Ministry of Water Resources

Bangladesh Water Development Board

Coastal Embankment Improvement Project, Phase-I (CEIP-I)

Long Term Monitoring, Research and Analysis of Bangladesh Coastal Zone (Sustainable Polders Adapted to Coastal Dynamics)

Literature Review & Lessons Learnt (Updated: March 2022)

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Long Term Monitoring, Research and Analysis of Bangladesh Coastal Zone

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Memo No: CEIP/LTMRA/0322/155 28 March 2022

Project Management Unit
Coastal Embankment Improvement Project, Phase-I (CEIP-I)
House No.15, 4tn Floor, Road
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Attn: Mr. Syed Hasan Imam, Project Director

Dear Mr Imam,

Subject: Submission of Literature Review & Lessons Learnt Report-Updated version (Component D-2)

It is our pleasure to submit herewith five copies of a further updated version of the Report on "***Component D-2**: Literature Review & Lessons Learnt*". This report was earlier submitted on 16th March 2022, summarising the available literature and reports on the main topics related to the subjects under study by the Long-Term Monitoring, Research and Analysis of Bangladesh Coastal Zone.

This updated version of the report includes a new chapter on Groundwater Salinity in addition to 9 other chapters on relevant topics such as Delta Tectonics and Subsidence, Delta Morphology and Sediment Supply, Riverbank Erosion, Polder Drainage and Management, Climate Change and SLR, Hydrodynamics and Salinity, and Coastal & Marine Biodiversity. The lessons learnt from each of the topics covered in the report are described in Chapter 10.

Thanking you,

Yours sincerely,

Dr Ranjit Galappatti
Team Leader

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Dr. Zia Uddin Baig, ADG (Planning), BWDB
Dr Kim Wium Olesen, Project Manager, DHI
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Mr Zahirul Haque Khan, Deputy Team Leader
Mr AKM Bodruddoza, Procurement Specialist
Ms Swarna Kazi, Sr. Disaster Risk Management Specialist, World Bank

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1 Introduction

1.1 Introduction and the Format of this Report

Coastal belt is considered to be the most vulnerable area of Bangladesh to adverse impacts of climate change. The risks due to climate change are cyclones and storm surges, riverbank erosion and vulnerability of islands and chars, sea level rise, salinity intrusion, floods, droughts, drainage congestion, coastal erosion etc. There have been many studies in the past and various papers are published addressing the issues.

Consultants have carried out a comprehensive review of published research papers and reports. Based on this literature review consultants have produced critical analyses of lessons learnt from completed initiatives, identified research and data gaps, and provided guidance for future initiatives concerning the coastal belt. This literature review will provide a learning process to the project professionals based on success or failure of the completed projects and studies. Moreover, the literature review will help providing

- Insights into the study area including climate, etc.;
- Ideas on coastal dynamics including the behaviour of the tidal and nontidal rivers,
- Information on site-specific driving parameters that are responsible for the changes in morphology.

All these will help the modeller and researcher to correctly diagnose problems, carry out a study and come out with suitable solutions. This component was carried over a long period during the entire length of the project, with the release of interim reports.

This report aims to summarise the available literature in the main topics related to the subjects under study by the Long-Term Monitoring, Research and Analysis of Bangladesh Coastal Zone, a study under the Coastal Embankment Improvement Project. The related topics described in the first Literature Review Report were:

- Delta tectonics and subsidence
- Morphology and sedimentation
- Riverbank erosion
- Polder drainage and management
- Climate change and sea level rise
- Salinity

The first Interim Report was submitted on 24 June 2019 covering the topics listed above. The second Interim Report which included an additional chapter on Coastal Biodiversity was published on 15 January 2020. Comments on Interim Report 1 were received after publication of Interim Report 2. This report is the Final Literature Review Report with an additional chapter titled Lessons Learnt.

The first section of each chapter provides synopses of the published material that relates to the main topic of the chapter. The second section of each chapter gives a full list of the papers identified by the project professionals. The selected papers from this list are summarized in the following section given with the reference number.

The first interim Literature Review was prepared using published material up to the middle of 2019. At the time of first submission not all the experts of the project team had commenced work on the project. These incomplete sections were added to and a new chapter No 8 on Biodiversity was added in the second interim Literature Review first submitted in January 2020. This final review report has an additional Chapter 9 on “Lessons Learnt”.

It must also be noted that this project has been carrying out in-depth studies of many Delta processes and that these studies would have increased and modified the earlier understanding of long-term processes affecting the Delta such as Delta Tectonics and Subsidence

2 Delta Tectonics and Subsidence

2.1 Introduction and Synopsis

2.1.1 Tectonics and Earthquake Vulnerability

The Ganges-Brahmaputra-Meghna Delta (GBMD) is a tectonically-influenced landscape positioned on the intersection of the Indian and Eurasian plates and is thus subject to earthquake geohazards. The references listed below provide state-of-the-art knowledge on the tectonic and earthquake vulnerability of the GBMD.

2.1.2 Subsidence

Subsidence, or the loss of elevation (sinking) of the delta plain is a critical process in delta evolution and maintenance of the delta plain, because it determines the magnitude and spatial distribution of accommodation. In this way, subsidence may drive river path selection (for example, by creating favourable gradients for channel avulsion) and also may produce land loss if it is not balanced with sediment deposition. It is widely recognized that subsidence rates in deltas are difficult to quantify, because calculated rates are in part a function of the depth interval over which they are measured and the time interval over which they are averaged. A compilation of subsidence data for the GBMD was recently published by Brown and Nicholls (2015), however, this synthesis did not consider differences in the geologic setting and measurement approach of the compiled rates. Here, we provide a synthesis of key studies that have assessed subsidence rates and their spatial variability in the GBMD. The rates discussed here were determined using various benchmarks including radiocarbon-dated fluvial deposits (Grall et al., 2018), archaeological records (Sarker et al., 2012; Hanebuth et al., 2013), tide gauges (e.g., Singh, 2002; Syvitski et al., 2009), Global Navigation Satellite System (GNSS) satellites (e.g., Reitz et al., 2015; Steckler et al., 2015), Interferometric Synthetic Aperture Radar (InSAR) satellites (Higgins et al., 2014), and Rod Surface Elevation Tables (RSETs, Bomer et al., in review). By nature of the measurement tools, these studies capture subsidence rates acting over different timescales and depth intervals in the GBMD. Results, summarized below, show that subsidence rates in the GBMD can vary greatly by geography and measurement approach.

Radiocarbon-dated fluvial deposits

A large collection (n=198) of primarily Holocene-aged radiocarbon dates of wood fragments embedded in clastic-rich deposits of the GBMD was recently produced through the BangaPIRE initiative (Pickering et al., 2014; Grall et al., 2018; Sincavage et al., 2018). Because these sediments were deposited near (within ~ 15 m of) the coeval land surface, these radiocarbon dates can provide estimates of accommodation, than thus subsidence throughout the Holocene, averaged over hundreds to thousands of years (Grall et al., 2018). They found modest subsidence rates that gradually increased seaward, from 0.1 mm/yr above the hinge zone (within a relatively tectonically stable portion of the delta) to 4 ± 1.4 mm/yr at the most coastward sites. Results were used to generate the first delta-wide subsidence map for the GBMD (Grall et al., 2018). Such an approach captures all subsidence occurring below the dated deposits, including sediment compaction and tectonic movement, and does not capture compaction of the shallowest delta strata that overly the dated deposits.

Archaeological records

Subsidence rates averaged over hundreds to thousands of years may be obtained from archaeological sites (e.g., mosques, temples, salt kilns) when they incorporate architectural elements that relate to sea level at the time of construction. Rates are typically determined by comparing the present-day elevation of the architectural elements to present-day sea level, and therefore capture subsidence due to deep and shallow processes. For example, Hanebuth et al.

(2013) estimated coastal subsidence by dating a 300-year old salt-making facility uncovered by Cyclone Sidr in the Sundarbans, finding an average centennial-timescale subsidence rate of 4.1 mm/yr. Another study employing archaeological sites to estimate subsidence rates in the GBMD was conducted by Sarker et al. (2012). They examined the relative elevation of four historic sites, including two mosques and two Hindu temples, to determine subsidence. They estimated negligible subsidence at one site to modest subsidence rates (1.25-2.5 mm/yr) at the others However, the subsidence rates estimated by Sarker et al. (2012) are sensitive to the architectural interpretation of the archaeological monuments. For example, subsidence at the Shakher Temple in the Sundarbans, was judged by the present-day elevation of the plinth level (the platform for the building that was constructed to raise it above flood level). Sarker et al. (2012) placed this horizon at the entrance of the temple at the top of the stairs, even with the interior of the temple, as is common for Muslim mosques. However, we propose that the plinth level of the Sharker Temple is more likely a lower architectural feature, marked by a ridge in the brickwork at the base of the entrance stairs 0.1 m above the ground and indicating a raised entrance as is common in Hindu Temples. Our interpretation yields 3.5 ± 0.5 mm/yr as an estimate for the subsidence in this part of the delta. This reassessment of the temple derived subsidence rate is also consistent with buried detrital brick fragments found to a depth of 1.5 m around the temple (Goodbred, pers.comm.). These fragments suggest 1.5 m of surface aggradation in 500 years, or a mean subsidence rate of 3.3 mm/yr.

Tide gauges

Tide gauges measure changes in absolute water level with typical temporal resolution ranging from minutes to an hour. Stations that have been in place for longer timescales allow for filtering out the noise of seasonal signals and meteoric tides, to obtain decadal-scale trends in water level change, of which subsidence may be a significant component. A number of studies have used tide gauges, particularly the records available from the five PSMSL (Permanent Service for Mean Sea Level, psmsl.org) to estimate subsidence in the GBMD (Singh, 2002; Syvitski et al., 2009) World Bank, 2010). Estimated rates vary from 1.4 to 18 mm/y. Rishat et al. (2016) further examined all 18 BIWTA tide gauges and BWDB river gauges. The analyses show a great deal of variability from uplift to high rates of subsidence. Several stations show temporally variable rates. For example, Syvitski et al. (2009) obtained a very high subsidence rate of 18 mm/y for Khepupara using PSMSL. Examining a longer time series of 1977-2012, Steckler et al. (2015) found that the rate increased from ~9 mm/y to ~21 mm/y in 1989 and then decrease to <1mm/y in 1997. The World Bank (2010) found a rate of only 2.9 mm/y for 1959 – 1986. The PSMSL data (1987-2000) largely corresponds to the period with the highest rates, almost double the average rate of 9 mm/y for the entire data set. While some stations show a stable rate, other stations also show variable rates with no correspondence of the changes between stations. Given the numerous issues of station stability, releveling to a poor geodetic network, shifting of gauges, 18.6 y nodal tide, etc., subsidence rates from tide gauges must be viewed with caution. The best rate estimates for Bangladesh are from Rishat et al. (2016) who found a relative sea level rise of 5-8 mm/y in the western delta, 6-10 mm/y in the eastern delta and 11-21 mm/y along the Chittagong coast.

GNSS

GNSS measures the movement of antennas that are mounted on either stainless-steel threaded rods cemented or epoxied into reinforced concrete buildings, or on tripods constructed out of welded stainless-steel rods driven into the ground. These systems capture subsidence where they are coupled to the ground, either the foundation of the building or at the ~2 m of the rods in the ground and are thus well suited for measuring subsidence due to deep/tectonic processes, with rates averaged over annual timescales. In Bangladesh, several groups have installed GNSS systems (e.g., Vernant et al., 2014; Reitz et al., 2015; Steckler et al., 2015; Steckler et al., 2016), returning subsidence rates of ranging from <1 to 17 mm/yr and spatially varying in relation to regional tectonics. Reitz et al. (2015) and Steckler et al. (2015) examined the vertical component of GNSS throughout Bangladesh for regional patterns. Sites in the NW are on stable Indian Craton at or landward of the Hinge Zone and show rates <1 mm/yr. The Sylhet basin, the foredeep of the Shillong Massif to the north, shows very high subsidence rates of 7–12 mm/yr. Dhaka shows rapid rates >12 mm/y due to extensive groundwater extraction in and around the city (Akther et al., 2010). The foldbelt in the east exhibits variable rates depending on whether the sites are located in synclines or anticlines. In the coastal belt, GPS subsidence rates near the sandy Brahmaputra (Lower Meghna) river mouth are 3-4 mm/y. However, higher rates (8+ mm/y) appear to be associated with muddier settings and may reflect near-surface consolidation and organic matter oxidation. In addition, GPS show a large seasonal component of up to 5-6 mm/y (Steckler et al., 2010). This is due to loading by surface and ground water from to the monsoon. It represents lithospheric-scale elastic deformation from an average of ~100 x 10^9 tonnes (maximum ~150 x 10^9) of water, approximately 7.5% of the annual flow of the Ganges, Brahmaputra and Meghna Rivers.

InSAR

This geodetic satellite system uses microwave frequencies in either the L, C or X bands (1.2, 5.3 or 10 GHz) to collect SAR images of the ground surface, with repeated observations allowing for estimating elevation change over timescales of months to a decade and capturing deep and shallow subsidence. To date, only one study has applied InSAR to determine subsidence in the GBMD (Higgins et al., 2014). They imaged a swath of approximately 75 x 185 km extending from north of Dhaka to the Meghna River mouth. Land subsidence of up to 10 mm/yr is seen in Dhaka and is likely due to groundwater pumping (Hoque et al., 2007; Akther et al., 2010). The rates are variable with little subsidence in the Pleistocene Madhupur Tract uplands and greater rates in marshy deposits on the periphery of the city. Outside of the city, rates vary from 0 to >18mm/yr, with the highest rates in Holocene organic-rich muds, including a channel of the Meghna that was filled by fine-grained sediments following the 1950 Mw8.5 Assam earthquake. Overall, the results demonstrate that a considerable amount of the young subsidence is primarily controlled by local stratigraphy, with rates varying by more than an order of magnitude depending on lithology.

RSETs

RSETs are instrumentation that measure subsidence with mm-scale accuracy, relative to deep (5-25 m) stainless steel benchmarks that are driven into the delta substrate. The instruments are visited seasonally to determine whether the land surface elevation has changed relative to the benchmark, so that measurements reflect processes acting over seasonal to decadal timescales (depending on the time since installation), and specifically capture the compaction component of subsidence that occurs within a few to tens of meters of the uppermost strata (i.e., the depth of the steel benchmark). This method has not yet been widely applied in the GBMD, however, preliminary results of Bomer et al. (in review) show that the natural surfaces of the Sundarbans are tracking with the effective sea level rise. The RSET network in the fluviotidal delta plain will be extended over the next decade as part of the greater initiative to improve embankment stability through the Coastal Embankment Improvement Project.

2.2 List of Publications Reviewed

2.2.1 A.1 Tectonics and Earthquake Vulnerability

A.1.1 Al Zaman M.D.A., Monira N.J. (2017) A Study of Earthquakes in Bangladesh and the Data Analysis of the Earthquakes that were generated In Bangladesh and Its' Very Close Regions for the Last Forty Years (1976-2016). J Geol Geophys 6: 300. doi: 10.4172/2381-8719.1000300

A.1.2 Betka, P.M., L. Seeber, S. Thomson, M.S. Steckler, R. Sincavage, C. Zoramthara, Slip-partitioning above a shallow, weak décollement beneath the Indo-Burman accretionary prism, Earth and Planetary Science Letters 503, 17–28, 10.1016/j.epsl.2018.09.003, 2018.

A.1.3 Carlton, B.D., Skurtveit, E., Bohloli, B., Atakan, K., Dondzila, E., and Kaynia, A.M. (2018). Probabilistic Seismic Hazard Analysis for Offshore Bangladesh Including Fault Sources. Proceedings 5th Geotechnical earthquake engineering and soil dynamics conference, Austin, Texas, 10-13 June.

A.1.4 Cummins, P.R. 2007. The potential for giant tsunamigenic earthquakes in the northern Bay of Bengal. Nature 449, 75-78, doi:10.1038/nature06088.

A.1.5 Debbarma, J., Martin, S.S., Suresh, G., Ahsan, A., Gahalaut, V.K. (2017) Preliminary observations from the 3 January 2017, Mw 5.6 Manu, Tripura (India) earthquake, Journal of Asian Earth Sciences, 148, 173–180, doi:10.1016/j.jseaes.2017.08.030.

A.1.6 Gahalaut, V.K., B. Kundu, S.S. Laishram, J. Catherine, A. Kumar, M.D. Singh, R.P. Tiwari, R.K. Chadha, S.K. Samanta, A. Ambikapathy, P. Mahesh, A. Bansal, and M. Narsaiah (2013) Aseismic plate boundary in the Indo-Burmese wedge, northwest Sunda Arc, Geology 41, 235-238, doi:10.1130/G33771.1.

A.1.7 Gahalaut, V.K., S.S. Martin, D. Srinagesh, S.L. Kapil, G. Suresha, S. Saikia, V. Kumar, H. Dadhich, A. Patel, S.K. Prajapati, H.P. Shukla, J.L. Gautam, P.R. Baidya, S. Mandal, A. Jain (2016) Seismological, geodetic, macroseismic and historical context of the 2016 Mw 6.7 Tamenglong (Manipur) India earthquake, Tectonophysics 688 (2016) 36–48, doi: 10.1016/j.tecto.2016.09.017.

A.1.8 Guzmán-Speziale, M., Ni, J.F. (2000) Comment on "Subduction in the Indo-Burma region: is it still active?" by Satyabala, S.P., Geophys. Res. Lett. 27, 1065-1066.

A.1.9 Hossain M.S., Khan M.S.H., Chowdhury K.R., Abdullah R. (2019) Synthesis of the Tectonic and Structural Elements of the Bengal Basin and Its Surroundings. In: Mukherjee S. (eds) Tectonics and Structural Geology: Indian Context. Springer Geology. Springer, Cham, doi: https://doi.org/10.1007/978-3-319-99341-6_6

A.1.10 Johnson, S.Y., Alam, A.M.N. (1991), Sedimentation and tectonics of the Sylhet trough, Bangladesh. Geol. Soc. Am. Bull. 103, 1513-1527.

A.1.11 Khan, Md.S.H., Md.S. Hossain and Md.A. Uddin (2018) Geology and Active Tectonics of the Lalmai Hills, Bangladesh – An Overview from Chittagong Tripura Fold Belt Perspective, Journal Geological Society Of India, 92, 713-720

A.1.11 Maurin, T., and C. Rangin (2009b), Structure and kinematics of the Indo-Burmese Wedge: Recent and fast growth of the outer wedge, Tectonics, 28, TC2010, doi:10.1029/2008TC002276.

A.1.12 Mazumder, R.K., (2018) Seismic damage assessment using RADIUS and GIS: A case study of Sylhet City, Bangladesh International Journal of Disaster Risk Reduction, https://doi.org/10.1016/j.ijdrr.2018.11.023

A.1.13 Molnar, P. (1987), The distribution of intensity associated with the great 1897 Assam earthquake and constraints on the extent of rupture, J. Geol. Soc. India, 30, 13 – 27.

A.1.14 Mondal, D.R., 2018. Evidence of the 1762 Arakan and prior earthquakes in the Northern Sunda Subduction, Ph.D. Thesis, City University of New York, 241 pp.

A.1.15 Mondal, D., C.M. McHugh, R.M. Mortlock, M.S. Steckler, S. Mustaque, Microatolls document the 1762 and prior earthquakes along the southeast coast of Bangladesh, Tectonophysics, 745, 196–213, 10.1016/j.tecto.2018.07.020, 2018.

A.1.16 Ni, J.F., Guzman-Speziale, M., Bevis, M., Holt, W.E., Wallas, T.C., Seager, W.R., 1989. Accretionary tectonics of Burma and the three-dimensional geometry of the Burma subduction zone. Geology 17, 68-71.

A.1.17 Palamenghi, L., Schwenk, T., Spiess, V., Kudrass, H.R., 2011. Seismostratigraphic analysis with centennial to decadal time resolution of the sediment sink in the Ganges–Brahmaputra subaqueous delta. Cont. Shelf Res. 31, 712–730. doi:10.1016/j.csr.2011.01.008.

A.1.18 Pickering, J., (2016). Response of the Brahmaputra River to Tectonic Deformation and Paleohydrological Events in the Foreland, Bengal Basin, Ph.D. Thesis. Vanderbilt University.

A.1.19 Rahman, M.Z., S. Siddiqua, A.S.M.M. Kamal (2017) Probabilistic seismic hazard analysis for Dhaka city, Bangladesh, GeoOttawa

A.1.20 Reitz, M.D., J. Pickering, S. Goodbred Jr., C. Paola, M. Steckler, and S.H. Akhter, Effects of tectonic deformation and sea level on river path selection, and application to Bangladesh, J. Geophys. Res. Earth Surf., 120, doi:10.1002/2014JF003202.

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2.3 Summary of Selected Papers

2.3.1 Reference A.1.1

A study of earthquakes in Bangladesh and the data analysis of the earthquakes that were generated in Bangladesh and its' very close regions for the last forty years (1976 - 2016), Md. Abdullah Al Zaman and Nusrath Jahan Monira. J Geology and Geophysics, Volume 6, 2017

Summary

Earthquakes pose a significant geohazard in Bangladesh because the country is located along several active tectonic plate boundaries. This study analysed earthquake magnitudes and frequencies over a 40 - year historical interval. They concluded that many earthquakes are low in magnitude, however such small magnitude earthquakes appear to be increasing in frequency.

Methodology

The study used historical data obtained from the USGS to analyse:

- The timing of historic earthquakes
- The magnitude of these earthquakes

Further consideration was given to the origin (epicentre) of the earthquakes, and past large-magnitude earthquakes occurring from 1548 to present were also discussed. It is noted that longer-term records are more likely to document earthquakes that had a significant impact on human populations and are therefore biased to record higher magnitude events.

Key findings & knowledge gaps

This study provides detailed summaries of a number of earthquakes that have occurred in Bangladesh in the past four decades. They show a greater frequency of earthquakes in the interval of 2007-2016 than in the preceding three decades. However, one shortcoming of this study is that the timeframe of analysis is fairly short compared with geologic time and may not accurately capture long-term trends.

2.3.2 Reference A.1.28

Locked and loading megathrust linked to active subduction beneath the Indo-Burman Ranges, Michael S. Steckler, Dhiman Ranhan Mondal, Syed Humayun Akhter, Leonardo Seeber, Jonathan Gale, Emma M. Hill, and Michael Howe. Nature Geoscience, Volume 6, p. 615-618, 2016,

Summary

While it is clear that evolution of the Bengal Basin has been significantly influenced by tectonics, the rates of present-day deformation were not well known. This study showed that plate convergence is presently occurring at rates of 13 - 17 mm/year along the Indo-Burman Ranges, meaning that earthquakes remain a present-day geohazard.

Methodology

The study used data obtained from GPS monitoring stations that measured present day plate movements in Bangladesh. Of these:

- 26 continuous GPS receivers were installed to cover much of the delta
- Stations monitored between 2003 - 2014
- 18 stations were selected that had 6-10-year time series

Additional data from Myanmar were used to investigate the Sagaing Fault.

Key findings & knowledge gaps

This study is notable for both its geographic breadth (it covers much of the delta spatially) and novel GPS data showing present day plate motions. From the data, the authors concluded that the delta remains tectonically active and that strain is occurring in such a way that it could produce a devastating mega-quake if released in a single event. The findings have implications for geohazards in Bangladesh.

2.3.3 Reference A.2.5

A base-level stratigraphic approach to determining Holocene subsidence of the Ganges-Meghna-Brahmaputra Delta plain, Celine Grall, Michael Steckler, Jennifer Pickering, Ryan Sincavage, Chris Paloa, Humayun Akhter, Volkhard Spiess. Earth and Planetary Science Letters, Volume 499, p. 23-26, 2018

Summary

Subsidence affects the sustainability of the coastal delta because elevation loss contributes to relative sea level rise. Knowing the rates of subsidence of the delta plain is therefore important for estimating the sediment needed in coastward regions to offset relative sea level rise. This paper made estimates of subsidence across much of the GBMD throughout the Holocene, showing that subsidence rates averaged over centennial to millennial timescales are fairly low and gradually increase coastward.

Methodology

The study used a large dataset of almost two hundred radiocarbon ages, which were considered to be representative of the depositional time of the sedimentary units in which the dated material was encased. These were:

- Plotted with depth
- Considered in the context of eustatic sea level rise
- Used to identify times dominated by aggradation vs progradation, and
- Placed with in the geomorphotectonic domains of the GBMD determined from previous studies

Three difference methods were used to estimate subsidence, which are described in detail in the paper.

Key findings & knowledge gaps

This study is noteworthy for 1) the wealth of radiocarbon data first presented here, and 2) producing the first delta-wide subsidence map. The rates identified here may be useful both for predicting the future sustainability of the delta plain and for identifying regions where humans are driving rapid subsidence. However, it should be noted that rates are averaged over hundreds to thousands of years and therefore do not necessarily show present-day rates of subsidence, i.e., they may underestimate subsidence at locations that are being loaded by fresh sediment such as the Sundarbans forest. This dataset should therefore be supplemented with modern (instrumental) measurements to get a more holistic picture of how subsidence is acting across difference space and time scales.

2.3.4 Reference A.2.7

InSAR measurements of compaction and subsidence in the Ganges-Brahmaputra Delta, Bangladesh, Stephanie Higgins, Irina Overeem, Michael Steckler, James Syvitski, Leonardo Seeber, and Humayun AkhterJ. Geophysical Research: Earth Surface, Volume 119, p. 1768-1781, 2014

Summary

This study estimated land surface subsidence over modern (instrumental) timescales for a portion of the GBMD using Interferometric Synthetic Aperture Radar (InSAR). They found land surface subsidence rates of 0 to more than 18 mm/yr, with variations in rate likely related to subsurface lithology and groundwater extraction. Rates were lowest in places underlain by older (i.e., compacted) clays.

Methodology

Data were compiled as follows:

- InSAR data were obtained for the period of 2007 to 2011
- Spatial coverage was 10,000 km2 including the city of Dhaka
- The L-band wavelength was used to minimize noise from vegetation

Key findings & knowledge gaps

This is the first study to employ InSAR to estimate subsidence rates in Bangladesh. It provides modern/present day rate of subsidence and is therefore a valuable complement to work by others that estimate subsidence over longer timescales. The spatial breadth of this study is limited to only a portion of the delta, however, InSAR satellites launched in 2014 and 2016 may provide additional data to build understanding of subsidence throughout the delta.

3 Delta Morphology and Sediment Supply

3.1 Delta Morphology

3.1.1 Introduction

The delivery and retention of sediment to fill accommodation generated by relative sea level rise (including subsidence, discussed above) is key to building and maintaining delta plains. This means that sediment flux and routing through the channel network plays a primary role in the construction and maintenance of the >100,000 km2 GBMD. The entire basin is composed of a stacked patchwork of highstand deltas (Goodbred and Kuehl, 1999; Goodbred et al., 2003; Pickering et al., 2017). Of these, the Holocene-aged delta (the GBMD) includes the uppermost 50-90 m of strata. Like in many deltas, the processes of sediment delivery and the resulting geomorphology of the GBMD are complex, because they are shaped by rapidly migrating rivers (Sarker et al., 2003), an enormous seasonal sediment load (Goodbred and Kuehl, 1999), and redelivery and reworking at the coast by large tides and frequent storms (Goodbred and Kuehl, 2000; Rogers et al., 2013; Darby et al., 2015). The delta may be considered as geomorphic zones dominated by specific sedimentation processes (Wilson and Goodbred, 2015); for simplicity we discuss delta building within three primary zones: (i) the landward fluvial-fan deltaplain, constructed principally by the big river channels, (ii) the coastward fluviotidal delta, in which tidal processes overprint and rework the fluvial deposits of the big rivers, and (iii) the tectonically influenced Sylhet basin and Comilla Terrace, which is also characterized by big river(s) but contributes little sediment flux to the broader delta.

3.1.2 The Fluvial-fan deltaplain

The upper fluvial delta plain was constructed and is maintained by sediment principally mobilized from the rapidly uplifting Himalayas and delivered to the delta plain via the presently 8 ± 4 and 10 ± 4 km wide channel belts of the respective Ganges and Brahmaputra Rivers, which carry nearly ~ 1 billion tons of sediment annually (Goodbred and Kuehl, 1999). As discussed below, the Meghna River contributes little sediment. The Ganges and Brahmaputra Rivers are constrained by topography where they enter the delta, meaning that they act as point sources for the fluvial fan delta plain, which extends ~200 km coastward from the delta apex, to an abrupt slope change (which marks the transition to the fluviotidal delta) (Wilson and Goodbred, 2015). A portion (~30%) of the fluvial sediment is stored within the delta plain; the rest exits the river mouth (presently the Padma, eastern GBMD) (Goodbred and Kuehl, 1999).

