Note: Water discharge, Qw = 32,500m³/s; sediment discharge, Qs = 0.74m³/s .................... 313
FIGURE 8.18: Area and rate of accretion and erosion over sub-aerial delta for scenarios of varying sediment discharge and relative sea level rise with polders and cross-dams. Note: Water discharge, \(Q_w=32,500\text{m}^3/\text{s}\); sediment discharge, \(Q_s = 0.74\text{m}^3/\text{s}\).................. 314

FIGURE 8.19: Delta land area for scenarios of varying water discharge and relative sea level rise with polders and cross-dams after 100 years................................................................. 315

FIGURE 8.20: Delta land area for varying sediment discharges and relative sea level rise with polders and cross-dams after 100 years ........ 316

FIGURE 8.21: Percentage of delta land area below sea level for varying water discharges and relative sea level rise with polders and cross-dams........................................................................... 317

FIGURE 8.22: Percentage of delta land area below sea level for varying sediment discharges and relative sea level rise with polders and cross-dams ............................................................... 317

FIGURE 8.23: Probability distribution function of island size normalised to total island area for the conjunctive scenarios of a) varying fluvial water discharge, b) varying fluvial sediment discharge, and c) varying amount of sea level rise with polders and cross-dams................................................................. 318

FIGURE 8.24: Probability distribution function of island shape factor for the conjunctive scenarios of a) varying fluvial water discharge, b) varying fluvial sediment discharge, and c) varying amount of sea level rise with polders and cross-dams ............................................................... 320

FIGURE 8.25: Probability distribution function of island aspect ratio for the conjunctive scenarios of a) varying fluvial water discharge, b) varying fluvial sediment discharge, and c) varying amount of sea level rise ........................................................................ 321

FIGURE 8.26: Probability distribution function of nearest-edge distance for the conjunctive scenarios of a) varying fluvial water discharge, b) varying fluvial sediment discharge, and c) varying amount of sea level rise ........................................................................ 322
FIGURE 8.27: Time-series plot of modelled shoreline rugosity for the conjunctive scenarios of varying rates of sea level rise with Polders and Cross-dams compared against Base-case scenario................................................................. 323

FIGURE 9.1: Spatial and temporal variation of flood:ebb flow ratio in a tidal cycle for experimental scenarios................................. 329

FIGURE 9.2: Ratio of net accretion to erosion in the ideal tidal delta over 100 years for experimental scenarios. Note: Number of polders and cross-dams are constant over simulation period. Abbreviations: Qw- Water discharge; Qs – Sediment discharge; SLR- Sea level rise; P – Polders, CD- Cross-dams.................................................. 331

FIGURE 9.3: Distance of upstream propagation of bed aggradation from delta front after 100 years for varying rate of relative sea level rise (RSLR) scenarios (0, 5, 10, 15 and 20mm/y).......................... 337

FIGURE 9.4: Time-series plot of modelled channel width for the experimental scenarios of varying rates of sea level rise ................. 337

FIGURE 9.5: Time-series plot of modelled channel width to depth ratio for the experimental scenarios of varying rates of sea level rise ....... 338

FIGURE 9.6: Time-series plot of modelled sub-aerial delta progradation for the varying rates of sea level rise (3a- 5mm/y; 3b-10mm/y; 3c-15mm/y; 3d- 20mm/y) compared with base case scenario (0mm/y) ............................................................................. 339

FIGURE 9.7: Sub-aerial delta area as a function of fluvial water discharge, human interventions and sea level rise (Qw- Water discharge; P- Polders; CD- Cross-dams; SLR- Sea Level Rise).............................. 340

FIGURE 9.8: Sub-aerial delta area as a function of fluvial sediment discharge, human interventions and sea level rise (Qs- Sediment discharge; P- Polders; CD- Cross-dams; SLR- Sea Level Rise) ..................... 340

FIGURE 9.9: Probability distribution function of nearest-edge distance for the varying amount of sea level rise and polders scenario........ 341
FIGURE 9.10: Modelled width of onshore fluvial deposition with human interventions plotted against varying amount of sea level rise. ................................................................. 342

FIGURE 9.11: Modelled width of onshore fluvial deposition with and without human interventions plotted against varying fluvial water discharges. ................................................................. 342

FIGURE 9.12: Modelled sub-aerial delta progradation for the varying rates of sea level rise under conjunctive scenarios .................. 343

FIGURE 9.13: Qualitative synthesis of the deltaic response to natural drivers. Water discharge vs sub-aerial delta area (i), vs progradation (iii); Sediment discharge vs sub-aerial delta area (ii), vs progradation (iv); Sea level rise vs sub-aerial delta area (v), vs number of islands (vi), vs progradation (vii), Aggradation (viii) .................. 347

FIGURE 9.14: Qualitative synthesis of the deltaic response to natural and human drivers. Human interventions vs area (i) and perimeter of sub-aerial delta (ii); Water discharge + sea level rise + human interventions vs sub-aerial delta area (iii), vs progradation (v); Sediment discharge + sea level rise + human interventions vs sub-aerial delta area (iv), vs progradation (vi) .................. 348

FIGURE 9.15: Erosion and accretion of lands in the Meghna Estuary (contemporary GBM delta) from 1973 to 2008. All the islands are polderised. Estimate based on satellite images. Source: (CEGIS, 2009) .............................................................................. 350

FIGURE 9.16: Time series of sub-aerial delta area in the Meghna Estuary between 1943 and 2012. Source: (CEGIS, 2009) .............. 352

FIGURE 9.17: Ground levels in Polder 32 lower than the water level in the distributary. Source: Photo by the author, taken during a site visit in May 2014................................................................. 353


FIGURE 10.1: Modelled water level after 2 days of hydrodynamics simulation 370

FIGURE 11.1: Probability distribution function of island size normalized to total island area for the selected and unselected model deltas 372

FIGURE 11.2: Probability distribution function of island aspect ratio for the selected and unselected model deltas 373

FIGURE 11.3: Probability distribution function of island shape factor for the selected and unselected model deltas 374

FIGURE 11.4: Visual representation of the modelled deltas during the calibration of horizontal eddy viscosity & diffusivity coefficient (in m²/s) 375

FIGURE 11.5: Visual representation of the modelled deltas during the calibration of critical shear stress of erosion and sedimentation 376

FIGURE 11.6: Visual representation of the modelled deltas during the calibration of Manning’s roughness coefficient and morphological acceleration factor 377

FIGURE 12.1: Pattern of accretion and erosion over the delta for the scenarios of: sub-plot: A1, A2 for 2c (2Qw:1Qs), sub-plot: B1, B2 for 2i (2Qw:3Qs), sub-plot: C1 for 2f (2Qw:2Qs) (base case), sub-plot: D1, D2 for 2e (1Qw:2Qs), sub-plot: E1, E2 for 2g (3Qw:2Qs) 384

FIGURE 12.2: Pattern of accretion and erosion over the delta for the scenarios of: A1- Base case-2f(RSLR=0mm/y), B1 and B2-3a(RSLR=5mm/y), C1 and C2 - 3b(RSLR=10mm/y), D1 and D2 - 3c(RSLR=15mm/y) and E1 and E2 -3d(RSLR=20mm/y) 389

FIGURE 12.3: Pattern of water flow in the delta just before (A) and after (B) high tides at 25 years for scenario of RSLR =20mm/y (3d). See FIGURE 6.13A for the key map and elevation legend 390
FIGURE 12.4: Pattern of water flow in the delta just before (A) and after (B) high tides at 50 years for scenario of RSLR =20mm/y (3d). See FIGURE 6.13 A for the key map and elevation legend............ 391

FIGURE 12.5: Pattern of water flow in the delta just before (A) and after (B) high tides at 75 years for scenario of RSLR =20mm/y (3d). See FIGURE 6.13 A for the key map and elevation legend............ 392

FIGURE 12.6: Pattern of water flow in the delta just before (A) and after (B) high tides at 100 years for scenario of RSLR =20mm/y (3d). See FIGURE 6.13A for the key map and elevation legend............ 393

FIGURE 12.7: Pattern of accretion and erosion over the delta for the scenarios of: A1- Base case-2f(no human interventions), B1 and B2-4a(with polders) .............................................................. 396

FIGURE 12.8: Pattern of accretion and erosion over the delta for the scenarios of: C1 and C2-4b (with cross-dams)............................................. 397

FIGURE 12.9: Pattern of accretion and erosion over the delta for the scenarios of: A1- Base case-2f(lower roughness land cover), B1 and B2-4c(higher roughness land cover). Dashed green circle indicates disintegration of an island and creation of new channel ........ 398

FIGURE 12.10: Pattern of accretion and erosion over the delta for the scenarios of: A1- Base case-2f(RSLR=0mm/y, Qs= Base case, Qw=1),B1& B2- 5a (2Qs:2Qw;0rslr), C1 &C2-5b (2Qs:2Qw;10rslr), D1&D2-5f (2Qs:2Qw;20rslr), E1&E2-5e (1Qs:2Qw;10rslr), F1&F2-5c (2Qs+45%:2Qw;10rslr), G1&G2-5d (6Qs:2Qw;10rslr), H1&H2 - 6b (2Qs:1Qw;10rslr) and I1&I2 - 6e (2Qs:3Qw;10rslr) .................. 407
Academic Thesis: Declaration Of Authorship

I, ................Balaji Angamuthu..........................

declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

......The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis .......

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;

2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;

3. Where I have consulted the published work of others, this is always clearly attributed;

4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;

5. I have acknowledged all main sources of help;

6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;

7. Either none of this work has been published before submission, or parts of this work have been published as: [please list references below]:

Signed: .................................................................

Date: .................................................................
Acknowledgements

This research is supported by an award (NE/J0027551) from the Natural Environment Research Council (Ecosystem Services for Poverty Alleviation Thematic Programme).

I acknowledge the use of the IRIDIS High Performance Computing Facility, and associated support services at the University of Southampton, in the completion of this work.

I would like to express my sincere gratitude to my supervisors Prof. Steve Darby and Prof. Robert Nicholls for giving me this opportunity, and for their patience, motivation, guidance and continuous technical support during this PhD. My sincere thanks goes to our Administrative Officer Julie Drewitt for her continuous support with the processes required to complete this study.

I would like to extend my thanks to the following people: ESPA Delta partners, Deltares, administrative and technical staffs at the faculty, isolutions and library staffs at the University for helping me to conduct this work. Especially to: Dr. Bert Jagers from Deltares for quickly fixing the reported parallel computing bug in the Delft3D software, David Baker from isolutions for providing the Delft3D installation support on the Iridis 3 and 4 supercomputers, Prof. Md. Mansur Rahman and Dr. Munir Ahmed for helping me to arrange the required logistics during my visit to the Bangladesh part of the Ganges-Brahmaputra-Meghna (GBM) delta, Shampa and Dr. Maminul Haque Sarker for sharing the data of the GBM delta, and Md. Nurul Kadir Seum, an ex-BUET student, for accompanying and helping me during my field visit to the Bangladesh.

I thank my family members, friends, lab and research group colleagues for all their supports. Especially I am grateful to my lab colleagues and friends: Julio Pastor Guzman, Sarchil Qader, Tristan Berchoux, Gregory Cooper, Paul Chelliah, Baskar, Hachem Kassem, and Sarwar Sohel for sharing their resources. Finally, I thank all of my mentors.
### Definitions and Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACE</td>
<td>Accumulated Cyclone Energy</td>
</tr>
<tr>
<td>B.P.</td>
<td>Before Present, reference year: 1950</td>
</tr>
<tr>
<td>D$_{50}$</td>
<td>Median particle size in sediment sample</td>
</tr>
<tr>
<td>ESLR</td>
<td>Eustatic Sea Level Rise</td>
</tr>
<tr>
<td>GBM</td>
<td>Ganges-Brahmaputra-Meghna</td>
</tr>
<tr>
<td>Landsat TM</td>
<td>Landsat Thematic Mapper sensor</td>
</tr>
<tr>
<td>LGM</td>
<td>Last Glacial Maximum</td>
</tr>
<tr>
<td>MORFAC</td>
<td>Morphological Acceleration Factor</td>
</tr>
<tr>
<td>MSL</td>
<td>Mean Sea Level</td>
</tr>
<tr>
<td>Qs</td>
<td>Fluvial sediment discharge</td>
</tr>
<tr>
<td>Qw</td>
<td>Fluvial water discharge</td>
</tr>
<tr>
<td>RSLR</td>
<td>Relative Sea Level Rise</td>
</tr>
<tr>
<td>SLR</td>
<td>Sea Level Rise</td>
</tr>
</tbody>
</table>

**Units:**

- cu.m: cubic metre
- km: kilometre
- km$^2$: square kilometre
- l: litre
- m: metre
- μm: micrometre
- m$^3$/s: cubic metre per second or cumecs
- mg: milligram
- mm: millimetre
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>sq.km</td>
<td>square kilometre</td>
</tr>
<tr>
<td>t</td>
<td>metric tonne</td>
</tr>
<tr>
<td>y</td>
<td>year</td>
</tr>
</tbody>
</table>
1. The Human Pressures on Global Deltas

1.1 Past, present and future state of global deltas

1.1.1 Past state, the beginning

Delta is an area of land formed by the rivers in the lake or sea while discharging into them. Modern river deltas began to form between 8,500 and 6,500 years B.P. (Stanley and Warne, 1994), but their surface features only began to form during the last 6,000 years (Hori and Saito, 2008). These deltaic lands remained pristine until humans started to use them. Extremely rich fertile lands, productive fisheries, and their other ecological and economic values, such as forestry and mineral resources, have long attracted humans to live in deltas. Some of the first major civilisations developed on the river deltas of the Nile, Indus, and Huanghe, some 5,000 years ago when the demand for hydraulic power began (Bianchi and Allison, 2009a). The flat nature of delta plains and the presence of rich organic soils allowed humans to develop agriculture easily in delta environments (Syvitski, 2008). Easy access to trading also attracted more humans to settle there (Syvitski and Saito, 2007). Consequently, the natural evolution of deltas began to be directly influenced by human activities such as agriculture, aquaculture, as well as the construction of water control structures and settlement infrastructure. The next level of significant human influence in the natural process of delta building happened due to colonisation around the world when land use changes within the catchments of river deltas were intensified from the 19th century, primarily for the purpose of agriculture and urbanisation (Richards et al., 1985) and intensifying greatly post World War II.

1.1.2 Present state, on-going issues

During the 20th century, there were dramatic increases in the use of the coastal zone by the humans. Based on the global population database, Landscan 2005 and the ground elevation model, Gtopo 30, Usery et al. (2010) estimate that about 11% (nearly 670 million) of the global population are living in locations that are less than five metres above sea level, covering a land area of
5.4 million km$^2$. Coastal migration has been common in both developed and developing nations (Nicholls et al., 2007). Human extractive activities within deltas include (Nicholls et al., 2007) & (Syvitski and Saito, 2007): 1) Sand mining; 2) Hydrocarbon production; and 3) Harvesting of fisheries and other living resources. The following engineering structures are also frequently constructed within deltas (Nicholls et al., 2007) & (Syvitski and Saito, 2007): 1) Channelisation and water diversion structures (Mississippi and GBM Deltas), 2) Polders (Rhone and GBM Deltas), 3) Hard bank protection works, 4) Oil-field infrastructure (Huanghe and Mississippi Delta), 5) Sea walls, foredune, Breakwalls at the shoreline, 6) Soft engineering measures such as beach nourishment, 7) Construction of highways (Colorado, Texas) and Airport runways (Fraser and Var Deltas), and 8) Urbanisation. However, as economic development progressed, human exposure to natural hazards, such as cyclonic storm surges, river flooding of the flat delta plains and the switching of distributary channels, has increased commensurately. Upstream impounding structures and other flood control measures have frequently been put in place to reduce flooding in deltas, but that has only encouraged even more people to settle in deltaic environments, further increasing the number of people at risk of flooding during larger flood events (Syvitski, 2008). People in the Asian deltas experience flooding from storm surges (Syvitski et al., 2009), as flood control structures can only often provide limited protection against ocean-generated storm surges (Syvitski, 2008).

The major direct impacts of human activities in deltas include (Nicholls et al., 2007) & (Syvitski and Saito, 2007): 1) Controlling the flow path of distributary channels (Po, Huanghe and Colorado Deltas), 2) Mitigating the seasonal flood wave (Mekong, Yangtze and Indus Deltas), 3) Irrigating crops (Nile and Krishna Deltas), 4) Drainage of coastal wetlands, 5) Deforestation and reclamation, 6) Discharge of sewage, fertilisers and contaminants into coastal waters, 7) Reduction in sedimentation within nearby coastal lagoons (Po/Venice Delta), 8) Agriculture (Krishna, Mahanadi, Nile and Indus Deltas), and 9) Salt extraction mining (Rhone Delta). Consequences on the natural coastal system due to rapid urbanisation include the enlargement of coastal inlets, the dredging of waterways and saline water intrusion into surface and ground water. Engineering structures make the coast harder, change flow circulation patterns
and alter freshwater availability (Nicholls et al., 2007). The direct impacts include land reclamation measures such as polderisation of deltaic islands, which prevents the natural process of land elevation rising and induces subsidence (Bianchi and Allison, 2009b, Syvitski and Saito, 2007). These various human influences often cause accelerated sediment compaction through the extraction of ground water and hydrocarbons (Syvitski, 2008). Of 15 major deltas analysed, including the Nile, Mississippi, Ganges-Brahmaputra, Huang-He, Indus, Niger, Danube, Mahanadi, Mangoky, McKenzie, Volga, Shatt el Arab, Yukon and Zambezi, 15,845 km$^2$ of wetlands were lost (out of a total of 30,225 km$^2$) to open water and agricultural and industrial land use in the period 1989 to 2001 (Coleman et al., 2008). Hence, human activities have considerably altered the natural coastal system and exert significant influences on contemporary delta morphodynamics through their effects on modified water flux, sediment flux, flow pathways and shoreline position (Syvitski and Saito, 2007).

The indirect impacts of human activities on deltas include water management and land-use change activities in the source catchment (Woodroffe et al., 2006). Increased human populations and economic growth both within the coastal areas and catchments have, during the 20th century, changed coastal areas across the world dramatically (Nicholls et al., 2008). Deforestation, poor agricultural practices, mining activities and urbanisation within source catchments have altered the sediment yield from most landscapes. Impacted drainage basins have been identified across Asia, Africa, the Philippines and Indonesia. However, dams, water diversions and flood control works are intercepting an increased portion of fluvial sediments before they have the opportunity to reach the world’s delta plains (Syvitski, 2008). FIGURE 1.1 shows the pre-Anthropocene (time prior to major human activities) and modern sediment loads. Upstream damming over the past 50 years has changed modern delta aggradation by reducing the number of distributary channels and constraining the switching of the distributary channels (Syvitski et al., 2009). The number of distributary channels is, therefore, decreasing in many deltas (e.g. Po, Nile, Magdalena) (Syvitski and Saito, 2007). Distributary channels within a delta play an important role in distributing sediment across the delta plain. Naturally, distributary channel banks are overtopped during seasonal flood events and thereby nutrient enriched sediment is supplied to the delta.
surface. However, floodwaters also damage infrastructure in the delta plain and may even cause loss of life. For example, to prevent the damages caused by flood events in the Nile Delta, the Aswan Dam was built across the Nile River, upstream of its delta. Subsequently, the number of distributary channels in the Nile Delta reduced from 16 to 2. After this upstream impoundment, the method of distributing sediment within the Nile delta by building barrages and diversions has been found to be ineffective (Syvitski, 2008). Many deltas have experienced similar problems. Existing distributary channel banks are also hard engineered to protect riverside inhabitants and to maintain required flow depths for navigation. Subsequently, water and sediment discharge to secondary distributary channels are reduced. This prevents the distribution of sediment across the delta plain. The funnelled water and sediment either gets delivered to the river mouth with little trapping, or elevates the distributary channel by sedimentation (Syvitski, 2008).

![Figure 1.1](image_url)  
**FIGURE 1.1**: Comparison between pre-Anthropocene and modern sediment loads. 1:1 line shows no influence by humans. Other lines indicate modern sediment loads with human influences such as deforestation and/or sediment trapping in reservoirs. Insets show global sediment trapping in large reservoirs. Source: (Syvitski et al., 2005)  

Another major indirect impact that humans have on the coastal zone is by modifying the rate of change in sea level rise. Since 1750, the beginning of the industrial revolution, the atmosphere and ocean have been warmed above the
natural rate, which has resulted in an increased rate of sea level rise above its natural level. However, the effect of this is mostly observed from 20th century onwards. Annual rates of global mean sea level rise of about 1.7mm/y for the 20th century and 3.0mm/y since 1993 have been estimated in the IPCC Fifth Assessment Report (Church et al., 2013). According to the IPCC Fifth assessment Report, the rate of sea level rise will increase further in the 21st century due to the human activities.

Based on the preceding discussions, it can be concluded that under the conditions of human influence, either directly or indirectly, the world’s deltas can no longer be considered to be either natural or self-maintaining. The current status of the world’s deltas graphically illustrates this point: Syvitski et al. (2009) found that all of the following deltas are currently in great danger of flooding and permanent inundation: Chao Phraya, Colorado, Krishna, Nile, Pearl, Po, Rhone, Sao Francisco, Tone, Yangtze and Yellow. Human influenced deltas that are suffering from flooding due to the reduction in aggradation, accelerated compaction and sea-level rise include the Ganges, Irrawaddy, Magdalena, Mekong, Mississippi, Niger and Tigris (Syvitski et al., 2009).

1.1.3 Future challenges facing the world’s deltas

Human impacts on the world’s deltas were high and growing through the 20th century and are likely to continue to increase through the 21st century, due to the continued increase in population (Woodroffe et al., 2006) and future socio-economic scenarios (Nicholls et al., 2008, Nicholls et al., 2011). This raises the question of how deltas might evolve in the future and how humans may better protect delta ecosystem and resources. Nicholls et al. (2016) demonstrate the interrelationship between the delta morphodynamics and deltaic communities. FIGURE 1.2 shows the vulnerability of human populations to the current trend of sea-level rise in 2050. Many of the vulnerable deltas are the Asian megadeltas. The Asian megadeltas are formed by the large rivers that drain the Himalayan-Tibetan massif. These rivers are fed by seasonal monsoon rainfall and discharge very large sediment loads. All of these Asian megadeltas are highly influenced by human activities, both within their catchments and the deltas themselves (Woodroffe et al., 2006). Changes in rainfall and runoff, and their effect on the sediment loads supplied to deltas, may play an equally
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

important role as sea level rise in influencing the progradation of a delta (Woodroffe, 2010). It has been shown that there is likely to be an increase in rainfall (Kumar et al., 2011) and river discharge (Whitehead et al., 2015a, Whitehead et al., 2015b, Darby et al., 2015) in parts of the Indian subcontinent due to anthropogenic climate change. However, with the decrease in fluvial sediment flux due to the construction of upstream reservoirs and improved land management practices, most major deltas are nevertheless expected to shrink in the future (Syvitski and Saito, 2007).

FIGURE 1.2: Relative vulnerability of coastal deltas as shown by the indicative population potentially displaced by current sea-level trends to 2050 (Extreme =>1 million; High= 1 million to 50,000; Medium = 50,000 to 5,000. Source: (Nicholls et al., 2007)

1.2 Knowledge of delta morphodynamics

The natural and human processes operating in deltas operate at varying scales and it is a challenge to separate the impacts caused by humans from the effects of natural processes. More research work is required to understand the effect of extreme events on delta systems (Woodroffe et al., 2006). The response of an individual delta to future environmental changes will also vary within that delta due its geomorphological variability. Any human interventions could further complicate these geomorphological processes (Woodroffe, 2010). Hence, we need to understand the extent to which delta morphodynamics can adjust in the future. Studies on coastal behaviour have often been done at millennial scales, to reconstruct the paleo-environment, or at sub-annual scales to understand the underpinning processes. Nevertheless,
our understanding of delta geomorphological processes over planning or engineering time scales (i.e., from decades to centuries) is limited (Woodroffe et al., 2006). FIGURE 1.3 shows the current level of reliability of knowledge over the whole range of time scales pertinent to delta morphodynamics. It is clear that we need to improve our ability to understand and predict geomorphological processes over time scale of between fifty and hundreds of years in particular (de Groot, 1998).

![FIGURE 1.3: Existing reliability of coastal morphodynamic knowledge. Source:(de Groot, 1998)](image)

1.3 Aims, Objectives and Scope of Research

The above sections have highlighted the need to enhance our understanding of the future morphological evolution of deltas over the planning time scale. Furthermore, a comprehensive search of the research literature (see Chapter 2 for a full review) has revealed that the understanding and prediction of tidal delta morphodynamics, particularly over this time scale, is still at a preliminary stage, with little or no work in many of the world's vulnerable deltas. Hence, the science that will be developed during this research can be applied to other tidal deltas where applicable. The overall aim of this research is to **determine how contemporary tidal delta morphology evolves over multi-decadal timescales under multiple drivers** i.e., to explore the influence of various drivers (fluvial discharges, sea level rise, human interventions such as polders, cross-dams and changing land cover roughness) of contemporary environmental change on deltaic morphodynamic response. The research questions that must be addressed can be detailed as follows:
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

1) How do fluvial water and sediment discharges affect tidal delta morphology?
2) What is the role of relative sea level rise (RSLR) in delta building?
3) What is the impact of deltaic human interventions, such as building polders, on tidal delta morphology?
4) What is the impact of the deltaic human intervention of building cross-dams on tidal delta morphology?
5) What is the impact of changing from a normal to a rough land cover on tidal delta morphology?
6) What are the combined effects of polders, cross-dams, RSLR and fluvial water and sediment discharge?

Based on the above research questions, the following hypotheses that have closer implications to the people and their environment are tested within the thesis:

1. Increased fluvial discharge will increase the area of sub-aerial delta,
2. Increased fluvial discharge will increase the number of distributaries,
3. Progradation will increase with increased fluvial discharge and the shape of clinoform will be a function of fluvial discharge,
4. Increase in sea level rise will reduce the area of sub-aerial delta and will increase the number of islands,
5. Increase in sea level rise will cause increased back water effects such as the upstream propagation of bed aggradation and widening of distributaries,
6. Increase in sea level rise will stop progradation and will only cause aggradation, and
7. When natural and human drivers are combined, the influence of deltaic human interventions on the morphodynamic change will dominate over the natural drivers.

The above research questions have been set based on the need for understanding the contemporary morphological evolution of an idealised tidal delta, albeit an idealised delta that is based loosely on the Ganges-Brahmaputra-Meghna (GBM) delta (see section 1.4 and Chapter 2). Regarding the scope of this study, its time scale is limited to the human influenced or engineering time scale of delta morphodynamic processes, which is up to a
Chapter 1: The Human Pressures on Global Deltas

century. Furthermore, only the influence of the factors and processes that are highlighted in bold text in the FIGURE 3.23 will be researched. This selection is based on knowledge gained from the literature reviews presented in Chapters 2 and 3. As only a few factors are chosen for detailed study in this research, this thesis offers a highly focused understanding of deltaic morphodynamic changes experienced in nature. Hence, there will be limitations to the transfer of knowledge gained through this research. The limitations and constraints of this research and its conclusions are discussed in detail in Chapter 9.

1.4 Inspiration from the Ganges- Brahmaputra-Meghna Delta

Knowledge gained from the literature review presented in Chapter 2 revealed that no attempt has been made to understand the morphodynamics of tidally-influenced deltas over decadal to centennial timescales. The Ganges-Brahmaputra-Meghna (GBM) delta, a tidally influenced delta, is one of the world’s most vulnerable (see FIGURE 1.2) deltas of the 21st century with a significant increase in its human population predicted and with millions living under extreme poverty (NICHOLLS and GOODBRED, 2004b, Woodroffe et al., 2006, Nicholls et al., 2007, Temmerman et al., 2013, Tessler et al., 2015). The GBM delta is the largest and most populated delta in the world (Woodroffe et al., 2006, Nicholls et al., 2007) and morphologically it is highly dynamic (Allison, 1998b). With at least 6,100 km² of land elevated less than 2m above mean sea level, the factors controlling delta evolution, including human influences, are not yet well constrained (Syvitski et al., 2009). Over 1.3million people have died in the GBM Delta as a result of storm surges in the past 200 years (Woodroffe et al., 2006). A severe cyclone strikes the delta on average once every three years. In 1970 and 1991, cyclonic events killed more than 500,000 and 100,000 in the GBM delta respectively (Ali, 1996). Despite disaster management in place, in 2007, Cyclone Sidr killed 3,406 people and caused damage amounting to an estimated cost of US $1.67 billion (Sarraf et al., 2011). Every year several thousand people are made landless and homeless due to the erosion of river banks (Sarker et al., 2011), thereby creating enormous pressure on the available land. The environment of the GBM delta
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

will be severely affected even for a modest rise in the water level of Bay of Bengal, as most of the delta is flat. For a metre sea-level rise in the Bay of Bengal, based on the delta surface elevation alone without considering existing flood protection structures, it is estimated that about 15 to 20 percent of Bangladesh would be inundated, affecting a population of 20 million people (Inman, 2009b). Moreover, the current delta is in danger of inundation due to a reduction in surface aggradation, along with accelerated compaction and sea level rise (Syvitski et al., 2009). In future, global warming induced environmental changes could further increase coastal inundation along this delta. In developing countries such as Bangladesh, the adaptive capacity is low (Woodroffe et al., 2006) and it remains uncertain how future development will affect inundation risk. At the same time, the past geomorphologic changes of the GBM delta are more or less known, but little is known about why and how these changes have happened (Sarker et al., 2011). Thus, more research is needed to advance our understanding of tidal delta morphology like the GBM delta. Chapter 2 presents a review of the previous work and the current level of understanding of the past and modern morphodynamics of the GBM delta, its catchments and the Bay of Bengal.

As the availability of reliable data is very scarce in many of the world’s deltas including the GBM delta, demonstrating the link between morphodynamic and environmental changes such as variations in fluvial sediment supply, polderisation, sea level rise, and subsidence is still very challenging (see Chapters 2 and 3). Aiming to investigate how contemporary tidal delta morphology evolves over multi-decadal timescales under multiple drivers, a morphodynamic model of an idealised tidal delta that shares a number of the essential characteristics of the Ganges-Brahmaputra-Meghna (GBM) delta is here used to explore the influence of various drivers of contemporary environmental change on deltaic morphodynamic response. Considering the large spatial and temporal scale of the present study, the geometrical shape of the study area and the number of experiments involved, laboratory based modelling is not a feasible means of meeting the aim of this research. Hence, a quantitative approach of numerical modelling (see Chapter 4) is here applied for the qualitative understanding of the delta morphodynamics.
1.5 Thesis layout

The thesis is structured as follows:

Chapter 2 describes the GBM delta, its catchments and the Bay of Bengal, including a review of the previous work and the current level of understanding of the past and modern morphodynamics of the GBM Delta.

Chapter 3 reviews previous work and the various theories regarding delta formation, evolution and the environmental drivers and processes influencing them.

Chapter 4 outlines the proposed methodology to carry out the research to meet the project objectives, describes the numerical model setup for the selected idealised delta and details the process of how the initial delta model was created for the deltaic morphodynamic experiments undertaken in this thesis.

Chapter 5 presents model simulation results that focus on identifying the role of variations in the imposed fluvial and water discharge on the delta morphodynamics and interprets those model results.

Chapter 6 presents model simulation results examining the role of relative sea level rise on the delta morphodynamics.

Chapter 7 presents model simulation results that explore how specific human interventions (such as polders, cross-dams and changing land cover roughness) affect delta morphodynamics, with an initial focus on examining the impacts of individual interventions one factor at a time.

Chapter 8 presents model simulation results for the combined influence of the various controlling factors explored in chapters 4 to 6, moving to the more realistic case of exploring how multiple changes affect delta morphodynamics.

Chapter 9 presents the discussions, conclusions, the limitations and constraints of this research, the implications for the real world contemporary tide dominated deltas, as well as providing recommendations for future research.
2. Morphological Evolution of the GBM Delta

This chapter reviews the available literature on the Ganges-Brahmaputra-Meghna (GBM) delta and the factors influencing its morphodynamics. The review includes the morphological evolution of the GBM delta in the past and for the present-day, the sediment budget of the delta, and the important characteristics of the Ganges, Brahmaputra and Meghna rivers catchment and the Bay of Bengal that affect the GBM delta’s evolution.

2.1 GBM delta

The GBM delta has one of the highest population densities of all deltas in the world (Coleman et al., 2008), and this human population exerts significant pressures on the delta system. In 2000, the population of the delta was approximately 150 million (Georgiou, 2013). The GBM delta is also one of the world’s most vulnerable deltas with a significant increase in its human population predicted and with millions living under extreme poverty in areas threatened by sea level rise and other processes (Nicholls and Goodbred, 2004a, Milliman et al., 1989, Huq et al., 1995, Nicholls et al., 2016). A lack of basic infrastructure such as roads, electricity, water, sanitary and medical facilities, along with poorly built and maintained flood embankments, makes the people and environment of the GBM delta (Schiermeier, 2014) vulnerable to both natural and man-made calamities. Even for a modest rise in the water level of the Bay of Bengal, the environment of the GBM delta will be severely affected as most of the terrain is flat. The extraction of groundwater, and the consequent local subsidence are major issues (Woodroffe et al., 2006). The continuous aggradation (net accumulation of sediment, which leads to an increase in the elevation of channel beds and/or floodplain surfaces) of the sediment-charged Ganges and Brahmaputra Rivers have caused an expensive and potentially dangerous situation (Allison, 1998a). The GBM delta plains are neither homogenous nor static. They vary every year and occasionally experience catastrophic changes. Flooding in the GBM delta has caused significant impacts on the people and on their agriculture and infrastructure. The major hazards currently experienced by the GBM delta are coastal erosion, cyclone, river floods,
storm surge, saline water intrusion, subsidence, water diversion/impoundment, and arsenic contamination of shallow soils (Woodroffe et al., 2006).

The modern GBM delta is the largest delta in the world, with a total area of around 105,641 km$^2$ (Syvitski and Saito, 2007) of which 6,200 km$^2$ lies less than 2 m above sea level and around 10,500 km$^2$ is affected by storm surges (Syvitski et al., 2009). Approximately 76% of the delta lies in Bangladesh, with the rest in India. The Ganges, Brahmaputra and Meghna Rivers (see Section 2.2 for an overview of the properties of these rivers and their catchment) and their distributaries deposit sediments in the delta (see FIGURE 2.1). Currently, there are two sediment depocenters: one on the subaqueous delta forming offshore, and the other on the subaerial delta forming above the subaqueous delta (Allison, 1998b). The Swatch of No Ground canyon system, located only 30 km off the current coast line, limits the progradation of the delta. Currently, progradation is active only at the eastern river mouth, as this does not discharge directly into the canyon (Goodbred Jr and Kuehl, 2000). To the west of the Meghna Estuary lies the Sunderbans, the world’s largest mangrove forest, which is one of the world’s great hotspots of biodiversity (Inman, 2009a) and a globally significant biosphere reserve (Nandy and Kushwaha, 2010).

FIGURE 2.1 shows the major features of the GBM delta. The current GBM delta is bordered by the Rajmahal Hills on the northwest and west, the Shillong Plateau on the north east, the Tripura and Chittagong Hills on the east and the Bay of Bengal on the south. Areas of uplifted Pleistocene surface that lie within the modern delta are (Morgan and McIntire, 1959): the Barind tract, the Madhupur Jungle, the Lalmai Hills, the Sylhet Hills, the Chhatak Hills, the Rajmahal Hill system and the Tripura Hills. The rest of the delta that is covered by Holocene alluvial deposits deposited by the present Ganges, Brahmaputra and Meghna Rivers and their distributaries (Morgan and McIntire, 1959). The alluvial lowlands can be divided into three geomorphological regions (Umitsu, 1993):

1. The Brahmaputra-Jamuna floodplain in the north of the basin, located between the Barind and Madhupur uplifted surfaces. The elevation of this floodplain ranges from about 20 m in the north to about 6 m in the south.
2. The Sylhet trough in the northeast of the basin, located between the Shillong Plateau, Madhupur surface and the Tripura Hills. The elevation of
the trough at its centre is less than 3m above sea level. The Old Brahmaputra River flows through the trough and confluences with the Meghna River at the southern corner of the delta.

3. The Ganges Delta in the south of the basin, located south of the Barind and Madhupur uplifted surfaces. The elevation of this part of the delta ranges from 15m in the northwest to 1-2m in the south.

FIGURE 2.1: Major features of the GBM delta.

FIGURE 2.2 shows that the western part of the modern GBM delta is a low energy coastal plain dominated by tides. The eastern part of the modern GBM delta, currently the active GBM River mouth, is an estuarine coastal plain dominated by both river flow and tides and it is a high energy coastal plain. The upper delta plain is dominated by fluvial processes. The deposits on the upper delta, that is the part of the delta above the zone of tidal inundation, are mainly composed of silt and sand (Coleman, 1969). The deposits on the lower delta plain are mainly silt, clay and peat (Coleman, 1969). The delta front of
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

the Ganges and Brahmaputra is punctuated alongshore by a number of ebb- and flood-dominated channels and shoals extending from interdistributary islands (Kuehl et al., 2005).

![Coastal Map of Bangladesh](image)

FIGURE 2.2: Coastal plain of Bangladesh. Reproduced from (Saito and Alino, 2008)

2.1.1 Past Morphological Evolution

2.1.1.1 Origin of the GBM delta

It is vital to understand the origin and past morphodynamics of the GBM delta to aid in identifying the primary factors influencing its current and future evolution. TABLE 2.1 gives an overview of the geological processes involved in the origin and early formation of the GBM delta (Parua, 2010, Lindsay et al., 1991).
### Geologic Time | Geologic Process
---|---
Early Triassic ~245 million years ago | Single continental mass, Pangea One Ocean, Panthalassa
| Pangea split into: Laurasia and Gondwana
| Laurasia broke into: North America and Asian-European landmass
Jurassic period | Indian portion of Gondwana plate split and started to move north
Eocene period (54 to 38 million years ago) | Indian plate collided with East Asia and Eurasian plates.
| Rise of Himalayas in the north and Arakan Yomas in the east
Oligocene period (40 to 30 million years ago) | A part of the northeastern Indian mass fractured and sank below the sea-level
| Sunken area received sediments to form the Bengal Basin. Filled over the next 37 million years to form the current Bengal Basin
| At about 21 million years ago, the stream dominated delta changed to tide dominated due to the increasing depth of embayment of the Bay of Bengal.
Tertiary period (16 to 15 million years ago) | Rivers from the east and west filled the Bengal basin.
Pleistocene period (about 1.5 million years ago) | Formation of Garo-Rajmahal Gap

**TABLE 2.1:** The origin and early formation of the GBM delta based on information from (Parua, 2010, Lindsay et al., 1991)

#### 2.1.1.2 Evolution of delta morphodynamics from the Last Glacial Maximum to the modern time

The following section summarises the morphological evolution of the delta since the Last Glacial Maximum (LGM) through to the late Holocene period.

##### 2.1.1.2.1 Influence of relative sea level rise and continental sediment flux on delta evolution

This section briefly explains the influence of sea level rise and input sediment flux on the evolution of the GBM delta since the LGM. **FIGURE 2.3** shows the conceptual understanding of the controls behind the delta development,
whereas FIGURE 2.4 shows the planform development of the GBM Delta in schematics since the LGM. Approximately 18,000 years ago, at the glacial maximum, sea level was 120m below its present level (see FIGURE 2.4 A). At this time, the water surface slope of the deep downcut channel on the Pleistocene surface and flow velocities were both relatively high. Very coarse sediments were discharged at the mouth of the downcut channel (Mikhailov and Dotsenko, 2007). The river discharge was very low compared to the modern day output (Goodbred Jr and Kuehl, 2000). Between 18,000 and 11,000 years B.P., sea level rose from -120 to -55m (see FIGURE 2.3), approximately at a time-mean rate of 0.93cm/y. Due to this major phase of sea level rise, the zone of sediment accumulation began to shift in the landward direction (see FIGURE 2.4 B) (Mikhailov and Dotsenko, 2007). However, the river discharge remained relatively low due to the arid climate at this time (Goodbred Jr and Kuehl, 2000). After 15,000 B.P., increased climate warming led to increased precipitation and an increased sediment input to the mouth of the river system (Goodbred Jr and Kuehl, 2000). At 11,500 B.P., adjustment of the accommodation space and stream gradient, along with the infilling of the basin with sand facies, occurred. However, sediment trapping was low due to the limited accommodation capacity (Goodbred Jr and Kuehl, 2000). From 11,000 to 7,000 B.P., the sea level rose from -55 to -10m (see FIGURE 2.3) at a rate of 1.12cm/y (Mikhailov and Dotsenko, 2007). Note that the rate of sea level rise was greater than that during the previous period. However, climate warming and reduced aridity set the southwest monsoon to a level that was much stronger than the present day one (Goodbred Jr and Kuehl, 2000). Despite the rapid rise in sea level, the rate of sediment deposition was greater than the rate of sea level rise. Thus, the delta was prograding significantly during this period (see FIGURE 2.4 C), with a rapid onshore migration of the sediment depocenter (Goodbred Jr and Kuehl, 2000). The development of the GBM delta started at least 1,000 years earlier than other early forming deltas in the world (Goodbred Jr and Kuehl, 2000). The main factor that contributed to this development, especially during the Holocene transgression, was the huge amount of sediment input due to a stronger-than-present southwest monsoon and intense precipitation (Goodbred Jr and Kuehl, 2000). The GBM delta received more than twice the amount of the modern day sediment discharge for a period of at least 4,000 years during the early Holocene (see FIGURE 2.3).
This implies that the timing of sediment input relative to sea level rise is critical, since it controls the development sequence of the delta (Goodbred and Kuehl, 2000). Around 7,500 years B.P., the Sylhet Basin remained isolated from the Bay of Bengal (see FIGURE 2.4 C). The basin subsidence, relative basin deepening due to rapid sea level rise, along with the western course of the Brahmaputra river corridor are the reasons for this isolation, causing a major sediment deficit in the Sylhet Basin (Goodbred Jr and Kuehl, 2000).

FIGURE 2.3: Plots of Eustatic sea level, South Asia Aridity index, and GB sediment storage. The hachured area shows period of high regional insolation. Reproduced from (Goodbred and Kuehl, 2000)

Note: Vertical arrows and annotations highlight correlations between climate, sea level, and events in the GBM fluvial delta system. The time scale is in radiocarbon, not calendar, years.

Between 7,000 and 4,000 years B.P., sea level rose from -10 to -5m (see FIGURE 2.3), approximately at a rate of 0.18 cm/yr (Mikhailov and Dotsenko, 2007), a significant reduction relative to the preceding period. The maximum marine
transgression happened before the rate of sea level rise began to drop. At the same time, the southwest monsoon lost its strength due to the increased aridity (Goodbred Jr and Kuehl, 2000). When the rate of sea level rise was greater than the rate of sediment deposition, the delta was undergoing aggradation (see FIGURE 2.4 E). The major fluvial and flood basin fill in the entire upper delta was occurring during this aggradation. However, the shoreline was relatively stable despite the filling at a rate of 1 cm/year (Goodbred Jr and Kuehl, 2000). The Sylhet Basin experienced very rapid infilling (>2 cm/year) following its connection to the Brahmaputra River (see FIGURE 2.4 D & E) after the latter changed its course to the east. Therefore, the maximum transgression occurred some 1,000 to 2,000 years later in the east than in the west. However, between 6,000 and 5,000 years B.P., the Brahmaputra River switched back to its western course. The maximum marine transgression on the western and eastern side of the delta was approximately 100 km and 300 km inland of the present day coastal line, respectively. The maximum transgression on the western side, including the Sunderbans and Kuakata region, (see FIGURE 2.4 D) (see FIGURE 2.1 for locations) occurred at about 7,000 years B.P. The difference in the maximum transgression between the eastern and western side of the delta can be explained by the Brahmaputra River depositing a sand unit in the Sylhet Basin during the period between 6,000 to 7,400 years B.P. The maximum transgression on the eastern side occurred as late as 5,000 to 6,000 years B.P. (see FIGURE 2.4 E). The large accommodation space in the Bengal Basin kept the formation of delta inland separately by the Ganges and Brahmaputra prior to 5,000 years B.P (see FIGURE 2.4 E) (Goodbred Jr and Kuehl, 2000). From aggradation, the delta once again entered into a stage of progradation after 5,000 years B.P when the rate of sea level rise reduced below the rate of sediment deposition. The reduced accommodation resulted in widespread dispersal of sand, infilling alluvial valleys and channels. The main fluvial depocenter migrated seaward (see FIGURE 2.4 E), and the initial development of a compound delta system with a prograding subaerial delta and subaqueous clinoform (sloping sediment depositional surface that is underneath the water) began (Goodbred Jr and Kuehl, 2000).
FIGURE 2.4: Paleo-geographic maps illustrating the Late Quaternary development of the GBM delta. Modified from (Goodbred Jr and Kuehl, 2000).

Note: (A) Lowstand system consisted of exposed laterite surfaces and incised alluvial valleys. (B) Initial phase of delta growth as rising sea level back flooded a large portion of the lowstand delta surface. (C) Major aggradation of subaerial delta during rapid sea-level rise. (D) Decelerating sea-level rise, progradation of Ganges coastal plain and initial growth of subaqueous delta. Brahmaputra load sequestered to inland Sylhet Basin, transgression of eastern delta front continues. (E) Progradation of subaerial and subaqueous deltas as both rivers discharge along eastern delta front. (F) Delta similar to modern system, prograding into modern river mouth estuary and on the shelf.
Between the period between 4,000 years B.P. and the present, sea level rose from -5m to the present day level (see FIGURE 2.3), at a rate of approximately 0.12 cm/y. The rate of sea level reduced further and the ocean level was more or less stabilised (Mikhailov and Dotsenko, 2007). The progradation of the delta continued with weakened but steady sea level rise and with few variations in the intensity of the southwest monsoon (see FIGURE 2.3) (Goodbred Jr and Kuehl, 2000). During this period, the delta’s growth in the west reached its present day extent (see FIGURE 2.4 F). About 200 years ago, the Brahmaputra River then switched back to its western course to join the Ganges. Since then the delta has been prograding into the Meghna Estuary, a process that continues to the present day (Goodbred Jr and Kuehl, 2000).

2.1.1.2.2 Avulsion and the trajectory of GBM delta building

This section explains how the dominance of avulsion after the maximum marine transgression shaped the GBM delta. Based on clay mineralogical and radiocarbon evidence, Allison et al. (2003) suggested that the progradation of the GBM lower delta plain after the maximum transgression would have happened in four or five phases, as shown in FIGURE 2.5. Due to avulsion, the Ganges migrated eastward and the Brahmaputra was shifting between its eastern and western course. A number of delta lobes were formed due to these rivers shifting.

A brief explanation of the history of river shifting that has led to the current delta lobe formation is now given. The earliest lower delta plain progradation started at the westernmost part of the delta by the Ganges (G1). Most of the Brahmaputra River drained, via an eastern route, into the Sylhet Basin to form an inland delta between 7,500 to 6,000 years B.P. (B1). Allison et al. (2003) suggested that, after Phase 1, the Ganges moved eastward, occupying a series of distributaries (G2); the Bangladesh Sunderbans are formed by these distributaries. It has been hypothesised (Allison et al., 2003) that at this time the Brahmaputra River was discharging through the Meghna Estuary (B2). Because of the westward direction of its current, the Brahmaputra River sediments were observed in the supratidal layer (area above the high tide water line that extends upland) during the Phase G2.
The progradation of the Ganges stopped seaward due to siltation at the distributaries offtake and the formation of the younger eastern channels. In all of the Ganges delta lobes, the disconnected Ganges distributaries have become tidally dominated channels. Only the Haringhata distributary, located at the eastern edge of the Sunderbans, remains connected with the Gorai whereas many lower tidal distributaries are now disconnected from their main river. Based on the supratidal deposition west of the Meghna Estuary in the lower delta plain, Allison et al. (2003) suggested that the progradation of this part of the lower delta plain was completed by 1,000 to 1,800 cal years B.P. It was found that the westernmost delta was in a similar position about 1,400 years prior to this, such that the lower delta plain growth progressed from west to east as shown in FIGURE 2.5. It has been mentioned by Allison et al. (2003) that the sub-deltas G1, G2 and G3 that border the Bay of Bengal have reached maturity and that they no longer undergo progradation. Currently, these lobes experience subsidence at rates of between 1 to 4 mm/y (Allison et al., 2003).
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

The main source of sediment to these Ganges delta lobes is now from tidal currents. The orientation of the distributaries in the Sunderbans in India and western Bangladesh is from north-west to south-east, whereas for the distributaries in the Kuakata (see FIGURE 2.1 for location) the orientation is from north-east to southwest. This difference in the orientation of distributaries and their connectivity influences the sediment distribution and morphological stability of the Ganges sub-deltas.

The final phase of the lower delta plain progradation is the progressive infilling of the Meghna estuary in the late Holocene by both the Ganges and the Brahmaputra (GB1). Floodplain cores taken from western Bangladesh have indicated that the present course of the Brahmaputra River is the western most that it has ever flowed. The merging of two of the world’s largest rivers two hundred years ago is unique in the process of delta formation. Four major, and several minor, prograding shoal-island complexes form the modern Meghna Estuary. Earlier stages of the delta progradation could have advanced in the same manner. The shoal-island complexes in the Meghna estuary have not extended as far as the adjacent Sunderbans and Kuakata Peninsula (Allison et al., 2003).

2.1.2 Sediment budget for the GBM delta

FIGURE 2.6 shows the late Quaternary sediment fill volumes for the GBM delta. The total sediment volume stored in both the subaerial and subaqueous part of the GBM delta since the early Holocene is approximately 8.5x10^{12} m^{3}. Of this, nearly 60% has been placed in store from ca. 11,000 to 7,000 yr B.P., during the phase of high river sediment discharge and rapid sea-level rise described previously (Goodbred and Kuehl, 2000). The sediment storage rates per year between 11,000 and 7,000 yr BP was 2.3±0.4x10^9 t/y and after 7,000 yr BP this rate reduced to 0.8±0.1x10^9 t/y due to the reduction in monsoon strength (Goodbred and Kuehl, 2000). Goodbred and Kuehl (1999) estimated the sediment budget of the GBM delta since 7ka during the Holocene period and showed that the sediment trapped in the flood and delta plain was ~ 0.32x10^6 t/y, in the subaqueous delta was 0.42x10^6 t/y and the balance (0.26x10^6 t/y) was assumed to be discharged to the Bengal Fan. Their estimate of the modern sediment budget of the GBM delta also showed a similar partitioning
between sediment stored in the subaerial and subaqueous parts of the delta. According to Kuehl et al. (1989), the submarine canyon, known as the Swatch of No Ground and shown in FIGURE 2.6, located approximately 30km offshore, is currently acting as a major conduit to convey the sediment discharged at the river mouth into the sea and thus limiting the seaward progradation of the GBM delta. Apart from sea level rise, the overthrust faulting, isostatic loading (due to extraction of underground resources), compaction and neotectonic movements in the GBM delta continuously create flood plain accommodation (Goodbred and Kuehl, 1999). The comparison of the estimate of the sediment budget during the Holocene period and modern time shows the continuous creation of accommodation space in the GBM delta.

FIGURE 2.6: Isopach map of the Ganges-Brahmaputra sediments deposited in the GBM delta since ca. 11,000 yr B.P. Reproduced from (Goodbred and Kuehl, 2000). Note: Dashed lines represent modern river channel and coast.

Wasson (2003) estimated the modern day suspended sediment budget for the GBM catchments and their delta (FIGURE A.5). Wasson (2003) also reported that the bed load in the modern GBM catchment is estimated to be between 600
and 2, 500 x10⁶ t/y. In addition to the variations in the natural factors, the sediment budget of the modern GBM delta is likely to be altered by the human interventions at both within the feeding rivers catchment and within the delta itself. However, the entire alteration on the sediment budget caused by the human interventions remains unknown.

FIGURE 2.7: Modern day suspended sediment budget for the GBM Catchment and delta. Flows are 10⁶ t/y. Inset in the source region shows percentage contribution from the source region for the Ganges and its tributaries. Source: (Wasson, 2003)

2.1.3 The Modern delta

2.1.3.1 The eastern GBM delta

2.1.3.1.1 Morphodynamic changes in the Meghna Estuary since 1776

Currently, GBM delta building is active primarily within the Meghna Estuary (see FIGURE 2.1) located in the eastern part of the delta. Based on the analysis of 1792 map and 1984 satellite images, Allison (1998b) estimated a net land accretion of 1,350 km² in the currently active river mouth. Based on this analysis Allison (1998b) showed that the currently active river mouth, which is located to the east of the Haringhata River (see FIGURE 2.1 for location), has
Chapter 2: Morphological Evolution of the GBM Delta

experienced land accretion at an average rate of 7.0km$^2$/y. Using the 1840 and 1990 bathymetric charts, Allison (1998b) showed there was a further accumulation of seabed volume of 4,800x10$^7$ m$^3$ in front of the current active river mouth. In the 1760-1770s, the Padma and the Meghna discharged separately (shown in FIGURE 2.8 A) into the Bay of Bengal. The Padma was discharging through the present day Tetulia Channel and the Meghna discharged further eastward along the northeast side of the Bhola Island (shown in FIGURE 2.8 A&B). At this time, the Brahmaputra was mainly flowing through its eastern course (see FIGURE 2.1) and discharging directly into the Meghna (Sarker et al., 2011). Since the shift of the Brahmaputra’s main flow to its western channel in the early 19th century, the Padma now carries both the Ganges and the Brahmaputra’s flow from Aricha and confluences with the Meghna at Chandpur (see FIGURE 2.1) (Sarker et al., 2011). The Ganges and Brahmaputra confluence 96 km upstream of their confluence with the Meghna and they flow another 177 km downstream to reach their mouth. The lower Meghna is highly braided and its banks are about 16 to 20 km apart (Coleman, 1969). Coleman (1969), based on the measurement of water discharge and sediment concentration, estimated that annually 1,000x10$^6$ t of sediment could be discharged into the Bay of Bengal. Sand bars with numerous channels exist at the river mouth bar (Coleman, 1969). The major distributaries at the river mouth are (shown in FIGURE 2.8) the: 1) Tetuliah, 2) Shahbajpur, 3) Hatiya and 4) Sandwip. The river and tidal flow split among these channels are not constant. These channels are divided by large islands such as Bhola, Hatiya and Sandwip. These islands have formed at the currently active river mouth centuries ago, but their size, shape and location varies constantly and they determine the proportion of water and sediment flow through the estuary channels (Sarker et al., 2011). The river mouth bar is not prograding rapidly considering the amount of sediment discharged by the rivers at the mouth. The bypassing of this high sediment flux could be due to the over steepness of the bar front slope which causes slumping; the presence of the Swatch of No Ground which attracts sediments into the Bengal fan, and/or; tectonically-induced subsidence (Coleman, 1969).

The reader may refer to FIGURE 2.8 for maps and satellite images showing the morphodynamic changes in the Meghna Estuary between 1776 and 2008, while TABLE 2.2 and FIGURE 2.9 provide further details about these changes.
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

Between 1776 and 1943 (shown in FIGURE 2.8 A&B), Noakhali, a town on the left bank of the Meghna River, retreated several km to the north but, at the same time, significant accretion of land can be observed on the south western Meghna Estuary (Sarker et al., 2011). In 1943 (shown in FIGURE 2.8 B), the flow from the Ganges, the Brahmaputra and the Meghna were discharged through three channels at the northeastern tip of Bhola Island: the Tetulia, Shahbajpur and Meghna. The flow of the eastern most Meghna was divided downstream by small islands.

A number of striking changes occurred in the Meghna Estuary during the period 1943 to 1973 (shown in FIGURE 2.8 B&C) and they are (Sarker et al., 2011) that: 1) a very large amount of land accretion occurred south of the Noakhali and the Bhola, 2) the eastern most flowing Meghna abandoned its channel due to the construction of two cross-dams across it (see Section 2.1.3.5 for more details about cross-dams) and shifted its flow completely to the Shahbajpur Channel. This separated the Hatiya Channel with the Meghna. Finally, 3) significant land accretion is observed in the Meghna Estuary during this period and currently the same trend continues, albeit at a reduced rate (Sarker et al., 2011). Further to this adjustment process, widening of the Hatiya Channel and narrowing of the Tetulia Channel have been observed. Severe land erosion and accretion as shown in FIGURE 2.10 is quite common in the Meghna Estuary due to the high sediment input and high fluvial and tidal energy.
Sarker (2013) observed that the main locus of delta building was in the Meghna Estuary during the last two centuries, but recently the delta building process has shifted westward from the Meghna Estuary to the Kuakata Peninsula (see FIGURE 2.1 for the locations). However, Sarker (2013) concluded that with a lack of long time-series data and good quality data, it is very difficult to quantify this historical evolution, and the implications for future changes, in detail.
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 2.9: Net accretion in the Meghna Estuary since 1776. Reproduced from (Sarker et al., 2011)

<table>
<thead>
<tr>
<th>Period</th>
<th>Net increase land area km²</th>
<th>Net mean annual accretion rate km²/yr</th>
<th>Location</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>1776 to 1943</td>
<td>760</td>
<td>+4.6</td>
<td>Bhola and Hatiya Islands (see FIGURE 2.8 A &amp; B)</td>
<td>Long-term accretion</td>
</tr>
<tr>
<td>1943 to 1973</td>
<td>1,100</td>
<td>+36</td>
<td>South of Noakhali and Bhola Island (see FIGURE 2.8 B &amp; C)</td>
<td>Fine fraction sediment produced by 1950 Assam earthquake (see FIGURE 2.9)</td>
</tr>
<tr>
<td>1973 to 1984</td>
<td></td>
<td>+10</td>
<td>Noakhali and Barisal (see)</td>
<td>Decreased rate of accretion</td>
</tr>
<tr>
<td>1984 to 1996</td>
<td></td>
<td>+30</td>
<td>Net accretion at Kuakata and Noakhali. Previously Kuakata experienced net erosion.</td>
<td>Second sediment wave produced by 1950 Assam earthquake (see FIGURE 2.9)</td>
</tr>
<tr>
<td>1996 to 2008</td>
<td></td>
<td>+10</td>
<td>Noakhali (see FIGURE 2.8 C &amp; D)</td>
<td>Accretion rate twice as long-term rate due to: 1) disconnection of the rivers and flood and tidal plains by flood and coastal embankments, 2) deforestation, and intensive agricultural practices in the catchment.</td>
</tr>
</tbody>
</table>

TABLE 2.2: Net accretion in the Meghna estuary as described in (Sarker et al., 2011)

Based on a time-series analysis of satellite images, Sarker et al. (2011) estimated the time required for land development at different locations within the Meghna Estuary, see TABLE 2.3. The factors controlling land building in the Meghna Estuary are: 1) the availability and characteristics of the supplied sediment, 2) fluvial and marine processes and 3) the estuary planform. Marine processes dominate at the outfall of the Tetulia Channel (see FIGURE 2.10), and the time taken to build land here is higher when compared with other land building locations. But, it is different in the marine process dominated Uri Char
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

area (see FIGURE 2.10). Tidal pumping and very active tidal circulation processes ensure a supply of sediment for land building in the south of the Noakhali and Urir Char areas and land building is more rapid here than in the Tetulia Channel (see FIGURE 2.10). The process of land building is most rapid where both fluvial and marine processes are active, provided sediment is available. The most rapid land building in the Meghna Estuary was observed within the Shahbajpur Channel (see FIGURE 2.10) (Sarker et al., 2011). During the dry season, the estuary is a well-mixed to a partly mixed system. The upper part of the estuary is river dominated and the southern part is highly wave influenced. However, a large part of the estuary in between is dominated by a mixed energy regime (Sokolewicz et al., 2008). During the monsoon, because of the high river discharge, a larger part of the estuary is river dominated, compressing the dry season dominated mixed energy zone. The erosion and deposition pattern of sediments vary significantly due to this seasonal variation (Sokolewicz et al., 2008).