Within the fluvial fan delta, the rivers have taken multiple pathways throughout the Holocene. Understanding these avulsions is important to reconstructing the history of sediment delivery to the coast, because the rivers are the primary sediment conduits within (most) deltas. It has been posited that the Ganges has swung periodically eastward over the past several thousand years, based on a limited number of radiocarbon ages (Allison et al., 2003). However, historical maps depict the Ganges in a westward position, flowing down the Hooghly channel circa 400 years ago (Chamberlain et al., 2020). The Brahmaputra River has also changed position throughout the Holocene, switching courses (ie., an avulsion) at an average timescale of every 1500-2000 years (Reitz et al., 2015). The paleochannels of the big braided rivers are rarely preserved in the surface morphology/topography of the delta, due to extensive reworking by a number of smaller meandering distributaries, which have created a scroll-plain of near-surface deposits in the landward delta. These are underlain by sand-dominated deposits, with low silt/clay and organic preservation (Wilson and Goodbred, 2015; Chamberlain et al., 2017), and little information to constrain the rates of sediment deposition. The sandy nature of the delta's stratigraphy is thought to contribute to low subsidence rates (Grall et al., 2018), which further support maintenance of the delta plain.

3.1.3 The Fluvio-tidal delta

Avulsions of the river(s) redirect sediment and allow for the construction of new land at the coast, while abandoned areas of the coastal delta see an increased dominance of tidal processes. The eastern portion of the fluviotidal delta includes the active Padma River mouth, while the western portion is presently fluvially inactive (in terms of the big rivers); both regions experience semi-diurnal, mesoscale tides.

Roughly 70 % of the sediment load of the GBMD system exits the Padma River mouth; of this ~ 10-20 % is redelivered to the fluviotidal delta through tidal/marine processes (Goodbred and Kuehl, 1999). A portion of the fluviotidal delta contains the natural Sundarbans forest, while other/inhabited regions have been poldered (enclosed with levees) to minimize routine flooding. This diversity allows for determining the effect of human modifications on land building processes (i.e., sedimentation) at and near the coast. Studies from within the Sundarbans mangrove forest have shown sedimentation rates can be as high as 6 cm over a single monsoon season (average ~1-2 cm yr-1; Rogers et al., 2013), or up to 5 g cm^{-2} (avg. 1.3 g cm-2; Rogers et al., 2013). Much of this is from inorganic accumulation (~97%; Rogers et al., 2013) supplied from the sediment-laden rivers that passively flood the landscape by tides and/or riverine floods, which tends to be finer-grained on average than more landward deposits of the fluvial fan delta (Wilson and Goodbred, 2015). A previous study by Auerbach et al. (2015) showed polders at an elevation deficit (-1.5 m) compared to the natural Sundarbans forest. While this was found to be primarily due to the preclusion of sediment since embankment construction, relative sea level rise in addition to effective sea level rise (from an increase in mean high water over the past few decades) are also factors (Pethick and Orford, 2013; Auerbach et al., 2015). This study revealed that land surface elevation relative to flood water height, and the associated hydroperiod, dictated sedimentation rates: rates as high as 25 cm yr^{-1} were observed in poldered areas when embankments catastrophically failed by Cyclone Aila.

Human modification of the delta has also been shown to have an effect on channel networks within the fluviotidal delta. For example, the construction of embankments in the 1970s to protect >5000 km^2 of agricultural land (former floodplain) cut off more than 1000 linear km of primary creeks, thereby driving siltation and channel infilling in the fluviotidal delta (Moshin-Uddin and Islam, 1982; Wilson et al., 2017), which has been documented at rates of 10s of cm per year over the past few decades (Chamberlain et al., 2017; Wilson et al., 2017). Similarly rapid rates of sedimentation were identified in older deposits of one coastal site in the Sundarbans forest (Chamberlain et al., 2017).

3.1.4 Sylhet basin and Comilla Terrace

Sylhet basin and Comilla Terrace are low-lying but tectonically active areas of the eastern delta. These areas were occupied throughout the mid- to late- Holocene by older paths of the Brahmaputra River (Pickering et al., 2014; Sincavage et al., 2018) and are also presently occupied by the Meghna River; sediment within the basin is relatively coarse-grained due to shedding from the bounding hillslopes (Sincavage et al., 2019). However, sediment from the Meghna river is largely sequestered within the basin, and so processes acting within this region contribute little to delta building at the coast.

3.2 Sediment Supply

3.2.1 Introduction

The concentration and distribution of sediment in the river channels and nearshore are important controls on delta morphology. Understanding sediment composition across different transport mechanisms also provides insight into the reworking and accretion of material across the delta. Estimates of suspended sediment concentration (SSC) and grain size distributions have been collected from discrete areas of the GBMD system, from the upstream portion in India, to the coastal shelf; however, the total number of observations are relatively few for the size and variability of the system. Both in situ measurements (e.g. Kuehl et al., 1989; Barua et al., 1994; Datta and

Subramanian, 1997; Singh et al., 2007; Hale et al., 2020) and remote sensing (Islam et al., 2001) methods have been used to make the currently published observations. There remains many gray literature observations of sediment concentrations collected by Bangladesh government agencies, but these data are not readily available nor have been compiled into a well-tested dataset.

In addition to estimates of concentration, the mineralogy of sediment samples is also recorded for the Ganga River in India (Chakrapani et al., 1995) and the Ganges, Padma, Jamuna and Meghna rivers in Bangladesh (Datta and Subramanian, 1997). Generally, the sediment of the GBMD is dominated by grain sizes ranging from fine sands to clays, with seasonal variability in transport due to monsoons. More detailed results from these analyses for suspended and bed load transport are summarized in the following subsections. The mineralogy of the delta sediments are important controls on the quality of groundwater, particularly arsenic and manganese that represent local health hazards.

3.2.2 Suspended Load

The majority of sediment in the GBMD is transported as suspended load that is transported along with flow or in response to turbulent resuspension. In the G-B rivers the fine-grained fraction of sediment is strongly silt dominated with little clay sized sediment. The concentration of suspended sediment has been assessed for several of the large rivers. Dry season estimates of SSC made using TM and AVHRR data averaged 750 mg/L for the Brahmaputra and 500 mg/L for the Ganges River. During the monsoon season, average SSC increased to 1100 mg/L and 1250 mg/L, respectively (Islam et al., 2001). The authors argue that the increase in Ganges wet season SSC is tied to bank erosion and deposition during peak flooding. This increase in concentration can also be seen in sediment yields of the Padma River, where yields increase four-fold from 50 Mt/yr in the dry season to 200 Mt/yr during the monsoon (Barua et al., 1994). Other estimates for suspended sediment load of the Brahmaputra (or Jamuna) River include 332 Mt/yr (Sarker et al., 2014), and 106 Mt/yr for the combined system (Datta and Subramanian, 1997). Sediment moves seaward by fluvial forcing, and generally westward by tidal forcing (Barua et al., 1994).

In the Ganga River in India, suspended sediments range from very fine sands to medium silts (Chakrapani et al., 1995; Singh et al., 2007). Suspended sediment in the main rivers of the GBMD is finer, with fine silts and clays. Textural analysis by Datta and Subramanian (1997) showed fine silts and clays in the Ganges, Meghna, Jamuna and Padma Rivers. In their estimation, the grain size of more than 95% of the suspended material is fine silt and clays (≤16 µm). Median grain sizes sampled in the Meghna Estuary are similarly fine, ranging from 13.8 to 25 µm, or fine to medium silts (Kuehl et al. 1989, Barua et al., 1994).

In the nearshore areas of the delta, observations of Barua et al. (1994) show that SSC values regularly exceed 1000 mg/L, which represents the direct supply of fluvial sediment delivered from the river mouth estuary to the inner shelf. Observations by Rogers et al. (2013) demonstrated a strong link between the annual river sediment plume and sediment deposition in the Sundarbans and tidal deltaplain. The study documents an average of 1 cm/yr of sediment across the region during the monsoon season, with up to 50% of the sediment mass derived directly from the seasonal river plume. More recently Hale et al. (2019) published estimates of tidal sediment transport in the Sibsa River, showing that mean transport in this single tidal channel are comparable to the mean monsoon discharge of the Ganges and Brahmaputra rivers. Collectively, these results on coastal sediment transport and deposition demonstrate that the sediments are closely coupled with river mouth discharge and advected onshore by tidal transport.

The mineralogy of these suspended sediments has also been reported. Mineral constituents in suspended sediment samples throughout the GBMD were predominantly quartz, followed by illite, kaolinite and feldspars (Datta and Subramanian, 1997). Trace amounts of chlorite, carbonates and montmorillonite were present at most sampling locations. Chakrapani et al., (1995) looked at the mineralogy upstream of the GBMD system in India and noted changes in the mineral abundance moving downstream towards Bangladesh. Upstream, a high percentage of micas was noted. Towards the Bay of Bengal, smectite abundance increases, exceeding the mica abundance. In addition, samples also contain low levels of chlorites, vermis and kaolinites (Chakrapani et al., 1995).

3.2.3 Bed Load

Coarse sediment in fluvial systems is transported by rolling, sliding or saltation (bouncing) along the channel bed. Bed load transport is initiated when bed shear sufficient to exceed the threshold for motion. In general, bed load makes up a smaller proportion of sediment load than suspended material, although the fraction for the GB rivers is larger than most large rivers and estimated at 30-50% of the total load. Each of the major rivers of the GBMD has sandy bed material (Sarker et al., 2014). Estimates for sediment transport of bed load are unknown, although previous work supposes it may be as high as suspended transport rates (Garzanti et al., 2010). The mineralogy of the bed load is similar to that of the suspended load. Sediments are quartz-dominated, with the presence of feldspars and clays (Datta and Subramanian, 1997).

Grain sizes of bed load are coarser than the suspended load. Upstream of the GBMD in India, bed load sediment is primarily fine sands (~60%) to very fine sands (~20%), with the remaining material being coarser sands, silts and clays (Singh et al., 2007). Moving into the GBMD, bed sediment samples were 76% fine to very fine sands, with silt-sized grains making up the remaining bed layer (Datta and Subramanian, 1997). However, recent detailed studies by Lupker et al. (2011) show that medium sand comprises a significant component (15-20%) of the Ganges sediment load as measured at Harding Bridge. Downstream of the junction of the Ganges and Brahmaputra rivers, bed sediments are even finer. Grain sizes in that reach are very coarse silts (Singh et al., 2007). In the coastal region, samples showed the dominant size clast were also fine to very fine sands (Stummeyer et al., 2002).

3.2.4 Sediment Supply to the Delta

Given the great importance of sediment delivery to maintain the GBMD delta surface in the face of rising sea level, several recent studies have investigated how sediment load has varied in recent decades or may do so in coming decades (Darby et al. 2015; Higgins et al., 2018; Rahman et al., 2018). The analysis by Rahman et al. (2018) considers trends in fluvial sediment discharge as measured by various studies and organizations between 1960 and 2008. Their principal results suggests that the combined sediment discharge of the GB rivers has declined by an average of 8-10 Mt/yr over the last half century, resulting in an approximate 50% decrease over this time. However, it is not clear that this trend is real because past estimates of river sediment discharge have been highly variable with assumed large errors, as accurate measurements on large braided channels are non-trivial. Indeed, the decreasing regression lines are anchored by several high estimates from early observations that are not consistent with later observations. Also, the correlation coefficient (R^2) for each regression is very low at ≤0.20, suggesting a poorly defined fit of the data. Furthermore, the analyses of past sediment discharge do not account for the ENSO phase during which they were measured, which is a known major control on water and sediment fluxes from the GBMD (Papa et al., 2012). Although the finding of a declining sediment load over the past 50 years cannot be discounted, it is far from certain that this trend is accurate or even real.

Two recent studies have considered future changes in sediment supply delivered to the GBM delta (Darby et al. 2015; Higgins et al., 2018). Darby and co-authors use the model Hydrotrend to consider the impact of different IPCCC climate-change scenarios and monsoon projections. Their results suggest that the supply of fluvial sediment to the GBMD could increase to by 15-50% in the next 50 years under a strengthened monsoon and increased water discharge. Most climate models do suggest a strengthened summer monsoon under a warming climate, but there is considerable uncertainty. In contrast to the projected increase in sediment supply due to climate change, Higgins and colleagues (2018) consider potential anthropogenic impacts that could cause a significant decrease. The study models the impacts of implementing India's proposed National River Linking Project, which would divert water from the Ganges and Brahmaputra river basins to more water stressed regions to the south and west. Their results suggest that sediment supply to the GBMD could decline by 40-75% if the project were to be fully implemented. Clearly, a sustained and robust sediment supply is essential for long-term maintenance of the GBMD, and the competing impacts of climate change and anthropogenic activities leave a great deal of uncertainty in future river discharge.

3.3 References for Key Literature

3.3.1 A.3 Delta Morphology

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3.4 Summary of Selected Papers

3.4.1 Reference A.3.3

Stratigraphic evolution of the late Holocene Ganges-Brahmaputra lower delta plain, Mead Allison, S. Khan, Steven Goodbred, Steven Kuehl. Sedimentary Geology, Volume 155, p. 317-342, 2003

Summary

Knowing the lobe activity (i.e., the timing and sequence of delta lobe development) is useful for constructing sediment patterns and river channel network activities. This study provides ranges of activity for different lobes of the Holocene GBMD, and is currently the most developed geochronologic sketch for macroscale GBMD growth during this time.

Methodology

The study used various data sources to understand GBMD evolution through the late Holocene including

- Sediment cores
- Clay minerology
- Elemental trends
- Radiocarbon dating

These were compiled to generate a chronologic map for delta progradation/movement of the trunk channel.

Key findings & knowledge gaps

The study yielded a broad chronology that identified 4 lobes of the Ganges, active from 5 - 0 ka. The chronology showed that the Ganges River depocenter swung progressively eastward throughout the late Holocene. One shortcoming of this work is that the chronology is relatively limited in its spatial coverage and in the number of ages. However, this is reflected in realistic uncertainties on the lobe activities.

3.4.2 Reference A.3.6

Flood risk of natural and embanked landscapes on the Ganges-Brahmaputra tidal delta plain, L. Aurbach, Steven Goodbred, Dhiman Mondal, Carol Wilson, Kazi Matin Ahmed, K Roy, Michael Steckler, Christopher Small, Jonathan Gilligan, and B. Ackerly. Nature Climate Change, Volume 5, p. 153-157, 2015

Summary

There is significant concern in how the populated and poldered islands of coastal Bangladesh may persist under conditions of relative sea level rise. This study assessed the land surface subsidence of poldered islands, showing that elevation loss there is due to a combination of sediment interruption, accelerated compaction, removal of forest biomass, and increased tidal range. Breaching of polders was shown to provide fresh sediment to offset subsidence.

Methodology

The study used a variety of methods and data including:

- GPS, to estimate elevations and subsidence at numerous sites in the study area
- A CTD, measure tidal channel water movement
- Shallow sediment cores; lithology and biomass were described
- Sediment accretion estimates, following a cyclone-induced polder breach.

Key findings & knowledge gaps

The study showed that poldered regions are losing elevation due to a combination of human-exacerbated factors. Natural sedimentation can be restored to offset subsidence; however this requires flooding of poldered islands. Implementing such a strategy can pose challenges to the livelihoods and comfort of people.

3.4.3 Reference B.1

Suspended sediment distribution and residual transport in the coastal ocean off the Ganges-Brahmaputra river mouth, D.K. Barua, S.A. Kuehl, R.L. Miller and W.S. Moore. Marine Geology, Volume 120, November 1994, Pages 41–61

Summary

In this work, the authors collect suspended sediment samples off the coast of the Ganges-Brahmaputra delta. By sampling along the continental shelf, they sought to estimate the distribution of sediment suspended in the column, as well as rates of sediment transport by tidal forcing. Using a combination of field and remote observations, the authors are able to estimate the amount of sediment that is transported back to the delta front via residual tidal transport.

Methodology

At 14 sites in the coastal ocean off the Meghna river mouth, measurements of tidal currents and suspended sediment concentrations were taken 1 m below the surface, mid-depth and 1 m above the shelf. Sites were located at the immediate river mouth, several sites moving westward along the shelf, where depths ranged from 5 – 10 m, and two sites where depths exceeded 10 m or neared 20 m. Sites nearest the estuary were sampled during the monsoon season (August), whereas sites further west or outward on the shelf were sampled during the dry season (October – December). Additionally, Landsat data from March was used to

Key findings & knowledge gaps

There was a slight coarsening of suspended sediments in the dry season. Sites sampled in the monsoon season had median grain sizes ranging from 0.012 to 0.0932 mm, fine silts to very fine sands. In the dry season, median grain sizes ranged from 0.0125 mm to 0.111 mm, or fine silts to fine sands. Nontidal transport makes up ~47% of total material transport, while tidal processes transport the remaining 53%. Due to the complex interaction of tidal and fluvial processes near the river mouth, material is preferentially transported in a southwest direction.

The key gaps of this paper: more thorough grain size distributions were not published for each of the sampling locales, and the sampling strategy was not completed for all sites in both monsoon and dry season, therefore it is hard to estimate how much grain size changes for a given location (near the estuary or westward along the delta front).

3.4.4 Reference B.7

Mineralogical and chemical variability of fluvial sediments 1. Bedload sand (Ganga-Brahmaputra, Bangladesh), E. Garzanti, S. Ando, C. France-Lanord, G. Vezzoli, P. Censi, V. Galy and Y. Najman, Earth and Planetary Science Letters, Volume 299, November 2010, Pages 368–281,

Summary

This study explores the textural, mineralogical and chemical compositions of bedload sediments of the major rivers in the Ganges-Brahmaputra delta. Using bar and bedload samples, they quantified how sediment size and mineral composition changes across the different sediment sources and transport paths, with the goal of identifying how sediment is physically or chemically altered as it is transported from source to sink.

Methodology

Bedload samples were collected from the Ganga, Brahmaputra and Meghna rivers during the monsoon season, while bar samples were collected from the Ganga, Brahmaputra and Padma rivers bars during the dry season. Chemistry, petrography, spectroscopy and the conversion of mineralogical compositions to chemical compositions. The elemental composition of the grains may not be relevant for the larger CEIP project but exploring the distribution and provenance of sediments is useful.

Key findings & knowledge gaps

The relevant results of this study show that bedload grain sizes become finer moving downstream within the system. Sediment in the Brahmaputra River are coarser than the Ganga River sediments, which, in turn, are coarser than sediment in the Padma-Meghna River. In all cases, bedload sediments are fine-grained sands. There are only small differences in the chemical composition of the Ganga and Brahmaputra. The authors argue that these small differences are due to the effective mixing by the large rivers.

The key gaps highlighted by this paper: bedload mineralogy, distribution and transport is only quantified during the monsoon season, and only for a few locations along the main river channels. Dry season measurements are taken from channel bars and may not be representative for dry season bedload transport. No samples were taken from any fluvial channels within the interior of the delta system, so the distribution of volume of bedload transported via these networks remains unknown.

4 Riverbank Erosion

4.1 Introduction and Synopsis

Bank erosion is one of the main concerning issues in Bangladesh. Bank erosion is problematic for most of the polders with erosion threatening polder embankments.

The largest rivers may have bank line shifts of hundreds of meters per year (Baki & Gan, 2012). Jamuna River can exhibit bank erosion up to 2 km/year (CEGIS, 2007). In the present study, the lower Meghna has substantial bank erosion rates, while the cohesive banks exhibit much smaller erosion rates, typically 5-10 m/year, even for relatively large rivers such as the Baleswar River.

Bank erosion rates clearly vary significantly in Bangladesh. The sediment regime appears to be the main reason for the variation. Hasegawa (1989) found that the highest bank erosion rates are found for medium to coarse sand, while the lowest erosion rates are found for finer (cohesion) and coarse (gravel) material. This suggests a clear correlation between the erodibility of the bank material and bank erosion.

Since gravel is essentially non-existing in Bangladesh, we must consider two regimes when modelling bank erosion in the rivers of Bangladesh:

- Sandy banks
- Cohesive banks

The rivers in the Southwest region are dominated by cohesive banks and will therefore exhibit much smaller erosion rates than e.g. Lower Meghna and Sangu located in the Southeast region, which were also in the plan for the project.

In addition to the sediment regime, we also need to consider the flow regime, although they are related, as most of the tidal rivers have significant cohesive sediment influence, while most of the fluvial systems have very little cohesive sediment influence on the morphology.

We know from observations that the flow velocities in the fluvial systems such as Jamuna are typically up to 3 m/s, while in the tidal rivers we normally see velocities around 1 m/s, i.e. flow conditions are much more mellow in the tidal rivers. We know from the tidal hydrographs that the net flows during the monsoon (vanishing net flows in the dry season) in the tidal rivers are much smaller than the tidal flows, so the cross-sections are shaped by the tidal flows, although the net flows can still impact the morphology because there is no net flow in the dry season, but the discharge magnitude i.e. the dominant discharge is not strictly the monsoon net flow.

In the fluvial systems, such as Jamuna River, the discharge varies significantly from dry season to monsoon, with Jamuna typically around 7,000 m^3/s during the dry season and up to 100,000 m^3/s during the monsoon. The Jamuna River width is controlled by the dominant discharge, at Bahadurabad around 36-38,500 m^3/s (Ali & Bhuiyan, 2005). Hence, during the monsoon the Jamuna discharge is much higher than the dominant discharge shaping the river, causing bank erosion during the monsoon, while the river exhibits very low morphological activity during the dry season.

Lower Meghna has the largest monsoon discharges in Bangladesh, but it does not exhibit the extreme bank erosion that we know from Jamuna River. Lower Meghna can erode 100-200 m/year based on 1988-2019 Landsat images. There are two main differences between Jamuna and Lower Meghna:

- Jamuna is sandy, Meghna is sand/silt
- Jamuna has no tidal flow, while Lower Meghna is mostly tidal, but with a significant net flow during the monsoon

In other words, the Lower Meghna has mixed characteristics from the tidal and fluvial systems.

Sangu River located in the Southeast region has higher bank erosion rates relative to width compared to the tidal rivers in the Southwest region. We have not yet investigated the Sangu River in detail, but we know that the river is dominated by monsoon flows, and we know that the riverbed is sandy. Sangu is in other words fluvial.

Bank erosion predictors are based on near-bank conditions, which can involve water depth, bank height, flow velocity, bed levels, shear stress and stream power (Larsen et al, 2006). Several authors have reported simulations of plan form developments, such as Nagata et al (2000), Darby et al (2002), Rinaldi et al (2008), Asahi et al (2013) and Baso et al (2018).

Most publications focus on fluvial conditions, while the present study is more aimed at tidal rivers. Fagherazzi et al (2004) focused on tidal rivers using the originally proposed model of Ikeda et al (1981) in which the erosion is modelled very simply by the difference between the near-bank velocity and the mean velocity in each cross-section. The work of Fagherazzi et al (2004) and Baso et al (2018) suggest that the erosion predictors for alluvial conditions can also be applied in tidal rivers.

4.2 List of Publications Reviewed

C.1 Alam, M.M., 1991, “Some distinctive aspects of braiding and anastomosing with reference to the Jamuna and Meghna rivers in Bangladesh”, Journal of Bangladesh academy of sciences, 15, pp 113-121.

C.2 Ali, M. M., & Bhuiyan, M. A. 2005. Finding a sustainable navigation route in Jamuna river using two-dimensional hydrodynamic and sediment models.

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C.4 Baki, A.B.M. and Gan, T.Y., 2012, “Riverbank migration and island dynamics of the braided Jamuna River of the Ganges Brahmaputra basin using multi-temporal Landsat images”, Quaternary International 263 pp 148-161

C.5 Bosa, S., Petti, M., & Pascolo, S. (2018). Numerical modelling of cohesive bank migration. Water, 10(7), 961.

C.6 CEGIS 2005, “Developing empirical methods for predicting morphological changes in the Padma River”, Prepared for Jamuna-Meghna River Erosion Mitigation Project, Bangladesh Water Development Board, Dhaka, Bangladesh.

C.7 CEGIS 2007, “Long-term Bank Erosion Processes of the Jamuna River”, Prepared for Jamuna-Meghna River Erosion Mitigation Project, Bangladesh Water Development Board, Dhaka, Bangladesh.

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C.9 CEGIS 2018, “Prediction of Riverbank Erosion along the Jamuna, the Ganges and the Padma Rivers in 2018”, Prepared for Bangladesh Water Development Board, Dhaka, Bangladesh.

C.10 Crosato, A., 1990, “Simulation of meandering river processes”, Communications on hydraulic and geotechnical engineering, No. 1990-03.

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C.19 Jurina. T. O. 2017, “Channel closure in large sand-bed braided rives”, M.Sc Thesis, Delft University of Technology, The Netherlands.

C.20 Karmaker, T. & Dutta, S. 2010, “Modeling composite riverbank erosion in an alluvial river bend” River Flow 2010 - Dittrich, Koll, Aberle & Geisenhainer (eds), pp-1315-1322

C.21 Khan, M and Ali, M.M., 2016, “An approach to predict the yearly bank erosion rates of Jamuna River: An application of the correlation of bank shear stress and river discharge”, International Journal of Engineering Development and Research, Vol:4, Issue2, pp 1180-1185.

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C.27 NHC and RPMCL, 2013, “Main River Flood and Bank Erosion Risk Management Program”, Final Report, Annex E, River and Char land Morphology and River Engineering, Funded by ADB and JFPR, Prepared for BWDB, Dhaka, Bangladesh.

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C.29 Thorne, C.R., Russell, A.P.G., Alam, M.K., 1993, “Planform Pattern and Channel Evolution of the Brahmaputra River, Bangladesh”, Geological Society, London, Special Publications, 75, pp 257-276.

4.3 Summary of Selected Papers

4.3.1 Mosselman (1995)

Mosselman (1995) is a good overview paper providing the basics of bank erosion modelling adopted in the study. Mosselman presented several bank erosion formulas that were under consideration in the present study:

- Excess shear stress
- Near-bank bed degradation
- Critical bank height

The excess shear stress formulation is used by many publications, while the near-bank degradation model is suited for sandy banks where it is a good assumption that the transverse bank slope does not change when the bank erodes. This has been adopted by DHI for the Jamuna River, but it was discarded quickly for the cohesive banks in the tidal rivers. The critical height formula postulated by Mosselman was initially pursued in the present study, and we found that it is very easy to adopt because bank erosion rates correlate very well with bed levels and therefore also the bank height. However, it was later abandoned, as it suffers from one serious drawback: It only ties erosion to the bank height, so mitigation schemes reducing flow velocities along a bank eroding in this manner would not lead to reduced bank erosion, which we found difficult to believe. It is possible that the critical height bank erosion formula can work in combination with e.g. shear stress or excess velocity, but we wanted to avoid too complex bank erosion formulas.

4.3.2 Baso et al (2018)

Baso et al modelled the Tagliomento River, which is a tidal river in Italy with mixed cohesive and non-cohesive sediments in the bed and riverbank. The model formulation was generally like what we adopt in the present study, with similar parameters, so this study has high relevance for the present project. They modelled bank erosion using an excess shear stress formulation with cantilever collapse included, and they hindcasted the Tagliomento River over a period of 5 years. The width of the Tagliomento River is around 140 m, much smaller than for the large tidal rivers modelled in the present study. Bank line shifting was handled in a Eulerian manner (moving the banks in the fixed grid), while MIKE 21C uses a more accurate Lagrangian method (moving the grid to account for bank erosion).

4.3.3 Hasegawa (1989)

Hasegawa (1989) forms the basis for the bank erosion formula applied in the tidal rivers in the present study. Hasegawa used the near-bank excess streamwise velocity concept also adopted in earlier publications, e.g. Ikeda et al (1981), which is central in the present work. Hasegawa derived his bank erosion formula for non-cohesive sediment but compared to non-cohesive and cohesive banks and found that the highest bank erosion rates are found for medium to coarse sand, while much lower rates are found for very fine (cohesive) and coarse (gravel) sediment.

4.3.4 Fagherazzi et al (2004)

Most publications focus on fluvial conditions, while the present study is more aimed at tidal rivers. Fagherazzi et al (2004) focused on tidal rivers using the originally proposed model of Ikeda et al (1981) in which the erosion is proportional to the difference between the near-bank velocity and the mean velocity in each cross-section. The paper is referenced because it adopted the excess velocity to bank erosion in tidal rivers.

5 Polder Drainage and Management

5.1 Introduction and Synopsis

The Coastal Embankment Project (CEP) was implemented during the 60'ies and early 70'ies and lead to the poldering of a huge area in the coastal zone of Bangladesh. Single crop areas were converted to two or three crop per year which increased agricultural production significantly and improved food security greatly. Relatively soon after construction the area stared to suffer from drainage congestions and a significant part of the poldered area became waterlogged. Today the problems faced in the polders are multiple (CEIP-1 (CES-JV) June 2013):

- Drainage congestion
- Storm surge vulnerability
- Deteriorated embankments
- Poor condition of drainage structure
- Sedimentation of drainage khals
- Riverbank erosion
- Wave erosion of embankments
- Settlement at embankments (difficult to raise embankments)
- Squatter families difficult to resettle
- Conflict amongst users (agriculture and fishery)
- Lack of sustainable operation and management of facilities

This section of the interim literature review report will mainly address the issues related to drainage congestions. Polder management and design issues will be addressed in subsequent interim literature review reports (when the relevant experts have been fielded), while other issues are addressed elsewhere in this report.