<table>
<thead>
<tr>
<th>Locations</th>
<th>Dominant process</th>
<th>Mean tidal range (m)</th>
<th>Time required for land development (year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outfall of Tetulia Channel</td>
<td>Marine</td>
<td>2</td>
<td>22</td>
</tr>
<tr>
<td>Shahbajpur Channel</td>
<td>Mixed energy</td>
<td>2</td>
<td>12</td>
</tr>
<tr>
<td>South of Noakhali</td>
<td>Mixed energy</td>
<td>3</td>
<td>12</td>
</tr>
<tr>
<td>Urir Char</td>
<td>Marine</td>
<td>6</td>
<td>16</td>
</tr>
</tbody>
</table>

TABLE 2.3: Time required for land development at different locations in the Meghna Estuary. Reproduced from (Sarker et al., 2011)
Previous paragraphs described the changing nature of the GBM delta morphodynamics using the maps and satellites imageries. Here, an attempt is
made to understand the past morphodynamic changes of the modern GBM delta using the standardised metrics (Edmonds et al., 2011, Passalacqua et al., 2013) that have practical implications to the people and their environment of the GBM delta. Number of other delta metrics such as shoreline rugosity, Clinoform dip and concavity, channel facies, and sedimentographgh is used in the research by Burpee et al. (2015), Liang et al. (2016) are not considered as they do not have direct relevance to the people and their environment of the GBM delta.

The normalised sub-aerial delta area metric denotes the number of bifurcations in a delta (Edmonds et al., 2011). FIGURE 2.11a shows that the number of smaller islands increased over time in the GBM delta because of the formation of new bars but at the same time number of bigger islands decreased due to the land reclamation measures such as cross-dams in 1950s. Thus, the multi-model distribution of the real delta in 1943 is gradually evolving towards unimodal distribution. However, as shown in the FIGURE 2.10, in the real world delta, there are number of islands of size that is only a fraction of the total area.

The island shape factor metric indicates the degree of drainage (Passalacqua et al., 2013) within the islands of the GBM delta estimated by the ratio of wetted perimeter to the square root of island area. FIGURE 2.11b clearly shows that the peak of the distribution increases over time with a shrink in the tail. This was mainly because of the increase in the number of islands caused by the formation of new bars. The shrink in the tail could be caused by the land reclamation measures such as Cross-dams in 1950s and 1960s (FIGURE 2.15). The introduction of cross-dams have increased the area (FIGURE 2.8 B to C) and decreased the perimeter due to the siltation of the distributaries.

The island aspect ratio metric indicates the degree of elongation of the islands (Passalacqua et al., 2013). Despite the increase in the number of islands in the GBM delta between 1943 and 2012 (FIGURE 2.11c), the major and minor axes of the new/modified islands (FIGURE 2.10) in the GBM delta have undergone changes proportionately to not cause any significant distortion in the distribution of the island aspect ratio.
Chapter 2: Morphological Evolution of the GBM Delta

The nearest-edge distance is defined as the shortest, straight line distance of a point in land to the nearest water (Edmonds et al., 2011). It indicates the spatial variation in the distributary density and is used to know the frequency of sediment nourishment in the floodplain. In the GBM delta, the frequency of smaller edge distance increases over time due to the formation of new bars and erosion of islands bank (FIGURE 2.11d and FIGURE 2.10). But, the increase of frequency in the tail over the time could be due to the land gained by the cross-dams over time. This implies that the increased distance of a point in land from the nearest water. Also, the sediment deposition outside the poldered area could be the other reason for the lifted tail. However, this metric does not take into account the elevation of the land which also influences the flooding and nourishment of sediment in the flood plain.

The changes to the above metrics and thus the morphodynamics of the GBM delta over the last few decades have been assumed due to the variation in both natural such as fluvial discharges and sea level rise, and human drivers such as cross-dams and polders (Sarker et al., 2011). However, the individual effect of each drivers and when combined are yet poorly understood and a study such as this is required to fill that knowledge gap.

Residual flow in the Meghna Estuary

Based on numerical modelling (Jakobsen et al., 2002), it is estimated that the residual flow (for a definition of the term residual flow see Section 3.3.1.2.3) within the Meghna estuary channels ranges between 3,000 to 30,000 m$^3$/s. This modelling showed predominantly southward residual flow in the Tetulia River, Shahbajpur Channel and in the area between Hatiya and Sandwip (see FIGURE 2.8 for the locations). The high river discharge during the monsoon influences the width of this southward residual flow. The total southward residual flow simulated in these channels was approximately 25,000m$^3$/s during the dry season and 60,000 m$^3$/s during the monsoon season. However, the modelling also showed a counter-clockwise northward residual flow in the Sandwip Channel, with the flow around 10,000m$^3$/s during the dry season and 15,000 m$^3$/s during the monsoon season. During the monsoon season, this northward residual flow magnitude varies between one-third and one-sixth of the river discharge, whereas during the dry season the magnitude equals the
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

River discharge. Hence, this circulation of southward and northward residual flow plays a significant role in the salinity and morphological conditions in the area. Through this study, the effect of variation in natural and human drivers, both individually and combined, on the residual flow of tidally influenced deltas, and thus morphodynamics, over multi-decadal timescales are explored (see Chapters 5 to 9).

Turbidity maximum in the Meghna Estuary

The river flow and sediment discharge between the monsoon and dry season varies by a factor of between 20 and 30. During the dry season, the sediment concentration in the northeastern tide dominated part of the estuary is almost equal to that during the monsoon season (4000mg/l) (Barua, 1990). The main source of sediment during the dry season is the temporary storage of the sediment within the turbidity maximum zone during the monsoon (Sarker et al., 2011). Based on an analysis of Landsat TM band 3 satellite images acquired in January 1989, July 1991 and September 1991, it has been inferred by Islam et al. (2002) that the turbidity maximum zone during the period of low river discharge occurs near the shore and within the river mouth channels.

Suspended sediment concentrations during the low discharge period are influenced by the tides and shallow bathymetry. The surficial bottom sediments are kept in suspension, again by the tides. The turbidity maximum zone migrates seaward during the high river discharge period where the water depth is greater than 5m. Suspended sediment concentrations of up to 1,400 mg/l are observed in the Shahbajpur Channel (see FIGURE 2.10 for the location) during high river discharges. During the high discharge period, suspended sediments can be transported up to 160 to 180 km from the river mouth, whereas during the low discharge period suspended sediments are transported only up to 130 to 140 km beyond the river mouth (Islam et al., 2002).

Sediment Dynamics in the Meghna Estuary

The main source of sediment to the Meghna estuary is delivered by the upstream rivers. About 70% of these sediments are cohesive, with a grain size less than 63μm (Ali et al., 2007). Ali et al. (2007) carried out numerical modelling between the post-monsoon 1997 and post-monsoon 1999 periods. Both during the monsoon and dry seasons, the net sediment transport over the
entire southern boundary of the estuary is outward. The sediment patterns in the estuary were found to be distinct between the monsoon and dry season. For example, during the dry season, due to the low river discharge and tidal pumping, the turbidity maximum was observed in the Shahbajpur Channel (see FIGURE 2.10 for the location). This shifted position of the turbidity maximum contributes to sedimentation within the Lower Meghna River (see FIGURE 9.15 for the location). Furthermore, erosion was found to occur within the Hatiya Channel (see FIGURE 2.10 for the location) and the outer estuary during the dry season because of the negligible supply of sediment from the river (Ali et al., 2007). During the monsoon season, the main flow is through the Shabajpur Channel. An anticlockwise circulation traps sediment entering the Hatia Channel before either settling or being transported out of the estuary. The outflowing sediment during the monsoon is carried southwest by the coriolis force (Ali et al., 2007). Despite the significant amount of sediment deposition in the Meghna estuary compensating for the geologic subsidence, only 2% of the annual sediment supply from the rivers is used for the land building process. Based on this, Ali et al. (2007) have classified the Meghna estuary’s sediment trapping efficiency as ‘low’.

2.1.3.2 The Western GBM Delta

The western part of the GBM delta, i.e. the zone west of the currently active river mouth, consists of the Kuakata Peninsula, the Sunderbans and Hooghly estuary (see FIGURE 2.1 for the locations). According to Allison (1998b) the western part has undergone net land erosion of 350 km² between 1792 and 1984 and erosion of a seabed volume of 850x10⁷ m³ in front of the western delta between 1840 and 1990. Comparison of the 1792 and 1984 maps shows that the western side of the Haringhata River (see FIGURE 2.1 for the location) exhibits net land loss at an average rate of 1.9 km²/y. Shorelines along the eastern bank of the Hooghly River (see FIGURE 2.1 for the location) have retreated 3 to 4 km since 1840. This shows a clear spatial trend of increasing erosion towards the west side of the active river mouth, especially west of the Haringhata River. As the current sediment discharge point is at the active river mouth, these eroding areas are at some distance from the active mouth and are probably eroding due to eustatic sea level rise and subsidence. It has been suggested that these sediments do not contribute to land accretion at the
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

currently active river mouth (Allison, 1998b). Using satellite images of the Indian Sunderbans, including the Hooghly Estuary mouth and the Sagar Island, Ganguly et al. (2006) estimated that this part of the delta has eroded 280 km² and accreted 80 km² between 1989 and 2004, resulting in net erosion of 200 km². The western Sunderbans are sediment starved both due to the decreased sediments discharged by the Ganges distributaries and due to the eastward migration of the river mouths. In addition, the subsidence caused by the tectonic processes and sediment compaction increase the shoreline erosion and saline water intrusion on the western delta front (Allison, 1998a). The two sources of sediment supply to the lower deltaic plain that is to the west of the Haringhata River are (Allison and Kepple, 2001): 1) Ganges distributaries (Hooghly, Gorai and their distributaries) and 2) GBM sediments discharged at the active river mouth and which then are transported westwards by the coastal currents (see FIGURE 2.1).

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Location</th>
<th>Sediment Sample</th>
<th>Sedimentation rate (mm/y)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hooghly Estuary and western Sunderbans</td>
<td>4 (maximum length of 360mm)</td>
<td>3.00 to 4.80</td>
<td>Banerjee et al. (2012)</td>
</tr>
<tr>
<td>2</td>
<td>Eastern Sunderbans</td>
<td>15 (within 100m of tidal channel banks)</td>
<td>10.10</td>
<td>Allison and Kepple (2001)</td>
</tr>
<tr>
<td>3</td>
<td>Eastern Sunderbans</td>
<td>48 (50km inland, within 450m of tidal channel banks)</td>
<td>10.00</td>
<td>Rogers et al. (2013a)</td>
</tr>
</tbody>
</table>

TABLE 2.4: Sedimentation measurements in the Western GBM delta

The inactive western delta receives minimal modern sediment input (Allison, 1998b). TABLE 2.4 shows sedimentation rates observed in the western part of the GBM delta plain. Rogers et al. (2013a) found that the eastern Sunderbans region is accreting rapidly enough to compensate for the relative sea level rise and deduced that the frequency of tidal flooding and period of inundation are
important for this accretion in the Sunderbans. They found that 63% of the deposited sediments came from the 2008 monsoon flood pulse discharged at the currently active river mouth. This total is equivalent to about 13% of the total sediment discharged at the GBM delta mouth. Hence, Rogers et al. (2013a) concluded that the annual monsoon sediment discharge in the Meghna estuary is vital to sustaining the contemporary sedimentation rate in the Sunderbans.

2.1.3.3 Land cover and land use

Physiography, climate and the elevation of the land above sea level determines land use in the GBM delta. Coastal land use in the delta is diverse but competitive and often conflicting (Allison, 1998a). The large number of polders built during the 1960s and 1970s have resulted in sediment deprivation in these areas (Sarker et al., 2011). FIGURE 2.1 shows the coastal polders in the Bangladesh part of the GBM delta. Embankment height varies from a metre to 7m (see FIGURE 2.13). Land use exerts potentially a significant control on morphodynamic processes in the delta, both in terms of the direct human interventions on the land surface, but also through the varying roughness values implied by different land use and land cover types (Allison, 1998a, Coleman et al., 2008, Sarker et al., 2011). The main land use categories in the delta are agriculture, fisheries, forest and urban (Ahmed, 2011) and their spatial variation is indicated in FIGURE 2.12. In recent years, notable temporal trends in land use include the increasing development of agriculture, shrimp farming and urbanisation.

FIGURE 2.13: Coastal embankment re-built in 2014 at the actively eroding north-eastern corner of the Bhola Island. Source: Photo by author, taken during a site visit in May 2014.

2.1.3.4 Subsidence

Goodbred and Kuehl (1999) note that subsidence of the GBM delta plain due to overthrust faulting, isostatic loading, compaction and neotectonic movements continuously creates accommodation space. FIGURE 2.14 shows the major geologic structural features of the Bengal Basin. The Bengal Basin has experienced subsidence since the Eocene as the Burmese plate overrides the eastern margin of the Indian continent (Kuehl et al., 2005). The GBM delta's lower area experiences tectonic subsidence (Hoque and Alam, 1997) due to the isostatic adjustment of the crust under the sediment load, the rise of the Himalayas, and due to the dewatering and compaction of the shale and mud of the Proto-Bengal Fan. Moreover, active faults or hinge zones bound these areas experiencing tectonic subsidence. This type of subsidence occurs over a larger area, but at a slower and uniform rate (Hoque and Alam, 1997). Polders built in the GBM delta altered the natural sedimentation process that was formerly compensating for the subsidence. Apart from building and operating polders, groundwater abstraction, urbanisation, deforestation, upstream water diversion and impounding structures are important direct or indirect drivers of human-accelerated subsidence (Hoque and Alam, 1997). Several layers of peat underlie the modern lower deltaic land surface. Peat layers are found in many...
places within 35m depth and, in some places, at or close to the surface of the delta (Hoque and Alam, 1997).

According to Schiermeier (2014), twenty Global Positioning System (GPS) receivers monitoring the subsidence in the GBM delta since 2003 show the ground sinking at a rate of 9mm/y and 2-4mm/y in the western and eastern part of the delta respectively. Steckler et al. (2010) also concluded that the rate of subsidence varies across the GBM delta. For example, it has been found that the areas underlain by peat are subsiding at a rate higher than the other areas. But, there is difference in the rate of subsidence observed based on well logs and carbon-14 dates (Hoque and Alam, 1997). Based on the evidence collected from peat layers and tree trunks in the lower deltaic plain, Hoque and Alam (1997) estimated that the rate of subsidence in the Hatiya and Faridpur troughs (see FIGURE 2.14) are in the range 0.25 to 3.35mm/y. In comparison, the rate of subsidence for the Sunderbans, estimated from the presence of peat layers and wood in Holocene sediments, are within the range 0.74 to 2.13mm/y. Hoque and Alam (1997) concluded that the rate of subsidence would actually vary from place to place due to the local geological conditions and human interventions and the part of the delta that lies on the two active troughs, Faridpur and Hatiya, might subside at a higher rate. Based on subsidence rates measured from four archaeological monuments in Patuakhali and the Sunderbans region, Sarker (2012) concluded that the rate of subsidence in the GBM delta is within the range of a few mm per year as shown in TABLE 2.5 and not in the range of one to two cm per year. Hanebuth et al. (2013), based on the carbon dating of the 17th century kiln in the coastal Sunderbans, reported a subsidence rate of 5.2±1.2mm/y for the last 360 years. FIGURE 2.14 show the locations of those subsidence measurement sites. But, to fully understand the processes of subsidence in the GBM delta, more accurate and long term measurement of the subsidence is required (Brown and Nicholls, 2015).
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

<table>
<thead>
<tr>
<th>Monuments (Time A.D)</th>
<th>Estimated rate of subsidence (mm/y)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doyamoyee Mondir (1208)</td>
<td>1.25</td>
<td>(Sarker, 2012)</td>
</tr>
<tr>
<td>Chunakhola Mosque (15th century)</td>
<td>1.30 to 2.50</td>
<td></td>
</tr>
<tr>
<td>Bibi Beguni Mosque (15th century)</td>
<td>1.30 to 2.50</td>
<td></td>
</tr>
<tr>
<td>Shaker Temple (17th century)</td>
<td>-0.60 to 0.88</td>
<td></td>
</tr>
<tr>
<td>Kiln in coastal Sunderban † (17th century)</td>
<td>4.00 to 6.40</td>
<td>(Hanebuth et al., 2013)</td>
</tr>
</tbody>
</table>

TABLE 2.5: Estimated rate of subsidence in coastal Bangladesh

FIGURE 2.14: Major structural features of the Bengal Basin and subsidence measurement sites. Modified after: (Hoque and Alam, 1997), (Sarker, 2012) and (Hanebuth et al., 2013)

2.1.3.5 Other human interventions

Cross-Dams (also known as closure dams), are fixed structures that permanently close off a river mouth or estuary. Cross-Dam 1 in 1957 and
Cross-Dam 2 in 1964 were built in the Meghna estuary as shown in FIGURE 2.15 (Islam, 1971). Each dam was approximately 16 km long. The amount of land reclaimed by Cross-Dam 1 was 207 km² up to 1970 (Islam, 1971) and 300 km² up to 1985 from the construction [online] Available at: www.sandwip.com/crossdam.pdf [Accessed 24 August 2014]. The amount of land reclaimed by the Cross-Dam 2 was 311 km² until 1970 (Islam, 1971) and 600 km² up to 1985 from the construction [online] Available at: www.sandwip.com/crossdam.pdf [Accessed 24 August 2014]. Though significant accretion has been observed since their construction, it is speculated by Sarker et al. (2011) that the significant sediment input to the delta after the 1950 Assam Earthquake may be a major reason behind the cross-dams apparent success in stimulating land reclamation.

FIGURE 2.15: Map showing Cross-dams 1 and 2 and the area reclaimed by them (shaded) in the eastern part of the Meghna Estuary. Source: (Islam, 1971)

In 1971, the Farakka Barrage (highlighted by the green coloured dot in FIGURE 2.16) was built across the Ganges at the apex of the Ganges delta. The barrage was constructed for the purpose of diverting the main flow of the Ganges to reduce siltation in the Hooghly distributary (can be seen downstream of
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

Farakka in FIGURE 2.16). It is reported that the Farakka Barrage has decreased the sediment load to the active distributaries of the GBM Delta (Mirza, 2004). As the flow in the Gorai Distributary of the Ganges reduced significantly over the last few decades, due to the silting up of its off-take, regular dredging has been carried at the Gorai offtake to keep water flowing (Groot and Groen, 2001). It remains unknown on how the morphology of the GBM delta would have naturally evolved without the influence of human management over the last 60 years. This study attempts to visualise and compare the morphodynamic response of tidal-influenced deltas with and without human interventions (see Chapters 5 to 9).

### 2.2 GBM Catchments

Goodbred Jr (2003) has revealed that there is a strong link between the GBM delta morphodynamics and its sediment source area (river catchments). Hence, it is essential to understand the hydrology of the GBM catchments and the factors and processes controlling the sediment input flux to the GBM delta. Islam et al. (1999) listed the following factors as affecting basin denudation in the GBM catchments: the rapid uplift of the Himalayas, poorly compacted and easily erodible recent alluvium, seismic activity, very high channel gradients, relief ratios and runoff, high annual rainfall, poor soil conservation, deforestation, and increase in agricultural area. The three rivers: Ganges, Brahmaputra and Meghna are building the GBM delta by discharging into the Bay of Bengal. FIGURE 2.16 shows the extent of the catchment and major tributaries of Ganges, Brahmaputra and Meghna Rivers. The catchment size, the countries the catchments lie in and the annual average rainfall are shown in TABLE 2.6. The important characteristics of these rivers and their catchments are outlined below.
Chapter 2: Morphological Evolution of the GBM Delta

Figure 2.16: Map showing the course of Ganges, Brahmaputra and Meghna rivers and their major tributaries. The catchments of each river are shown in different colours. The red colour circle shows the Eastern Himalayan Syntaxis. Brahmaputra River, 2013. [online] Available at: http://en.wikipedia.org/wiki/Brahmaputra_River [Accessed 02 October 2013]

<table>
<thead>
<tr>
<th>River</th>
<th>Catchment size in (10^3 km^2)</th>
<th>Catchment lie in countries</th>
<th>Annual average rainfall (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ganges</td>
<td>1,060</td>
<td>80% in India, Rest in Nepal, China (Tibet) and Bangladesh</td>
<td>1,200</td>
</tr>
<tr>
<td>Brahmaputra</td>
<td>630</td>
<td>China (Tibet), India, Bhutan and Bangladesh</td>
<td>1,900</td>
</tr>
<tr>
<td>Meghna</td>
<td>77</td>
<td>India and Bangladesh</td>
<td>4,900</td>
</tr>
</tbody>
</table>

Table 2.6: GBM rivers- catchment size, boundaries and rainfall based on information from (Singh, 2008a, Singh, 2008b, Sarker et al., 2003)

2.2.1 Ganges Catchment

The River Ganges drains the southern side of the Himalayas, the Indian Peninsular Craton and its alluvial plain (Figure 2.16). The river is approximately
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

2,500km in length from its origin to the Bay of Bengal. FIGURE 2.17 shows the longitudinal profile of the Ganges River from source to sea. The river source is a Himalayan glacier, located at an altitude of 3,800m. Around 25% of the catchment lies within the Himalayas. When the river enters the alluvial plain the elevation is 290m, which is 300km downstream of its source. Subsequently the Ganges flows 1,700km over its alluvial plain, with the apex of the delta located at the split of the river into the Hooghly and Padma distributaries (Singh, 2008a).

FIGURE 2.17: Longitudinal elevation profile of the Ganga River main stream. The sharp break in the slope indicates the river transition from the Himalayas to its alluvial plain. Reproduced from (Singh, 2008a)

The water flow in the Ganges is perennial but the magnitude of runoff varies significantly over the seasons. Rainfall, subsurface flow and glacier melt water are the main sources of water for this river. About 70-80% of the catchment’s annual rainfall falls between June and September during the south-west monsoon season. FIGURE 2.18 shows the annual variation of rainfall in the Ganges basin and the flow discharge at Hardinge Bridge on the Padma distributary. FIGURE 2.19 shows the time series of annual peak flow of the Ganges at Hardinge Bridge (see FIGURE 2.1 for the location) measured between 1934 and 1998. The contribution from subsurface flow dominates during the post-monsoon season with the glacier melt water during the summer time (Singh, 2008a). The peak flow in the river occurs between mid-August and mid-September, whereas the minimum flow is in March or April. About 460 x 10⁹ m³ of water is discharged by the Ganges River into its delta every year. At
Hardinge Bridge, the total sediment transport, excluding the solute load, is approximately 550 million t/y (Sarker et al., 2003), with 355 million t/y being transported as suspended load and the rest as bed load. The $D_{50}$ of the bed material is 0.15mm (fine sand) (Sarker et al., 2003). Around 90% of the annual sediment loads is discharged during the monsoon season (Goodbred and Kuehl, 1999). Based on sediment measurements for a 13 year period between 1979 and 1995, Islam et al. (1999) derived a sediment rating curve relationship, see FIGURE 2.20, between the water discharge and suspended sediment discharge for the Ganges River. During low flows, the ratio between sediment and water is $0.1m^3/kg$ whereas during high flows the ratio is $1.0m^3/kg$.

FIGURE 2.18: (a) Ganges basin averaged rainfall and (b) discharge of the Ganges at Hardinge Bridge for two periods: pre-Farakka Barrage, 1951 – 1974 (solid) and post-Farakka Barrage1975 – 2004 (dashed). Source: (Jian et al., 2009)
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 2.19: Pre-Farakka (before 1975) and Post-Farakka annual peak water discharge of the Ganges at Hardinge Bridge (1934-1998). Horizontal dashed line indicates mean peak water discharge of the above two periods. Source: (Mirza, 2004)

FIGURE 2.20: Suspended sediment rating curve for the Ganges River at Hardinge Bridge based on observations between 1979 and 1995. Source: (Islam et al., 1999)

Human archaeological sites along the river date back to at least 3,500 to 3,000 years B.P. The present population density is about 300 persons per km² with about 250 million living in the catchment. Currently, more than 62% of the catchment is covered by agricultural land and only 14% by forest. Urbanisation, along with the construction of artificial canals and embankments, water diversions for irrigation and navigation, water impoundment, sand mining, and encroachment of natural depressions, floodplains and wetlands are the main human interventions that influence the natural flow system (Singh, 2008a).
Currently, 564 dams and 482 irrigation water diversion structures regulate water flow within the Ganges basin in India (Ganga, 2013 [online] Available at: http://india-wris.nrsc.gov.in/wrpinfo/index.php?title=Ganga [Accessed 10 November 2013]) and there are about 5 water regulating structures in Nepal (Mirza, 2004). The type of land use in northern India, which comprises the major part of the catchments of the Ganges, Brahmaputra and Indus Rivers, for the years 1870 and 1970 are shown in FIGURE 2.21. It is very obvious that there has been a significant increase in agricultural land over this 100 year period. Furthermore, there has been an increase in urbanisation and surface water area. This increase in the surface water area could be due to the number of dams built during this time. All of these land area categories have increased through conversion of natural lands such as wetlands, forests and woods, grass and scrub. Forests, woods and grass areas have therefore reduced significantly during this recent historical period.

FIGURE 2.21: Landuse in northern India in 1870 (lower) and 1970 (upper) based on (Richards et al., 1985)
2.2.2 Brahmaputra Catchment

The Brahmaputra River initially drains the northern slope of the Himalayas but it finally discharges southwards through the Himalaya. About 60% of the catchment lies within the Himalayas. FIGURE 2.16 shows the area drained by the Brahmaputra River. The total length of the river is about 2,800km. FIGURE 2.22 shows the longitudinal slope of the river from its source to sea. The river is very steep within the Eastern Syntaxis Zone (FIGURE 3.15) and in this zone it flows through a gorge of approximately 5,000m depth. The river’s delta begins when it splits into two distributaries: the Jamuna and the Old Brahmaputra, approximately 250km upstream of the Jamuna’s confluence with the Ganges distributary, the Padma. The river is perennial with high variations in the river flow over the seasons. The main sources of water are the monsoon rainfall and snowmelt in the Himalayas. The catchment’s geology and climate varies significantly. The headwater region is located in the rain shadow region of the Himalaya in Tibet and hence receives an annual rainfall of only 300mm. The annual rainfall in the Eastern Syntaxis Zone is 5,000 mm and along the southern slopes of the Himalayas it varies between 1,000 and 2,000 mm. At Cherrapunji, the eastern part of the catchment, the annual rainfall is 12,700mm. FIGURE 2.23 shows the monthly distribution of the river flow. The peak flow in the river occurs between mid-July and the end of August, whereas the minimum flow occurs in February or March. The ratio between minimum flow and maximum flow in a year could range between 10 and 15. About $670 \times 10^9 \text{ m}^3$ of water is discharged by the Brahmaputra River into the Bay of Bengal every year (Singh, 2008b).
FIGURE 2.22: Longitudinal elevation and water discharge profile of the Brahmaputra River main stream. See FIGURE 2.16 for the location of the Eastern Syntaxis. Reproduced from (Singh, 2008b).


At Bahadurabad (see FIGURE 2.1 for the location) on the Jamuna River, approximately 200 km upstream of the confluence with the Padma River, the total sediment transport, excluding the solute load, is estimated to be 590 million t/y of which suspended sediment load is approximately 390 million t/y, with the rest transported as bed load (Sarker et al., 2003). Clay and silt (sediment size less than 0.063mm) forms the suspended sediment load. The D$_{50}$ of the bed material is 0.20mm (fine sand) (Sarker et al., 2003). Similarly to
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

the Ganges, around 90% of the Brahmaputra’s sediment load is discharged during the monsoon season (Goodbred and Kuehl, 1999). Islam et al. (1999) derived a sediment rating curve relationship linking the water discharge to the sediment discharge observed at the Bahadurabad gauging station, see FIGURE 2.24, and for the Ganges-Brahmaputra Rivers downstream of their confluence at the Mawa gauging station (see FIGURE 2.1 for the location), see FIGURE 2.24. At Bahadurabad, during low flows, the ratio between sediment and water is less than 1.0m$^3$/kg whereas during high flows the ratio is 1.0m$^3$/kg or greater.

FIGURE 2.24: Suspended sediment rating curves for the Brahmaputra River at Bahadurabad (left) and for the Ganges-Brahmaputra Rivers at Mawa (right) based on observations taken between 1979 and 1995. Source: (Islam et al., 1999)

The erosion rate within the catchment is considered by Singh (2008b) to be greater than the Ganges and also greater than the world average. Erosion rates from the different parts of the catchment are shown in FIGURE 2.25. The erosion rate in the Eastern Syntaxis Zone (see FIGURE 2.16 for the location) is the highest in the world and this high erosion rate influences tectonic activity in the region (Singh, 2008b). Wasson (2003) reported that landslides are a major source of sediment in the Himalaya and they are triggered both by natural causes, as well as by human activities such as road construction. Wasson (2003) also mentioned that an 1894 landslide in a sub-catchment of the Ganges produced about 70 to 188 times the mean annual sediment load of
that sub-catchment. According to Keefer (2002), an earthquake of magnitude 4 or greater will trigger landslides. TABLE 2.7 lists Himalayan earthquakes, with a magnitude greater than 6, that have occurred between 1833 and 1999 within the catchments of the Ganges and Brahmaputra. The earthquake archive (ShakeMap Archive, 2011. [online] Available at: http://earthquake.usgs.gov/earthquakes/shakemap/list.php?y=2004&n=global [Accessed 25 July 2013]) shows that at least one earthquake of magnitude greater than 4 has occurred every year within the catchments of the Ganges and Brahmaputra, indicating that seismicity is potentially a significant control on erosion processes within the catchments of these rivers.

<table>
<thead>
<tr>
<th>Year</th>
<th>Date</th>
<th>Magnitude</th>
<th>Epicentre</th>
<th>Name of earthquake</th>
</tr>
</thead>
<tbody>
<tr>
<td>1833</td>
<td>26/8/1833</td>
<td>7.7</td>
<td>Kathmandu</td>
<td>The 1833 Nepal Earthquake</td>
</tr>
<tr>
<td>1897</td>
<td>12/6/1897</td>
<td>&gt;8.0</td>
<td>Assam</td>
<td>The 1897 Assam Earthquake</td>
</tr>
<tr>
<td>1905</td>
<td>04/04/1905</td>
<td>7.8 (8.6)</td>
<td>Kangra Valley</td>
<td>The 1905 Kangra Earthquake</td>
</tr>
<tr>
<td>1934</td>
<td>15/01/1934</td>
<td>&gt;8.0</td>
<td>Nepal &amp; Bihar</td>
<td>The 1934 Bihar-Nepal Earthquake</td>
</tr>
<tr>
<td>1950</td>
<td>15/08/1950</td>
<td>8.7</td>
<td>Assam</td>
<td>The 1950 Assam Earthquake</td>
</tr>
<tr>
<td>1991</td>
<td>20/10/1991</td>
<td>6.6</td>
<td>Uttarkashi-Tehri</td>
<td>The 1991 Uttarkashi Earthquake</td>
</tr>
<tr>
<td>1999</td>
<td>29/03/1999</td>
<td>6.8</td>
<td>Chamoli, UP</td>
<td>The Chamoli Earthquake of 1999</td>
</tr>
</tbody>
</table>

Human activities in the catchment include deforestation, urbanisation, construction of flood protection works, dams for hydro power generation and encroachment of floodplains and natural depressions. Currently, there are 7 dams and 24 irrigation water diversion structures regulating water flow within the Brahmaputra basin in India (Brahmaputra, 2013 [online] Available at: http://india-wris.nrsc.gov.in/wrpinfo/index.php?title=Brahmaputra [Accessed 10 November 2013]) and China is constructing the Zangmu Dam across the River Brahmaputra in Tibet (Zangmu Dam, 2013 [online] Available at: http://en.wikipedia.org/wiki/Zangmu_Dam [Accessed 10 November 2013]). However, Whitehead et al. (2015a) study shows increases in the fluvial discharges to the GBM delta under simulations of plausible future climate change and socio-economic scenarios.

2.2.3 Meghna Catchment

The Meghna River is the smallest of the three catchments that discharge through the GBM delta (FIGURE 2.16). Rainfall is the main source of water flow in this river, with the peak river flow occurring in the month of August. The average annual discharge of the river is 4,600 m³/s. During the southwest monsoon the river peaks at 13,700 m³/s. The Upper Meghna River drains the Manipur Hills and Meghalaya Hills and confluence with the Padma distributary in the delta. Downstream of this confluence the river is called the Lower Meghna River (see FIGURE 2.1 for the location). This reach of the river is tidally...
influenced. The total sediment load, excluding the solute load, from the Upper Meghna River (see FIGURE 2.1 for the location) at Bhairab Bazar is 13 million t/y (Sarker et al., 2003). Currently, there are 5 dams and 6 irrigation water diversion structures regulating water flow within the Meghna basin in India (Barak, 2013 [online] Available at: http://india-wris.nrsc.gov.in/wrpinfo/index.php?title=Barak_and_others [Accessed 10 November 2013]).

The above sections on the catchments revealed that fluvial discharges to the GBM delta are getting altered by both the natural and human drivers. However, the science of deltaic morphodynamic response to such variations need to be fully understood especially when the effect of climate change (Whitehead et al., 2015a) and more human activities are predicted in these catchments (Sarker et al., 2011, Sarker, 2013, Akter et al., 2016).

2.3 Bay of Bengal

2.3.1 Sea Level rise and tides

Church and White (2006) reported that global sea level was relatively stable during the 18th century, but that there has been a eustatic sea level rise of 60mm in the 19th century, and 190mm in the 20th century. Cazenave et al. (2008) mentioned that the rate of eustatic sea level change at the head of the Bay of Bengal ranges between about 2 and 5mm/y between 1993 and 2008. The GBM delta front experiences a semidiurnal tide. Tidal amplitude at the Meghna Estuary is greater than 4m, whereas it is about 2m in India. This shows a decreasing trend in the tidal amplitude from the east to the west (Allison et al., 2003). Singh (2002) reported an increase in mean tidal trend over the eastern part of the GBM delta during the 22 year period between 1977 and 1998. However, Pethick and Orford (2013) argued that as the tidal range has been changing over time, mean sea level cannot be used to measure temporal changes in actual sea level rise and instead the concept of effective sea level rise should be used to study the individual effects of factors such as eustatic sea level, land subsidence, tidal amplitude and fresh water input.
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

<table>
<thead>
<tr>
<th>Tide gauge</th>
<th>Period</th>
<th>Observed effective sea level rise (mm/y)</th>
<th>% tidal range</th>
<th>% subsidence</th>
<th>% Eustatic sea level rise</th>
<th>% fresh water base level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hiron Point</td>
<td>1990-2011</td>
<td>10.7</td>
<td>28.6</td>
<td>51.0</td>
<td>20.4</td>
<td>0.0</td>
</tr>
<tr>
<td>Mongla</td>
<td>1998-2010</td>
<td>14.5</td>
<td>58.7</td>
<td>42.7</td>
<td>14.2</td>
<td>-15.7</td>
</tr>
<tr>
<td>Khulna</td>
<td>1968-1999</td>
<td>17.2</td>
<td>83.2</td>
<td>40.5</td>
<td>11.6</td>
<td>-35.3</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>14.1</td>
<td>56.8</td>
<td>44.7</td>
<td>15.4</td>
<td>-17.0</td>
</tr>
</tbody>
</table>

TABLE 2.8: Observed effective sea level rise and estimated percentage contribution of each factors. Source: (Pethick and Orford, 2013)

The study by Pethick and Orford (2013) assumed, based on previous studies, a eustatic sea level rise of 2mm/y at all stations and 5, 6 and 7mm/y of subsidence at Hiron Point, Mongla and Khulna stations respectively (see FIGURE 2.1 for the locations of these stations). TABLE 2.8 shows the percentage contribution by each factor. The tide gauge station at Hiron Point is located in an uninhabited mangrove forest area in the Sunderbans, whereas the ones at Mongla and Khulna are located in a densely populated area with extensive polders. There is a trend in increasing observed sea level rise at the stations and the percentage contribution from the tidal range. Pethick and Orford (2013) explain that the converging tidal channels and the reduced frictional damping of the tidal range due to polders in the tidal plains are the main reasons for this increase. Fresh water inputs contribute negatively to the effective sea level rise due to the seasonal variation and the gradual decrease in the flow to the Gorai Distributary (see FIGURE 2.1 for the location) from the Ganges. Kay et al. (2015) study on future climate change and subsidence in the GBM delta revealed a possible increase in sea level and thus more likelihood of flooding.
With the current rate of sea level rise and sediment supply at highstand and with human interventions, the evolution of the modern delta morphodynamics would be different from the past evolution. The current rate and amount of sea level rise could alter the area of sub-aerial delta, the number of islands, and could cause increased back water effect such as upstream propagation of bed aggradation and widening of distributaries. Also, depending upon the balance between the fluvial sediment supply and accommodation space created, the current sea level rise could stop the progradation of the delta resulting in only aggradation. However, this could be different under the influence of tides. All of these processes and responses need to be explored. This study attempts to understand the morphodynamic response of tidally influenced deltas to modern sea level rise both individually (see Chapter 6) and combined with other drivers (see Chapter 8 and 9).

2.3.2 Storm Surges

The GBM delta is hit by a cyclonic storm nearly every year (Ahmed, 2011). Figure 2.26 shows the number of different types of cyclonic storm that have hit the GBM delta between 1890 and 2009 (Hossain, 2012). This indicates that about 150 cyclones have hit the delta in 120 years. The GBM delta has encountered 60 severe cyclones (cyclone with wind speed range: 90 to 119 km/h) between 1797 and 1991. Among those cyclones, 32 were accompanied by storm surges (Saito and Alino, 2008). Figure 2.27 shows the frequency of cyclonic storms in ten year intervals between 1890 and 2009. Generally, there is an increasing trend in the number of cyclonic storms towards the end of 20th century, with a drastic increase in their numbers since 1960s (probably reflecting to the improvement in measurement and recording reliability rather than a real increase) (Hossain, 2012). These tropical cyclones are strongly influenced by the Walker and Hadley Circulations (airflow patterns in the tropics in lower atmosphere) (Choudhury, 1994).

However, Figure 3.26 is limited because it accounts only for changes in the numbers of cyclones observed, rather than accounting for changes in both their numbers and magnitude. In contrast, the Accumulated Cyclone Energy (ACE) is a parameter that is generally used to show the activity and destructive potential of tropical storms. The ACE of active tropical storms in a year is
calculated by adding the squares of the estimated maximum sustained wind velocity. Wind speeds at every six-hour intervals during an active tropical storm and greater than magnitude of 35 knots (65 km/h) are used in calculating ACE (ACE, 2013. [online] Available at: www.wmo.int/pages/prog/arep/wwrp/tmr/documents/ACE.doc [Accessed 10 December 2013]). FIGURE 2.28 shows yearly time series of ACE calculated for tropical storms hitting the GBM delta since 1877(Knapp and Kruk, 2009).

Comparing FIGURE 2.27 and FIGURE 2.28, it can be observed that, although the number of cyclonic storms increased towards the end of the 20th century, the ACE values indicate that the magnitude of these storms may not be of destructive potential. But, if in the future for the same frequency of storms but with increased magnitude occurs, this could result in storms of destructive potential in nature and thus influence the delta morphodynamics. In FIGURE 2.28, the gap of cyclones in 1940s can be associated to severe drought in the region and unrecorded measurements during the Second World War (Choudhury, 1994). Figure 3.27 also shows evidence for cycles of periods of high ACE followed by periods of relatively low ACE. The periods of high ACE tend to be clustered in times that could be related to the years of when the (El Nino Southern Oscillation) ENSO Index is positive (Southern Oscillation means variations in the temperature of the surface of the tropical eastern Pacific Ocean) or weak El Nino (warm phase of ENSO) years and the periods of low ACE could be related to the years of strong El Nino after (Choudhury, 1994) and SOI time series, 2015. [online] Available at:
FIGURE 2.26: Different types of cyclonic storm that hit the GBM Delta between 1890 and 2009. Source: (Hossain, 2012)

FIGURE 2.27: Frequency of cyclonic storm in the GBM Delta in 10 year period between 1890 and 2009. Source: (Hossain, 2012)

FIGURE 2.28: Yearly time series of Accumulated Cyclone Energy (ACE) of cyclones hitting the GBM delta since 1877 based on (Knapp and Kruk, 2009)
Ahmed (2011) reported that most of the storms have occurred either during the early summer time (April-May) prior to the monsoon season, or during the post monsoon time (October-November). FIGURE 2.29 shows the monthly distribution of recorded cyclonic storm in the GBM delta between 1584 and 2009 (Hossain, 2012). The return period of a 12m high surge is 1 in 20 years whereas for the 7m high surge it is 1 in 5 years (Saito and Alino, 2008). However, the impact of the storm surges on the morphodynamics of the GBM delta over centennial scale is not available. But, this is beyond the scope of this study.

![Figure 2.29: Monthly distribution of recorded cyclonic storm in the GBM Delta between 1584 and 2009. Source: (Hossain, 2012)](image)

2.4 **Summary**

- The three rivers: Ganges, Brahmaputra and Meghna, including two of the world’s largest, are building the GBM delta by discharging their sediments into the Bay of Bengal.
- Despite the rapid rise in sea level during the post glacial maximum, the rate of sediment deposition in the Bengal Basin was greater than the rate of sea level rise. The GBM delta received more than twice the amount of the modern day sediment discharge for a prolonged period during the early Holocene.
- The progradation of the GBM lower delta plain after the maximum transgression would have happened in four or five phases. Due to avulsion, the Ganges migrated eastward and the Brahmaputra was shifting between its eastern and western course. A number of delta
lobes were formed due to these shifts. After the weakened but steady sea level rise, and with few variations in the intensity of the southwest monsoon, the delta growth along the western part of the delta reached the present day extent. The Sunderbans in the western part are currently accreting at 10mm/y, enough to compensate for the present day relative sea level rise.

- About 200 years ago, the Brahmaputra River switched back to its western course to join the Ganges River (merging two of the world’s largest rivers—a unique in the process of delta formation). Since then the delta has been prograding into the Meghna estuary, a process that continues to the present day.
- The modern GBM delta is one of the largest deltas in the world and has one of the highest population densities; this human population exerts significant pressures on the delta system.
- Severe land erosion and accretion is quite common in the Meghna estuary due to the high sediment input and high fluvial and tidal energy. Because of lack of long time-series data and good quality data, it is very difficult to understand the recent and future development of the delta. This calls for the better systematic understanding of the hydrodynamic and morphodynamic behaviour of the contemporary GBM Delta.
- Annually 1,000x10^6 t of sediment could be discharged into the Bay of Bengal. Despite the significant amount of sediment deposition, the sediment trapping efficiency of the Meghna estuary’s has been classified as “low”.
- The submarine canyon known as the Swatch of No Ground is currently acting as a major conduit to convey the sediment discharged at the river mouth into the sea and thus limiting the seaward progradation of the GBM delta.
- Direct human interventions on the morphodynamics within the GBM delta include the construction of barrage and cross-dams across the distributaries, land use change, and polderisation.
- Subsidence measured within the Sunderban and Kuakata Peninsula ranges between -0.60 to 6.4mm/y whereas the analysis of the observed tidal water levels in that region showed RSLR ranging between 10.7 to 17.2mm/y. The comparison of the estimate of the sediment budget
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

during the Holocene period and modern time shows the continuous creation of accommodation space in the GBM delta.

- About 150 cyclones have hit the delta in the past 120 years. However, the impact of the storm surges on the morphodynamics of the GBM delta over centennial scale is as yet unknown.

- Monsoon rainfall, earthquake induced landslides and human interventions within the catchments such as land use change, water storage and diversion structures are the major factors influencing the water or sediment supply to the GBM delta. The ratio between minimum flow and maximum water discharge to the delta in a year could range between 10 and 20. 90% of the annual sediment loads is discharged during the monsoon season between June and September. Therefore, seasonality is potentially a strong control on the sediment supply to the delta and hence, the delta morphology.
Chapter 3: Deltas – Features, Evolution, Processes and Factors

3. Deltas – Features, Evolution, Processes and Factors

This chapter presents a literature review that covers deltaic features, their classification, evolution, controlling factors and the processes influencing their evolution. The science of delta restoration is also briefly discussed. This chapter is required to understand the existing knowledge of deltaic morphodynamics and to identify the knowledge gap in this science.

3.1 Definition, classification and features

3.1.1 Deltas

Deltas are developed where a river discharges into a lake, sea or ocean, causing the deceleration of the flow and deposition of the river's sediments. Deltas are formed by a pattern of distributary channels with multiple lobes of sedimentation. The characteristics of a delta have been summarised by Kleinhans et al. (2012) as follows:

- Deltas will have more bifurcations than confluences;
- Delta distributaries are subjected to back water effects, causing flooding, avulsion and altering the distribution of water among the various channels;
- Delta distributaries are separated by flood basins. Sedimentation may occur in these basins during floods;
- Delta banks are moderately to highly cohesive, such that channels are sinuous and migrating;
- Deltas form mouth-bars near their marine or lacustrine boundary;
- Near the delta mouth-bars, sediments are redistributed;
- Delta expansion and its channel system are influenced by the waves, tides and base level;
- Within a delta, the bifurcations become confluences when the tide drives the flow. These characteristics play a significant role in shaping the features of the deltas.
3.1.2 Classification of deltas

A classification of deltas is required to recognise, conceptualise and summarise our understanding of the natural processes of delta morphodynamics. Nemec (2009) classified deltas into alluvial and non-alluvial types. Alluvial deltas have been further classified based on such characteristics as their feeder system, thickness contribution, tectono-physiographic setting, delta front regime, grain size, delta face slope and various other physiographic attributes (Nemec, 2009).

Based on the dominant influence of forces acting to transport sediments and shape modern deltas, Galloway (1975) developed an influential triangular classification of deltas with example deltas from field observations as shown in FIGURE 3.1. This is still used today and forms the basis of this thesis. As implied by the names, the action of waves dominates in wave dominated deltas, tides in tide dominated deltas and river forces in river dominated deltas. Naturally, mixed influence deltas such as mixed wave and tide influenced deltas, may also be evident. Simple as this classification is, it does not take into account some of the many other factors that could influence delta morphodynamics: river catchment characteristics, sediment type and size, water depth of receiving basin and relative sea level changes (Hart, 1995). However, a weakness of this classification is that it has no criteria set to estimate the degree of reworking and thereby to locate a delta within the classification triangle (Nemec, 2009). For example, the morphodynamics of a delta may vary in time and space and for example a tide dominated delta at one time could be converted into a wave dominated delta in the future. Therefore, this classification is inadequate to explain and represent the real morphodynamics of many deltas (Syvitski and Saito, 2007). Despite several criticisms of Galloway’s triangular classification it is nevertheless widely used to generate an initial understanding of the surface features of modern deltas.
Orton and Reading (1993) added a factor, dominant sediment grain size, to Galloway’s triangular classification. The grain size of sediments supplied to the delta is a potential influence on the shape and size of the delta. According to Orton and Reading (1993) the nature of the sediment supplied may control 1) the slope and patterns of distributary channels, 2) the river mouth hydrodynamics and 3) the reworking of the sediments by tides and waves and shoreline types. As Orton and Reading’s delta classification is based on Galloway’s triangular classification, it inherits all the limitations of Galloway’s system. In addition, Orton and Reading’s delta classification may also be criticised for linking the two dependent variables: grain size and degree of reworking, and for not setting criteria to determine the dominant grain size of a delta front. Despite several criticisms, because of their pragmatic approach both types of delta classification system reviewed above are suitable and required here, compared to other classification types, to recognise and conceptualise the action of marine processes and feeder system dynamics on the morphodynamics of the subaerial part of deltas (Nemec, 2009).
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

3.1.3 Features of deltas

Different types of deltas have different features because of the difference in the influencing factors forcing morphodynamic processes on each individual delta. The components of fluvial and tide dominated deltas can be divided into two main parts based on their morphology and sedimentary environment. These two parts are the subaerial delta and subaqueous delta, respectively. The subaerial delta is divided into two regions: 1) the marine and fluviolly influenced lower delta plain and 2) the exclusively riverine influenced upper delta plain. The subaqueous delta is divided into three regions: 1) the delta-front platform or sub tidal delta plain, 2) the delta-front slope, and 3) the prodelta. FIGURE 3.3 shows the basic environments of river, tide and wave
dominated deltas in plan, whereas FIGURE 3.4 shows the features of tide-dominated deltas in cross section. Tide-dominated deltas, unlike tide-dominated estuaries, will have clear topset-foreset-bottomset clinof orm morphology and delta prograding features (Goodbred and Saito, 2012).

FIGURE 3.4: Basic environments of fluvial, tide and wave-dominated deltas. Source: (Gupta, 2011)

Galloway (1975) recognised the morphologic and stratigraphic features for the three extreme types of delta defined in his triangular classification.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Fluvial dominated</th>
<th>Wave dominated</th>
<th>Tide dominated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry</td>
<td>Elongate to lobate</td>
<td>Arcuate</td>
<td>Estuarine to irregular</td>
</tr>
<tr>
<td>Channel type</td>
<td>Straight to sinuous distributaries</td>
<td>Meandering distributaries</td>
<td>Flaring straight to sinuous distributaries</td>
</tr>
<tr>
<td>Bulk composition</td>
<td>Muddy to mixed</td>
<td>Sandy</td>
<td>Variable</td>
</tr>
<tr>
<td>Framework facies</td>
<td>Distributary mouth bar and channel fill sands, delta margin sand sheet</td>
<td>Coastal barrier and beach ridge sands</td>
<td>Estuary fill and tidal sand ridges</td>
</tr>
<tr>
<td>Framework orientation</td>
<td>Parallels depositional slope</td>
<td>Parallels depositional strike</td>
<td>Parallels depositional slope</td>
</tr>
</tbody>
</table>

TABLE 3.1: Characteristics of deltaic depositional systems (Galloway, 1975)
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

3.1.3.1 Distributary channels

Distributary channels are channel branches that discharge fluvial flow and sediments in the seawards direction. The proportion of flow in each distributary channel varies (Hart, 1995). According to Coleman and Wright (1975) distributary channels can be classified into three main types: 1) Bifurcating distributary channels are the ones where the main river channel is divided into many channels with many river mouths. Examples of such channels can be found in the Mississippi, Mahakam, Niger and Rajang deltas. Bifurcating channels decrease in size and slope seaward as the flow carried by them decreases. This type of channel is developed where the subsidence rate is low, the tidal range, waves and offshore slope are small, and fine grained sediments are discharged. 2) Rejoining distributary channels are the ones where the bifurcating channels rejoin to form a complex network of channels with many river mouths. These types of channels can be seen in the Ganges-Brahmaputra delta. In the Ganges-Brahmaputra delta, the distributary channels with depth/width aspect ratios of less than one are flood dominated, whereas distributary channels with a ratio greater than 1 are ebb-dominated (see Section 3.3.1.2.3 for their morphological significance). Varying fluvial
discharges, high tides, intermediate waves and relatively steep offshore slopes provide the environment required for the development of rejoining channels.

3) Single distributary channels are deltas with only one or a few channels dividing from the main river channel. Channels of this type can be found in the Sao Francisco and Fraser deltas, for example. High tides and waves and steep offshore slope promote the development of this type of distributary channel pattern.

FIGURE 3.5: Types of end-member distributary channel patterns. Source: (Coleman and Wright, 1975)

Terminal distributary channels are the last branch of distributary channels in a sub-aerial delta. Olariu and Bhattacharya (2006b) mentioned that the distribution of sediment into the delta front area is controlled by the number of distributary channels. According to them, a river dominated delta will have many (tens to hundreds) terminal distributary channels, whereas tide dominated deltas will have a moderate number (ten to twenty) of distributary channels, and wave dominated deltas will have low numbers (1 or 2) of terminal distributary channels. As the distance between the terminal distributary channels in river dominated deltas is, therefore, relatively low, it is common for the mouth bars (see Section 3.1.3.2) to merge. In contrast, in the other two cases, mouth bars are usually not connected (Olariu and Bhattacharya, 2006b).
3.1.3.2 Mouth bars

River mouths are the location where the interaction of marine and fluvial forces takes place at the greatest level. Mouth bars form at river mouths and their morphology is controlled by fluvial discharge, waves, tides and their relative strengths, sediment type and size and receiving basin characteristics (Hart, 1995). Coleman and Wright (1975) classified river mouth bars, based on their field observations, into five major types (Figure 2.6): radial, lunate, middle ground or bifurcating, subaqueous jettied and tidal ridges.

Radial type mouth bars tend to form where the frictional force is dominant, with buoyancy effects being secondary. Here the sands are distributed to several miles on either side of the river mouth. Lunate mouth bars will form where the inertial forces are dominant due to the steep discharging river, with frictional forces being secondary. In this lunate type, a shoal or bar is formed by the river, albeit not as wide as in the radial type, and located more towards the sea after eroding its own bed near the mouth. Middle ground or bifurcating bars form where both buoyancy and frictional forces are significant. A widespread sandbar with shallow channels on either side is typical of this type of mouth bar. Subaqueous jettied bars form where inertial forces are dominant.
and buoyancy is a secondary influence. Sands are not widely deposited in this type of mouth bar. Tidal ridge bars form where a high tidal range exists to create strong bidirectional sediment transport. Large linear tidal ridge bars are formed seaward of the river mouth with their axis normally parallel to the river channel and perpendicular to the shoreline. These types of bars can be found in the Ganges-Brahmaputra, Colorado, Indus, Chao Phraya and Irrawady deltas (Coleman and Wright, 1975).

3.1.3.3 Intertidal plains

In a tide dominated delta, the lower delta plain within the subaerial delta plain comprises channel mouth bars, tidal flats, marshes and mangroves infringed by the tidal channels. Where large fluvial sediments are discharged in tide dominated deltas, large elongated channel bars of size greater than 100m in length form. A number of such channel mouth bars can unite to form shallow intertidal flats which then emerge and become vegetated to form a new delta-plain. Delta progradation in tide dominated deltas typically occurs between the subtidal and supratidal region (Goodbred and Saito, 2012). Tidal channels in the lower delta plain are the ones which drain the tidally inundated areas. Tidal flats, lagoons, bays and swamps or marshes form the interchannel areas. However, these areas are regularly flooded by tides, or occasionally by large river or storm surge floods. Soils of these interchannel areas are very rich in fertility and are therefore often highly suitable for cultivation. However, due to the frequent construction of polders and dykes in such environments, flooding of the interchannel area is largely prevented (Hart, 1995).

However, changes to the above deltaic features due to the change in driving forces are poorly understood. We need to understand how the features such as the connection of distributaries, and the number of distributary channels changes due to the changes in forcing. Also, need to know what happens to delta morphodynamics when the interaction of distributaries and tidal flood plain, an important delta building process (Hiatt and Passalacqua, 2015), is stopped. A hypothesis, when natural and human drivers are combined, the influence of deltaic human interventions on the morphodynamic change will dominate over the natural drivers, has been tested in this study.
3.2 Evolution of deltas

3.2.1 Response of deltas to sea level rise

FIGURE 3.7 shows the response of Asian mega-deltas during the Holocene sea level rise. This response history can be divided into 4 stages as shown in the figure. During stage 1, when the sea level was rising rapidly following the glacial maximum, the deltas began to aggrade. In stage 2, the maximum transgression occurred around 6,000 years ago when sea level stabilised to around the present day level. By stage 3, and with the stabilised sea level, the deltas began to prograde into the sea. During stage 4, the deltas reached their present day configuration. Stage 5 represents an assumed behaviour of deltas under future sea level rise. As the present status of deltas is different from the ones during the early Holocene, the evolution of deltas to the future sea level rise will likely be different from that experienced in stages 1 to 4 (Woodroffe et al., 2006).

FIGURE 3.7: A schematic cross-section of the reconstruction of the response of Asian megadeltas to sea-level change during the Holocene and hypothetical prediction of their response to future sea level rise. Source: (Woodroffe et al., 2006)
Hori and Saito (2008) used FIGURE 3.8 to explain the growth of deltas during the Holocene sea level rise. According to Hori and Saito (2008) no deltas have experienced a stable sea level since their initiation at about 8,000 years B.P. The Asian deltas were prograding since the mid-Holocene, as the sea level was either relatively stable or was falling slowly. However, unlike the rapid rise in sea level during the early Holocene, currently there is now a steady rise in sea level. Deltas such as the Mississippi and Nile are now only experiencing the highest Holocene sea level. Considering the recent amount of sediment deposition happening in the GBM delta, the GBM delta is a good example of a modern delta that is undergoing both aggradation and progradation (Hori and Saito, 2008). We are yet to completely understand the response of modern deltas over multi-decadal timescales to the currently varying rates of relative sea level rise, and basin water forcing. Also, as the review suggests that the effect of human interventions on the response of modern delta during relative sea level rise needs to be studied.

![FIGURE 3.8: Longitudinal section of deltas showing response to sea level rise: (a) stable sea level; and (b) steadily rising sea level. Source: (Hori and Saito, 2008)](image)

3.2.2 Delta growth and abandonment

Roberts (1997) explained the growth and abandonment cycle of the Mississippi delta, a river dominated delta, using the different features of the delta in the hierarchy of its formation during the Holocene Period: 1st order - Mississippi Deltaic Plain, formed by the Mississippi River, 2nd order - Six delta complexes within the Mississippi Deltaic Plain, 3rd order - sixteen delta lobes within the six delta complexes, 4th order - sub deltas formed within each delta lobe, 5th
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

and last order—crevasse-splay and overbank splay. Each delta complex has several major distributaries, and each major distributary is associated with one delta lobe. Secondary channels and breaks in the natural levees of major distributaries inside each delta lobe will, in turn, produce sub-deltas and crevasse-splays. The duration of crevasse-splays from initiation to abandonment is of a few decades, whereas for the sub-deltas it is about 150–200 years. FIGURE 3.9, the delta cycle, explains these processes, from the initial formation during the regressive phase to complete abandonment during the transgressive phase, for the Mississippi delta (Roberts, 1997). Rapid delta growth begins with the stream capture and delta building under river dominance, a phase that lasts for about 1,000 to 2,000 years before delta switching occurs. Further to the shift of the main stream, the fluvially abandoned part of the delta comes under the dominance of marine energy. Delta features such as wave reworked beaches, spits and barrier islands evolve during the transgressive phase.

FIGURE 3.9: A graphic representation of the delta cycle stressing processes and responses in the river-dominated regressive and marine-dominated transgressive phases of development. Source: (Roberts, 1997)

The delta cycle as actually expressed for any individual delta could vary in detail depending upon the influencing marine force. For example, with severe seasonal variations in the river discharge, the eastern part of the GBM delta is currently under marine dominance for more than 50% of the time, even during its regressive phase. The western part of the GBM delta, which is currently in its transgressive phase, is not deteriorating as much as the Mississippi delta. Tidal flooding in the western part of the GBM delta has maintained this part of
the delta in a relatively stable configuration for at least for the last 1,000 years, despite there being no major active distributaries flowing through the region (Rogers et al., 2013a). Hori and Saito (2008) used a plan view representation to explain the evolution of fluvial and wave dominated deltas and their features. Ten delta complexes were formed in the Huanghe delta due to river channel shifts. In the case of tide dominated deltas, no river shifts happen as the river channel is deep and stable, but distributary shifts are common with newly forming river-mouth sandbars (Hori and Saito, 2008). Sea level rise will also enable delta building. The delta growth and abandonment cycle with tides and sea level rise needs to be explored.