The polders in the coastal zone of Bangladesh are designed to be drained by gravitation through sluice gates ("flap gates"), i.e. when the water level inside the polder is higher than outside then the sluice gates open and discharge drainage water into the peripheral rivers. Today, the drainage of the polders is ineffective creating widespread waterlogging inside the polders. The drainage congestion problem is greatly exacerbated by subsidence of the land inside the polders and sea level rise, which decreases the window for gravity drainage of the polders and thus contribute to accelerating water logging in the polders. The drainage congestion problem has been attributed to three main causes, viz.:

- Poor maintenance of the drainage structures and siltation of drainage canals (khals) inside the polders and lack of proper operation of the facilities. The proposed interventions in CEIP-1 (see CES-JV, June 2013) underlines this: In 16 of 17 polders replacement of existing sluices were recommended while re-excavation of khals were proposed in all 17 polders.
- Diminishing freshwater flow from upstream due to, for instance, construction of the Farakka Dam and freshwater abstraction at large-scale irrigation schemes causing siltation of peripheral rivers.
- The construction of the polders has greatly reduced the tidal volume, the flow velocities in the peripheral rivers therefore decreases and the size of the peripheral rivers decrease significantly though siltation. As a result, the tidal variation diminishes, and especially low tide levels increases preventing effective drainage of the polders.

The relative importance of each of these causes will vary across the coastal zone. In the western part of the delta the freshwater flow has been negligible also before the construction of the coastal polders, hence here the reduced tidal volume is the main reason, while in the south-central region the diminishing flow through the Gorai River may play a larger or additional role. Further east towards Meghna River the freshwater flow is abundant, and siltation of peripheral river seems to les of a problem there.

In areas where siltation of peripheral rivers have been identified as the main cause of drainage congestion, 'tidal river management (TRM)' (see Gain et al, 2017) has been identified as a comprehensive approach for sustainably managing polder drainage. Tidal river management involves breaching of the embankments to one or more polders for a period of time (few years). This has two beneficial effects: 1) the tidal volume will increase and thus flow velocities will increase in the peripheral rivers that will erode and restore original size; and 2) the water entering the polders will carry a high silt load that will accelerate land accretion.

5.2 List of Publications Reviewed

D.1 Animesh K. Gain, David Benson, Rezaur Rahman, Dilip Kumar Datta, Josselin J. Rouillard (2017): Tidal river management in the south west Ganges-Brahmaputra delta in Bangladesh: Moving towards a transdisciplinary approach? Environmental Science and Policy.

D.2 IWM (2006): Monitoring the performance of Beel Kedaria TRM and baseline study for Bell Khuksia. Final Report. Volume I: Main Report

D.3 IWM (2006): Khulna Jessore Drainage rehabilitation Project. Monitoring the effect of East Beel Khuksia TRM basin and dredging of the Hari River for drainage improvement of Bhabodah Area.

D.4 IWM (2018): Technical Report on Survey, Storm Surge, Wave, Hydrodynamci Modelling and design parameters on Drainage system and Embnakment crest level for Packagae-1, -2 and -3, Salinity and Morphological Study. Summary Report.

D.5 CES JV (2013): Coastal Embankment Improvement Project, Phase-1 (CEIP-1). Final Report. Volume 1: Main Report

5.3 Summary of Selected Papers

5.3.1 Reference D.1

Tidal river management in the south west Ganges-Brahmaputra delta in Bangladesh: Moving towards a transdisciplinary approach? Animesh K. Gain, David Benson, Rezaur Rahman, Dilip Kumar Datta, Josselin J. Rouillard. In Environmental Science and Policy (2017).

Summary

Due to both natural and anthropogenic forces, the south west part of the Ganges-Brahmaputra coastal area is facing diverse problems such as waterlogging, salinity, and loss of biodiversity. In order to address these challenges, local people have identified 'tidal river management (TRM)' as a comprehensive approach for sustainably managing the polders. In order to identify existing implementation barriers and to effectively apply the TRM approach, a transdisciplinary approach is essential, supported by the active involvement of key agencies and local stakeholders. The proposed transdisciplinary framework can potentially be applied to TRM projects for solving waterlogging and associated problems in order to achieve greater sustainability of the area.

Methodology

The paper describes three recent tidal river management projects, viz. Beel Bhaina, Beel Khukhia and Beel Pakhimara. The paper describes the "baseline conditions" in the beels, the implementation of TRM, the challenges, and the outcome of the TRM implementation. Key issues addressed are implementation arrangement, (unfair) compensation, conflicts amongst user groups as well as "physical" challenges such as uneven distribution of sedimentation inside the polders.

Key findings & knowledge gaps

Key findings are that TRM has a high potential for removing waterlogging in beels and restoring navigability in the peripheral rivers and thereby improving food security in the coastal zone. In order to address multi-faceted challenges and conflicts amongst user groups (e.g. farmers, aqua culture, etc.) a transdisciplinary approach is identified as a potentially useful governance device for resolving such complex problems.

The proper selection of beels (downstream to upstream), hydrological and morphological studies on sediment distribution in the beels, and socioeconomic and institutional investigation of compensation mechanisms should ensure appropriate options for successful operation of TRM. The paper reports that feasible sites should lie more than 50 km inland of the Sundarbans (mangrove forests in Bangladesh) regions. Highly saline zones are unsuitable for TRM sites as sandy and saline sediment precludes agriculture. In the south west Ganges-Brahmaputra Delta, there are more than 35 suitable beels for TRM operation, which comprises an area of about 15,000 ha.

According to the paper further research is needed to identify the success and hindrance factors of TRM projects, and to further test through field validation the transdisciplinary framework as an enabling approach to TRM projects.

5.3.2 Reference D.2

IWM (2006): MONITORING PREFORMANCE OF BEEL KEDARIA TRM AND BASELINE STUDY OF BEEL KHUKSIA

Summary:

This report describes the monitoring of the performance of the Tidal River Management Implementation in Beel Kedaria and the baseline study of Beel Khuksia during April-September 2005, for maintaining the drainage capacity of Teka-Hari River. The potential of using Beel Bakar and East and West Beel Khuksia as alternate tidal basins was also studied. This was a part of the Khulna Jessore Drainage Rehabilitation Project which was launched in 1994 to solve the drainage congestion problems in the Khulna Jessore area.

All 4 beels were investigated as possible sites for a tidal basin. There was opposition to the use of Beel Khuksia (both East and West) but it was possible to use Beel Kedaria as demonstrably effective tidal basin, for maintain the drainage capacity of Hari River, increasing the tidal volume in the Hari River from 0.96 million m3 to 3.25 million m3. This report is about the detailed monitoring that took place in the Kedaria tidal basin while assessing the potential of other related tidal basins for further development as TRM basin.

Temporarily closing down the tidal basin operation due to land owner demand resulted in severe siltation in the upper Hari River reducing drainage capacity. The possibility of reviving the Hari River by re-opening the Kedaria tidal basin was attempted with only limited success.

The study of Beel Bakar led to the conclusion that it was not a suitable venue for TRM.

Methodology:

The detailed field monitoring and survey of the tidal basin and Hari River made it possible to quantify the impact of creatin the tidal basin. The consequences of interrupting the TRM process and restarting after a period of time was also very informative.

Key finding & Knowledge Gaps:

The effectiveness of a well located TRM basin in maintaining Tidal Cubature and an active tidal regime was demonstrated in Beel Kedaria. However, it was also demonstrated that all beels are not equal in their suitability for TRM. The other finding was that the local population does not invariably support this innovation and that stakeholder consultation is an important aspect not to be neglected.

5.3.3 Reference D.3

IWM (2007): MONITORING THE EFFECTS OF EAST BEEL KHUKSIA TRM BASIN AND DREDGING OF HARI RIVER FOR DRAINAGE IMPROVEMENT OF BHABODAH AREA

Summary:

This study examined the effectiveness of using the sequential operation of tidal basins in the KJDRP area to sustainable maintaining the drainage capacity of the Hari River using a combination of field measurements, mathematical modelling and stakeholder consultation.

The successful operation of the Beel Kedaria tidal basin was interrupted for 4 months in 2005 to enable the planting of a boro crop on some lands in the area. The heavy siltation that occurred during the time of closure could not be reversed by re-opening the tidal basin and the entire Teka-Hari River had to be revived by undertaking a dredging programme over a 17 km stretch of the river.

The modelling tools were employed to select the size, location and link canal dimensions to execute a Short Term Action Plan to revive the drainage mechanisms.

Methodology:

The field measurement methods and modelling activities carried out have proved essential for planning and designing interventions for maintain a healthy drainage system. Monitoring the system as it adjusts to interventions was found to be crucial to understanding processes. However, continuing stakeholder consultation was also essential.

Key findings & Knowledge Gaps:

While the effectiveness of the interventions had been demonstrated, it was found that to ensure smooth and long-term operation of a tidal basin for TRM , a compensation scheme had to be introduced to mitigate the negative economic impacts on some communities during some phases of TRM activities.

Training and Knowledge enhancement within the local community, WMO and LGI are required.

Longer term study and actions are necessary to ensure sustainability of the programme.

6 Climate Change and Sea Level Rise

6.1 Introduction and Synopsis

Bangladesh is widely recognized to be one of the most climate vulnerable country in the world. UNDP (2004) has identified Bangladesh as the most vulnerable country in the world to tropical cyclones and the sixth most vulnerable country to floods. By 2050, Bangladesh could face incremental costs of flood protection (against sea and river floods) of US$2.6 billion initial costs and US$54 million annual recurring costs (Dasgupta et al. 2010).

The following review relates to past studies, with a particular focus on the effects of climate change on:

- Sea level
- Cyclone Intensity and Frequency
- Rainfall
- River discharge
- Temperature

The specific consequences of climate change on different physical processes (e.g. flooding, salinity intrusion, changes in sediment delivery to the delta) are not part of this section but they are assessed in different chapters.

Relative **sea level rise** is one of the aspects of major concern for this low-lying country. Predicted median values of sea level rise by 2100 range roughly between 50 and 90 cm depending on the scenario (i.e. reduced carbon emission vs. business as usual) but could even exceed 2 m for the 95% of most extreme - business as usual - scenarios.

It is hard to detect statistically significant changes in **cyclone** activities based on data. Estimates for the North Indian Ocean, based on models, suggest an increase in frequency of all TCs for all categories and in particular for the most extreme ones.

Historic data in general does not reveal a significant trend in **rainfall**. The projections indicate an increase in monsoon and post-monsoon precipitation over the basin, a decrease in pre-monsoon precipitation, and a shift in the timing of peak monsoon precipitation.

Historic data in general does not reveal a significant trend in **discharge** due to climate change. However, in the dry season, flow has decreased due to upstream development, and withdrawal of water for irrigation and other purposes. The projections indicate an increase in runoff in most seasons if upstream developments are ignored. This may have a positive impact on water availability in the dry season, but also an increase in flood events in the wet season.

Overall, the studies indicate that there has been a consistent increase in **temperature** over the last 40 years in the basin, and the projection data indicate that temperature is likely to increase further under climate change.

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6.3 Summary of Selected Papers

6.3.1 Sea Level

SMRC (2003)

The SAARC Meteorological Research Council (SMRC) carried out a study on relative sea level rise at the Bangladesh coast. The study used 22 years historical tidal data at three coastal stations. The study showed that the rate of relative sea level rise along the Bangladesh coast is several times higher than the mean global rate of sea level rise and, in particular, 4 mm/year at Hiron Point, 6 mm/year at Char Changa and 7 mm/year at Cox's Bazar). However, it must be pointed out that these rates include the effect of subsidence.

SYVITSKI et al (2009)

Syvitski et al (2009) estimated the relative sea level rise rate by means of high-resolution satellite images at 33 representatives deltas. For the Bangladesh coastal zone, the relative sea level rise was estimated between 8-18 mm/year.

Vousdoukas et al (2018)

In this paper, probabilistic projections of Extreme Sea Levels (ESL) for the present century were estimated, taking into consideration changes in mean sea level, tides, wind-waves and storm surges.

Between the year 2000 and 2100 the authors projected a very likely increase (5–95th percentile) of the global average 100-year ESL of 34–76 cm under a moderate-emission-mitigation-policy scenario and of 58–172 cm under a business as usual scenario on the global scale. For South East Asia, a very likely increase in the 100-year ESL was estimated equal to 37-79 cm under RCP 4.5 and 62-188 cm under RCP 8.5. The contribution due to sea level rise was estimate equal to a median value of 57 cm (very likely range 26 – 93 cm) for RCP 4.5 and 91 cm (very likely range 52-214 cm) for RCP 8.5.

Coastal Embankment Improvement Project, Phase–I (CEIP-I):

Design conditions of crest levels during CEIP-I were derived assuming a sea level rise of 50 cm w.r.t. to the current situation (see e.g. IWM & Royal Haskoning, 2018).

6.3.2 Cyclone Intensity and Frequency

Current situation

Bangladesh is a global hotspot for tropical cyclones and its adverse impacts on society (Dasgupta et al., 2016). For example, between 1960-2004 more than half a million inhabitants of Bangladesh died as a consequence of TCs, primarily due to storm surge (Schultz et al., 2005).

In the current situation, generally-speaking, tropical cyclones (TC) generate in the Bay of Bengal, propagate northwards and make landfall in a southwest / northeast direction at Bangladesh (see Figure 6-1). Once on land, the intensity of the TC decreases due to lack of warm water supply and increased land roughness. Generation occurs both during the early summer time period (April, May, June, July) as in the late rainy season period (September, October, November, December; see for more information Dasgupta et al., 2016).

In 45 years of time, the Joint Typhoon Warning Center (JTWC) for the Indian Ocean (IO) basin, reported 45 TCs with wind speeds higher than 20 m/s. This means there is, on average, every year a TC that makes landfall in Bangladesh. When only focusing on the most intense TCs (maximum wind speeds higher than 50 m/s; denoted as extremely severe cyclone storm and super cyclone storm) the probability decreases with 80%. This means that, on average, every 5 or 6 years such a heavy TC makes landfall in Bangladesh.

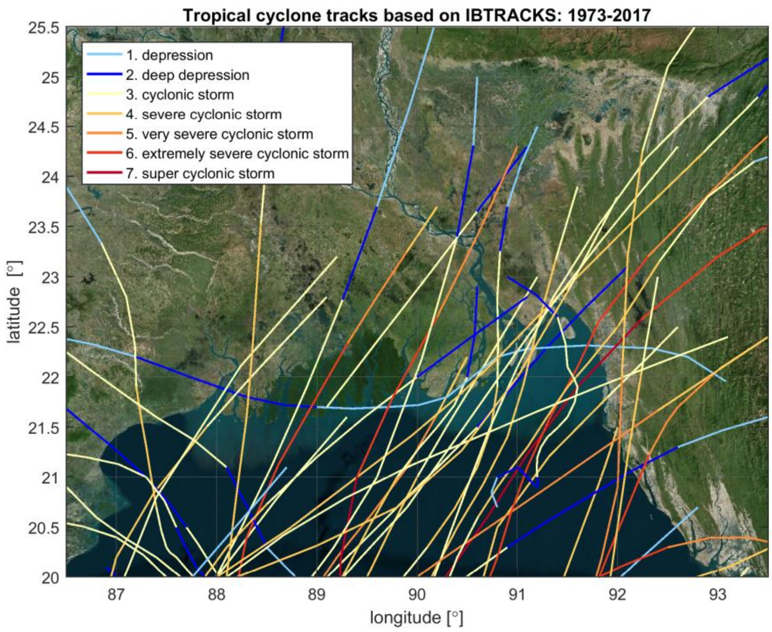

Figure 6-1 Tropical Cyclone (TC) tracks and intensity based on the IBTRACKS database. Here the Joint Typhoon Warning Centre for the Indian Ocean (IO) was used as data source. The tracks are coloured-coded based on the India Meteorological Department (IMD).

Future situation

For the future situation it is challenging to detect any change in tropical cyclone activity based on data. When observing the data from the Joint Typhoon Warning Centre, this suggests a larger number of TCs for the time period 1980 – 2000 with respect to the years before/after. The same can be said for the number of the most extreme TCs only. Six out of the eight TCs with wind speeds larger than 50 m/s occurred in the ten-year time period 1988 – 1997, while only one event occurred after 2000 (i.e. TC Sidr, 2007 with a maximum reported wind speed of 67 m/s). Therefore, the data seems to suggest a decreasing trend in the number of (strong) TCs. However, due to relatively short data record, one need to assume that these perceived trends are based on randomness.

Knutson et al. (2015) carried out a numerical modally study to assess projection in TC frequency and intensity for different oceanic basins. CMIP5 multimodel ensembles were used to compare conditions under RCP 4.5 for the late twenty-first century to the period 1982-2005. For the North Indian Ocean, an average increase of 19.5% in the frequency of TCs of all different intensities was found, with a peak in increase for TCs with stronger intensities (category 4-5). This was also accompanied by an increase in duration maximum wind speed (3%) and precipitation rate (10-20%).

Coastal Embankment Improvement Project, Phase–I (CEIP-I):

Design conditions of crest levels during CEIP-I were derived assuming an increase of 8% cyclonic wind speed (see e.g. IWM & Royal Haskoning, 2018).

6.3.3 Rainfall

MOEF (2005)

The effects of increased flooding resulting from climate change will be the greatest problem faced by Bangladesh as both coastal (from sea and river water), and inland flooding (river/rainwater) are expected to increase. Most of the climate models estimate that precipitation will increase during the summer monsoon because air over land will warm more than air over oceans in the summer. Monsoon precipitation would increase at a rate of 12 % and 27 % for 2030 and 2075 respectively. It is notable that the estimated increase in summer precipitation appears to be significant; it is larger than the standard deviation across models. This does not mean that increased monsoon is certain, but increases confidence that it is likely to happen.

Table 6-1 Climate scenarios for precipitation (source: MOEF, 2005)

Year	Precipitation change (%)		
	Annual	DJF	JJA
2030	5	2	6
2050	6	5	8
2100	10	10	12

Shahid, (2011)

Only few researches have been carried out so far to study the rainfall related extreme weather events in Bangladesh. Based on a trend analysis of rainfall at stations in Bangladesh, a significant increase of annual and pre-monsoon rainfall is observed. In general, an increasing trend in heavy precipitation days and decreasing trends in consecutive dry days are observed. Significant change in most of the extreme rainfall indices are observed in Northwest Bangladesh.

Nepal and Shresta (2015)

These authors describe a literature review on the impact of climate change on the hydrological regimes of the Indus, Ganges and Bramaputra basins. The main findings and most relevant literature references are summarized below:

Ganges basin

Current climate

Most of the Ganges basin is strongly influenced by the summer monsoon with the eastern part receiving the highest rainfall. The effect of the monsoon weakens from east to west; the Koshi catchment in the east receives 72–81% of rainfall during the monsoon season (June to September), while the Bhagirathi and Mandakini sub-basins to the west receive only 55–65%.

Observed trends

Singh, Kumar, Thomas and Arora (2008) report that historically, annual precipitation in the Ganges Basin has remained stable. Nepal (2012), in an analysis of precipitation trends in the Koshi catchment, found an increasing trend in annual precipitation at 22 of 36 stations and a decreasing trend at 14 stations, but the results were significant at only three stations (two increasing and one decreasing). This means they also could not detect a clear indication of an increasing or decreasing trend.

Projected climate change impacts

Pervez, & Henebry (2014) project an overall increase in monsoon precipitation of 12.5% and 10% over the Ganges Basin during the first epochs of the 21st century for two (A1B and A2) emission scenarios, respectively. At the same time, they project a decrease in rainfall during the pre-monsoon and increase during the post-monsoon seasons. For the successive epochs of the 21st century, monsoon precipitation is likely to increase at a similar rate under the A1B scenario, and it is likely to increase at a gradually higher rate under the A2 scenario than the rates of the first epoch for the Ganges basin.

Immerzeel et al. (2010) project an 8% increase in upstream precipitation in the Ganges Basin based on five different GCMs and the A1B scenario. Kumar et al. (2011) project an increase in summer monsoon precipitation over India by 9–16% towards the end of the century. Raqubul Hasib and

Saiful Islam (2014) project that rainfall in the basin increases with 5.5% in 2050 and 7.3% in 2080. There is also an increasing trend in the maximum 1 day rainfall. On the other hand, the number of events with over 20mm/day of rainfall in the monsoon season shows a decreasing trend. Masood et al. (2015) project that by the end of 21st century the increase in mean precipitation is 20-36%.

<u>Brahmaputra basin</u>

Current climate

Nepal and Shresta (2015): with the exception of the upper reaches, which lie in the Himalayan rain-shadow area, the Brahmaputra basin is heavily influenced by the summer monsoon, with annual rainfall ranging from 1200mm in parts of Nagaland (India) to over 6000mm on the southern slopes of the Himalayas, with a mean annual value of 2300mm. Some 60–70% of annual rainfall falls in the monsoon from June to September with a further 20–25% in the pre-monsoon from March through May. At least some precipitation falls as snow at elevations above 1500m asl.

Observed trends

Flügel et al. (2008) studied the variation in annual mean and seasonal precipitation in the upper Brahmaputra River basin from 1961 to 2005 and found a slight increase in mean annual precipitation as well as in autumn, spring and summer, but no statistically significant trends. Immerzeel (2008) concluded that the precipitation did not show any clear trend and was mainly determined by the monsoon. Yang et al (2016) note that: “while projections of future climate have tilted towards increasing precipitation, analysis of observed precipitation indicates decreasing trends”.

Projected climate change impacts

An overall increase in monsoon precipitation of 12% and 16% over the Bramaputra Basin during the first epochs of the 21st century for two (A1B and A2) emission scenarios in predicted, respectively, with a decrease during the pre-monsoon and increase during the post-monsoon seasons. Similar to the Ganges, precipitation is likely to decrease during the pre-monsoon and likely to increase during the post-monsoon seasons compared to the baseline. The peak of monsoon precipitation is likely to shift from July to August (Pervez, & Henebry, 2014).

Immerzeel (2008) projects an accelerated increase in precipitation with a greater increase over the Tibetan Plateau than over the plains areas; the increase in precipitation in summer could indicate a potential increase in extreme events. Masood et al. (2015) project that by the end of 21st century the increase in mean precipitation is 16% and 30-40% in the Brahmaputra and Meghna basins respectively.

6.3.4 River Discharge

Current situation

In the monsoon the combined flow of the Ganges and the Brahmaputra reaches a peak between 80,000 to 140,000 m^3/s in the July/August or early September period (Moef, 2005). Meltwater is important for the Brahmaputra basin, but plays only a modest role for the Ganges rivers; discharge generated by snow and glacial melt In the Brahmaputra basin is 27%, in the Ganges this is 10% (Immerzeel et al, 2010).

Observed trends

Transboundary inflow in the dry season has decreased due to upstream development, and withdrawal of water for irrigation and other purposes (Moef, 2005).

Projections

Immerzeel et al, 2010 project that upstream snow and ice reserves of these basins, important in sustaining seasonal water availability, are likely to be affected substantially by climate change, but to what extent is yet unclear. Of the two rivers, the Brahmaputra and is most susceptible to reductions of flow.

Nepal and Shresta (2015) state that climate change may result in increased flood risk in the Brahmaputra Basin. The overall impact on annual discharge is likely to be low. Shrinking of glaciers in response to rising temperatures might result in a marked reduction in water availability in some rivers in the medium-to-long term.

Masood et al. (2015) project that by the end of 21st century the increase in mean runoff is 16%, 20-36% and 30-40% in the Brahmaputra, Ganges, and Meghna, respectively. Future changes of runoff are larger in the dry season (November–April) than in the wet season (May–October). Amongst the three basins, the Meghna shows the highest increase in runoff, indicating higher possibility of flood occurrence. The uncertainty due to the specification of key model parameters in model predictions is found to be low for estimated runoff.

Saiful Islam et al. (2017) combined a number of regional climate models with a hydrological model of the Brahmaputra river basin. They concluded that most of the regional Climate Models (RCMs) show an increasing tendency of the discharge of Brahmaputra River at Bahadurabad station during the monsoon season. The models showed better mutual agreement for the monsoon discharges flow than for pre-monsoon discharges.

Kundzewics et al (2008) project that a global temperature increase of 2°C will result in an increase in the flooded area for annual peak discharge in Bangladesh by at least 23–29%

Pervez, & Henebry (2014) state that peak monsoon precipitation (and therefore discharge) is likely to shift from July to August as a result of climate change. The projected increases in precipitation by these authors (see before) will result in similar increases in runoff.

Mohammed et al (2017) project that floods are likely to become more frequent in the future and that their magnitude will become more severe. Hydrological droughts are projected to become less frequent in the future and their magnitude to become less severe. The average timing of both floods and hydrological droughts is projected to shift earlier compared to the present hydrological regime. Mean monthly discharges are projected to increase in the pre-monsoon months and decrease in the post-monsoon months

Whitebread et al (2013) used a hydrological model of the Ganges, Brahmaputra and Meghna River Systems to simulate flow and water quality along the rivers under a range of future climate conditions. Model results for the 2050s and the 2090s indicate a significant increase in monsoon flows under the future climates, with enhanced flood potential. Low flows are predicted to fall with extended drought periods, which could have impacts on water and sediment supply, irrigated agriculture and saline intrusion.

6.3.5 Temperature

MOEF (2005):

Observed data indicates that the temperature is generally increasing in the monsoon season (June, July and August). Average monsoon time maximum and minimum temperatures show an increasing trend annually at the rate of 0.05 °C and 0.03 °C, respectively. Average winter time (December, January and February) maximum temperatures show no trend, while minimum temperatures show an increasing trend of 0.016 °C per year. The SAARC Meteorological Research Centre (SMRC) has studied surface climatological data on monthly and annual mean maximum and minimum temperature, and monthly and annual rainfall for the period of 1961-90. The study showed an increasing trend of mean maximum and minimum temperature in some seasons and decreasing trend in some others. Overall the trend of the annual mean maximum temperature has shown a significant increase over the period of 1961-90. General Circulation Model (GCM) used by the US

Climate Change Study team for Bangladesh reported that the average increase in temperature would be 1.3°C and 2.6°C for the years 2030 and 2075, respectively. In 2075 the variation would be 2.1°C and 1.7°C for winter and monsoon. In 2075 there would not be any appreciable rainfall in winter at all. The climate models all estimate a steady increase in temperatures for Bangladesh, with little inter-model variance. The effects of increased flooding resulting from climate change will be the greatest problem faced by Bangladesh as both coastal (from sea and river water), and inland flooding (river/rainwater) are expected to increase.

Table 6-2 Climate scenarios for rainfall and temperature (source: MOEF, 2005)

	Temperature change (°C)		
Year	Annual	DJF	JJA
2030	1.0	1.1	0.8
2050	1.4	1.6	1.1
2100	2.4	2.7	1.9

Nepal and Shresta (2015) provide a literature review on the impact of climate change on the hydrological regimes of the Indus, Ganges and Bramaputra basins. The main findings are summarized below:

<u>*Ganges basin*</u>

Observed trends

Many studies have shown an increasing trend in temperature in the Ganges Basin. Shrestha et al (1999) reported that the maximum temperature in Nepal increased at a rate of 0.6 °C per decade between 1978 and 1994, with higher rates at stations located at higher altitudes. Nepal (2012) reported that the maximum temperature in the Koshi catchment (a sub-basin of the Ganges) increased with 0.6 °C per decade over the last four decades. Similarly, Liu and Chen (2000) reported a temperature increase on the Tibetan Plateau at a rate of 0.16 °C per decade between 1955 and 1996.

Projected climate change impacts

Climate modelling studies project that the temperature in the basin is likely to increase further under climate change. Immerzeel et al. (2012) projected an annual increase in temperature of 0.6 °C per decade between 2000 and 2100 in the Langtang catchment in Central Nepal based on five different GCMs. Similarly, Kumar et al. (2011) projected significant warming over India towards the end of the twenty-first century. Masood et al. (2015) project that that by the end of 21st century the entire Ganges Brahmaputra Meghna (GBM) basin is 4.3° C warmer than the reference situation.

<u>*Brahmaputra basin*</u>

Observed trends

Flügel et al. (2008) identified an increase in average annual temperature in the upper Brahmaputra River basin of 0.28 °C per decade from 1961 to 2005. In average, during winter, autumn, spring and summer the predicted temperature increases was respectively of 0.37, 0.35, 0.24, and 0.17 °C per decade. All trends were significant at the 95% significance level and were observed at most of the stations investigated. Immerzeel (2008) found a temperature increase of 0.6 °C per 100 years based on the Climatic Research Unit data-set for 1900–2002, with a higher increase in the spring season. Yang et al (2016) state that there is general agreement between observed and projected increases in temperature and the retreat of 20 glaciers in the region has been attributed to this increasing temperature.