FIGURE 3.10: Plan view of the evolution of fluvial, wave and tide dominated deltas. Source: (Hori and Saito, 2008)

3.2.3 Migration of the sediment feed point

Where a sediment supply point is fixed for a delta, that delta will prograde outward by filling the entire available space in the lateral direction. When the levees built by the river are weak, this type of delta will form. But, when the levees built are stronger and high enough to flush the sediment downstream, then elongated deltas will form. FIGURE 3.11 indicates that, where a sediment supply point for a delta is migrating downstream, that delta will prograde outward in the longitudinal direction, without filling the entire space in the lateral direction. The quantity of lateral filling depends on the migration rate. River-dominated deltas with abundant supplies of mud can build this type of delta (e.g., the present Mississippi delta downstream of New Orleans) where low tides and waves exist. In either case, the delta will stop prograding
outward when a line of steeply sloping bathymetry is encountered. In elongated deltas, the process of transverse delta building will start at this point (Kim et al., 2009). It is required to study the effect of engineering structures such as cross-dams or the closure of distributary on the migration of sediment feed point.

Based on the above points, it can be inferred that a part of the delta will be in one of the following states: (a) growing, b) relatively stable or c) deteriorating. Ignoring the effects of local geology, the state of a delta is seen to be influenced by the amount and type of sediment supplied, especially the fluvial contribution, and the rate of relative sea level rise. However, since the early 19th century, humans have had a strong influence on the fluvial sediment supply and the rate of relative sea level rise, thereby hindering the natural evolution of deltas as described in Section 1.1.2.

### 3.3 Factors and processes affecting delta evolution

Deltas are formed at the interface between the alluvial feeder system and the receiving water basin. Processes affecting delta morphodynamics can be broadly classified into two types (Suter, 1997): Autogenic processes are the ones that are a part of the delta itself. Allogenic processes are the ones that
are not part of the delta, but which influence the morphodynamics of the delta. Autogenic processes here comprise distributary switching, avulsion, and lobe switching as a whole. Allogenic processes include fluvial and sediment discharge and eustatic sea level change. In a natural delta, the amount of fluvial sediment supplied and relative sea level change controls whether the delta will prograde, degrade or stay relatively stable. Figure 3.12 shows the influence of climate and tectonics in each physical system that has control on deltas and including deltas. Understanding of the allogenic and autogenic processes is essential to the understanding of delta morphodynamics in the past and future.

![Conceptual framework for understanding interactions between climate and tectonics in deltaic settings. Source: (Hart, 1995)](image)

**Figure 3.12**: Conceptual framework for understanding interactions between climate and tectonics in deltaic settings. Source: (Hart, 1995)

### 3.3.1.1 River catchment factors

The rate at which rivers supply water and sediments to their deltas is a function of a number of natural and human factors including: catchment size, shape, slope, land use, geology, landslides, climate, sand mining, agricultural practices, dams and water diversion structures. As discussed previously, most of the river catchments in the world are now affected by human activities to a greater or lesser degree (Hart, 1995).

#### 3.3.1.1.1 River discharge

The flow of river discharge to deltas typically varies seasonally. For example, for the Ganges and Brahmaputra Rivers, 80% of the total annual flow is discharged during the monsoon season between June and September. Therefore, seasonality is potentially a strong control on the sediment supply to the delta and hence, the sedimentation rate, morphology of inter channel areas and river mouth processes (Hart, 1995). In the GBM delta, approximately 95% of the sediment is discharged during the monsoon flood season (Rogers et al., 2002).
Hoogendoorn et al. (2008) mentioned that large floods have high potential to induce erosion and to distribute sediments across large areas of deltas. However, confusion exists over the long-term impact of extreme events on delta evolution, as although the geomorphic significance of such events is undoubtedly potentially very high, their overall effectiveness may be diminished by their rarer occurrence.

3.3.1.1.2 Sediment flux

The size of a delta is determined by the supply of sediment and the rate of relative sea level rise (RSLR) (Syvitski and Saito, 2007). Rao et al. (2010) shows that, under the pristine condition of sediment supply to the Krishna-Godavari delta, the delta grew by 48.7 km$^2$ between the 1930s and 1965, but between 1965 and 2008 when the sediment supply to the delta decreased significantly, due to upstream dam construction, the delta shrank by 76 km$^2$ as the volume of supplied sediment was insufficient to cope with RSLR. Syvitski and Saito (2007) have shown that a decrease in the sediment supply, due to dam construction, to the Po delta is linked to a declining number (from 16 to 5) of distributary channels over the last 300 years. Similar changes can be observed in many deltas such as the Ganges, Indus, Mississippi, Mahanadi, Nile, Rhone and Magdalena due to upstream dam construction and other human interventions (Syvitski and Saito, 2007). Walling (2013) mentions that, considering the likely rate of future RSLR, the sustainable input of sediment to deltaic regions is crucial for the future longer-term stability of the world’s deltas. However, the quantity of sediment supplied to most of the world’s deltas over the last two centuries was much higher than under the pristine condition due to significant change in land use and poor agricultural practices within their catchments. But, this trend is changing now with the amount of sediment supplied now being equal to or below the pristine condition due to the interception of sediments by dams, improved agricultural practices and soil conservation measures within the catchments of deltas (Syvitski, 2008, Walling, 2013). See section 3.3.2.4 for more detail on how different sediment types would affect delta morphology. The current rate of water and sediment flux to the deltas is influenced by the changes in both the natural and human drivers.
3.3.1.2 Receiving basin factors

Marine forces such as tides, waves and coastal currents play a significant role in influencing depositional patterns on deltas. Their role is imparted by mixing the receiving basin water and the discharged fluvial flow, redirecting and redistributing the sediment flows and thereby shaping the delta morphodynamic features at the river-mouth area and within the intertidal zone (Wright, 1977). The following characteristics of the receiving basin: depositional slope, subsidence rates, basin size and shape are determined by the tectonic settings along the continental shelf. The rate of progradation of the delta, and whether the delta will be exposed to wave forces, will depend on the slope of the receiving basin. A delta located on a receiving basin with steep slopes will be subjected to wave action, whereas a delta on a flatter receiving basin will prograde much more quickly (Hart, 1995).

3.3.1.2.1 Sea level change

Both climate and tectonics control eustatic sea level change. Relative sea level (RSL) is the sum of eustatic sea level change and local subsidence or uplift (Hart, 1995). Nicholls et al. (2014) proposed the following components for relative sea level while considering the scenarios for evaluating coastal impacts: \[ \Delta RSL = \Delta SL_c + \Delta SL_{rm} + \Delta SL_{rg} + \Delta SL_{rlm}. \] Here, \( \Delta RSL \) is the total change in relative sea level, \( \Delta SL_c \) is the global mean sea level change which is a function of thermal expansion of ocean, glaciers, ice caps and ice sheets, \( \Delta SL_{rm} \) is the regional variation in sea level due to the local meteo-oceanographic factors such as wind, atmospheric pressure, ocean circulation and local thermal expansion, \( \Delta SL_{rg} \) is the regional variation in sea level due to changes in the earth’s gravitational field and \( \Delta SL_{rlm} \) is the vertical land movement due to, natural and human-induced geological processes, such as neotectonics, glacio-isostatic adjustment and sediment compaction.

FIGURE 3.13 shows relative sea level rise (RSLR) observed in the Mississippi and Chao Phraya deltas influenced by natural and human induced subsidence respectively. Due to the extraction of the groundwater, the recent rate of RSLR in Bangkok, Thailand is higher than in Grand Isle, USA. According to Woodroffe et al. (2006), delta evolution during future sea level rise will be different from that which occurred during the last postglacial sea-level rise, as modern deltas
have prograded much further out into the sea. In deltas, accommodation space is created by the relative sea level rise (RSLR). The balance between this accommodation space and the rate of sediment supply for a delta would decide the future evolution of that delta. The current rate and amount of sea level rise depends upon the emission scenarios. The morphodynamic response of modern deltas to the currently varying amount and rate of sea level rise influence needs to be studied.

![Image](image-url)

**FIGURE 3.13**: Contrasting relative sea level change observations from the 19th to the early 21st centuries. Source: (Nicholls et al., 2014)

### 3.3.1.2.2 Waves

High wave energy effects can occur at river mouths that are located at relatively steep offshore slopes and that are exposed directly to the ocean. Waves vigorously mix the outflowing fluvial flow with the receiving basin water. The effect leads to rapid deceleration of flow and reduced sediment transport capacity. Reworking of the deposited sediments by waves can lead to the return of the sediments to the onshore environment, resulting in the formation of morphodynamic features such as subaqueous levees, swash bars and constricted river mouths. For most of the year, the river mouth could be constricted or blocked completely if there is not sufficient fluvial flow discharged through the river outlet (Wright, 1977).
3.3.1.2.3 Tides

Based on the tidal range, the tidal regime of the receiving basin can be classified into (Hart, 1995): micro tidal regimes – where the tidal range is less than 2m; meso tidal regime – where the tidal range is between 2 and 4m; macro tidal regime – where the tidal range is between 4 and 6m, and; hyper tidal regime – where the tidal range is greater than 6m. Tidal currents entering the receiving basin may run either parallel or perpendicular to the delta front depending upon the orientation of the delta and the receiving basin (Hart, 1995). The mean tidal ranges for a range of global deltas are shown in FIGURE 3.14. Tides influence delta morphodynamics by creating the following effects (Wright, 1977):

1) Large tides vigorously mix the outflowing fluvial flow and the receiving basin water and thus reduce or remove any buoyancy effect,
2) When the river discharge is low, as could be the case for most of the year, the tides are more dominant especially in causing the bidirectional movement of sediments,
3) Tides can influence much larger areas of deltas both vertically and horizontally as they rise and fall during a tidal cycle,
4) Sediments discharged by the fluvial flows are reworked by the tides and create tide dominated morphodynamic features such as tidal ridges near the river-mouth, and
5) Tides create bell or funnel-shaped river mouths that are much wider than the upstream tidal limit section of the river. Because of tides, heavy meandering also happens near the upstream tidal limit of the section.
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 3.14: Mean wave height versus mean tidal range for major large river deltas. Source: (Goodbred and Saito, 2012)

The hydrodynamics of tide dominated deltas are strongly influenced not only by tides but also by fluvial discharge and marine energies such as storm surges and waves. However, the duration of these forces varies from days to seasons. Sediments discharged during large fluvial flows into a meso to macro tidal system will get mixed thoroughly by tides to a level that density stratification is avoided (see section 3.3.1.3.5 for the importance of density stratification on deltaic morphodynamics). Hence, stratification is not of significance in tide dominated deltas (Goodbred and Saito, 2012).

The height of tides approaching deltas is amplified by the bed friction, fluvial discharge and narrowing planform of the continental shelves. As the water depth increases, with decreasing width toward landward, an increase in the velocity of tides occurs. These tidal properties are further amplified within the deltaic channels due to the reduced upstream cross-sectional areas until the tidal energy is completely lost to frictional forces. These deltaic channels are called “hypersynchronous estuaries” and are flood dominated. When the reduction of cross-sectional areas equals the effect of bed friction, then the estuaries are called “synchronous estuaries”. When the bed friction effect dominates the reduction of cross-sectional areas, then the estuaries are called
“hyposynchronous estuaries”, with their channels being ebb dominated. The process of tidal asymmetry in hypersynchronous and hyposynchronous estuaries plays a key role in sediment transport and influences large parts of deltas (Goodbred and Saito, 2012). In a flood-dominated tidal system, the shorter duration flood tide will have higher current velocities than the longer duration ebb tide in order to accommodate the tidal prism. This tidal asymmetry causes a net onshore sediment transport in a flood-dominated tidal system and this process is called “tidal pumping” (Goodbred and Saito, 2012). In contrast, in an ebb-dominated tidal system, the shorter duration ebb tide will have higher velocities than the longer duration flood tide in order to accommodate the tidal prism, which then leads to net offshore sediment transport (Goodbred and Saito, 2012).

Sediments discharged by the outward flowing rivers and sediments transported onshore by tides may converge at a point, termed the “turbidity maximum”, where a high concentration of suspended sediment occurs. The turbidity maximum can occur anywhere between the river-mouth and coastal shelf. The precise location of the turbidity maximum depends on the magnitude of fluvial discharge, the tidal prism and sediment size. The resultant flow vector that develops from river, tidal and other marine flow forces is called “residual flow”. The timing, magnitude and direction of the residual flow vary as the properties of the forces building it can vary. Hence, sediment transport will vary depending upon the residual flow. For suspended sediments, the turbidity maximum will occur far away from the river-mouth on the shelf during the wet season high fluvial discharge due to the high momentum fluvial jet that can discharge fluvial sediments far into the sea. In contrast, the turbidity maximum will occur closer to landward during the dry season low fluvial discharge (Goodbred and Saito, 2012). Both the turbidity maximum and any persistent residual flow (even if it is of low magnitude) play a significant role in the long-term morphodynamic evolution of tide-dominated deltas (Goodbred and Saito, 2012). Both the positive and negative effect of tides on the multi-decadal timescale of delta building processes is yet to be understood. The role of tides in shaping the deltaic features over multi-decadal timescales is attempted in this study.
3.3.1.2.4 Storm surges

Storm surges are abnormal rises of the sea or lake water surface due to low atmospheric pressure and high winds. In the ocean, when such surges coincide with high spring tides, a very high surge is produced (Murty et al., 1986). The most vulnerable delta to storm surges, the GBM delta, has been hit by 154 cyclones between 1877 and 1995 (Sarraf et al., 2011) but relatively little is known about the influence of storm surges on the morphodynamics of the GBM delta, therefore this represents a significant knowledge gap. In the Mississippi Delta, hurricanes such as Katrina and Rita deposited 5 to 10 cm of sediment over large areas of coastal wetlands, but at the same time converted about 100km² of coastal lands into open water (Day et al., 2007).

3.3.1.3 Deltaic factors and processes

There are a number of factors and processes within the delta that influences its morphodynamics. The following sub-sections present both the natural and human induced factors and processes that are found within the deltas.

3.3.1.3.1 Land cover and land use

The nature of land cover within deltas can be classified into natural and human categories. Forests, grasslands, tidal creeks, rivers and estuaries are the natural land cover. For the purpose of socio-economic reasons, humans have frequently modified part of the natural land cover of deltas for their uses such as agriculture, urbanisation, irrigation system, extraction of underground resources, dredging of river bed, flood embankments, fish and shrimp farming. These land uses exert significant controls on the pattern of sedimentation and erosion within deltas (Ahmed, 2011, Rogers et al., 2013b). Such controls implied that existing and future flood protection structures and irrigation systems could be used for the purpose of delta land-building (Nittrouer et al., 2012, Ibáñez, 2013). Some of the possible effects of different land use types typically encountered in deltas are, therefore, now reviewed.

3.3.1.3.2 Polder dykes

Polders are a region enclosed by embankments with flow control structures to protect the land from flooding, especially from the sea. Polder dykes are used
to keep saline water away from land that is normally used for agriculture (TeBrake, 2002). For example, in the Bangladesh part of the GBM delta, some 123 polders were built in the 1960s and 1970s to protect against tidal floods and salinity intrusion (Sarraf et al., 2011). However, the enclosed area in the GBM delta is lowered as fresh sediments are not allowed to be deposited within the poldered area in a way that could counteract subsidence (Auerbach et al., 2015). As the tides are not allowed to flood the tidal plains, the river beds therefore become silted up. The combined effect of lowered land due to subsidence inside the poldered area and the silted up river channels can cause water-logging inside the polders (Rogers et al., 2013a). Deltas with polders include: Rhine (Alkema and Middelkoop, 2005), GBM (Auerbach et al., 2015), Mississippi (Pistrika and Jonkman, 2010), Po (Renes and Piastra, 2011), and Chao Phraya (Molle et al., 1999).

There is general perception that polder dykes are protecting the poldered area from flooding however with increasing subsidence (see section 3.3.1.3.4) and sea level rise (see section 3.3.1.2.1) regular flooding due to breaching and overtopping of polder dykes can be expected. This study attempts to find the effect of polders both individually and combined with other drivers on the change in flood risk and delta morphodynamics (see Chapter 7, 8 and 9).

### 3.3.1.3.3 Mangroves

Mangroves play a significant role in maintaining the elevations of many tropical deltas (Rogers et al., 2013a). Mangroves are dense, tropical tidal forests that depend on air and water temperatures, the availability of water, mineral nutrients and light. Mangroves grow in the intertidal zone between the mean sea level and the high water spring tide. When a mud deposited bar is exposed above the low water level, mangroves begin to grow on it. Mangroves then establish themselves with special roots called prop roots that prop above the ground level. These special roots enable mangroves to grow even in water-logged areas. Both the dense network of mangrove trunks and their prop roots increase the flow resistance through the mangroves and reduce the current velocity of river discharges and tidal flows. This, in turn, induces sedimentation. Moreover, the network of underground roots enhances soil stability and increases the resistance to erosion. This demonstrates that there exists a strong relationship among the biota, hydrodynamics, morphodynamics
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

and atmosphere within mangrove forest ecosystems. Mangroves are good at dissipating the force of cyclonic storms and tsunamis, but sometimes when they are unable to cope with such massive force they are uprooted. Mangroves have survived drastic climatic and sea level changes during the Holocene (Augustinus, 1996), however their future survival is under threat as human activities have squeezed the space required for the mangroves to adapt to the on-going rate of sea level rise. Their future existence depends on the balance between the rate of accretion and rate of sea level rise (Shearman et al., 2013).

As raised in section 3.3.1.3.1, land cover affects the pattern of sedimentation and erosion in the deltaic floodplains. Here an attempt is made to study the effect of changing land cover roughness on the morphodynamics of tidal floodplain and its interaction with distributaries over multi-decadal timescales (see section 7.4).

3.3.1.3.4 Subsidence

Subsidence is both a natural and human induced process in modern deltas. Natural subsidence is caused by tectonics and sediment compaction (Hoque and Alam, 1997).

1) Tectonic subsidence

The two major factors causing tectonic subsidence are: isostatic adjustment of the crust due to the sediment load, and dewatering and compaction of underground rocks. Normally, active faults or hinge zones bound the areas experiencing tectonic subsidence. This subsidence occurs over a larger area but at a slower and uniform rate. Tectonic activities could also lead to uplift (Hoque and Alam, 1997).

2) Subsidence due to sediment and peat layer compaction

Natural sediment compaction occurs due to dewatering and rearrangement of soil grains (Syvitski et al., 2009). Peat layers are often associated with swamp mud and undergo compaction even under normal pressures of sediment columns (Hoque and Alam, 1997). In the case of polders, due to the lack of fresh sediments and drained peat lands, the oxidisation of organic matter accelerates soil compaction and hence subsidence (Kimberly G. Rogers, 2013). During floods, the surcharge load due to the flooded water and fresh sediment
above the ground will be taken by the pore water pressure initially. This results in an increase in the pore water pressure. This increased pressure will cause the pore water to flow out of the pressurised zone. As time goes on, the entire surcharge pressure taken by the pore water will be transferred to the surrounding soils, which will then lead to an increase in the effective stress (stress of the soil). The process of transfer depends on soil permeability, the ground water level in the region and its interaction with the river water level. With silt and clay, the process of transfer is gradual and that will result in settlement of the ground over time.

3) Human induced subsidence

Sediments deposited by rivers, tides and coastal currents naturally compensate subsidence. Tides and coastal currents help the redistribution and the sedimentation brought by the rivers across the coastal delta. Polders have hindered this natural sedimentation process. This has resulted in land elevation lowering (Auerbach et al., 2015) and water logging problems. In addition to the adverse impacts of polders, groundwater abstraction, urbanisation, deforestation, upstream water diversion and impounding structures are all significant contributors to subsidence within the world’s deltas (Hoque and Alam, 1997, Syvitski and Saito, 2007, Syvitski, 2008, Syvitski et al., 2009). During ground water abstraction, reduction in pore water pressure will result in increase in soil’s stress (effective stress) over time and that will result in subsidence of the ground over time.

Subsidence in the world’s deltas varies depending upon the relative significance of the inducing processes. The Mississippi delta, for example, experiences subsidence at a rate between 0.3 and 3.6mm/y due to isostatic adjustment (Syvitski, 2008). Syvitski et al. (2009) listed the following deltas where the underground extraction of water, oil and gas over the 20th century occurred at major levels: the Brahmani, Godavari, Ganges, Mississippi, Niger, Tigris, Chao Phraya, Colorado, Krishna, Nile, Po, Tone, Yangtze and Yellow. Subsidence in the Po delta reached a maximum value of 60mm/y after the extraction of methane reached its maximum level in 1960. Between 1955 and 1978, the Mississippi delta lost coastal wetlands at a rate of 110km²/y due to rapid subsidence but this rate has reduced to 25km²/y from 1990 to 2000.
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

(Syvitski, 2008). This implies that the rate of subsidence can vary across a delta in space and time. The Chao Phraya River and Yangtze deltas are known for experiencing subsidence due to ground water abstraction. In the Chao Phraya delta, between 1970 and 1990, the shoreline retreated by 0.7km due to subsidence of 2m and sea level rise of 0.5 m (Syvitski, 2008). Central Shanghai in the Yangtze delta relies on the embankment for its protection from flooding as subsidence has lowered the ground level of the city below storm-surge levels (Syvitski, 2008). However, the lack of long-term measurement of subsidence and inaccurate method to measure it can lead to poor management of deltas.

3.3.1.3.5 Formation of river mouth bars

The exact processes by which river mouth bars form, migrate and dissipate remain unknown (Sarker et al., 2011) and hence, a thorough understanding of the processes behind the formation and evolution of these intriguing features is required. According to Wright (1977), the discharge of fluvial flow into the receiving basin and the subsequent sediment depositional patterns will be dominated either by inertia and turbulent diffusion, turbulent bed friction or by outflow buoyancy at the river-mouth. Additionally, discharge and depositional patterns will be influenced by tides and waves where they exist.

Inertia dominated fluvial discharge into the receiving basin

In this case, the inertial forces associated with the fluvial flow dominate the discharge into a deep receiving basin. This type of discharge leads to spreading and diffusion of the fluvial flow due to strong turbulence. Deceleration of the fluvial flow happens according to the turbulent jet theory (flow driven by momentum effect) (Wright, 1977). The fluvial flow entering the basin is not horizontally or vertically confined. Exchange of momentum from the fluvial flow to the receiving basin water occurs through eddies formed at the boundaries of the fluvial outflow. Such hydrodynamics leads to the formation of lunate bars with coarse material being deposited near the river-mouth. There is no action of bed friction on the inertia forces and the associated turbulent diffusion. Naturally, such conditions are rare as bed friction in fact often plays a significant role (Wright, 1977).
Friction dominated fluvial discharge into the receiving basin

In this case, as the depth of the receiving basin is shallower or equal to the river mouth, the bed friction and high shear stress produced by the velocities near the bed dominates in driving the fluvial and sediment deposition pattern. The vertical expansion of the fluvial outflow is restricted due to the shallow depth and hence the vertical velocity distribution of the jet is altered. The horizontal expansion and deceleration of the flow happens at a rate higher than in the inertia dominated case. Subaqueous levees and middle-ground bars with channel bifurcation are the salient depositional features created when the bed friction dominates. Where bed friction dominates due to shallow and flat bathymetry, deltas prograde with successive formation of these depositional features (Wright, 1977).

Buoyancy dominated discharge into the receiving basin

Buoyancy forces (defined as the upward force exerted by a fluid against the weight of an immersed object) dominate when a high water depth to fluvial flow ratio occurs at the river mouth, leading to the fluvial flow being discharged into a relatively deep receiving basin. This leads to high density gradients caused by temperature or salinity and flow stratification. Less dense fluvial fresh water remains above the denser saline water and buoyant jet. Flow divergence occurs at the surface of the water, whereas flow convergence occurs at the interface between the fresh and saline water. This flow divergence and convergence creates secondary flow. Formation of bar-finger sands, straight distributaries with few bifurcations are the salient features when the buoyancy force dominates (Wright, 1977).

Edmonds and Slingerland (2007) numerically modelled the formation of river mouth bars and proposed various stages of river mouth bar formation. When the confined channel flow jet enters basinward, because of the rapid expansion in the cross sectional area, the jet slows down. Eventually, the sediment transport capacity of the flow decreases and starts depositing the sediment. Thus, the river mouth starts forming and this location is the initial location of the river mouth bar (Edmonds and Slingerland, 2007). Subsequently, both the upstream bar face and the bar top become eroded due to the high flow velocity over the bar. Then, the flow again decelerates and the eroded sediment gets
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

deposited behind the bar top. Thus, progradation of the river mouth bar happens as shown in ‘A’ in FIGURE 3.15 (Edmonds and Slingerland, 2007). When the water depth over the river mouth bar is sufficiently shallow to exert enough pressure on the upstream side of the bar to divert the flow around the bar, then the bar stops prograding as shown in ‘B’ in FIGURE 3.15. As a result of this, there will be flow deceleration on top of the bar which then reduces the shear stress over the bar top. From this time, the bar starts aggrading as shown in ‘C’ in FIGURE 3.15. Through this work, Edmonds and Slingerland (2007) showed that when the bar depth is approximately 40% of the inlet channel depth, the bar stops prograding (Edmonds and Slingerland, 2007). The expanding turbulent jet is a function of (Edmonds and Slingerland, 2007):
offshore basin slope, channel initial width, initial channel depth, initial channel velocity, grain size and gravity. The momentum of the channel flow jet and the sediment grain size influences the distance the river mouth bar forms from the river mouth (Edmonds and Slingerland, 2007).
FIGURE 3.15: Modelled bathymetric and velocity field evolution during river mouth bar formation (Edmonds and Slingerland, 2007). In the figure, A - river mouth bar progrades, B - river mouth bar stops prograding and levees grows basinward and C - river mouth bar aggrades and widens and cause the levees to spread.
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 3.16: Conceptual formation and evolution of mouth bars and terminal distributary channels. Source: (Olariu and Bhattacharya, 2006b)

Terminal distributary channels are the channels at the very end of a distributive channel system within a delta. They begin from the last channel bifurcation and extend into the subaqueous portion of the delta. These channels are associated with the formation of mouth bars. The number of terminal distributary channels decides the spread of the discharged sediments into the delta front. The frequency of formation and evolution of mouth bars and terminal distributary channels depends on: 1) the ratio of bed load to suspended load, 2) the amplitude of variation of seasonal river discharge, and 3) accommodation space. When a high bed load is discharged with high amplitude of seasonal variation into a delta with less accommodation space,
the cycle of delta lobe evolution will be shorter. FIGURE 3.16 shows the formation and evolution of the mouth bars and terminal distributary channels in three phases as described by (Olariu and Bhattacharya, 2006b). In the first phase as shown in the views A, B and C of FIGURE 3.16, new terminal distributary channels are formed because of the new mouth bar. In the second phase, as shown in the views D and E of FIGURE 3.16, the lateral and upstream accretion of the mouth bars leads to two asymmetrical terminal distributary channels. In the last phase, as shown in the views F and G of FIGURE 3.16, more accretion in one channel leads to its abandonment and the above cycle continues in the open distributary channel.

The analysis carried out by (Falcini et al., 2012) on the distribution of river sediment plumes during the historic 2011 Mississippi River flood showed that more sedimentation at the mouth of the Atchafalaya River happened than at the mouth of the Mississippi River, even though the latter carried more sediment than the former. More sedimentation happened at the mouth of the Atchafalaya River because the coastal currents and winds diffused the sediment plume. In contrast, and despite the higher sediment load, comparatively less sedimentation occurred at the mouth of the Mississippi River because the levees confined flow in the Mississippi River, inhibiting the formation of a diffuse sediment plume and instead discharging a narrow sediment jet far offshore. This implies that the formation of mouth bars can also be influenced by the tides, and engineering structures such as cross-dams, and polder embankments. The effect of engineering structures on the formation of mouth bars are yet to be understood.

3.3.1.3.6 Distributary switching

The processes of distributary switching and avulsion are yet to be fully understood (Sarker et al., 2011). Avulsion is the partial or complete shift of main channel flow to a new channel. The divergence point is the location where the avulsive (new) channel splits the old channel and starts to flow as a main channel. The convergence point is the location where the avulsive channel confluences with the old channel, downstream of the divergence point. Not all avulsion channels have a convergence point because, before they meet the old channel downstream of the divergence point, they may either discharge into a
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

sea or a lake or flow into a new area of floodplain. The spatial scale of avulsion could happen in a channel of length from a few tens of metres to hundreds of kilometres. The temporal scale of avulsion could vary from a single day to thousands of years. The process of avulsion may happen rapidly by shifting flow into a new channel or gradually by forming a crevasse splay, then infilling wetland and forming channel coalescence (Smith and Rogers, 1999).

Avulsion is triggered by events of the type shown in TABLE 3.2. Only an event of small magnitude is required to trigger avulsion in deltas that are already close to the avulsion threshold. This implies that bigger events are not always required to trigger avulsion. But, bigger events could trigger avulsion in deltas that are not close to an avulsion threshold. The fluvial processes that push a river to avulsion threshold include increases in sinuosity, growth of delta, growth of natural levee, growth of alluvial fan, channel filling, and increase in delta convexity. All of these processes are integral to the river and are related to the overall rate of sedimentation. This implies that the rate of sedimentation can be used to predict the frequency of avulsion. According to Kleinhans et al. (2012), bifurcation in a delta happens due to the following reasons:

1. Flow splitting around the river mouth bars due to the sudden expansion of the sediment-laden jet,
2. Crevassing through breaches in levees due to backwater effects,
3. Changes in energy gradient due to delta extension or relative sea level rise, and
4. Uplift or downwarp of river reaches and floodplains due to tectonics and/or subsidence.

Information that will propagate downstream and influence the bifurcation are: flow and sediment flux and the information that will propagate upstream and influence the bifurcation are (Kleinhans et al., 2012): backwater effects on water levels, propagation of sedimentation or erosion, increase in the effective energy gradient due to tides and shallow water in the delta (alternating flows or reversing flows). Within deltas, when flow is dominated by the tides, the bifurcations become confluences. Where banks are moderately strong compared to the forces exerted by the flow, avulsion is influenced by meander migration. Where banks are strong, avulsion happens at points of weakness in
the banks (Kleinhans et al., 2012). Local morphological factors that influence bifurcation are (Kleinhans et al., 2008): the presence of a resistant lip in the levee at the entrance of the new channel, the amount of sediment entering the new bifurcate, the angle of the bifurcation on the upstream flow direction, migrating bars, and the presence of an upstream meander.

<table>
<thead>
<tr>
<th>Processes and events that create instability and lead toward an avulsion threshold, and/or act as avulsion triggers</th>
<th>Can act as trigger?</th>
<th>Ability of channel to carry sediment and discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td>**Group 1. Avulsion from increase in ratio, ( S_a/S_e ), owing to decrease in ( S_e )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Sinuosity increase (meandering)</td>
<td>No</td>
<td>Decrease</td>
</tr>
<tr>
<td>b. Delta growth (lengthening of channel)</td>
<td>No</td>
<td>Decrease</td>
</tr>
<tr>
<td>c. Base-level fall (decreased slope †)</td>
<td>No</td>
<td>Decrease</td>
</tr>
<tr>
<td>d. Tectonic uplift (resulting in decreased slope)</td>
<td>Yes</td>
<td>Decrease</td>
</tr>
<tr>
<td>**Group 2. Avulsion from increase in ratio, ( S_a/S_e ), owing to increase in ( S_e )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Natural levee/alluvial ridge growth</td>
<td>No</td>
<td>No change</td>
</tr>
<tr>
<td>b. Alluvial fan and delta growth (convexity)</td>
<td>No</td>
<td>No change</td>
</tr>
<tr>
<td>c. Tectonism (resulting in lateral tilting)</td>
<td>Yes</td>
<td>No change</td>
</tr>
</tbody>
</table>

**TABLE 3.2: Causes of avulsion.** Part of the table reproduced from (Smith and Rogers, 1999)

* \( S_a \) is the slope of the potential avulsion course; \( S_e \) is the slope of the existing channel
† In settings where the up-river gradient is greater than the gradient of the lake floor or shelf slope, base-level fall may result in river flow across an area of lower gradient
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

We are yet to understand the role of residual flows and engineering structures, in tidally influenced deltas, in causing or preventing the development of avulsion and bifurcation. A hypothesis of whether polders will affect the evolution of intraisland channel network with or without sea level rise has been tested in this study (see Chapter 7 and to 9). Also, further to this study by Anwar (2013), the effect of cross-dams on the bifurcations are studied here (see Chapters 7 to 9).

3.3.1.3.6.1 Bifurcation due to morphodynamic backwater

In the Mississippi River, intradelta lobe (division within delta lobe) switching occurs approximately every 100 years and delta lobe switching at the apex of the delta occurs approximately every 1ka (Edmonds et al., 2009). The intradelta lobe switching is governed by downstream processes and not by upstream ones. Through laboratory experiments, the location and timing of downstream controlled avulsions have been predicted by Edmonds et al. (2009). The hypothesis that they tested is that, under homopycnal (i.e., where the density of the outflowing fluvial flow is more or less equal to the density of the receiving basin water) and river dominated delta conditions, the intradelta lobe avulsions are the result of (Edmonds et al., 2009): distributary channel lengthening (the set up) and the growth of river mouth bars (the trigger). When the growth of the river mouth bar has stagnated at the mouth of the distributary channel, it acts as an obstruction to the channel flow. This obstruction will reduce the velocity of the flow and subsequently creates a local bow wave which then causes bed aggradation immediately upstream of the river mouth bar as shown in FIGURE 3.17. This process of creating a local bow wave and local bed aggradation continues upstream of the river mouth bar in the distributary channel. This wave of bed aggradation and the water level rise propagating upstream in the distributary channel is called the morphodynamic backwater. The morphodynamic backwater causes an increased flow over the distributary channel levees because of the rise in the water level. This will significantly increase the percentage of wetted levees until an avulsion is initiated (see FIGURE 3.17). Avulsion initiation is caused by the increased flow depth at the eroded levee. Already having knowledge of the antecedent conditions such as irregular levee topography, previous channel flow paths and spatial variation of accommodation space, the magnitude and the duration of
application of the shear stress on the levees can be used as a reliable predictor of avulsion location (Edmonds et al., 2009). Delta morphology is controlled by the relative rates of the upstream propagation of the morphodynamic backwater and the construction of the river mouth bar. If the rate of the upstream propagation of the morphodynamic backwater is faster than the river mouth bar construction, then the delta morphology will be dominated by the avulsion process. Otherwise, the delta will continue to prograde basinward and bifurcate at the river mouth bar (Edmonds et al., 2009).

FIGURE 3.17: Initiation of deltaic avulsion due to river mouth bar stagnation, bed and water surface aggradation (Edmonds et al., 2009). Circled numbers 1, 2, and 3 are three locations shown in the location plan.

\( t \) – Time at start of experiment relative to \( t_a \) - time at initiation of avulsion. Square on x-axis denotes the time at which river mouth bar (RMB) stagnates, upside down triangles denotes bed aggradation at the corresponding location and star on x-axis denotes initiation of avulsion at location 3.

The backwater effect is a function of fluvial and tidal discharges in tidally influenced deltas. Forces such as sea level rise will also influence the backwater effect and an attempt is made here to find out the influence of varying backwater effects on the evolution of deltaic land building processes (Chapters 5 to 9).

3.3.1.3.6.2 Stability of bifurcation

A bifurcation is said to be unstable when one of the bifurcation channels receives more sediment than its transport capacity and the other one receives
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

less sediment than its transport capacity. That means there will be erosion in the channel with less sediment and deposition in the channel with more sediment. The split of water and sediment discharge at a bifurcation decides its stability and the duration of avulsion (Kleinhans et al., 2008). Factors influencing the division of water and sediment include (Kleinhans et al., 2008): internal factors such as local bars and meandering dynamics and external factors such as upstream and downstream boundary conditions. Changes in discharge from upstream, for example due to upstream bifurcation or avulsion evolution, can also influence the stability of a bifurcation (Kleinhans et al., 2008). The following downstream boundary conditions can influence the stability of a bifurcation if it is within the backwater length (Kleinhans et al., 2008): a delta connected to one bifurcate may prograde, a delta connected to one bifurcate may be removed by nearshore processes, mouth bars may migrate and levees may prograde, tidal inlets may evolve, and hydraulic resistance or other characteristics of one bifurcate change.

Kleinhans et al. (2008) studied the influence of the internal factors on the bifurcation stability by conducting numerical experiments. The findings from this study show that in a bifurcation, downstream of a bend, if the bifurcate channel is connected to the inner bend then it will receive more sediment. Conversely, if it is connected to the outer bend then it will receive more water. The bifurcate connected to the inner bend could counteract the slope and bend radii advantages and thus significantly delay avulsion. Bifurcation dynamics strongly depend on the length of the upstream bend and the channel width-depth ratio. The beginning of the upstream bend acts as the perturbation as that initiates the development of bars. Kleinhans et al. (2008) proposed that the rate of change of bifurcation symmetry and the bifurcation channel dominance are determined by the following: gradient advantage, upstream bend, width-depth ratio of the upstream channel, sediment sorting, local bank irregularities, bank erosion and formation trends, possible scour holes or vortex bars just downstream of the bifurcation, and boundary conditions.

In contrast to the Kleinhans et al. (2008) study, Geleynse et al. (2010) simulated a straight, flat channel that discharges a steady flow of water and a mixture of sand and silt sediment into a sloping receiving basin with a substrate consisting of fully mixed sand and silt. This numerical experiment
demonstrated the influence of upstream depositional features within the feeder channel on the flow distribution across the downstream formed delta.

Normally, asymmetrical bifurcations are more stable than symmetrical ones (Edmonds and Slingerland, 2008). In nature, process perturbations (bifurcation itself, alternating side bars and river meandering) and white noise perturbations (floods, circulation dynamics in the standing body of water, water surface slope and planform advantages) convert symmetrical bifurcations into asymmetrical ones. The channel roughness, aspect ratio, non-uniform water surface elevation at the bifurcation and the influence of bed ramp on the flow field keeps the asymmetrical bifurcation stable (Edmonds and Slingerland, 2008). Bifurcation channels of an asymmetrical bifurcation will have asymmetrical water and sediment discharge, widths and depths (Edmonds and Slingerland, 2008). With the increasing engineering interventions expected to protect the interests of humans within the deltas in the future, the effect of engineering structures on the stability of bifurcation in deltas need to be studied.

3.3.2 Interaction of factors and processes

The prediction of future delta morphodynamics over time scales of ~100 years requires a thorough understanding of the interaction of the above discussed factors and processes. In this section the current level of this understanding is presented. Apart from the study by Geleynse et al. (2011), all the other studies presented below do not consider the effects of tides and their interactions with the fluvial and sediment discharge in deltas. However, the studies presented below nevertheless give some understanding of the amount of influence that the considered factors and processes have on specific deltas.

3.3.2.1 Interaction of river catchment and receiving basin factors

Geleynse et al. (2011) was the first to use numerical modelling (the process-based numerical model Delft3D was used) to understand the different classification of deltas mentioned by Galloway (1975) and Orton and Reading (1993). Simulations were carried out with steady fluvial and sediment flow with sand and silt discharging into linearly sloping receiving basins, each with a different initial sediment bed configuration. The three initial sediment bed
configurations modelled are: 1) 100% sand, 2) 50% sand and 50% silt and 3) 100% silt. For the wave dominated scenario, a significant wave height of 1.0 m and a peak period of 5.0 s were used. For the tide dominated scenario, a semi-diurnal tide of 1.5m amplitude was used. The symbols shown in the FIGURE 3.18 from the left to upper-right trend are: $\alpha$ mean distributary depth, $\beta$ sinuosity, $\gamma$ shoreline roughness, $\delta$ subaerial delta volume, $\epsilon$ river valley width, $\zeta$ longitudinal slope. The simulation results show that under all forcing conditions, the mean distributary depth, sinuosity and shoreline roughness all increase as the bed configuration shifts from pure sand to pure silt, whereas at the same time the subaerial delta volume, river valley width and longitudinal slope all decrease. Under wave-riverine conditions, radially symmetric deltas with channels oriented parallel to shoreline are formed. Under tidal-riverine conditions, rougher shorelines with long channels are formed. More channel incision can be noticed when the initial bed configuration has silt in it. Paola et al. (1992) studied the different rate of variation of water flux, sediment flux, subsidence and grain size on the pattern of progradation of the fluvial delta in a basin. However, that study did not take into account the effect of tides and the variation of forces on delta metrics of sub-aerial delta.
3.3.2.2 Influence of receiving basin depth on delta formation

Using a process-based numerical model, Storms (2007) modelled the initial formation of a river dominated delta under homopycnal conditions under both shallow and deep receiving basin scenarios. Numerical simulations were conducted using Delft3D with steady fluvial and sediment flows with equal proportions of fine sand and cohesive clay discharging directly into the basins with substrate consisting of 50% clay and 50% sand. The results of the numerical simulations show a well-developed bifurcated delta system for the shallow receiving basin scenario (SIM A) and only three bifurcated channels,
with one being elongated, for the deep receiving basin scenario (SIM B). In the shallow receiving basin scenario, a lunate bar forms initially and as this bar moves basinward, a river mouth bar forms at the initial point of deposition which then bifurcates and creates more stable mouth bars and bifurcations. Since the total is split among the bifurcated channels, the cross sectional area of the channels and bed slope both decreases towards the basin. In the deep receiving basin scenario, initially a mouth forms with a bifurcation, however the subsequent formation of stable mouth bars inhibits further bifurcation. Instead, here the delta protrudes with its main channel elongating towards basin. The simulation results also show that only a constant discharge is needed for the initial delta formation.

FIGURE 3.19: Numerical simulation of initial delta formation. SIM A – simulation with shallow receiving basin and SIM B – simulation with deep receiving basin. Source: (Storms, 2007)

3.3.2.3 Control of upstream discharge on number of distributaries

Edmonds et al. (2010) conducted a numerical study of the response of distributaries within a self-formed, river dominated, delta to changes in
flow discharge at the delta head. Based on the numerical modelling of the delta channel network, for a long-term increase in the flow discharge at the head of the delta, existing bifurcations and channels will find a way to discharge the increase in flow. There is no avulsion for increases in flow discharge that are less than 60%. This is due to the existing channel capacity being able to accommodate the extra flow. When the increase in the flow discharge is more than 60%, avulsion occurs by flooding and the creation of new channels. The increase in flow discharge does not cause any abandonment of channels. The number of distributary channels is directly linked with the river discharge. When there is a long-term decrease in the flow discharge, the delta channel network bifurcations become unstable along with the abandonment of the channels. The abandonment is directly proportional to the decrease in the magnitude of the discharge. The channels are abandoned by filling of the cohesive sediments. The size of the channel decides the abandonment and not the location of a bifurcation in the network. In this modelling experiment, it has been found that smaller channels are preferentially abandoned (Edmonds et al., 2010). However, there is a need to study the effect of changing fluvial discharge in the number of distributaries where the flow is bidirectional due to tides (see Chapter 5).

3.3.2.4 Control of sediment cohesion on delta shapes

Kim (2012) suggested that for a successful deltaic land building process, both sand and mud are required. Based on numerical experiments, with a steady river flow of 1000 m³/s carrying equilibrium concentrations of cohesive and non-cohesive sediment into a standing body of water that is free from waves, tides and buoyancy, the following conclusions were made (Edmonds and Slingerland, 2010):

- **At low cohesion**: The simulated delta is fan-like in shape with fewer bifurcations. Here, the shear stresses are strong enough to cause enough erosion to prevent the stagnation of river mouth bars. Bifurcations are usually unstable. Avulsions are infrequent because the shoreline roughly progrades basinward uniformly (Edmonds and Slingerland, 2010).
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

- **At intermediate cohesion:** Deltas with many bifurcations are formed. Here, more and frequent river mouth bar stagnation and channel splitting occurs and hence results in more avulsions (Edmonds and Slingerland, 2010).

- **At higher cohesion:** The shape of the simulated delta is like a bird’s foot. Here, avulsions and bifurcation of river mouth bars are prevented (Edmonds and Slingerland, 2010). Sediment cohesion is as important as river, wave and tidal energies in influencing the number of distributary channels in a delta (Edmonds and Slingerland, 2010).

![Simulated deltas with varying cohesion](image)

**FIGURE 3.20:** Shoreline traces of simulated deltas. The relative positions of the tracings reflect their position in the parameter space where total cohesion increases from bottom right to upper left. Source: (Edmonds and Slingerland, 2010)

### 3.4 Temporal and spatial scales of delta processes

The above discussed factors, processes and their interactions occur over varying time and spatial scales. Delta dynamics occurs at a spatial scale of 100 metres to kilometres and at temporal scales of decades to a few centuries. Delta dynamics occur at engineering, planning, recent historical and societal scales (Woodroffe, 2003). It is still not completely understood what deltaic processes occur at these scales and what factors and interactions are
significantly responsible for acts at these scales. The understanding of the processes and their interactions remains very complex (de Groot, 1998).

**FIGURE 3.21**: Spatial and temporal variability in natural and socio-economic processes. Source: (Woodroffe et al., 2006)

FIGURE 3.21 shows the schematic representation of spatial and temporal variability in the natural processes and human usage of mega deltas. It is clear from this representation that all physical, socio-economic and deltaic processes act at different scales (Woodroffe et al., 2006) and hence there is considerable complexity in understanding their interactions. Cowell et al. (2003) proposed a hierarchical scale framework called “Coastal Tract”, shown in FIGURE 3.22, for the purpose of separating lower and higher order coastal changes from the scale of interest. Based on this coastal tract, Brommer and Bochev-van der Burgh (2009) proposed at the scale of deltas, the immediately

---

**Natural Processes**

- Geomorphic variability
- Climatic variability
- Subsidence

**Socio-economic processes**

- Land tenure
- Urban centres
- Water control
- National economy

**Legend:**

- 10^2 km^2
- 10^3 km^2
- 10^4 km^2
- 10^5 years
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

higher order processes such as tides, storm surges and seasonal variability will act as intrinsic conditions and the lower order processes such as sea level rise, climate change and subsidence will act as the boundary conditions. However, the successive higher order processes such as turbulence and sea swell will be noise at this scale of interest. Though this approach looks clear, the coupling at different scales is not yet properly understood (Brommer and Bochev-van der Burgh, 2009).

FIGURE 3.22: Coastal tract cascade. Source: (Brommer and Bochev-van der Burgh, 2009) after (Cowell et al., 2003)

Moreover, Day et al. (2007), proposed a hierarchy of forcings or pulsing events, see TABLE 3.3, that will influence the different morphological units of the delta complex at different time scales. A proper investigation is required to find out the relative magnitude of the impact created by both normal and extreme events on delta morphodynamics at multi-decadal timescales.

3.5 Delta evolution in the future

Currently, the natural process of delta land maintenance and building has been hindered in many of the world's deltas due to human induced conditions of varying sediment input, subsidence, and accelerated sea level rise. Thus, the long-term future trend of delta building depends on redressing the current imbalance between sediment input, subsidence and sea level rise. This implies that management options may be required to avoid any significant land losses
within deltas in the future. Yet, such management options require an understanding of the natural processes involved in building delta surfaces (Paola et al., 2011).

<table>
<thead>
<tr>
<th>Event</th>
<th>Time scale</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major changes in river channels</td>
<td>500-1000 years</td>
<td>New delta lobe formation (avulsions), major sediment deposition</td>
</tr>
<tr>
<td>Major river floods</td>
<td>50-100 years</td>
<td>Avulsion enhancement, major sediment deposition, enhancement of crevasse formation and growth</td>
</tr>
<tr>
<td>Major storms</td>
<td>20-25 years</td>
<td>Major sediment deposition, enhanced production</td>
</tr>
<tr>
<td>Average river floods</td>
<td>Annual</td>
<td>Enhanced sediment deposition, freshening (lower salinity), nutrient input, enhanced primary and secondary production</td>
</tr>
<tr>
<td>Normal storm events (frontal passage)</td>
<td>Weekly</td>
<td>Enhanced sediment deposition, enhanced organism transport, higher net materials transport</td>
</tr>
<tr>
<td>Tides</td>
<td>Daily</td>
<td>Marsh drainage, stimulated marsh production, low net transport of water and materials</td>
</tr>
</tbody>
</table>

TABLE 3.3: A hierarchy of forcings or pulsing events affecting the formation and sustainability of deltas. Source: (Day et al., 2007)

3.5.1 Delta management

Delta restoration science is just developing and much research is needed to understand the local, regional and long-term impacts associated with performing water and sediment diversions to sustain artificial delta land building processes (Edmonds, 2012, Meselhe et al., 2012). For efficient restoration of a delta, a thorough understanding of the sediment sources and sinks and an ability to predict the rate of land growth for any restoration works are required. River diversions should be designed to maximise sediment delivery from the river. The rate of growth of delta land depends on the balance between sediment sources and sinks. Other factors affecting the efficiency of land-building are (Edmonds, 2012): river mouth morphodynamics (coastal current, waves, storms, submarine canyon), the contribution of organic matter from plants (process unknown), the composition of newly formed land (sand and silt mixture is good for forming stable land). When water and sediment diversions need to be undertaken, the
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

best location from the land building point of view and the number of diversion locations should be considered. A delta restoration is said be effective only when both the sedimentological and ecological restoration are performed as they interact (Edmonds, 2012). According to Paola et al. (2011) the effect of storm surges on any future delta restoration works should also be studied. Nittrouer et al. (2012) found that about 8 million metric tonnes of sand were deposited in the delta plain due to an accidental flow diversion through a spillway during the 2011 Mississippi River flood. Thus, carefully designed flow diversion structures with an optimised spillway width and depth can be used for successfully building deltaic lands. Proposed approaches for the restoration of the Mississippi River delta (Day et al., 2007) include:

1. Reconnecting the river and the deltaic flood plain,
2. Using dredged sediments to create and restore wetlands,
3. Restoring barrier islands by engineering measures such as pumping offshore sands, constructing breakwaters, groins, ripraps and plantings, and
4. Restoring hydrological processes by removing spoil banks, backfilling canals closing deep navigation channels, installing locks, trapping sediments and protecting interior shorelines against erosion.

Different deltas require different management options to suit their physical environment and socio-economic requirements. Ibáñez (2013) proposes that with better management of water, sediment and nutrient fluxes, land elevations higher than under natural conditions could be gained to counteract the accelerating rate of RSLR and avoid, or at least minimise, any future land losses. According to Ibáñez (2013), the option of rising embankments should be combined with rising grounds. Ibáñez (2013) proposed the following adaptation measures for river deltas to cope with the high-end scenarios of SLR:

1. Use existing irrigation systems to deliver sediments to fields and wetlands,
2. Allow high organic accretion and reduce mineral input to fields and wetlands,
3. Practice controlled diversions during extreme flood events to allow the deposition of suspended sediments,
4. Engage local farmers and stakeholders to plan sedimentation options on their lands,
5. Restore sediment input flux by using reservoir by-passing techniques, and
6. Make use of the re-suspended sediments for land aggradation.

The amount of sediment delivered should be efficiently trapped to restore the building process of the delta and also the effect of current flood alleviation and any land reclamation practices on the delta building processes should be studied (see Chapter 6 to 9).

3.6 Summary

- Deltas are developed where a river discharges into a lake, sea or ocean by decelerating the flow and depositing the river’s sediments.
- Existing classifications of deltas are inadequate to explain and represent the real morphodynamics of a delta. However, classifications by Galloway, and Orton and Reading will be used here to provide an initial understanding of modern deltas.
- The dominant influence of fluvial, tidal and wave forcings on deltaic features such as distributary channels, mouth bars and floodplains have been reviewed. It is evident that the planform of fluvially dominated deltas tend to appear elongated, whereas tidally dominated deltas look estuarine or irregular and wave dominated deltas will often look curved.
- As the present status of deltas is different from those during the early Holocene, the evolution of deltas under future sea level rise will be different to that experienced in the past.
- It can be inferred that a part of the delta will be in one of the following states: (a) growing, b) relatively stable or c) deteriorating. Based on the existing knowledge of the drivers and processes influencing the morphodynamics of the deltas, a driver model has been developed, FIGURE 3.23, to group the drivers, sub-drivers and processes to easily understand their nature of influence on the state of a delta. Only the factors and processes highlighted in bold text in FIGURE 3.23 will be
considered in this thesis. Ignoring the effects of local geology, the state of a delta is seen to be influenced by the amount and type of sediment supplied especially the fluvial contribution, and the rate of relative sea level rise. Therefore, it is worth investigating the variation of water and sediment discharge (see Chapter 5) and the relative sea level rise on delta morphodynamics (see Chapter 6).

- Though it is known that polderisation leads to sediment starvation inside the polders, the effect of this excess sediment on delta morphodynamics outside the polders is unknown and hence needs to be studied (see Chapters 7).
- The type of land cover plays a significant role in determining the floodplain sedimentation and hence the effect of mangroves on the floodplain sedimentation need be studied (see Chapter 7).
FIGURE 3.23: Influencing factors and processes on delta morphodynamics. The factors and processes highlighted in bold text will be considered in this thesis.
4. Investigating the evolution of an idealised mega-delta: A model based methodological design

4.1 Overview of methodological approach

As the availability of reliable data is very scarce in many of the world’s deltas, demonstrating the link between morphodynamic and environmental changes such as variations in fluvial sediment supply, polderisation, sea level rise, and subsidence is still very challenging (see Chapters 2 and 3). Moreover, the interactions between the factors are complex and non-linear in nature as the intensity of these environmental changes varies over time. Aiming to answer the question of how contemporary delta morphology evolves over multi-decadal timescales under multiple drivers, a morphodynamic model of an idealised tidal delta that shares a number of the essential characteristics of the Ganges-Brahmaputra-Meghna (GBM) delta is here used to explore the influence of various drivers of contemporary environmental change on deltaic morphodynamic response.

The long-term evolution of deltas can be predicted by a number of techniques, including the use of laboratory and mathematical models (Southgate, 2001). Considering the large spatial and temporal scale of the present study, the geometrical shape of the study area and the number of experiments involved, laboratory based modelling is not a feasible means of meeting the objectives of this research (see Section 1.3). On the other hand, in principle an accurate numerical model (underpinned by high quality data, appropriate model schematisation techniques and high performance computing) affords the opportunity to simulate delta morphodynamics over large spatial scales and over several decades (Dastgheib et al., 2008), thereby meeting the objectives of this research. The different types of quantitative models that are potentially available to predict delta behaviour include (Swift et al., 1971) (Southgate, 2001):
1. Behaviour based models:
   a) Statistical models based on the past data, and
   b) Empirical models derived from experimental or field observations

2. Process based morphodynamic models based on the physics of fluid dynamics and sediment transport.

Statistical models may be simple in terms of their mathematical operations but these operations are performed without any physical basis (De Vriend, 1991). Empirical and semi-empirical models lack detailed empirical information and they cannot be used for a detailed study such this one. Large numbers of models of this type are available for tidal basins, ebb tidal-deltas, etc., (Tessler et al., 2016, Dastgheib et al., 2008). A number of rule-based models also exist and are still being developed (Seybold et al., 2007, Fagherazzi, 2008, Seybold et al., 2009). However, many such rule-based models are yet to be verified and some do not even satisfy the fundamental conservation laws (Odoni and Lane, 2011). Moreover, these models are inadequate when it comes to modelling processes such as tides (Liang, 2013). In contrast, a process-based numerical model can be used to simulate past morphodynamic changes and to scrutinise which drivers and physical processes have played significant roles in forcing the predicted morphological changes. A thoroughly validated long-term process-based model can, therefore, be used to predict the geomorphology of delta environments, albeit with some uncertainty (Coe, 2003). Recently, process-based models have been applied to simulate long-term morphodynamic processes of deltas (Tessler et al., 2016, Gupta et al., 2012, Renaud et al., 2016, Szabo et al., 2016, Caesar et al., 2015, Liang et al., 2016).

For these reasons, process-based numerical modelling will be used in this study. In order to study the processes behind the morphodynamic changes of the delta, modelling of both horizontal dimensions in space are required. Hence, two dimensional coastal area numerical models will be preferred over the one-dimensional plan-shape or profile models (Coe, 2003). Hence, for the purpose of understanding the influence of environmental factors on the morphodynamic response, a process-based model, Delft3D (see Appendix 10 for the selection of modelling software and details of the Delft3D software) is used in this study.
Modelling approach

In the traditional modelling approach, a morphodynamic model will normally first be calibrated and validated using field and/or laboratory data and then it would be used to understand and quantify the responses of the modelled system to changes in forces and system features (Roelvink, 2011, Dissanayake et al., 2009). However, it is not possible to take this approach during this study, for the following reasons:

1) The calibration and validation period should be of similar duration to the forecast period, which here is 100 years. Due to the lack of data especially at the required time and spatial interval over 100 years, a model of satisfactory level cannot be achieved.

2) To model the large areas required for analyses of mega-deltas and over multi-decadal time scales would require a significant amount of simplification to represent delta features and forcing in order to keep the computational cost feasible. Hence, even a perfectly calibrated and validated morphodynamic model cannot be expected to accurately predict the responses of the system over (say) 100 years because of the significant amount of simplification that is required.

3) During calibration, the model parameters are normally adjusted to give the best fit between the modelled and observed data. However, it is known that such models can still depart from the reality when they are used outside the calibration/validation period (Roelvink, 2011, Dissanayake et al., 2009). As the calibrated models are likely to depart from the truth as the simulation progresses, they are not suitable for multi-decadal time scale simulation.
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 4.1: Diagrammatic overview of the methodology

Thus, in this study, a realistic analogue modelling approach will be used. This kind of approach, in which the essential attributes of an exemplar delta (in this case, the GBM) are modelled, if not its actual topography, is mainly suitable for long-term qualitative assessments of the system response to various forcing (Roelvink, 2011). This methodological approach is relatively new as past studies applying this approach include the qualitative understanding of the long-term morphodynamics of the North Sea tidal basins (Dissanayake et al., 2009, van der Wegen, 2013, van der Wegen and Roelvink, 2008, van der Wegen et al., 2008, Dastgheib et al., 2008) and the Yangtze River estuary (Guo...
et al., 2015). It is believed that this approach represents the first attempt to model an idealised mega delta to the scale (FIGURE 4.3) and metrics (FIGURE 4.10) of a real delta. In the realistic analogue approach, a highly schematised model will be built initially to produce the morphology that is similar to the real GBM delta. The amount of simplification can be extreme by broadly representing the real GBM delta taking into account only the significant features and forces. The starting case of the modelled delta will be compared to the real delta planform and morphometric properties to check how analogous it is to the real case (FIGURE 4.1). See Appendix 10 for the technical details of the software, Delft3D, used in this study.

4.2 Model setup

4.2.1 Starting case model set-up

This section describes the model setup procedure to produce an analogous delta that is similar to the sediment rich, eastern part of the real GBM delta in the 1940s (see Chapter 2). The specific date 1940s was selected because at this time the Meghna estuary was in a relatively pristine condition, at least compared to the changes seen in the second half of the twentieth century. The initial condition of the model for experiments generated by the spin-up run represents the status of the GBM delta in 1940s (FIGURE 2.8C and see Section 2.1.3.1.1). The GBM delta was relatively less intervened in 1940s with no flood protection structures such as polder dykes or land reclamation measures such as Cross-dams (Nowreen et al., 2014). Pre 1950s, the human interventions in the delta was mainly in the form of building a temporary low level flood embankment, which was allowed to fail itself every year (Nowreen et al., 2014). Moreover, the visual comparison of the historical maps of the GBM delta revealed that by 1940s, the GBM delta had reached equilibrium or at least near equilibrium; post the confluence of the Ganges- Brahmaputra Rivers in 1776. The processes of deltaic morphodynamic changes that happened between 1776 and 1940s are described in Section 2.1.3.1.1. A schematised two dimensional morphodynamic model was constructed using the Delft3D software, as detailed in the sub-sections below.
4.2.1.1 Model extent, bathymetry and grid

The model has a rather simplified planform compared to the actual 1943 Meghna estuary, lower Meghna River, Padma River and the Bay of Bengal, as shown in FIGURE 4.2. The effect of the existing Ganges and Brahmaputra delta lobes and the eastern part of the continent is represented in the model by including erodible cone-shaped banks to the dimensions of the Meghna estuary in 1943 (FIGURE 4.3a). Thus, the model consists of a 350km long channel, representing the rivers upstream of the estuary, with width converging from 7km at the mouth to 3km at the landward river head. The landward river head in the model is representing the downstream of confluence of the Ganges and Jamuna at Baruria Transit (FIGURE 4.2). The Meghna estuary is represented by a funnel with dimensions (180km by 120 km) very similar to the real estuary (blacklines in FIGURE 4.2). The model is extended offshore to represent the Bay of Bengal and to reduce the influence of downstream boundary conditions on the delta forming area, with the initial bathymetry (based on BWDB 2000s bathymetric survey of lower Meghna River and Meghna Estuary) as indicated in FIGURE 4.3b. The basin has a steeper bed slope near the downstream boundary to represent the steeper continental shelf associated with the presence of the submarine canyon, the Swatch of No Ground. The model domain is discretised with square and rectangular cells as shown in FIGURE 4.3a. The model mesh has a resolution of 200m x 200m within the channel, estuary and in the basin for the width of estuary. In comparison, the basin extension on either side of the estuary has a resolution of 200m x 400m near the estuary, reducing to 200m x 1600m in the outer sea. The generated model grid fulfils numerical stability requirements and therefore avoids any numerical diffusion/dispersion errors. The banks of the channel are non-erodible, whereas the banks of the estuary are erodible.
FIGURE 4.2: 1943 map of the GBM delta. Brown lines are land boundaries and blue shades are watercourses.
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 4.3: A sketch of the schematised 2D model (not to scale): (a) geometry (top view) see FIGURE 4.2 for the basis of selection, and (b) initial bathymetry (longitudinal view) based on BWDB 2000s bathymetric survey of lower Meghna River and Meghna Estuary.
Chapter 4: Investigating the evolution of a mega-delta: a model based methodological design

The upstream river discharge and downstream water level form open boundaries in the model grid, whereas elsewhere the model grid boundaries are closed. The closed model boundaries represent the less active deltaic lobes and the Tripura and Chittagong Hills on the west and east of the contemporary GBM delta, respectively. The upstream river discharge is estimated based on the fluvial discharge of the Ganges, Brahmaputra and Meghna Rivers entering the delta at the top of the lower Meghna River. The downstream water level denotes the sea level in the Bay of Bengal.

4.2.1.2 Boundary conditions

The hydrodynamic boundary of the model at the downstream limit of the domain is forced by a semi-diurnal tide with a range of 0.75m. The tidal range is uniform across the boundary and constant over time and this is a simplified representation of the water level in the Bay of Bengal ignoring the tidal constituents and the effect of spring-neap tidal cycles. Sediment transport at the downstream boundary is set by an equilibrium sediment concentration in which case sediment input and output are not constrained. This means that sediment concentration at this boundary adapts to the local flow conditions near instantaneously. However, the large extent of the model makes this a broad representation of the conditions similar to the real world GBM delta.

Based on the available observed time series of daily river discharges and sediment concentrations in the Padma River at Baruria Transit (see FIGURE 4.2 for the location) during the monsoon season for the period 1992-2012, best fit regression plots for the sand and fine sediment were plotted as shown in FIGURE 4.4 and FIGURE 4.5.
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 4.4: Best fit regression plot for the observed daily water discharge vs sand sediment in the Padma River at Baruria Transit

Note: The correlation coefficient is 0.50 for sand and is positively correlated at moderate strength. The correlation is statistically significant at a probability level of 0.01.

FIGURE 4.5: Best fit regression plot for the observed daily water discharge vs silt and clay sediment in the Padma River at Baruria Transit

Note: The correlation coefficient is 0.43 for sand and is positively correlated at moderate strength. The correlation is statistically significant at a probability level of 0.01.
The concept of dominant discharge has been adopted here mainly due to the amount of fluvial sediment discharged to the GBM delta. While 95% of the annual sediment is discharged during the monsoon season in the GBM delta (Rogers et al., 2013a), the magnitude of interaction of fluvial and tidal force is at its maximum, and the amount of sediment available to shape the morphodynamics of the delta is significant during the monsoon season (Rogers et al., 2013a). Only 5% of annual sediment is discharged during the dry season of the fluvial discharge where only tidal reworking on the discharged sediment occurs. Hence, the seasonality of fluvial discharge was not considered in this thesis and also because of the huge computational demand required and time constraint to conduct experiments with seasonality. However, the effect of seasonality was studied separately for over 20 years for the Base case experimental scenario (see Section 4.3), which showed quicker channel erosion than without the seasonality due to the increased flood:ebb flow ratio (see section 5.3). This effect of seasonality on bifurcation is in agreement with Chatanantavet et al. (2012). However, the seasonality is important as mentioned by Guo (2014) and Chatanantavet et al. (2012). The seasonality should be considered as a separate factor in influencing the delta morphodynamics and further research is recommended to include seasonality while understanding the influence of variations in natural and human drivers on delta morphodynamics.

Here the concept of dominant discharge as used by Thorne et al. (1993) and David S.Biedenharn (1999) is chosen to define the water and sediment discharges at the upstream boundary of the model. The dominant discharge is here defined as the discharge that transports the most sediment over an extended period of time. Thus, dominant discharge is a function of not only the amount of sediment transported by a given water discharge but also the frequency of occurrence of that flow. Using the regression equations derived above, the dominant discharge plot as shown in FIGURE 4.6 was made for a range of water discharges observed in the Padma River at Baruria Transit (see FIGURE 4.2 for the location). FIGURE 4.6 shows that the modal sediment load is discharged by the Padma River for water discharges between 60,000 and 70,000 m³/s.
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 4.6: Dominant discharge plot for the Padma River at Baruria Transit

FIGURE 4.7: Cumulative sediment load curves for the Padma River at Baruria Transit
FIGURE 4.7 shows a cumulative plot of percentage sediment load against the water discharges. About 30% of the sediment load is transported by water discharges between 60,000 and 70,000 m$^3$/s. Hence, the upstream boundary of the model in the baseline simulations is forced by a constant river discharge of 65,000 m$^3$/s. The dominant discharge has a return period equal to 1 year. Interestingly, the maximum monthly average discharge (70,000 m$^3$/s) is not far off from this estimate of the dominant flow. The percentage of time the dominant discharge flow is equalled or exceeded in a year is equal to 7% or 26 days (FIGURE 4.8). Based on these considerations, the sediment transport rates at the upstream boundary are set to 0.11 kg/m$^3$ for sand and 0.12 kg/m$^3$ for silt.

![Flow duration curve for Padma River at Baruria Transit 1968-2012](image)

FIGURE 4.8: Flow duration curve for Padma River at Baruria Transit 1968-2012

4.2.1.3 Optimising computation efficiency

Hydrodynamic and transport processes vary over hours to days whereas morphological changes occur over much longer periods thus (Sebesvari et al., 2016). This means that bed levels in the model can be updated at time intervals equal to the product of the morphological acceleration factor
(MORFAC) and the hydrodynamic time step, thereby enabling quicker computation while maintaining mass conservation. Generally, a MORFAC value of up to 500 is recommended for tidal conditions (Ranasinghe et al., 2011), and here a value of 30 is used. Sensitivity tests revealed that MORFACE values greater than 30 did not produce a delta that converges to the key characteristics of the real Meghna estuary.

Based on the flow duration curve (FIGURE 4.8) of the Padma River at Baruria Transit (see FIGURE 4.2 for the location), the dominant discharge value is, on average, only exceeded for 7% of the time each year (i.e., 26 days in a year). So, if the model with a dominant discharge has been run for a hydrodynamic time of 1 day with a morphological acceleration factor of 30, then the elapsed morphological time is 1.15 years (=30 days*1 year/26 days). This implies that, in the model set-up employed here, 1.15 years of morphological evolution can be simulated in 1 hydrodynamic time step when using a morphological acceleration factor of 30.

All the simulations conducted herein were performed in parallel computing mode on 64* 2.6GHz processors using the Supercomputer, Iridis4, at the University of Southampton. One hydrodynamic day of computation takes about 4 hours using the processors mentioned above.

4.2.1.4 Model parameters

A number of simulations over a time period of up to 50 morphological years were initially carried out by varying the model layout and the parameters, one by one and also in combination, to study the impact of the model parameter values on the formation of the analogue delta. TABLE 4.1 shows the model parameters used for the runs in this study and summarises the basis of their selection.

4.2.1.5 Sensitivity analysis

The following parameters: Longitudinal Slope Factor, Transverse Slope Factor, Critical shear stress for erosion and sedimentation, Horizontal eddy viscosity, Horizontal eddy diffusivity, dry cell erosion, tidal force and morphological acceleration factor were varied during the spin-up run simulations to produce a delta that is similar to the GBM delta in 1940s. Appendix 11 presents the
Chapter 4: Investigating the evolution of a mega-delta: a model based methodological design

delta metrics plots from this sensitivity analysis. These parameters were varied within acceptable limit to produce a delta that is similar to the GBM delta.

FIGURE 11.1 to FIGURE 11.6 shows the sensitivity of these parameters in developing a successful, tidally influenced delta. Compared to the delta metrics plots (FIGURE 11.1 to FIGURE 11.3 in Appendix 11), the visual comparison of the modelled deltas in FIGURE 11.4 to FIGURE 11.6 in Appendix 11 helped to select the successful spin-up run of the numerical delta. Also, there were cases where no numerical delta formed, for example for Mannings's roughness coefficient, n =0.033. Also, the amount of tidal range at the upstream boundary increased beyond the observed value of 600mm at Baruria Transit (see FIGURE 4.2 for location) with decreasing Manning's roughness.

4.2.1.6 Model run

Hydrodynamic computations were performed using a time step of 0.25min. The model was initialised with a water level set to zero (mean sea level) and sediment concentrations were also initially set to zero. Every simulation runs first for 2 hydrodynamic days (or 4 complete tidal cycles) before starting the morphodynamic simulations. This lag time is sufficient for adaptation of the hydrodynamic processes over the entire model domain. Morphodynamic updates occur every 7.5 minutes, due to the morphological factor of 30, as discussed previously. The initial sediment layer thickness at the bed is 40m, which is assumed to be equal to the maximum depth of the lower Meghna River. The initial model condition was allowed to morphologically evolve in time (spin-up of the model from an idealised case to a starting case for each experiment) to generate a sub-aerial delta. An attempt has been made here to create the starting case for each experiment to replicate the properties of the GBM delta wherever possible, as discussed further in section 4.2.2.
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Basis of selection for model parameter</th>
<th>Model value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial bed composition</td>
<td>In mid 1980s, at 9 boring locations (Anonymus, 1986), each 20m deep, in the Sandwip and Noakhali Islands (see FIGURE3.1 for the locations) revealed sub-surface layer consisting of: 45% Sand+ 55% silt</td>
<td>50% very fine sand and 50% coarse silt</td>
</tr>
<tr>
<td>Sediment fraction</td>
<td>In Padma River (Sarker et al., 2003), bed sediment $D_{50}$ is 0.12mm (very fine sand) Ali et al. (2007) used cohesive $D_{50}$ of 0.05mm (coarse silt)</td>
<td>Non-cohesive $D_{50}$ = 0.12mm</td>
</tr>
<tr>
<td>Bed slope factor for bed load transport</td>
<td>Longitudinal: 1 Transverse: Calibration</td>
<td>1 for longitudinal and 100 for transverse</td>
</tr>
<tr>
<td>Spatially constant hydrodynamic roughness</td>
<td>Calibration. Assuming bed with dunes and no vegetation</td>
<td>Manning’s $n$ = 0.055</td>
</tr>
<tr>
<td>Dry cell erosion factor</td>
<td>Calibration</td>
<td>1</td>
</tr>
<tr>
<td>Sediment transport formula</td>
<td>Van Rijn 1993 (calculates bed &amp; suspended load) advection-diffusion equation used</td>
<td>Van Rijn 1993</td>
</tr>
<tr>
<td>Horizontal eddy viscosity</td>
<td>Calibration</td>
<td>1 m$^2$/s</td>
</tr>
</tbody>
</table>

For cohesive sediments

| Critical shear stress for erosion              | Calibration and Ali et al. (2007) used 0.2 N/m$^2$ for $D_{50}$ = 0.05mm                            | 0.1 N/m$^2$                                           |
| Critical shear stress for sedimentation       | Calibration and Ali et al. (2007) used 0.1 N/m$^2$ for $D_{50}$ = 0.05mm                            | 0.1 N/m$^2$                                           |
| Fall velocity                                 | 2.25mm/s for 0.05mm based on Stoke’s law                                                             | 2.25mm/s                                              |
| Horizontal eddy diffusivity                   | Calibration                                                                                          | 10 m$^2$/s                                            |

**TABLE 4.1:** Model parameters for runs in this study Note: # - model parameters identified as sensitive to produce a realistic analogue delta
Chapter 4: Investigating the evolution of a mega-delta: a model based methodological design

4.2.2 Model results

4.2.2.1 Hydrodynamics of the ideal model

Once the morphodynamic equilibrium was reached after 57 hydrodynamic days of simulation, the following hydrodynamic results were achieved (see next section for the morphodynamic results). The tidal range at the upstream boundary of the model is around 0.6m. The sediment flux exchange at the downstream boundary model is none. The tidal range within the modelled delta ranges from 2.5 to 3m. This range matches well with the average tidal range within the Meghna estuary during the monsoon season. The channel depths in the modelled delta range from 30 to 50m. The maximum water depth in the islands is 0.1m. The maximum water flow velocity in the channels is 1.65m/s for the outflow and 0.65m/s for incoming flow. The maximum water flow velocity in the islands for flows in both the directions is around 0.10m/s. Both the modelled bathymetry (based on BWDB 2000s bathymetric survey of lower Meghna River and Meghna Estuary) and the tidal flow velocities (Ali et al., 2007, Jakobsen et al., 2002) are broadly representative of the actual values observed within the Meghna Estuary.

4.2.2.2 Morphodynamics of the ideal model

FIGURE 4.10 shows the temporal variation of the bed level in the modelled delta area. After 60 morphological years, it can be seen that the rate of bed level change reduces significantly. This indicates that the morphological evolution of channels and the rate of aggradation and progradation of the delta have slowed to reach morphodynamic equilibrium after approximately 63 morphological years. It also implies that hydrodynamic equilibrium is reached in the delta area. Unlike the mouth bar formation conceptualised by (Olariu and Bhattacharya, 2006a) for river dominated scenario (see FIGURE 2.16), the terminal distributaries and mouth bars evolved as in a typical tide dominated deltas (Leonardi et al., 2013). In this study, each mouth bar formation resulted in trifurcation (see FIGURE 4.9), result of tide dominated case, rather than bifurcation. The extent of the model permits proper exchange of sediment between the sea and delta as in agreement with (van der Wegen et al., 2008).
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 4.9: Location plan of longitudinal section of the idealised delta

FIGURE 4.10: Longitudinal section of modelled delta bed level through its centre (x-x) during the starting case simulation. Figure shows delta evolution reaching equilibrium. See FIGURE 4.9 for location X-X

The extent to which the analogue delta is an appropriate representation of the GBM delta can be assessed by comparing selected simulated and observed delta metrics. First, the ratio of cumulative distributaries channel width to river width reflects the power of fluvial and tidal energy (Syvitski and Saito, 2007). Here, the cumulative distributaries channel width is a function of bank-full
discharge and is positively influenced by tides. This ratio for the modelled
delta was found to be (56km/3km)18.7, compared to the observed (1943)
value of 28.5 (Syvitski and Saito, 2007).

The following standardised metrics: island area, island shape factor, island
aspect ratio and nearest-edge distance (Edmonds et al., 2011, Passalacqua et
al., 2013) are used to compare the model outputs against the real delta and
each other as they have closer implications to the people and environment of
the real world delta as is the focus of this study. There are number of other
delta metrics used in the research by Burpee et al. (2015), Liang et al. (2016).
But, they are not considered here as either they do not have direct relevance to
the people and their environment of the GBM delta or not relevant to the type
of the delta, tidally influenced, studied here. See section 2.1.3.1.1 for the
description of these metrics. FIGURE 4.11 to FIGURE 4.14 show that there is a
good match between these delta metrics for the real and modelled delta
systems. The probability distribution function of island area for both numerical
and real deltas is multi-model (FIGURE 4.11) and it shows good match despite
the difference in the tail. The probability distribution function of island shape
factor for the numerical delta is multi-model whereas that of the GBM delta in
1943 is unimodal (FIGURE 4.12). This shows the difference in the degree of
drainage of islands between the numerical and real world delta. This could be
because of the limitation of pixel resolution to extract all the intraisland
channels from the satellite images of the real world delta. Despite this, FIGURE
4.12 shows good match in the range of values. FIGURE 4.13 shows good match
of island aspect ratio unimodal distribution between the real world delta and
numerical delta. This indicates good match of island shapes between them.
Despite the smaller number of islands in the numerical delta than in the real
world delta, FIGURE 4.14 shows good match of nearest-edge distance
distribution trend between the real world delta and numerical delta. Also, this
plot indicates that the size of islands in the real world delta is greater than in
the numerical delta. This indicates that the analogue model delta produced
after the 63 morphological years ‘spin-up’ can be used as the initial condition
to understand the responses of the delta to change in forces and delta
features, as described in Section 4.3.
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 4.11: Probability distribution function of island size normalised to total island area for the GBM delta in 1943 and modelled idealised tidal delta

FIGURE 4.12: Probability distribution function of island shape factor for the GBM delta in 1943 and modelled idealised tidal delta
FIGURE 4.13: Probability distribution function of island aspect ratio for the GBM delta in 1943 and modelled idealised tidal delta

FIGURE 4.14: Probability distribution function of nearest-edge distance for the GBM delta in 1943 and modelled idealised tidal delta

4.3 Design of simulations

The starting case model established by producing the morphometric properties similar to the real GBM delta (see above) becomes the initial condition used to simulate morphological responses to varied forcings and added land
reclamation measures. Each of these experiments were conducted over simulation periods equivalent to 100 morphological years. Paola et al. (1992) used a simple coupled sediment-transport model to understand the influence of factors such as fluvial water and sediment flux, subsidence, and gravel fraction on the response of alluvial basin’s vertical sedimentation pattern. That study considered the effect of sinusoidal variation of the factors over time at rate equal to natural time-scale, slower and quicker than the natural time-scale.

The numerical experiments designed here is based on the similar principle to what was conducted by Paola et al. (1992) but here the effect of seasonality is not included (see Section 4.2.1.2) whereas the effect of tides is considered. Moreover, with physically based numerical model, this study is designed to understand the response of morphodynamics over the entire delta scale and over multi-decadal timescales. Especially, the focus is on to understand the delta morphodynamics from the people and their environment point of view. The stratigraphy of the modelled delta is not the focus in this study due to the above reason and also due to the computational constraint for the modelled delta scale. However, further work is recommended to study the delta stratigraphy over the delta scale. The base case experimental scenario (2f) (see section 4.3.1) is considered here as the natural time-scale whereas the rate of change in factors in other experimental scenarios can be seen as slower or quicker than the natural time-scale. Similar to the basin response to the varied rate of change in factors in Paola et al. (1992) study, morphodynamic response of the delta is expected (see Chapters 5 to 9 for the results and discussion). In addition to that, the human intervention factors (see Section 4.3.3) and the combined effect of natural and human factors (see Section 4.3.4) are considered in this study.

4.3.1 Fluvial water and sediment discharge

The evolution of distributary channels and mouth bars are influenced by the fluvial and sediment discharges (see Chapter 4). The following scenarios of fluvial and sediment discharges are studied:

Scenario2a - No sediment discharge
Upstream damming over the past 50 years has significantly reduced the input of sediment supply to deltas all over the world (Syvitski et al., 2009). Vörösmarty et al. (2003) reported that sediment trapped by large reservoirs on major rivers such as Nile, Indus, Krishna, Colorado, and Ebro have lead to up to a 100% reduction in sediment load on some rivers. Hence, sediment starvation is an increasingly common problem for many deltas and this trend of sediment load reduction is also expected to continue in the future. This scenario therefore represents the total elimination of fluvial sediment supply to the delta (see Chapter 5).

**Scenarios 2b to 2j (matrix of water and sediment discharge combination)**

Simulations of future climate over the Ganges, Brahmaputra and Meghan River basins by Caesar et al. (2015) indicated an increasing precipitation ranging from 8% to 28% by the end of this century. As explained in section 4.2.1, sediment discharge is a function of water discharge. Based on the simulation results from Caesar et al. (2015), Darby et al. (2015) suggested that, under the influence of anthropogenic climate change, water flux may increase in the range of 50% to 77% in the Ganges and 23% to 39% in the Brahmaputra by the end of this century. Similarly, it is reported that the sediment flux in the Ganges will increase by 34% to 37% and in the Brahmaputra will increase by 52% to 60%. This implies that the dominant fluvial discharge of the rivers discharging into the river deltas will likely significantly change in the future. However, as described in scenario 2a, further human interventions such as inter basin water transfers (Whitehead et al., 2015b) within these catchments can result in decreased water and sediment discharges to deltas. These potential impacts are explored here using a matrix of water and sediment discharge combinations representing a range of fluvial discharges to the idealised delta. Temporally constant discharges are shown in FIGURE 4.15. Three cases each of varying water and sediment discharge results in a combination of 9 scenarios as shown in TABLE 4.2. These combinations of varying water and sediment discharge remain constant over time (see Chapter 4).
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 4.15: Fluvial water and sediment discharge constant over time.

In addition, the following scenarios of different trajectories of sediment discharge entering a delta were studied (see FIGURE 4.16). The rate and amount of change in sediment discharge depends on the properties of the catchment and specifically the influencing factors as shown in FIGURE 4.16. Here, following the trend line of each, a hypothetical rate of change of sediment discharge over time was assumed for each scenario. However, an attempt has been made here to keep the assumed rate of change as realistic as possible by extracting information for representative Asian rivers.

<table>
<thead>
<tr>
<th>Sediment Discharge (Qs)</th>
<th>Water discharge (Qw)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Qw – Low (32,500 m³/s)</td>
<td>2Qw – Medium (65,000 m³/s)</td>
<td>3Qw – High (97,500 m³/s)</td>
</tr>
<tr>
<td>Qs – Low (Sand: 0.065 kg/m³, fine: 0.06 kg/m³)</td>
<td>2b = Qs:Qw</td>
<td>2c = Qs:2Qw</td>
<td>2d = Qs:3Qw</td>
</tr>
<tr>
<td>2Qs – Medium (Sand: 0.13 kg/m³, fine: 0.12 kg/m³)</td>
<td>2e = 2Qs:Qw</td>
<td>2f = 2Qs:2Qw (base case)</td>
<td>2g = 2Qs:3Qw</td>
</tr>
<tr>
<td>3Qs – High (Sand: 0.195 kg/m³, fine: 0.18 kg/m³)</td>
<td>2h = 3Qs:Qw</td>
<td>2i = 3Qs:2Qw</td>
<td>2j = 3Qs:3Qw</td>
</tr>
</tbody>
</table>

TABLE 4.2: Combination of varying water and sediment discharge (Options 2b to 2j)
Chapter 4: Investigating the evolution of a mega-delta: a model based methodological design

1) Scenario 2k - Land clearance and intensification of agricultural land use

The impact of land clearance and subsequent land use activities such as agricultural practices within the catchment can increase sediment load in rivers (Walling and Fang, 2003). This scenario represents such an impact on increased sediment supply to deltas by increasing the sediment discharge at a rate of 75% over a 30 year time period (FIGURE 4.17 and FIGURE 4.18), following Walling (2011) who reported that for a Asian catchment (Citarum River in Indonesia) with steep terrain and frequent landslides, the sediment discharge increased by 75% over a 30 year time period.

2) Scenario 2l - Soil conservation, sediment control and sand mining

The scenario of sediment discharge reduction due to the above listed actions was studied by decreasing the sediment discharge by 40% over a period of 25 years (FIGURE 4.17 and FIGURE 4.18), matching the response of the Sanchuan River in China (see Walling, 2011). It is evident from this finding from Walling (2011) that there is a potential, if not already happening elsewhere, to reduce sediment supply to deltas.
by soil conservation and sediment control programmes in larger drainage basins.

FIGURE 4.17: Sediment concentration of sand for the experimental 100 years. Note: 2f- base case, 2k-Land clearance & agriculture in catchment, 2l-soil conservation in catchment, 2m1- dams and water storage catchment, 2m2- dams and water storage catchment, 2n-sediment impulse from catchment.

3) Scenario 2m - Construction of dams and diversion of water
The study by Gupta et al. (2012) on the role of mega dams in Asia revealed that mega dams have led to a 20 to 90% reduction in the annual sediment flux delivered by Asian rivers to the ocean. Rivers flowing through China showed reductions of sediment supply of greater than 75% due to the construction of more than 5,000 large dams (higher than 30m) in the last 50 years. Similarly, in India about 3,000 (higher than 15m) dams have been built in the last 60 years. It is reported that the current day trend of sediment supply to the ocean may decline further in the future as a result of more dams being built across the world’s rivers. Walling (2011) mentioned that, because of the hydropower and water supply dams, as well as diversions of water for irrigation, there has been a reduction of 80% of the annual sediment load over 20 to 70 (sudden to marked and progressive decrease) years in various Asian rivers (Chao Phraya and Indus). Based on these
previous studies, the scenario of sediment discharge reduction reflecting the construction of dams and diversion of water was studied by decreasing the amount of sediment supply to the delta by 80% over periods of 20 years and 70 years, but without varying the water discharge over the same time interval (FIGURE 4.17 and FIGURE 4.18).

4) **Scenario 2n -Sediment impulse from catchment**

The scenario was modelled as a step change in the sediment discharge by multiplying the base case sediment discharge by a constant factor of 3 over time (FIGURE 4.17 and FIGURE 4.18). This scenario represents sediment impulse from catchment due to a dam burst/decommissioning (Ding and Langendoen, 2016) or earthquake induced landslides (Dadson et al., 2004). For example, Sarker (2008) reported that the amount of suspended bed material load entering the GBM delta was three times higher than the sediment load observed during normal times and associated this increase in sediment load to the 1950 Assam Earthquake induced landslides within the catchment of the Brahmaputra river.

![FIGURE 4.18: Sediment concentration of silt for the experimental 100 years. Note: 2f- base case, 2k-Land clearance & agriculture in catchment, 2l-soil conservation in catchment, 2m1- dams and water storage catchment, 2m2- dams and water storage catchment, 2n-sediment impulse from catchment.](image-url)
4.3.2 Relative Sea Level Rise (RSLR)

The process of the evolution of modern river deltas under forcing by contemporary and future sea level rise is unknown (see Section 1.1.2 and 3.3). Hence, the effect of RSLR on deltas needs to be studied. Pethick and Orford (2013) estimated a RSLR rate of 10mm/y to 20mm/y occurring on the western part of the GBM delta (see Section 2.1.3.4 and 2.3.12.3.1). Therefore, the effect of RSLR was studied for the following rates: 5mm/y, 10mm/y, 15mm/y & 20mm/y (FIGURE 4.19) by increasing the height of the tidal water level boundary conditions (Scenarios 3a to 3d).

4.3.3 Human interventions

In many of the world’s large deltas (including the GBM delta), various land reclamation measures in the forms of polderisation and building cross-dams have taken place over the last 70 years. However, there remains a lack of a proper understanding of how these factors influence delta morphology in the past and future, especially when more such land reclamation measures are possible in the future (Woodroffe et al., 2006, Ibáñez, 2013, Day et al., 2007, Sarker et al., 2011).
4.3.3.1 Polders

Coastal embankments within the coastal area of deltas do not allow fluvial and tidal water discharges to flood the floodplains (see FIGURE 3.1 and 3.12). However, it is known that this use of embankments leads to sediment starvation inside polders (Rogers et al., 2013b), but the effect of this excess sediment on delta morphodynamics outside the polders remains unknown. To investigate this, the islands of the modelled were not allowed to flood completely in order to replicate the presence of polders. The coastal embankments are represented here by thin dams as shown in FIGURE 4.20, a structure of infinite height, which blocks the flow of water and sediment in and out of islands (Scenario 4a).

FIGURE 4.20: Initial condition of the model for the scenario with polders.

4.3.3.2 Cross-dams

About 1,000 km² land was reclaimed in 30 years’ (1957-1985) time in the north-eastern part of the Meghna Estuary after building two cross-dams (also known as closure dams; fixed structures that permanently close off a river mouth or estuary) across the eastern channel of the Lower Meghna River (see section 2.1.3.5). However, the effect of these cross-dams on the other part of the estuarine morphodynamics remains unknown. The effect of cross-dams was studied by completely blocking (sudden closure of the channel) the flow in
one of the distributaries, at locations that is similar to the eastern channel of the Lower Meghna River, to study the response of increased water and sediment flow through the other distributaries (Scenario 4b). The cross-dams are modelled as shown in FIGURE 4.21 on the basis that the distributary between the two cross-dam will not experience any direct fluvial flow and any flow entering that channel to experience minimal flow velocity to enhance sedimentation.

FIGURE 4.21: Initial condition of the model for the scenario with cross-dams.

### 4.3.3.3 Changing land cover

The rate, amount and type of sedimentation in a floodplain are not only a function of floodplain topography and distance from the main channel in the floodplain but are also influenced by floodplain land cover. This is because the type of land cover plays a significant role in determining the sediment transport capacity of the water flowing through the floodplains and thus the floodplain sedimentation. The effect of changing land cover on the floodplain sedimentation was studied (Scenario 4c) here by varying the Manning’s roughness co-efficient (n value equal to 0.10 to represent mangroves) along the perimeter of the island to represent Mangrove fringes. Mangroves are reported to be efficient sediment trappers in the floodplain (Woodroffe, 2013).
4.3.4 Combined effect of environmental change and anthropogenic interventions

In reality, the driving factors are unlikely to vary in isolation (Akter et al., 2016, Dada et al., 2016, Rahman et al., 2011, Coleman et al., 2008, Wilson and Goodbred, 2015) (Day et al., 1997). Therefore, co-varying the controlling factors in ways that represent likely changes in the GBM delta (and other similar deltas) can offer a further insight in understanding the delta response. The impact of combining human interventions (polders, cross-dams, etc., with environmental change, in particular changes in relative sea level rise and fluvial water and sediment discharges are also studied.

4.4 Summary

1. As the availability of reliable data is very scarce in river deltas, demonstrating the link between morphodynamic change within such deltas and environmental factors controlling those responses - such as fluvial sediment supply, polders, sea level rise, subsidence etc. - is still challenging as the interactions between them are very complex and non-linear.
2. A number of factors play a significant role in influencing deltaic mophodynamics, however the following most important ones from the GBM delta include the influence of tides, water and sediment discharge, cross-dams, polders and mangroves.

3. Process-based numerical modelling software is used in this study. A realistic analogue modelling approach is used and not the traditional virtual reality one due to the lack of reliable data over the simulation period. The preferred approach is mainly suitable for long-term qualitative assessments of the system response to forcing.

4. A highly schematised realistic analogue model of an idealised tidal delta was built to match the morphometric properties of the real GBM delta. Comparison of the modelled hydrodynamics and morphodynamics with the real delta revealed a degree of similarity. The basis of the selection of model parameters was tested by sensitivity analysis during the process of producing an idealised tidal delta.

5. The starting case model established by producing the morphometric properties similar to the real GBM delta becomes the initial condition to simulate the experiments with varied forcing and added land reclamation measures.

6. The following list of experiments were carried out: (i) varying combination of water and sediment discharges (ii) changes in relative sea level, and (iii) land reclamation due to land cover such as mangroves and engineering structures such as the building of polders and cross-dams.

7. The results and discussion of the following model experiments (15 Nos.) are presented in Chapter 5.
## Experiment scenario

<table>
<thead>
<tr>
<th>(Qw: Fluvial water discharge) (Qs: Fluvial sediment discharge)</th>
<th>Experiment number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero fluvial sediment discharge (2Qw:0Qs)</td>
<td>2a</td>
</tr>
<tr>
<td>See TABLE 4.4</td>
<td></td>
</tr>
<tr>
<td>Land clearance and intensification of agricultural land use (2Qw: 3.5Qs in100y)</td>
<td>2k</td>
</tr>
<tr>
<td>Soil conservation, sediment control and sand mining (2Qw:2Qs to 0Qs in 60 y)</td>
<td>2l</td>
</tr>
<tr>
<td>Construction of dams and diversion of water (2Qw:2Qs to 0Qs in 80 y)</td>
<td>2m1</td>
</tr>
<tr>
<td>Construction of dams and diversion of water (2Qw:2Qs to 0Qs in 25 y)</td>
<td>2m2</td>
</tr>
<tr>
<td>Sediment impulse from catchment (2Qw:6Qs)</td>
<td>2n</td>
</tr>
</tbody>
</table>

**TABLE 4.3: List of varying fluvial discharge simulations**

<table>
<thead>
<tr>
<th>Sediment Discharge (Qs)</th>
<th>Water discharge (Qw)</th>
<th>Qw – Low (32,500m³/s)</th>
<th>2Qw – Medium (65,000m³/s)</th>
<th>3Qw - High (97,500m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qs – Low (Sand: 0.065kg/m³, fine : 0.06 kg/m³)</td>
<td>2b = Qs/Qw</td>
<td>2c = Qs/2Qw</td>
<td>2d = Qs/3Qw</td>
<td></td>
</tr>
<tr>
<td>2Qs – Medium (Sand: 0.13kg/m³, fine : 0.12 kg/m³)</td>
<td>2e = 2Qs/Qw</td>
<td>2f = 2Qs/2Qw (base case)</td>
<td>2g = 2Qs/3Qw</td>
<td></td>
</tr>
<tr>
<td>3Qs – High (Sand: 0.195kg/m³, fine : 0.18 kg/m³)</td>
<td>2h = 3Qs/Qw</td>
<td>2i = 3Qs/2Qw</td>
<td>2j = 3Qs/3Qw</td>
<td></td>
</tr>
</tbody>
</table>

**TABLE 4.4: Combination of varying water and sediment discharge (Options 2b to 2j)**
8. The results and discussion of the following simulations (4 Nos.) are presented in Chapter 6.

<table>
<thead>
<tr>
<th>Experiment scenario</th>
<th>Total amount of RSLR in 100 years</th>
<th>Experiment number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate of RSLR = 5mm/y</td>
<td>0.5m</td>
<td>3a</td>
</tr>
<tr>
<td>Rate of RSLR = 10mm/y</td>
<td>1.0m</td>
<td>3b</td>
</tr>
<tr>
<td>Rate of RSLR = 15mm/y</td>
<td>1.5m</td>
<td>3c</td>
</tr>
<tr>
<td>Rate of RSLR = 20mm/y</td>
<td>2.0m</td>
<td>3d</td>
</tr>
</tbody>
</table>

TABLE 4.5: List of relative sea level rise simulations

9. The results and discussion of the following simulations (3 Nos.) are presented in Chapter 7.

<table>
<thead>
<tr>
<th>Experiment scenario</th>
<th>Experiment number</th>
</tr>
</thead>
<tbody>
<tr>
<td>With coastal embankments all around the perimeter of the deltaic islands (Polders) as shown in FIGURE 4.20</td>
<td>4a</td>
</tr>
<tr>
<td>With two cross-dams as shown in FIGURE 4.21</td>
<td>4b</td>
</tr>
<tr>
<td>With higher roughness in the tidal floodplains as shown in FIGURE 4.22</td>
<td>4c</td>
</tr>
</tbody>
</table>

TABLE 4.6: List of direct human intervention and changing land cover simulations
Chapter 4: Investigating the evolution of a mega-delta: a model based methodological design

10. The results and discussion of the following simulations (16 Nos.) are presented in Chapter 8.

<table>
<thead>
<tr>
<th>With polders and cross-dams</th>
<th>0mm/y Relative Sea Level Rise (RSLR)</th>
<th>10mm/y RSLR</th>
<th>20mm/y RSLR</th>
</tr>
</thead>
<tbody>
<tr>
<td>2Qs = 1.48 m$^3$/s 1Qw = 32,500 m$^3$/s (low)</td>
<td>6a (2Qs:1Qw;0rslr)</td>
<td>6b (2Qs:1Qw;10rslr)</td>
<td>6c (2Qs:1Qw;20rslr)</td>
</tr>
<tr>
<td>2Qs = 1.48 m$^3$/s 2Qw = 65,000 m$^3$/s (medium)</td>
<td>5a (2Qs:2Qw;0rslr)</td>
<td>5b (2Qs:2Qw;10rslr)</td>
<td>5f (2Qs:2Qw;20rslr)</td>
</tr>
<tr>
<td>2Qs = 1.48 m$^3$/s 3Qw = 97,500 m$^3$/s (high)</td>
<td>6d (2Qs:3Qw;0rslr)</td>
<td>6e (2Qs:3Qw;10rslr)</td>
<td>6f (2Qs:3Qw;20rslr)</td>
</tr>
</tbody>
</table>

TABLE 4.7: Combination of scenarios of varying fluvial water discharge and relative sea level rise with polders and cross-dams

<table>
<thead>
<tr>
<th>With polders and cross-dams</th>
<th>0mm/y Relative Sea Level Rise (RSLR)</th>
<th>10mm/y RSLR</th>
<th>20mm/y RSLR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1Qs = 0.74 m$^3$/s (low) 2Qw = 65,000 m$^3$/s</td>
<td>5g (1Qs:2Qw;0rslr)</td>
<td>5e (1Qs:2Qw;10rslr)</td>
<td>5i (1Qs:2Qw;20rslr)</td>
</tr>
<tr>
<td>2Qs = 1.48 m$^3$/s 2Qw = 65,000 m$^3$/s</td>
<td>5a (2Qs:2Qw;0rslr)</td>
<td>5b (2Qs:2Qw;10rslr)</td>
<td>5f (2Qs:2Qw;20rslr)</td>
</tr>
<tr>
<td>2Qs+45% over 100 years = 2.15 m$^3$/s (high) 2Qw = 65,000 m$^3$/s</td>
<td>5h (2Qs+45%:2Qw;0rslr)</td>
<td>5c (2Qs+45%:2Qw;10rslr)</td>
<td>5j (2Qs+45%:2Qw;20rslr)</td>
</tr>
<tr>
<td>6Qs% = 4.44 m$^3$/s (extreme) 2Qw = 65,000 m$^3$/s</td>
<td>-</td>
<td>5d (6Qs:2Qw;10rslr)</td>
<td>-</td>
</tr>
</tbody>
</table>

TABLE 4.8: Combination of scenarios of varying fluvial sediment discharge and relative sea level rise with polders and cross-dams

Note: # - average value of the range of simulated increase in sediment flux for the Ganges and Brahmaputra catchments towards the end of this century for the projected anthropogenic climate change by Darby et al. (2015)

% - scenario of increase in sediment discharge due to earthquake induced landslides in the catchments (Sarker and Thorne, 2009). Here, only the fine sediment is increased as the increase in sand concentration led to huge sedimentation near the upstream boundary to trigger the model instability.
5. The role of variations in fluvial water and sediment discharges in controlling the morphology of tidally influenced deltas

5.1 Introduction

The numerical model experiments, described in Chapter 4, to understand the role of fluvial and water discharges on the morphodynamics of the idealised delta were performed. This chapter now presents the results from those numerical modelling experiments and analyses and discusses the model results with the aim of systematically understanding how variations in fluvial and water discharges, imposed from the catchment upstream, affect the morphodynamics of the simulated, tidally influenced, delta. In the following sections, the response of the model over 100 years under the varying fluvial water and sediment discharges are presented and discussed in terms of their impact on (i) residual flow hydrodynamics and (ii) deltaic morphodynamics.

5.2 Residual flow

Residual flow in a tidally influenced delta is defined as the net flow of water due to the interaction of outgoing fluvial (freshwater) discharge and the incoming tidal discharge (Goodbred and Saito, 2012). In the case of diurnal tides, due to the variation of intensity in tidal discharge over time, the residual flow intensity and direction both change over time. FIGURE 5.1 illustrates the residual flow parameters simulated at the delta apex for the initial condition, and after 100 years of morphological simulation, for scenarios 2e, 2f, 2g (low, medium and high water discharges) and 2c, 2f and 2i (low, medium and high sediment discharges). For the range of fluvial water discharges (32,500; 65,000 and 97,500 cumecs) considered here, the residual flow is in all cases bidirectional (FIGURE 5.1C), but FIGURE 5.1C also shows that the volume of water exchanged over the tide between the low (2e) and high (2g) water discharges varies substantially. In scenario 2g (Qw = 97,500 m³/s), the volume of incoming water during the tidal flood flow is much less (19million m³), due to the high resistance from the incoming fluvial discharge, than the outgoing water flux (147million m³, 7.5 times the incoming water flux) on the
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

ebb flow. In contrast, for scenario 2e (\(Q_w = 32,500\) m\(^3\)/s) the volume of outgoing water (ebb flow) is only twice the volume of the incoming flood flow (46 and 89 million m\(^3\), respectively).

FIGURE 5.1: Time series of modelled water level (A), velocity (B), water discharge (C), bed level (D), bed (E) and suspended load transport (F) at the delta apex for the initial condition and after 100 years of simulation for: water discharge scenarios: 2e (1\(Q_w:2Q_s\)), 2f-basecase (2\(Q_w:2Q_s\)), 2g (3\(Q_w:2Q_s\)) and sediment discharge scenarios: 2c (2\(Q_w:1Q_s\)), 2i (1\(Q_w:3Q_s\))

Note: Water discharge, \(Q_w = 32,500\) m\(^3\)/s; sediment discharge, \(Q_s = 0.74\) m\(^3\)/s
Due to the greater back water effect, water levels over the entire tidal range for the high fluvial discharge scenario (2g; $Q_w = 97,500 \text{ m}^3/\text{s}$) is greater, by a factor varying between 1.2 to 2, than the low water discharge scenario (2e; $Q_w = 32,500 \text{ m}^3/\text{s}$) (FIGURE 5.1A) resulting in a higher outgoing velocity during low tides and a lower incoming velocity during high tides under the high versus low fluvial discharges, respectively (FIGURE 5.1B). The residual flow follows this same trend of flow velocity (FIGURE 5.1C).

![Graph showing the ratio of flood to ebb flow in a tidal cycle at the delta apex during the initial condition and after 100 years of simulation for varying water and sediment discharge scenarios.](image)

**FIGURE 5.2**: Ratio of flood to ebb flow in a tidal cycle at the delta apex during the initial condition and after 100 years of simulation for varying water and sediment discharge scenarios: 2b(1Qw:1Qs), 2c(2Qw:1Qs), 2d(3Qw:1Qs), 2e(1Qw:2Qs), 2f(2Qw:2Qs), 2g(3Qw:2Qs), 2h(1Qw:3Qs), 2i(2Qw:3Qs), 2j(3Qw:3Qs)

Note: Water discharge, $Q_w = 32,500 \text{ m}^3/\text{s}$; sediment discharge, $Q_s = 0.74 \text{ m}^3/\text{s}$

The relative strength between the flood and ebb flow of the tidal cycle is strongly influenced by the fluvial water discharge, as shown in FIGURE 5.2. It is clearly evident that the higher the riverine flow the stronger the ebb flow, whereas the lower the river flow the stronger the flood flow. In the simulations conducted herein, the ratio of the flood to ebb flow is 0.5 for the low river discharge (scenario 2e; $Q_w = 32,500 \text{ m}^3/\text{s}$) and 0.1 for high river discharge (scenario 2g; $Q_w = 97,500 \text{ m}^3/\text{s}$), respectively, meaning that a factor of 3 variation in fluvial water discharge induces a factor of 5 variation in the flood to ebb flow ratio. The low flood to ebb ratio under high river discharge conditions is due to the amplification of tides within the delta as a result of back water effects, with decreasing tidal velocity and increasing water levels during high tides and the opposite during low tides (FIGURE 5.1 A, B & C). Low
slack water is inversely proportional to the fluvial water discharge (FIGURE 5.1 A, B & C). The fluvial water discharge does not seem to alter the high slack water significantly (FIGURE 5.1 A, B & C) as the effect of channel bed friction at the peak of flood tides is negligible. FIGURE 5.1C shows that, as expected based on simple transport capacity versus supply considerations, channel bed erosion increases with increasing water discharge and decreases with increasing sediment discharge (FIGURE 5.1D). More sediment is imported into the delta during the low water discharge scenario 2e (1Qw:2Qs) (the outgoing sediment volume is 122million cu.m and the incoming volume is 60million cu.m), whereas more sediment is exported out of the delta during the high water discharge scenario 2g (3Qw:2Qs) (outgoing and incoming sediment volumes of148million cu.m and 15million cu.m, respectively) (FIGURE 5.1E&F). This process is in agreement with the process described by Goodbred and Saito (2012). In addition, variations in the incoming fluvial water discharge also influence the phase lag between the water level, velocity, residual flow, and sediment transport. Thus, overall the simulations reveal that the incoming fluvial discharge strongly influences the residual current and sediment transport regime within this simulated tidal deltaic environment. The interaction dynamics between the fluvial water discharge and the tidal discharge as presented in this section are consistent with the findings of Leonardi et al. (2015). However, changes in the hydrodynamics and sediment transport regime of the delta have the potential to induce morphodynamic changes, which in turn may feedback to affect the hydrodynamics and sediment transport regime; these interactions are explored in further detail in section 4.3.

5.3 Morphodynamic changes

The following sub-sections present and analyse the morphodynamic changes (represented here by (i) the sub-aerial delta area, (ii) patterns of erosion and accretion, and (iii) aggradation and progradation of the delta) imposed on the delta over the 100 morphological years of model simulation, for the various scenarios of varying fluvial water and sediment discharges.

5.3.1 Patterns of erosion and accretion on the delta

FIGURE 5.3 shows the spatial distribution of the tidal flood to ebb flow ratio (in blue coloured text) over the simulated delta for various scenarios of imposed water and
Chapter 5: The role of variations in fluvial water and sediment discharges in controlling the morphology of tidally influenced delta

sediment discharge supply. The tidal flood to ebb flow ratio is not sensitive to sediment discharge, as shown in FIGURE 5.3. In most distributaries, the ratio is around 0.30 but near the observation points 5, 7, 8 and 16 the ratio varies between 0.50 and 0.70. However, the flood:ebb flow ratio varies with water discharge as shown in FIGURE 5.4 for the scenarios of higher: 2g (3Qw:2Qs), medium: 2f(2Qw:2Qs) and lower water flows: 2e (1Qw:2Qs). Thus, the flood:ebb flow ratio increases with increasing water discharge. At observation point 16 (see FIGURE 5.3 for its location), the flood:ebb flow ratio is 0.18 for scenario 2g (3Qw:2Qs), but due to channel erosion it increases to a value of 0.69 for scenario 2f (2Qw:2Qs) and 0.76 for scenario 2e (1Qw:2Qs). At observation points 7 and 8 (see FIGURE 5.3 for their locations), the flood:ebb flow ratio is higher compared to the value at other distributary mouths. These results are important because the tidal flood:ebb flow ratio plays an important role in influencing the patterns of erosion and accretion that occur within the delta. This can be demonstrated clearly for the varying water discharge scenarios. At all the observation points in the delta, a higher flood:ebb flow ratio is evident in the low water discharge scenario 2e(1Qw:2Qs) compared to the medium 2f(2Qw:2Qs) and high 2g(3Qw:2Qs) water discharge scenarios (see FIGURE 5.4), leading to a significantly greater net volume gain (i.e., volume of accretion of 1,597 million m$^3$ after 100 years) in the delta (see FIGURE 4.6 B2 & E2, and FIGURE 5.11).
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 5.3: Location of tidal flow observation points (brown colour) and spatial distribution of tidal flood to ebb flow ratio (blue colour) in the delta after 100 years of simulation

Note: Water discharge, \( Q_w = 32,500 \text{m}^3/\text{s} \); sediment discharge, \( Q_s = 0.74 \text{m}^3/\text{s} \)
FIGURE 5.4: Ratio of flood to ebb flow in a tidal cycle for varying water discharge scenarios after 100 years of simulation: 2g(3Qw:2Qs), 2f(2Qw:2Qs) and 2e(1Qw:2Qs). See FIGURE 5.3 for the location of observation points.
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

Note: Water discharge, $Q_w = 32,500\text{m}^3/\text{s}$; sediment discharge, $Q_s = 0.74\text{m}^3/\text{s}$
Chapter 5: The role of variations in fluvial water and sediment discharges in controlling the morphology of tidally influenced delta

Graph C: Ratio of water to sediment discharge (Qw/Qs) at location 16 after 100 years

Graph D: Ratio of water to sediment discharge (Q/Qs) at location 6 after 100 years

+ve = flood flow
-ve = ebb flow
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis.
Chapter 5: The role of variations in fluvial water and sediment discharges in controlling the morphology of tidally influenced delta

FIGURE 5.5: Ratio of water to sediment discharge for scenarios after 100 years of simulation: 2c(2Qw:1Qs), 2g(3Qw:2Qs), 2f(2Qw:2Qs), 2i(2Qw:3Qs), 2e(1Qw:2Qs) at observation points 1 (A), 14 (B), 16(C), 6(D), 7(E), 10(F), 13(G). See FIGURE 5.3 for the location of observation points
Note: Water discharge, Qw= 32,500m3/s; sediment discharge, Qs = 0.74m3/s

FIGURE 5.5 shows the ratio of water to sediment discharge (Qw/Qs) of a tidal cycle after 100 years of simulation at various deltaic channel locations. This ratio (i.e., Qw/Qs) indicates the local relative sediment transport capacity of the channel and is, therefore, a good metric of geomorphic adjustment potential. Generally, a trend of shorter flood phase and longer ebb phase can be observed as a function of water discharge. For the low water discharge scenario 2e (1Qw:2Qs), there is a much longer and lower Qw/Qs flood flow but a shorter and lower Qw/Qs ebb flow when compared to the medium (2f; 2Qw:2Qs) and high (2g; 3Qw:2Qs) water discharge scenarios(see FIGURE 5.5 A). Similar trends in the Qw/Qs ratio can also be found elsewhere in the delta (see FIGURE 5.5 B to G). The low sediment discharge scenario 2c (2Qw:1Qs) has a longer duration and greater magnitude Qw/Qs flood and ebb flow than the medium (2f; 2Qw:2Qs) and high (2i; 2Qw:3Qs) sediment discharge scenarios. The larger relative sediment transport capacity (i.e., higher value of Qw/Qs) in scenarios 2c (2Qw:1Qs) and 2g (3Qw:2Qs) clearly leads to more channel
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

bed and bank erosion being simulated, as shown in FIGURE 12.1 A2 and B2 (Appendix 12). In contrast, the lower relative sediment transport capacity in scenarios 2e (1Qw:2Qs) and 2i (2Qw:3Qs) leads to more channel bed and land accretion FIGURE 12.1 D2 and E2). As the discussion in the previous paragraph confirms the role of the flood:ebb flow ratio in influencing the pattern of erosion and accretion in the delta, the ratio of Qw/Qs explains the how the relative balance between the supply rate of sediment and transport capacity of the flow influences net accretion and erosion for varying scenarios of water and sediment discharge, as shown in FIGURE 12.1 (Appendix 12). The role of tides and their interaction with the fluvial water discharge near the mouth of distributaries, as simulated herein, complies with the findings of Leonardi et al. (2015).

FIGURE 12.1 (Appendix 12) shows the plan view of the patterns of erosion, progradation and aggradation of the delta after 100 years of simulation time for various scenarios of water and sediment discharge. FIGURE 12.1 C1(Appendix 12) shows the net accretion and erosion simulated after 100 years for scenario 2f (the base case scenarios in which 2Qw:2Qs). Both channel and land erosion and accretion occur throughout the delta domain. Most accretion (indicated by the blue shades), both on the sub-aerial delta and within the distributary channels, occurs closer to the seaward side of the delta, with some accretion also simulated at the heads of the distributary channels. The dark red patches, indicating erosion of channel banks or near channel banks along the sub-aerial delta, are more extensive under conditions of relative sediment starvation, with the main locus of the erosion being distributed both along channel banks, particularly in the landward part of the delta, and on the channel and sea-floor bed towards the sea. Channel erosion in the location indicated in FIGURE 12.1 C1 (Appendix 12) also results in the splitting of one large island into two islands. Comparison of the pattern of net erosion and accretion of the base case scenario (2f; 2Qw:2Qs) with other scenarios revealed the following differences:

1) FIGURE 12.1 A1 and A2 (Appendix 12) for the low sediment discharge scenario 2c (2Qw:1Qs). In this scenario accretion within the tidal floodplain is generally less in magnitude and spatial extent, whereas there is greater erosion of banks of island at the delta apex, as well as of the channels and sea-floor bed.
2) FIGURE 12.1 B1 and B2 (Appendix 12) for the high sediment discharge scenario 2i (2Qw:3Qs). In this scenario, a greater amount of accretion is simulated within the tidal floodplain, but with less within and in front of the prograding islands. Furthermore, a greater amount of accretion is also simulated on the bed of the channels and sea-floor. Channel erosion is similar to the base case.

3) FIGURE 12.1 D1 and D2 (Appendix 12) for the low water discharge scenario 2e (1Qw:2Qs). In this scenario, the model simulates a greater amount of accretion within the tidal floodplain and continuity of accretion in front of the prograding deltaic islands is also evident. The simulation also includes a greater amount of accretion of the channels and sea-floor bed, relative to the preceding scenario 2i (2Qw:3Qs). Simulated channel erosion is again similar to the base case.

4) FIGURE 12.1 E1 and E2 (Appendix 12) for the high water discharge scenario 2g (3Qw:2Qs). In this simulation there is more accretion directly in front of the prograding islands and also a greater extent of accretion within the tidal floodplain. In this scenario there is also greater erosion of the channels and sea-floor bed, except on the distributaries bifurcating around the central island, along with more intensive erosion of the banks of island at the delta. No channel erosion occurs in this scenario.

However, the morphodynamic response in the delta for scenarios of low (2c; 2Qw:1Qs) and high (2i; 2Qw:3Qs) sediment discharge is not significant enough to influence the hydrodynamics of the distributaries (see FIGURE 5.3), but the feedback from varying the water discharge scenarios to hydrodynamics is much more prominent (see FIGURE 5.4).
Chapter 5: The role of variations in fluvial water and sediment discharges in controlling the morphology of tidally influenced delta

FIGURE 5.6 shows the water discharge simulated at the top end of the eroding channel. The water discharge for the low (imposed) water discharge scenario 2e (1Qw:2Qs) is greater than the other cases, including the medium (imposed) water discharge 2f (2Qw:2Qs). This implies that distributary channel erosion in low discharge scenario (2e; 1Qw:2Qs) occurs much more quickly than in the medium (imposed) discharge scenario (2f; 2Qw:2Qs). In contrast, the channel is dry or the high (imposed) water discharge scenario (2g; 3Qw:2Qs) due to the lack of any channel erosion in this case. FIGURE 5.7 shows that there is a gradual increase in flow in either direction at the top end of the eroding channel, whereas FIGURE 5.8 shows the change in residual flow simulated at the bottom end of the eroding channel due to erosion at its top end in scenarios 2e (1Qw:2Qs) and 2f (2Qw:2Qs). These results show that changes in residual flow simulated in the distributary channels can lead to changes in the channel network. For example, the erosion of a distributary channel modifies the flow split among the other channels in the delta, especially the ones adjacent to the eroding channel. Similarly, due to this channel erosion, smaller number of islands is observed in high (imposed) water discharge scenario (2g; 3Qw:2Qs) than in the other cases however no definable trend of change in perimeter happened.

FIGURE 5.6: Water discharge through eroding channel at its top end after 25 years for scenarios: 2c (2Qw:1Qs), 2e (1Qw:2Qs), 2f (base case- 2Qw:2Qs), 2g (3Qw:2Qs) and 2i (2Qw:3Qs).

Note: Water discharge, Qw = 32,500m³/s; sediment discharge, Qs = 0.74m³/s
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 5.7: Water discharge through eroding channel at its top end for scenario: 2f-base case (2Qw:2Qs)

Note: Water discharge, \( Q_w = 32,500 \text{ m}^3/\text{s} \); sediment discharge, \( Q_s = 0.74 \text{ m}^3/\text{s} \)

FIGURE 5.8: Water discharge through eroding channel at its bottom end for scenario: 2f-base case (2Qw:2Qs)

Note: Water discharge, \( Q_w = 32,500 \text{ m}^3/\text{s} \); sediment discharge, \( Q_s = 0.74 \text{ m}^3/\text{s} \)
Chapter 5: The role of variations in fluvial water and sediment discharges in controlling the morphology of tidally influenced delta

Net volume of accretion (Million cu.m) vs accretion depth (m)  
Net volume of erosion (Million cu.m) vs erosion depth (m)

FIGURE 5.9: Net volume of accretion and erosion against the depth of accretion and erosion after 100 years for scenarios: 2c(A1&A2), 2f(B1&B2), 2i(C1&C2), 2e(D1&D2), 2g(E1&E2) Note: Water discharge, Qw= 32,500 m³/s; sediment discharge, Qs = 0.74 m³/s
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 5.9 shows the net volume of simulated accretion/erosion plotted against the depth of accretion/erosion in increasing order of the imposed sediment and water discharges. Larger volumes of erosion and deeper erosion can be observed for the high water discharge scenario 2g (3Qw:2Qs) (see plot E2 in FIGURE 5.9) relative to the low water discharge scenario 2e (1Qw:2Qs) (see D2 in FIGURE 5.9). The same trend can be seen for the simulated volume of net accretion (See Plot E1 and D1 in FIGURE 5.9). FIGURE 5.9 A to C indicates that the volume of accretion or erosion is not as sensitive to sediment discharge as water discharge. FIGURE 5.10 also shows the same trend for accretion and erosion for these scenarios. However, the net volume gained in scenario 2e (1Qw:2Qs) is greater, see FIGURE 5.11, when compared to scenario 2g (3Qw:2Qs) as the volume of erosion in scenario 2g (3Qw:2Qs) is much greater than its volume of accretion and vice versa in scenario 2e (1Qw:2Qs). For similar reasons, the net volume of accretion gained in the high sediment discharge scenario 2i (2Qw:3Qs) is greater than in the low sediment discharge scenario 2c (2Qw:1Qs). Changes in the imposed fluvial water and sediment discharges supplied to the delta result in modifications to the patterns of residual current flows and sediment transport within the distributary channels, which in turn changes the pattern of accretion and erosion across the delta. FIGURE 5.10 shows that there is an increasing trend of sediment accretion in the delta as the imposed water discharge increases, but the erosion of channels and land also increases with increasing water discharge. FIGURE 5.11 clearly shows that the net erosion/accretion is strongly influenced by both the imposed water and imposed sediment discharge. For scenarios 2c (2Qw:1Qs), 2d (3Qw:1Qs), and 2g (3Qw:2Qs) the simulation results indicate net erosion, but with net accretion for scenarios 2b (1Qw:1Qs), 2e (1Qw:2Qs), 2f (2Qw:2Qs), 2h (1Qw:3Qs), 2i (2Qw:3Qs) and 2j (3Qw:3Qs). Maximum net accretion occurred in the scenario 2n(2Qw:6Qs) due to excessive sediment discharge induced by sediment impulse from catchment. The scenarios of low imposed water discharge (2b; 1Qw:1Qs, 2e; 1Qw:2Qs, and 2h; 1Qw:3Qs) exhibit high net accretion. The maximum simulated net erosion is associated with the high water discharge scenario 2d (3Qw:1Qs) and is even greater than in the case of the zero sediment discharge scenario (scenario 2a; 2Qw:0Qs). However, at low water discharge, the applied sediment discharges are not as influential as they are for the medium and high water discharges. Though these plots indicate the sum of accretion and erosion within the delta they do not explicitly show what is happening over the sub-aerial delta. In section 5.3.3, the
process of erosion and accretion over the deltaic islands is therefore discussed in greater detail.