Projected climate change impacts

Immerzeel (2008) projected an accelerated seasonal increase in both maximum and minimum temperatures in the Brahmaputra Basin from 2000 to 2100 based on the results of six statistically downscaled GCM models. The changes were more prominent on the Tibetan Plateau than on the flood plain. By the end of the century, the average temperature of the basin is projected to increase by 3.5 °C and 2.3 °C for the A2 and B2 scenarios, respectively. Dobler et al. (2011), also projected an increase in temperature in all seasons, with greater increases at higher elevation.

6.3.6 Reference E.28

Global warming and changes in the probability of occurrence of floods in Bangladesh and implications, M. Monirul Qader Mirza, Global Environmental Change, Volume 12, Issue 2, July 2002, Pages 127–138

Summary

The research presents flood problems in Bangladesh, with particular focus on flood types, characteristics of peak discharge, flood duration and linkages between global warming and floods recession and damage, possible changes in occurrence of peak discharges and future likely implications are illustrated.

Bangladesh is very prone to flooding due to its location at the confluence of the Ganges, Brahmaputra and Meghna (GBM) rivers and because of the hydro-meteorological and topographical characteristics of the basins in which it is situated. Floods cause serious damage to the economy of Bangladesh, a country with a low per capita income. Global warming caused significant effects on the hydrology and water resources of the GBM basins and might ultimately lead to more serious floods in Bangladesh. The use of climate change scenarios from four general circulation models as input into hydrological models demonstrates substantial increases in mean peak discharges in the GBM rivers. These changes may lead to changes in the occurrence of flooding with certain magnitude. Extreme flooding events will create a number of implications for agriculture, flood control and infrastructure in Bangladesh. Concerted efforts are needed to strengthen capacity building in the agriculture sector in Bangladesh in order to reduce crop damage.

Methodology

In this study, different types of paper have been reviewed and tried to focus on type of floods, characteristics of peak discharge, flood duration and recession, flood damage, global warming and its effects on floods in Bangladesh, and also future implications.

Findings and Research Gaps

There are four types of flood in Bangladesh: flash flood; riverine floods; rain floods and storm surge. The area flooded in Bangladesh during the period 1954–1999 shown that more area inundated in Bangladesh during the period 1980–1999 than that of the period 1960–1980. Therefore, estimates of flood damage were also high in recent decades due to depth and duration of flooding. The characteristics of peak discharges of the Ganges, Brahmaputra and Meghna rivers are unique in terms of magnitude and timing of occurrence. Precipitation patterns of the river basins highly influence their characteristics. For example, although the basin area of the Brahmaputra River is about half of that of the Ganges River, mean annual peak discharge of the former is considerably higher than the latter. In 1998, the peak discharges in the Brahmaputra and Ganges occurred only 2 days apart. A similar simultaneous occurrence of peak flows of the two rivers also occurred in 1988 that also caused a devastating flood. The magnitudes of peak discharges of the major rivers were almost equal in 1998 and 1988; longer duration of floods in 1998 was attributed to drainage congestion around the confluence of the Ganges and Brahmaputra rivers caused by high tidal activity and subsequent backwater effect. During the period 1954–1999, floods killed 11,571 people in Bangladesh, of which 7109 people were killed during the floods of 1987,1987 and 1988 (Mirza et al., 2002).

A sensitivity analysis for 20-year floods for the Ganges, Brahmaputra and Meghna rivers demonstrates a range of possibilities of changes in probability of flood occurrences for various GCM scenarios. The analysis further demonstrates that possible changes in these probabilities of occurrences are not consistent for the three large rivers. CSRIO9 model indicate the largest possible increases in peak discharge of the Ganges River basin compared to other models. For Brahmaputra river basin the GFDL model project the highest increase in precipitation and The HadCM2 model for Meghna river basin which is the wettest river basin among the three. Mean annual precipitation is 3.5 times higher than the Ganges and about 1.5 times higher than the Brahmaputra. The largest changes in probability are expected for the Brahmaputra and Meghna rivers. This implies a greater risk in flood planning and management in Bangladesh in future.

The analysis also demonstrates that crop agriculture in Bangladesh will be at greater risk in a warmer climate than compared to current conditions. Crop cultivation encompasses both human and natural elements. Therefore, adaptation in agricultural systems needs adjustments in human activities, socio-cultural (behavioural) aspects of present and past agricultural practices, and environmental factors in response to the anticipated changes in climate system and its consequential impact (Ahmed, 2001). Since the loss of crop production under warming scenarios could be quite significant, ‘‘no adaptation’’ would mean that the anticipated loss would have to be borne primarily by the poor farmers and the consumers.

6.3.7 Reference E.29

Multi-factor impact analysis of agricultural production in Bangladesh with Climate change, A. C. Ruane, D. C. Major, W. H. Yu, M.Alam, S. G.Hussain, M.S.A. Khan, A. S. Khan, A. Hassan, B. M. T. A. Hossain, R. Goldberg, R. M. Horton and C. Rosenzweig, Global Environmental Change, Volume 23, Issue 1, February 2013, Pages 338–350

Summary

Bangladesh lies on mostly flat, alluvial land at the mouth of the Ganges-Brahmaputra-Meghna (GBM) Basins that drain monsoon runoff from a large portion of South Asia and is widely recognized as a country with high sensitivity to climate variability and change. Bangladesh uses more than 70% of its land for agricultural purposes (FAOSTAT, 2009), often with multiple cropping seasons. However, in these study diverse vulnerabilities of Bangladesh’s agricultural sector are divided into 16 sub-regions. This region is assessed using experiments designed to investigate climate impact factors in isolation and in combination. Climate information from a suite of global climate models (GCMs) is used to drive models assessing the agricultural impact of changes in temperature, precipitation, carbon dioxide concentrations, river floods, and sea level rise for the 2040–2069 period in comparison to a historical baseline. It is observed from the analysis that, Agriculture in Southern Bangladesh is severely affected by sea level rise, whereas increasing river flood areas reduce production in affected sub-regions. It was also observed that, impacts are increasing under the higher emissions scenario.

Methodology

Climate simulations were analysed by the studies reviewed in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4). Climate change scenarios are generated by comparing a givenGCM’s2040–2069 period (referred to as the ‘‘2050s’’) with control simulations of that GCM over a 1970–1999 baseline, and then imposing these changes on historical observations to detect the effect of natural disaster in changing climate, the climate change projection results are incorporated in hydrologic and hydrodynamic models. Both are relatively high (A2) and low (B1) future emissions pathway were analysed and compared to the baseline period. Versatile mathematical simulation packages are used for this research work. An ensemble of climate scenarios was created for each sub-region from 16 GCMs and 2 emissions scenarios, capturing a consistent temperature rise and wide uncertainty among projected precipitation changes. The MIKE BASIN hydrologic model was employed over the entire GBM Basins that drain through Bangladesh to simulate river floods for each baseline and future year. Flood protection infrastructure in Bangladesh was also taken into account. Coastal inundation in the 2050’s was simulated by the UK Department for Environment, Food, and Rural Affairs in collaboration with IWM and CEGIS (DEFRA, 2007) using theMIKE21 Two-Dimensional Estuary Model. Process-based crop model simulations were run with the Crop Environment Resource Synthesis (CERES). Online Material. Process-based crop model simulations were run with the Crop Environment Resource Synthesis (CERES) rice and wheat models which include the beneficial effects of enhanced carbon dioxide concentrations on plant growth.

Findings and research Gaps

It is observed that, due to global warming, the ensemble of crop model simulations driven by scenarios from 16 GCMs, median boro production decreases by 12.1% nationally. While on the other hand, projected rainfall changes reduce median national aus production by 1.4%, aman simulations were barely sensitive to the projected changes in rainfall. River flood damages only reduce national aus production by a median of 1.9%. During the later aman season, substantial climate change increases in flood damage occur in nearly all sub-regions, simulated by the hydrologic model. Authors estimate that, 31% land will be lost due to 62 cm sea level rise. Mean sea level rise will also affect crop production. According to analysis, there will be national losses of National losses of 2.3% (aus), 1.3% (aman), 0.7%(boro), and 0.2% (wheat) are projected when the A2 and B1scenarios are averaged.

6.3.8 Reference E.30

Vulnerability of rural livelihoods to multiple stressors: A case study from the southwest coastal region of Bangladesh, Masud Iqbal Md. Shameem, Salim Momtaz, Ray Rauscher, Ocean & Coastal Management, Volume 102, Part A, December 2014, Pages 79–87

Summary

The paper explores, the process by which major stresses and hazards shape the vulnerability of people's livelihoods in dynamic social-ecological environments in the southwest coastal region of Bangladesh. Drawing on qualitative and quantitative data from a case study was identified the key drivers of change in social-ecological systems and evaluate whether these drivers have affected livelihood outcomes and various components of human wellbeing. This analysis suggested that increasing salinity intrusion, tropical cyclone and land-use change (directly and through changes in ecosystem services) affect the access to livelihood assets at household scale. This undermines social wellbeing by seriously impacting food and water security. Through identification of key stresses and their interactions, and the consequent impacts on ecosystems services and household capitals, the current study proposes a conceptual framework to understand the present-day vulnerability to multiple stressors in the context of the coastal region of Bangladesh. The research only analysis at a household level or sector level which is not sufficient but analysis in broader context is required to contribute of reduction of vulnerability.

Methodology

This study was carried out in Chila, a union of Mongla Upazila (Sub-district) in the district of Bagerhat. In this current study, the livelihood approach was applied to understand the impacts of underlying factors that produce changes in ecosystem services. These changes directly impact on people's asset status and the strategies that are open to them to achieve beneficial livelihood outcomes. The stresses and hazards causing livelihood vulnerabilities comprise many of the same factors characterized as drivers of ecosystem change in the Millennium Ecosystem Framework (UNEP, 2006). Therefore, the terms stresses and hazards are used synonymously with drivers in this study. Data were collected between September 2012 and January 2013 using a combination of qualitative and quantitative methods. Information on source of income, land-use, livelihood assets, farming practices, social network, disturbances and responses of households was collected through this household survey. The qualitative techniques of rapid rural appraisal (RRA) tools were used in focus group discussions to understand the dynamics of livelihood adaptation in the study area. Twenty groups with 5-8 people in each group from different sections of the community participated in group discussions focusing on key stresses

Findings and Research Gaps

Based on analysis of survey data (n= 372) together with local and published information, the study identified the major impacts of environmental stressors on various components of rural livelihoods. These are: land use changes, Salinity intrusion, and tropical cyclones. In the study area results included: 33% of the respondents perceived that shrimp farming had not been responsible for mangrove destruction (Sundarban mangrove forest),27% identified somewhat responsible and 20% as being mostly responsible. With the growing salinity intrusion in surface and ground water, the socio-ecological system has experienced changes, manifested in scarcity of freshwater resources and transformation of agro-ecological system into degraded state. These changes have contributed to declining agriculture productivity and associated sub-sectors. The storm surge accompanied by cyclone inundates low-lying areas, causes salinity intrusion, contaminates freshwater ponds used as drinking water sources and contributes to escaping shrimp-stock from the ponds.

The hazards and stresses have impacted local livelihoods directly and through changes in environment and ecosystem conditions are as follows: 1) Damaging natural capital and increasing financial inequality. 2) Damage to physical capital Tropical cyclones that often traverse 3) Impacts on human capital 4) Impacts on social capital. Comparison with rice cultivation, shrimp farming is less labour intensive. Shiva (1995) has observed that rice cultivation on 40 ha of land requires 50 labourers, while shrimp farm of the same size provides employment of only 5 people. Large farmer and processors enjoy greater opportunity for negotiation than the small farmer which creates inequality of benefit. Besides this increase inequality in landownership, loss of income diversifications', disruption of livelihoods and damage of physical capital are also seen. Almost all the survey population (97%) reported that rice cultivation in this area had declined substantially with the rapid expansion of shrimp cultivation. This made these communities' food security vulnerable because they had to rely on rice import from other parts of the country. The study will to be required in a broader aspect instead of local to identify the combined vulnerability and take proper measures to development, equity and resilience of socio-ecological systems. Research gap is that it does not provide any indication and solution of multiple vulnerabilities. An action research program can be formulated on a larger area for climate risk assessment and devising solution and implementation in as a pilot program with the potential of scalability.

6.3.9 Reference E.31

Assessing the impacts of climate and land use and land cover change on the fresh water availability in the Brahmaputra River basin, Md Shahriar Pervez, Geoffrey M. Henebry, ASRC Federal InuTeq, Contractor to U.S. Geological Survey (USGS), Earth Resources Observation and Science (EROS) Center, 47914 252nd Street, Sioux Falls, SD 57198, USA. 2Geospatial Sciences Center of Excellence (GSCE), South Dakota State University, 1021 Medary Ave.,Wecota Hall 506B, Brookings, SD 57007-3510, USA

Summary

The study focuses on to evaluate sensitivities and patterns in freshwater availability due to projected climate and land use changes in the Brahmaputra basin by using the Soil and Water Assessment Tool. The daily observed discharge at Bahadurabad station in Bangladesh was used to calibrate and validate the model and analyse uncertainties with a sequential uncertainty fitting algorithm. The sensitivities and impacts of projected climate and land use changes on basin hydrological components were simulated for the A1B and A2 scenarios and analysed relative to a baseline scenario of 1988–2004. There is large inter-model variability in the simulation of spatial characteristics of seasonal monsoon precipitation (Sabade et al., 2011); therefore, conclusions based on one down scaled precipitation may not be optimal and may defer when multiple GCMs are considered.

Methodology

SWAT model has been used in this study. To simulate this model weather data (daily precipitation, maximum/minimum air temperature, solar radiation, wind speed, and relative humidity) stream flow data (discharge data at Bahadurabad gauge station) and land use data has been collected from different organizations. ArcSWAT (Winchell et al., 2010) – was used to parameterize the model for the Brahmaputra basin. The period 1988–1997 was used to calibrate the model, and 1998–2004 (excluding2002) was used to validate the model. The calibrated and validated model was run for the entire time period 1988–2004 under an average atmospheric CO2 concentration of 330 ppm. These simulation results were used as the baseline scenario. Calibrated and validated Model has been used for experimental design, precipitation, and land use projections. The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) for the region has been followed and six scenarios were established based on changing CO2, Temperature and Precipitation. To designed future climate and land use change impact assessment simulations with estimated CO2 concentration, temperature increase, and land use change scenarios for each 10-year period of the 21st century. The scenarios were executed with third-generation Canadian GCM version 3.1(CGCM3.1). Statistical Downscaling Model (SDSM)-downscaled precipitation (Pervez and Henebry,2014), projected temperature and CO2 concentration, and downscaled IMAGE-projected land use information for the A1B and A2 scenarios.

Findings and Research Gaps

It was found that the annual average simulated stream flow at Bahadurabad gauge station was 22,875 m3s−1, which was slightly larger than the average observed stream flow (22,345 m3s−1) for the same period. The annual total water yield was predicted to increase by 2% and 5% in response to a 1.5× and 2× increase in CO2 concentration, respectively. The average annual precipitation in the Brahmaputra basin was predicted to increase from 1849 mm to 2013 mm and 2029 mm, a 9% and 10% increase com-pared to baseline precipitation and groundwater recharge was predicted to increase by 47% and 49% annually under the A1Band A2 scenarios. The stream flow patterns during FMA suggested that the impacts of spring snowmelt on the stream flow could diminish by 2030. The long-term patterns in the groundwater recharge showed a significant decreasing trend for the early monsoon period (MJJ) and a significant increasing trend for the later monsoon period. The sensitivity scenario results indicated that increase in CO2concentration caused basin wide average ET to decrease because of physiological forcing, which resulting in increases in average total water yield, stream flow, and groundwater recharge. The impacts of climate and land use change were predicted to be more pronounced for the seasonal variability in hydrological components than the inter annual variability in the Brahmaputra basin. The study combined analyses of sensitivity of hydrological components to climate change and long-term impacts of future climate and land use change on freshwater availability can offer much needed inputs for resource, but it should be evaluated at the sub basin level to provide a more complete picture to make a decision. There are some uncertainties in this study. These are model is calibrated against flow, therefore, predicted estimates of those components that were not calibrated were more uncertain Also future climate change projections, GCM predictors and model down scaling was not accurately predicted.

7 Hydrodynamics and Salinity

7.1 Introduction and Synopsis

The 4th IPCC report highlights the increased vulnerability of the coastal zones around the world due to sea level rise in the 21st Century. Key concerns due to sea level rise include flooding and salinisation and its implications for water resources. Rising sea level increases the salinity of both surface water and ground water through saltwater intrusion. Bangladesh is not an exception in this context, salinity is already a major problem in the coastal zone both in relation to surface water and groundwater.

Fresh water supplied to the coastal zone by the distributaries from the Ganges and Padma Rivers. The south west and south central regions of Bangladesh are sculpted by a number of large tidal estuaries within which the saline waters from the Bay of Bengal are in a constant but fluctuating battle with the fresh water from the north.

Many of the large tidal estuaries in Southwest Bangladesh and in West Bengal were carved out of the landscape by previous channels occupied by the Ganges in the west and the Brahmaputra (not Jamuna) in the in the distant past when they flowed separately into the Bay of Bengal.

The salinity distribution of the surface water in the estuaries is a balance between saline water arriving with the incoming tide from the Bay of Bengal and the freshwater flow from the river system upstream. The yearly variation in the river discharges creates a yearly variation in the horizontal salinity distribution in the coastal zone, with saline water penetrating furthest north towards the end of the dry season. The spatial variation in freshwater flow with least flow in the western part of the delta is reflected directly in the length of saline intrusion.

The enormous outflow of freshwater though the Lower Meghna during the monsoon season has the effect of diluting the salinity in the northern Bay of Bengal. This flow which also flows westwards along the coastline has the effect of reducing the salinity of the Bay thereby reducing saline intrusion in the Bishkhali, Baleswar, Pussur and Sibsa during the monsoon period. This westward flow also carried finer sediments flowing out of the Lower Meghna westwards and with the tide into the western part of the delta. Already today saline intrusion in surface water is exacerbated by reduced dry season flow in some of the important distributors to the Ganges River (e.g. the Gorai River) and due to water extraction at large irrigation schemes. It may be expected that the freshwater diversions from the proposed Ganges Barrage will bring about a dramatic improvement in salinity conditions.

Sea level rise and changing river flows caused by climate change and continued development in the catchment are likely to increase saline intrusion. It has been projected that 59 cm rise in sea level produces a change of 0.9 ppt at Mongla and the salinity front of 10 ppt line moves 21 km upstream in Pussur River (Bhuiyan 2012). Model simulation results show that the salinity intrusion due to SLR is higher in the western part. It is however important to stress that these model projections have been carried out without taking into account the important morphological response of the delta to SLR. The expected response of the delta will be widespread deposition and increase of bed elevation which will reduce salinity intrusion.

Ground water saltwater intrusion is the movement of saline water into freshwater aquifers, which can lead to groundwater quality degradation, including drinking water sources, and other consequences. Saltwater intrusion can naturally occur in coastal aquifers, owing to the hydraulic connection between groundwater and seawater. Because saline water has a higher mineral content than freshwater, it is denser and has a higher water pressure. As a result, saltwater can push inland beneath the freshwater. Certain human activities, especially groundwater pumping from coastal freshwater wells, have increased saltwater intrusion in many coastal areas. Water extraction drops the level of fresh groundwater, reducing its water pressure and allowing saltwater to flow further inland.

Very few (modelling) studies of ground water salinity have been undertaken in the coastal zone of Bangladesh. However, Hasan et al (2015) undertook a modelling study of GW salinity of an area of 1534 km^2 in the Khulna-Jessore area. The baseline simulation suggested that GW salinity varies from 250 mg/l to 5500 mg/l. Under climate change conditions the freshwater zone decreased somewhat while areas with severe salinity (salinity > 2000 ppm) will increase by 14%. This suggest that access to freshwater will become an even larger problem in the future.

7.2 Impact of Polder Building on Tidal Dynamics

The progressive construction of coastal embankments in the coastal zone – principally to prevent tidal inundation of the land during high tides – from the 1960s onwards, had two major hydrodynamic impacts on how the tides propagated into the Southwest region. -this was a) a reduction in the tidal cubature (the total volume of the tide displaced during a cycle) which at the same time increased the tidal range and reduced the peak flow velocities.

The increase in Tidal range can be observed in the water level records at a station such as Chalna on a major river like the Rupsa-Pussur. The reduction in peak velocities resulted in the deposition of sediments in the river channel system as observed in the entire southwest zone. The sedimentation in the smaller rivers also resulted in tidal choking and reduction of tidal range in many minor peripheral rivers surrounding the newly built polders. This reduction in range gave rise to water.-logging in some polders due to the reduction in capacity of the drainage regulators which we diven purely by gravity.

It is not often recognised that the protection of some polders from extreme water levels (usually caused by storm surges) by raising the crest levels of embankments also result in raising the extreme water levels elsewhere is the Delta. It is therefore necessary to re-compute the propagation of storm surges though the system after the new embankments have been constructed, and additional lands are protected.

7.3 List of Publications Reviewed

F.1 Bhuiyan 2012. Assessing impacts of sea level rise on river salinity in the Gorai river network, Bangladesh; Estuarine, Coastal and Shelf Science, Volume 96, 1 January 2012, Pages 219–227.

F.2 Z.H. Khan 2015, External drivers of change, scenarios and future projections of the surface water resources in the Ganges coastal zone of Bangladesh.

F.3 Hasan et al., Modelling Study on Impact of Climate Change on Groundwater Salinity: Case Study of Southwest Bangladesh. FEFLOW 2015 Conference, Berlin, September 2015

F.4 DHI 1993. Final Report, Mathematical Modelling of Pussur-Sibsa River System and Karnafuli River Entrance. Ministry of Shipping, Peoples Republic of Bangladesh.

F.5 DHV-Haskoning Consortium and Associates 2001, Feasibility Report, Gorai River Restoration Project, Volume 1: Main Report, BWDB, Ministry of Water Resources

7.4 Summary of Selected Papers

7.4.1 Reference F.1

Assessing impacts of sea level rise on river salinity in the Gorai river network, Bangladesh, M. J. A. N.Bhuiyan, DushmantaDutta, Estuarine, Coastal and Shelf Science, Volume 96, 1 January 2012, Pages 219–227

Summary

The paper presents the outcomes of possible effects of sea level rise with the aid of a hydrodynamic (HD) model conducted in the coastal area of Gorai river network in the South West region of Bangladesh for developing a comprehensive understanding. Developed salinity flux model has been integrated with an existing hydrodynamic model in order to simulate flood and salinity in the complex waterways in the coastal zone of Gorai river basin. The integrated model has been calibrated and validated by comparisons with measurements (tide, salinity). The model has been applied for future scenarios with sea level rise and the results obtained indicate the risk and changes in salinity.

Methodology

The study area is the Gorai river basin located on the South-West region of Bangladesh. It comprises an area between latitude 21030'N to 24000' N and longitude 88050' E to 90010' E. The area is bounded by Ganges River in the North, tributaries from Meghna River in the East, international boundary in the West and the Bay of Bengal in the South. The Hydrodynamic model used for simulating flow, water level and salinity, was developed at the Public Work Research Institute (PWRI) of Japan (Yoshimoto et al., 1992). Necessary data for HD and salinity model has been collected from Bangladesh Water Development Board (BWDB)and the Institute of Water Modelling (IWM). The HD model has been calibrated and verified for year 2002.The calibrated parameter is Manning's roughness found to be within the range of 0.015e0.035 for all river sections. The calibration (1-April 2002 to 11-May 2002) and verification (12-May 2002 to 8-June 2002) are performed using the water level and salinity data at selected stations. The statistical indicators used for evaluating the performance of the model are relative root mean squared error (RRMSE); mean absolute error (ABSERR); the Nash-Sutcliffe modelling efficiency index (EF); the goodness-of-fit (R2) and the percentage (%) of deviation from observed. Considering the worst-case scenario of IPCC fourth assessment report i.e. using SLR of 0.59 m, the integrated model has been applied in the same study area to simulate the worst possible impacts.

Findings and research Gaps

The changes in maximum salinity at different stations, due to the impact of the projected SLR have been calculated. The results clearly show that the SLR impact on salinity intrusion is highly significant. Due to sea level rise, the salinity has increased in the river and salinity intrusion length has also increased. Sea level rise of 59 cm produced a change of 0.9 ppt at Mongla. Salinity front of 10 ppt line moves 21 km upstream in Pussur River. The results also show that the salinity intrusion due to SLR is higher in the western part. However, the simulation does not incorporate changes in the downstream salinity (at Bay of Bengal) due to climate change condition.

7.4.2 Reference F.2

External drivers of change, scenarios and future projections of the surface water resources in the Ganges coastal zone of Bangladesh, Z.H. Khan, F.A. Kamal, N.A.A. Khan, S.H. Khan, M.M. Rahman, M.S.A. Khan, A.K.M.S. Islam and B.R. Sharma

Summary

The paper stipulates that currently there is an enormous amount of freshwater suitable for irrigation of agricultural crops throughout the year in the Barisal, Patuakhali, Barguna and Pirojpur districts. External drivers of change that might have effect on water resources were identified. The quantity of freshwater in the coastal zone is likely to decrease due to the combined effects of external drivers such inadequate trans-boundary flows, climate change and land use change, which will increase river salinity during the dry season. By 2030, the area suitable for irrigation (less than 2 ppt river water salinity) is likely to be decreased by about 11% under a moderate climate change scenario (A1B). However, under this scenario, in 2030, salinity of the rivers in Barisal, Barguna, Patuakhali and Jhalokathi districts will not exceed 2 ppt, meaning continued high availability of river water for irrigation in these regions, even with 22 cm sea level rise. However, this freshwater pocket in the south-central zone is likely to become more saline (2-4 ppt) with climate change and 52 cm sea level rise in 2050. The research did not predict the future land use change and present and future crop-water requirement.

Methodology

The key objectives of Basin Development challenge (at Ganges basin) was to identify the important external drivers that influence water resources and evaluate the impact of these drivers on anticipated changes in drainage congestion, salinity intrusion, water availability and risk of inundation from cyclone-induced storm surges. Through comprehensive Questionnaire survey, Focus Group Discussions and Triangulation Workshop key external drivers were found out, and ranked according to their likely impact. Climate change (sea level rise), Trans boundary flow, land and water use change are found to be the most significant external driver. Based on current hydrological situation, appropriate mathematical models have been selected for studying the baseline conditions and effects of external drivers on salinity intrusion, water availability, drainage congestions and risk of inundation due to storm surges. The models available at IWM have been utilized to simulate the baseline (2012) and changed conditions 2030.

The study was conducted at two scales: regional level for the coastal regions of Bangladesh and at local level for the selected polders (Polder 3, Polder 30 and Polder 43/2f). Regional models [South West regional model (SWRM) and Bay of Bengal (BOB) model] were used to simulate salinity intrusion and cyclonic storm surge; while on the other hand, dedicated local level models were used for drainage modelling to investigate the water logging and irrigation opportunity at present and climate change condition. The outputs prepared for analysis of mathematical model are following; salinity zoning map of the coastal Ganges; flood depth-duration map; water storage volume inside polders; storm surge risk map.

Findings and Research Gaps

The research works prepares the salinity distribution over the south-west and south-central coast of Bangladesh, at present condition and its anticipated change in projected period, which helps to identify the fresh availability at river. The research also focuses on the drainage performance of the selected coastal polders and evaluate possibility water management practises in that particular area.

The research covers a wide range of analysis, and still scope for a future study, like detailed polder level water management, ground water use efficiency and working with arsenic contamination at south-west and south-central coastal zone.

This study did not predict the future land use change and present and future crop-water requirement. This research is only applicable in the coastal area of Bangladesh.

7.4.3 Reference F.3

Modelling Study on Impact of Climate Change on Groundwater Salinity: Case Study of Southwest Bangladesh, Md. Rezaul Hasan, M. Atiqur Rahman, AFM Afzal Hossain (IWM, Bangladesh) & C. Tomsu (DHI-WASY, Germany)

Summary

In this paper the groundwater salinity in a pilot area of the southwest of Bangladesh is modelled. The surface water salinity is increasing due to reduced upstream water flow and salinity intrudes increasingly into the coastal aquifer towards countryside every year. Moreover, sea level rise due to climate change contributes in salinity intrusion process particularly for shallow sandy aquifers. The pilot study was undertaken to evaluate the impact of climate change on the present groundwater salinity in nine upazilas (sub-district) of three districts in the southwestern coastal region of Bangladesh.

An advanced groundwater model, FEFLOW, was used to simulate the behaviour of salinity propagation in the shallow aquifer system of the study area. Due to scarcity of model input data a data collection program was undertaken to support model setup and calibration.

According to the model simulations the impacts of river water salinity to the aquifer were determined. The IPCC recommendation in respect of sea level rise in the year 2050 was considered in the present study to investigate the effect of climate change on groundwater salinity. Finally, a map showing distribution of groundwater salinity varying from 250 mg/l to 5500 mg/l was produced. From model results it is observed that under climate change condition, area under severe salinity (>2000 mg/l) increases by 14%.