FIGURE 5.10: Total volume change in the delta area for “2” scenarios after 100 years

FIGURE 5.11: Net volume change in the delta for “2” scenarios after 100 years

Note: Water discharge, $Q_w = 32,500 \text{m}^3/\text{s}$; sediment discharge, $Q_s = 0.74 \text{m}^3/\text{s}$; 2a - 2Qw:0Qs, 2b-1Qw:1Qs, 2c-2Qw:1Qs, 2d-3Qw:1Qs, 2e-1Qw:2Qs, 2f-2Qw:2Qs (base case), 2g-3Qw:2Qs, 2h-1Qw:3Qs, 2i-2Qw:3Qs, 2j-3Qw:3Qs, 2k-Land clearance & agriculture in catchment, 2l-soil conservation in catchment, 2m1- dams and water storage catchment, 2m2- dams and water storage catchment, 2n-sediment impulse from catchment.
5.3.2 Progradation and aggradation of the delta

FIGURE 5.12: Location plan of longitudinal and cross sections of the idealised delta

FIGURE 5.13 clearly shows that the simulated progradation of the subaqueous delta increases with both increased fluvial water discharge and increasing relative sediment supply. The clinoform of the delta, as well as the topset, foreset and bottom set are all clearly visible, as required for a tidally-influenced delta (Goodbred and Saito (2012). FIGURE 5.13, and FIGURE 5.14FIGURE 5.15, also show that the simulated progradation of the delta is more sensitive to variations in water discharge than to variations in the sediment discharge (FIGURE 5.15), due to the tidal asymmetry near the distributary mouths. When the confined ebb flow enters the sea, because of the rapid expansion in the cross-sectional area, the jet slows down. Eventually, the sediment transport capacity of the flow decreases and starts depositing the sediment, as described by Edmonds and Slingerland (2007). Because high water discharges (e.g. in scenario 2g, where 3Qw:2Qs) have greater momentum during low tides (see FIGURE 5.5) as compared to lower discharges, sediments are deposited at a longer distance from the mouths of the distributaries, as observed by Islam et al. (2002). This same effect also led to longer and flatter foresets for higher flow discharge under relatively high sediment supply conditions (see FIGURE 5.13). FIGURE 5.4C confirms that the flood:ebb flow ratio in a tidal cycle near the distributary mouths for the high water discharge scenario 2g (3Qw:2Qs) is 2 to 3
times lower than for the lower discharge scenarios 2e (1Qw:2Qs) and 2f (2Qw:2Qs). FIGURE 5.5 D, E, F and G also shows that there is a longer and greater ebb flow (Qw/Qs) near the distributary mouths for scenario 2g(3Qw:2Qs) than for either scenarios 2e (1Qw:2Qs) and 2f (2Qw:2Qs). Hence, the length and slope of the delta clinoform is a function of the fluvial water and sediment discharge, as expressed here by the ratio Qw/Qs. The clinoform angle, based on the longitudinal profile of the delta elevation shown in FIGURE 5.13, is measured as the horizontal angle between the rollover point and the clinoform toe. The calculated time series of the clinoform angle is presented in FIGURE 5.14. It can be observed that the clinoform angle is a function of the fluvial water discharges. The clinoform angle increases with decreasing water discharges due to the greater sediment deposition caused by the reduction in the momentum of the flow.

Cross sections of the simulated delta, shown in FIGURE 5.16, FIGURE 5.17 and FIGURE 5.18, indicate that the erosion of the bed and banks of distributary channels increases with fluvial discharge and decreases with increasing sediment discharge. Tidal asymmetry can be observed all over the delta as shown in FIGURE 5.3 and FIGURE 5.4. Tidal asymmetry varies with water discharge, but not with sediment discharge. Even though the hydrodynamics and sediment transport capacity of the flow in the distributaries are similar for varying sediment discharge scenarios, with constant water discharge, the sediment available to transport varies. Plots of the ratio Qw/Qs (see FIGURE 5.5) show that for constant Qw, the Qw/Qs ratio varies for these scenarios due to the varied Qs. Smaller values of the Qw/Qs ratio for scenario 2i (2Qw:3Qs) implies that there is more sediment available to transport than in scenario 2c (2Qw:1Qs). Thus, more sediment deposition and less bank erosion can be observed (see FIGURE 5.16B, FIGURE 5.17B and FIGURE 5.18B) in scenario 2i (2Qw:3Qs) than in scenario 2c (2Qw:1Qs). Due to the varied hydrodynamics, sediment transport capacity will be different for varying water discharge scenarios. The greater Qw/Qs ratio for scenario 2g (3Qw:2Qs) in the Qw/Qs plots of FIGURE 5.5 indicates that there is greater relative sediment transport capacity in that scenario versus either of scenarios 2e (1Qw:2Qs) or 2f (2Qw:2Qs). Hence, more sediment is required to be transported and subsequently more bank and bed erosion (see FIGURE 5.16A, FIGURE 5.17A, and FIGURE 5.18A) in scenario 2g (3Qw:2Qs) than in scenarios 2e (1Qw:2Qs) or 2f (2Qw:2Qs).
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 5.13: Longitudinal section of the delta through its centre (x-x) for varying water discharge scenarios: 2e (1Qw:2Qs), 2f-basecase (2Qw:2Qs) and 2g (3Qw:2Qs). See FIGURE 5.12 for location

Note: Water discharge, Qw = 32,500m³/s; sediment discharge, Qs = 0.74m³/s

FIGURE 5.14: Time-series plot of clinoform slope angle for the experimental scenarios of varying fluvial sediment discharge
Chapter 5: The role of variations in fluvial water and sediment discharges in controlling the morphology of tidally influenced delta

FIGURE 5.15: Longitudinal section of the delta through its centre (x-x) for varying sediment discharge scenarios: 2c (2Qw:1Qs), 2f-base case (2Qw:2Qs) and 2i (2Qw:3Qs). See FIGURE 5.12 for location.

Note: Water discharge, Qw = 32,500m³/s; sediment discharge, Qs = 0.74m³/s
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

A - Scenarios: 2e (1Qw:2Qs), 2f-base case (2Qw:2Qs) and 2g (3Qw:2Qs)

B - Scenarios: 2c (2Qw:1Qs), 2f-base case (2Qw:2Qs) and 2i (2Qw:3Qs).

FIGURE 5.16: Cross section of the delta at location1-1 for initial condition and after 100 years of simulation. See FIGURE 5.12 for location

Note: Water discharge, Qw = 32,500m³/s; sediment discharge, Qs = 0.74m³/s
Chapter 5: The role of variations in fluvial water and sediment discharges in controlling the morphology of tidally influenced delta

A - Scenarios: 2e ($Q_{w}:2Q_{s}$), 2f-base case ($2Q_{w}:2Q_{s}$) and 2g ($3Q_{w}:2Q_{s}$)

B - Scenarios: 2c ($2Q_{w}:1Q_{s}$), 2f-base case ($2Q_{w}:2Q_{s}$) and 2i ($2Q_{w}:3Q_{s}$).

FIGURE 5.17: Cross section of the delta at location 2-2 for initial condition and after 100 years of simulation. See FIGURE 5.12 for location

Note: Water discharge, $Q_{w} = 32,500m^3/s$; sediment discharge, $Q_{s} = 0.74m^3/s$
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

A- Scenarios: 2e (1Qw:2Qs), 2f-basecase (2Qw:2Qs) and 2g (3Qw:2Qs)

B- Scenarios: 2c (2Qw:1Qs), 2f-base case (2Qw:2Qs) and 2i (2Qw:3Qs).

FIGURE 5.18: Cross section of the delta at location 3-3 for initial condition and after 100 years of simulation. See FIGURE 5.12 for location

Note: Water discharge, Qw = 32,500 m³/s; sediment discharge, Qs = 0.74 m³/s
5.3.3 Sub-aerial delta area

Sub-aerial delta area changes are, of course, driven by processes of accretion and erosion in the delta. For the purpose of understanding the dynamics of accretion or erosion on the sub-aerial delta, in FIGURE 5.20 response curves are shown based on net delta surface area changes plotted at 25 year intervals. FIGURE 5.20A shows that the area of accretion in scenario 2g (3Qw:2Qs) is greater than in scenarios 2f (2Qw:2Qs) and 2e (1Qw:2Qs) initially, however after 25 years, the reverse is the case. This is because the land area for scenario 2g (3Qw:2Qs) increases in the first 25 years but decreases afterwards, whereas for scenarios 2e (1Qw:2Qs) and 2f (2Qw:2Qs) the land area continuously increases (FIGURE 5.23). FIGURE 5.20B also confirms that erosion over the land area is greater for scenario 2g (3Qw:2Qs) than 2f (2Qw:2Qs) and 2e (1Qw:2Qs).

Flooding of the deltaic floodplain occurs during the flood flow phase of the tides when the water level in the distributaries of the delta is higher due to the interaction of outgoing fluvial water and incoming tidal water discharges. The amount of sediment discharge in the flood phase of the tides influences the amount of accretion and erosion over the land surface. FIGURE 5.19 shows that the higher sediment discharge during flood flows associated with scenarios 2e (1Qw:2Qs) and 2i (2Qw:3Qs) leads to greater rates of accretion as shown in FIGURE 5.20C and FIGURE 5.21C. FIGURE 5.19 also shows that the smaller sediment discharges during ebb flows for scenarios 2g (3Qw:2Qs) and 2c (2Qw:1Qs) lead to greater rates of erosion as shown in FIGURE 5.20D and FIGURE 5.21D. This finding implies that the higher the sediment discharge during flood flows then the higher the corresponding rate of accretion over the land surface; but the smaller the sediment discharge during the ebb flows then the higher the rate of erosion. Because of the deep erosion of island banks, as shown in the dark red patches on FIGURE 12.1 and volumes in FIGURE 5.9, the rate and area of erosion is always greater than the corresponding accretion. Because of the greater sediment transport capacity in scenario 2g (3Qw:2Qs), due to the tidal asymmetry induced for the reasons discussed in Section 5.3.2, its rate of accretion is less and the rate of erosion is greater than for the other scenarios.

For a constant fluvial water discharge and varying sediment discharge, FIGURE 5.21 shows that the area and rate of accretion over the existing land area increases with sediment discharge, while the area and rate of erosion decreases with sediment.
discharge due to the tidal asymmetry, for the reasons discussed in Section 5.3.2. The rate of accretion and erosion exponentially decays over time and reaches approximate steady state after 50 years and nearly converge to each other after 75 years of the simulation period.
Chapter 5: The role of variations in fluvial water and sediment discharges in controlling the morphology of tidally influenced delta

FIGURE 5.19: Time-series of sediment discharge at location 10 (A, B) and 15 (C, D) after 100 years. See FIGURE 5.3 for the location of observation points 10 and 15.

Note: Water discharge, \( Q_w = 32,500 \text{ m}^3/\text{s} \); sediment discharge, \( Q_s = 0.74 \text{ m}^3/\text{s} \)
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 5.20: Area and rate of accretion and erosion over delta land area for scenarios of varying water discharge: 2e(1Qw:2Qs), 2f- base case(2Qw:2Qs) 2g (3Qw:2Qs) (Water discharge, Qw= 32,500m³/s: sediment discharge = 0.74m³/s)
Chapter 5: The role of variations in fluvial water and sediment discharges in controlling the morphology of tidally influenced delta

FIGURE 5.21: Area and rate of accretion and erosion over delta land area for scenarios of varying sediment discharge: 2a(2Qw:0Qs), 2c(2Qw:1Qs), 2f-base case (2Qw:2Qs), 2i(2Qw:3Qs) (Water discharge, Qw= 32,500m³/s: sediment discharge = 0.74m³/s)
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 5.22: Comparison of sub-aerial delta land constructed between the initial state and after 100 years of the simulation for the base case (2f; 2Qw:2Qs) scenario. The net change in sub-aerial delta extent over this time period for this base case scenario is +21 km², compared to the initial delta extent of 694 km².

Note: Water discharge, Qw= 32,500m³/s; sediment discharge, Qs = 0.74m³/s

FIGURE 5.22 shows the modelled sub-aerial delta at the beginning of the experiment (blue line) and after 100 years of morphological simulation for the base case scenario 2f (2Qw:2Qs) (black line). It is evident that the sub-aerial delta has undergone both erosion and accretion over this time. Erosion of the island banks are shown in red coloured hatching, whereas accretion of the land, mainly in the form of progradation of the islands into the sea, is shown in green coloured hatching. FIGURE 12.1 C1 (Appendix 12) for the amount of net accretion and erosion over 100 years for the base case scenario 2f (2Qw:2Qs) at these locations. Most islands have experienced erosion. Significant erosion can be observed on the banks of islands at the delta apex. In contrast, islands on the delta front experienced little or no erosion. Channel erosion on the bank of one island (indicated by the arrow in FIGURE 5.22), has led to the split of that island into two. Apart from accretion at the delta front, some accretion can be seen at the head of the distributaries. The footprint of the delta land...
area for the other scenarios of varying fluvial water and sediment discharge is not significantly different to the basecase, with the difference being only in the extent of accretion and erosion.

FIGURE 5.23 shows the net changes in the percentage of sub-aerial delta area over the 100 years simulation period for all the scenarios of varying fluvial water and sediment discharge considered here (scenarios 2a to 2m). Increases in the delta area for all the scenarios are similar in the first 25 years of the simulation period because there is still bed erosion in the channel contributing to the delta formation. After 25 years, however, the effect of sediment input from bed erosion is reduced and the effect of varying fluvial water and sediment discharges at the upstream boundary is expressed more prominently. It is seen that sub-aerial delta area increased for scenarios: 2b (1Qw:1Qs), 2c (2Qw:1Qs), 2e (1Qw:2Qs), 2f (2Qw:2Qs), 2h (1Qw:3Qs), 2i (2Qw:3Qs), 2j (3Qw:3Qs), 2k (2Qw:3.5Qs in 100 years), 2l (2Qw:2Qs to 0Qs in 60 years) 2m1 (2Qw: 2Qs to 0Qs in 80 years) and 2n (2Qw:6Qs), but decreased for scenarios: 2a (2Qw:0Qs), 2d (3Qw:1Qs), 2g (3Qw:2Qs), 2m2 (2Qw: 2Qs to 0Qs in 25 years) when compared to the initial condition. The land area and it’s trajectory for scenarios 2b (1Qw:1Qs), 2e (1Qw:2Qs) and 2h (1Qw:3Qs) are identical. Also, they all have maximum gain in land area (8% after 100 years) followed by catchment sediment impulse scenario (6.4% after 75 years) - 2n (2Qw:6Qs) and the land use change scenario (4.58% after 100 years) - 2k (2Qw:3.5Qs in 100y). The maximum land loss (-2.75% after 100 years) is associated with the scenario with high water but low sediment discharge (scenario 2d; 3Qw:1Qs) which is then followed by zero sediment discharge (2a;2Qw:0Qs) with land loss of - 0.41% (after 100 years) and the catchment damming scenario 2m2 (2Qw:2Qs to 0Qs in 25 years) (0.33% after 100 years).
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 5.23: Time series of absolute change and percentage variation of modelled delta land area over 100 years from the total initial land area for 2 series experiments

Note: Water discharge, $Q_w = 32,500m^3/s$; sediment discharge, $Q_s = 0.74m^3/s$; $2a$ - $2Q_w:0Q_s$, $2b$ - $1Q_w:1Q_s$, $2c$ - $2Q_w:1Q_s$, $2d$ - $3Q_w:1Q_s$, $2e$ - $1Q_w:2Q_s$, $2f$ - $2Q_w:2Q_s$ (base case), $2g$ - $3Q_w:2Q_s$, $2h$ - $1Q_w:3Q_s$, $2i$ - $2Q_w:3Q_s$, $2j$ - $3Q_w:3Q_s$, $2k$ - Land clearance & agriculture in catchment, $2l$ - Soil conservation in catchment, $2m$ - Dams and water storage catchment, $2n$ - Sediment impulse from catchment.
Chapter 5: The role of variations in fluvial water and sediment discharges in controlling the morphology of tidally influenced delta

FIGURE 5.24: Net change in sub-aerial delta area after 100 years as a function of $Q$ varying water and sediment discharges

Note: Water discharge, $Q_w = 32,500\text{m}^3/\text{s}$; sediment discharge, $Q_s = 0.74\text{m}^3/\text{s}$

FIGURE 5.24 shows that (i) the net gain in sub-aerial delta area decreases with increasing water discharge and increases with increasing sediment discharge, and (ii) land area is more sensitive to variations in fluvial water discharge than variations in sediment discharge. This is because of the tidal asymmetry for the reasons discussed in the previous sections 5.3.1 and 5.3.2. Similar trends can be observed for the net volume change in the delta as shown in FIGURE 5.11. For decreasing water discharge ($Q_w$), there is a greater area and rate of accretion over the sub-aerial delta as shown in FIGURE 5.20 and FIGURE 5.21. Thus, the effect of sediment supply is dominated by the effect of water discharge. Thus, the simulations conducted here indicate that the morphological response is driven by the balance between the volumetric supply rate of sediment and the capacity of the flow to deposit/remove that sediment.

FIGURE 5.25 shows that the number of smaller island increases with increasing fluvial discharge. However, the total number of islands in high water discharge 2g (2g - 3Qw:2Qs) scenario is only 13 when compared to 14 in low water discharge 2e(1Qw:2Qs) and 15 in medium water discharge 2f (2Qw:2Qs) scenarios respectively. Because of the channel erosion at the north-west part of
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

the delta, one bigger island got split into two islands in low and medium discharge scenarios but not in high discharge scenario (FIGURE 12.1 in Appendix 12). This can be seen as the raise of the distribution tail on 2e(1Qw:2Qs) and 2f(2Qw:2Qs) scenarios(FIGURE 5.25). Moreover, the islands bank erosion was greater in high water discharge scenario (2g) causing the increase in the frequency of smaller islands. FIGURE 5.26 shows little or no difference among the distribution of delta areas for varying fluvial sediment discharge scenarios. For the above reasons, FIGURE 5.27 shows that the islands tending towards both rounded and elongated shapes with increasing fluvial water discharges. Also, similar trend can be observed for decreasing fluvial sediment discharges in FIGURE 5.28.

FIGURE 5.25: Probability distribution function of island size normalised to total island area for the experimental scenarios of varying fluvial water discharge

FIGURE 5.26: Probability distribution function of island size normalised to total island area for the experimental scenarios of varying fluvial sediment discharge
Chapter 5: The role of variations in fluvial water and sediment discharges in controlling the morphology of tidally influenced delta

FIGURE 5.27: Probability distribution function of island aspect ratio for the experimental scenarios of varying fluvial water discharge

FIGURE 5.28: Probability distribution function of island aspect ratio for the experimental scenarios of varying fluvial sediment discharge
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 5.29: Probability distribution function of island shape factor for the experimental scenarios of varying fluvial water discharge

FIGURE 5.29 shows that the island shape factor increases, a metric representing the degree of drainage within the islands, with increasing fluvial water discharges. This is mainly due to the decrease in island area caused by the increased bank erosion with increasing water discharge (see FIGURE 12.1 in Appendix 12). However, the increase in the frequency of island shape factor due to the decrease in fluvial water discharge was due to the increased dissection of the islands caused by the channels. FIGURE 5.30 shows no difference in distributions that means island shape factor of the islands are not sensitive to the changes in the fluvial sediment discharges.

FIGURE 5.30: Probability distribution function of island shape factor for the experimental scenarios of varying fluvial sediment discharge
**Chapter 5: The role of variations in fluvial water and sediment discharges in controlling the morphology of tidally influenced delta**

![Probability distribution function of nearest-edge distance for the experimental scenarios of varying fluvial water discharge](image)

**FIGURE 5.31:** Probability distribution function of nearest-edge distance for the experimental scenarios of varying fluvial water discharge

FIGURE 5.31 shows that the progradation of the islands at the delta front over 100 years has led to the increase in the frequency of smaller edge distance in all the fluvial discharge scenarios. The next fluctuation in the distribution is for the scenarios of low (2e) and medium (2f) water discharges. This is increased frequency in the nearest-edge distance is caused by the erosion of channel in the north-western part of the delta (see FIGURE 12.1 in Appendix 12). However, as there was no channel erosion in the high water discharge (2g) scenario (see FIGURE 12.1 in Appendix 12), no more change in the nearest edge distance can be observed. No difference in the distribution of the nearest-edge distance was observed on the scenarios of varying fluvial sediment discharges.

The results of this research are broadly consistent with the estuarine morphodynamics examined by Guo et al. (2015) under combined river and tidal forcing. Both the study by Guo et al. (2015) and this research agree that river discharge plays an important role in tidal delta morphodynamics by supplying sediment, enhancing ebb flow and modifying tidal asymmetry. Also, in both these studies, high river discharges induces ebb flow dominance and thus restrict the development of flood channels. However, the model employed by Guo et al. (2015) was purely based on sand sediment but in this thesis it is predominately fine sediment with sand, a
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

mixture that is more representative for most tide dominated deltas Goodbred and Saito (2012). However, the focus of the research by Guo et al. (2015) is to understand the morphodynamic processes over long term-millennium timescale with fluvial sediment input at equilibrium concentrations and was not on the delta metrics presented in this study. The delta metrics such as the sub-aerial delta area (See FIGURE 5.23), island shape factor, island aspect ratio, nearest-edge distance, progradation and aggradation (see FIGURE 12.1) of the delta chosen in this study have direct practical implications for studying the morphodynamic effects on ecosystem and deltaic communities.

5.4 Summary

1. How does fluvial water and sediment discharge affect tidal delta morphology?

A. Tidal asymmetry was apparent across the entire simulated delta and is highly sensitive to varying fluvial water discharges (FIGURE 5.2). The simulated ratio of the flood to ebb flow at the delta apex is 0.5 for low river discharge ($Q_w = 32,500 \text{ m}^3/\text{s}$) but 0.1 for high river discharge (3$Q_w = 97,500 \text{ m}^3/\text{s}$), respectively. This finding is significant because a smaller tidal asymmetry facilitates more sediment being imported into the delta (net volume change of $+1,597 \text{ million cu.m}$ over 100 years for low river discharge ($Q_w = 32,500 \text{ m}^3/\text{s}$) and $-1,828 \text{ million cu.m}$ over 100 years for high water discharge (3$Q_w = 97,500 \text{ m}^3/\text{s}$)), and vice versa when the tidal asymmetry is higher (FIGURE 5.9). Allison (1998b) estimated change in bathymetric volume for the GBM delta in the range of 8 to 48 million cu.m over 150 years (see Chapter 2.1.3).

B. Patterns of erosion and accretion and aggradation/degradation of the channel bed vary as a function of changing water and sediment discharges (FIGURE 12.1). These morphodynamic responses are all influenced by the tidal asymmetry and the resulting impact this has on the local balance between the sediment transport capacity of the flow and the supply rate of sediment. The numerical experiments undertaken
in this thesis show that, under relatively high tidal asymmetry and sediment transport capacity (i.e., high values of the ratio $Q_w/Q_s$) erosion and degradation dominate, whereas the lower the tidal asymmetry and sediment availability then accretion and aggradation are more likely to dominate (see FIGURE 5.4, FIGURE 5.5 and FIGURE 5.11).

C. Channel erosion and network evolution in the delta is a function of water discharge, especially the flood to ebb flow ratio. Channel erosion in conditions of low water discharge scenarios (where the water discharge, $Q_w = 32,500 \text{ m}^3/\text{s}$) is more rapid than in the case of the medium water discharge ($2Q_w = 65,000 \text{ m}^3/\text{s}$) scenarios due to the higher flood to ebb flow ratio. No channel erosion was simulated in the high water discharge ($3Q_w = 97,500 \text{ m}^3/\text{s}$) scenarios due to the ebb-dominated residual flow (see FIGURE 5.6 to FIGURE 5.8).

D. Tidal asymmetry at the mouth of distributaries increases the rate of progradation of the subaqueous delta. Progradation is more sensitive to water discharge than sediment discharge as the momentum of water discharging into the sea is a function of fluvial water discharge and low tides (see FIGURE 5.13). The delta clinoform's length and slope are also found to be a function of fluvial water discharge and the relative supply rate of sediment (see FIGURE 5.13). The slope of the clinoform's foreset decreases with increasing water discharge.

E. The delta land area increases (1.14% increase for $2Q_w:1Q_s$ and 3.96% for $2Q_w:3Q_s$) with increasing sediment discharge but decreases (8.23% increase for $1Q_w:2Q_s$ but only 0.09% increase for $3Q_w:2Q_s$) with increasing water discharge (FIGURE 5.24) and. Channel bed and bank erosion increases with fluvial water discharge and decreases with sediment discharge. Low water discharges ($Q_w = 32,500 \text{ m}^3/\text{s}$) induce more land accretion, however the simulations undertaken in this thesis show that only high water discharges ($Q_w = 97,500 \text{ m}^3/\text{s}$) cause distant sedimentation (further inland, far away from the distributaries) over the sub-aerial delta. The balance between the transport and supply of sediment during the flood flow of the tides influences the process of accretion and erosion on the sub-aerial delta. The area of sub-aerial
delta land is, therefore, directly proportional to the ratio of flood to ebb flow in a tidal cycle (FIGURE 5.24). The relative proportion of fluvial water and sediment discharge influences the residual current and sediment transport and thus the tidal delta morphodynamics.

F. The results of this research are broadly consistent with the estuarine morphodynamics examined by Guo et al. (2015) under combined river and tidal forcing. Both the study by Guo et al. (2015) and this research agree that river discharge plays an important role in tidal delta morphodynamics by supplying sediment, enhancing ebb flow and modifying tidal asymmetry. Also, in both these studies, high river discharges induces ebb flow dominance and thus restrict the development of flood channels. However, the model employed by Guo et al. (2015) was purely based on sand sediment but in this thesis it is predominately fine sediment with sand, a mixture that is more representative for most tide dominated deltas (Goodbred and Saito (2012).
6. Role of relative sea level rise on the morphodynamics of tidally influenced deltas

6.1 Introduction

This chapter reports the results of the numerical experiments, described in Section 4.4 that focused on establishing the influence of relative sea level rise (RSLR) on the morphodynamics of the simulated delta. As per the structure of Chapter 5, the following sub-sections present and explain the change firstly in the simulated residual flow and secondly on the morphodynamics of the delta under varying conditions of imposed RSLR.

6.2 Residual flow

As explained in the preceding chapter, residual flow in a tidally influenced delta is the net flow of water due to the interaction of the outgoing fluvial (freshwater) discharge and the incoming tidal discharge. In the case of diurnal tides, due to the variation of intensity in tidal discharge over time, residual flow intensity and direction both change over time. Consequently, when RSLR is superimposed on the normal tidal cycle, the interaction of fluvial and tidal discharge potentially alters the residual flow and its characteristics. The effect of back water in either direction of flow, landward and seaward, is enhanced by sea level rise as shown in FIGURE 6.1A where both the high and low water level at the delta apex is shown to increase with rising sea level. The flow velocity during high and low tides increases with RSLR, with maximum flow velocities obtained in model run 3d (RSLR=20mm/y), as shown in FIGURE 6.1B. Similar trends are obtained for water discharge with more flood and ebb flow in run 3d (RSLR=20mm/y). As the flood flow increases with RSLR, the flood:ebb flow ratio also increases with RSLR, as shown in FIGURE 6.2. Greater erosion of the bed level at the delta apex can also be seen (see FIGURE 6.1D) as RSLR increases.
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

![Graph A: Water level vs. Time]

- Water level (m)
- Time (hour)
- Water level peaks at 12:00 and drops to -1.5 at 06:00.

![Graph B: Depth averaged flow velocity vs. Time]

- Depth averaged flow velocity (m/s)
- Time (hour)
- + value = flood flow
- - value = ebb flow
- Velocity changes from +0.6 to -0.8 from 00:00 to 12:00.

![Graph C: Water discharge vs. Time]

- Water discharge (cu.m/s) Thousands
- Time (hour)
- Discharge ranges from -300 to 150
- Maximum discharge at 06:00 and minimum at 12:00.
Chapter 6: Role of relative sea level rise on the morphodynamics of tidally influenced deltas

FIGURE 6.1: Time series of modelled water level (A), velocity (B), water discharge (C), bed level (D), bed (E) and suspended load transport (F) at the delta apex for initial and after 100 years of simulation for relative sea level rise (RSLR) scenarios: Base case-2f(RSLR=0mm/y), 3a(RSLR=5mm/y), 3b(RSLR=10mm/y), 3c(RSLR=15mm/y), and 3d(RSLR=20mm/y)
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 6.2: Modelled ratio of flood to ebb flow of water and sediment for the initial condition and after 100 years for the base case (2f; RSLR = 0 mm/y) and relative sea level rise scenarios (3a: 5 mm/y, 3b: 100 mm/y, 3c: 15 mm/y, 3d: 20 mm/y).

The model simulations indicate that the flood flow entering the channel at the delta apex increases with increasing RSLR. For example, the flood: ebb flow ratio increases by up to 19% (from 0.27 to 0.33) due to an increase in RSLR of 2 m compared with value simulated in the base case scenario (2f; RSLR = 0 mm/y). This result implies that there is a gradual increase in the dominance of the tidal discharge against the fluvial discharge as RSLR increases, albeit it must still be recognised that in all simulations the ebb flow still dominates the flood flow. Rather, the key impact of the RSLR is to tend to change and influence the available accommodation space. Jervey (1988) defines accommodation space as “the space available for potential sediment accumulation”, as shown in FIGURE 6.3. The morphodynamic response at the shoreline to undergo submergence (FIGURE 6.4A) or erosion (FIGURE 6.4B) and aggradation (FIGURE 6.4C) or progradation (FIGURE 6.4D) depends on the rate of RSLR, the rate and character of sediment supply, the hydrodynamic conditions, and the resulting sediment transport capacity to deposit or erode (Swift and Thorne, 2009).
Chapter 6: Role of relative sea level rise on the morphodynamics of tidally influenced deltas

FIGURE 6.3: Sediment accommodation space and its relationship to relative sea level rise (Source: (Coe, 2003))

FIGURE 6.4: Morphodynamic response of shorelines to varying relative sea level rise and rate of sediment supply after (Posamentier, 1999)
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

**FIGURE 6.5:** Maximum flow velocity in the delta area during high and low tide of initial condition and after 100 years for base case-2f(RSLR=0mm/y) and sea level rise scenarios: (3a:5mm/y, 3b:100mm/y, 3c:15mm/y, 3d:20mm/y)

Due to the raised low and high water levels, the backwater effect increases with increasing RSLR in both flow directions, during both high and low tides, and thus reduces (seawards) flow velocities. The maximum flow velocity within the delta area during both low and high tides is shown to decrease with increasing sea level rise, as per **FIGURE 6.5**. The maximum flow velocity during low tides decreased by up to 46% relative to the initial condition due to increasing RSLR and, by the end of the simulation, is up to 40% lower than the base case scenario (2f; RSLR = 0mm/y). The maximum flow velocity during high tides decreased by up to 29% relative to the initial condition and is up to 35% lower than the base case scenario (2f; RSLR = 0 mm/y).

As the morphodynamic response of the sub-aerial delta to RSLR is influenced by the hydrodynamic conditions, it is important to analyse the flow parameters across the tidal floodplains and within distributaries. Comparing **FIGURE 6.6 A and F**, it is evident that for zero RSLR, the flow velocities during high tides in the distributaries and tidal floodplain are not significantly altered. However, **FIGURE 6.6 B to E** (with the insets plotting data at 25 year intervals) shows that there is a reduction in channel flow velocities and an increase in tidal floodplain velocities with increasing RSLR for scenario 3a (RSLR = 5mm/y).
Similar trends are also apparent in FIGURE 6.7 for RSLR scenario 3d (RSLR = 20mm/y). Compared to scenario 3a (RSLR = 5mm/y), flow velocities in scenario 3d (20 mm/y) reduce quickly in the distributary channels, whereas the magnitude of velocities over the tidal floodplain is greater in scenario 3d (RSLR = 5mm/y) than in scenario 3a (RSLR=20mm/y). The increased backwater effect in the distributaries also decreases their flow velocities. But, the increased depth of flow, due to the reduced effect of bed friction, results in increased flow velocities over the tidal floodplain. As RSLR increases, the flow area over the delta, the depth of flow within the distributary channels, and the depth and extent of flooding over the tidal floodplain all, as expected, increase. The depth and extent of tidal floodplain flooding increases with increasing RSLR as shown in FIGURE 6.9 for scenario 3a (RSLR = 5 mm/y), FIGURE 6.10 for scenario 3d (RSLR of 20 mm/y) and FIGURE 6.11 (after 100 years) for scenarios 3a to 3d. An increased depth of flooding also leads to increased accommodation space over the tidal floodplain and the increased flow results in increased sediment flow. Thus, the submergence of tidal floodplain due to RSLR thereby also induces the condition of sediment accretion or erosion (depending on the local balance between sediment transport capacity and supply) over the existing sub-aerial delta.
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 6.6: Spatial distribution of flow velocity over the delta during high tides for scenarios: Initial (A), 3a at 25y (RSLR=0.125m) (B), 3a at 50y (RSLR=0.25m) (C), 3a at 75y (RSLR=0.375m) (D), 3a at 100y (RSLR=0.5m) (E) and base case-2f at 100y (RSLR=0m) (F)
Chapter 6: Role of relative sea level rise on the morphodynamics of tidally influenced deltas

FIGURE 6.7: Spatial distribution of flow velocity over the delta during high tides for scenarios: Initial (A), 3d at 25y (RSLR=0.5m) (B), 3d at 50y (RSLR=1m) (C), 3d at 75y (RSLR=1.5m) (D), 3d at 100y (RSLR=2m) (E) and base case-2f at 100y (RSLR=0mm) (F)
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 6.8: Spatial distribution of flow velocity over the delta during high tides for scenarios: Initial (A), 3a at 100y (RSLR=0.5m) (B), 3b at 100y (RSLR=1m) (C), 3c at 75y (RSLR=1.5m) (D), 3d at 100y (RSLR=2m) (E) and base case-2f at 100y (RSLR=0mm) (F)
Chapter 6: Role of relative sea level rise on the morphodynamics of tidally influenced deltas

FIGURE 6.9: Spatial distribution of water depth over the sub-aerial delta during high tides for scenarios: Initial (A), 3a at 25y (RSLR=0.125m) (B), 3a at 50y (RSLR=0.25m) (C), 3a at 75y (RSLR=0.375m) (D), 3a at 100y (RSLR=0.5m) (E) and base case-2f at 100y (RSLR=0m) (F)
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 6.10: Spatial distribution of water depth over the sub-aerial delta during high tides for scenarios: Initial (A), 3d at 25y (RSLR=0.5m) (B), 3d at 50y (RSLR=1m) (C), 3d at 75y (RSLR=1.5m) (D), 3d at 100y (RSLR=2m) (E) and base case-2f at 100y (RSLR=0mm) (F)
Chapter 6: Role of relative sea level rise on the morphodynamics of tidally influenced deltas

FIGURE 6.11: Spatial distribution of water depth over the sub-aerial delta during high tides for scenarios: Initial (A), 3a at 100y (RSLR=0.5m) (B), 3b at 100y (RSLR=1m) (C), 3c at 75y (RSLR=1.5m) (D), 3d at 100y (RSLR=2m) (E) and base case-2f at 100y (RSLR=0mm) (F)
6.3 Morphodynamic changes

The following sub-sections outline the modelled impacts of relative sea-level rise on various morphological aspects, namely (i) the pattern of erosion and accretion, (ii) rate of progradation and aggradation of the delta, (iii) the overall sub-aerial delta area, and (iv) the number of islands and perimeter length of the islands.

6.3.1 Patterns of erosion and accretion in the delta

As discussed in the previous section, the rise in water levels due to the RSLR results in significant changes to the water depths and flow velocities simulated over the delta, including on the tidal floodplains. These perturbations to the flow hydraulics in turn perturb the morphodynamic equilibrium and the delta will therefore try to restore a new equilibrium by adjusting its morphology through processes of accretion and erosion. FIGURE 12.2 in Appendix 12 shows the simulated pattern of accretion and erosion over the delta after 100 years for various scenarios of sea-level rise, from which the following points can be summarised:

1) As RSLR increases, the deposition of sediment on the channel bed and land increases but, at the same time, erosion of islands and the land surface also increases. For the range of modelled RSLR scenarios explored in this study, net erosion is marginally greater than net accretion after 100 years of the simulation.

2) Overall, land tends to be lost on the landward side, whereas aggradation and progradation are focused at the delta front for all the scenarios.

3) Erosion of banks and sediment deposition within the channel increases with increasing RSLR and this could lead to channel thalweg shift with further RSLR.

4) The model simulations suggest that there is, under all RSLR scenarios, a continuous net accretion on the seaward side of the delta islands.

5) Feather shaped patterns of accretion over the sub-aerial delta surface are simulated under all RSLR scenarios.
Chapter 6: Role of relative sea level rise on the morphodynamics of tidally influenced deltas

These modelled patterns of accretion and erosion over the delta can be explained through reference to an understanding of the balance between the rate of sediment supply and changes in accommodation space. Both the accommodation space and rate of sediment supply vary over time and space. If increases in accommodation space dominate over the rate of sediment supply then erosion occurs, whereas if the rate of sediment supply dominates the accommodation space then accretion occurs. If the changing accommodation space is balanced by the rate of sediment supply, then sediment bypasses the delta surface with no (or few) net morphodynamic changes (Swift and Thorne, 2009).

FIGURE 6.12 and FIGURE 6.13 show the elevation of the simulated delta, both below and above Mean Sea level (MSL) for the initial conditions and at 25 years intervals for the range of modelled RSRL scenarios. It is immediately evident that the elevation of the delta surface increases with the RSLR. However, the pattern of the sub-aerial delta for the same amount of RSLR can be different see FIGURE 6.13B (well-defined pattern for RSLR of 0.5m in 100 years at the rate of 5mm/y) and FIGURE 6.12E (roughly-defined pattern for RSLR of 0.5m in 25 years at the rate of 20mm/y) as the rate of RSLR and the subsequent interaction with tidal floodplain flow varies the processes of accretion and erosion over the sub-aerial delta. The sub-plots A & B from FIGURE 12.3 to FIGURE 12.6 in Appendix 12 shows the formation of feather shaped aggradation lobes over the sub-aerial delta and the flow pattern over the tidal floodplains and channels just before and after the peak of high tides for RSLR scenario 3d (RSLR = 20 mm/y) at 25 year intervals. During the rising limb, the water is distributed over the flood plain first via the already established channels and then by submergence if the RSLR is greater than the land elevation (see sub-plot A from FIGURE 12.3 to FIGURE 12.6 in Appendix 12. A tidal floodplain can be flooded by more than one distributary and hence there will be an area, approximately near the middle of the islands, over the tidal floodplain where the water from all the distributaries meets to result in net flow or no flow where the maximum sediment deposition occurs near the slack water. During the falling limb of the tides, the flow reverses to flow back into the distributaries along the path of least flow resistance (see sub-plot B from FIGURE 12.3 to FIGURE 12.6 in Appendix 12). These flow paths gradually
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

develop around the area of deposition that builds up the land over the sub-aerial delta and the zone of erosion due to the increased sediment transport capacity. This process repeats during each rising and falling limb of tides to establish an elevated land with the highest elevation far from the distributaries and surrounded by flow channels. The width and depth of the flow channels increases with RSLR as shown in the sub-plots A & B from FIGURE 12.3 to FIGURE 12.6 in Appendix 12.

FIGURE 6.14 compares the elevation of the delta surface after 100 years of the simulation under all the various RSLR scenarios explored here. It can be observed from FIGURE 6.14 that the elevation of the delta, especially the tidal floodplain and channel bed, increases with an increasing rate of RSLR whereas the area of land above mean sea level declines as the rate of sediment supply is in all cases dominated by the greater increase in accommodation space. The interaction of floodplain and channel flow during the rise and fall of the tides is also a significant driver of bank erosion along the distributary channels. The shape of the islands that remain above the sea level is influenced by the series of processes of accretion and erosion over the tidal floodplain and the nearest distance between points in the land to the water. The point of land furthest from the distributaries remains relatively less submerged with increasing relative sea level rise compared to the land nearest to the distributaries.
Chapter 6: Role of relative sea level rise on the morphodynamics of tidally influenced deltas

FIGURE 6.12: Elevation of the delta for scenarios: Initial (A), 3a at 25y (RSLR=0.125m) (B), 3a at 50y (RSLR=0.25m) (C), 3a at 75y (RSLR=0.375m) (D), 3a at 100y (RSLR=0.5m) and base case-2f at 100y (RSLR=0m) (F)
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

**FIGURE 6.13:** Elevation of the delta for scenarios: Initial (A), 3d at 25y (RSLR=0.5m) (B), 3d at 50y (RSLR=1m) (C), 3d at 75y (RSLR=1.5m) (D), 3d at 100y (RSLR=2m) and base case-2f at 100y (RSLR=0mm) (F)
Chapter 6: Role of relative sea level rise on the morphodynamics of tidally influenced deltas

FIGURE 6.14: Elevation of the delta for scenarios: Initial (A), 3a at 100y (RSLR=0.5m) (B), 3b at 100y (RSLR=1m) (C), 3c at 75y (RSLR=1.5m) (D), 3d at 100y (RSLR=2m) and base case-2f at 100y (RSLR=0mm) (F)
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 6.15: Net volume of accretion and erosion against the depth of accretion and erosion after 100 years for scenarios: Base case-2f(SLR=0mm/y), 3a(SLR=5mm/y), 3b(SLR=10mm/y), 3c(SLR=15mm/y), 3d(SLR=20mm/y)
Chapter 6: Role of relative sea level rise on the morphodynamics of tidally influenced deltas

The net volume of accretion, as shown in FIGURE 6.15, increases with increasing RSLR, with the locus of accretion prominent in water depths between 10 and 20m in particular. Accretion in this depth range can be associated with aggradation and progradation of the islands at the delta front. Thus, the accommodation space created at the delta front, for all the RSLR scenarios considered here, is dominated by the rate of sediment supply and thus triggering aggradation and progradation (see FIGURE 12.2 in Appendix 12). The net volume of erosion increases for depths greater than 10m with increasing RSLR (see FIGURE 6.15), but decreases for depths smaller than 10m with increasing RSLR. The increase in net volume of erosion with increasing RSLR is mainly associated with greater bank (see FIGURE 12.2 Appendix 12) and landward (see FIGURE 6.19) erosion of the islands.

FIGURE 6.16A shows that the cumulative volume of accretion over the subaerial delta, distributaries bed and at the delta front is greatest for the highest sea level rise scenario explored here (scenario 3d; RSLR = 20 mm/y) and least for the zero RSLR (base case) scenario. Similarly, the cumulative volume of erosion is greatest for the highest sea level rise scenario (3d; RSLR = 20 mm/y) and least for the zero RSLR (base case) scenario (see FIGURE 6.16 B). This implies that greater accommodation space is created for the higher relative sea-level rise scenarios. However, the time series of cumulative volume of change for the zero RSLR (base case) scenario is always greater than in the RSLR scenarios considered here, see FIGURE 6.16C. Also, the cumulative volume of change always results in net accretion in the zero RSLR (base case) scenario.

The model simulations highlight that for the delta building process in the first 25 years of the simulations, FIGURE 6.16C, the rate of sediment supply is greater than the accommodation space created over the delta, as the net volume of change shows an increasing and positive trend. In the second 25 years and thereafter the accommodation space created is greater than the rate of sediment supply, resulting in a more destructive phase (see FIGURE 6.16C) for the high RSLR scenarios 3b (10 mm/y), 3c (15 mm/y) and 3d (RSLR = 20 mm/y) resulting in a shift from net accretion phase to net erosion phase. Greater the rate of RSLR than quicker the shift whereas for the lower sea-level
rise scenario 3a (RSLR = 5 mm/y), on the other hand, a steady state delta building process is reached in the second 25 year simulation period (see FIGURE 6.16C) and then subsequently the delta building process declines at a much slower rate than the other higher RSLR scenarios. The overall rate of the delta building process decreases increases with increasing RSLR. Time series of sub-aerial delta area (see FIGURE 6.23 in section 6.3.3) exhibit a similar trend to the one shown in FIGURE 6.16.
Chapter 6: Role of relative sea level rise on the morphodynamics of tidally influenced deltas

FIGURE 6.16: Cumulative volume of accretion (A), erosion (B) and net change (C) in the delta for scenarios (Basecase (0mm/y), 3a:5mm/y, 3b:100mm/y, 3c:15mm/y, 3d:20mm/y)
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

![Graph A: Elevation vs. Area with different cases and conditions.]

![Graph B: Elevation vs. Sub-aerial delta area with different sea level rise scenarios.]

- Base case 100y
- 3a100y
- 3d100y
- Initial condition

- 0mm/y
- 5mm/y
- 10mm/y
- 15mm/y
- 20mm/y
- Initial condition

- MSL=2m
- MSL=1m
- MSL=0m
Chapter 6: Role of relative sea level rise on the morphodynamics of tidally influenced deltas

FIGURE 6.17: Hypsometric curve showing area vs elevation of the delta for scenarios: Initial and after 100 years for Base case-2f (RSLR=0mm/y), 3a (RSLR=5mm/y) and 3d (RSLR=20mm/y) (A) over sub-aerial and sub-aqueous delta, (B) over and near sub-aerial delta, (C) time series of delta land building trajectory as a function of rate of sea level rise.

FIGURE 6.17A shows the hypsometric curve for selected RSLR scenarios. The green circled area in FIGURE 6.17A shows how erosion and accretion reshaped the slope of the bathymetry between -15m and -30m water depth after 100 years for RSLR scenarios of zero, 5 mm/y and 20 mm/y RSLR. FIGURE 6.17B shows that the aggradation over the initial sub-aerial delta increases with increasing RSLR. After 100 years of simulation time there is little or no change in the elevation-area relationship for the base case scenario of zero sea level rise, but aggradation and the slope of the sub-aerial delta terrain increases with increasing RSLR. Hypsometric curve (FIGURE 6.17B) shows the natural delta building process with increasing sea level rise. FIGURE 6.17C shows the trajectory of natural deltaic land building process over the initial sub-aerial delta for the range of RSLR scenarios considered here. The state of the modelled delta began to lose the initial sub-aerial delta straightaway for the RSLR rates of 20 and 15mm/y. But after 50 years of simulation, as the rate of sediment supply exceeded the accommodation space created by RSLR, the state of the delta for the RSLR rate scenario of 20mm/y first enters into sediment accumulation phase and then followed by 15mm/y. Similar trend will
be followed by the RSLR rate scenarios of 10 and 5mm/y rate beyond 100 years. This implies that higher the rate of RSLR, then faster the state of the delta land building process will be. Because initially channels are undergoing morphodynamic adjustment in the form of bank erosion due to sea level rise but once the water level has reached above the tidal floodplain, aggradation over the sub-aerial delta increases whereas the accretion at the delta front happens throughout the SLR. The rate of submergence or erosion increases with the increasing rate of sea level rise. Hence, greater the rate of sea level rise than rapid the phase of delta adjustment in undergoing erosion and aggradation (FIGURE 6.17C). After 100 years of simulation, the scenario of 0mRSLR has reached equilibrium however other RSLR scenarios will only reach equilibrium beyond 100 years. But in the real world, the rate of sea level rise may not be constant over space and time. These results show the natural ability of the modern deltas to adapt to sea level rise. But, we may not see these happening in most real deltas because of structural interventions (See Chapters 8 and 9).

6.3.2 Progradation and aggradation of the delta

![Diagram](image)

FIGURE 6.18: Ground elevation and bathymetry for the base case scenario (2f;RSLR=0mm/y) after 100 years of simulation. Location plan of longitudinal and cross sections of delta
Chapter 6: Role of relative sea level rise on the morphodynamics of tidally influenced deltas

FIGURE 6.19: Longitudinal section of the delta through its centre (x-x) for various sea level rise scenarios after 100 years: 3a (RSLR=0.5m @ 5mm/y), 3b (RSLR=1m @ 10mm/y), 3c RSLR=1.5m @15mm/y), 3d (RSLR=2m, 20mm/y) 2f-basecase (RSLR=0). See FIGURE 6.18 for the location of longitudinal section line x-x.

FIGURE 6.19 shows that the progradation and aggradation of the delta increases with increasing RSLR, as the rate of sediment supply dominates the accommodation space created by the RSLR. The clinoform of the delta looks similar for all the RSLR scenarios explored here. Also, the clinoform angle of these sea level rise scenarios did not show any difference. However, FIGURE 6.19 and FIGURE 6.21 show that both land and bank erosion increase with increasing RSLR. Tidal asymmetry, RSLR, the availability of accommodation space and the rate of sediment supply all influence the deltaic progradation and aggradation for the reasons explained in sections 6.2, 6.3.1 and 6.3.3. Increasing sediment transport of flow with increasing RSLR leads to increased erosion of the island’s bank and land and increased progradation. FIGURE 6.19 indicates that the delta front received the sediment supply exceeding the
accommodation space.

FIGURE 6.20: Cross section of the delta at location 1-1 See FIGURE 6.18 for location

FIGURE 6.21: Cross section of the delta at location 3-3 See FIGURE 6.18 for location

6.3.3 Subaerial delta - area, shape and number of islands

The model simulations clearly indicate that the flood flow increases with sea level rise, which in turn causes an increased back water effect and thus increased land submergence during high tides, as discussed in section 6.2. The extent and depth of flooding is a function of RSLR as shown in 6.2 and thus can influence the rate of accretion and erosion over the sub-aerial delta (see section 6.3.1). Indeed, the greater the depth of flooding then the greater the accommodation space that is created over the sub-aerial delta. If the rate of sediment supply dominates the accommodation space over the tidal floodplain, it results in accretion over the land, but otherwise erosion of the
Chapter 6: Role of relative sea level rise on the morphodynamics of tidally influenced deltas

Land surface dominates. Figure 6.22 shows the time series of accretion and erosion over the sub-aerial delta for the sea-level rise scenarios considered herein. Accretion here includes sediment deposition over the sub-aerial delta, whereas erosion includes erosion of channels/islands, bank and land erosion. The area of accretion and erosion over the sub-aerial delta (see Figure 6.22 A & B) is lower in the base case than for any of the other sea level rise scenarios, and the rate of accretion and erosion increases with relative sea level rise (see Figure 6.22 C & D). The land area experiencing accretion and erosion and the magnitude of accretion and erosion all increase in the first 40 years and then decrease to more or less a steady state and converge. The land area over which accretion/erosion occurs is greater in scenario 3d (RSLR = 20 mm/y) initially but decreases over time to become the smallest, whereas it is other way around for scenario 3a (RSLR = 5 mm/y) (see Figure 6.22 A & B). Also, the maximum deposition occurs at a point inland that is farthest from the channel during high tides as the rate of sediment supply exceeds the rate of sediment transport. As the process of accretion and erosion occurs over the tidal floodplain continuously over the RSLR, the extent and depth of flooding and flow velocities will vary over time and space as described in section 6.2 and its interaction with the flow of water between the tidal floodplain and distributary channels will vary over space and time during the rise and fall of tides.
FIGURE 6.22: Area and mean rate of accretion and erosion over sub-aerial delta Note: Base case-2f (RSLR= 0mm/y), 3a (RSLR=5mm/y), 3b (RSLR=10mm/y), 3c (RSLR=15mm/y) and 3d (RSLR=20mm/y)
FIGURE 6.23 shows the time series of sub-aerial delta area over the 100 years of the simulation period for all the sea-level rise scenarios explored herein. As the sea level rises, the sub-aerial delta area shrinks (see FIGURE 6.23 and FIGURE 6.24). The existing sub-aerial delta undergoes submergence due to RSLR, leading to severe land aggradation and erosion, with the latter dominating the former during the RSLR. However, aggradation leads to increases in land elevation that remain above the raised sea level. Aggradation over the submerged tidal plain occurs when the rate of sediment supply exceeds the accommodation space created by RSLR. But, if the rate of sediment supply is less than the created accommodation space, RSLR leads to the loss of the sub-aerial delta. Both the accommodation space created by RSLR and the rate of sediment supply varies over time and space over the delta. The shrink in area implies the rate of aggradation cannot keep pace with the rate of RSLR. The initial delta land area shrinks by 17%, 30%, 40%, and 50% after 100 years for RSLR values of 0.5m (3a), 1.0m (3b), 1.5m (3c) and 2.0m (3d), respectively. For the base case scenario with no sea-level rise there is almost no land above 2m (see FIGURE 6.25), whereas 50% of the initial sub-aerial delta area would still exist above 2m for the sea level rise scenario 3d (RSLR = 20 mm/y) due to the additional aggradation over the tidal floodplain. Sea level rise leads to rapid inundation of lowland but with highlands growing prominently over the deltaic islands as shown in FIGURE 6.12,FIGURE 6.13, and FIGURE 6.14.
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 6.24: Percentage change in initial sub-aerial delta area after 100 years as a function of relative sea level rise for scenarios: Base case-2f (RSLR= 0mm/y), 3a (RSLR=5mm/y), 3b (RSLR=10mm/y), 3c (RSLR=15mm/y) and 3d (RSLR=20mm/y)

FIGURE 6.25: Elevation vs sub-aerial delta area relationship for base case (2f; RSLR=0mm/y) after 100 years
Chapter 6: Role of relative sea level rise on the morphodynamics of tidally influenced deltas

FIGURE 6.26: Probability distribution function of island size normalised to total island area for the experimental scenarios of varying rates of sea level rise

FIGURE 6.27: Probability distribution function of island shape factor for the experimental scenarios of varying rates of sea level rise

FIGURE 6.26 shows that the number of islands increases with increasing sea level rise i.e., sea level rise leads to increase in the number of bifurcations. Also, it can be seen that the number of bigger islands decreases with increasing sea level rise (see FIGURE 12.2 in Appendix 12). FIGURE 6.27 shows that the modal of the distribution function increases with increasing sea level rise. It can be seen that the degree of drainage increases with the increasing
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

sea level rise. This is mainly because of the increase in the perimeter (FIGURE 6.31) and decrease in the area of the islands (FIGURE 6.23). These geometrical changes of the islands are due to the pattern formed by the process of aggradation and erosion or submergence due to sea level rise. This pattern of evolved islands due to the sea level rise has resulted in the increase of island aspect ratio as shown in FIGURE 6.28 that means the shape of the islands have changed from more circular to elongate (see FIGURE 12.2 in Appendix 12).

FIGURE 6.28: Probability distribution function of island aspect ratio for the experimental scenarios of varying rates of sea level rise

FIGURE 6.29: Probability distribution function of nearest-edge distance for the experimental scenarios of varying rates of sea level rise
Chapter 6: Role of relative sea level rise on the morphodynamics of tidally influenced deltas

FIGURE 6.29 shows that the nearest-edge distance decreases as the aggradation and erosion or submergence of the land due to the sea level rise leads to a number of smaller islands. For the same reason, as expected, the tail of the nearest-edge distance for the sea level rise scenarios is smaller than the base case, zero sea level rise scenario. This indicates that the channel density increases with increasing SLR.

FIGURE 6.30: Time series of number of deltaic islands in sub-aerial delta for sea level rise scenarios: Base case-2f (RSLR= 0mm/y), 3a (RSLR=5mm/y), 3b (RSLR=10mm/y), 3c (RSLR=15mm/y) and 3d (RSLR=20mm/y)

FIGURE 6.30 shows that the number of delta islands also increases with increasing RSLR. This is because the continuous processes of accretion and erosion over the sub-aerial delta and the associated submergence of land leads either to the formation of new, smaller, islands or the splitting of a large land mass into a number of smaller islands. However, the submergence of the existing sub-aerial delta, the increased flood flow and the evolved flow pattern over tidal floodplain due to RSLR lead to a non-linear relationship between RSLR and the number of deltaic islands, as explained in section 6.3.1.
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 6.31: Plot of island shape factor in sub-aerial delta for sea level rise scenarios: Base case-2F (RSLR= 0mm/y), 3a (RSLR=5mm/y), 3b (RSLR=10mm/y), 3c (RSLR=15mm/y) and 3d (RSLR=20mm/y)

FIGURE 6.31 shows that the island shape factor, a metric representing the degree of drainage, increases with increasing sea level rise mainly due to the pattern of aggradation and erosion or submergence of islands due to the sea level rise (see section 6.3). This led to the increase in the perimeter and decrease in the sub-aerial delta. FIGURE 6.31 shows the natural morphodynamic response of delta to RSLR but these processes may be hindered or altered by the structural interventions (See Chapters 8 and 9).

6.4 Discussions

Generally, the modelled processes of delta land building due to relative sea level rise in this study agrees with the hypothesis (FIGURE 3.7) by Woodroffe et al. (2006) where inundation of the sub-aerial delta, erosion of the banks and redeposition over the sub-aerial delta are predicted. In addition to the processes identified, the modelled delta also undergoes the deposition of river sediment over the inundated sub-aerial delta. Though a qualitative understanding of the deltaic response to the sea level rise can be achieved in this study, an estimation of the required amount of sediment to the modern delta to cope with the predicted RSLR over this century as estimated by Blum and Roberts (2009) cannot be performed in this study. The modelled delta in
this study shows that the intertidal zone gains elevation due to the sea level rise (FIGURE 6.12 to FIGURE 6.14) and then it is hypothesised here, based on Townend and Pethick (2002), that the intertidal storage volume of the delta will be reduced, which will then lead to the switching back to ebb dominance of flow from flood dominance that was caused by the sea level rise.

6.5 Summary

1. What is the role of relative sea level rise (RSLR) in delta building?

A. The following relative sea level rise (RSLR) scenarios: RSLR = 5mm/y, 10mm/y, 15mm/y and 20mm/y were considered and compared against a base case scenario of zero RSLR. It was found that residual flow over the delta is altered by the magnitude of relative sea level rise, with the magnitude of the back water effect (and thus water levels and the ratio of flood to ebb flow – with up to a 19% increase for RSLR of 2m over 100 years) increasing with increasing RSLR (FIGURE 6.1).

B. Flow velocities within the distributary channels decrease with increasing RSLR because of back water effects (velocities are decreased by up to 46% of their initial value for RSLR of 2m over 100 years), whereas the flow velocities over the delta land surface increase (from zero to up to 0.1m/s) with increasing RSLR due to the reduced effect of bed friction (FIGURE 6.6 to FIGURE 6.8). Water depth, and thus the accommodation space over the delta, including on the tidal floodplains, increases with RSLR (FIGURE 6.9 to FIGURE 6.11).

C. Both the accommodation space and the rate of sediment supply vary over time and space with varying RSLR. If the accommodation space dominates over the rate of sediment supply then erosion occurs, but if the rate of sediment supply dominates over the accommodation space then accretion occurs. If the accommodation space is balanced by the rate of sediment supply, then sediment by-passes leaving no significant morphodynamic change (FIGURE 12.2 in Appendix 12).
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

D. As RSLR increases, the deposition of sediment on the channel bed and land increases (cumulative accretion is 28% greater than the base case for RSLR of 2m after 100 years) but, at the same time, erosion and submergence of delta islands also increase (with a cumulative erosion 30% greater than the base case for RSLR of 2m after 100 years) (FIGURE 6.16). With increasing RSLR, this response leads to a shift of the channel thalweg (FIGURE 12.2 in Appendix 12). Overall, land tends to be lost on the landward side, whereas aggradation and progradation are focused at the delta front, for all the scenarios investigated in this study. Feather shaped patterns of accretion over the sub-aerial delta surface are simulated, FIGURE 6.12 and FIGURE 6.13) under all RSLR scenarios investigated in this thesis.

E. Progradation and aggradation of the delta was found to increase with increasing RSLR as the rate of sediment supply dominates over the accommodation space created by the increasing RSLR (FIGURE 6.19).

F. The number of delta islands (an increase of 150% of the initial value after 100 years for RSLR of 2m) and the perimeter of those islands increase with increasing RSLR (FIGURE 6.25). Whereas the sub-aerial delta area shrinks (by 50% of the initial delta area after 100 years for RSLR of 2m) with increasing RSLR (FIGURE 6.23) as the accommodation space dominates over the rate of sediment supply. This finding highlights that considerable volumes of sediment are required to offset the impacts of RSLR.

G. With the help of a numerical model, van der Wegen (2013) showed that in tidal basins, sea level rise alters tidal asymmetry and the basin shifts from exporting to importing sediment with the formation of shoals moving landward. The model results for sea level rise in this thesis reveal similar processes to those discussed by van der Wegen (2013), with rapid inundation of lowland but with highlands growing prominently over the deltaic islands. Similarly, the planform evolution of the deltaic islands and distributaries (FIGURE 6.12 and FIGURE 6.13) to the sea level rise scenarios explored in this thesis agrees with empirical findings by Stefanon et al. (2012) who demonstrated that change in tidal
Chapter 6: Role of relative sea level rise on the morphodynamics of tidally influenced deltas

prism due to sea level rise on a pure tidal channel network strongly influences the channel cross-sectional areas, network structure and its drainage density. However, the findings in this thesis are at the scale of a tidal delta and include the tidal interaction with fluvial discharge rather than at a tidal channel level without fluvial interactions.
Chapter 7: Impact of human interventions and land cover on tidally influenced deltas

7. Impact of human interventions and land cover on tidally influenced deltas

7.1 Introduction

This chapter presents findings from a series of numerical experiments that are designed to evaluate how common management interventions, such as polders, cross-dams and the use of rough land cover, may impact morphological evolution. As well as modelling fluvial and marine processes, the methodology adopted in this study allows an investigation of the role of realistic human interventions on the delta. The following sections present the results from those numerical experiments, as well as discussing the associated processes and morphodynamic changes.

7.2 Influence of Polders

7.2.1 Residual flow

FIGURE 7.1 X and Y shows the simulated flood:ebb flow ratio over the delta domain for the base case (scenario 2f- no polders) and a scenario (4a) with polders. It is evident that the flood:ebb flow ratio is smaller in scenario 4a (with polders) than in the base case (2f- no polders) scenario. The reduction in the flood:ebb flow ratio indicates that there is an increase in tidal asymmetry when polders are introduced. It should be noted that in the model scenario 4a (with polders) water is not allowed to overtop or breach the polders and the polderised banks are assumed to be non-erodible. Hence, any morphodynamic changes that are induced by changes in the hydraulic regime will only be manifest in the regions outside of the polderised sub-aerial delta. Considering the observation points 4 and 5 in FIGURE 7.2, it is evident that the morphological response at these locations follows a different trend from other locations within the simulated delta. This is because the amount of water that was originally flooding the tidal plains now, in scenario 4a (with polders), stays and leads to higher water levels and therefore increased ebb flow within the
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

distributaries when the tide is receding. This interpretation is supported by FIGURE 7.2B, which shows greater flow velocities within the distributaries during low tides in scenario 4a (with polders) when compared to both the initial condition (see FIGURE 7.2) and the base case (2f- no polders) scenario, see FIGURE 7.2C. A similar trend can also be observed during high tides (see FIGURE 7.2 E and F). The enhanced flow velocities during high tides in scenario 4a (with polders) results from an increased water depth and reduced bed friction effect. FIGURE 7.3 E and F also shows the greater extent and depth of flooding after 100 years over the tidal floodplain in the islands at the delta front and elsewhere for the base case (2f-no polders scenario) relative to scenario 4a (with polders).

FIGURE 7.4 and FIGURE 7.5 provide comparisons of the water to sediment discharge ratio (Qw/Qs) between the scenarios with (4a) and without (2f) polders. The ratio Qw/Qs provides an indication of the sediment transport capacity of the flow, with lower values indicating a smaller transport capacity. When polders are introduced the results indicate that Qw/Qs was increased by up to two times, during flood and ebb flows, as compared to the no polders scenario (2f), see FIGURE 7.4 and FIGURE 7.5. While the magnitude of Qw/Qs between the flood and ebb flow is nearly equal, the duration of the flood flow phase is only 50% that of the ebb flow, resulting in ebb dominated flow. Furthermore, the introduction of polders causes a shift in tidal phase due to all the water staying within the distributaries during the flood phase. The increased volume of water and greater water depth in the distributaries, along with the reduced bed friction, causes the increased Qw/Qs ratio, thus increasing the sediment transport capacity of flow in the polderised scenario (4a).
Chapter 7: Impact of human interventions and land cover on tidally influenced deltas

FIGURE 7.1: Location of tidal flow observation points (brown colour) and spatial distribution of tidal flood to ebb flow ratio (blue colour) in the delta after 100 years for scenarios: (X) – basecase (2f- no interventions) and (Y) – 4a (With polders)
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 7.2: Spatial distribution of flow velocity over the delta during low tides for scenarios: Initial (A), 4a (with polders) at 100y (B), and base case-2f (no interventions) at 100y (C) and during high tides for scenarios: Initial (D), 4a (with polders) at 100y (E), and base case-2f (no interventions) at 100y (F)
FIGURE 7.3: Spatial distribution of water depth over the sub-aerial delta during high tides for scenarios: Initial (A), 4a (with polders) at 25y (B), at 50y(C), at 75y (D), at 100y (E), and base case-2f (no interventions) at 100y (F)
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 7.4: Ratio of water to sediment discharge for scenarios: basecase (2f- no interventions) and 4a (with polders) at observation points 2 (A), 15 (B), 6(C). See FIGURE 7.1 for the locations of the identified observation points
FIGURE 7.5: Ratio of water to sediment discharge for scenarios: basecase (2f-no interventions) and 4a (with polders) at observation points 8 (A), 9 (B), 12 (C). See FIGURE 7.1 for the locations of the identified observation points.
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

7.2.2 Patterns of erosion and accretion over the delta

FIGURE 12.7A1 and B1 in Appendix 12 shows the morphodynamic changes after 100 years for the base case (2f-no polders) and polders (4a) scenarios, respectively. The fact is that there is no flow of water into the polderised area and no erosion of island bank within the sub-aerial delta. FIGURE 12.7B1 in Appendix 12 shows that there is erosion of the channel bed within the distributary channels and sediment deposition on the seaward side of the prograding islands. FIGURE 12.7B2 in Appendix 12 shows the difference in the simulated patterns of erosion and accretion over the delta for the two scenarios with and without polders. The following differences are evident:

1) Erosion of the bed of the distributary channels in scenario 4a (with polders) is greater than (by 200 million m$^3$) the base case scenario (2f-no polders).
2) The polderised area of the prograding islands at the delta front is deprived of sediment in the polders scenario (4a).
3) Within the polderised area of other islands, both accretion and erosion along the edges/near the banks of the islands occur in the base case (2f-nopolders) scenario, but not in scenario 4a (with polders).
4) No channel erosion is predicted in scenario 4a (with polders) but instead accretion is simulated at the head of minor distributaries.
5) Greater net accretion (by 591 million m$^3$ when compared to scenario 2f-no polders) is simulated towards the sea in scenario 4a (with polders).

The above differences can be explained as follows. Since polders prevent the flooding of the embanked area, excess water stays within the distributary channels. This additional water has the effect of increasing the sediment transport capacity of the flows within the distributary channels, as described in section 7.2.1. This, in turn, leads to greater bed erosion of the major distributary channels and the increased sediment volumes conveyed in the distributary channels are discharged at the mouths of these distributaries, causing more sediment deposition at the delta front than in the base case (scenario 2f-no polders). Wherever the rate of sediment supply exceeded the sediment transport capacity of the flow net accretion occurs.
FIGURE 7.6 B2 shows that there is less net erosion in water depths greater than 5m in scenario 4a (with polders) as compared to the basecase (no polders) scenario, see FIGURE 7.6 A2. This is because no bank or land erosion of the embanked area is allowed in scenario 4a (with polders). However, the increased erosion in water depths less than 5m can be seen clearly. This increased erosion could be associated with erosion of the bed of the distributary channels. The net volume of accretion for scenario 4a (with polders) is marginally smaller than in the basecase (2f-nopolders) scenario for all flow depths. This is due to the area over which accretion can occur in the basecase (2f-no polders) scenario being greater than for the polders (4a) scenario. Most of the accretion in both scenarios is located on the islands prograding at the delta front and towards the sea, as shown on FIGURE 12.7 in Appendix 12.

FIGURE 7.6: Net volume of accretion and erosion against the depth of accretion and erosion after 100 years for scenarios: Base case-2f(no human interventions), and 4a (with polders)
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 7.7: Elevation of the delta for scenarios: Initial (A), 4a (with polders) at 25y (B), at 50y (C), 75y (D), at 100y (E) and base case-2f (no human interventions) at 100y (F)
Chapter 7: Impact of human interventions and land cover on tidally influenced deltas

7.2.3 Progradation and aggradation of the delta

FIGURE 7.8: Ground elevation and bathymetry for the base case scenario (2f; no human interventions) after 100 years of simulation. Location plan of longitudinal and cross sections of delta.

FIGURE 7.9: Longitudinal section of the delta through its centre (x-x) for scenarios: Initial, base case (2f- no human interventions) and with polders (4a). FIGURE 7.8 for location X-X.
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 7.10: Cross section of the delta at locations 1-1 (A), 2-2 (B) and 3-3 (C) for scenarios: Initial, base case (2f - no human interventions) and with polders (4a). See FIGURE 7.8 for location of cross-sections.

FIGURE 7.9 compares the elevation of the delta along a profile located on the centre line shown in FIGURE 7.8. The data in this figure shows that
progradation of the sub-aqueous delta and progradation of the islands at the delta front in the scenario (4a) with polders is marginally lagging behind the base case scenario (2f) due to the greater sediment transport capacity (increased Qw/Qs ratio) in the ‘with polders’ scenario, as shown in FIGURE 7.4 and FIGURE 7.5.

Deepening and widening of the distributary channels is common in both scenarios. However, the green dashed circles in FIGURE 7.10 show that the distributary channels are deeper in scenario 4a (with polders) than in the base case scenario (2f - no polders), again due to the increased sediment transport capacity in the former versus the latter.

7.2.4 Morphodynamic changes of the sub-aerial delta

FIGURE 7.11 A and C shows, respectively, the distribution of accretion and erosion simulated over the sub-aerial delta. As no accretion or erosion of the poldered area is possible in scenario 4a (with polders), the area of the sub-aerial delta over which accretion and erosion occurs is much smaller than in the base case (2f - no polders) scenario. Hence, any accretion or erosion over the sub-aerial delta is restricted to the areas outside of the polderised regions. Both the area and rate of erosion and accretion for scenario 4a (with polders) are less than in the base case (2f - no polders) scenario throughout the 100 years duration of the simulations investigated in this thesis. The area and rate of accretion (FIGURE 7.11 A and B) increases in the first 50 years and after that they decrease and become steady. The area of erosion gradually increases over time and nearly reaches steady state after 75 years (FIGURE 7.11 C). Only after 75 years does the area of erosion become greater than the area of accretion (FIGURE 7.11 A and C). The rate of erosion remains steady throughout the period (FIGURE 7.11 D) and is smaller than the rate of accretion during the first 50 years, becoming nearly equal after that time (FIGURE 7.11 B and D). This is because in scenario (4a - with polders), the accretion and formation of the sub-aerial delta outside the embanked area has to happen first to cause the erosion of the sub-aerial delta, since the embanked areas are prevented from experiencing erosion. As described in section 7.2.2, when the rate of sediment supply is greater than the sediment transport capacity of flow,
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

Accretion of the sub-aerial delta occurs. As the delta front and head of the distributaries are those areas where the rate of sediment supply can generally exceed the sediment transport capacity, due to the reduced momentum of the flow, they are the only areas where net accretion occurs.
Chapter 7: Impact of human interventions and land cover on tidally influenced deltas

FIGURE 7.11: Area and mean rate of accretion and erosion over sub-aerial delta for scenarios: 4a (polder), 4b (cross-dam), 4c (higher roughness land cover) and base case (2f-no interventions)
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 7.12: Comparison of sub-aerial delta land constructed between the initial state and after 100 years of the simulation for the polders (4a) scenario. The net change in sub-aerial delta extent over this time period for this polders scenario is +92 km², compared to the initial delta extent of 694 km².

FIGURE 7.12 shows the land boundary of the sub-aerial delta at the initial point of the simulation and after 100 years of the simulation for the scenarios without and with polders. It is evident that, due to the presence of polders and restricted bank erosion, no net erosion and only minor net accretion of the sub-aerial delta has occurred. This net land accretion is gained in the form of progradation and deposition at the head of the minor distributaries. Wherever the rate of sediment supply exceeded the sediment transport of the flow, net accretion occurred (see section 7.2.1 and 7.2.2). FIGURE 7.13 shows time series of the sub-aerial delta area for the two scenarios. In the case of polders, the rate of increase in sub-aerial delta area is greater in the first 50 years and, with reduced rate, is nearly reaching equilibrium after 100 years. The increase of 12% in sub-aerial delta area from the initial area after 100 morphological years was mainly due to the progradation of the delta lands gained due to the siltation at the head or landward end of the minor distributaries and prevention of land and bank erosion. Poldered areas were not subjected to any
accretion or erosion in the model, however in the real world this may not be the case. For these reasons, the sub-aerial delta area in scenario 4a (with polders) is greater than the base case (2f- no polders) scenario, by about 10%.

**FIGURE 7.13:** Time-series of simulated sub-aerial delta area for scenarios with human interventions: 4a (with polders) and 4b (with cross-dams) and 4c (higher roughness land cover) compared with base case scenario (2f- no interventions)

**FIGURE 7.14:** Time-series of sum of sub-aerial delta islands perimeter for scenarios with human interventions: 4a (with polders) and 4b (with cross-dams) and 4c (higher roughness land cover) compared with base case scenario (2f- no interventions)
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 7.14 shows the time series of the perimeter of the sub-aerial delta. The perimeter of the sub-aerial delta provides a measure of the roughness of the coast, with the greater the value meaning the greater the roughness and vice versa. In scenario 4a (with polders), prevention of channel erosion and accretion at the head of minor distributaries reduces the perimeter of the islands whereas the accretion of the prograding islands on the seaward side increases the perimeter. These processes lead to a net increase in perimeter length for scenario 4a (with polders) after 25 years and is increased by 6% after 100 years. When compared to the base case (2f- no polders) scenario, a smaller perimeter (6% increase vs 22%) with a larger sub-aerial delta area (13% increase vs 3%) is achieved in scenario 4a (with polders).

7.2.5 Discussions

Consistent with the findings of Pethick and Orford (2013) and Elias and van der Spek (2006), the model results in this thesis shows that tidal asymmetry (FIGURE 7.1) increases by reduced frictional damping and an increased rate of channel convergence due to the polders. As reported in FIGURE 12.7 in Appendix 12, it has been hypothesised in the CEGIS (2009) report that the net accretion and progradation in the Meghna Estuary (see FIGURE 9.15) over the last 50 years are could be due to the excessive sediments outside the polders. Similar to the observation by Falcini et al. (2012), sediment is discharged far into the sea in the model with polders (See FIGURE 12.7B1 in Appendix 12 with polders) than (See FIGURE 12.7A1 in Appendix 12 without polders) without the polders. Despite the reworking of the sediment discharged into the sea is carried out by the tides in the modelled ideal delta, the effect of polders on discharging the sediment far into the sea can be seen (See FIGURE 12.7B2 in Appendix 12).

7.3 Influence of Cross-dams

7.3.1 Residual flow

FIGURE 7.15 shows the flood:ebb flow ratio for cases with (scenario 4b) and without (scenario 2f) cross-dams. It is evident that the effect of introducing cross dams is to significantly increase the value of the ratio (see FIGURE 7.15
Chapter 7: Impact of human interventions and land cover on tidally influenced deltas

Y), such that with cross dams the flood and ebb flows are equalised in the distributaries with cross-dams. Elsewhere, the value of the ratio is decreased, meaning there is a greater ebb and smaller flood flow. This is presumably because cross-dams do not allow the flow of water through, reducing the flow velocities in the distributaries where cross-dams are located (see FIGURE 7.18 during low tide and FIGURE 7.19 during high tide), inducing a back water effect. This back water effect results in diversion of flow to other distributaries in the delta and increased water discharges and flow velocities (see FIGURE 7.18 during low tide and FIGURE 7.19 during high tide) there. Diversion of flow through the other distributaries causes an increase in flow velocities (see dashed black circles in FIGURE 7.18 B to E) and hence increased ebb and flood flow, but with the ebb flow dominating over the flood flow. Increased flow discharges (Qw) would in turn result in an increased sediment transport capacity (Qw/Qs). Those distributaries with increased water discharge clearly show an increase in the Qw/Qs ratio for the cross-dams scenario, see FIGURE 7.17 A and FIGURE 7.16 B at observation locations 16 and 5, respectively. On the other hand, for the distributaries with decreased water discharge the Qw/Qs ratio is reduced in the case with no cross-dams at locations: 1 (FIGURE 7.16 A), 7 (FIGURE 7.17 B) and 11 (FIGURE 7.17 C). Not much change in the Qw/Qs ratio is seen at observation location 14 (FIGURE 7.16 C), while the Qw/Qs ratio increased from nearly zero to 10,000 at location 5 and is increased by up to two times at location 16, as well as being accompanied by a tidal phase shift. The duration of flood flow increased and, with equal magnitude of the ebb and flood flow, tidal asymmetry is removed at this location. FIGURE 7.20 shows water depth during high tides over the islands. Due to the introduction of cross-dams, the islands adjacent to the structures (FIGURE 7.20 B to E) experience a greater depth of flooding than in the base case scenario (2f- no cross-dams) (FIGURE 7.20 F). This is because of the back water effect (afflux) created by the cross-dams that increases the water level in the distributaries.
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 7.15: Location of tidal flow observation points (brown colour) and spatial distribution of tidal flood to ebb flow ratio (blue colour) in the delta after 100 years for scenarios: (X) – basecase (2f- no interventions) and (Y) – 4b (With cross-dams)
Chapter 7: Impact of human interventions and land cover on tidally influenced deltas

FIGURE 7.16: Ratio of water to sediment discharge for scenarios: basecase (2f- no interventions) and 4b (with cross-dams) at observation points 1 (A), 5 (B), 14(C). See FIGURE 7.15 for the location of observation points.
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 7.17: Ratio of water to sediment discharge for scenarios: basecase (2f- no interventions) and 4b (with cross-dams) at observation points 16 (A), 7 (B), 11(C). See FIGURE 7.15 for the location of observation points
FIGURE 7.18: Spatial distribution of flow velocity over the delta during low tides for scenarios: Initial (A), 4b (with cross-dams) at 25y (B), at 50y (C), at 75y (D), at 100y (E), and base case-2f (no interventions) at 100y (F). Dashed black oval lines indicates the evolution of channel over time for 4b (with cross-dams) scenario.
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 7.19: Spatial distribution of flow velocity over the delta during high tides for scenarios: Initial (A), 4b (with cross-dams) at 25y (B), at 50y (c), at 75y (D), at 100y (E), and base case-2f (no interventions) at 100y (F)
FIGURE 7.20: Spatial distribution of water depth over the sub-aerial delta during high tides for scenarios: Initial (A), 4a (with cross-dams) at 25y (B), at 50y(C), at 75y (D), at 100y (E), and base case-2f (no interventions) at 100y (F)
7.3.2 Patterns of erosion and accretion

Morphodynamic changes from the initial condition

FIGURE 12.8C1 in Appendix 12 shows the pattern of simulated erosion and accretion over the delta at the end of the 100 year simulation period for the cross-dam scenario (4b). The figure clearly shows that sediment deposition is focused within the distributary channels where the cross-dams are situated. However, the banks of the distributaries with cross-dams also experienced erosion. Channel deepening and widening due to bed and bank erosion on the other distributaries can also be observed. Progradation of the islands on the delta front is also affected by the (remote) presence of the cross-dams. In particular, erosion is evident on the island’s front, which in turn inhibits further progradation of the southern island of the delta. However, progradation of the islands on the delta front that are located on either side of the southern island has occurred, with more sediment deposition located on the seaward side. The island located at the delta apex experienced less erosion in the cross dam scenario relative to the base case scenario (see FIGURE 12.8 C2 in Appendix 12). The pattern of erosion and deposition towards the sea is also influenced by the cross-dams, with more bed erosion focused in front of the southern island and more sediment deposition on either side (FIGURE 12.8 C2 in Appendix 12).

FIGURE 7.21 A and B shows that water discharges within the eroded channel are increased by a factor of between 6 and 9 times in the cross dam scenario (4b) when compared to the base case (2f) scenario. FIGURE 7.21 C also shows that there is nearly a zero water discharge in the distributary with the cross-dam whereas in the base case (2f) scenario the flow discharge is greater than 20,000 cumecs during flood flows and 60,000 cumecs during the ebb flow. Cross-dams also alter the flow pattern within the delta as a whole. This leads to decreased sediment transport capacity with increased sediment supply on the side of the delta with cross-dams, and vice versa on the other side of the delta that has no cross-dams, as described in section 7.3.1. Due to the resistance to flow caused by the cross-dams within their distributary channel, water is diverted to flow through the other distributary channels. For those distributaries acting as main flow carrier, their mouths experienced erosion
due to the higher sediment transport capacity. The effect of cross-dams on the water flow patterns and on the delta's morphodynamics can be seen over the entire delta. Because of the presence of the cross-dams, the morphodynamics of the delta is undergoing severe adjustment through processes of erosion and accretion to achieve a new equilibrium.
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 7.21: Water discharges for scenarios: basecase (2f- no interventions) and 4b (with cross-dams) at observation points 4 (A), 5 (B), 15(C). See FIGURE 7.15 for the location of observation points
Chapter 7: Impact of human interventions and land cover on tidally influenced deltas

FIGURE 7.22: Net volume of accretion and erosion against the depth of accretion and erosion after 100 years for scenarios: Base case (2f-no interventions) (A1 & A2) and 4b (with cross-dams) (B1 & B2)

FIGURE 7.22 B2 shows that greater amounts of erosion are generated in the cross dam scenario in water depths greater than 5m when compared to the base case scenario, see FIGURE 7.22 A2. This increased erosion is mainly associated with channel widening and deepening on the opposite side of the delta that has no cross-dams, along with the seaward erosion of the prograding southern island. FIGURE 7.22 B1 shows that there is also greater accretion in the cross-dams scenario (4b), but the locations of zones of accretion are focused mainly within the distributaries and prograding islands in the cross-dam scenario, whereas they are restricted to prograding islands only in the base-case (2f- no cross-dams) scenario.
7.3.3 Progradation and aggradation of the delta

FIGURE 7.23: Longitudinal section of the delta through its centre (x-x) for cross-dams (4b) scenario. See FIGURE 7.8 for location X-X

FIGURE 7.23 and FIGURE 7.24 A show that the progradation of the delta can be highly influenced by cross-dams (scenario 4b). Erosion on both the sub-aerial and sub-aqueous delta is clearly evident. The high sediment transport capacity of the flow, as described in section 7.3.1, eroded the seaward side of the island on the delta front. However, the sediment transport capacity of the flow drops a short distance towards the sea, causing the deposition of the sediment and merging with the existing bed profile of the sea. Due to the back water effect of the structure, in the cross dam scenario there is less bank erosion of the island at the delta apex compared to the base case (2f - no cross-dams) scenario.

When compared to the base case (scenario 2f - no cross-dams), the dashed purple boxes in FIGURE 7.24 show the deepening and widening of channels induced in the cross dam scenario due to increased water discharge and sediment transport capacity on the opposite side of delta. This may be...
Chapter 7: Impact of human interventions and land cover on tidally influenced deltas

correlated to the dashed green circles in FIGURE 7.24 which show sediment deposition within the distributaries due to the reduced sediment transport capacity there.

FIGURE 7.24: Cross section of the delta at locations 1-1, 2-2 and 3-3. See FIGURE 7.8 for location of cross-sections. Dashed green circle indicates deposition and purple box indicates erosion.
7.3.4 Morphodynamic changes of the sub-aerial delta

FIGURE 7.11 C and D show that the area and rate of erosion over the sub-aerial delta for the cross-dam (4b) scenario is greater for the first 50 years and then gradually decreases to merge with the base case (2f - no cross-dams) scenario, becoming steady after 75 years. This is because of the greater amount of distributary bank erosion on the side of the delta opposite to the cross dams. Also, the seaward side of the southern island experienced erosion in scenario 4b (cross-dams) whereas it progrades in the base-case (2f - no cross-dams) scenario. Once the distributaries have adjusted their dimensions to take the additional flow diverted to them, as described in section 7.3.1, then the rate and area of erosion in scenario 4b (with cross-dams) decreases and merges with the base-case (2f – no cross-dams) scenario. FIGURE 7.11 A and B shows that the area and rate of accretion for the cross-dam (4b) scenario is marginally smaller than in the base case (2f - no cross-dams) scenario during the first 50 years of the simulation, and then becomes marginally greater for the next 25 years, before merging with the base-case after 75 years. Compared to the base-case scenario, when cross-dams are present at the island at the delta apex and the prograding islands at the bottom left of the delta have greater accretion as the rate of supply of sediment exceeds the sediment transport capacity of the flow at these locations. Accretion over the sub-aerial delta occurs only during the flood flow phase of tides. As described in section 7.3.1, and as shown in FIGURE 12.8C2 in Appendix 12, accretion over the sub-aerial delta in the cross-dams (4b) scenario could have occurred due to the backwater effect resulting in an increased extent of flooding and reduced sediment transport capacity.

FIGURE 7.25 shows the sub-aerial delta for scenario 4b (with cross-dams) after 100 years of simulation (black lines) and at the initial condition (blue lines). The red and green blocks in FIGURE 7.25 show the location of net erosion and accretion after 100 years for the cross-dams (4b) scenario when compared with the initial condition. The net erosion along channel banks and the southern island front can be observed. Net accretion of islands on the delta front and at the heads of minor distributaries are the net land gain to the sub-aerial delta in 100 years, however, see FIGURE 12.8 in Appendix 12 for more sedimentation on the beds of distributaries which are eventually in the process of welding.
Chapter 7: Impact of human interventions and land cover on tidally influenced deltas

islands to form a one larger island. FIGURE 7.25 clearly indicates the part of the delta that experienced a higher rate of sediment supply than the sediment transport capacity of the flow and vice versa, as described in section 7.3.1.

FIGURE 7.25: Comparison of sub-aerial delta land constructed between the initial state and after 100 years of the simulation for the cross-dams (4b) scenario. The net change in sub-aerial delta extent over this time period for this cross-dams scenario is -21 km², compared to the initial delta extent of 694 km².

FIGURE 7.13 shows the time series of sub-aerial delta over 100 years for the scenarios with (4b) and without (2f) the cross-dams. Cross-dams can be used to connect islands, however after 100 morphological years about 4% of the initial sub-aerial delta area is lost. This is not, however, a significant loss considering the delta areas adjacent to the cross-dams have experienced severe sedimentation (see FIGURE 12.8 in Appendix 12) as a process of land gain when the other part of the delta experienced channel deepening and widening and hindered progradation of the southern delta island. This implies that the presence of cross-dams within the distributaries of the simulated delta steers the local development of the sub-aerial delta, but may not result in a net gain of area across the whole sub-aerial delta.
FIGURE 7.14 shows time series of sub-aerial delta perimeter for the cross-dams (4b) scenario increases at the same rate as the base case (2f- no cross-dams) for the first 50 years and then increases at rate slower than the base case. Erosion of banks and accretion of prograding islands increases the perimeter of the sub-aerial delta whereas the accretion at the head of minor distributaries results in decreasing it. Here, for the cross-dams (4b) scenario the perimeter of the sub-aerial delta increases throughout the 100 year simulation period.

7.3.5 Discussions

The pre-feasibility study on (see FIGURE 9.15) cross-dam connecting the Sandwip Island and the mainland in the Meghna Estuary did not predict any significant morphological effects elsewhere in the estuary (see FIGURE 9.15) (Anonymus, 1986) which contradicts the findings in this thesis. This could be because the proposed Sandwip cross-dam in the pre-feasibility study is not on one of the main distributaries and also due to the vicinity of the proposed cross-dam in relation to the entire delta. However, the effect of cross-dams on the sub-aerial delta area reported in this thesis is what was anticipated by Sarker et al. (2011) based on the past experience of building cross-dams (see FIGURE 9.15) in the Meghna Estuary. In the long term, the construction of cross-dams and subsequent sedimentation and land reclamation can lead to the abandonment of that part of the delta (Anwar, 2013) and then focus of the morphological evolution will shift to the other active parts of the delta. This human induced processes could be looked in a way similar to the natural processes of distributary shift (FIGURE 2.10 and FIGURE 12.8 in Appendix 12) in tide dominated deltas as explained by Hori and Saito (2008).

Although, these land reclamation measures can provide certain benefits, there involves the cost implication of maintaining those engineering structures to retain and improve the functional performance of them (Dasgupta et al., 2011). Otherwise, mismanagement and lack of maintenance of these engineering structures can have adverse effect of increased flood risk due to poor drainage, erosion and breaching of embankments and increased river bed siltation(Paul and Mahmood, 2016). For a sustainable management of delta, the exchange of flow between the distributaries and tidal floodplains should be enabled. If embankments are built with flow control structures, they should be regularly
Chapter 7: Impact of human interventions and land cover on tidally influenced deltas

operated and maintained to let this exchange happen more naturally (Paul and Mahmood, 2016). However, according to Townend and Pethick (2002) this is not possible as although it increases the gross inter-tidal area but it does not increases the inter-tidal area of the channel. Hence, they recommend complete removal of the flood embankment to achieve the following benefits:

a) Lower water levels and hence decreased flood risk
b) Less impact on the coastal embankments
c) Increased area for inter-tidal habitat and floodplain sedimentation
d) More space for adjustments to happen naturally

Otherwise, relative sea level rise can lead to the loss of sub-aerial or wetland part of the delta as there will not be enough sediment to replenish and nourish the floodplains similar to what happened in the Mississippi delta due to the construction of embankments along the distributaries (Paola et al., 2011).

7.4 Influence of roughness (varying land cover)

7.4.1 Residual flow

FIGURE 7.27 X shows the flood:ebb flow ratio over the delta after 100 years of the simulation for the base case scenario (2f- lower roughness) and FIGURE 7.27 Y for the higher roughness land cover scenario (4c). The change in land cover has the effect of altering the flood:ebb flow ratio with increasing values at locations 6, 7 and 8 and decreases at locations 4 and 5. Elsewhere, there is only a marginal difference in the ratio between the two scenarios. The difference is because of the interaction of flow between the rougher tidal floodplain and distributaries, which creates changing flow patterns within the distributaries, see FIGURE 7.26 A and B. FIGURE 7.26 B shows that there is nearly an equal intensity and duration of the flood and ebb flow at location 8 and this is why the flood:ebb flow ratio is increasing towards 1 in scenario 4c (with higher roughness land cover) compared to the base case (2f – lower roughness) scenario, whereas FIGURE 7.26 A shows the opposite. The changing flow patterns within the distributaries alter the sediment transport capacity of the flow. FIGURE 7.28 and FIGURE 7.29 show the ratio of Qw/Qs
after 100 years at the various observation points over the delta. The intensity and duration of flood and ebb flow of Qw/Qs ratio after 100 years is not significantly different for the higher roughness land cover scenario (4c) when compared to base case (2f- lower roughness) scenario at locations 1, 3 and 15, see FIGURE 7.28. However, at locations 4 and 8, this is not the case as in these locations the water discharges are different, as shown in FIGURE 7.26 A and B. FIGURE 7.30 B and C shows similar flow velocity patterns after 100 years during low tides for the higher roughness land cover scenario (4c) and the base-case (2f- lower roughness) scenario. FIGURE 7.30 E and F shows similar trends during high tide within the distributaries, but smaller velocities over the sub-aerial delta when the rough land cover is present. This implies the effect of changing land cover on the morphodynamics of the delta is nearly vanished, generally however there will be some local spots where the pattern of velocities will still be different.
Chapter 7: Impact of human interventions and land cover on tidally influenced deltas

FIGURE 7.26: Water discharges for scenarios: basecase (2f- lower roughness land cover) and 4c (higher roughness land cover) at observation points 4 (A), 8 (B) and 15(C). See FIGURE 7.27 for the locations.
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 7.27: Location of tidal flow observation points (brown colour) and spatial distribution of tidal flood to ebb flow ratio (blue colour) in the delta after 100 years for scenarios: (X) – basecase (2f- lower roughness land cover) and (Y) – 4c (higher roughness land cover)
FIGURE 7.28: Ratio of water to sediment discharge for scenarios: basecase (2f- lower roughness land cover) and 4c (higher roughness land cover) at observation points 1 (A), 3 (B), 15(C). See FIGURE 7.27 for the location of observation points.
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 7.29: Ratio of water to sediment discharge for scenarios: basecase (2f- lower roughness land cover) and 4c (higher roughness land cover) at observation points 6 (A), 8 (B), 13(C). See FIGURE 7.27 for the location of observation points
FIGURE 7.30: Spatial distribution of flow velocity over the delta during low tides for scenarios: Initial (A), 4c (higher roughness land cover) at 100y (B), and base case-2f (lower roughness land cover) at 100y (C) and during high tides for scenarios: Initial (D), 4c (higher roughness land cover) at 100y (E), and base case-2f (lower roughness land cover) at 100y (F)
7.4.2 Patterns of erosion and accretion

FIGURE 12.9D1 in Appendix 12 shows the net morphodynamic changes simulated over the delta for the rough land cover scenario. Erosion of island banks and channel bed, accretion over the sub-aerial delta, and progradation of islands at the delta front can all be observed. FIGURE 12.9D2 in Appendix 12 shows the difference in the pattern of erosion and accretion between scenario 4c (higher roughness land cover scenario) and the base case (2f- lower roughness land cover) scenario. Greater amounts of sediment deposition are induced on the bed of the distributaries and towards the sea in the higher roughness land cover scenario (4c). Alteration, mostly in the form of erosion, of the island boundaries due to the increased land cover roughness is also apparent. The green colour dashed circle in FIGURE 12.9D1 in Appendix 12 shows that the change to a rough land cover leads to the disintegration of a prograding delta island and results in the creation of a new distributary channel. A pattern of flow circulation created during high tides and the resulting sub-aerial delta erosion on this island gradually evolves to split one island into two. As described in section 7.4.1, wherever the altered flow pattern increased the sediment transport capacity of the flow beyond the rate of sediment supply, net erosion has occurred and vice versa for accretion. In the higher roughness land cover scenario (4c), sediments from the eroded banks of the distributary channels lead to increased sediment concentration and hence deposition within the channels and near the mouths of the distributaries.

FIGURE 7.31 B2 shows that the net volume of erosion over the delta for depths greater than 5m is greater in the rough land cover scenario than in the base case (see FIGURE 7.31 A2 for the base case data). FIGURE 7.31 A1 and A2 shows that the net volume of accretion over the delta is greater in the higher roughness land cover (4c) scenario than in the base case scenario (2f- lower roughness land cover). Erosion can be associated with the channel bank erosion and accretion with sediment deposition on the bed of the distributaries, on the prograding islands, and at the head of minor distributaries.
Chapter 7: Impact of human interventions and land cover on tidally influenced deltas

FIGURE 7.31: Net volume of accretion and erosion against the depth of accretion and erosion after 100 years for scenarios: Base case (2f-lower roughness land cover) (A1&A2) and 4c (higher roughness land cover) (B1 &B2).
7.4.3 Progradation and aggradation of the delta

**FIGURE 7.32:** Longitudinal section of the delta through its centre (x-x) for higher roughness land cover (4c) scenario. See FIGURE 7.8 for location X-X

FIGURE 7.32 shows that, in the higher roughness land cover (4c) scenario, the simulated delta progrades a little quicker than in the base case (2f - lower roughness land cover) scenario. However, a greater amount of channel bank erosion can also be caused by the increase in land cover roughness (scenario 4c) when compared to the base case scenario (2f- lower roughness land cover), due to the interaction of flow between the rougher tidal floodplain and the distributaries. The dashed green circle in FIGURE 7.33 B and C shows that there is greater channel deepening and widening after 100 years in the higher roughness land cover scenario (4c) when compared to the base case (2f- lower roughness land cover) scenario. But, not all the channels experienced such a change as they were deeper than the eroded channel. As mentioned in section 7.4.1, the amount of alteration of flow patterns due to the change in land cover varied over the delta and the net morphodynamic changes actually simulated at any point was due to the specific local balance between the sediment transport capacity of flow and rate of sediment supply.
Chapter 7: Impact of human interventions and land cover on tidally influenced deltas

FIGURE 7.33: Cross section of the delta at locations 1-1, 2-2 and 3-3. See FIGURE 7.8 for cross-section locations. Dashed green circle indicates greater channel erosion.

7.4.4 Morphodynamic changes of the sub-aerial delta

FIGURE 7.11 D shows that the rate of erosion of the sub-aerial delta is about 2 to 3 times greater in the higher roughness land cover scenario (4c) than in the base case (2f- lower roughness land cover) scenario during the first 25 years,
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

but then gradually reduces to coincide with the base case scenario rate. The area over which erosion occurs in the rough land cover scenario decreases over time, eventually reaching a level that is even below the base case value, see FIGURE 7.11 C. The adjustment occurs mainly through the erosion of island banks. The sub-aerial delta area over which accretion occurs remains steady throughout the 100 year simulation period (FIGURE 7.11 A) in the rough land cover scenario and remains below the base case (2f – lower roughness land cover) for 75 years, becoming marginally greater after that. But, the rate of accretion decreases over time and stays greater than in the base case (FIGURE 7.11 B) due to the increased roughness of the sub-aerial delta. Accretion over the sub-aerial delta can happen when it is flooded during the flood phase of tidal flow. Greater accretion is caused by the smaller flow velocity over the sub-aerial delta in the rough land cover scenario as compared to the base case (2f-lower roughness land cover) scenario; see FIGURE 7.30 E and F.

FIGURE 7.34: Comparison of sub-aerial delta land constructed between the initial state and after 100 years of the simulation for the higher roughness land cover (4c) scenario. The net change in sub-aerial delta extent over this time period for this land cover scenario is -36 km², compared to the initial delta extent of 694 km².
The red coloured hatched area in FIGURE 7.34 shows that increasing the roughness of the land cover (scenario 4c) causes modification to the island boundaries as a result of the process of bank erosion. This is because of the change in flow momentum at the interface of the distributaries and the tidal floodplain, with flow flowing back from the higher roughness floodplain to lower roughness distributary channels and vice versa. The eroded banks of the islands are rougher than in the base case (2f – lower roughness land cover) scenario. Net accretion of the sub-aerial delta, after 100 years of the simulation, in the higher roughness land cover scenario (4c) occurs at the heads of minor distributaries and on the prograding islands, see the green coloured hatched areas in FIGURE 7.34. It is important to note here that fresh accretion also creates islands with rougher banks. FIGURE 7.13 shows the time series of sub-aerial delta area for the higher roughness land cover (4c) and lower roughness land cover (2f - base case) scenarios. The rate of decrease in the sub-aerial delta area is very rapid in the first 25 years and then reduces. A total of 6% of the initial sub-aerial delta is lost over 100 years, mainly because of the creation of rough coasts. FIGURE 7.14 shows time series of the sub-aerial delta perimeter over the 100 year simulation period. There is a 46% increase in initial sub-aerial delta perimeter due to the increase in land cover roughness. The perimeter of the 4c (higher roughness land cover) scenario clearly shows the interaction of floodplain and distributaries channel flow in reshaping the islands’ boundaries due to the change in land cover. This increase in sub-aerial delta perimeter is mainly due to the rough coast being created by the erosion of existing island banks, progradation of islands only with rough banks and they clearly dominated the reduction in sub-aerial delta perimeter caused by the accretion at the head of minor distributaries. This is not the case in the base case scenario. This implies the rough land cover will have rough coasts with greater perimeter for the same amount of sub-aerial delta area.
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 7.35: Probability distribution function of island size normalised to total island area for the modelled delta with polders

FIGURE 7.36: Probability distribution function of island size normalised to total island area for the modelled delta with cross-dams

FIGURE 7.35 and FIGURE 7.36 show the multi-modal distribution of delta area for the scenarios of polders and cross-dams respectively. As the erosion of the poldered area was not allowed in the modelled delta, with only accretion, the sub-aerial delta area increased resulting in the modal shift of the distribution tail in the polders scenario whereas the increased erosion of islands bank and disturbed progradation of the islands at the delta front due to the introduction of cross-dams resulted in the amplification and modal shift of its distribution.
Chapter 7: Impact of human interventions and land cover on tidally influenced deltas

The total number of islands remained the same in the polders scenario whereas the total number of islands increased from 12 to 19 over the 100 years of simulation in the cross-dams scenario.

FIGURE 7.37: Probability distribution function of island size normalised to total island area for the modelled delta with changing landcover roughness (LC)

FIGURE 7.37 clearly indicates that increasing the roughness of the land cover leads to more bifurcations by the creation of number of smaller islands. The number of islands in the increased landcover roughness scenario increased from 12 to 34 over the 100 years of simulation.

The probability distribution function of island shape factor for the polders scenario is unimodal (FIGURE 7.38) rather than the initial multi-model distribution and it resembles the shape of the distribution of the real world GBM delta (see FIGURE 2.11). As the erosion of channel banks are not allowed in the polders scenario, the change in island shape factor is due to the accretion of the islands at the delta front, and accretion at the intraisland channels head. It is important to note that polders have prevented the evolution of interisland channel networks and the dissection of islands. Thus, the area of the islands increased for relatively little increase in their perimeter. However, with polders the degree of drainage inside the poldered area remains unaltered. The distribution of island shape factor for the cross-dams scenario follows the same trend as the base case scenario but with increased number of islands. Increasing the land cover roughness led to increased number of smaller islands.
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

but with decreased island shape factor mainly at the delta front. However, the tail of this scenario’s distribution shows an increased boundary roughness and intraisland channels dissection of bigger islands. FIGURE 7.39 shows that with no erosion of the poldered area being allowed in the modelled delta, the shape of islands has moved away from both being circular and elongate. Whereas the peak of the distribution for the change in land cover roughness scenario has shifted towards being more circular shape of islands.

FIGURE 7.38: Probability distribution function of island shape factor for the modelled delta with and without human interventions

FIGURE 7.39: Probability distribution function of island aspect ratio for the modelled delta with and without human interventions
Chapter 7: Impact of human interventions and land cover on tidally influenced deltas

**FIGURE 7.40:** Probability distribution function of nearest-edge distance for the modelled delta with polders, and cross-dams

Based on the **FIGURE 7.40,** probability distribution function of nearest-edge distance, it can be concluded that for scenario with polders, the increase in the nearest-edge distance is due to the land growing outside the poldered area with no erosion of the poldered area. The nearest-edge distance of the polders scenario is greater than the initial and base case scenario after 100 years of simulation. Whereas in the case of scenario with Cross-dams, bank erosion has decreased the nearest-edge distance. Actually, the nearest edge distance should have increased due to the welding of islands by Cross-dams but in the modelled delta even though the welding of islands have not happened but excessive sedimentation within the channel containing the Cross-dams shows that this process is happening (**FIGURE 12.8** in Appendix 12).

**FIGURE 7.41** shows that increased number of islands due to increased land cover roughness of the islands results in decreased edge distance. But, excessive bank erosion during the morphodynamic adjustment process caused by the change in land cover roughness led to decreased frequency of the nearest-edge distance.
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

282

FIGURE 7.41: Probability distribution function of nearest-edge distance for the modelled delta with changing landcover roughness

7.4.5 Discussions

Sarker et al. (2011) reported that mangroves are used for land reclamation measures when a new bar is formed within the GBM delta. However, little is known about the morphodynamic processes when the Uri-grass land cover is changed to mangroves. However, because of the rough land cover such as mangroves on the fringe of the islands, the tidal delta plain is a dense network of funnel-shaped tidal channels (Wilson and Jr., 2015). The model results in this thesis shows that increasing the roughness of the land cover leads to the process of establishing a dense network of funnel-shaped tidal channels (FIGURE 12.9D1 in Appendix 12) along the perimeter of the deltaic islands. Consistent with the findings of Woodroffe (2013), also increased roughness in the model lead to the rapid accretion over the sub-aerial delta (FIGURE 7.30 and FIGURE 12.9 in Appendix 12). Carlton (2009) findings suggest that mangrove fringes can be used as land stabiliser in front of the embankments or along the deltaic coast and their establishment can lead to rapid accretion (Woodroffe, 2013).
7.5 Summary

1. What is the impact of deltaic human intervention, such as building polders, on tidal delta morphology?

A. The model simulations reveal that tidal asymmetry increases across the delta when islands are polderised (FIGURE 7.1). In the numerical model with polders, water is not allowed to overtop or breach the polders and the polderised banks are treated as non-erodible. Hence, any morphodynamic changes are constrained to occur outside of the polderised sub-aerial delta.

B. With the introduction of simulated polders, the sediment transport capacity within the distributaries is found to be increased. Erosion of the bed of the distributaries (by 200 million m$^3$ more than in the base case scenario, an increase of 5%), sediment deposition on the seaward side of the prograding islands and greater accretion/reduced erosion towards the sea (by 250 million m$^3$ more than in the base case scenario, an increase of 4%) are all evident in the polders scenario (see FIGURE 12.7B2 in Appendix 12). No channel erosion, but instead accretion, is induced at the head of minor distributaries (see FIGURE 12.7B1 in Appendix 12).

C. As the delta front and head of the distributaries are those areas where the rate of sediment supply exceeds the sediment transport capacity, in the poldered scenarios these are the only areas where net accretion occurred, and erosion is always smaller than accretion in these locations (FIGURE 7.12).

D. In the simulations, polders lead to an increase in sub-aerial delta area over time. It was found that the sub-aerial delta area with polders is 10% greater than the simulation without polders, for a perimeter that is 16% smaller than without polders. The effect of subsidence inside the polders is, however, not considered in this study. It is acknowledged that in the real world, subsidence inside the polders can result in regular
breaching and overtopping of coastal embankments leading to increased flood risk within poldered areas (Auerbach et al., 2015).

E. Consistent with the findings of Pethick and Orford (2013), the model results in this thesis shows that tidal asymmetry (FIGURE 7.1) increases by reduced frictional damping and an increased rate of channel convergence due to the polders. As reported in FIGURE 12.7 in Appendix 12, it has been hypothesised in the CEGIS (2009) report that the net accretion and progradation in the Meghna Estuary over the last 50 years are could be due to the excessive sediments outside the polders.

2. What is the impact of the deltaic human intervention of building cross-dams on tidal delta morphology?
A. The model simulations reveal that tidal asymmetry, all over the delta, is significantly altered, being either increased or decreased by varying amounts, depending on local context within the model domain, by the introduction of cross-dams (FIGURE 7.15). Cross-dams alter flow patterns over the entire delta due to the back water effects they cause. Distributaries experiencing increased flow discharges result in erosion as the sediment transport capacity of the flows (FIGURE 7.17) become greater than the rate of sediment supply in these locations, but accretion in distributaries with decreased flow discharges is also simulated (FIGURE 12.8 in Appendix 12).

B. Cross-dams steer the locations where the sub-aerial delta grows and subsequently land loss can occur elsewhere in the delta due to the change in residual flow and increased sediment transport capacity. Model simulation with cross-dams indicated that after 100 morphological years there is a net loss of about 4% of the initial sub-aerial delta area. This is not a significant loss considering the delta areas adjacent to the cross-dams have experienced severe sedimentation (see FIGURE 12.8 in Appendix 12) however, the key point is that the model results show that there may not be a significant net land gain at the overall delta scale due to the introduction of cross-dams.
Chapter 7: Impact of human interventions and land cover on tidally influenced deltas

C. The pre-feasibility study on (see FIGURE 9.15) cross-dams in the Meghna Estuary did not predict any significant morphological effects elsewhere in the estuary (see FIGURE 9.15) (Anonymus, 1986), which contradicts the findings in this thesis. This could be because the proposed Sandwip cross-dam (orange colour line in FIGURE 9.15) is not on one of the main distributaries and due to the vicinity of the proposed cross-dam in relation to the entire delta. However, the effect of cross-dams on the sub-aerial delta area reported in this thesis is what was anticipated by Sarker et al. (2011) based on the past experience of building cross-dams (see FIGURE 9.15) in the Meghna Estuary.

3. What is the impact of changing the roughness of the land cover on tidal delta morphology?

A. Tidal asymmetry over the delta is altered by increasing roughness due to the interaction of flow between the rougher tidal floodplain and unaffected distributaries (FIGURE 7.27). The extent to which flow patterns are altered due to the change in land cover is varied over the delta and the net morphodynamic changes are induced as a result of a shift in the local balance between the sediment transport capacity of flow and rate of sediment supply (FIGURE 7.29). Reductions in flow velocities of up to 60% relative to the base case values (see FIGURE 7.30) are also simulated.

B. Erosion of island banks and the channel bed, accretion over the sub-aerial delta and progradation of islands at the delta front are all simulated in the higher roughness scenario (FIGURE 12.9 in Appendix 12). Greater amounts of sediment deposition on the bed of the distributaries and towards the sea are other morphodynamic changes associated with the higher roughness scenario (an increase of 13% over base case: lower roughness scenario). Higher roughness scenario (Manning’s n=0.10) can lead to greater channel erosion (FIGURE 7.26) than in the base case scenario of lower roughness (Manning’s’ n=0.055).

C. Higher roughness scenario creates very rough sub-aerial delta coasts through the process of bank erosion (FIGURE 7.34). Higher roughness
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

scenario can lead to a relatively smaller (by 8% to base case) delta area with a greater (by 25% to base case) perimeter as compared to the base case scenario.

D. Sarker et al. (2011) reported that mangroves are used for land reclamation measures when a new bar is formed within the GBM delta. However, little is known about the morphodynamic processes when the Uri-grass land cover is changed to mangroves. However, because of the higher roughness land cover such as mangroves on the fringe of the islands, the tidal delta plain is a dense network of funnel-shaped tidal channels (Wilson and Goodbred, 2015). The model results in this thesis shows that increasing the roughness of the tidal floodplain leads to the process of establishing a dense network of funnel-shaped tidal channels (FIGURE 12.9D1 in Appendix 12) along the perimeter of the deltaic islands. Consistent with the findings of Woodroffe (2013), increasing the roughness of the land cover in the model lead to the rapid accretion over the sub-aerial delta (FIGURE 7.30 and FIGURE 12.9 in Appendix 12).
Chapter 8: The impacts of variations of multiple drivers on the morphology of tidally influenced deltas

8. The impacts of variations of multiple drivers on the morphology of tidally influenced deltas

8.1 Introduction

In this chapter, the numerical model experiments are used to understand the combined influence of the controlling factors explored in chapters 5 to 7. These are: (i) fluvial water and sediment discharges, (ii) relative sea level rise (RSLR) and (iii) deltaic human interventions on the morphodynamics of the modelled idealised tidal delta. This chapter presents, analyses and discusses the numerical model outputs with the aim of understanding their combined influence on tidal delta morphology over a 100 years timescale. In reality, the driving factors such as human interventions and environmental change are unlikely to vary in isolation in the way explored in the previous chapters 5, 6 and 7. Therefore, the impact of combining human interventions (polders, cross-dams, etc) with environmental change, in particular changes in relative sea level rise and fluvial discharges that represent likely changes in many real-world deltas were studied and presented here.

8.2 Combined effect of environmental change and anthropogenic interventions

The following sub-sections present and analyse the morphodynamic changes (represented here by the sub-aerial delta area, patterns of erosion and accretion, and aggradation and progradation of the delta) imposed on the delta over a 100 year model simulation for various scenarios that investigate the impacts of combining human interventions (polders, cross-dams, etc) with environmental change, in particular changes in relative sea level rise and fluvial water and sediment discharges. The following scenarios are studied:
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

<table>
<thead>
<tr>
<th>With polders and cross-dams</th>
<th>0mm/y Relative Sea Level Rise (RSLR)</th>
<th>10mm/y RSLR</th>
<th>20mm/y RSLR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qs = 1.48 m³/s</td>
<td>6a (2Qs:1Qw;0rslr)</td>
<td>6b (2Qs:1Qw;10rslr)</td>
<td>6c (2Qs:1Qw;20rslr)</td>
</tr>
<tr>
<td>Qw = 32,500 m³/s (low)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Qs = 1.48 m³/s</td>
<td>5a (2Qs:2Qw;0rslr)</td>
<td>5b (2Qs:2Qw;10rslr)</td>
<td>5f (2Qs:2Qw;20rslr)</td>
</tr>
<tr>
<td>Qw = 65,000 m³/s (medium)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Qs = 1.48 m³/s</td>
<td>6d (2Qs:3Qw;0rslr)</td>
<td>6e (2Qs:3Qw;10rslr)</td>
<td>6f (2Qs:3Qw;20rslr)</td>
</tr>
<tr>
<td>Qw = 97,500 m³/s (high)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Qs += 45% over 100 years</td>
<td>5h (2Qs+:2Qw;0rslr)</td>
<td>5c (2Qs+:2Qw;10rslr)</td>
<td>5j (2Qs+:2Qw;20rslr)</td>
</tr>
<tr>
<td>Qw = 65,000 m³/s (high)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6Qs + 4.44 m³/s (extreme)</td>
<td>-</td>
<td>5d (6Qs:2Qw;10rslr)</td>
<td>-</td>
</tr>
<tr>
<td>Qw = 65,000 m³/s</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TABLE 8.1: Combination of scenarios of varying fluvial water discharge and relative sea level rise with polders and cross-dams

Note: # - average value of the range of simulated increase in sediment flux for the Ganges and Brahmaputra catchments towards the end of this century for the projected anthropogenic climate change by Darby et al. (2015)

% - scenario of increase in sediment discharge due to earthquake induced landslides in the catchments (Sarker and Thorne, 2009). Here, only the fine sediment is increased as the increase in sand concentration led to huge sedimentation near the upstream boundary to trigger the model instability.

8.2.1 Residual flow

FIGURE 8.1 X and Y show the simulated flood:ebb flow ratio over the delta after 100 years for the base case scenario (2f- no polders and cross-dams) and scenario 5a (with polders and cross-dams), respectively. It is evident that cross-dams built across the distributaries block the flow through its distributaries and cause a back water effect and associated diversion of water to other...
Chapter 8: The impacts of variations of multiple drivers on the morphology of tidally influenced deltas

distributaries. Thus, the insertion of cross-dams alters the flow pattern of the deltaic distributaries (see section 7.3.1). Polders, by preventing the inundation of the tidal floodplains, act to increase the tidal prism in the delta (see section 7.2.1). Polders lead to a decrease in the flood:ebb flow ratio whereas the cross-dams alter the value of this ratio depending upon the alteration of flow pattern. When compared to the base case, FIGURE 8.1B shows that the polders and cross-dams act together in altering the flood:ebb flow ratio, but with the effect of cross-dams dominating.

FIGURE 8.2 X and Y shows the flood:ebb flow simulated over the delta after 100 years for the base case (2f- no RSLR, polders and cross-dams) and varying fluvial water discharge scenarios (6b=2Qs:1Qw;10rslr, 5b=2Qs:2Qw;10rslr, and 6e=2Qs:3Qw;10rslr) and RSLR of 10 mm/y, polders and cross-dams, respectively. The flood:ebb flow ratio decreases with increasing fluvial water discharge (as per the results in section 5.2). The effect of increasing the fluvial water discharge on the ratio is enhanced by the polders (FIGURE 8.2B), whereas the effect of cross-dams on the ratio is enhanced by the increasing water discharge as shown in FIGURE 8.2B. At each observation location, the effect of cross-dams and increasing water discharges dominate the response of the ratio. Cross-dams block the flow of water and divert the flow to other distributaries and the amount of flow diverted increases with increasing water discharge. The ebb flow of the tide increases with increasing water discharge and for any increase in ebb flow, the flood:ebb flow ratio decreases.