Methodology

An advanced groundwater model, FEFLOW, was used to simulate the behaviour of salinity propagation in the shallow aquifer system of the study area. FEFLOW is a 3D model utilising a flexible mesh for simulation of fluid flow and transport of dissolved constituents in the subsurface.

Due to scarcity of model input data an action plan for primary data collection was undertaken. Twenty-seven groundwater observation wells including twenty-four wells in twelve lines across three major rivers were installed. The data collection on groundwater salinity has been conducted for one hydrological year. Moreover, auto recorders in each line wells along with a river gauge station have been installed. Besides, hydro-chemical investigation on groundwater salinity from selected existing tube wells was carried out during pre- and post-monsoon season. Other relevant data for the model development were collected from secondary sources.

Findings and Research Gaps

The key findings regarding impact of climate change on ground water salinity are summarised above (in Summary). The key shortcomings of the study are that limited data on subsoils are available for setting up the model and define the extend of the various aquifers and only a limited number of observations points are available for model calibration.

Another limitation is that the climate change projections are only available for the specific are (Khulna-Jessore) and it is not straight forward to extrapolate the findings in this area to the remaining coastal zone. Hence, this type of analyses should be extended to cover a larger part of the coastal zone. Moreover, the paper does not address the influence of ground water abstraction (which is likely to increase with increased population) on the salinity, which may have significant impact close to the peripheral rivers.

7.4.4 Reference F.4

DHI 1993. Final Report, Mathematical Modelling of Pussur-Sibsa River System and Karnafuli River Entrance. Ministry of Shipping, Peoples Republic of Bangladesh.

Summary

This study investigated alternatives for improving navigability at the Mongla Port (on Pussur River) and the Karnafuli River Entrance.

The study at Mongla Port included the evaluation of many alternatives for maintaining navigable depths on Pussur River. This included detailed flow and sediment measurements made on both the Pussur and Sibsa river, which ran parallel to it, as well on three connecting rivers, Solmari Jhapjhapia and Chunkuri. The upstream supply of fresh water from the Ganges via the Gorai was also taken into account. The many alternative schemes tested included several dredging options and the closure of connecting rivers. In order to understand the impact of poldering on tidal dynamics, the de-embanking options and flooding of a selected polder to increase tidal cubature were tested in the model.

These early model studies were useful for gaining a detailed understanding of tidal circulations in the Pussur-Sibsa System as well as the impact of poldering on tidal dynamics and sedimentation in some connecting rivers.

The Pussur Sibsa Model was the forerunner of the Southwest Region Model which was developed in parallel by the Surface Water Simulation Modelling Programme (SWSMP), which is still being used by IWM.

Methodology

MIKE11 software, which was the one-dimensional river modelling software being developed under the SWSMP was used in this study. Extensive river survey programmes were mounted to measure tidal flow measurements and simultaneous sampling of suspended sediments at several river cross sections at neap and spring tides. Bed material samples were also collected and analysed.

These measurements were used to calibrate the hydrodynamic model and to reach understanding of sediment transport processes.

Findings and Research Gaps

This was the very first detailed model study of the flow if tidal waters in the southwest region of Bangladesh. While a good understanding was reached regarding the dynamics of the tidal movement of water and the influence of embankments, the origins of the fine sediment which was distributed throughout the river system in the region was not determined. The mechanisms responsible for waterlogging of certain polders were not investigated because this was beyond the scope of this study.

8 Groundwater salinity

8.1 Introduction

The freshwater resources are essential to the livelihood of Bangladesh population providing drinking water and water for irrigation of crops. Salinity intrusion threatens the water resource, both surface water and in particular groundwater. In the coastal areas salt intrusion in the groundwater aquifers occurs both through surface and subsurface processes. The problems can be worsened by poor water management or simply the lack of any alternative sources of water. Salinity intrusion is an increasing problem in Bangladesh and is likely to further deteriorate in the future. The sources and mechanisms causing salinity of the groundwater aquifers are understood at the larger scale but need to be investigated at a local, polder level and in the perspective of additional pressure caused by climate change.

The shallow groundwater aquifers inside the polders hold important water resources but it interfaces with the sea along the coast line, the rivers crossing the delta, the deep geological layers, drainage canals, the root zone and the surface. Salt is transported across the dynamic interfaces between salt, brackish and freshwater bodies. In addition, the aquifers are heterogenous and subject to groundwater abstraction which may cause mixing and mobilise salt deposited in low permeable layers. Changes in polders in terms of embankments, canal and drainage networks as well as water use will affect the balance and the risk of further salt intrusion.

This review focuses on salinity, specifically groundwater salinity, and in particular:

- The status and trends in groundwater salinity in the coastal zone area
- The processes affecting salt concentrations in groundwater
- The drivers and human practices affecting salt concentration in groundwater
- Groundwater salinity in relation to polders

Reports and papers after year 2000 from studies within Bangladesh were selected for this review.

8.2 List of Publications Reviewed

1 M. Salehin, M.A. Chowdhury, D. Clarke, S. Mondal, S. Nowreen, M. Jahiruddin, A. Haque, 2018: Mechanisms and Drivers of Soil Salinity in Coastal Bangladesh, Springer, Ecosystem Services for Well-Being in Deltas, pp 333-347.

2 A. Nuruzzaman, 2014: Causes of Salinity Intrusion in Coastal Belt of Bangladesh, International Journal of Plant Research

3 M.R. Hasan, M.A. Rahman, A. Hossain, C. Tomsu 2015, Modelling Study on Impact of Climate Change on Groundwater Salinity: Case Study of Southwest Bangladesh, FEFLOW 2015 Conference, Modelling the World of Groundwater,

4 World Bank 2010, Implications of Climate Change for Fresh Groundwater Resources in Coastal Aquifers in Bangladesh

5 Deltares 2015, SWIBANGLA: Managing salt water intrusion impacts in coastal groundwater systems of Bangladesh, Deltares report number: 1207671-000-BGS-0016

6 S. Rahman, R.H. Sarker, Md. Mia, 2017, Spatial and Temporal Variation of Soil And Water Salinity in The South-Western and South-Central Coastal Region of Bangladesh, Irrigation and Drainage 2017

7 S. Worland, G. Hornberger, S. Goodbred, 2015, Source, Transport and Evolution Of Saline Groundwater in a Shallow Holocene Aquifer on the Tidal Delta Plain of Southwest Bangladesh, Water Resources Research 2015

8 World Bank Group, 2019, Water Global Practice, Multi-Hazard Groundwater Risks to the Drinking Water Supply in Bangladesh, Policy Research Working Paper 8922

9 World Bank Group, 2014, Development Research Group, Climate Change, Soil Salinity and the Economics of High-Yield Rice Production in Coastal Bangladesh, Policy Research Working Paper 7140
10 F. Naus, P. Schot, K. Groen, K. Ahmed, J. Griffioen, 2019, Groundwater salinity variation in Upazila Assasuni (southwestern Bangladesh), as steered by surface clay layer thickness, relative elevation and present-day land use, Hydrology and Earth Systems Sciences., 23, 2019
11 M. Islam, M. Hoque, K. Ahmed, A. Butler, 2019, Impact of Climate Change and Land Use on Groundwater Salinization in Southern Bangladesh—Implications for Other Asian Deltas, Environmental Management, 64, 2019
12 M. Mainuddin, F. Karim, D. Gaydon, J. Kirby, 2021, Impact of climate change and management strategies on water and salt balance of the polders and islands in the Ganges delta, Scientific Reports 2021

8.2.1 Status and trends in groundwater salinity in the coastal zone

The current status of groundwater salinity and the expected future development is addressed in several of the papers and reports.

World Bank (2010)

The study aimed at understanding the implications of climate change on the groundwater systems in coastal Bangladesh. This is achieved by collection of hydrogeological data and development of groundwater flow and salt transport models. The effect of climate change is associated with 3 key processes, (1) Sea-level rise induced lateral intrusion of salt into the aquifer, (2) vertical infiltration of sea water from the surface by storm surges, (3) groundwater pumping induced mixing and salinisation. The study concluded that the subsurface salinity distribution is most likely transient, and seawater is moving inland as a result of sea-level rise. The impacts of sea-level rise on coastal inundation and extent of storm surges is of greater concern for groundwater salinity than lateral intrusion. Pumping in these areas, even without climate change, is an important determinant of salinization rate. The report also points to a lack of estimates of localized salinization and suggests data collection along with detailed models to better understand the spatial and temporal scales of salinity intrusion processes in order to support site specific management decisions.

Rahman et. al (2017)

The paper addresses spatial and temporal distribution of salt in soil and groundwater in the coastal region of Bangladesh. The analysis shows that soil salinity during recent decades has been increasing and moved further inland from the coast. This is consistent with a trend of higher salt concentrations in rivers and groundwater which negatively impacts resources for drinking water and irrigation.

Tidal surges are mentioned as a source of salt contamination of polders reaching groundwater. Groundwater is an important source of irrigation and it becomes even more important as river flow discharges decrease. Increasing groundwater abstraction may further mobilise salt and increase salt intrusion which is evident according to maps of the south-western Bangladesh. A map of groundwater salinity in the coastal region of Bangladesh from 2012 is presented showing ranges of salinity (conductivity) ranging from 0.21 dS/m further inland to 19.5 dS/m close to the sea (Sundarbans). Excessive groundwater abstraction, shrimp farming, salt production and inundation by saline water during storm surges are listed as the main reasons for salt contamination in the area.

World Bank Group (2019)

The Policy Research Working Paper points to the need for multi-hazard groundwater risk maps to allow water resource managers and policy makers in Bangladesh to identify vulnerable areas. Both arsenic and salt is considered. Elevated groundwater salinity is common in shallow coastal aquifers of southern Bangladesh and 4 risk categories were introduced for mapping purposes (Table 8-1). The groundwater risk map shows that high risk areas cover up to 5 % of Bangladesh, mainly the southern coastal region, according to the criteria. Approximately 26 million people are exposed to high to extremely high groundwater salinity risk (EC >1,500 µS/cm).

Table 8-1 Drinking water risk levels (model 1)

Risk level	Arsenic (As) conc. µg/L	Electric conductivity, EC µS/cm	Groundwater depth m below ground
Extremely High	> 100	> 1500	> 8
High Risk	> 50	> 750	> 6
Medium Risk	> 10	> 750	> 5
Low Risk	> 10	> 500	> 4

8.2.2 The processes affecting salt concentrations in groundwater

Salinity in groundwater and surface water is closely interlinked in the coastal zone. Salt intrusion to the freshwater groundwater aquifers is generally described by an equilibrium disturbed by progressing anthropogenic stresses and climate change. It is, however, essential to distinguish the main processes describing the intrusion and the interfaces between predominantly fresh and saline water bodies. The review has identified key references addressing the intrusion mechanisms and processes.

Deltares (2015)

The objectives of the project included raising awareness, improving knowledge and increasing skills among stakeholders with respect to managing salinization. This however requires knowledge about the basic processes responsible for salt transport. Measures of adaptation, mitigation and preventive actions were explored. The project describes the coastal region as complex in terms of hydrogeology, with irregular, interbedded deposits containing freshwater and brackish or salt water. There is not a single well-defined front or interface between fresh and saline water and salinity intrusion processes in polders include transport and mixing vertically, laterally, by storm surge and due to groundwater pumping. The project points to technologies and mitigation measures including artificial recharge. Management strategies, however, requires systematic monitoring and establishment of a national database to provide a better basis for assessing the potential and efficiency of management measures for salt control. Figure 8- shows cross sectional profiles explaining key drivers and processes to be considered at the local scale.

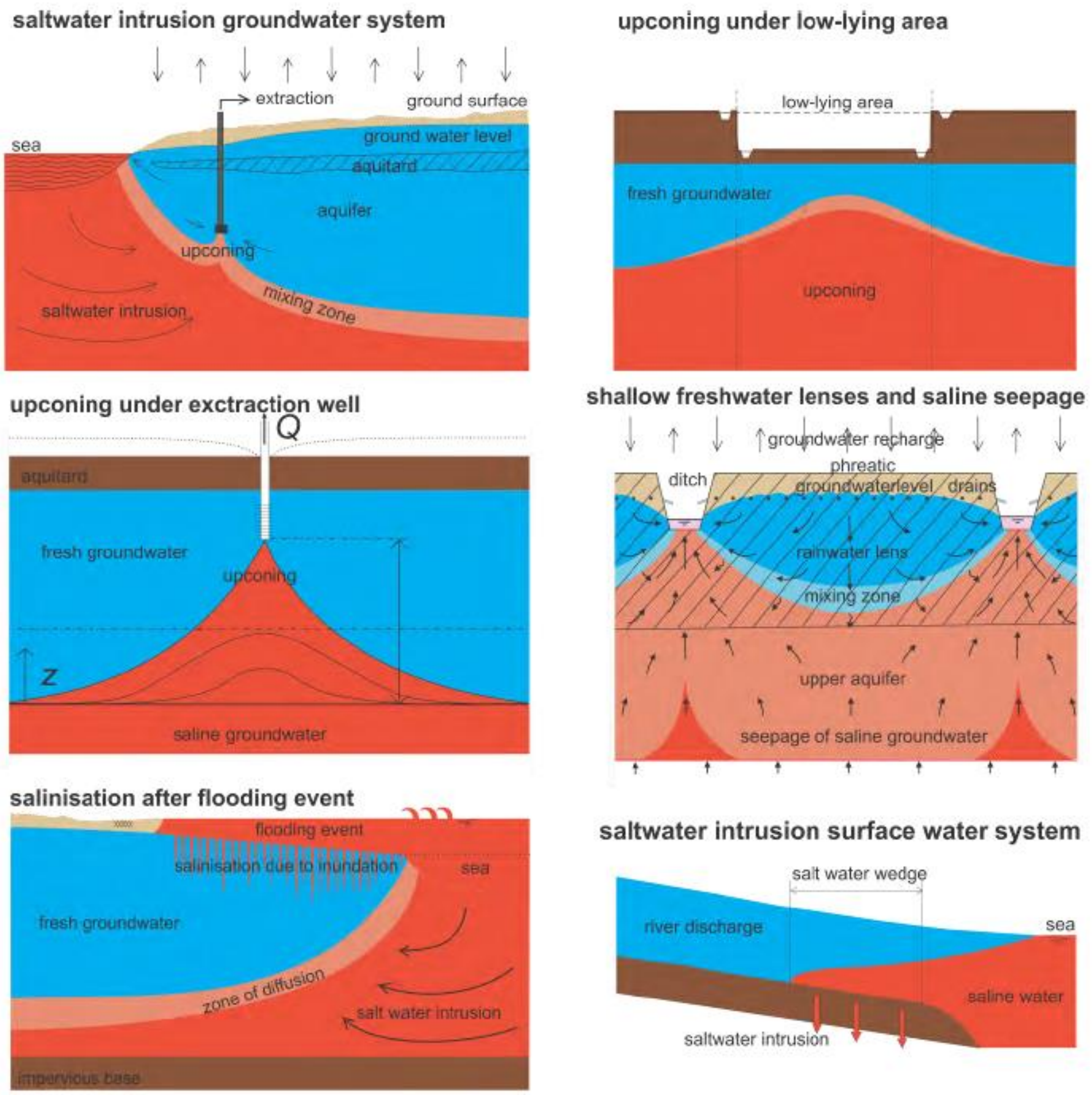

Figure 8-1 Deltares 2015 (figure 53) – illustration of salinity intrusion processes

Salehin et. al (2018)

Salehin et. al 2018 identifies soil salinity as the dominant factor in explaining the low crop productivity in Coastal Bangladesh. Apart from the challenging natural and climatic conditions inappropriate water control structures, e.g. drainage systems, are mentioned. Salehin et. al 2018 listed the mechanisms and processes related to soil salinity in unprotected coastal areas and in protected polders areas. In a soil salinity perspective, the groundwater salinity is essential as capillary rise from the groundwater table into the root zone and irrigation with brackish groundwater will reduce crop yields. Contamination of the shallow groundwater is critical as the fine-grained soils predominant in delta have considerable capillary rise potential. The capillary forces introduce an upward directed salt transport into the root zone and the surface drainage systems. Groundwater table management is important in preventing salinification. The interlinked and integrated nature of salt transport between surface water and groundwater is clearly recognized.

Islam et. al (2019)

Salinity in soil and groundwater water affects millions of people living in deltas. The paper applies field data and numerical models to investigate the link between salinity intrusion and land use. Both climate change and land use changes (e.g. in response to climate change and salinization) will likely be important drivers for a continued salt intrusion to the shallow groundwater aquifer.

The expected future sea level rise and increase in storm surge inundation events, combined with land use changes, e.g. expanding salt water shrimp farms replacing cropped agricultural areas, will add to salinization of shallow groundwater layers. This implies reduced available resources for drinking water and irrigation inside polders and in the South West region in general.

The study uses a groundwater model to simulate salinity in profiles crossing Polder 31. By changing land use and introducing shrimp farms it is demonstrated that salinity will likely increase significantly within 10-200 years. An increasing frequency of storm surge inundations will also lead to higher salinity concentrations of the shallow groundwater aquifer.

The study showed that land use management plays an important role with respect to salinization of shallow groundwater. Relocation of shrimp farms and restoration of embankments were identified as feasible landscape management solutions in order to adapt to climate change while preventing further salinity intrusion. Connecting the areas inside the polder to the tidal fluctuations during the rainy season was also suggested as a useful management measure. Figure 8-2 shows the mechanisms and processes identified which affect soil salinity. It is evident that soil salinity is closely related to salinity of surface water and groundwater. Figure 8-3 shows the distribution of salinity in shallow ground water in Bangladesh.

Mechanism/ drivers	Processes	Long-term change factors
Climate variability	Irregular rainfall (less rainfall not being able to flush out salts in monsoon; less rainfall forcing more irrigation in dry season)	Increased irrigation
Groundwater salinity	Accumulation of salts from capillary rise of saline groundwater table	Increased sea levels Increased river salinity Increased pumping in upstream freshwater zones
Depth to water table	Capillary rise (water table is < 2 m from surface)	Increased pumping Sea-level rise
Cyclonic storm surges	Overtopping of polders Trapped saline water in low-lying floodplain areas with silted up drainage canals Persistent inundation of tidal plains through embankment breaches	Higher sea levels Increased frequency of surges
River water salinity	Direct tidal inundation in unprotected areas Tidal inundation in polders through embankment breach and/or due to faulty water control structures and poor management Lateral seepage of saline river water through soil/embankment	Reduced river flows due to climate variability Reduced river flows due to upstream diversion Reduced river flows due to upstream dams Sea-level rise
Salinity of irrigation water	Irrigation with saline river or groundwater	Increased irrigation for leaching Saline intrusion into groundwater aquifers
Brackish shrimp cultivation	Deliberate introduction of saline water inside polders Lateral seepage from shrimp *ghers* to adjacent land Contamination of shallow groundwater	National policies Market forces/prices Power relations

Figure 8-2 Mechanisms and processes affecting soil salinity (Salehin et. al. 2018)

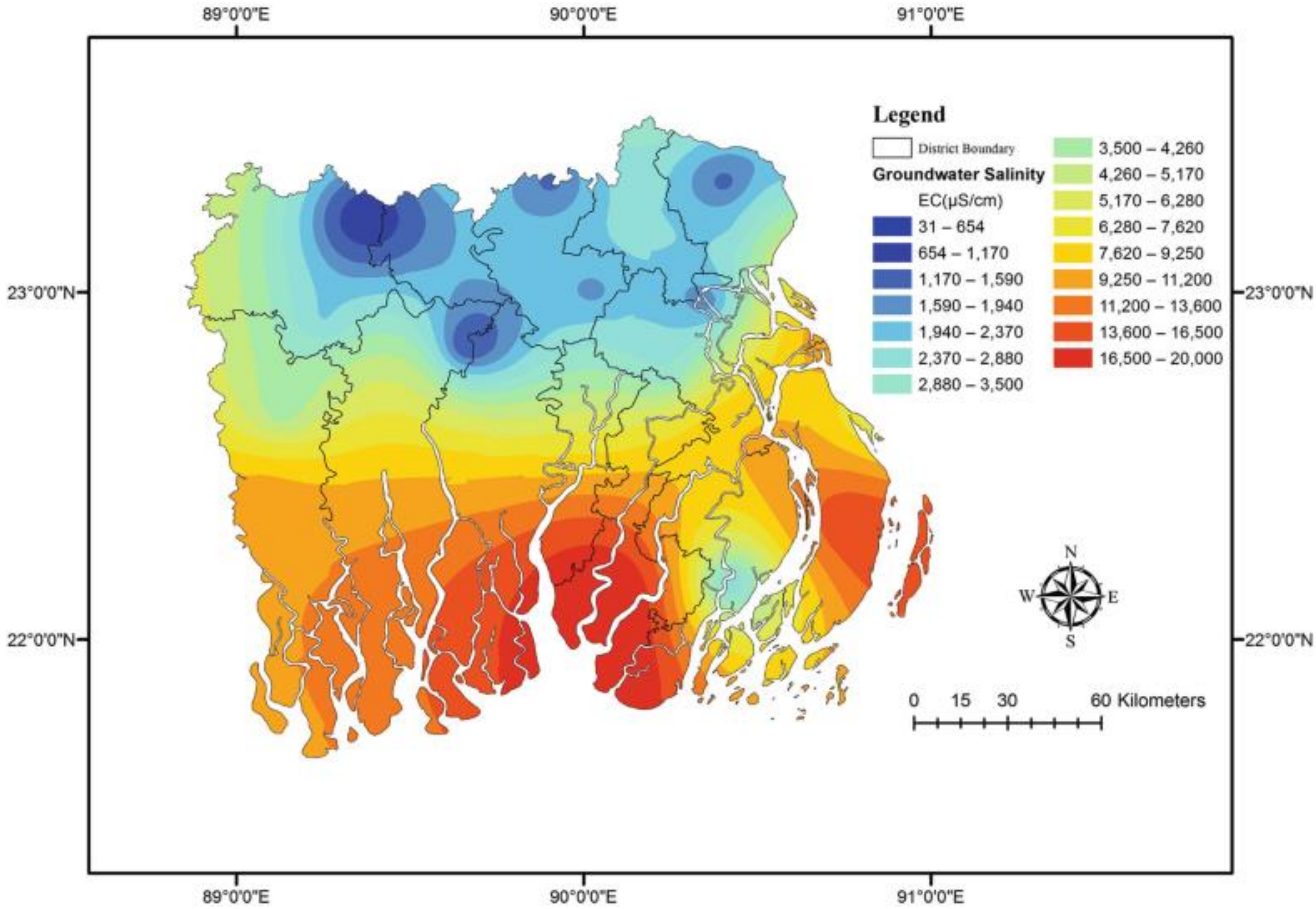

Figure 8-3 Salinity in shallow groundwater (data: Bangladesh Water Development Board), Salehin et. al. 2018

8.2.3 Groundwater salinity in relation to polders

Worland et. al (2015)

The study focuses on groundwater salinity at an embanked tidal polder focusing on the relation between hydrogeology and the distribution of fresh, brackish and saline water in the aquifer. A distinction is made with respect to groundwater sources and transport of salt depending on spatial and temporal scales of the Ganges-Brahmaputra-Meghna river delta. Density-driven seawater intrusion may occur on the long term in the deep aquifer. For the shallow aquifer inside the polders storm surge inflows, tidal channel mixing and groundwater abstraction may play important roles. The authors also point to paleo-seawater deposits as a likely explanation to the measured salt concentrations and the generally brackish water (around 5 g/l).

A field study of Polder 32 investigated measured salt concentration in the shallow aquifer in relation to stratigraphy. Conceptual and numerical groundwater models were introduced and led to the conclusion that mixing of brackish groundwater with freshwater occur by annual recharge and as a function of the distribution of fine-grained surface deposits (silts and clays). The hydrogeological heterogeneity also implies that poorly delineated freshwater lenses replenished by recharge are ulnerable to salinity intrusion due to pumping.

Mainuddin et. al (2021)

The paper used a polder water and salt balance model to examine the impact of crop management, salt management and climate change at Dacope (Polder 31) and Amtali (Polder 43) in Bangladesh. Local management practices to remove salt from polders are considered feasible and effective in combatting impacts of projected climate change with respect to salinification. The authors state that crop production could be increased substantially by improving polder infrastructure and by adopting better salt management methods in surface water, groundwater and soil.

The salinity of the rivers adjacent to the polders varies due to the tide and season. Salinity is low in the rainy season (less than 1 dS/m) but it increases and reaches up to 25 dS/m in the dry season. The polders are characterised by dense drainage networks of ponds and canals. Sluice gates are installed with the purpose of draining the polder while storing freshwater to be used during the dry season. The measured salt concentration of the shallow groundwater aquifer varies with the season between 0.4 to 11.0 dS/m.

The conceptual polder model (Figure 4) was used in a number of scenarios. The scenarios considered climate change, crop rotations and different irrigation water allocation strategies with respect to surface water and groundwater. Based on scenario results the study concludes that strategies to reduce salt concentrations in the soil lead to higher crop evapotranspiration corresponding to greater crop production. Lowering of high salinity groundwater table, adapting field drainage systems to reduce soil salinity and operation of polder drainage canals to remove salt are all effective management measures according to the model results. Climate change increases rainfall and runoff and decreases the demand for alternative saltier sources of irrigation water.

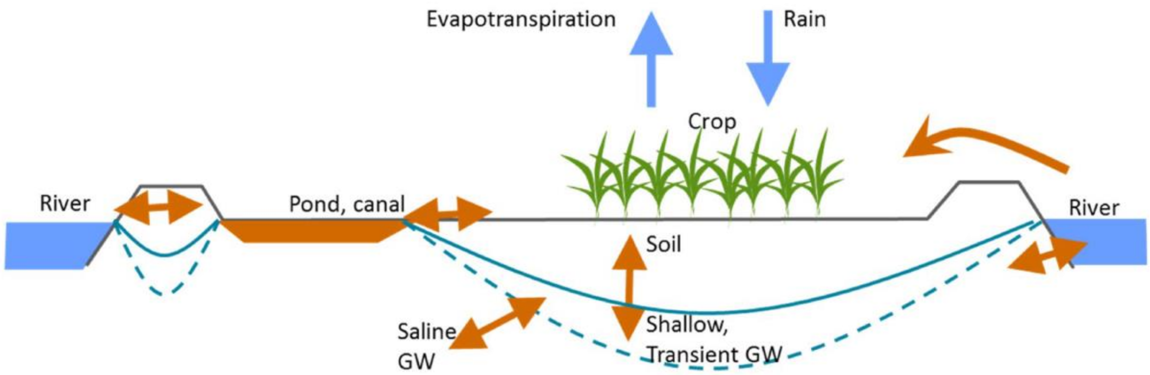

Figure 8-4 Conceptual polder water and salt balance model (Mainuddin et. al 2021)

8.2.4 Summary of groundwatyer salinity litterature review

The papers and reports reviewed all conclude that salinity in groundwater is a widespread and increasing problem in the polders of coastal Bangladesh. Despite the spatial variation in measured salt concentrations a clear upward trend has been observed in recent decades and salinization is likely to deteriorate further due to climate change. Risk maps also clearly demonstrate the scale of the problem when looking at groundwater and soil samples of South Western Bangladesh.

Several of the papers and reports reviewed look into the underlying processes and mechanisms responsible for groundwater salt intrusion. Generally, a distinction is made between the deep aquifer sequences where sea water intrusion forces the freshwater interface further inland and the shallow aquifer subject to, on one hand tidal dynamics and storm surges, and on the other hand anthropogenic stresses. Inside polders human factors affecting salinity include land use, groundwater pumping, irrigation and drainage.

Groundwater salinity is closely interlinked with surface ware salinity and thus climate change effects with respect sea level rise, higher storm surge frequency and reduced river freshwater discharges, all provide boundary conditions on the outside to salt concentrations levels inside polders. The polder infrastructure in terms of embankments and drainage infrastructure as well as water management play important roles in preventing or controlling salt intrusion. All the above point towards surface water and groundwater data collection and integrated analysis at the individual polders to derive efficient management strategies and options. Integrated models at the appropriate spatial and temporal scale provide a useful tool when assessing long term development and climate change.

A prerequisite for making informed decisions and taking appropriate water management actions is availability of data and analytical tools. Local field and monitoring data on hydrogeology, salt concentrations and delineation of freshwater lenses are required at individual polders to assess the water balance and the salt transport between soil, surface water and groundwater. The papers and reports reviewed have identified types of effective management measures in general but their feasibility and applicability must be evaluated as part of site specific polder management plans.

8.2.5 River Discharge

In the monsoon the combined flow of the Ganges and the Brahmaputra reaches a peak between 80,000 to 140,000 m^3/s in the July/August or early September period (Moef, 2005). Meltwater is important for the Brahmaputra basin but plays only a modest role in the Ganges river; discharge generated by snow and glacial melt In the Brahmaputra basin is 27%, in the Ganges this is 10% (Immerzeel et al, 2010).