FIGURE 8.3 shows the ratio of water to sediment discharge (Qw/Qs) for the base case scenario (2f), and scenarios with cross-dams and polders (A) [5a=2Qs:2Qw;0rslr, 5b=2Qs:2Qw;10rslr 5f=2Qs:2Qw;20rslr], (B) [5e=1Qs:2Qw;10rslr, 5b =2Qs:2Qw;10rslr, 5c =2Qs+45%:2Qw;10rslr, 5d = 6Qs:2Qw;10rsrl], (C) [6b: RSLR =10 mm/y,1Qw, 5b: RSLR =10 mm/y,2Qw, 6e: RSLR=10mm/y,3Qw], (D)[6a: RSLR = 0 mm/y ,1Qw, 6b: RSLR =10 mm/y, 1Qw, 6c: RSLR = 20 mm/y,1Qw], (E) [6d: RSLR = 0 mm/y ,3Qw, 6e: RSLR =10 mm/y ,3Qw, 6f: RSLR = 20 mm/y ,3Qw]. The value of the simulated ratio (Qw/Qs) in these scenarios indicates the local sediment transport capacity of the flow in the distributaries, with the larger the Qw/Qs value indicating increased sediment transport capacity and vice versa. FIGURE 8.3 shows that at location
2, i.e., near the delta apex, the duration of sediment transport in the ebb flow is greater than that of flood flow, resulting in net export of sediment from the delta. FIGURE 8.3 B, at location 2, shows that the intensity of \( Q_w/Q_s \) ratio increases with decreasing sediment discharge. Therefore, as expected, despite the influence of RSLR, polders and cross-dams, the sediment transport capacity increases with the decreasing rate of sediment supply. FIGURE 8.3 C shows that the duration of flood flow increases with decreasing water discharge, whereas the intensity increases with increasing water discharge. Comparing the time series of \( Q_w/Q_s \) ratio in FIGURE 8.3 D and E, it can be seen that the intensity of \( Q_w/Q_s \) ratio increases with increasing water discharge. This implies that the sediment transport capacity of the flow is more highly influenced by the water discharge than by the RSLR, polders and cross-dams. Similarly, the combined influence of fluvial water and sediment discharges, RSLR, polders and cross-dams at locations 6 (at the left most distributary mouth) and 10 (near the central island) can be seen in FIGURE 8.4 and FIGURE 8.5.
Chapter 8: The impacts of variations of multiple drivers on the morphology of tidally influenced deltas

FIGURE 8.1: Location of tidal flow observation points (brown colour) and spatial distribution of tidal flood to ebb flow ratio (blue colour) in the delta after 100 years for scenarios: (X) - basecase (2f- no interventions within the delta) and (Y) - 5a (With polders and cross-dams)
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 8.2: Location of tidal flow observation points (brown colour) and spatial distribution of tidal flood to ebb flow ratio (blue colour) in the delta after 100 years for scenarios: (X) - basecase (2f, no interventions within the delta, RSLR=0m, 2Qw=65,000 m³/s) and (Y) With polders and cross-dams: 6b(2Qs:1Qw;10m), 5b(2Qs:2Qw;10m), 6e (2Qs:3Qw;10m)

Note: Water discharge, Qw = 32,500 m³/s; sediment discharge, Qs = 0.74 m³/s
Chapter 8: The impacts of variations of multiple drivers on the morphology of tidally influenced deltas
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 8.3: Ratio of water to sediment discharge after 100 years at observation location 2. See FIGURE 8.2 for the location of observation point

For scenarios (A)- base case (2f) and with polders and cross-dams combination with: 5a(2Qs:2Qw;0rslr), 5b(2Qs:2Qw;10rslr), 5f(2Qs:2Qw;20rslr), (B)- base case (2f) and combination: 5e(1Qs:2Qw;10rslr), 5b(2Qs:2Qw;10rslr), 5c(2Qs+45%.2Qw;10rslr), 5d(6Qs:2Qw;10rslr), (C)- base case (2f) and combination: 6b(2Qs:1Qw;10rslr), 5b(2Qs:2Qw;10rslr), 6e(2Qs:3Qw;10rslr), (D)- base case (2f) and combination: 2e(2Qs:1Qw;0rslr), 6a(2Qs:1Qw;0rslr), 6b(2Qs:1Qw;10rslr), 6c(2Qs:1Qw;20rslr), (E)- base case (2f) and combination: 2g(2Qs:3Qw;0rslr), 6d(2Qs:3Qw;0rslr), 6e(2Qs:3Qw;10rslr), 6f(2Qs:3Qw;20rslr)

Note: Water discharge, Qw= 32,500m$^3$/s; sediment discharge, Qs = 0.74m$^3$/s
Chapter 8: The impacts of variations of multiple drivers on the morphology of tidally influenced deltas.
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 8.4: Ratio of water to sediment discharge after 100 years at observation location 6. See FIGURE 8.2 for the location of observation point.

For scenarios (A) base case (2f) and with polders and cross-dams combination with: 5a(2Qs:2Qw;0rslr), 5b(2Qs:2Qw;10rslr), 5f(2Qs:2Qw;20rslr), (B) base case (2f) and combination: 5e(1Qs:2Qw;10rslr), 5b(2Qs:2Qw;10rslr), 5c(2Qs+45%.2Qw;10rslr), 5d(6Qs:2Qw;10rslr), (C) base case (2f) and combination: 6b(2Qs:1Qw;10rslr), 5b(2Qs:2Qw;10rslr), 6e(2Qs:3Qw;10rslr), (D) base case (2f) and combination: 2e(2Qs:1Qw;0rslr), 6a(2Qs:1Qw;0rslr), 6b(2Qs:1Qw;10rslr), 6c(2Qs:1Qw;20rslr), (E) base case (2f) and combination: 2g(2Qs:3Qw;0rslr), 6d(2Qs:3Qw;0rslr), 6e(2Qs:3Qw;10rslr), 6f(2Qs:3Qw;20rslr)

Note: Water discharge, Qw = 32,500 m³/s; sediment discharge, Qs = 0.74 m³/s
Chapter 8: The impacts of variations of multiple drivers on the morphology of tidally influenced deltas

![Graph A](image-url)

![Graph B](image-url)

![Graph C](image-url)
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 8.5: Ratio of water to sediment discharge after 100 years at observation location 10. See FIGURE 8.2 for the location of observation point

For scenarios (A)- base case (2f) and with polders and cross-dams combination with: 5a(2Qs:2Qw;0rslr), 5b(2Qs:2Qw;10rslr), 5f(2Qs:2Qw;20rslr) , (B)- base case (2f) and combination: 5e(1Qs:2Qw;10rslr), 5b(2Qs:2Qw;10rslr), 5c(2Qs+45%:2Qw;10rslr), 5d(6Qs:2Qw;10rslr), (C)- base case (2f) and combination: 6b(2Qs:1Qw;10rslr), 5b(2Qs:2Qw;10rslr), 6e(2Qs:3Qw;10rslr), (D)- base case (2f) and combination: 2e(2Qs:1Qw;0rslr), 6a(2Qs:1Qw;0rslr), 6b(2Qs:1Qw;10rslr), 6c(2Qs:1Qw;20rslr), (E)- base case (2f) and combination: 2g(2Qs:3Qw;0rslr), 6d(2Qs:3Qw;0rslr), 6e(2Qs:3Qw;10rslr), 6f(2Qs:3Qw;20rslr)

Note: Water discharge, Qw= 32,500m³/s; sediment discharge, Qs = 0.74m³/s

8.2.2 Patterns of erosion and accretion over the delta

FIGURE 12.10 B1 and B2 shows the simulated pattern of erosion and accretion after 100 years for the scenario (5a) with polders and cross-dams together. In this scenario, sedimentation inside the poldered area and bank erosion of the islands are not allowed. The results show progradation of the delta front.
Chapter 8: The impacts of variations of multiple drivers on the morphology of tidally influenced deltas

islands (except the southern one), sedimentation in the distributaries with cross-dams, and erosion elsewhere. Instead of progradation, the seaward side of the southern island experienced erosion purely due to the high sediment transport capacity of flow caused by the introduction of cross-dams, as described in section 7.3.3. When compared to the base case (FIGURE 12.10B2 in Appendix 12), a greater amount of sedimentation towards the sea is evident on either side of the southern island. The pattern of erosion and accretion over the delta in scenario 5a (the scenario with both polders and cross-dams) is, overall, similar to the pattern observed in the scenario with cross dams (4b) only (See section 7.3.2). However, the effect of polders at places such as in the south-west corner of the delta, by causing greater erosion on the bed of the distributaries compared to the pure cross-dams scenario, can also be seen (See section 7.3.2).

Due to the polders, the flow of water and sediment is confined within the distributaries. Cross-dams increase the tidal asymmetry of the flow in the distributaries that have no cross-dams. Because of the tidal asymmetry caused by both the polders and the cross-dams, more sediment is transported towards the sea. As the flow enters the sea, the momentum of the flow decreases resulting in the reduction of the sediment transport capacity of the flow and thus depositing the sediment on the sea bed (Edmonds and Slingerland, 2007). However, due to the presence of the cross-dams, there is a larger sediment capacity along the front edge of the southern island, inducing erosion to occur there. Also, the sediment deposition adjacent to the mouth of distributary with a cross-dam (No.2) and upstream of the cross-dam (No.1) near the delta apex is due to the increased backwater effect caused by these structures. Within the distributaries, where the tidal asymmetry has increased, this process results in net erosion.

FIGURE 12.10 B1 and B2, C1 and C2, D1 and D2 in Appendix 12 show the pattern of accretion and erosion simulated after 100 years for scenarios 5a (2Qs:2Qw:0rslr), 5b (2Qs:2Qw:10rslr), and 5f (2Qs:2Qw:20rslr), which in each case also include the effects of both polders and cross-dams. The pattern of erosion and accretion as described above for scenario 5a (2Qs:2Qw:0rslr) can also be generally seen in scenario 5b (2Qs:2Qw:10rslr), and indeed scenario 5f
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

(2Qs:2Qw;20rslr). But, net accretion over the bed of the distributaries and sea increases with the increasing RSLR scenarios: 5b (2Qs:2Qw;10rslr) and 5f (2Qs:2Qw;20rslr). The depth of water in the distributaries also increases with increasing RSLR, thus increasing the accommodation space, reducing the tidal asymmetry and the local sediment transport capacity of the flow, as explained in section 6.2. The process of accretion caused by cross-dams and polders is therefore enhanced by increasing RSLR, but the process of erosion is counteracted by the effects of the increasing RSLR.

FIGURE 12.10 E1 and E2, C1 and C2, F1 and F2, and G1 and G2 in Appendix 12 show the pattern of accretion and erosion simulated after 100 years for scenarios with varying water and sediment discharges: 5e (1Qs:2Qw;10rslr), 5b (2Qs:2Qw;10rslr), 5c (2Qs+45%;2Qw;10rslr) and 5d (6Qs:2Qw;10rslr), which in all cases have 1 m of RSLR, polders and cross-dams. The accretion increases and erosion decreases with increasing fluvial sediment discharge over the template of accretion and erosion described above. The effect of increasing sediment discharge acts together with the effect of cross-dams and polders to cause more accretion and acts against each other to cause less erosion as the sediment supply equals or exceeds the sediment transport capacity of the flow in the distributaries, as explained in section 8.2.1.

FIGURE 12.10 H1 and H2, C1 and C2, I1 and I2 in Appendix 12 show the pattern of accretion and erosion simulated after 100 years for a further range of scenarios with varying water and sediment discharges: 6b (2Qs:1Qw;10rslr), 5b (2Qs:2Qw;10rslr) and 6e (2Qs:3Qw;10rslr). Again, all these scenarios maintain 1m of RSLR, and include polders and cross-dams. The accretion decreases and erosion increases over the bed of the distributaries with increasing fluvial water discharge. Increasing water discharge also decreases the flood:ebb flow ratio outside the zone of the cross-dams. The magnitude of the tidal prism and its asymmetry both increase with increasing water discharge, as explained in section 8.2.1. This leads to an increasing sediment transport capacity as shown in FIGURE 8.4 and FIGURE 8.5C during the ebb phase, thereby inducing a tendency for greater erosion. The distance of seaward deposition of sediment increases with increasing water discharge as the momentum of flow, and thus the sediment transport capacity of the flow, increases with increasing water discharge.
Chapter 8: The impacts of variations of multiple drivers on the morphology of tidally influenced deltas

discharge. The effect of both cross-dams and water discharge dominate the pattern of erosion and accretion.
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 8.6: Net volume of accretion and erosion against the depth of accretion and erosion after 100 years for scenarios: Base case (2f-no interventions) (A1 & A2) and with interventions 5a (2Qs:2Qw:0rslr) (B1 & B2), 5b (2Qs:2Qw;10rslr) (C1 & C2), 5f(2Qs:2Qw;20rslr) (D1 & D2)

Note: Water discharge, Qw= 32,500m³/s; sediment discharge, Qs = 0.74m³/s
Chapter 8: The impacts of variations of multiple drivers on the morphology of tidally influenced deltas

Net volume of accretion (Million cu.m) vs accretion depth (m)  
Net volume of erosion (Million cu.m) vs erosion depth (m)

FIGURE 8.7: Net volume of accretion and erosion against the depth of accretion and erosion after 100 years for scenarios: 5e (1Qs:2Qw:10rslr) (E1 & E2) and 5c (2Qs+45% over 100 years:2Qw:10rslr) (F1 & F2), 5d (6Qs:2Qw:10rslr) (G1 & G2)

Note: Water discharge, Qw= 32,500m$^3$/s; sediment discharge, Qs = 0.74m$^3$/s
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 8.8: Net volume of accretion and erosion against the depth of accretion and erosion after 100 years for scenarios: 6b (2Qs:1Qw;10rslr) (H1 &H2) and 6e (2Qs:3Qw;10rslr) (I1 &I2)

Note: Water discharge, Qw= 32,500m³/s; sediment discharge, Qs = 0.74m³/s

FIGURE 8.6 shows that, when compared to the base case scenario (2f- no RSLR, no polders and cross-dams), the simulated net accretion decreases at 10m depth with increasing RSLR, but increases at water depths of 5 and 20m with increasing RSLR (FIGURE 8.6 A1, B1, C1 and D1) for all the scenarios (5a=2Qs:2Qw;0rslr, 5b=2Qs:2Qw;10rslr and 5f=2Qs:2Qw;20rslr) with polders and cross-dams. The erosion at depths of 30 and 40m is decreased due to polders. However, erosion for depths smaller than 30m increases with increasing RSLR (FIGURE 8.6 A2, B2, C2 and D2). FIGURE 8.7 shows, when compared to the base case scenario, that simulated accretion increases with increasing sediment discharge (FIGURE 8.7 E1, F1 and G1), whereas erosion at depths greater than 5m decreases with increasing sediment discharges for scenarios of varying fluvial sediment discharge (5e=1Qs:2Qw;10rslr, 5b=2Qs:2Qw;10rslr,
Chapter 8: The impacts of variations of multiple drivers on the morphology of tidally influenced deltas

$5c=2Qs+45\%:2Qw;10rslr$ and $5d=6Qs;2Qw;10rslr$) with RSLR of 10 mm/y, polders and cross-dams. FIGURE 8.8 shows that the net volume of accretion over the delta decreases with increasing water discharge and the net volume of erosion increases with increasing water discharge with RSLR of 10 mm/y, polders and cross-dams. The simulated erosion, for depths smaller than 0.5 m, increases with decreasing water discharge whereas for depths greater than 0.5 m it increases with increasing water discharge. The net erosion in shallow locations is associated with the distributaries, whereas erosion in deeper areas tends to be focused more to the front of the southern island and the island on the south-east corner of the delta. The accretion zones are associated with sediment deposition on the distributaries and sea bed and also to the progradation of the islands on the delta front (except the southern one) as the seaward side of the southern island experienced erosion purely due to the high sediment transport capacity of flow caused by the introduction of cross-dams as described in section 7.3.

FIGURE 8.9: Volume of accretion and erosion in delta area after 100 years for varying relative sea level rise and sediment discharges with polders and cross-dams
Note: RSLR=1m; $5e$ (1Qs:2Qw;10rslr), $5b$ (2Qs:2Qw;10rslr), $5c$ (2Qs+45\%:2Qw;10rslr) and $5d$ (6Qs:2Qw;10rslr)
Note: Water discharge, $Qw=32,500\text{m}^3/\text{s}$; sediment discharge, $Qs=0.74\text{m}^3/\text{s}$
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 8.10: Ratio of volume of accretion to erosion in delta after 100 years for base case and scenarios of relative sea level rise and water discharges with polders and cross-dams

Note: 6a (2Qs:1Qw;0rslr), 6b (2Qs:1Qw;10rslr), 6c (2Qs:1Qw;20rslr), 5a (2Qs:2Qw;0rslr), 5b (2Qs:2Qw;10rslr), 5f (2Qs:2Qw;20rslr), 6d (2Qs:3Qw;0rslr), 6e (2Qs:3Qw;10rslr) and 6f (2Qs:3Qw;20rslr). Water discharge, Qw=32,500m³/s; sediment discharge, Qs = 0.74m³/s

FIGURE 8.9 shows that with increasing fluvial sediment supply to the delta, the trend of increasing accretion and decreasing erosion is maintained, even with the human interventions of polders and cross-dams within the delta. For the same amount of accommodation space created by the RSLR, increased accretion and decreased erosion occurs with increased sediment supply.

FIGURE 8.10 shows the ratio of the volume of accretion to erosion and summarises how both accretion and erosion are highly influenced by the increasing water discharge and RSLR. On one side, the sediment transport capacity of the flow and sediment supply increases with increasing water discharge, while on the other the accommodation space and the rate of sediment deposition increases with increasing RSLR, as explained in section 8.2.1. The effect of these processes on the volume of accretion and erosion over the delta can be seen in FIGURE 8.10.
8.2.3 Progradation and aggradation of the delta

FIGURE 8.11: Ground elevation and bathymetry for the base case scenario (2f;SLR=0mm/y) after 100 years of simulation. Location plan of longitudinal and cross sections of delta

FIGURE 8.12: Longitudinal section of the delta through its centre (x-x) for initial condition and after 100 years for base case and scenarios with polders and cross-dams, 5e (1Qs:2Qw;10rslr), 5b (2Qs:2Qw;10rslr), 5c (2Qs+45%:2Qw;10rslr), and 5d (6Qs:2Qw;10rslr) See FIGURE 8.11 for location

Note: Water discharge, $Q_w=32,500m^3/s$; sediment discharge, $Q_s=0.74m^3/s$
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 8.13: Cross section of the delta at location 1-1 for initial condition and after 100 years for base case and scenarios with polders and cross-dams, 5e (1Qs:2Qw;10rslr), 5b (2Qs:2Qw;10rslr), 5c (2Qs+45%:2Qw;10rslr), and 5d (6Qs:2Qw;10rslr). See FIGURE 8.11 for location. Green dashed lines indicate the effect due to cross-dams.

Note: Water discharge, Qw = 32,500 m$^3$/s; sediment discharge, Qs = 0.74 m$^3$/s

FIGURE 8.12 compares the progradation of the delta at the initial condition and after 100 years for scenarios of increasing sediment supply: 2f (base case), 5e (1Qs:2Qw;10rslr), 5b (2Qs:2Qw;10rslr), 5c (2Qs+45%:2Qw;10rslr) and 5d (6Qs:2Qw;10rslr) with, in all cases, 1 m of RSLR, polders and cross-dams. The comparison of the shape of the clinoform shows that the progradation of the delta is highly influenced by the cross-dams and is not sensitive to the increasing sediment supply. With the islands polderised, however, the positive effect of increasing sediment supply on the aggradation of the land is not productive. Hence, the effect of cross-dams and polders dominate the progradation and aggradation of the delta. FIGURE 8.13 compares the cross-section of the delta at location 1-1 for the initial condition and after 100 years for scenarios 5e (1Qs:2Qw;10rslr), 5b (2Qs:2Qw;10rslr), 5c (2Qs+45%:2Qw;10rslr) and 5d (6Qs:2Qw;10rslr) (with 1 m of RSLR, polders and cross-dams in each of these cases). FIGURE 8.13 shows that the erosion of distributaries decreases with increasing fluvial sediment supply despite the increase in RSLR. The green dashed oval and box lines in FIGURE 8.13 indicate the accretion and erosion, respectively, due to the cross-dams. A similar pattern of progradation of the delta and morphodynamic changes of the distributaries is also seen in the simulations for scenarios 5g (1Qs:2Qw;0rslr), 5a (2Qs:2Qw;0rslr), 5h (2Qs+45%:2Qw;0rslr) and 5i (1Qs:2Qw;20rslr), 5f (2Qs:2Qw;20rslr) and 5j (2Qs+45%:2Qw;20rslr).
Chapter 8: The impacts of variations of multiple drivers on the morphology of tidally influenced deltas

FIGURE 8.14: Longitudinal section of the delta through its centre (x-x) for initial condition and after 100 years for base case and scenarios with polders and cross-dams; 6c (2Qs:1Qw;20rslr), 5f (2Qs:2Qw;20rslr), and 6f (2Qs:3Qw;20rslr). See FIGURE 8.11 for location

Note: Water discharge, Qw= 32,500m$^3$/s; sediment discharge, Qs = 0.74m$^3$/s

FIGURE 8.14 compares the progradation of the delta for the initial condition and after 100 years of the simulation for scenarios 2f (base case), 6c (2Qs:1Qw;20rslr), 5f (2Qs:2Qw;20rslr), and 6f (2Qs:3Qw;20rslr) with polders and cross-dams. FIGURE 8.14 shows that the progradation of the deltaic clinoform increases with increasing water discharge whereas its aggradation decreases with increasing water discharge. The shape of the clinoform is defined more by the effect of cross-dams and increasing water discharge than by the effect of RSLR (see sections 5.3.2, 6.3.2 and 7.3.3). FIGURE 8.16 compares the cross-section of the delta at location 1-1 for the initial condition and after 100 years of the simulation for scenarios 6c (2Qs:1Qw;20rslr), 5f (2Qs:2Qw;20rslr), and 6f (2Qs:3Qw;20rslr) with polders and cross-dams. FIGURE 8.16 shows that the erosion of the bed of the distributaries significantly increases with increasing water discharge. Increasing the RSLR and water discharge together acts to increase bed erosion. The green dashed lines in FIGURE 8.16 indicate the dominance of the effect of cross-dams on the cross-sectional morphodynamics of the distributaries. A similar pattern of progradation of the delta and morphodynamic changes of the distributary cross-sections is also simulated in scenarios 6a (2Qs:1Qw;0rslr), 5a (2Qs:2Qw;0rslr), and 6d (2Qs:3Qw;0rslr) and 6b.
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

(2Qs:1Qw;10rsr), 5b (2Qs:2Qw;10rsr), and 6e (2Qs:3Qw;10rsr). FIGURE 8.15 shows that the clinoform angle is sensitive to the variation in fluvial water discharges and sea level rise but not much to the sediment discharges under the conjunctive scenarios. When only the fluvial water discharge was varied, the response of the clinoform angle was similar (see Section 5.3.2) to the combined response but during the individual variation of sea level rise clinoform angle was not varying much (see Section 6.3.2).

FIGURE 8.15: Time-series plot of modelled clinoform angle for the varying rates of fluvial discharges, and sea level under combined scenarios

FIGURE 8.16: Cross section of the delta at location1-1 for initial condition and after 100 years for base case and scenarios with polders and cross-dams, 6c (2Qs:1Qw;20rsr), 5f (2Qs:2Qw;20rsr), and 6f (2Qs:3Qw;20rsr). See FIGURE 8.11 for location. Green dashed lines indicate the effect due to cross-dams.

Note: Water discharge, Qw = 32,500m$^3$/s; sediment discharge, Qs = 0.74m$^3$/s
8.2.4 Morphodynamics of the sub-aerial delta

FIGURE 8.17 A and B show the time series of accretion over the sub-aerial delta formed outside the poldered area for scenarios of increasing water discharge. The area of accretion is initially zero as no morphodynamic changes of poldered islands and banks are allowed in the model. Any accretion or erosion shown in FIGURE 8.17 is, therefore, focused only on the land area developed outside the poldered area. Because of the presence of polders, both the area of accretion and erosion is smaller than in the base case (2f) scenario. For all the scenarios of varying water discharge considered here, the area of accretion increases with increasing RSLR for scenarios of 10 mm/y RSLR (6a=2Q_s:1Q_w;0rslr to 6b=2Q_s:1Q_w;10rslr, 6d=2Q_s:3Q_w;0rslr to 6e=2Q_s:3Q_w;10rslr), whereas the area of accretion decreases for 20 mm/y RSLR (Scenario 6c=2Q_s:1Q_w;20rslr, 6f=2Q_s:3Q_w;20rslr). The amount of accretion increases with increasing RSLR (6a=2Q_s:1Q_w;0rslr, 6b=2Q_s:1Q_w;10rslr, 6c=2Q_s:1Q_w;20rslr) and decreases with increasing water discharge (6a=2Q_s:1Q_w;0rslr, 6d=2Q_s:3Q_w;0rslr, 6f=2Q_s:3Q_w;20rslr). The amount of accretion decreases for 20 mm/y RSLR (Scenario 6c=2Q_s:1Q_w;20rslr, 6f=2Q_s:3Q_w;20rslr).

FIGURE 8.17 C shows that the area of erosion begins with zero and increases with increasing water discharge (6a=2Q_s:1Q_w;0rslr and 6d=2Q_s:3Q_w;0rslr) and decreases with increasing RSLR (6b=2Q_s:1Q_w;10rslr and 6e=2Q_s:3Q_w;10rslr). As the RSLR increases, the extent of sub-aerial delta formed outside the poldered area decreases because of the increased submergence and accommodation space created. FIGURE 8.17 D shows that the amount of erosion increases with increasing water discharge and RSLR, with the RSLR especially enhancing the rate of erosion significantly.

FIGURE 8.18 A and B show the time series of accretion over the sub-aerial delta land formed outside the poldered area for scenarios of increasing sediment discharge. The area of accretion over the sub-aerial delta begins from zero and increases with increasing sediment discharge (scenarios 5a=2Q_s:2Q_w;0rslr, 5b=2Q_s:2Q_w;10rslr, and 5f=2Q_s:2Q_w;20rslr). The amount of accretion increases with increasing sediment discharge (5e=1Q_s:2Q_w;10rslr -> 5b=2Q_s:2Q_w;10rslr -> 5c=2Q_s+45%:2Q_w;10rslr -> 5d=6Q_s:2Q_w;10rslr) and increasing RSLR (5a=2Q_s:2Q_w;0rslr -> 5b=2Q_s:2Q_w;10rslr -> 5f=2Q_s:2Q_w;20rslr). Increasing RSLR enhances the effect of increasing sediment discharge. FIGURE 8.18C shows that the area of erosion
decreases with increasing RSLR and sediment discharge. The amount of erosion increases with increasing RSLR and sediment discharge (see FIGURE 8.18D). The increase in RSLR results in increasing accommodation space. The increased rate of sediment supply results in increased sediment deposition to balance the accommodation space created by the RSLR. A greater extent of sub-aerial delta will be generated for the scenario \( (Sd=6Qs:2Qw;10rslr) \) with higher rate of sediment supply due to the quicker rate of formation of the sub-aerial delta. Hence, the rate of erosion increases with increasing sediment discharge.
Chapter 8: The impacts of variations of multiple drivers on the morphology of tidally influenced deltas

FIGURE 8.17: Area and rate of accretion and erosion over sub-aerial delta for scenarios of varying water discharge and relative sea level rise with polders and cross-dams. Note: Water discharge, $Q_w = 32,500 \text{m}^3/\text{s}$; sediment discharge, $Q_s = 0.74 \text{m}^3/\text{s}$
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 8.18: Area and rate of accretion and erosion over sub-aerial delta for scenarios of varying sediment discharge and relative sea level rise with polders and cross-dams. Note: Water discharge, $Q_w = 32,500\text{m}^3/\text{s}$; sediment discharge, $Q_s = 0.74\text{m}^3/\text{s}$
Chapter 8: The impacts of variations of multiple drivers on the morphology of tidally influenced deltas

FIGURE 8.19: Delta land area for scenarios of varying water discharge and relative sea level rise with polders and cross-dams after 100 years

Note: 6a (2Qs:1Qw:0rslr), 6b (2Qs:1Qw:10rslr), 6c (2Qs:1Qw:20rslr), 5a (2Qs:2Qw:0rslr), 5b (2Qs:2Qw:10rslr), 5f (2Qs:2Qw:20rslr), 6d (2Qs:3Qw:0rslr), 6e (2Qs:3Qw:10rslr), 6f (2Qs:3Qw:20rslr). Water discharge, Qw = 32,500 m$^3$/s; sediment discharge, Qs = 0.74 m$^3$/s

FIGURE 8.19 shows that the sub-aerial delta area decreases with increasing RSLR and water discharge but is not decreased to values less than the initial delta area. Despite RSLR, the sub-aerial delta is always greater than the initial area due to the prevention of bank and land erosion of the poldered area in the model. However, the amount of sub-aerial poldered area below sea level increases with increasing RSLR, as shown in FIGURE 8.21. More than 90% of the poldered area falls below the sea level after 100 years for all scenarios with 2m of RSLR (6c=2Qs:1Qw:20rslr, 5f=2Qs:2Qw:20rslr, 6f=2Qs:3Qw:20rslr), but only 10% of the poldered area falls below the sea level after 100 years for the scenarios with 1m of RSLR (6b=2Qs:1Qw:10rslr, 5b=2Qs:2Qw:10rslr, 6e=2Qs:3Qw:10rslr), see FIGURE 8.21. FIGURE 8.19 also shows that the extent of the sub-aerial delta formed outside the poldered areas increases with decreasing water discharge and decreases with increasing RSLR.

FIGURE 8.20 shows that the sub-aerial delta extent decreases with increasing RSLR, but increases with increasing sediment discharge. The sub-aerial delta area is not smaller than the initial area due to the prevention of bank and land erosion of the poldered area in the model. However, the amount of sub-aerial...
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

Poldered area below sea level increases with sea level. More than 90% of the poldered area falls below the sea level after 100 years for 2m RSLR scenarios (5f=2Qs:2Qw;20rslr, 5i=1Qs:2Qw;20rslr, 5j=2Qs+45%:2Qw;20rslr) but only 10% of poldered area falls below the sea level after 100 years for 1m RSLR scenarios (5b=2Qs:2Qw;10rslr, 5c=2Qs+45%:2Qw;10rslr, 5d=6Qs:2Qw;10rslr, 5e=1Qs:2Qw;10rslr), see FIGURE 8.22. FIGURE 8.20 also shows that the amount of sub-aerial delta formed outside the poldered increases with increasing sediment discharge and decreases with increasing RSLR.

![Figure 8.20: Delta land area for varying sediment discharges and relative sea level rise with polders and cross-dams after 100 years](image)

Note: 5d (6Qs:2Qw;10rslr), 5h (2Qs+45%:2Qw;0rslr), 5c (2Qs+45%:2Qw;10rslr), 5j (2Qs+45%:2Qw;20rslr), 5a (2Qs:2Qw;0rslr), 5b (2Qs:2Qw;10rslr), 5f (2Qs:2Qw;20rslr), 5g (1Qs:2Qw;0rslr), 5e (1Qs:2Qw;10rslr), 5i (1Qs:2Qw;20rslr), Water discharge, Qw=32,500m³/s; sediment discharge, Qs = 0.74m³/s; Qs=Qss (sand sediment)+Qsf (fine sediment)

The amount of sub-aerial delta change from the initial condition after 100 years, individually, due to the low water discharge (2e) is +57km², polders induce an increase in extent of +92km², while SLR leads to a loss of -214km², and cross-dams a net loss of -21km². However, applying the principle of superposition shows that the individual effect of polders, cross-dams, sea level rise, water and sediment discharges (total area=608sq.km) is not the same as the combined effects (area=780 sq.km). This implies that the morphodynamic response of the system is non-linear. Despite RSLR, poldered areas will remain unsubmerged. The effect of polders and cross-dams dominate the morphological evolution of the sub-aerial delta with the trend of individual
Chapter 8: The impacts of variations of multiple drivers on the morphology of tidally influenced deltas

influence of fluvial sediment and water discharge remains the same when combined.

FIGURE 8.21: Percentage of delta land area below sea level for varying water discharges and relative sea level rise with polders and cross-dams
Note: 6b (2Qs:1Qw;10rslr), 6c (2Qs:1Qw;20rslr), 5b (2Qs:2Qw;10rslr), 5f (2Qs:2Qw;20rslr), 6e (2Qs:3Qw;10rslr), 6f (2Qs:3Qw;20rslr). Water discharge, Qw = 32,500m$^3$/s; sediment discharge, Qs = 0.74m$^3$/s

FIGURE 8.22: Percentage of delta land area below sea level for varying sediment discharges and relative sea level rise with polders and cross-dams
Note: 5g (1Qs:2Qw;0rslr), 5f (2Qs:2Qw;20rslr), 5h (2Qs+45%:2Qw;0rslr), 5b (2Qs:2Qw;10rslr), 5c (2Qs+45%:2Qw;10rslr), 5d (6Qs:2Qw;10rslr), 5e (1Qs:2Qw;10rslr). Note: Water discharge, Qw = 32,500m$^3$/s; sediment discharge, Qs = 0.74m$^3$/s
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 8.23: Probability distribution function of island size normalised to total island area for the conjunctive scenarios of a) varying fluvial water discharge, b) varying fluvial sediment discharge, and c) varying amount of sea level rise with polders and cross-dams

FIGURE 8.23 a and b show that under the combined scenario with decrease in fluvial water discharge and increase in fluvial sediment discharge led to increase in the number of islands or bifurcations. Similar to the individual influence by the sea level rise (FIGURE 6.26), increasing sea level rise leads to
increasing number of islands or bifurcations (FIGURE 8.23c). The distributions are multi-modal and are similar to the real world GBM delta (FIGURE 2.11). The unimodal shape of the island shape factor distribution for the conjunctive scenarios of varying fluvial water and sediment discharges, FIGURE 8.24 a and b, indicates the domination of polders over other drivers (see FIGURE 7.40). However, the multi-modal shape of the distributions shows the dominance of the sea level rise (FIGURE 6.27) over the polders and cross-dams (FIGURE 8.24c). FIGURE 8.25 shows that the distributions of the island aspect ratio for the conjunctive scenario is unimodal and looks similar to the real world delta one (FIGURE 2.11). FIGURE 8.26 shows the dominance of polders over other drivers in influencing the nearest-edge distance of the modelled delta. This is because of no erosion of the poldered area allowed in the model.
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

**FIGURE 8.24:** Probability distribution function of island shape factor for the conjunctive scenarios of a) varying fluvial water discharge, b) varying fluvial sediment discharge, and c) varying amount of sea level rise with polders and cross-dams
Chapter 8: The impacts of variations of multiple drivers on the morphology of tidally influenced deltas

FIGURE 8.25: Probability distribution function of island aspect ratio for the conjunctive scenarios of a) varying fluvial water discharge, b) varying fluvial sediment discharge, and c) varying amount of sea level rise
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 8.26: Probability distribution function of nearest-edge distance for the conjunctive scenarios of a) varying fluvial water discharge, b) varying fluvial sediment discharge, and c) varying amount of sea level rise
Chapter 8: The impacts of variations of multiple drivers on the morphology of tidally influenced deltas

FIGURE 8.27: Time-series plot of modelled shoreline rugosity for the conjunctive scenarios of varying rates of sea level rise with Polders and Cross-dams compared against Base-case scenario

FIGURE 8.27 shows that in the conjunctive case, the rugosity of the shoreline decreases with increasing sea level rise but the shoreline rugosity increased when only the sea level rise was varied without human interventions. This implies that the natural process of delta building during sea level rise at the delta front is hindered by the engineering structures such as polder dykes.

8.3 Discussions

Number of studies have attempted to understand the processes and the influence of drivers behind the observed morphological evolution of the delta especially to find the role of each drivers on the past morphodynamic changes (Dada et al., 2016, Anwar, 2013, Zhang et al., 2016, Rahman et al., 2011, Coleman et al., 2008, Paola et al., 2011, Wilson and Goodbred, 2015). Albert and Jorge (1998) predict that future morphological evolution of the delta (Ebro) will be similar to that of the abandoned deltaic lobes due to the reduced fluvial sediment supply to the delta and relative sea level rise and also predict that any hard engineering measures to protect the delta will not provide a long term solution to the problem. Whereas Rovira and Ibàñez (2007) recommends a sediment management plan to restore the natural fluvial sediment supply to the delta (Ebro) in order to stop the degradation of the delta and to counteract
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

the effect of RSLR. They call this as a sustainable approach against the engineering option of building polders to protect the delta from inundation. Similarly, the findings of this study show that the polders provide a greater sub-aerial delta than without polders but may not provide a sustainable long term solution (see FIGURE 8.21 and FIGURE 8.22). With the help of a numerical model, Manh et al. (2015) studied both the individual and combined effect of the future construction of dams, future climate change and relative sea level rise (RSLR) on the floodplain sediment dynamics of the Mekong River delta. It has been found that the reduction in the fluvial sediment supply to the delta due to the construction of dams dominated the other two factors in influencing the amount and extent of sedimentation on the deltaic floodplain with the climate change having the second-order effect. This implies that the main drivers influencing the morphological evolution of the delta could vary between the deltas and could vary over time and space within the same delta. However, it is believed that the results of this study provide more insight into the interaction of the factors and their influence on the delta metrics such as the area and perimeter of the sub-aerial delta.

8.4  Summary

1. **What are the combined effects of anthropogenic interventions such as polders and cross-dams, and environmental change such as RSLR and fluvial water and sediment discharge?**

   A. The model simulations undertaken in this thesis reveal that tidal asymmetry is increased by the presence of polders and is significantly (30 to 200%) altered (increased or decreased) across the delta by the cross-dams due to the diversion of the flow (FIGURE 8.1). The alteration of the tidal asymmetry by the cross-dams is enhanced by the increasing water discharge (FIGURE 8.2 B). Thus, the local sediment transport capacity of the flow is altered, resulting in increased accretion and decreased erosion adjacent to cross-dams, and vice versa elsewhere. Tidal asymmetry increases with increasing RSLR and water discharge (FIGURE 8.3 to FIGURE 8.5). Increased water discharge enhances the accommodation space created by the increasing RSLR resulting in both increased accretion and erosion (FIGURE 8.6). The accretion increases
and erosion decreases with increasing sediment discharge (FIGURE 8.7 and FIGURE 8.9). The effect of cross-dams and polders dominate the pattern of erosion and accretion over the delta with the role of fluvial discharge and RSLR embedded on top (FIGURE 12.10 in Appendix 12). Similarly, the progradation and aggradation of the delta is dominated by the effect of cross-dams, polders and increasing water discharge (FIGURE 8.12 and FIGURE 8.14).

B. The sub-aerial delta area was found to decrease with increasing RSLR and water discharge (FIGURE 8.19). Both the factors acting together to decrease the area however, the delta area was found to be greater than the initial value (an increase of up to 13% over the initial value for 0m RSLR, and up to 8% for 2m of RSLR) and the base case value after 100 years as the banks of the poldered area are prevented from erosion, breaching and overtopping. In contrast, the sub-aerial delta area increases (by 12% of the initial value for 0m RSLR and by up to 7% for 2m RSLR) with increasing sediment discharge (FIGURE 8.20), but decreases with increasing RSLR. However, the land area protected by polders is below the increasing sea level. The sub-aerial delta area thus indicates that the combined influence of a range of driving factors is not simply the sum of the individual factors. For example, considering the following factors: low sediment discharge, polders, cross-dams under 1 m of RSLR (over the 100 year simulation period) one by one individually, the sub-aerial delta area would be 608 km$^2$, but combining those factors in fact results in a sub-aerial delta area of 780km$^2$. This implies that the combined influence of factors on the morphodynamic response is not the same as the sum of the individual effect of factors when combined.
9. Discussion and conclusion

9.1 Introduction

In this chapter, the key findings of this thesis, as presented and discussed in the previous chapters (from 4 to 8) are summarised and discussed with implications for real world tide dominated deltas. The limitations of the current research are also discussed, with recommendations for future work provided and then overall conclusions are drawn.

9.2 Lessons derived from the methodological approach

As the availability of reliable data is very scarce in many of the world’s deltas, demonstrating the link between morphodynamic and environmental changes such as variations in fluvial sediment supply, sea-level rise, subsidence and direct interventions such as construction of polders is still very challenging (see Chapters 2 and 3). To address the aim of investigating how contemporary tidal delta morphology evolves over multi-decadal timescales under multiple drivers, in this thesis a morphodynamic model of an idealised tidal delta that shares a number of the essential characteristics of the Ganges-Brahmaputra-Meghna (GBM) delta was used to explore the influence of various drivers of contemporary environmental change on deltaic morphodynamic response. It is believed that this approach represents the first attempt to model an idealised mega delta to the scale (FIGURE 4.3) and metrics (FIGURE 4.10) of a real delta. A number of simulations over a time period of up to 50 morphological years were initially carried out by varying the model layout to produce an ideal tidal delta that resembles the major morphological features of the contemporary GBM delta. This research showed that a process-based numerical model can be successfully used to build an idealised mega delta and to experiment with varied forcing of natural and human drivers (Chapters 4 to 7). As well as fluvial and marine processes, this methodology also allows for an investigation of the role of realistic human interventions on the delta (Chapter 6 and 7). It should be noted that this method demands the use of a super computer as the simulation of such numerical models is computationally heavy (Section 4.2.1.3). Nevertheless, one advantage of the adopted method is that it can be
used to qualitatively understand the processes and mechanisms of morphodynamic changes of a delta over multiple timescales under multiple drivers; the model is in effect used as a substitute for the general lack of empirical data from real world deltas. Even though the rate and magnitude of morphodynamic changes in the real world delta may not match those simulated here, the relative role of the factors considered and their trends provides generic insights that will be applicable to the morphodynamics of real-world tidally-influenced deltas. Also, this method can be used to understand the influence of any delta specific drivers. The method adopted here is successfully used to systematically understand the influence of drivers on deltaic morphodynamics. However, there may be a limitation in applying the findings of this research to real world tidal deltas where the nature of sediment supply could be different to the one used here. This methodological approach is relatively new as past studies applying this approach include the qualitative understanding of the long-term morphodynamics of the North Sea tidal basins (Dissanayake et al., 2009, van der Wegen, 2013, van der Wegen and Roelvink, 2008, van der Wegen et al., 2008, Dastgheib et al., 2008) and the Yangtze River estuary (Guo et al., 2015). It is recommended to use this approach for future similar studies following the theory of applying enough of the essential physics to model the major morphological features.

9.3 Addressing the research questions

The numerical model results obtained in this study (Chapters 5 to 8) were systematically analysed to determine the response of estuarine hydrodynamics, residual flow and deltaic morphodynamics to imposed changes in a range of driving variables. Overall, the numerical modelling experiments provide important new insights into the multi-decadal morphodynamic behaviour of large tidal deltas.
Chapter 9: Discussions and conclusions

FIGURE 9.1: Spatial and temporal variation of flood:ebb flow ratio in a tidal cycle for experimental scenarios.

FIGURE 9.1a to c shows that the flood:ebb flow ratio increased with decreasing water discharge and increased with increasing water discharge over 100 years of simulation at the apex, middle and near the distributaries mouth of the ideal tidal delta. It is clearly evident that higher the riverine flow than stronger the ebb flow, whereas the lower the river flow than stronger the flood flow. Sea level rise led to the raised low and high water levels. Thus, the backwater effect
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

increased with increasing RSLR in both the flow directions, during high and low tides, and resulted in net increase in flood:ebb flow ratios over the delta.

FIGURE 9.1d to f implies that there is a gradual increase in the dominance of the tidal discharge against the fluvial discharge as RSLR increases, albeit it must still be recognised that in all the simulations the ebb flow still dominated the flood flow as the flood:ebb flow is less than 1. The introduction of polder-dykes in the model prevented the inundation of the tidal floodplains, thus increased the tidal prism and ebb flow. It should be noted that in the model scenario with polder-dykes, water was not allowed to overtop or breach the polder-dykes, and the poldered banks are assumed to be non-erodible. The effect of introducing cross dams significantly altered the value of the flood:ebb flow ratio, such that the flood and ebb flows are equalised in the distributaries (FIGURE 9.1 h & i) with cross-dams. Elsewhere, the value of the flood:ebb flow ratio has decreased, meaning that there is a greater ebb and smaller flood flow. When these drivers were combined, the effect of engineering structures on the residual flow dominated over the effect of natural drivers (see section 8.2.1.

Net accretion and erosion over the modelled delta

The spatial and temporal change of the accretion and erosion over the delta can be summarised numerically by the ratio of net accretion and erosion over 100 years as shown in FIGURE 9.2. The ratio of net accretion to erosion for the base case scenario after 100 years is equal to 1 (FIGURE 9.2), which shows that this scenario is in equilibrium. If the value of this ratio is less than one, it indicates net erosion, vice versa otherwise. The ratio of net accretion to erosion (FIGURE 9.2) over the entire delta shows the same trend as the response of the sub-aerial delta area to varying fluvial discharges in FIGURE 5.24. The value of this ratio is increasing with increasing sediment discharge and decreases with increasing water discharge. This ratio after 100 years decreases from 1.18 to 0.89 (25% decrease) for three times increase in water discharge and increases from 0.94 to 1.06 (12.7% increase) for three times increase in sediment discharge. This indicates that the volume of accretion and erosion over the delta is highly sensitive to the fluvial water discharge and relative sediment supply. For all the (5, 10, 15 & 20mm/y) RSLR scenarios explored,
net erosion is marginally greater than net accretion after 100 years of the simulation as their ratio value is around 0.97. It is net accretion for the polders scenario as the ratio of net accretion to erosion is marginally greater than 1. This can be associated with the accretion and mainly due to the prevention of islands bank erosion. Whereas it is net erosion for the cross-dams scenario with the accretion:erosion ratio value of 0.97. FIGURE 9.2 shows summarises how both accretion and erosion are highly influenced by the human interventions when combined with the variations of natural drivers. Generally, this ratio has increased due to the addition of engineering structures. As the RSLR increases, the ratio of net accretion to erosion increases however that is not the case individually for RSLR. But, the trend of individual effect of fluvial discharges is retained except for the fluvial sediment discharges (see Section 8.2.2).

FIGURE 9.2: Ratio of net accretion to erosion in the ideal tidal delta over 100 years for experimental scenarios. Note: Number of polders and cross-dams are constant over simulation period. Abbreviations: Qw- Water discharge; Qs – Sediment discharge; SLR- Sea level rise; P – Polders, CD- Cross-dams

In response to the hypotheses posed in Chapter 1, the following insights are acquired and presented by hypotheses:

1. Increased fluvial discharge will increase the area of sub-aerial delta
FIGURE 5.24 shows that the delta land area increases (1.14% increase for 2Qw:1Qs and 3.96% for 2Qw:3Qs) with increasing sediment discharge but decreases (8.23% increase for 1Qw:2Qs but only 0.09% increase for 3Qw:2Qs) with increasing water discharge. Channel bank erosion increases with fluvial water discharge (FIGURE 5.9E2) and decreases with increasing sediment discharge (FIGURE 5.9C2). FIGURE 5.24 shows that as both the sediment and water discharge increases the slope of net increase in sub-aerial delta area becomes flatter. This change in slope of sub-aerial delta plot against water discharge shows that increasing water discharge with increasing relative sediment supply will result in increase in sub-aerial delta. Within the tidally influenced deltas, sediment nourishment area is a function of residual flow than mere fluvial sediment flux. This metric sub-aerial delta area has closer implications to the people and their environment. A change to the sub-aerial delta area has direct socio-economic impacts. The findings in this study (See FIGURE 5.23) are consistent with Kong et al. (2015) where sub-aerial delta area increased with increasing sediment supply to the delta (Yellow River delta) and Dada et al. (2016) where the human induced reduction in the sediment supply to the delta (Niger), triggered the imbalance between the riverine sediment flux and nearshore dynamics leading to the erosion of the deltaic coast.

2. Increased water discharge will increase the number of distributaries

FIGURE 5.25 shows that number of distributaries increased with decreasing fluvial water discharge. This is mainly because of the channel erosion or splitting of the large island in the north-western part of the modelled delta into two. This is different from the river dominated deltas where the number of distributaries increases with increasing river discharge Edmonds et al. (2010) (see Section 3.3.2.3) because of the presence of tidal force in this study. In the tide dominated deltas, the flow is bidirectional due to the interaction of tidal and river discharges. Where the ebb dominance occurs, the number of distributaries decreases and where the flood dominance occurs the number of distributaries increases. However, as shown by Edmonds et al. (2010), the delta network is more stable for increasing water discharge than decreasing water
discharge. As explained by Kleinhans et al. (2012), within deltas, when flow is dominated by the tides, the bifurcations becomes confluences. The bifurcations are influenced by the downstream propagation of flow and sediment flux and the upstream propagation of: back water effect, propagation of sedimentation or erosion, energy gradients due to tides and reversing flows within the delta (see section 5.2).

FIGURE 5.6 to FIGURE 5.8 show that channel erosion and network evolution in the delta is a function of the flood to ebb flow ratio. Channel erosion in conditions of low water discharge scenarios (where the water discharge, Qw = 32,500m³/s) is more rapid than in the case of the medium water discharge (2Qw = 65,000m³/s) scenarios due to the higher flood to ebb flow ratio. No channel erosion was simulated in the high water discharge (3Qw = 97,500m³/s) scenarios due to the ebb-dominated residual flow. Greater ebb flow in adjacent distributary i.e., greater resistance to flood flow than in the bifurcating distributary was observed in the model. The flood:ebb flow ratio at point 14 in adjacent distributary is smaller than the ratio at point 5 in bifurcating distributary (see FIGURE 5.4). The value of this ratio decreases by 3 fold, from 0.6 to 0.2, when the water discharge is increased by a factor of 3 i.e., it becomes more ebb dominated. During dry seasons, when the river flow is minimal, the relative increase in flood flow due to the decreased resistance by the river flows, results in quickening the processes of channel erosion. The role of tides plays a significant role in influencing the number of bifurcations in the tidally influenced deltas. This implies that greater the flood flow than quicker the channel erosion and more number of bifurcations (see Section 4.2.1.2).

Similar to the distribution of water across the delta (FIGURE 5.6 to FIGURE 5.8), the number of bifurcations affects the distribution of sediment across the delta and subsequently the delta building processes. A bifurcation will decrease the nearest-edge distance between a point in land and the nearest water. Also, it improves the hydrological connection between the distributaries and islands by increasing the structural and process connectivity.

3. Progradation will increase with increased water discharge and the shape of clinoform will be a function of fluvial discharge.
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

Tidal asymmetry at the mouth of distributaries increases the rate of progradation of the subaqueous delta. Progradation is more sensitive to water discharge (see FIGURE 5.13) than sediment discharge (FIGURE 5.15) as the momentum of water discharging into the sea is a function of fluvial water discharge and low tides (see FIGURE 5.13). The delta clinoform’s length and slope are also found to be a function of fluvial water discharge and the relative supply rate of sediment. The slope of the clinoform’s foreset decreases with increasing water discharge (see Section 5.3.2).

Similar to the response on progradation pattern to rapid variation in water flux (Paola et al., 1992), in this study also the response of morphodynamic change to greater fluvial discharge is more prominent for the spatial and temporal scale of interest. The progradation of the delta islands depends upon the stability of the clinoform. Cyclones, rate of sedimentation and earthquake can influence the stability of the foreset (Michels et al., 2003, Swenson et al., 2005). However, that process is not modelled in the Delft3D software and is beyond the scope of this study.

4. Increase in sea level rise will reduce sub-aerial delta and will increase number of islands

Under the natural condition of the delta, FIGURE 6.23 shows that as the sea level raises the existing sub-aerial delta area shrinks. The initial sub-aerial delta undergoes submergence due to RSLR, leading to severe land aggradation and erosion, with the latter dominating the former during the RSLR as the accommodation space dominates over the rate of sediment supply. Also, these processes leads to increase in the number of islands with increasing sea level rise (FIGURE 6.26). However, aggradation led to an increase in land elevation that remain above the raised mean sea level (FIGURE 6.17b) and the amount of aggradation increases with the increasing RSLR. The simulation revealed that the pattern of the sub-aerial delta for the same amount of RSLR can be different (islands bank have a well-defined pattern for RSLR of 0.5m in 100 years at the rate of 5mm/y) and (islands bank have a roughly-defined pattern for RSLR of 0.5m in 25 years at the rate of 20mm/y) as the rate of RSLR and the subsequent interaction with the tidal floodplain flow varied the processes of
accretion and erosion over the sub-aerial delta. With the help of a numerical model, van der Wegen (2013) showed that in tidal basins, sea level rise alters tidal asymmetry and the basin shifts from exporting to importing sediment with the formation of shoals moving landward. The model results for sea level rise in this thesis reveal similar processes to those discussed by van der Wegen (2013), with rapid inundation of lowland but with highlands growing prominently over the deltaic islands. Similarly, the planform evolution of the deltaic islands and distributaries (FIGURE 6.12 and FIGURE 6.13) to the sea level rise scenarios explored in this thesis agrees with empirical findings by Stefanon et al. (2012) who demonstrated that change in tidal prism due to sea level rise on a pure tidal channel network strongly influences the channel cross-sectional areas, network structure and its drainage density. However, the findings in this thesis are at the scale of a tidal delta and include the tidal interaction with fluvial discharge rather than at a tidal channel level without fluvial interactions.

The reduction in sub-aerial delta area and the increase in number of islands have huge implications to the people and environment of the delta that are relying on the sub-aerial delta. However, this natural process of morphodynamic evolution during RSLR helps natural gravity induced land drainage and less hydrological problems. But, increased perimeter can lead to increased maintenance of any coastal protection measures.

5. Increase in sea level rise will cause increased back water effects such as upstream propagation of bed aggradation

In the model, the upstream propagation of bed aggradation increased with increasing RSLR, as shown in FIGURE 9.3 and FIGURE 12.2 in Appendix 12, because of increased upstream propagation of: back water effect, energy gradients due to tides and reversing flows within the delta (FIGURE 6.1). Viparelli et al. (2015) model results on the Mississippi river also showed upstream migration of bed aggradation over time due to increased backwater effect caused by the sea level rise. The following relative sea level rise (RSLR) scenarios: RSLR = 5mm/y, 10mm/y, 15mm/y and 20mm/y were considered and compared against a base case scenario of zero RSLR. It was found that residual flow over the delta is altered by the magnitude of relative sea level rise.
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

rise, with the magnitude of the back water effect (and thus water levels and the ratio of flood to ebb flow – with up to a 19% increase for RSLR of 2m over 100 years) increasing with increasing RSLR (FIGURE 6.1 and FIGURE 9.1 d to f). Despite the upstream boundary is fixed with dominant fluvial discharge in the model, preventing the upstream propagation of backwater distance, the SLR increased the tidal prism resulting in increased backwater effects (FIGURE 6.1A to C).

Edmonds et al. (2009) conducted a physical experiment to show that in river dominated deltas, a stagnated mouth bar triggers an upstream propagation of bed aggradation and intradelta lobe avulsion. Even though this process of propagation of bed aggradation is similar to the one triggered by the mouth bar formation (Edmonds et al., 2009) no intradelta lobe avulsion can be observed in the model due to the sea level rise. But, the pattern of sedimentation over the sub-aerial delta during sea level rise might have been influenced by this backwater effect. The relative rate of progradation to aggradation is important on channel network evolution (Jerolmack, 2009). As the aggradation increases due to accelerated sea level rise, greater number of islands or bifurcations can be observed in the modelled delta (see FIGURE 6.26). The effect of backwater due to sea level rise also increases the flood risk of the deltaic islands (FIGURE 6.23) and this is in agreement with the findings of Hiroaki et al. (2015).
FIGURE 9.3: Distance of upstream propagation of bed aggradation from delta front after 100 years for varying rate of relative sea level rise (RSLR) scenarios (0, 5, 10, 15 and 20mm/y)

The other outcome of backwater effect can be seen in the widening of the channels width towards the sea as shown in FIGURE 9.4. The increase of channel width towards the sea in the base case scenario is due to the progradation of the islands at the delta front. Also, the time-series plot of the channel width-depth ratio, FIGURE 9.5, shows that this ratio increases with increasing with sea level rise. The increasing trend of this ratio indicates the process of channel widening and aggradation.

FIGURE 9.4: Time-series plot of modelled channel width for the experimental scenarios of varying rates of sea level rise
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

6. Increase in sea level rise will stop progradation and will only cause aggradation

FIGURE 6.17 and FIGURE 6.19 show that both progradation and aggradation of the delta can happen during the sea level rise scenarios in the tidally influenced deltas. The progradation and aggradation of the delta increases with the increasing RSLR, as the rate of sediment supply exceeds the accommodation space created by the RSLR at the delta front of the tidally influenced, modelled delta. Despite the sea level rise, it can be seen that the progradation of the sub-aerial delta front has kept pace at the rate equal to or greater than the zero sea level rise scenario as shown in FIGURE 9.6. The clinoform of the delta looked similar for all the RSLR scenarios explored here (FIGURE 6.19). This is because of the bidirectional flow by the interaction of river and tidal discharges which do not happen in the river and wave dominated deltas. Plink-Björklund (2012) has recognised similar process of sub-aerial and subaqueous aggradational progradation in the ancient tidally influenced deltas and reported that the contemporary GBM delta as the modern day analogous to those ancient features. This behaviour of the modelled delta to sea level rise is similar to that conceptualised (see FIGURE 3.10FIGURE 3.11) by Hori and Saito (2008) for the modern GBM delta for steady sea level rise. However, in the real world,
the rate of relative sea level rise can vary over space and time (Pethick and Orford, 2013) and also, the modelled delta reveals that during sea level rise, the accommodation space (FIGURE 6.9 to FIGURE 6.11) and the rate of sediment supply can vary over both space and time over the delta. However, it is not sure whether this pattern of aggradational progradation might have happened in the evolution of the GBM delta during the Holocene period because of the Lowstand system, higher rate and quantity of sediment supply and sea level rise during that period than the modern day values (Goodbred Jr and Kuehl, 2000). The model shows that the delta front of the tidally influenced deltas may not experience the submergence problem of sea level rise however the landward part of the delta would. We still see the formation of new mouth bars at the delta front of the GBM delta but have never grown beyond as a bar and these bars never welded together to form one bigger island. This could be due to the increased fluvial dominance in the monsoon season.

FIGURE 9.6: Time-series plot of modelled sub-aerial delta progradation for the varying rates of sea level rise (3a- 5mm/y; 3b-10mm/y; 3c-15mm/y; 3d- 20mm/y) compared with base case scenario (0mm/y)

7. When drivers are combined, deltaic human interventions will dominate over the environmental change
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 9.7: Sub-aerial delta area as a function of fluvial water discharge, human interventions and sea level rise (Qw - Water discharge; P - Polders; CD - Cross-dams; SLR - Sea Level Rise)

FIGURE 9.8: Sub-aerial delta area as a function of fluvial sediment discharge, human interventions and sea level rise (Qs - Sediment discharge; P - Polders; CD - Cross-dams; SLR - Sea Level Rise)

First, the response of sub-aerial delta when both the natural and human drivers are varied is presented. FIGURE 6.23 shows that without engineering structures the sub-aerial delta area decreases with increasing SLR. Also, the area decreases with increasing fluvial water supply and the trend remains the same with the addition of polders and cross-dams (FIGURE 9.7). But, note that with both SLR and polders, the area is greater than the scenario without them.
FIGURE 9.8 shows that the area increases with increasing fluvial sediment concentration but not much with both polders and SLR. However, in scenarios with polders and SLR, the percentage of poldered area below MSL increased with increasing SLR (FIGURE 8.21 and FIGURE 8.22). As the polders can erode in the real world scenario, the actual trend of delta area may be in between the solid and dashed lines in the FIGURE 9.7 and FIGURE 9.8.

In the combined drivers’ scenario, the accretion and erosion over the sub-aerial delta occurred only outside the poldered area as the morphodynamic change of the poldered islands and banks was not allowed in the model (see Section 8.2.4). Hiatt and Passalacqua (2015) research work on the Wax Lake delta showed the significance of hydrological connection between the distributaries and islands. Also as the model results demonstrated(FIGURE 5.20,FIGURE 5.21, and FIGURE 6.22), accretion and erosion over the sub-aerial delta depends upon the hydrological connectivity between the distributaries and islands. Residual flow and intra-island channels play a significant role in this hydrological connection. However, such connection is prevented by the polder dykes in the combined scenarios (FIGURE 7.11,FIGURE 8.17, and FIGURE 8.18).

![FIGURE 9.9: Probability distribution function of nearest-edge distance for the varying amount of sea level rise and polders scenario](image)

In natural state, the nearest-edge distance of a point in land to the nearest water decreased with increasing SLR leading to the process of aggradation over the existing sub-aerial delta during SLR(FIGURE 6.29). But, that is not the case.
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

during SLR with polders as no flooding of the tidal floodplain is allowed (see FIGURE 9.9, FIGURE 7.11, FIGURE 8.17, and FIGURE 8.18). This implies that polders are preventing the bifurcation of islands or evolution of deltaic channel networks, and aggradation of poldered area. Thus, if a polder is breached than greater extent and longer duration of flooding can be expected because of no aggradation and the relatively lower land elevation of the poldered area (Auerbach et al., 2015).

FIGURE 9.10: Modelled width of onshore fluvial deposition with human interventions plotted against varying amount of sea level rise.

FIGURE 9.11: Modelled width of onshore fluvial deposition with and without human interventions plotted against varying fluvial water discharges.
Figure 9.12: Modeled sub-aerial delta progradation for the varying rates of sea level rise under conjunctive scenarios.