Observed trends

Transboundary inflow in the dry season has decreased due to upstream development, and withdrawal of water for irrigation and other purposes (Moef, 2005).

Projections

Immerzeel et al, 2010 project that upstream snow and ice reserves of these basins, important in sustaining seasonal water availability, are likely to be affected substantially by climate change, but to what extent is yet unclear. Of the two rivers, the Brahmaputra and is most susceptible to reductions of flow.

Nepal and Shresta (2015) state that climate change may result in increased flood risk in the Brahmaputra Basin. The overall impact on annual discharge is likely to be low. Shrinking of glaciers in response to rising temperatures might result in a marked reduction in water availability in some rivers in the medium-to-long term.

Masood et al. (2015) project that by the end of 21st century the increase in mean runoff is 16%, 20-36% and 30-40% in the Brahmaputra, Ganges, and Meghna, respectively. Future changes of runoff are larger in the dry season (November–April) than in the wet season (May–October). Amongst the three basins, the Meghna shows the highest increase in runoff, indicating higher possibility of flood occurrence. The uncertainty due to the specification of key model parameters in model predictions is found to be low for estimated runoff.

Saiful Islam et al. (2017) combined a number of regional climate models with a hydrological model of the Brahmaputra River basin. They concluded that most of the regional Climate Models (RCMs) show an increasing tendency of the discharge of Brahmaputra River at Bahadurabad station during the monsoon season. The models showed better mutual agreement for the monsoon discharges flow than for pre-monsoon discharges.

Kundzewics et al (2008) project that a global temperature increase of 2°C will result in an increase in the flooded area for annual peak discharge in Bangladesh by at least 23–29%

Pervez, & Henebry (2014) state that peak monsoon precipitation (and therefore discharge) is likely to shift from July to August as a result of climate change. The projected increases in precipitation by these authors (see before) will result in similar increases in runoff.

Mohammed et al (2017) project that floods are likely to become more frequent in the future and that their magnitude will become more severe. Hydrological droughts are projected to become less frequent in the future and their magnitude to become less severe. The average timing of both floods and hydrological droughts is projected to shift earlier compared to the present hydrological regime. Mean monthly discharges are projected to increase in the pre-monsoon months and decrease in the post-monsoon months

Whitebread et al (2013) used a hydrological model of the Ganges, Brahmaputra and Meghna River Systems to simulate flow and water quality along the rivers under a range of future climate conditions. Model results for the 2050s and the 2090s indicate a significant increase in monsoon flows under the future climates, with enhanced flood potential. Low flows are predicted to fall with extended drought periods, which could have impacts on water and sediment supply, irrigated agriculture and saline intrusion.

8.2.6 Reference E.28

Global warming and changes in the probability of occurrence of floods in Bangladesh and implications, M. MonirulQader Mirza, Global Environmental Change, Volume 12, Issue 2, July 2002, Pages 127–138

Summary

The research presents flood problems in Bangladesh, with particular focus on flood types, characteristics of peak discharge, flood duration and linkages between global warming and floods recession and damage, possible changes in occurrence of peak discharges and future likely implications are illustrated.

Bangladesh is very prone to flooding due to its location at the confluence of the Ganges, Brahmaputra and Meghna (GBM) rivers and because of the hydro-meteorological and topographical characteristics of the basins in which it is situated. Floods cause serious damage to the economy of Bangladesh, a country with a low per capita income. Global warming caused significant effects on the hydrology and water resources of the GBM basins and might ultimately lead to more serious floods in Bangladesh. The use of climate change scenarios from four general circulation models as input into hydrological models demonstrates substantial increases in mean peak discharges in the GBM rivers. These changes may lead to changes in the occurrence of flooding with certain magnitude. Extreme flooding events will create a number of implications for agriculture, flood control and infrastructure in Bangladesh. Concerted efforts are needed to strengthen capacity building in the agriculture sector in Bangladesh in order to reduce crop damage.

Methodology

In this study, different types of paper have been reviewed and tried to focus on type of floods, characteristics of peak discharge, flood duration and recession, flood damage, global warming and its effects on floods in Bangladesh, and also future implications.

Findings and Research Gaps

There are four types of flood in Bangladesh: flash flood; riverine floods; rain floods and storm surge. The area flooded in Bangladesh during the period 1954–1999 shown that more area inundated in Bangladesh during the period 1980–1999 than that of the period 1960–1980. Therefore, estimates of flood damage were also high in recent decades due to depth and duration of flooding. The characteristics of peak discharges of the Ganges, Brahmaputra and Meghna rivers are unique in terms of magnitude and timing of occurrence. Precipitation patterns of the river basins highly influence their characteristics. For example, although the basin area of the Brahmaputra River is about half of that of the Ganges River, mean annual peak discharge of the former is considerably higher than the latter. In 1998, the peak discharges in the Brahmaputra and Ganges occurred only 2 days apart. A similar simultaneous occurrence of peak flows of the two rivers also occurred in 1988 that also caused a devastating flood. The magnitudes of peak discharges of the major rivers were almost equal in 1998 and 1988; longer duration of floods in 1998 was attributed to drainage congestion around the confluence of the Ganges and Brahmaputra rivers caused by high tidal activity and subsequent backwater effect. During the period 1954–1999, floods killed 11,571 people in Bangladesh, of which 7109 people were killed during the floods of 1987,1987 and 1988 (Mirza et al., 2002).

A sensitivity analysis for 20-year floods for the Ganges, Brahmaputra and Meghna rivers demonstrates a range of possibilities of changes in probability of flood occurrences for various GCM scenarios. The analysis further demonstrates that possible changes in these probabilities of occurrences are not consistent for the three large rivers. CSRIO9 model indicate the largest possible increases in peak discharge of the Ganges River basin compared to other models. For Brahmaputra river basin the GFDL model project the highest increase in precipitation and The HadCM2 model for Meghna river basin which is the wettest river basin among the three. Mean annual precipitation is 3.5 times higher than the Ganges and about 1.5 times higher than the Brahmaputra. The largest changes in probability are expected for the Brahmaputra and Meghna rivers. This implies a greater risk in flood planning and management in Bangladesh in future.

The analysis also demonstrates that crop agriculture in Bangladesh will be at greater risk in a warmer climate than compared to current conditions. Crop cultivation encompasses both human and natural elements. Therefore, adaptation in agricultural systems needs adjustments in human activities, socio-cultural (behavioural) aspects of present and past agricultural practices, and environmental factors in response to the anticipated changes in climate system and its consequential impact (Ahmed, 2001). Since the loss of crop production under warming scenarios could be quite significant, ‘‘no adaptation’’ would mean that the anticipated loss would have to be borne primarily by the poor farmers and the consumers.

8.2.7 Reference E.29

Multi-factor impact analysis of agricultural production in Bangladesh with Climate change, A. C. Ruane, D. C. Major, W. H. Yu, M.Alam, S. G.Hussain, M.S.A. Khan, A. S. Khan, A. Hassan, B. M. T. A. Hossain, R. Goldberg, R. M. Horton and C. Rosenzweig, Global Environmental Change, Volume 23, Issue 1, February 2013, Pages 338–350

Summary

Bangladesh lies on mostly flat, alluvial land at the mouth of the Ganges-Brahmaputra-Meghna (GBM) Basins that drain monsoon runoff from a large portion of South Asia and is widely recognized as a country with high sensitivity to climate variability and change. Bangladesh uses more than 70% of its land for agricultural purposes (FAOSTAT, 2009), often with multiple cropping seasons. However, in these study diverse vulnerabilities of Bangladesh’s agricultural sector are divided into 16 sub-regions. This region is assessed using experiments designed to investigate climate impact factors in isolation and in combination. Climate information from a suite of global climate models (GCMs) is used to drive models assessing the agricultural impact of changes in temperature, precipitation, carbon dioxide concentrations, river floods, and sea level rise for the 2040–2069 period in comparison to a historical baseline. It is observed from the analysis that, Agriculture in Southern Bangladesh is severely affected by sea level rise, whereas increasing river flood areas reduce production in affected sub-regions. It was also observed that, impacts are increasing under the higher emissions scenario.

Methodology

Climate simulations were analysed by the studies reviewed in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4). Climate change scenarios are generated by comparing a givenGCM’s2040–2069 period (referred to as the ‘‘2050s’’) with control simulations of that GCM over a 1970–1999 baseline, and then imposing these changes on historical observations to detect the effect of natural disaster in changing climate, the climate change projection results are incorporated in hydrologic and hydrodynamic models. Both are relatively high (A2) and low (B1) future emissions pathway were analysed and compared to the baseline period. Versatile mathematical simulation packages are used for this research work. An ensemble of climate scenarios was created for each sub-region from 16 GCMs and 2 emissions scenarios, capturing a consistent temperature rise and wide uncertainty among projected precipitation changes. The MIKE BASIN hydrologic model was employed over the entire GBM Basins that drain through Bangladesh to simulate river floods for each baseline and future year. Flood protection infrastructure in Bangladesh was also taken into account. Coastal inundation in the 2050's was simulated by the UK Department for Environment, Food, and Rural Affairs in collaboration with IWM and CEGIS (DEFRA, 2007) using theMIKE21 Two-Dimensional Estuary Model. Process-based crop model simulations were run with the Crop Environment Resource Synthesis (CERES). Online Material. Process-based crop model simulations were run with the Crop Environment Resource Synthesis (CERES) rice and wheat models which include the beneficial effects of enhanced carbon dioxide concentrations on plant growth.

Findings and research Gaps

It is observed that, due to global warming, the ensemble of crop model simulations driven by scenarios from 16 GCMs, median boro production decreases by 12.1% nationally. While on the other hand, projected rainfall changes reduce median national aus production by 1.4%, aman simulations were barely sensitive to the projected changes in rainfall. River flood damages only reduce national aus production by a median of 1.9%. During the later aman season, substantial climate change increases in flood damage occur in nearly all sub-regions, simulated by the hydrologic model. Authors estimate that, 31% land will be lost due to 62 cm sea level rise. Mean sea level rise will also affect crop production. According to analysis, there will be national losses of National losses of 2.3% (aus), 1.3% (aman), 0.7%(boro), and 0.2% (wheat) are projected when the A2 and B1scenarios are averaged.

8.2.8 Reference E.30

Vulnerability of rural livelihoods to multiple stressors: A case study from the southwest coastal region of Bangladesh, Masud Iqbal Md. Shameem, Salim Momtaz, Ray Rauscher, Ocean & Coastal Management, Volume 102, Part A, December 2014, Pages 79–87

Summary

The paper explores, the process by which major stresses and hazards shape the vulnerability of people's livelihoods in dynamic social-ecological environments in the southwest coastal region of Bangladesh. Drawing on qualitative and quantitative data from a case study was identified the key drivers of change in social-ecological systems and evaluate whether these drivers have affected livelihood outcomes and various components of human wellbeing. This analysis suggested that increasing salinity intrusion, tropical cyclone and land-use change (directly and through changes in ecosystem services) affect the access to livelihood assets at household scale. This undermines social wellbeing by seriously impacting food and water security. Through identification of key stresses and their interactions, and the consequent impacts on ecosystems services and household capitals, the current study proposes a conceptual framework to understand the present-day vulnerability to multiple stressors in the context of the coastal region of Bangladesh. The research only analysis at a household level or sector level which is not sufficient but analysis in broader context is required to contribute of reduction of vulnerability.

Methodology

This study was carried out in Chila, a union of Mongla Upazila (Sub-district) in the district of Bagerhat. In this current study, the livelihood approach was applied to understand the impacts of underlying factors that produce changes in ecosystem services. These changes directly impact on people's asset status and the strategies that are open to them to achieve beneficial livelihood outcomes. The stresses and hazards causing livelihood vulnerabilities comprise many of the same factors characterized as drivers of ecosystem change in the Millennium Ecosystem Framework (UNEP, 2006). Therefore, the terms stresses and hazards are used synonymously with drivers in this study. Data were collected between September 2012 and January 2013 using a combination of qualitative and quantitative methods. Information on source of income, land-use, livelihood assets, farming practices, social network, disturbances and responses of households was collected through this household survey. The qualitative techniques of rapid rural appraisal (RRA) tools were used in focus group discussions to understand the dynamics of livelihood adaptation in the study area. Twenty groups with 5-8 people in each group from different sections of the community participated in group discussions focusing on key stresses

Findings and Research Gaps

Based on analysis of survey data (n= 372) together with local and published information, the study identified the major impacts of environmental stressors on various components of rural livelihoods. These are: land use changes, Salinity intrusion, and tropical cyclones. In the study area results included: 33% of the respondents perceived that shrimp farming had not been responsible for mangrove destruction (Sundarban mangrove forest),27% identified somewhat responsible and 20% as being mostly responsible. With the growing salinity intrusion in surface and ground water, the socio-ecological system has experienced changes, manifested in scarcity of freshwater resources and transformation of agro-ecological system into degraded state. These changes have contributed to declining agriculture productivity and associated sub-sectors. The storm surge accompanied by cyclone inundates low-lying areas, causes salinity intrusion, contaminates freshwater ponds used as drinking water sources and contributes to escaping shrimp-stock from the ponds.

The hazards and stresses have impacted local livelihoods directly and through changes in environment and ecosystem conditions are as follows: 1) Damaging natural capital and increasing financial inequality. 2) Damage to physical capital Tropical cyclones that often traverse 3) Impacts on human capital 4) Impacts on social capital. Comparison with rice cultivation, shrimp farming is less labour intensive. Shiva (1995) has observed that rice cultivation on 40 ha of land requires 50 labourers, while shrimp farm of the same size provides employment of only 5 people. Large farmer and processors enjoy greater opportunity for negotiation than the small farmer which creates inequality of benefit. Besides this increase inequality in landownership, loss of income diversifications', disruption of livelihoods and damage of physical capital are also seen. Almost all the survey population (97%) reported that rice cultivation in this area had declined substantially with the rapid expansion of shrimp cultivation. This made these communities' food security vulnerable because they had to rely on rice import from other parts of the country. The study will to be required in a broader aspect instead of local to identify the combined vulnerability and take proper measures to development, equity and resilience of socio-ecological systems. Research gap is that it does not provide any indication and solution of multiple vulnerabilities. An action research program can be formulated on a larger area for climate risk assessment and devising solution and implementation in as a pilot program with the potential of scalability.

8.2.9 Reference E.31

Assessing the impacts of climate and land use and land cover change on the fresh water availability in the Brahmaputra River basin, Md Shahriar Pervez, Geoffrey M. Henebry, ASRC Federal InuTeq, Contractor to U.S. Geological Survey (USGS), Earth Resources Observation and Science (EROS) Center, 47914 252nd Street, Sioux Falls, SD 57198, USA. 2Geospatial Sciences Center of Excellence (GSCE), South Dakota State University, 1021 Medary Ave.,Wecota Hall 506B, Brookings, SD 57007-3510, USA

Summary

The study focuses on to evaluate sensitivities and patterns in freshwater availability due to projected climate and land use changes in the Brahmaputra basin by using the Soil and Water Assessment Tool. The daily observed discharge at Bahadurabad station in Bangladesh was used to calibrate and validate the model and analyse uncertainties with a sequential uncertainty fitting algorithm. The sensitivities and impacts of projected climate and land use changes on basin hydrological components were simulated for the A1B and A2 scenarios and analysed relative to a baseline scenario of 1988–2004. There is large inter-model variability in the simulation of spatial characteristics of seasonal monsoon precipitation (Sabade et al., 2011); therefore, conclusions based on one down scaled precipitation may not be optimal and may defer when multiple GCMs are considered.

Methodology

SWAT model has been used in this study. To simulate this model weather data (daily precipitation, maximum/minimum air temperature, solar radiation, wind speed, and relative humidity) stream flow data (discharge data at Bahadurabad gauge station) and land use data has been collected from different organizations. ArcSWAT (Winchell et al., 2010) – was used to parameterize the model for the Brahmaputra basin. The period 1988–1997 was used to calibrate the model, and 1998–2004 (excluding2002) was used to validate the model. The calibrated and validated model was run for the entire time period 1988–2004 under an average atmospheric CO2 concentration of 330 ppm. These simulation results were used as the baseline scenario. Calibrated and validated Model has been used for experimental design, precipitation, and land use projections. The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) for the region has been followed and six scenarios were established based on changing CO2, Temperature and Precipitation. To designed future climate and land use change impact assessment simulations with estimated CO2 concentration, temperature increase, and land use change scenarios for each 10-year period of the 21st century. The scenarios were executed with third-generation Canadian GCM version 3.1(CGCM3.1). Statistical Downscaling Model (SDSM)-downscaled precipitation (Pervez and Henebry,2014), projected temperature and CO2 concentration, and downscaled IMAGE-projected land use information for the A1B and A2 scenarios.

Findings and Research Gaps

It was found that the annual average simulated stream flow at Bahadurabad gauge station was 22,875 m3s−1, which was slightly larger than the average observed stream flow (22,345 m3s−1) for the same period. The annual total water yield was predicted to increase by 2% and 5% in response to a 1.5× and 2× increase in CO2 concentration, respectively. The average annual precipitation in the Brahmaputra basin was predicted to increase from 1849 mm to 2013 mm and 2029 mm, a 9% and 10% increase com-pared to baseline precipitation and groundwater recharge was predicted to increase by 47% and 49% annually under the A1Band A2 scenarios. The stream flow patterns during FMA suggested that the impacts of spring snowmelt on the stream flow could diminish by 2030. The long-term patterns in the groundwater recharge showed a significant decreasing trend for the early monsoon period (MJJ) and a significant increasing trend for the later monsoon period. The sensitivity scenario results indicated that increase in CO2concentration caused basin wide average ET to decrease because of physiological forcing, which resulting in increases in average total water yield, stream flow, and groundwater recharge. The impacts of climate and land use change were predicted to be more pronounced for the seasonal variability in hydrological components than the inter annual variability in the Brahmaputra basin. The study combined analyses of sensitivity of hydrological components to climate change and long-term impacts of future climate and land use change on freshwater availability can offer much needed inputs for resource, but it should be evaluated at the sub basin level to provide a more complete picture to make a decision. There are some uncertainties in this study. These are model is calibrated against flow, therefore, predicted estimates of those components that were not calibrated were more uncertain Also future climate change projections, GCM predictors and model down scaling was not accurately predicted.

9 Coastal & Marine BIODIVERSITY

The coastal zone contains distinctive development opportunities that can be instrumental in reducing the vulnerability and poverty of coastal communities and can contribute significantly to the development of Bangladesh as a whole. Some of these are untapped, others have significant expansion potentials. The zone has a diversity of natural resources, including coastal fisheries and shrimp, forest, salt and minerals. In recent years, Bangladesh coastal areas received international attention due to its high potential for exploitation of both onshore and offshore natural gas. The coastal zone, including the estuaries and brackish ecosystems, contains several ecosystems that have important conservation values. Some parts of the world's largest uninterrupted stretch of mangrove ecosystem - the Sundarban – in Bangladesh has been declared a World Heritage Site (WHS) in 1997, whereas coral-associated ecosystems are found around St. Martin's Island. These ecosystems are not only biodiversity hotspots, but they also provide the ecological foundation for an important common property resource - the fisheries and biological diversity of the Bay of Bengal (BOB).

Coastal ecosystems provide many vital ecological and economic services, including shoreline protection, productive commercial and sport fisheries, and nutrient cycling. Key near-shore ecosystems such as sea grass meadows, marshes, and mangroves are particularly valued for their extremely high productivity, which supports a great abundance and diversity of fish as well as shrimp, oysters, crabs, and other invertebrates. Because of the abundance of juvenile fish and shellfish they contain, near-shore ecosystems are widely considered as nurseries. The nursery role of coastal estuaries and marine ecosystems is well accepted by all and it is often cited to support protection and conservation of these areas. Mangrove ecosystem is directly linked with the enhanced productivity of the nursery ground for marine fish and shellfish fauna (Hussain & Hoq 2010) and protection from the tidal surges and cyclones.

Mangroves are available in the form of natural forests (Sundarban) and planted (in Barisal, Noakhali, Chittagong and Cox's Bazaar Coastal Areas) forests together covering about 50% of the forest area of Bangladesh. The coastal mangrove forests constitute about 60% of the commercial productive forests including plantations, it covers 580 km2. It extends along the coast in isolated groups with the exception of the Sundarban, which accounts for 74% of the reserve forest of the country. The Sundarban and mangrove forest in other parts of coastal area including offshore islands support a wide range of mammals, birds, amphibian, reptiles and crustacean.

The southern part of Bangladesh is bordered by about 710 km long coastline of the Bay of Bengal, which has the continental shelf of up to 50 m depth with an area of about 37,000 km^2. The Exclusive Economic Zone (EEZ) of Bangladesh (Figure 9-1) lies from the base line to 200 nautical miles seaward (S&T. 1993).

An exclusive economic zone (EEZ) is a sea zone prescribed by the 1982 United Nations Convention on the Law of the Sea (UNCLOS) over which a state has special rights regarding the exploration and use of marine resources, including energy production from water and wind. It stretches from the baseline out to 200 nautical miles (nmi) from its coast.

EEZ km^2	Shelf km^2	EEZ+TIA km^2 (Total Internal Area)
89,392	66,438	230,390

(Source: https://en.wikipedia.org/wiki/Exclusive_economic_zone)

The coastal zone of Bangladesh, covering an area of 47,201 km^2 and inhabited by 31 million people (adjusted in 2010), has a dynamic and complex environmental and social setting. For the purpose of the 'Long Term Monitoring, Research and Analysis of Bangladesh Coastal Zone (Sustainable Polders Adapted to Coastal Dynamics)' - a study under the Coastal Embankment Improvement Project-1 (CEIP-1) the entire coastal zone is divided into four zones- Ganges Tidal Plain West (GTPW), Ganges Tidal Plain East (GTPE), Meghna Deltaic Plain (MDP) and Chittagong Coastal Plain (CCP). Salient ecological and habitat features are described for each of the coastal zones including the floral and faunal species inhabiting the zones. Protected areas declared by the government along the coast and continental shelf for the protection and conservation of the habitat, ecological services and species have also been mentioned.

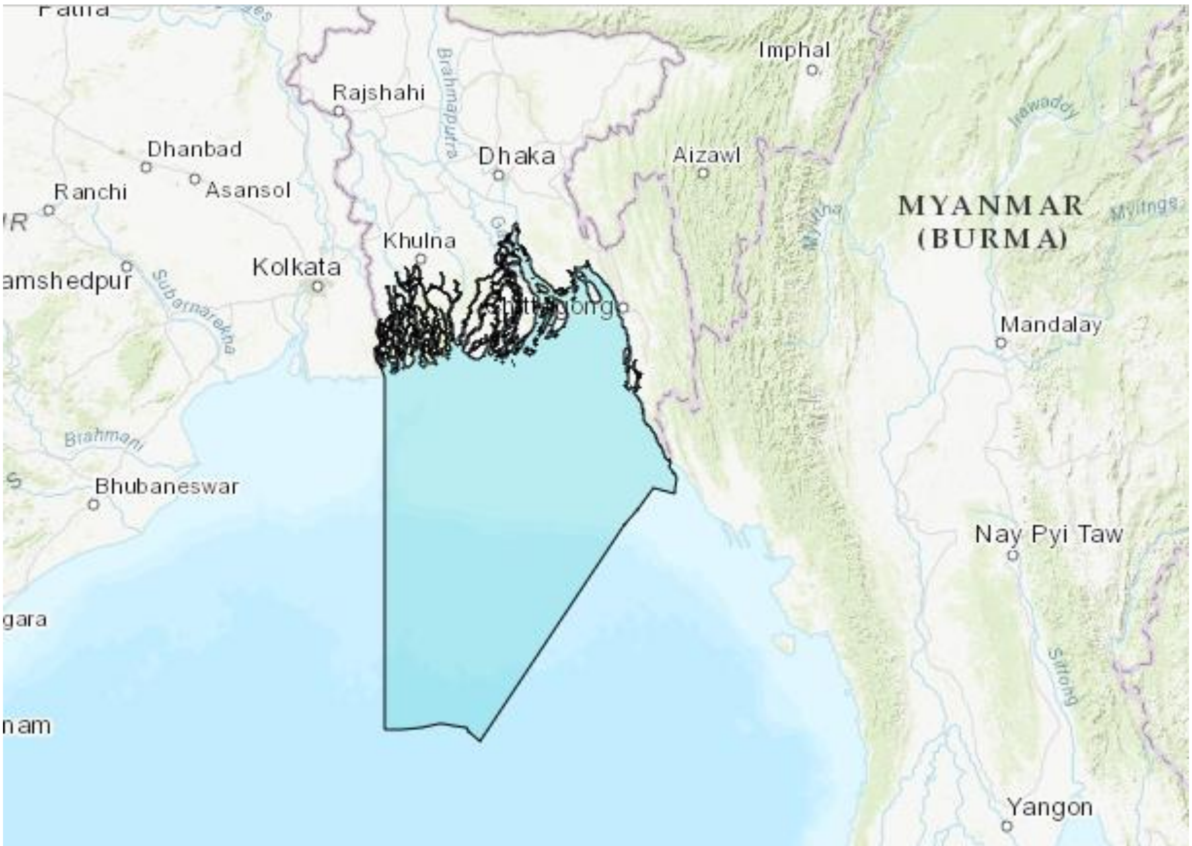

Figure 9-1. Demarcated area showing Exclusive Economic Zone including the coast of Bangladesh.

(Source: https://www.arcgis.com/home/webmap/viewer.html?layers=ba4891c6d1b544939e18143e06d69e88)

9.1 Ganges Tidal Plain (West)

The Sundarban (Figure 9-2) is the largest single continuous productive mangrove forest of the world, spreading over the southern part of Bangladesh and west Bengal State of India. The Sundarban is a unique ecosystem and have great interest in a number of ways. Global mangroves are calculated to be just over 1,80,000 km^2, a small area compared to other forests. Bangladesh is the 8th country in the world, which possess a vast mangrove forest. This is the place where the mainland Bangladesh meets the Bay of Bengal, making the area a globally unique ecological niche. Out of the global total true mangrove species numbering 35, Sundarban has 12-13 sp. The Sundarban mangrove forests provide timber; pulp wood, fuel-wood, raw materials for industries. The major commercial timber/wood species of Sundarban are Sundri (*Heritiera fomes*), Gewa (*Excoecaria agallocha*), Keora (*Sonneratia apetala*), Goran (*Ceriops roxburghiana*). The most important non-wood forest product is Nipa palm - *Nypa fruiticans*. It is mentionable here that the World Heritage Convention (WHC) declared "Sundarban as natural and cultural site of outstanding universal value". Sundarban is the first RAMSAR site of Bangladesh declared under "The Convention on Wetlands" (also called the Ramsar Convention). Three wildlife sanctuaries – Sundarban West, Sundarban South and Sundarban East Wildlife Sanctuaries - declared by the government are located along the coast facing the Bay of Bengal. Moreover, three dolphin sanctuaries (Figure 9-3) have also been declared located along the Pussur, Shela and Bhola Rivers in the north Sundarban for the conservation and protection of the Gangetic and Irrawaddy dolphins.

A total of 334 species of (Spermatophytes and Pteridophytes) belonging to 245 genera were identified from the Sundarban forest and the adjoining areas. Of these no fewer than 123 occur in the present reserve forest of the Bangladesh Sundarban. The forest is rich in biotic diversity comprising 400 species of fishes, 53 species of reptiles, over 315 species of birds and 50 species of mammals. There are 283 species of finfish in Indian Sundarban and 222 species of finfish in Bangladesh Sundarban, 100 species of shellfish community, 15 species of shrimp, 8 species of prawn, 1 species of lobster, 5 species of crabs, 3 species of snails, 22 species of mussels and shells, 4 species of cuttlefish and squids (MOEF 2002).

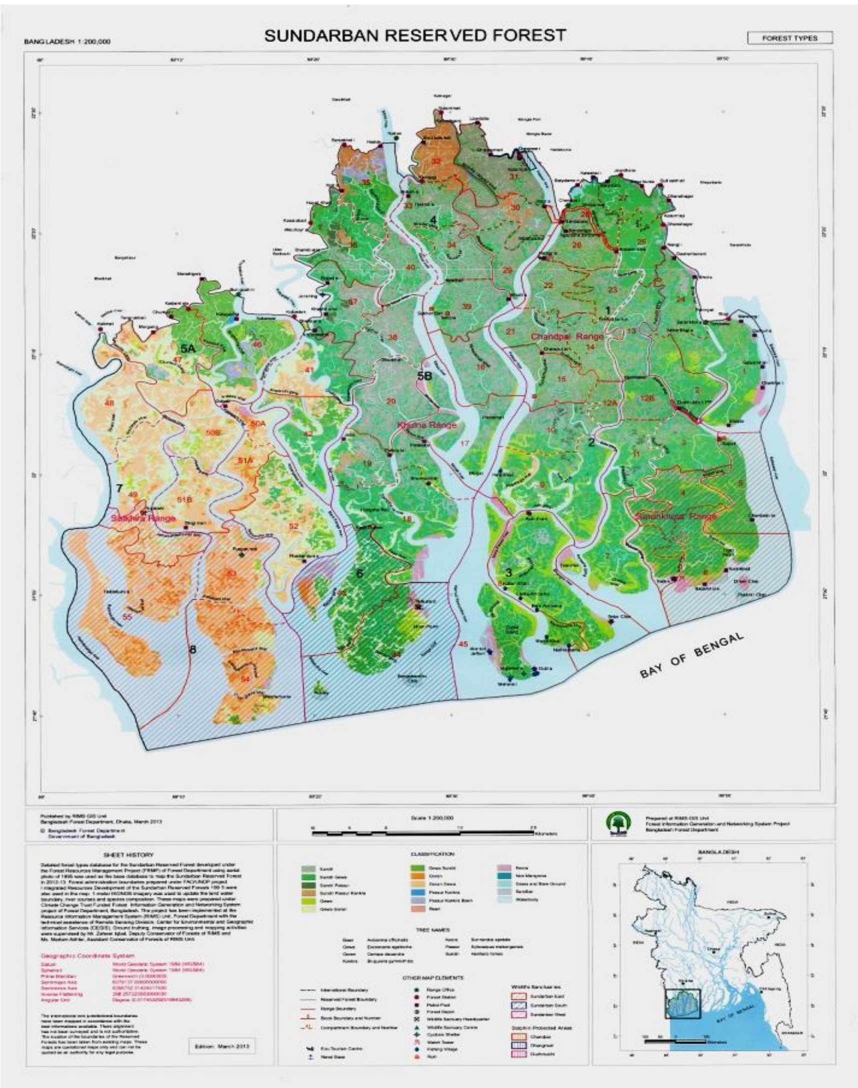

Figure 9-2. Sundarban mangrove forest – the largest mangrove patch in the world. Shaded areas are the designated wildlife sanctuaries.

In addition to fin fish Bangladesh also has a rich diversity of shellfish, especially of Caridean shrimps, several of which are of commercial interest and export value. A total of 63 shrimp and prawn from inland and marine water of Bangladesh have been recorded. The brown shrimp, *Metapeneaus monoceros*, contribute about 56% of the total shrimp catch, though *Peneaus monodon* is the targeted species because of its export value. *Peneaus monodon*, *P. indicus*, *P. semisulcatus*, *Metapeneaus monoceros*, *M. brevocornis* are important penaeids. The shrimp and prawn culture sector of Bangladesh are very important in economic terms contributing significantly to foreign exchange earnings and employment generation in rural areas. About 600,000 coastal people are directly employed in this industry. In addition to the finfish and shrimps, more than 300 mollusc species are recorded from Bangladesh. Two species of *Trochus* sp. are recorded from the St. Martin's Island, which are depleted worldwide. Octopus and Cuttlefish (Sepia) occur in deep waters of the Bay and are exportable commodities.

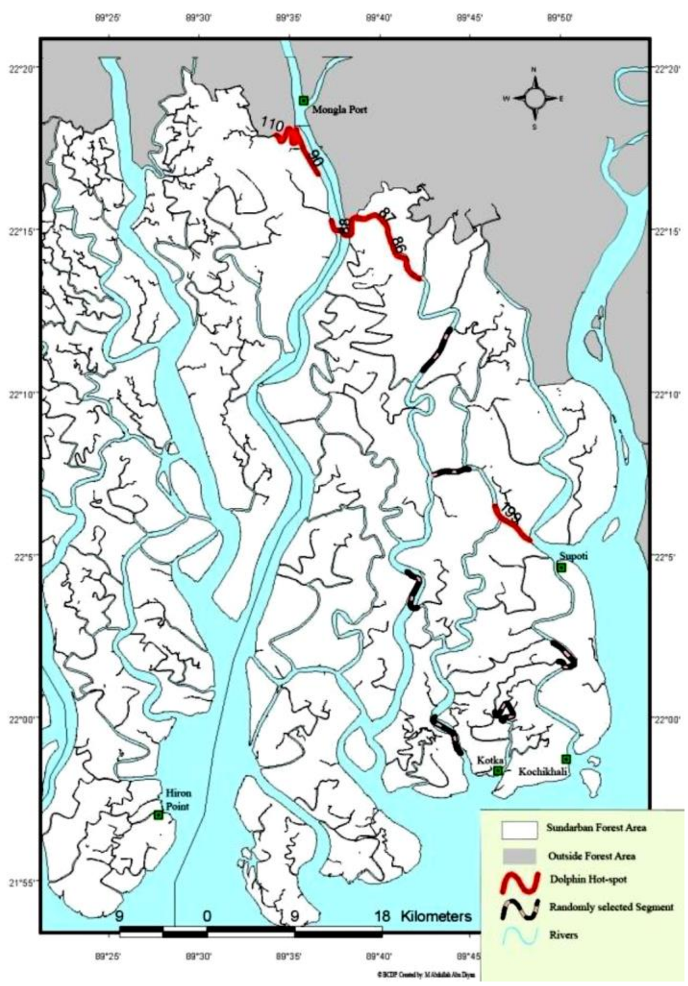

Figure 9-3. Location of the three dolphin hotspots later declared as dolphin sanctuaries indicated by red lines in the Sundarban. (Source: Smith et al. 2010)

Bangladesh Wildlife (Protection & Security) Act (2012) described 30 shark and ray species (SRO No. 301-Law/2021 dated 13 September 2021) including sea horse, 6 species of whales, 14 species of cetaceans, 22 species of crabs and lobsters as protected marine species. The Swatch of No Ground (SoNG) has now been identified as a cetacean hotspot for globally endangered Irrawaddy dolphins, and several other cetaceans. The government has declared SoNG as the first Marine Protected Area (MPA) in the Bay of Bengal (Figure 9-4). Recently the government has declared 174300.00 hectares as Saint Martin Marine Protected Area (SMPA) through a gazette notification No. 22.00.0000.067.22.023.15/5 dated 04 January 2022 (Figure 9-5). St. Martin's Island is the nesting ground for four of the globally endangered marine turtles (Rashid 1997). Among the estuarine/marine fish species several are found to be threatened, among them one is endangered Yellow-tailed Pangas (*Pangasius pangasius*), and several are vulnerable (*Anguilla bengalensis, Plotosus canius, Carcharhinus limbatus and C. melanopterus*). Marine reptiles in Bangladesh such as sea snakes and marine turtles are found all along the coast. Among the marine turtle species, three are critically endangered (Hawksbill Turtle - *Eretmochelys imbricata*, Green Turtle - *Chelonia mydas*, Leatherback Turtle- *Dermochelys coriacea*), while two species are vulnerable (Loggerhead turtle - *Caretta caretta*, and Olive Ridley turtle - *Lepidochelys olivacea*). Ten species of marine mammals are found in the Bay of Bengal, Bangladesh waters. Of these four are vulnerable (Irrawaddy Dolphin - *Orcaella brevirostris*, Bryde's Whale - *Balaenoptera edeni*, Sperm Whale - *Physeter macrocephalus* and Finless Porpoise - *Neophocaena phocaenoides*) (IUCN 2015).

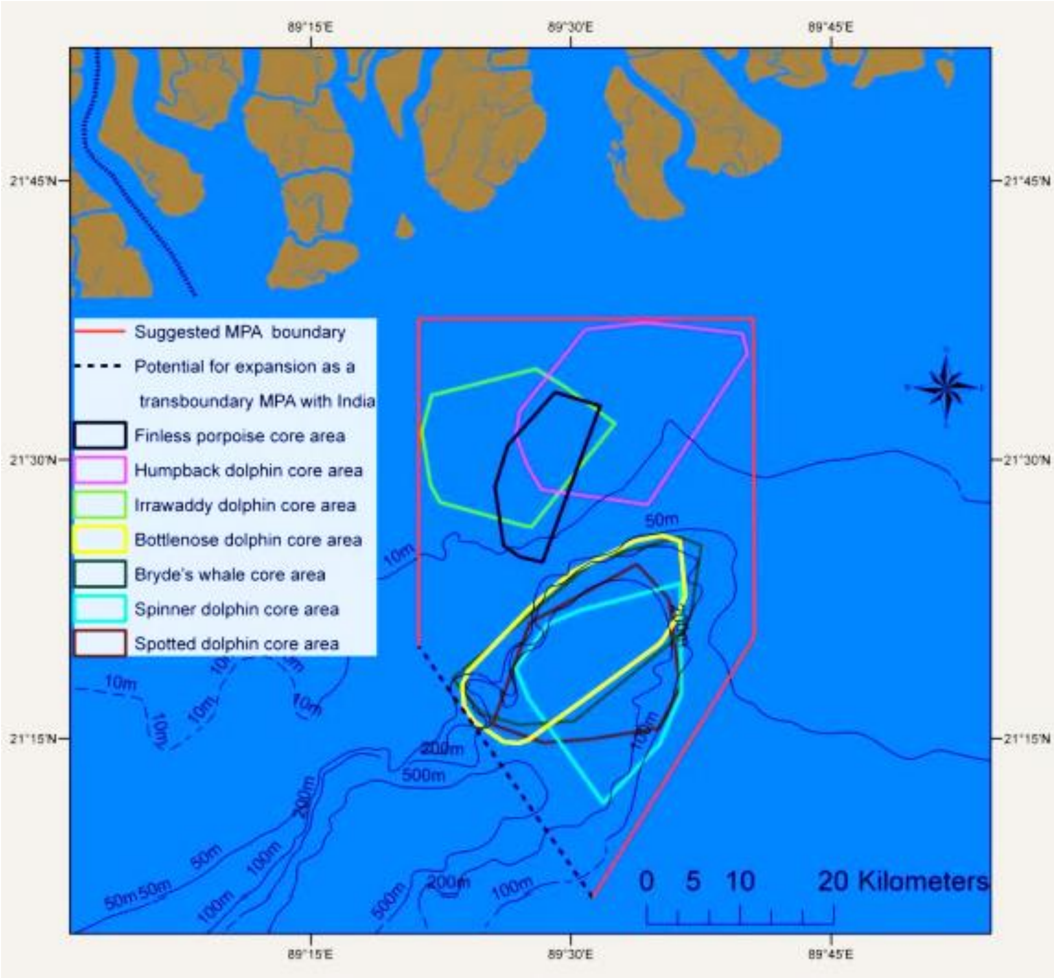

Figure 9-4. Swatch of No Ground Marine Protected (SoNG) Area. Map showing polygons encompassing priority habitat for all seven cetaceans commonly found in coastal and submarine canyon waters of Bangladesh. Source: WCS/BCDP 2015.

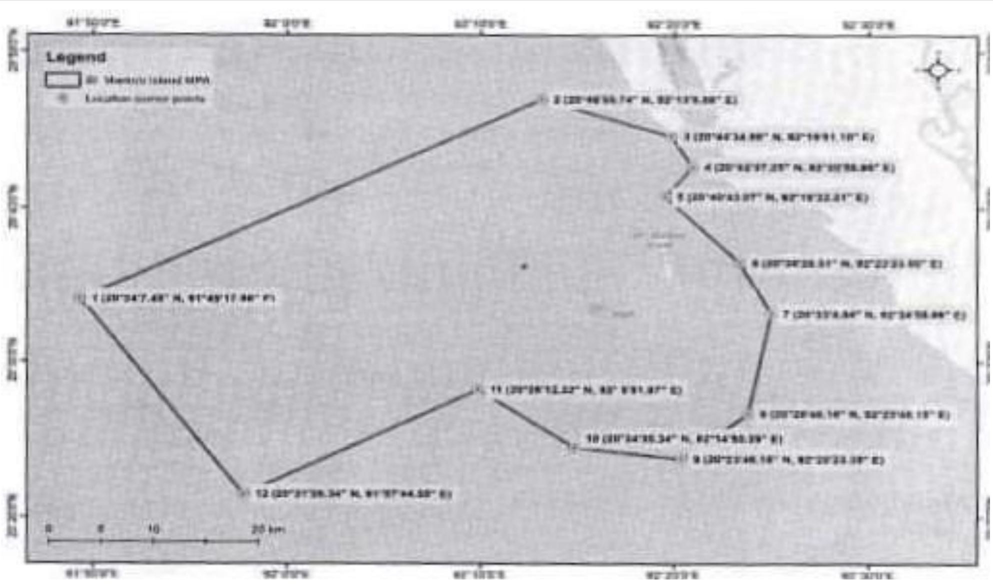

Figure 9-5. Recently declared St. Martin Marine Protected Area. (Source: www.bforest.gov.bd)

9.2 Ganges Tidal Plain (East)

The Government of Bangladesh on 24th June 2019 declared Nijhum Dweep Marine Protected Area (NDMPA) (Figure 9-6) under Section 28 of the Marine Fisheries Ordinance 1983 (Ordinance No. XXXV of 1983). The 3,188 sq. km NDMPA area covers coastal and off-shore areas of Bhola, Noakhali and Patuakhali districts. It includes areas that are important for hilsa migration and spawning, foraging areas for the dolphins and staging areas for some of the critically endangered migratory bird species.

Fisheries provide millions of people with a source of livelihood. Yet across the world, these resources are fast diminishing because of pollution, habitat destruction, overfishing, natural disasters and climate change. Traditional approaches to halt this decline focus on regulating against destructive practices, but with little effect. The polders do have some impact on the local fish movement, migration, fish composition and breeding in a particular locality due to physical and biological factors of the aquatic environment. The Hilsa fish is anadromous (=fish born in freshwater who spend most of their lives in saltwater and return to freshwater to spawn) in nature (an uncommon phenomenon in tropical waters), living in the sea for most of its life, but migrating up to 1,200 kilometers inland along major rivers in the Indian sub-continent for spawning. It is also one of the most important single-species fisheries in the Bay of Bengal, which Bangladesh shares with Myanmar and India. 250 million people are dependent on Hilsa for nutrition and more than half a million people for their livelihoods. Hilsa also has significant cultural value (Mohammed & Wahab 2013).

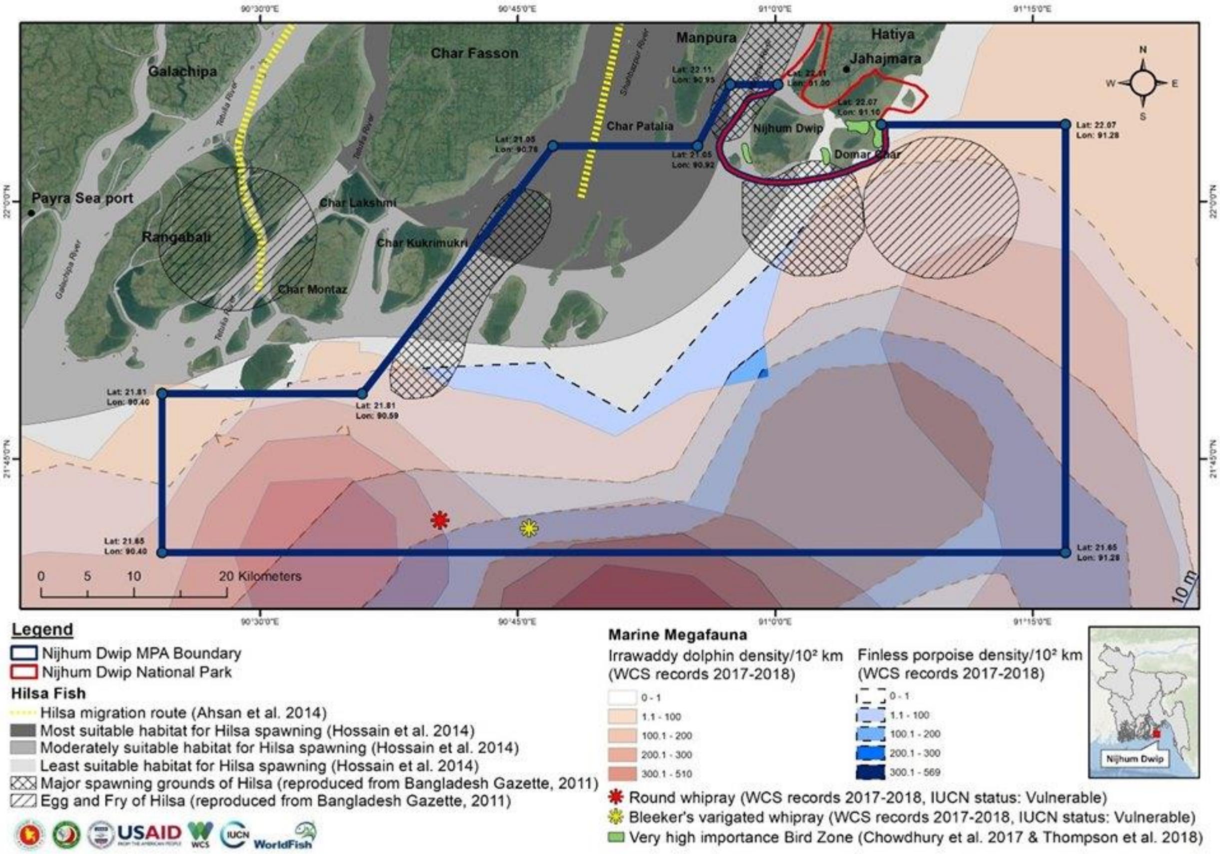

Figure 9-6. Recently declared Nijhum Dweep Marine Protected Area.

Hilsa was once abundant in the 100 rivers of Bangladesh. Fishers used to catch plenty of fish, which were sold fresh to local and urban markets. It was cheap and affordable for the poor. From the 1970s, the Hilsa fishery began to gradually decline, with output reaching a low point of 0.19 million tons in 1991–1992. This situation was attributed to a combination of closure of migratory routes, river siltation, over-fishing, indiscriminate harvesting of brood stocks and juveniles (locally known as jatka), use of fishing nets with very small mesh sizes, the mechanization of fishing gear, increased numbers of fishers, pollution, and hydrological and climatic changes. Such a significant decline in Hilsa catches prompted the government of Bangladesh to declare some of the country’s coastal rivers as Hilsa sanctuaries, restricting fishing during the breeding season. To compensate for loss of earnings due to fishing restrictions, the government started providing affected fisher communities (187,000 households) with 30 kilograms of rice per household per month and supporting alternative income-generating activities (AIGAs). While no study has been carried out to rigorously evaluate the ecological and social impact of the intervention, it is widely believed by both scientists from the Department of Fisheries, and the fishers themselves, that it has had significant positive ecological impacts (Mohammed & Wahab 2013).

Hilsa catch remained at similarly low levels from the base year of 1991–1992 to 2001–2002. Catch levels further declined during 2002–2003 (Figure 9-7), which marked the implementation of economic incentive-based mechanisms to halt further decline, and to focus on efforts to increase Hilsa production. Regulations on the catching of small Hilsa, a ban on fishing of jatka (juvenile Hilsa less than 23 cm in size) and restrictions on the catching of brood (mature and about to spawn) Hilsa during the breeding season were adopted in 2003–2004. The government mobilized its resources to build awareness, and introduced monitoring and enforcement involving the coast guards, navy, and fishery officers, including the seizure and destruction of monofilament nets. To compensate for the loss of earnings, the government started providing ‘affected’ fisher communities (187,000 households) with 30 kilograms of rice per household per month and providing training and cash to develop alternative income-generating activities (AIGAs) for fishermen and women.

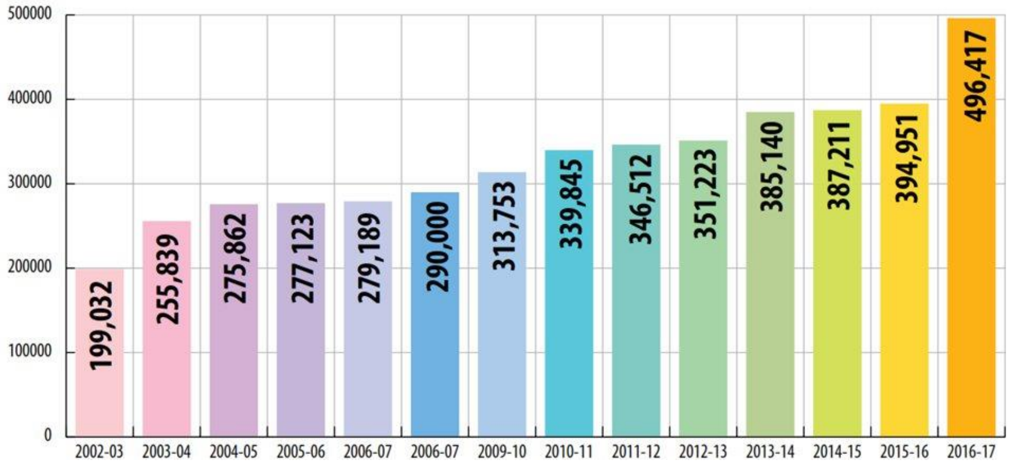

Figure 9-7. Hilsa fish production increased following adoption of incentives and mitigation measures (Source: DOF 2018).

Tengragiri Wildlife Sanctuary declared as a protected area – Wildlife Sanctuary (WLS) by the government in 2010 (Figure 9-8). The mangrove forest covers an area of 4,048.58 acres. The Tengragiri forest stretches from Taltali Upazila of Barguna District to the beach of Kuakata of Patuakhali District. Although it is officially named 'Tengragiri forest', locally it is known as 'Fatrarban'. The forest is located about 71 km southwest from the Kolapara Upazila at the extreme southern part of the country. The sanctuary supports several national and globally significant species including the endangered Fishing Cat (*Prionailurus viverrinus*).

Sonarchar Wildlife Sanctuary (SWLS) (Figure 9-8) – an off-shore island located within Patuakhali District was declared by the government as a protected area in 2012 covering an area of 2,026.48 acres. The sanctuary is covered with planted mangroves, extensive mudflats and submerged sand bars that expose during low tide and provides an excellent feeding and roosting habitat for migratory and resident waterbirds. The mangroves act as a nursery for a myriad of aquatic species especially invertebrates and fishes.

Figure 9-8. Location of Tengragiri WLS and Sonarchar WLS in the coastal areas of Barguna and Patuakhali Districts.

9.3 Meghna Deltaic Plain

Moving east from the Sundarban and adjoining areas is the Meghna Estuary. Meghna Estuary is the easternmost sector of the Ganges Delta. The Estuary conveys the joint discharge of the Ganges/Padma, Jamuna/Brahmaputra, and Meghna Rivers and hence is very dynamic. The estuary is formed inside Bangladesh by the joining of the Surma and Kushiyara rivers originating from the hilly regions of eastern India. Down to Chandpur, this area is hydrographically referred to as the Upper Meghna. After the Padma joins, it is referred to as the Lower Meghna which falls to the Bay of Bengal. Major tributaries in the Meghna river region included the Dhaleshwari River, Gumti River, and Feni River. The Meghna empties into the Bay of Bengal via four principal mouths, named Tetulia, Shahbazpur, Hatiya, and Bamni.

The government declared six Hilsa sanctuaries for its conservation (Figure 9-9). The sanctuaries are: a 100 km strip of the Meghna River—from Shatnol to Char Alexandar; a 90 km strip of the Shahbazpur Channel at the Meghna estuary in Bhola district; a 100 km strip of the Tentulia River in Bhola district; a 40 km strip in Andharmanik River in Patuakhali district; a 20 km strip at the lower Padma (Padma Confluence) in Shariatpur district; and an 82 km strip of the Meghna River (from Hizla to Mehendiganj) in Barisal district. Three of these sanctuaries are located in the coastal areas. Moreover, the government has banned all kinds of fishing for 65 (sixty-five) days from 20 May to 23 July in the coastal and marine areas for conservation of fishes as this period constitutes the breeding season for many fishes and other aquatic species (DOF Memo No. 33.00.0000.129.99.067.14(Part-2)-30 dated 04 February 2019). In addition, there exists a ban from October 9 to 30 imposed to ensure safe spawning of the hilsa fish during its peak breeding period and from March to May to assist and protect the migrating juvenile from the rivers to the sea.

The entire area is tidal-influenced round the year. Tides are semidiurnal with two high and two low cycles during a lunar day. Tidal behaviour varies along the coast in terms of magnitude but not of pattern. The tide ranges from 0.07 m during neap tide to 4.42 m during spring tide. The tidal range increases in the direction from South–West (around 4 m range at South Bhola) towards North–East (around 7 m range at Sandweep).

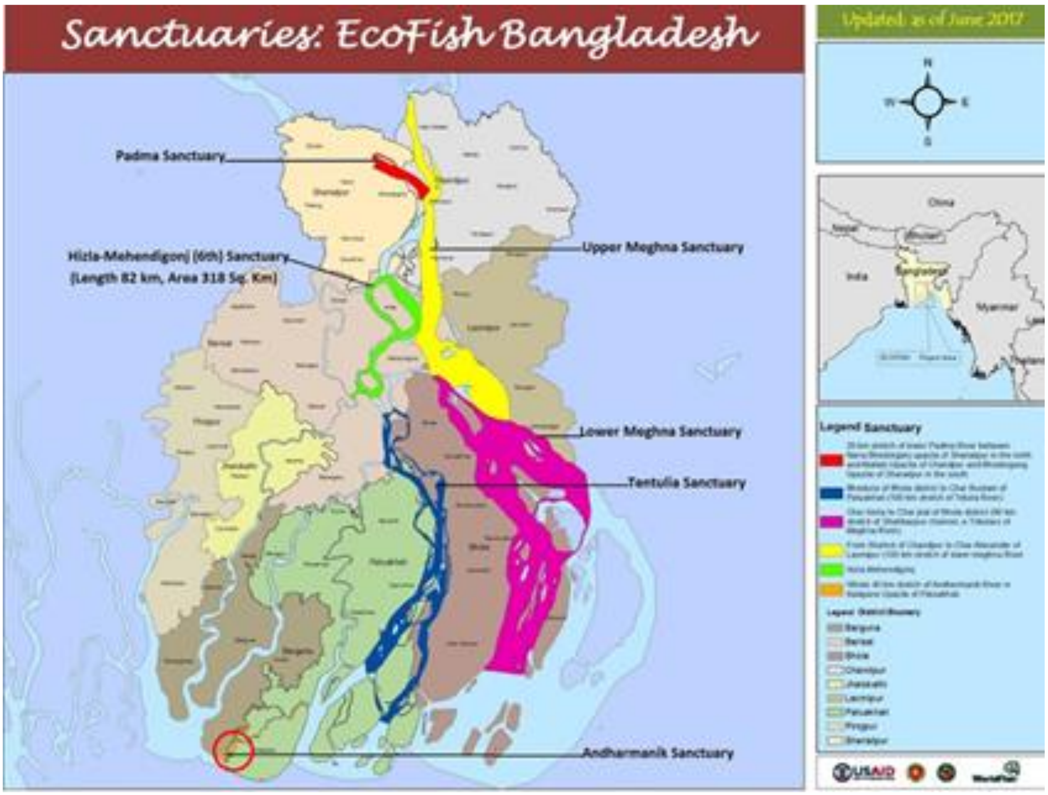

Figure 9-9. Hilsa fish sanctuaries shown in color codes.

There is a pronounced seasonal variation of wind, river discharge, and sediment supply from the river system. The highest discharges occur in August-September and the lowest in February (MES 2000). This freshwater runoff is a dominant feature that influences the dynamics of the coastal and marine environment. From January to June the balance is restored to create estuarine conditions. These seasonal variations like increased salinity, changed flow, sediment, flow distribution affect the occurrence, abundance and composition of aquatic and other water- and tide-dependent flora and faunal species. The tidal counter currents are biological hotspots within the river and estuarine areas. The attractive force of eddy currents traps primary nutrients and woody debris that retain nutrients and provides substrate and an array of cover and hydraulic gradients, which support fish and other invertebrate species.

Coastal waters (together with inland waters) are also covered by the Protection and Conservation of Fish Rules (1985). This regulation refers to methods of fishing, fish species that cannot be caught during a particular season, mesh size of fishing nets, prohibition of landing and carrying fish of a certain size.

Hossain *et al*. (2012) reported 53 fin fish species from the Meghna estuary. Among them are *E. tetradactylum, G. giuris, H. nehereus, L. subviridis, O. rybicundus, P. paradesius, Arius bilineatus, Osteogeneiosus sp., Setipinna taty, J. carutta, O. microlepis, A. caelatus A. thalassinus, B. mino* and *H. sona* each contributing more than 1% of the composition. Hossain et al. (2007) reported about 161 species collected by different types of net from Naaf river estuary located in the southeast bordering Myanmar, where Islam (1987) observed 97 species from the same area. Islam *et al*. (1992) reported about 185 species from the coastal waters of Bangladesh collected from the estuarine set bag net. Islam (2005), Ahammad (2004), Kamal (2000) and Nabi *et al*. (2011) identified 48, 76, 46 and 45 finfish species from Chittagong coast, Moheskhali Channel, Karnaphulli river estuary and Bakkhali estuary respectively. The fewer numbers of species recorded by Hossain *et al*. (2012) at the Meghna estuary may be due to long term changes in hydrological, meteorological parameters, fishing intensity, and disturbances to the ecosystem.