Figure 9.10 shows that without polders and cross-dams, the width of onshore fluvial deposition increased with increasing sea level rise but that is not the case with polders and cross-dams. Figure 9.11 shows that without polders and cross-dams, the width of onshore fluvial deposition increased with increasing fluvial water discharge but with the same trend decline in the magnitude of the width can be observed with polders and cross-dams. Unlike the increase of sub-aerial delta progradation with increasing sea level rise (Figure 9.6), under the conjunctive scenarios, the progradation of the sub-aerial delta decreased with increasing sea-level rise Figure 9.12. This implies that the progradation of the sub-aerial delta under the influence of the human interventions is strongly affected by the increasing sea level rise.

The distribution function of the modeled sub-aerial delta metrics in Figure 8.23 to Figure 8.26 under the combined scenarios shows a good match with the real world GBM delta in Figure 2.11. This match is not possible under the conditions of purely natural environmental change (Figure 5.25 to Figure 5.31 and Figure 6.26 to Figure 6.29) and this shows that the influence of deltaic human drivers dominates the morphodynamic response of the delta both within the model and in the real world delta. There may be little discrepancy in the match as the model has not fully captured the morphodynamic response of the GBM delta due to the addition of cross-dams structure. Unlike the natural process of delta building shown in Figure 6.17, with the islands being polderised, the positive effect of increasing sediment supply and RSLR on the aggradation of the land is not productive. As shown in
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

this study, with polders this would not happen (section 6.3) and this volume of land building sediment to SLR is lost only for a marginal gain in sub-aerial delta outside the poldered area (FIGURE 9.7 and FIGURE 9.8) at the risk of permanent inundation of the entire sub-aerial delta (FIGURE 8.21 and FIGURE 8.22). Unlike in the results shown in section 6.3.3, when combined, polders prevent the natural processes of delta building such as aggradation over the sub-aerial delta, bifurcations of islands/increase in the number of islands, increase in the island shape factor (FIGURE 6.30 & FIGURE 6.31), and evolution of channel network. Also, the nearest-edge distance of a point in land from water decreased with increasing SLR but not with polders (FIGURE 9.9). Thus, when polders breach, the poldered area can subject to greater extent of flooding because of the relatively lower land elevation. Similarly, cross-dams prevented the progradation of the southern island and influenced the shape of clinoform (FIGURE 7.23), and prevented the upstream propagation of bed aggradation due to RSLR (FIGURE 9.3). Though polders can prevent the channel erosion and reduce the perimeter of deltaic islands but can affect the connectivity of distributaries/intraisland channels and the distribution of sediment flux over the delta. With the poldered area (section 8.2.4) below the increased RLSR, polders can fail suddenly and cause permanent inundation of the deltaic islands unless the poldered area is allowed to gain elevation to compensate for the rising sea level (Auerbach et al., 2015). The conjunctive response of the idealised, modelled delta indicates that delta is cooking for a catastrophe as the natural process of land building is hindered by the human intervention such as polders. Hence, the responses of delta under combined drivers indicate that the human interventions can lead to unsustainable delta building processes if not properly planned. These findings also indicated what delta morphodynamics have been missed with human interventions such as polders and cross-dams.

For a sustainable management of delta, the exchange of flow between the distributaries and tidal floodplains should be enabled. If embankments are built with flow control structures, they should be regularly operated and maintained to let this exchange happen more naturally (Paul and Mahmood, 2016, Hiatt and Passalacqua, 2015). Otherwise, relative sea level rise can lead to the loss of sub-aerial or wetland part of the delta as there will not be enough sediment to
replenish and nourish the floodplains similar to what happened in the Mississippi delta due to the construction of embankments along the distributaries (Paola et al., 2011).

Based on the key findings presented in Chapters 5 to 8, FIGURE 9.13 and FIGURE 9.14 have been developed to illustrate schematically the qualitative understanding gained in this study. These figures show the relationship between the responses of the ideal tidal delta to the varied forcing imposed on the model in a qualitative sense. FIGURE 9.13 shows the qualitative understanding for variations in the imposed natural forces only, whereas FIGURE 9.14 does so for both natural and human induced changes. The delta land area increases with increasing sediment discharge (FIGURE 9.13ii) but decreases with increasing water discharge (FIGURE 9.13i). Progradation is more sensitive to water discharge (FIGURE 9.13iii) than sediment discharge (FIGURE 9.13iv) as the momentum of water discharging into the sea is a function of fluvial water discharge and low tides whereas the sub-aerial delta area shrinks (FIGURE 9.13v) with increasing RSLR as the accommodation space dominates over the rate of sediment supply. The number of delta islands (FIGURE 9.13vi) and the perimeter of those islands increase with increasing RSLR. Progradation (FIGURE 9.13vii) and aggradation (FIGURE 9.13viii) of the delta was found to increase with increasing RSLR. It was found that the sub-aerial delta area with polders is greater than the simulation without polders (FIGURE 9.14i) and for a perimeter that is smaller than without polders (FIGURE 9.14ii). Model simulation with cross-dams indicated that after 100 morphological years that there may not be a significant net land change overall due to the introduction of cross-dams (FIGURE 9.14i). Higher roughness scenario can lead to a relatively smaller delta area (FIGURE 9.14i) but with a greater perimeter (FIGURE 9.14ii) as compared to the base case scenario. Both the increasing RSLR and water discharge factors together decrease the sub-aerial delta area (FIGURE 9.14iii) however, the delta area was found to be greater than the initial value and the base case value after 100 years as the banks of the poldered area are prevented from erosion, breaching or overtopping. In contrast, the sub-aerial delta area increases with increasing sediment discharge, but decreases with increasing RSLR (FIGURE 9.14iv). However, in the combined response scenarios, the land area protected by polders is below the increasing sea level. Under combined response scenarios, the progradation and
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

Aggradation of the delta (FIGURE 9.14v & vi) is dominated by the effect of cross-dams, polders and increasing water discharge. Thus, the combined influence of natural and human drivers is not simply the sum of their individual influence.
Chapter 9: Discussions and conclusions

FIGURE 9.13: Qualitative synthesis of the deltaic response to natural drivers. Water discharge vs sub-aerial delta area (i), vs progradation (iii); Sediment discharge vs sub-aerial delta area (ii), vs progradation (iv); Sea level rise vs sub-aerial delta area (v), vs number of islands (vi), vs progradation (vii), Aggradation (viii)
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 9.14: Qualitative synthesis of the deltaic response to natural and human drivers. Human interventions vs area (i) and perimeter of sub-aerial delta (ii); Water discharge + sea level rise + human interventions vs sub-aerial delta area (iii), vs progradation (v); Sediment discharge + sea level rise + human interventions vs sub-aerial delta area (iv), vs progradation (vi)

Abbreviations: Qw - Water discharge; Qs - Sediment discharge; SLR - Sea level rise; P - polders, CD - Cross-dams; RLC - Rough Land Cover
Chapter 9: Discussions and conclusions

9.4 Implications for real world tidal-dominated deltas

The following sub-sections present the application of the findings in this study to the real world contemporary GBM delta and discusses about the implications for the delta management suitability to apply for the other tide-dominated deltas.

9.4.1 The modern GBM delta

The blue shaded areas in Figure 9.15 show the accretion or gain of sub-aerial delta in the Meghna Estuary (i.e., the contemporary GBM delta) between 1973 and 2008 in the form of the development of mudflats and progradation of the delta whereas the red shaded areas show erosion or the loss of sub-aerial delta in the form of channel widening and erosion of island banks. As shown in Figure 9.16, during this period, the sub-aerial delta area of the Meghna Estuary has increased from 12% to 24% with respect to the 1943 reference value. This indicates that there has been a net accretion of the sub-aerial delta in the Meghna Estuary between 1973 and 2008. Based on the results of the ideal, tidal delta morphological models with varied forcing under the controlled conditions presented and discussed in Chapters 5 to 8, the following lessons can be learnt for the GBM delta. Despite a RSLR of at least 10mm/y (Islam et al., 2015) during 1960-2011, this net accretion of the sub-aerial delta in the Meghna Estuary could be due to (i) the land reclamation caused by the cross-dams built in 1957 and 1964, (ii) protection of the poldered area by the coastal embankment as shown in Figure 9.17 and/or (iii) a relative increase in sediment supply to the delta as estimated by Darby et al. (2015).
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 9.15: Erosion and accretion of lands in the Meghna Estuary (contemporary GBM delta) from 1973 to 2008. All the islands are polderised. Estimate based on satellite images. Source: (CEGIS, 2009)

Note: The green lines indicate cross-dams built in 1950s and 1960s (Islam, 1971) and orange line indicates the proposed cross-dam (Anonymus, 1986), yet to build.

As described in Chapter 2, as a part of the land reclamation measure, two cross-dams were built across the eastern most distributary, the Meghna Channel, of the Meghna Estuary in 1957 and 1964, respectively. Consequently, sedimentation and land reclamation occurred on the distributary (south of Noakhali in FIGURE 9.15) with cross-dams, and on the ones directly linked to the distributory with cross-dams (see Section 7.3.2). However, during this process of land reclamation, severe bank erosion on the northern part of the Hatiya Island (see FIGURE 9.15) and on the eastern part of the Bhola Island (see FIGURE 9.15) was also experienced. This bank erosion could be due to the increased water discharge (see Section 5.3.1 and 7.3.2) through the Shahbajpur Channels because of the diversion of the flow caused by the cross-dams. The
processes identified through the model results in this thesis are consistent with those from Anwar et al. (2013) based on estimated time series of accretion and erosion in the Meghna Estuary determined using satellite images. According to Anwar et al. (2013), the Shahbajpur Channels are widening due to the increased discharge caused by cross-dams and the abandonment of the eastern course of the Lower Meghna. However, the pre-feasibility study on Sandwip cross-dam, not built yet, did not predict any significant morphological effects elsewhere in the Meghna Estuary (Anonymus, 1986), which contradicts the findings in this thesis.

FIGURE 9.17 shows a photo of Bangladesh Polder 32 coastal embankment, on the river and landward sides. As it shows the ground levels of the sediment starved poldered area of the sub-aerial delta are lower than the water level (Auerbach et al., 2015) in the adjacent distributary. However, although the coastal embankment protects the land from flooding, it thereby disconnects the tidal floodplain from the regular flooding that induces sedimentation. Polders cause excess sediment within the deltaic distributaries and this (see Section 7.2) could be the reason behind the aggradation and progradation of the Bhola and Hatiya islands (blue shaded areas south of these islands in FIGURE 9.15). This implies, as explained in Chapters 5 and 8, that sufficient sediment is supplied to this zone of the delta front to enable the progradation of the delta despite the additional accommodation space being created by the increasing RSL that the delta is facing.

FIGURE 9.18 shows the time series of the Meghna Estuary sub-aerial delta perimeter between 1943 and 2012. The decrease in the perimeter of the sub-aerial delta between 1943 and 1983 is due to the welding of the islands caused by land reclamation, whereas the increase in perimeter after 1983 is due to the progradation of the delta and the development of many smaller mud flats (see FIGURE 9.19). Because of the protection of the poldered area by the coastal embankments, and bank erosion on the northern part of the Hatiya Island and on the eastern part of the Bhola Island, widening of the Shabajpur Channels and siltation of the Meghna Channel in the eastern part of the delta, the latter perhaps due to the cross-dams, the effect of polders and cross-dams could have dominated in shaping the GBM delta morphodynamics such that no bigger island was formed or eroded completely. However, if the current trend
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

of erosion continues on the Hatiya Island, the entire island will be eroded completely over the next few decades. If this leads to the increased conveyance capacity of the Shabajpur Channel, the erosion of the eastern bank of the Bhola Island could be reduced or even stop in the future. The welding of a number of mudflats to form bigger islands over the next decades depends upon existing human interventions in the delta. The maintenance of polders can help preserve the poldered area from erosion, but with increased fluvial water discharge and RSLR, sediment starved polders will only increase the vulnerability of the protected area from regular flooding due to the breaching and overtopping of the embankment in the future.

FIGURE 9.16: Time series of sub-aerial delta area in the Meghna Estuary between 1943 and 2012. Source: (CEGIS, 2009)
FIGURE 9.17: Ground levels in Polder 32 lower than the water level in the distributary. Source: Photo by the author, taken during a site visit in May 2014.

FIGURE 9.18: Time series of the sum of islands perimeter in the Meghna Estuary between 1943 and 2012. Source: (CEGIS, 2009)
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

Based on the results of multiple ideal, tidal delta morphological simulations, the following lessons can be learnt for the GBM delta. It could be inferred from the model results that because of the addition of polder-dykes and cross-dams and with sufficient sediment supply, the area of the GBM delta had increased by about 25% over the last 60 years as reported by Sarker et al. (2011) despite relative sea level rise of 5mm/y or more (Islam et al., 2015, Brown and Nicholls, 2015). The processes identified through the model results in this research are consistent with those from Anwar (2013) based on estimated time series of accretion and erosion in the GBM delta determined using satellite images. This implies that sufficient sediment was supplied to this zone of the GBM delta to enable the progradation of the delta despite the additional accommodation space created by the sea level rise. However, that sediment is not used to raise the land of the poldered area. The introduction of cross-dams in 1950s and 1960s would have significantly altered the flow patterns over the delta and led to the welding of islands on the planned side and erosion of the island banks elsewhere in the delta. Also, the introduction of polder-dykes in the 1960s would have caused excess sediment within the deltaic distributaries and this (see section 3.3) could be one of the reasons behind the aggradation and progradation of the islands in the GBM delta. This implies that the effect of polder-dykes and cross-dams are dominating in shaping the GBM delta morphodynamics over the last few decades. This implies that the state of the

Chapter 9: Discussions and conclusions

delta has changed from self-maintaining to requiring attention and has come with issues such as poor land drainage, increased salinity, loss of biodiversity, socio-economic problems (Nowreen et al., 2014) and increased flood risk of the poldered area (Auerbach et al., 2015).

9.4.2 Implications for delta management

The delta management options for moving forward for the GBM delta includes do nothing. But, as the model results reveal this option can lead to irreversible catastrophe if those poldered areas are not elevated, then the risk of inundation would increase over time and catastrophe may become unavoidable. Hence, immediate action is required. However, the option of removing polder-dykes to allow the natural state of the delta will not be socio-economically acceptable (Szabo et al., 2016). Moreover, the option of raising or maintaining existing polder-dykes will only provide a short-term solution as demonstrated by this work. The maintenance of polder-dykes can help preserve the poldered area from erosion, but with increased fluvial water discharge and RSLR, sediment starved polder-dykes will only increase the vulnerability of the protected area from regular flooding due to the breaching and overtopping of the embankment in the future. Hence, based on this study results, we can conclude that an option of raising land and replicating the natural response of deltas is a better long-term solution. We recommend a proper feasibility study based on the option identified as best here to be carried out before the implementation of the delta management policies. Limited exploration of this option as tidal river management has begun in the GBM delta. Tidal river management with polder-dykes i.e., intentional breaching of polder-dykes to allow controlled flooding and sedimentation inside the poldered area in the GBM delta have worked at few instances but failed at other times due to improper planning and implementation (Nowreen et al., 2014). Also, the flooding following the cyclone Aila in 2009 showed the opportunity to raise the land by breaching polder-dykes (Auerbach et al., 2015). There are studies attempting to model the tidal river management to raise the poldered areas (Amir et al., 2013). But, this would have to happen at the delta scale rather than at individual polder to address the challenge the idealised model demonstrates. Because of little urbanisation (Ahmed, 2011, Szabo et al., 2016) in the GBM delta, there will be little environmental
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

constraint to raise the land when compared to Yangtze (Changjiang) because of its huge urbanisation (He et al., 2016). Therefore, the cost and energy requirements of the delta land building plan for the GBM delta could be less expensive than the Yangtze (Changjiang). Rapid improper urbanisation in the Amazon delta has been identified (Szabo et al., 2016) but we recommend any such urban development to incorporate the natural processes of delta land building. This implies that each delta and the country it is in have different socio-economic background. Hence, as reported in Tessler et al., 2016, the nature and intensity of problem, resilience, and solution depends on each delta and the country the delta is located.

As well as the GBM delta, these results have implications for other tide-dominated deltas. Many tide-dominated deltas such as the GBM, Fly, Changjiang, Indus and Amazon have a similar funnel shaped morphology of their river mouths, well-developed channel bars and islands (Goodbred and Saito, 2012), as modelled in this thesis. Most tide-dominated deltas are located in low latitude regions and drain high-standing, tectonically active mountains. Also, these deltas comprise interbedded deposits of sand and mud. However, there do exist important differences between these deltas; for example, the shifting of distributaries is rapid relative to the progradation of the delta in the Fly, whereas the distributary channels are stable relative to the progradation of the delta in the GBM (Goodbred and Saito, 2012).

The following deltas, the Indus and Colorado, are already highly degraded due to the decreased sediment supply caused by upstream damming and water extraction. Similar challenges are likely to be faced by the Changjiang, GBM, Ayeyarwady and Mekong deltas in the coming decades. Comparatively, the Fly, Amazon and Copper deltaic systems and their catchments are less human-impacted (Goodbred and Saito, 2012). The findings in this thesis using an idealised tide-dominated delta can be applied to other similar tide-dominated deltas to help better understand their natural processes of delta building. However, it will not be possible to fully understand the morphodynamics of such real world deltas if the nature of sediment supply, influenced by both natural and human drivers, of those real world deltas is different to the one used here and where the delta’s behaviour is strongly influenced by additional drivers such as the effects of local geology.
9.5 Limitations and recommendations for further research

9.5.1 Limitations of current research

A number of factors may influence the morphodynamics of real world deltas, however this study investigated a relatively limited range of factors, specifically: fluvial discharges, relative sea level rise, and deltaic human interventions including polders and cross-dams, albeit these are considered to be the major human interventions in real world systems such as the Ganges-Brahmaputra-Meghna delta. Therefore, this research can lead to only a partial understanding of the actual deltaic morphodynamic changes induced by specific environmental disturbances. Hence, there will be some limitations to the transfer of knowledge gained through this research to real world tidal deltas. Specific factors that were not considered in this research but which could conceivably have significance in tidal delta morphology over decadal to centennial timescale are: secondary flows, waves, Coriolis force, local geological effects, storm surges, seasonality of discharges. The tidal constituents are not used at the downstream boundary to capture the effects of spring and neap tide. The operation of flow control structures such as sluice gates on coastal embankments for tidal flow management is also not considered here.

The realistic analogue approach used in this thesis is only suitable for qualitative assessment. Hence, the magnitude and rate of morphodynamic changes in real world deltas could be different to the modelled changes outlined here. The limitations of the current research due the software used include: (i) coastal embankments in the Delft3d software are modelled as thin dams of unlimited height and are not subjected to breaching or overtopping, however in the real world regular breaching of the embankment and overtopping occurs, (ii) within the software, dry bank erosion is not modelled based on the geotechnical bank stability process, (iii) consolidation of the deposited sediment is not modelled, (iv) due to the size of the model, it was not possible to study the stratigraphic analysis of the ideal tidal delta like studied by Smith et al. (2015) and Geleyne et al. (2011) using a small scale numerical model and its response to the varied forcing.
9.5.2 Recommendations for further research

9.5.2.1 Methodological Approach

Future research effort is required to study the influence of the factors that are not considered here. Also, the long term effects of sequences of events on the morphodynamics of the deltas, such as a cyclone-induced storm surge followed by large monsoon flooding or vice versa, warrant consideration. More research is required to understand the morphological effects due to the breaching and overtopping of flood embankments, and the operation of flow control structures of the poldered areas. Further research is required to present the model outputs as a useful delta metrics concisely.

According to Orton and Reading (1993) the nature of the sediment supplied may control 1) the slope and patterns of distributary channels, 2) the river mouth hydrodynamics and 3) the reworking of the sediments by tides and waves and shoreline types. The grain size of sediments supplied to the delta has a potential influence on the shape and size of the delta. Hence, the influence of grades of sediment supplied to the different type of deltas can be studied to find their influence on the shape and size of the delta.

9.5.2.2 Simulating idealised deltas

As this research focuses on the decadal to centennial morphodynamics of large, tidally influenced, deltas using a realistic analogue approach, similar work can be carried out on river and wave dominated deltas as classified by Galloway (1975) (see FIGURE 3.1) to systematically explore the morphodynamic response of other delta types to environmental changes.

9.5.2.3 Applications to real world deltas

A full understanding of other tide dominated deltas is required to find the suitability of the application of this research to those deltas. Based on the findings in this thesis, further work still needs to be carried out to recognise the implications of the predicted morphodynamic responses on deltaic ecosystems and communities. Different types of deltas require different delta management options to suit their specific physical environment and socio-economic requirements. Hence, a multidisciplinary research is required to
study delta restoration measures using soft engineering measures (Temmerman et al., 2013) such as: raising the elevation of the lowered, poldered land; reconnecting the river and deltaic flood plain; creating and restoring wetlands; and restoring hydrological and bio-geomorphological processes. Especially, further research is required on the deltas that are already degraded to reinstate the function of deltaic systems to perform in a more sustainable way, i.e., to both use and conserve these deltaic environments. Though delta management measures such as sediment diversions has been studied for river dominated delta such as the Mississippi (Nittouer et al., 2012, Bos, 2011), this work needs to be expanded to include other types of deltas such as tide and wave dominated systems.

9.6 Overall conclusions

The main findings in this thesis are summarised as follows:

1. This research showed that a quantitative numerical modelling approach may be successfully applied to develop a structured qualitative understanding of large-scale delta morphodynamics. Numerical model enabled us to envisage the morphodynamic response of deltas with and without local human interventions. It represents the first attempt to model an idealised mega delta over the large spatial and temporal time scales that are pertinent to the challenges faced by the world’s most threatened delta systems. The method adopted here was successfully used to systematically understand the influence of both natural and human drivers on deltaic morphodynamics. Similar approaches could in the future also be adopted to systematically explore the morphodynamic response of other delta types, such as wave- and river-dominated deltas, to environmental and human changes.

2. It was found that all of the factors (fluvial water and sediment discharge, relative sea-level rise, construction of polders and cross-dams, changing land cover roughness) considered here, both individually and combined, influence tidal asymmetry (differences in the magnitude and duration between ebb and flood tidal currents) over the modelled delta. However, the relative magnitude of the flood:ebb flow ratio varies between 0.1 (high water discharge) and 1.0 (cross-dams). This is important because
the tidal asymmetry and rate of sediment supply together effect residual flows, patterns of erosion and accretion, aggradation and progradation of the delta and hence the overall sub-aerial delta morphodynamics.

3. As expected, the area of the simulated sub-aerial delta increases with increasing fluvial sediment discharge, but decreases with increasing water discharge, for scenarios with or without RSLR and/or the presence of anthropogenic deltaic structures. However, delta progradation rates are more sensitive to variations in water discharge than they are to variations in fluvial sediment supply.

4. Under all the RSLR scenarios considered here (5, 10, 15 and 20mm/y), both the accommodation space and the rate of sediment supply vary over time and space over the delta. Overall, land tends to be lost on the landward side, whereas aggradation and progradation are focused at the delta front for all the investigated scenarios. Despite the inundation of lowland near the distributaries, aggradation enables the land far away from the distributaries to cope with the sea level rise. Human modifications are important. For example, the sub-aerial delta shrinks with increasing RSLR, but it does not shrink when the sub-aerial delta is polderised. Indeed, the use of polders is found to lead to an increase in sub-aerial delta area over time, provided that the polders are not restricted by erosion. However, the polders become more vulnerable to flooding as they lose relative elevation. Cross-dams built across a deltaic distributary to steer zones of land accretion also are shown to accomplish their local goal, but may not result in net land gain at the scale of the delta as a whole. This latter finding is contrary to the widespread perception of delta managers, who often assume that they are achieving a net gain in delta area (Islam, 1971), albeit there is some evidence that this perception is now starting to change (Sarker et al., 2011).

5. The combined influence of factors on the morphodynamic response is not the same as the sum of the individual effect of factors when combined. For example, the increase in water discharge and SLR are acting together to decrease the sub-aerial delta area whereas the increase in sediment discharge is acting against the SLR to increase the sub-aerial delta area. Human interventions affect the distribution of
6. Lessons from the idealised simulations for the contemporary Ganges-Brahmaputra-Meghna (GBM) delta include the points that human interventions such as cross-dams and polders have likely dominated in influencing the past 60 years of the morphodynamic evolution of the delta. This has led to a state where further human involvement is now required to maintain or reinstate the delta. However, while the maintenance of polders can also help preserve the poldered area from erosion, with increased fluvial water discharge and RSLR, sediment starved polders will only increase the vulnerability of the poldered area from regular flooding due to the breaching and overtopping of the embankment in the future. Hence, the future trend of morphological evolution of the GBM delta depends on continuing human intervention. Any long-term strategy to influence the morphodynamics of the delta should consider the impact that it will have over the entire delta, including any residual risks that it will create. It is important to replicate the natural response of the delta’s land building process to avoid similar hazardous position in the future.

7. Overall, this thesis systematically explored the links between contemporary environmental changes and tidal delta morphodynamics over multi-decadal timescales and thus (i) provides new guidelines to understand the factors stimulating morphodynamic changes on large deltas, (ii) insight into the possible effects of future scenarios of climate, catchment management and other relevant factors on tidal delta morphology, and (iii) forms a basis to plan future actions to direct the geomorphological and biodiversity responses of large tidal deltas.
Appendices
10. Modelling software (Appendix)

10.1 Selection of modelling software

The overall aim of this research is to determine how contemporary tidal delta morphology evolves over multi-decadal timescales under multiple drivers i.e., to explore the influence of various drivers (fluvial discharges, sea level rise, human interventions such as polders, cross-dams and changing land cover roughness) of contemporary environmental change on deltaic morphodynamic response. Thus, a process-based modelling software tool that will meet this aim should satisfy at least the following criteria: 1) maintain mass balance of water and sediment, 2) model hydrodynamic processes: unsteady flow, tides, waves, coriolis force, 3) model geomorphologic processes: land erosion and accretion, mouth bar formation, channel avulsion, bathymetric change, 4) let realistic representation of delta features: islands, land use including vegetation and engineering structures such as polders, 5) feasible computational run time, 6) should have been thoroughly tested with proven reliability, 7) easy to set up a model and 8) should output the required parameters. Further to the comparison of commonly used morphodynamic modelling software, see TABLE 10.1 for the list of software, Delft3D is selected here as it has been shown to fulfil the above criteria and it has been successfully used to simulate the long-term morphological simulation of the tidal basins of the Netherlands (Dissanayake, 2011), San Pablo Bay (van der Wegen et al., 2011) Columbia River Mouth (Moerman, 2011), Wax Lake Delta in the Atchafalaya Bay (Hanegan, 2011), sediment diversion works in the Mississippi Delta (Fuhrhop, 2013) and Yangtze River Estuary (Guo, 2014).
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

<table>
<thead>
<tr>
<th>Model Software</th>
<th>Flow model</th>
<th>Sediment transport and morphology updating method</th>
<th>Grid system</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Delft3D</strong></td>
<td>2DH/3D</td>
<td>2DH/3D Online with MORFAC, parallel online;</td>
<td>Curvilinear FD</td>
</tr>
<tr>
<td><strong>Mike21</strong></td>
<td>2DH/Q3D</td>
<td>2DH/Q3D Offline, online with MORFAC</td>
<td>Rectangular, Curvilinear, FD, Unstructured FV</td>
</tr>
<tr>
<td><strong>Telemac</strong></td>
<td>2DH/3D</td>
<td>2DH/Q3D Offline, no acceleration</td>
<td>Unstructured FE</td>
</tr>
<tr>
<td><strong>ADCIRC</strong></td>
<td>2DH/3D</td>
<td>2DH/3D Online</td>
<td>Unstructured FE/FV</td>
</tr>
<tr>
<td><strong>ROMS-SED</strong></td>
<td>3D</td>
<td>3D Online with MORFAC</td>
<td>Curvilinear FD</td>
</tr>
<tr>
<td><strong>FVCOM</strong></td>
<td>2DH/3D</td>
<td>2DH/3D Online with MORFAC</td>
<td>Unstructured FV</td>
</tr>
<tr>
<td><strong>XBeach</strong></td>
<td>2DH</td>
<td>Q3D Online with MORFAC</td>
<td>Rectangular FD</td>
</tr>
</tbody>
</table>

**TABLE 10.1:** Comparison of commonly used morphodynamic modelling software. Modified from (Roelvink, 2011) and based on Chen et al. (2011).

Note: 2DH – Two dimensional horizontal, 3D – three dimensional, Q3D – Quasi-three dimensional, FD - Finite Difference, FE - Finite Element and FV – Finite Volume
10.2 Description of the Delft3D modelling software

Deltaic hydrodynamic and morphodynamic processes were modelled by the Delft3D software in depth-averaged, two dimensional condition. The software is based on the physical laws of conservation of mass, momentum and energy (Deltares, 2013) and the hydrodynamic flow is computed by solving the Reynolds-averaged Navier-Stokes equations for incompressible and free surface flows. The system of equations for hydraulics consists of the continuity equation (see EQUATION 1) and horizontal momentum equations (see EQUATION 2 and EQUATION 3) (Lesser et al., 2004). These equations in unsteady state are solved numerically by the finite difference method using an Alternating Direction Implicit (ADI) method (Deltares, 2013). The model grid in this study is defined in cartesian rectangular grid system. Brief description of the depth averaged equations in Cartesian co-ordinate system are written as follows after Lesser et al. (2004):

EQUATION 1: Continuity equation based on (Lesser et al., 2004)

\[
\frac{\partial \zeta}{\partial t} + \frac{\partial [h \bar{u}]}{\partial x} + \frac{\partial [h \bar{v}]}{\partial y} = S
\]

EQUATION 2: Momentum equation in x-direction based on (Lesser et al., 2004)

\[
\frac{\partial \bar{u}}{\partial t} + \bar{u} \frac{\partial \bar{u}}{\partial x} + \bar{v} \frac{\partial \bar{u}}{\partial y} + g \frac{\partial \zeta}{\partial x} + c_f \frac{\bar{u}}{h} \left( \sqrt{\bar{u}^2 + \bar{v}^2} \right) - \nu \left( \frac{\partial^2 \bar{u}}{\partial x^2} + \frac{\partial^2 \bar{u}}{\partial y^2} \right) - f_{cor} v = 0
\]

EQUATION 3: Momentum equation in y-direction based on (Lesser et al., 2004)

\[
\frac{\partial \bar{v}}{\partial t} + \bar{u} \frac{\partial \bar{v}}{\partial x} + \bar{v} \frac{\partial \bar{v}}{\partial y} + g \frac{\partial \zeta}{\partial y} + c_f \frac{\bar{v}}{h} \left( \sqrt{\bar{u}^2 + \bar{v}^2} \right) - \nu \left( \frac{\partial^2 \bar{v}}{\partial x^2} + \frac{\partial^2 \bar{v}}{\partial y^2} \right) - f_{cor} v = 0
\]

\[
c_f = \frac{g}{C^2}
\]

where, \( \zeta \) is water level (m), \( h \) is water depth in (m), \( \bar{u} \) and \( \bar{v} \) are depth averaged velocity (m/s) in x and y directions respectively, \( S \) is water discharge source or sink term, \( g \) is gravitational acceleration factor (m/s²), \( c_f \) is friction coefficient, \( \nu \) is kinematic viscosity, \( C \) is Chezy coefficient (m¹/²/s) and \( f_{cor} \) is Coriolis parameter (1/s).
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

The processes modelled include hydrodynamics, drying and flooding of intertidal flats, sediment transport, bed level update and dry bank erosion. The alternate process of wetting and drying of intertidal flats is modelled by specifying a threshold water depth of 0.1m to determine the state of a grid cell as wet or dry during the flow calculations. The results from hydrodynamic calculations are then used to compute the sediment transport as described below and subsequently bed level is updated due to the sediment flux erosion and deposition while maintaining the mass balance. The effect of bed slope on the bed load transport is considered by including the longitudinal and transverse bed slope factor according to (Bagnold, 1966) and (Ikeda, 1982). The process of bank erosion on dry cells, adjacent to a wet cell, was modelled without incorporating the principles of soil bank stability. The rate of sediment transport from a dry cell, adjacent to a wet cell, depends upon the specified dry cell erosion factor. Once a dry cell became a wet cell, then that cell was included in the hydrodynamic computation.

Within Delft3D, cohesive sediment can be modelled as suspended load and non-cohesive sediment as suspended and bed load (Deltares, 2013). Suspended sediment transport of both the sand and silt is calculated by solving the depth averaged version of the three-dimensional advection-diffusion equation:

\[
\frac{\partial c}{\partial t} + \frac{\partial u_x c}{\partial x} + \frac{\partial u_y c}{\partial y} + \frac{\partial (u_z - w_s) c}{\partial z} = \left( \frac{\partial}{\partial x} \left( \frac{\partial c}{\partial x} \right) \right) + \left( \frac{\partial}{\partial y} \left( \frac{\partial c}{\partial y} \right) \right) + \left( \frac{\partial}{\partial z} \left( \frac{\partial c}{\partial z} \right) \right)
\]

Where \( c \) is the mass concentration of the sediment (kg/m\(^3\)) and is based on Rouse’s suspended sediment concentration profile, \( u_x, u_y, u_z \) are water flow velocities in x, y and z directions, \( \varepsilon_{s,x}, \varepsilon_{s,y}, \) and \( \varepsilon_{s,z} \) are eddy diffusivities in x, y and z directions and \( w_s \) is the settling velocity of sediment (m/s). Settling velocity for silt was calculated using Stoke’s law and for sand it was calculated based on the equation by Van Rijn (1993):

\[
\text{EQUATION 5:}
\]
\[ w_s = \frac{10\nu}{D} \left( \sqrt{1 + \frac{0.01RgD^3}{\nu^2}} - 1 \right) \]

Where \( \nu \) is the kinematic viscosity coefficient of water (m\(^2\)/s), \( D \) is the grain diameter of the sand (125\( \mu \)m), \( R \) is the submerged specific gravity and is equal to \( \frac{\rho_s - \rho_w}{\rho_w} \), \( \rho_s \) is the specific density of sediment (kg/m\(^3\)), \( \rho_w \) is the specific density of water (kg/m\(^3\)), and \( g \) is acceleration due to gravity and is equal to 9.8m/s\(^2\).

The sediment dynamics is modelled using Partheniades-Krone formula (EQUATION 6 and 7) for cohesive suspended sediment transport. The effect of flocculation on settling velocity is considered here.

Erosive silt flux, \( F_e \) (kg/m\(^2\)/s) is calculated based on:

EQUATION 6:

\[ F_e = \left( \frac{\tau_0}{\tau_{ce(C)}} - 1 \right) \text{ when } \tau_0 > \tau_{ce(C)} \text{ and is zero when } \tau_0 \leq \tau_{ce(C)} \]

Depositional silt flux, \( F_d \) (kg/m\(^2\)/s) is calculated based on:

EQUATION 7:

\[ F_d = w_s c_b \left( \frac{\tau_0}{\tau_{cd(C)}} - 1 \right) \text{ when } \tau_0 < \tau_{cd(C)} \text{ and is zero when } \tau_0 \geq \tau_{cd(C)} \]

Where \( \tau_0 \) is the computed bed shear stress (N/m\(^2\)), \( \tau_{ce(C)} \) and \( \tau_{cd(C)} \) are critical shear stresses for erosion and deposition, \( c_b \) is the silt concentration near the bed (kg/m\(^3\)). The bed level is updated according to the calculated fluxes.

Bed load transport of sand is calculated according to Van Rijn (1993) equation:

EQUATION 8:

\[ q_b = 0.006w_sD \left( \frac{u (u - u_c)^{1.4}}{RgD^{1.2}} \right) \]

Where \( q_b \) is the bedload sediment discharge of sand per unit width (m\(^2\)/s), \( u \) is the depth-averaged flow velocity (m/s), and \( u_c \) is the critical depth-averaged velocity (m/s) for initiation of motion of the sand based on the Shield curve.
10.3 Modelled water level across varying grid sizes

FIGURE 10.1: Modelled water level after 2 days of hydrodynamics simulation

The modelled water level in this study (see FIGURE 10.1) shows the model is free from numerical diffusion/dispersal errors. The black boxes indicate the convergence of water levels across the varying grid sizes as explained in Chapter 4, section 4.2.1.
11. Model parameter sensitivity analysis

(Appendix)
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 11.1: Probability distribution function of island size normalized to total island area for the selected and unselected model deltas

Note: LS - Longitudinal Slope Factor, TS - Transverse Slope Factor, Critical shear stress for erosion (E) & Sedimentation (A) in N/mm², Vis - Horizontal eddy viscosity, Diff - Horizontal eddy diffusivity in m²/s
FIGURE 11.2: Probability distribution function of island aspect ratio for the selected and unselected model deltas

Note: LS - Longitudinal Slope Factor, TS - Transverse Slope Factor, Critical shear stress for erosion \( \xi \) & Sedimentation (A) in N/mm\(^2\), Vis - Horizontal eddy viscosity, Diff- Horizontal eddy diffusivity in m\(^2\)/s
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 11.3: Probability distribution function of island shape factor for the selected and unselected model deltas

Note: LS - Longitudinal Slope Factor, TS - Transverse Slope Factor, Critical shear stress for erosion (E) & Sedimentation (A) in N/mm², Vis - Horizontal eddy viscosity, Diff - Horizontal eddy diffusivity in m²/s
Horizontal eddy viscosity = 1, Horizontal eddy diffusivity = 100

Horizontal eddy viscosity = 100, Horizontal eddy diffusivity = 10

Horizontal eddy viscosity = 10, Horizontal eddy diffusivity = 10

Horizontal eddy viscosity = 100, Horizontal eddy diffusivity = 100

FIGURE 11.4: Visual representation of the modelled deltas during the calibration of horizontal eddy viscosity & diffusivity co-efficient (in m$^2$/s)
Critical shear stress for erosion & sedimentation: 0.05 & 0.1 N/mm²

Critical shear stress for erosion & sedimentation: 0.05 & 0.05 N/mm²

Critical shear stress for erosion & sedimentation: 0.2 & 0.1 N/mm²

Critical shear stress for erosion & sedimentation: 0.2 & 0.2 N/mm²

FIGURE 11.5: Visual representation of the modelled deltas during the calibration of critical shear stress of erosion and sedimentation
Manning’s roughness co-efficient, n=0.044

Morphological acceleration factor, MORFAC=120

Manning’s roughness co-efficient, n =0.066

Morphological acceleration factor, MORFAC=60

FIGURE 11.6: Visual representation of the modelled deltas during the calibration of Manning’s roughness co-efficient and morphological acceleration factor
12. Model Results (Appendix)
12.1 Fluvial discharges

A1 – Scenario 2c (2Qw:1Qs) - Elevation difference between initial and after 100 years

A2 – Elevation difference between scenarios 2c (2Qw:1Qs) and base case, 2f (2Qw:2Qs) after 100 years

Note: Water discharge, Qw = 32,500 m$^3$/s; sediment discharge, Qs = 0.74 m$^3$/s
Appendix 12 - Model results

B1 - Scenario 2i (2Qw:3Qs) - Elevation difference between initial and after 100 years

B2 - Elevation difference between scenarios 2i (2Qw:3Qs) and base case, 2f (2Qw:2Qs) after 100 years

Note: Water discharge, Qw = 32,500m3/s; sediment discharge, Qs = 0.74m3/s
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

Note: Water discharge, Qw = 32,500 m³/s; sediment discharge, Qs = 0.74 m³/s
Appendix 12 - Model results

D1 - Scenario 2e ($1Q_w:2Q_s$) - Elevation difference between initial and after 100 years

D2 - Elevation difference between scenarios 2e ($1Q_w:2Q_s$) and base case, 2f ($2Q_w:2Q_s$) after 100 years

Note: Water discharge, $Q_w = 32,500 \text{m}^3/\text{s}$; sediment discharge, $Q_s = 0.74 \text{m}^3/\text{s}$
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

**FIGURE 12.1:** Pattern of accretion and erosion over the delta for the scenarios of: sub-plot: A1, A2 for 2c (2Qw:1Qs), sub-plot: B1, B2 for 2i (2Qw:3Qs), sub-plot: C1 for 2f (2Qw:2Qs) (base case), sub-plot: D1, D2 for 2e (1Qw:2Qs), sub-plot: E1, E2 for 2g (3Qw:2Qs)

Note: Water discharge, Qw = 32,500m³/s; sediment discharge, Qs = 0.74m³/s

E1 – Scenario 2g (3Qw:2Qs) - Elevation difference between initial and after 100 years

E2 – Elevation difference between scenarios 2g (3Qw:2Qs) and base case, 2f (2Qw:2Qs) after 100 years
12.2 Relative sea level rise
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

B1 - Scenario 3a (RSLR=5mm/y) - Elevation difference between initial and after 100 years

B2 - Elevation difference between scenarios 3a (SLR=5mm/y) and base case, 2f (RSLR=0mm/y) after 100 years
Appendix 12 - Model results

C1 - Scenario 3b (RSLR=10mm/y) - Elevation difference between initial and after 100 years

C2 - Elevation difference between scenarios 3b (SLR=10mm/y) and base case, 2f (RSLR=0mm/y) after 100 years
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

D1 – Scenario 3c (RSLR=15mm/y) - Elevation difference between initial and after 100 years

D2 – Elevation difference between scenarios 3c (SLR=15mm/y) and base case, 2f (RSLR=0mm/y) after 100 years
E1 - Scenario 3d (RSLR=20mm/y) - Elevation difference between initial and after 100 years

E2 - Elevation difference between scenarios 3d (RSLR=20mm/y) and base case, 2f (SLR=0mm/y) after 100 years

FIGURE 12.2: Pattern of accretion and erosion over the delta for the scenarios of: A1- Base case-2f(RSLR=0mm/y), B1 and B2-3a(RSLR=5mm/y), C1 and C2 - 3b(RSLR=10mm/y), D1 and D2 - 3c(RSLR=15mm/y) and E1 and E2 -3d(RSLR=20mm/y)
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 12.3: Pattern of water flow in the delta just before (A) and after (B) high tides at 25 years for scenario of RSLR =20mm/y (3d). See FIGURE 6.13A for the key map and elevation legend.
FIGURE 12.4: Pattern of water flow in the delta just before (A) and after (B) high tides at 50 years for scenario of RSLR =20mm/y (3d). See FIGURE 6.13 A for the key map and elevation legend.
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

FIGURE 12.5: Pattern of water flow in the delta just before (A) and after (B) high tides at 75 years for scenario of RSLR =20mm/y (3d). See FIGURE 6.13 A for the key map and elevation legend
FIGURE 12.6: Pattern of water flow in the delta just before (A) and after (B) high tides at 100 years for scenario of RSLR =20mm/y (3d). See FIGURE 6.13A for the key map and elevation legend.
12.3 Human interventions
12.3.1 Polder embankments

A1 - Base case Scenario 2f (no human interventions within the delta) - Elevation difference between initial and after 100 years
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

**FIGURE 12.7:** Pattern of accretion and erosion over the delta for the scenarios of: A1 - Base case-2f (no human interventions), B1 and B2-4a (with polders)

B1 - Scenario 4a (with polders) - Elevation difference between initial and after 100 years

B2 - Elevation difference between scenarios 4a (with polders) and base case, 2f (no human interventions) after 100 years
12.3.2 Cross-dams

C1 - Scenario 4b (with cross-dams) - Elevation difference between initial and after 100 years

C2 - Elevation difference between scenarios 4b (with cross-dams) and base case, 2f (no human interventions) after 100 years

FIGURE 12.8: Pattern of accretion and erosion over the delta for the scenarios of: C1 and C2-4b (with cross-dams)
12.3.3 Change in landcover roughness

**FIGURE 12.9:** Pattern of accretion and erosion over the delta for the scenarios of: A1 - Base case-2f(lower roughness land cover), B1 and B2-4c(higher roughness land cover). Dashed green circle indicates disintegration of an island and creation of new channel.
12.4 Conjunctive scenarios

A1 – Base case Scenario 2f (no human interventions within the delta) - Elevation difference between initial and after 100 years
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

B1 - Scenario 5a (2Qs:2Qw;0rsIr, Polders+Cross-dams), - Elevation difference between initial and after 100 years

B2 - Elevation difference between scenarios 5a (2Qs:2Qw;0rsIr, Polders+Cross-dams) and base case-2f after 100 years
C1 - Scenario 5b (2Qs:2Qw;10rslr, Polders+Cross-dams) - Elevation difference between initial and after 100 years

C2 - Elevation difference between scenarios 5b (2Qs:2Qw;10rslr Polders+Cross-dams) and base case-2f after 100 years
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

D1 - Scenario 5f (2Qs:2Qw;20rslr, Polders+Cross-dams), - Elevation difference between initial and after 100 years

D2 - Elevation difference between scenarios 5f (2Qs:2Qw;20rslr, Polders+Cross-dams) and base case-2f after 100 years
Appendix 12 - Model results

E1 - Scenario 5e (1Qs:2Qw;10rslr, Polders+Cross-dams) - Elevation difference between initial and after 100 years

E2 - Elevation difference between scenarios 5e (1Qs:2Qw;10rslr, Polders+Cross-dams) and base case-2f after 100 years
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

F1 - Scenario 5C (2Qs+45%;2Qw;10rslr, Polders+Cross-dams) - Elevation difference between initial and after 100 years

F2 - Elevation difference between scenarios 5c (2Qs+45%;2Qw;10rslr, Polders+Cross-dams) and base case-2f after 100 years
Appendix 12 - Model results

G1 - Scenario 5d (6Qs:2Qw;10rslr, Polders+Cross-dams) - Elevation difference between initial and after 100 years

G2 - Elevation difference between scenarios 5d (6Qs:2Qw;10rslr, Polders+Cross-dams) and base case-2f after 100 years
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

H1 - Scenario 6b (2Qs:1Qw;10rslr, Polders+Cross-dams) - Elevation difference between initial and after 100 years

H2 - Elevation difference between scenarios 6b (2Qs:1Qw;10rslr, Polders+Cross-dams) and base case-2f after 100 years
Figure 12.10: Pattern of accretion and erosion over the delta for the scenarios of: A1 - Base case-2f (RSLR=0 mm/y, Qs= Base case, Qw=1), B1 & B2- 5a (2Qs:2Qw:0rslr), C1 & C2-5b (2Qs:2Qw:10rslr), D1&D2-5f (2Qs:2Qw:20rslr), E1&E2-5e (1Qs:2Qw:10rslr), F1&F2-5c (2Qs+45%:2Qw:10rslr), G1&G2-5d (6Qs:2Qw:10rslr), H1&H2 - 6b (2Qs:1Qw:10rslr) and I1&I2 - 6e (2Qs:3Qw:10rslr)

Note: Water discharge, Qw = 32,500 m³/s; sediment discharge, Qs = 0.74 m³/s
Glossary

**Accommodation space** is the space made available for potential sediment accumulation, which is a function of both sea level fluctuation and subsidence.

**Accretion** is an accumulation of sediment in a particular location, such as a floodplain or bar surface.

**Aggradation** is a net accumulation of sediment, which leads to an increase in the elevation of channel beds and floodplain surfaces.

**Anthropocene** is an informal geologic chronological term that serves to mark the evidence and extent of human activities that have had a significant global impact on the Earth’s ecosystems.

**Avulsion** is the abandonment of a river channel and the formation of a new river channel.

**Bar** in a river is an elevated region of sediment (such as sand or gravel) that has been deposited by the flow.

**Bathymetry** refers to the depth relative to water surface.

**Bed load** is the coarser fraction of a river’s sediment load, which is moved by traction along the bed of the channel by rolling, sliding and saltation.

**Behaviour based models** are the models representing the observed behaviour of a coastal system with a simple mathematical model that may or may not be related to underlying physical processes.

**Bifurcation (river)** in a river means when a river flowing in a single stream separates into two or more separate streams which continue downstream.

**Braided channel** is a channel in which the flow divides and rejoins around numerous bars.

**Cenozoic Era** is the geologic era covering the period from 66 million years ago to the present.

**Clinoform** is a sloping depositional surface, commonly associated with strata prograding into deep water containing bottomsets, foresets and topsets.
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

**Conceptual model** here means an explanation of how the system (or sub-system) functions, including the key controlling factors and processes and their relative importance, of the reasons for the historical development of the system (or sub-system) and of the reasons for present trends within the system (or sub-system).

**Coriolis force** is an intertial force caused by the rotation of the earth.

**Crevasse Splay** is a sedimentary fluvial deposit which forms when a stream breaks its natural or artificial levees and deposits sediment on a floodplain.

**Cyclone** is defined as “an atmospheric system characterised by the rapid inward circulation of air masses about a low-pressure center, usually accompanied by stormy, often destructive weather.” Super cyclone when wind speed over 220km/h, very severe cyclone when wind speed ranges between 119 and 220km/h, severe cyclone when wind speed ranges between 90 and 119km/h, cyclonic depression when wind speed ranges between 60 and 90km/h, deep depression when wind speed ranges between 51-59km/h and depression when wind speed ranges between 32 and 50km/h.

**Delta** is an area of land formed by the rivers in the lake or sea while discharging into them.

**Denudation** is the long-term sum of processes that cause the wearing away of the earth’s surface leading to a reduction in elevation and relief of landforms and landscapes.

**Discretisation** is the process of transferring continuous models and equations into discrete counterparts.

**Ebb-dominated** is a tidal asymmetry where ebb current is stronger than flood current.

**Embedded** means fixed into the surface of something.

**Engineering timescale** means tens to hundreds of years; the timescale over which coastal morphology and processes adjust to human interventions.

**Eocene** is an epoch, lasting from 56 to 33.9 million years ago.
Glossary

**Erosion** is the process by which soil and rock are removed from the Earth's surface by water flow, and then transported and deposited in other locations.

**Estuary** is the tidal mouth of a river where the tide meets the stream.

**Extreme events** are events such as tropical storms that are very energetic and that will produce important modification in a very short period of time.

**Eustatsy** means a change of sea level throughout the world, caused typically by movements of parts of the earth's crust or melting of glaciers.

**Facies** is a distinctive rock unit that forms under certain conditions of sedimentation, reflecting a particular process or environment.

**Fault** is a planar fracture or discontinuity in a volume of rock, across which there has been significant displacement along the fractures as a result of earth movement.

**Flood-dominated** is a tidal asymmetry where flood current is stronger than ebb current.

**Froude number** is the ratio between inertial and gravitational forces.

**Geological timescale** means thousands to hundreds of thousands of years.

**Hindcast Simulation** is a type of testing a model where known or best estimated inputs for past events are entered into the model to see how well the output matches the known results.

**Holocene epoch** is a geological epoch which began at the end of the Pleistocene (at 11,700 calendar years BP) and continues to the present. The Holocene is part of the Quaternary period.

**Homopycnal** is a situation at a river-mouth where the density of the outflowing fluvial flow is more or less equal to the density of the receiving basin water.

**Hypopycnal** is a situation at a river-mouth where the density of the outflowing fluvial flow is lower than the density of the receiving basin water.

**Hypopycnal** is a situation at a river-mouth where the density of the outflowing fluvial flow is higher than the density of the receiving basin water.

**Idealised** means considered as an ideal form of something.
Input reduction techniques means selecting representative conditions of small-scale processes (e.g., tides), without any chronological order, to describe the long-term residual effects that will be influenced by them (e.g., transport fields) within the model.

Intertidal zone is the area that is exposed to the air at low tide and submerged at high tide.

Isopachs are contour lines of equal thickness over an area.

Isostasy is the state of balance, or equilibrium, which sections of the earth's lithosphere (whether continental or oceanic) are thought ultimately to achieve when the vertical forces upon them remain unchanged.

Land reclamation means conversion of intertidal areas into land by embanking and drainage.

Lithology refers to rock characteristics such as grain size, and physical and chemical properties.

Lithosphere is the solid part of the earth consisting of the crust and outer mantle.

Lowstand refers to a time during which sea levels are at their lowest.

Meandering channel is a single channel that follows a winding course.

Model is a representation of a real-world entity but not the "real thing" itself.

Model calibration is the process of tuning all parts of the model system realistically until the difference between the model output and the observed data is small.

Model reduction techniques means reformulating the model at the scale of interest without describing the details of smaller-scale effects.

Model validation is the process of testing model outputs against observed data without making any adjustments to the model.

Monsoon is a seasonal prevailing wind in the region of South and South East Asia, blowing from the south-west between May and September and bringing
rain (the wet monsoon), or from the north-east between October and April (the dry monsoon).

**Neotectonics** involves the study of the motions and deformations of the Earth's crust which are current or recent in geologic time.

**Overthrust faulting** is a geological fault in which the upper side appears to have been pushed upward by compression.

**Peat** is a brown material consisting of partly decomposed vegetable matter forming a deposit on acidic, boggy, ground, which is dried for use in gardening and as fuel.

**Physical (process)-based models** are models that are based on the description of underlying physics.

**Pleistocene epoch** is the geological epoch which lasted from about 2,588,000 to 11,700 years ago, spanning the world's recent period of repeated glaciations.

**Polders** is a low-lying tract of land enclosed by embankments (barriers) known as dikes that forms an artificial hydrological entity, meaning it has no connection with outside water other than through manually operated devices.

**Principle of superposition** means the net response caused by two or more forces is the same as the sum of individual response caused by those forces.

**Progradation** refers to the growth of a river delta farther out into the sea over time.

**Quaternary period** is the most recent of the three periods of the Cenozoic Era in the geologic time scale.

**Regression (marine)** is a geological process occurring when areas of submerged seafloor are exposed above the sea level.

**Reinstate** means restore something to its former state.

**Residual flow** is the resultant flow vector that develops from river, tidal and other marine flow forces.
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

**Return period** is the frequency, in years, with which a given event can be expected to occur.

**Schematisation** is a technique of reducing the number of conditions we have to simulate by choosing a representative condition.

**Sediment yield** is the total amount of sediment that exits a drainage basin, or passes a given point, over a period of time.

**Sediment budget** is a balance of the sediment volume entering and exiting a particular section of the coast or an estuary.

**Semi-diurnal** means occurring or coming approximately once every 12 hours, such as the tides.

**Shoals** is a characteristically linear landform completely within or extending into a body of water.

**Short-term events** are events such as storm surges and river floods with duration that lasts for only few days or utmost couple of weeks.

**Simulation** means experimenting with an abstract model.

**Sinuosity** means a measure of the degree of meandering along a section of channel.

**Solute load** is the dissolved material carried in the flow as ions.

**Steady state** the form associated with dynamic equilibrium if none of the inputs are changing over time. **Unsteady state** is exactly other way around.

**Sub-aerial delta** is a part of the delta that is above and in between high and low tide level.

**Sub-aqueous delta** is a part of the delta that is below the low tide.

**Submarine Canyon** is a steep-sided valley cut into the sea floor of the continental slope, sometimes extending well onto the continental shelf.

**Subsidence** is the motion of the Earth's surface as it shifts downward relative to a datum.
**Subtidal zone** is the area below the low tide water line. This area is always covered by water.

**Supratidal zone** is the area above the high tide water line that extends upland. This area is rarely covered by water.

**Suspended load** is fine sediment that is transported in suspension above bed.

**Syntaxis** means a convergence of mountain ranges, or geological folds, towards a single point.

**Tectonic** means of, relating to, or caused by large-scale movements of the Earth's lithosphere.

**Tidal asymmetry** means differences in intensity and duration between ebb and flood tidal flows.

**Tidal inlet** is characterised by narrow mouth areas linking the sea with a tidal lagoon behind a barrier beach.

**Tidal prism** is the volume of water flowing through an inlet on a single tide.

**Transgression (marine)** is a geologic event during which sea level rises relative to the land and the shoreline moves toward higher ground, resulting in flooding.
List of References

AHMED, A. 2011. Some of the major environmental problems relating to land use changes in the coastal areas of Bangladesh: A review. *Journal of Geography and Regional Planning*, 4, 8.


BANERJEE, K., SENTHILKUMAR, B., PURVAJA, R. & RAMESH, R. 2012. Sedimentation and trace metal distribution in selected locations of
The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

Sundarban mangroves and Hooghly estuary, Northeast coast of India. *Environmental Geochemistry and Health*, 34, 27-42.


List of References

(ed.) Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: IPCC.


The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis


HANECAN, K. C. 2011. Modeling the evolution of the Wax Lake Delta in Atchafalaya Bay, Louisiana. MSc, Delft University of Technology.


The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis


HOSSAIN, M. M. 2012. Storm surges and coastal erosion in Bangladesh - State of the system, climate change impacts and 'low regret' adaptation measures. MSc Research, Leibniz Universität Hannover.


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.*


KLEINHANS, M. G., FERGUSON, R. I., LANE, S. N. & HARDY, R. J. 2012. Splitting rivers at their seams: bifurcations and avulsion. *Earth Surface Processes and Landforms,* n/a-n/a.


LIANG, M. 2013. *Reduced-Complexity Models (RCMs) for river delta formation with channel dynamics.* PhD Dissertation, University of Minnesota.

The morphodynamic characteristics of a mega tidal delta over decadal to
centennial timescales: a model-based analysis

and the Evolution of the Ganges-Brahmaputra Delta Complex. The

Future sediment dynamics in the Mekong Delta floodplains: Impacts of
hydropower development, climate change and sea level rise. Global and
Planetary Change, 127, 22-33.

Numerical modeling of hydrodynamics and sediment transport in lower
Mississippi at a proposed delta building diversion. Journal of Hydrology,
472-473, 340-354.

Sediment transport in the shelf canyon “Swatch of No Ground” (Bay of
Bengal). Deep Sea Research Part II: Topical Studies in Oceanography, 50,
1003-1022.

MIKHAILOV, V. & DOTSENKO, M. 2007. Processes of delta formation in the
mouth area of the Ganges and Brahmaputra rivers. Water Resources, 34,
385-400.

MILLIMAN, J. D., BROADUS, J. M. & FRANK, G. 1989. Environmental and
Economic Implications of Rising Sea Level and Subsiding Deltas: The Nile
and Bengal Examples. Ambio, 18, 340-345.

MIRZA, M. M. Q. 2004. The Ganges Water Diversion: Environmental Effects and
Implications, Springer.

MOERMAN, E. 2011. Long-term morphological modelling of the Mouth of the
Columbia River. MSc, Delft University of Technology.

management in raised bed systems: a case study from the Chao Phraya
delta, Thailand. Agricultural Water Management, 39, 1-17.

Basin, East Pakistan and India. Geological Society of America Bulletin, 70,
319-342.

the bay of Bengal. Progress in Oceanography, 16, 195-233.

richness in Sunderbans. Journal of the Indian Society of Remote Sensing,
38, 431-440.

NEMEC, W. 2009. Deltas — Remarks on Terminology and Classification. In:
Publishing Ltd.

change and coastal vulnerability assessment: scenarios for integrated

NICHOLLS, R. J. & GOODBRED, S. L. Towards an integrated assessment of the
Ganges-Brahmaputra delta. 5th International conference on Asian
marine geology and 1st annual meeting of IGCP475 DeltaMAP and APN
Mega-Deltas, 2004a Bangkok, Thailand.

NICHOLLS, R. J. & GOODBRED, S. L. 2004b. Towards an integrated assessment
of the Ganges-Brahmaputra delta. 5th International conference on Asian
marine geology and 1st annual meeting of IGCP475 DeltaMAP and APN
Mega-Deltas. Bangkok.


The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis


The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis


The morphodynamic characteristics of a mega tidal delta over decadal to centennial timescales: a model-based analysis

India and Bangladesh. Environmental Science: Processes & Impacts, 17, 1082-1097.