Downstream of the Meghna estuary is an assortment of countless islands, constantly disappearing and emerging, swallowing the homes of some and creating new niches for others. Some are permanent while some emerge with each low tide while others are washed away. These islands and associated mudflats are the prime staging areas for the migratory birds, particularly waders and other waterbirds during the winter. Bangladesh holds an important strategic location in the migratory flyway (Figure 9-10) where migratory birds from West Asian-East African Flyway, Central Asian Flyway, East Asian-Australasian Flyway regularly visit the coastal and inland river areas. Many of the migratory birds like Spoonbill Sandpiper, Nordmann's Greenshank, Asian Dowitcher, Great Knot are critically endangered. Some of the birds breed in the Siberian Tundra and winter along the coasts of Teknaf, Cox's Bazaar, Hatiya, Nijhumdweep, Sandweep Islands and Sundarban.

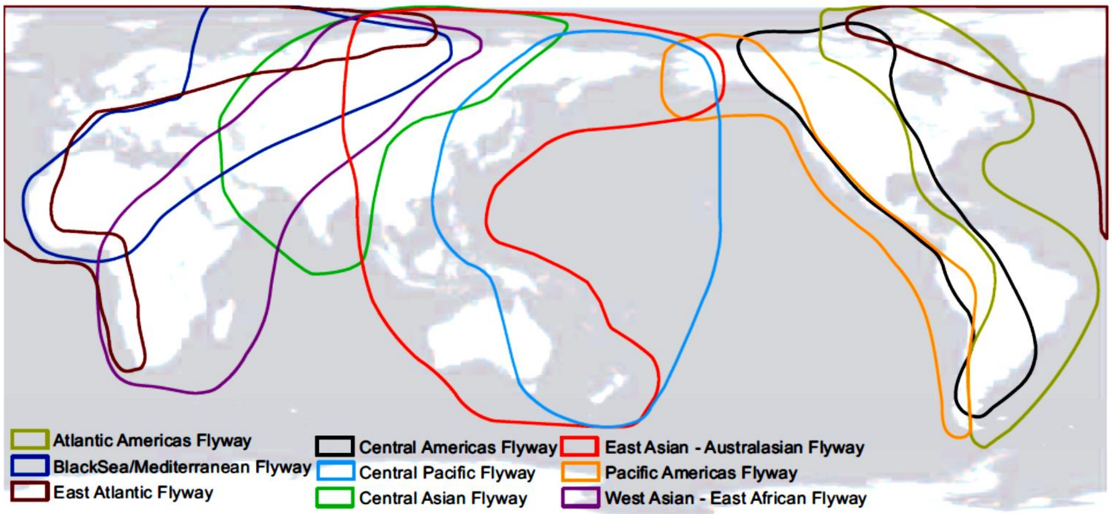

Figure 9-10. Schematic map of major flyways of waterbirds based primarily on migratory routes of shorebirds (Source: Internet).

The coastal mudflats are the hidden treasures of biological diversity. Every year more than one hundred thousand birds visit these mudflats to feed on the invisible life that flourishes on mud, silt and clay found in intertidal areas. These areas generally support a range of invertebrates, which are extremely productive biologically. These include benthic organisms, molluscs, crustaceans and marine worms. Mudflats provide an important nursery and feeding ground for many fish species. Shallow water zones along our south-central coast are critical habitats for Hilsa and Pangas. It's striking that the coastal mudflats still hold seven globally threatened and twelve other near-threatened resident and migratory birds. Irrawaddy Dolphins still come to the water surface to breathe and to offer a smile to the fishermen. Most of these areas are still wild and unchanged, such as Sonadia Island in Cox's Bazaar and the islands around Hatiya, Sandweep and Bhola. They are yet to be marred by development. However recent plans to embank Sonadia Island and construct coal-fired power plants and LNG terminals may deteriorate the natural landscape and obliterate ecological functions. The polders may protect the low-lying islands from tidal surges, human lives and property at the cost of upsetting many of the ecological functions and disturbing natural habitats.

Conservation in Bangladesh has mostly focused on the forests and their fascinating diversity, although how much we have managed to protect our forests is debatable. Attention to coastal or intertidal wetlands has been largely limited, or even totally omitted as areas of conservation interest by many of our decision-making bodies. Yet mudflats and tidal areas offer immense and irreplaceable value in biological diversity, number, uniqueness, beauty and their contributions to human livelihoods (Choudhury 2017).

The coastlines and estuarine coastal water-logged areas of Bay of Bengal harbor at least five species of sea grass; *Halodule univervis*, *Halophila decipiens*, *Halophila beccarii*, *Ruppia maritima*, *Halophila pinifolia*. Sea grass, *H. beccarii* occurs in the intertidal area and riverside co-existing with mangroves

(*Avicennia alba* and *A. marina*), salt marsh grass, and scattered sparsely in the estuarine habitat with macro-algae *Ulva intestinalis*. Seagrass *R. maritima* occurs in the aquaculture ponds and water-logged areas while *H. pinifolia* occurs patchily in the sandy areas of Saint Martin's Island (Hena *et al*. 2015).

9.4 Chittagong Coastal Plain

Further east-southeast is the more stable coastline from Chittagong to Teknaf embracing the Naaf River estuary (bordering Myanmar) and the Saint Martin's Island in the southeast about 12 km into the Bay of Bengal. The coastal area comprises one of the priced fishing zones – the South Patches and the South of South Patches (Figure 8-11).

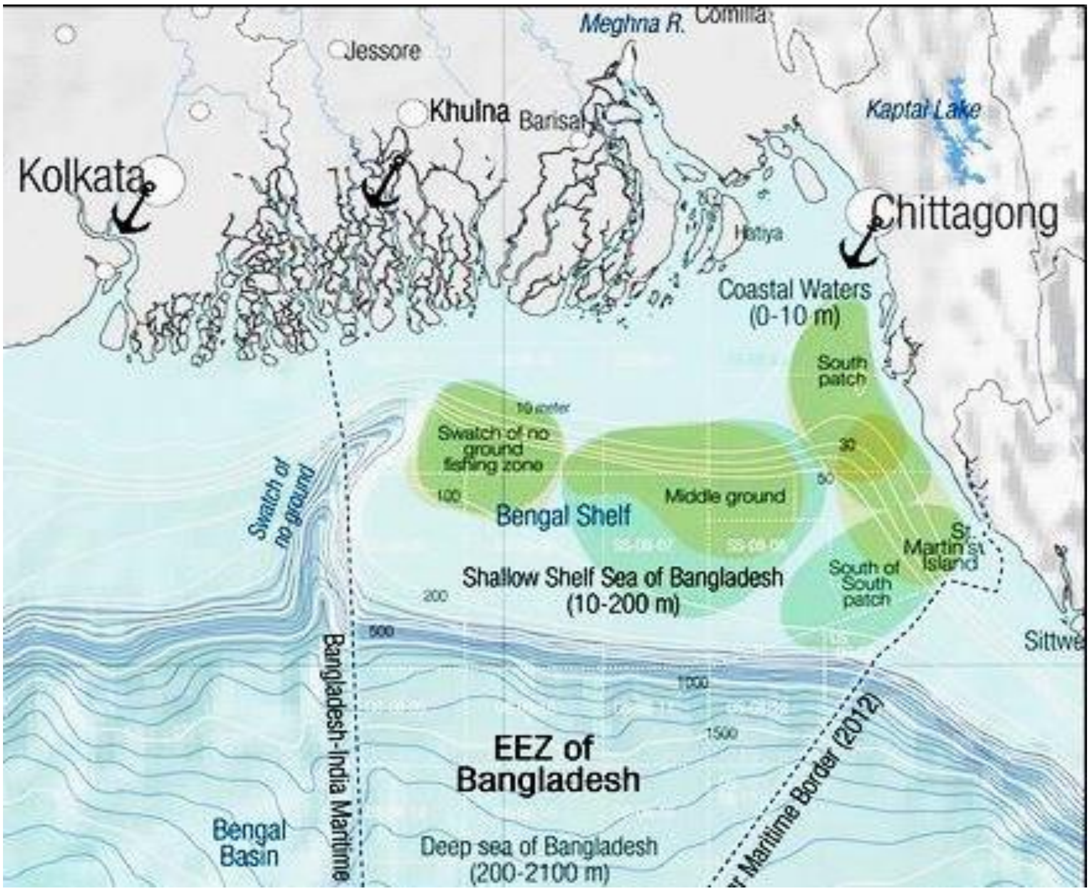

Figure 9-11. Fishing zones in the coastal and marine area of Bangladesh (Source: Chowdhury 2014).

The main block of natural mangrove forest in Cox's Bazaar coast, the hundred-year-old Chakoria Sundarban, occupied the low-lying saline swamp at the mouth of the Matamuhuri River delta (Figure 9-12). The swamp consisted of innumerable low-lying islands, which would mostly submerge at high tides. The water would remain brackish up to the inner boundaries even during the rainy season. Unlike the Sundarban mangrove forest along the southwestern coast of Bangladesh, the Chakoria Sundarban was protected from the open sea by Moheshkhali hills, an outlier of tertiary age. The presence of the forest along the coast is recognized to provide a buffer against storm and erosion damage as well as providing habitat for a variety of marine and terrestrial organisms (Hossain et al. 2001).

The vegetation before forest removal consisted of saltwater halophytes with abundance of Dalbergia spinosa and Aegialities rotundifolia. There were about 20 species of trees and none attained a height of more than 12 meters (Chowdhury 1969). Mangroves occurred in specific ecological zones on the islands, the coastal and riverine shorelines and in the upland locations. The area supported a very good habitat for different types of birds, mammals, reptiles, amphibians, and fish.

The mangroves have since disappeared totally and the factors responsible for the destruction of mangrove forest are removal of forest produces for fuel wood, high grazing pressures, fishing, human settlement, salt production, and shrimp farming. In addition to this, the fishermen build dams in the mouth of the creeks, thereby disrupting tidal inundation and causing water stagnation. For this change in hydrology, the seedlings in stagnant water failed to survive which seriously affected forest regeneration (Siddiqi *et al*. 1994). Such interference, coupled with the government policy of covering the reserve mangrove forest to shrimp farms and human settlement, has led to the drastic depletion of the mangrove. Similarly, the polders though provide refuge restricts and disrupts tidal inundation and exchange of nutrients that affect ecosystem and ecological services.

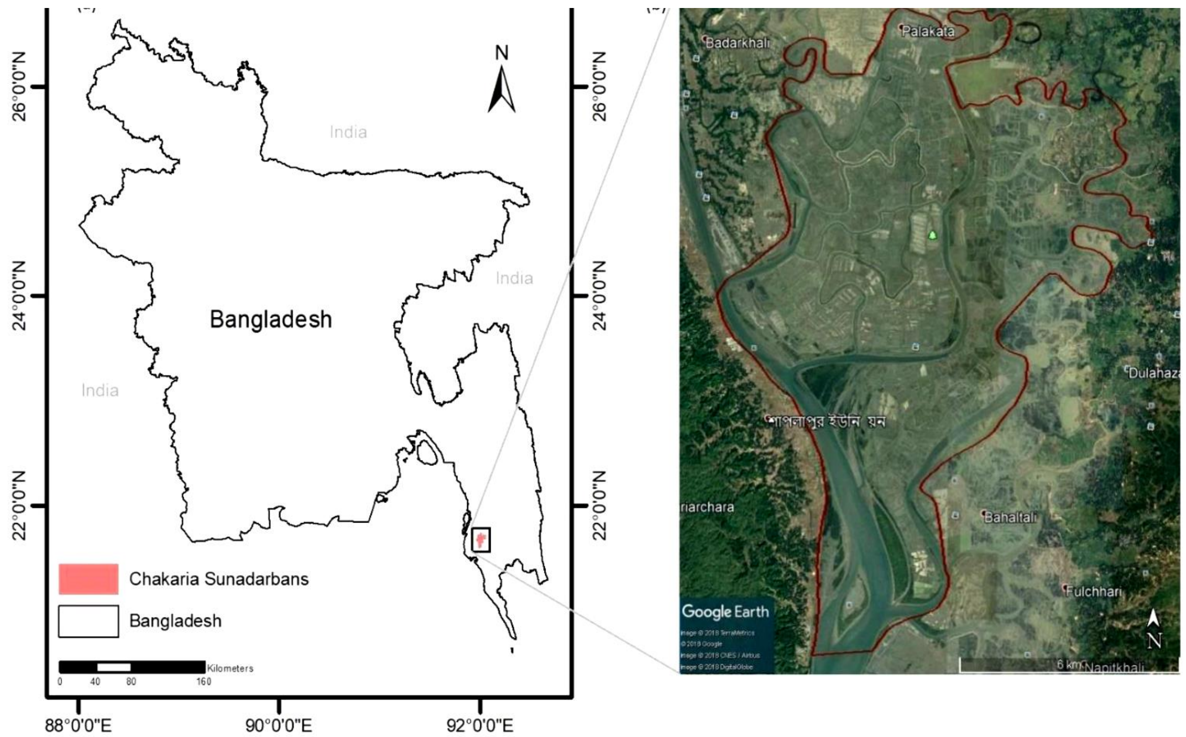

Figure 9-12. Location of the Chakoria Sundarban – (a) map of Bangladesh showing the location and (b) Chakaria Sundarban mangrove forest on Google Earth image

Down south along the coast the Cox's Bazaar-Teknaf coastal area comprises a mosaic of unique habitats and supports an assemblage of diverse ranges of flora and fauna. Many of the fauna and flora species are nationally and globally important and threatened, and therefore have got immense conservation significance. Rapid expansion of economic activities, including conversion of mangroves to shrimp farming and salt production, establishment of a large number of shrimp hatcheries, expansion of huge unplanned tourism, unsustainable harvesting of marine and estuarine resources, resulted in the rapid degradation of its habitat quality and consequent loss of biodiversity, rendering the site to a critical state. These activities have caused and have been causing disruption in ecological integrity and its functioning leading to ecological imbalance. Realizing the biodiversity degradation in the area and its consequences, the Government of Bangladesh declared, along with few others, Cox's Bazaar-Teknaf beach area and Sonadia Island as Ecologically Critical Areas (ECA) under the provision of Article I of the Bangladesh Environment Conservation Act, 1995 (Figure 9-13). The Department of Environment (DoE) is mandated for the management of the ECAs.

The Sonadia Island, located on the west of Cox's Bazaar and south-southwest of Moheshkhali Island and between the right bank of the Moheshkhali Channel Estuary and left bank of Kutubdia Channel Estuary. The island hosts remnants of the original mangrove forest crisscrossed by several tidal creeks and channels. It is one of the biodiversity hotspots and supports some internationally significant wildlife species, particularly some critically endangered migratory birds and marine turtles. The surrounding Bay of Bengal (BOB) waters support several species of endangered cetaceans. Recently a unique Porifera - Siliceous Sand-Sponge (*Tetilla dactyloidea*) has been reported for the first time in Bangladesh from the tidal creeks of Sonadia Island (Rashid & Khan, In Press. 2019). The island has been leased to Bangladesh Economic Zones Authority (BEZA) in 2017 by the Ministry of Land (MOL) vide Memo No. 31.00.0000.041.41.222.16.264 dated 26/04/2017 on the recommendation of the Deputy Commissioner, Cox's Bazaar (Memo No. 05.20.2200.128.32.225.2015.1351 dated 17/11/2016. BEZA has taken the initiative for feasibility study and Master Plan to set up Eco-tourism Park in Sonadia Island. BEZA has planned to use only 30% of the space so that there is no adverse impact on the environment. However, the Ministry of Water Resources (Planning Section-1) asked BWDB to construct embankment disregarding the status of Sonadia Island as an ECA, which prohibits any activity that may cause any physical change to the landscape (Memo No. MOWR/Planning Section-1/42.00.0000.039.14.026.17-16 dated: 21/01/2018).

Teknaf Peninsula is one of the longest sandy beach ecosystems (80 kilometres) in the world (Figure 9-13). It represents a transitional ground for the fauna of the Indo-Himalayan and Indo-Malayan ecological sub-regions. Important habitats at the site include mangrove, mudflats, beaches and sand dunes, canals and lagoons and marine habitat. The site provides breeding areas for two globally threatened species of marine turtles and, lying along international bird migration flyways, serves as a significant bird area. Its inshore waters also host globally threatened marine mammals. Other important species include several crustacean species, fishes and molluscs.

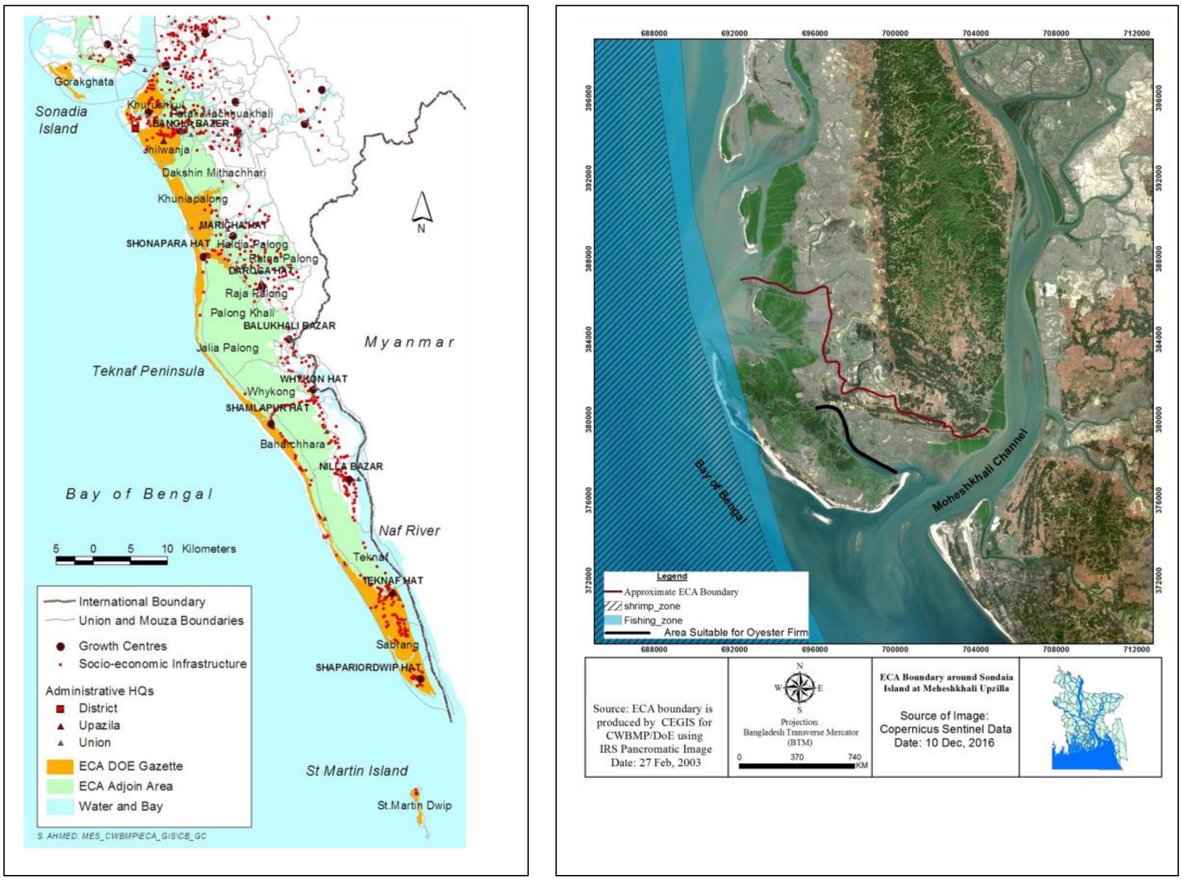

Figure 9-13. (Left) The Cox's Bazaar – Teknaf coastline and (Right) Sonadia Island Ecological Critical Areas (Source: CWBMP/UNDP/Department of Environment).

The Cox's Bazaar-Teknaf ECA's northern, western and southern boundaries are delineated by waterways – the northern boundary by the Moheshkhali Channel from the Bay of Bengal up the channel as far as Ghorokghata; the western boundary by the beach along the Bay of Bengal; and the southern boundary by the tip of the Peninsula bordered by both the Bay and the Naaf River Estuary. The site's eastern boundary follows mouza lines and incorporates the mouzas of Kurushkul and

Jhilonja (Cox's Bazaar Upazilla), Jungle Khuniapalong, Jungle Dohapalong, Pechar Dweep and Jungle Goaliapalong (Ramu Upazilla), Jaliapalong and Inani (Ukhia Upazilla) and Shilkhali, Baradail, Lengurbil, Teknaf, Sabrang and Shahparir Dweep (Teknaf Upazilla). The boundaries of the Shilkhali, Baradail, Lengurbil and Teknaf mouzas are shared with the adjacent Teknaf Reserve Forest or Teknaf Game Reserve. While most mouzas share boundaries with adjacent mouzas, the Sabrang and Shahparir Dweep mouzas share boundaries with the Naaf River estuary.

The area acts as a corridor between terrestrial and marine biodiversity, with the site's habitats including sand dunes and beaches, mudflats, mangrove and estuaries facing the Bay of Bengal (BOB).

Sand dunes and beaches: The sandy beach extends the length of the site from Moheshkhali Channel in the north to the tip of the Teknaf Peninsula in the south, a distance of some 75 km. Sand dunes occur along the beach, with dune vegetation distinguishable between several zones (Rahman et.al. 2001). Vegetation is relatively sparse with few plants in the open pioneer zone immediately preceding the drift line. The vegetation is denser in the herbaceous zone with some mat forming herbs, and a mixture of herbaceous plants and shrubs including climbing species occurs in the middle mixed or bushy zone. Tree species interspersed with patches of low marshy areas dominate the inner inland zone, which merges into the hinterland of mudflats, sandy beaches and cultivated fields.

Mudflats: The 100-150 ha of grassy mudflat at Badar Mokam (Shahparir Dweep) is important spoon-billed sandpiper (*Calidris pygmaea*) habitat. Intertidal mudflats along the Naaf River are suitable wader feeding ground. Large extent of mudflats at Subrang and Shahparir Dweep have been converted and used for salt production.

Mangrove: Sparse patches of naturally occurring mangrove occur along the estuarine muddy banks of khals running down the hills, adjacent to the sand dunes along the coast line. Mangrove occurs in larger areas along the Naaf River estuary in Teknaf, but does not exceed 10-20m in width at any one place and has been mostly planted by the Forest Department (Coastal). Small patches of natural mangrove thickets occur sporadically along the Naaf River riverbank and along the Reju Khal.

Estuaries: The major estuaries of the site include the Moheshkhali Channel and Bak-khali River in the north and the Naaf River in the south east, which provide significant habitat for flora and fauna including mudflats and mangrove. The Naaf River estuary is the most unique and highly productive ecosystem within the site. Several major canals occur along the length of the coastline, and are connected to the inland canals during high tide. The Reju khal is the main one, entering the BOB between the Ramu and Ukhia Upazillas; others include the Baharchara, Rajarchara, Inani, Monkhali, Katabunia and Shilkhali canals. Hundreds of other small canals also occur along the coast line, originating from hill streams and carrying freshwater runoff to the BOB. The smaller ones remain dry throughout the winter, only becoming active with the monsoonal runoff. There are more than two hundred culverts and bridges along the Marine Drive to facilitate drainage of the hill streams.

Two hundred and forty eight (248) species of plants were recorded from 65 spots along the roads and homesteads close to the coastal areas. Of those, 47 were timber species, 35 were fruit species, 34 were ornamental and 31 were medicinal plants. Among these five were rare including *Clinogyne dichotoma* (Patipata), *Gymnema acuminata, Mangifera sylvatica* (Jangliam, Uria), *Rauvolfia serpentina* (Sharpagandha) and *Terminalia chebula* (Haritaki). A total of 128 species of sand dune vegetation have been recorded from the coast. Of the dune grasses, creeping plants, herbs, shrubs and tree species recorded, the largest number of taxa belonged to the Poaceae (Gramineae) and Fabaceae (Leguminosae) families. Estuarine vegetation adjacent to sand dunes included mangrove patches dominated by *Acanthus ilicifolius* and *Phragmites karka* (CWBMP 2005).

Algal formations are found on the boulders at Inani and between Teknaf and Shilkhali. Invasive alien species known to occur within the site include *Mimosa pudica, Ipomea carnea, Lantana camara, Mikania cordata* and *Eichornia crassipes* (water hyacinth).

A total of 90 mammals were recorded from the Cox's Bazaar – Teknaf Peninsula, of which 22 were fairly common, 18 were few, 40 were occasional and 10 were extinct (NCSIP-1 1997). At present important terrestrial mammal species include Elephas maximus (Asiatic Elephant). Seven species are globally endangered as per the IUCN Red List, 2015 and a further 14 vulnerable. At the national level, 24 species are critically endangered, 23 endangered and 19 vulnerable. The near- and off-shore waters support at least five species of globally threatened coastal marine cetaceans.

The area is important for a wide variety of waterfowl and shorebirds with more than 200 species of common residents, and a variety of common and rare migratory birds that visit the site for resting, roosting, feeding and wintering and to use the site as a staging ground during migration.

The NCSIP-1 (MoEF, 2001b) recorded 389 species of birds from the Cox's Bazaar and Chittagong Forest Divisions, of which 279 are resident and 100 migratory. Of those species recorded 235 species were non-passerine and 154 were passerine, with the three largest families being passerine. Among the non-passerine species, waterfowl represented 109 species. Five species are locally extinct. Three species recorded along the coast are listed as globally threatened - *Calidris pygmeus* (Spoon-billed Sandpiper), *Limnodromus semipalmatus* (Asian Dowitcher) and *Tringa guttifer* (Nordmann's Greenshank). The spoon-billed sandpiper is one of the rarest migratory birds in the world, with a population of just 200-250 pairs in the wild (Bird *et al*. 2010, Zöckler et al. 2008).

The NCSIP-1 (MoEF, 2001b) recorded 78 species of reptiles, including 24 species of turtles and tortoises, 14 lizards and 40 snake species, of which 15 species were poisonous. Some of the common species include Olive Ridley turtle, forest Calotes, common gecko and two lizards, checkered keel back snake, red-necked keel back water snake, dog-faced water snake, banded krait and king cobra. The BOB waters surrounding the site support four species of marine turtles including Olive Ridley (*Lepidochelys olivacea*), Hawksbill (*Eretmochelys imbricata*), Loggerhead Turtle (*Caretta caretta*) and Green Turtle (*Chelonia mydas*), while the coastal beaches are important nesting sites for the Olive Ridley, Hawksbill and Green Turtles (Rashid and Islam, 2005).

Ten species of frogs and one species of toad were recorded at the site during the NSCIP-1 survey (MoEF, 2001b). The bull frog (*Hoplobatrachus tigerinus*), skipper frog (*Euphlyctis cyanophlyctis*) and climber frog (*Kaloula pulchra*) were all fairly common, while the others were few and occasional.

The critical biodiversity areas in Cox's Bazaar - Teknaf Wildlife Sanctuary, Himchhari National Park and Inani National Park – located along the coast face a grave risk of peril due to high level of human interventions due to the construction of the Marine Drive, tourist lodges/resorts and following the Rohingya influx. Already, more than 2,000 hectares of forest have been lost as a result of the expansion of campsites after the arrival of over 750,000 Rohingyas since August 2017. Before the latest influx, more than 300,000 Rohingyas were already living in the area. The financial cost of this destruction of forest in Ukhia and Teknaf upazilas stands at about Tk 1,865 crore, but the long-term consequences are more environmental than financial (Forest Department 2018). Clearing of forests and vegetation enhances soil erosion and promote landslide. It also amplified human-elephant conflict, with 13 human casualties so far in the area. The remaining elephant habitat is under severe pressure from uncontrolled firewood collection in the forest. It is affecting water resources, irrigation, and groundwater reserves including local biodiversity, marine resources, acoustic environment, and air quality.

A survey of the fisheries fauna of the Naaf River estuary from the mid-1980s to early 1990s recorded 67 species of fish (Islam, 1993b). The NSCIP-1 (MoEF, 2001b) recorded 123 fish species from the Cox's Bazaar - Chittagong study area by observing fish catches from local rivers and estuary. The dominant species were represented by a few groups of small-sized fishes. Of the 123 species, at least 23 can be regarded as locally threatened. Species diversity reflects the different fish habitats occurring at the site. Common estuary species include the Estuarine catfish (Mystus gulio), Engraulids (Coilia dussumieri, Thryssa hamiltoni), Tade mullet (Liza tade), Speigler's mullet (Valamugil speigleri), Flathead mullet (Mugil cephalus), Croakers (Sciaenidae), Giant sea-perch (Lates calcarifer), Silver grunt (Pomadasys argenteus), Yellowfin seabream (Acanthopagrus latus), Terapon perch (Terapon jarbua), Four-finger threadfin (Eleutheronema tetradactylum), Whiting (Sillago sihama), Silverbiddy (Gerres fillamentosus), Spotted butterfish (Scatophagus argus) and Eel catfish (Plotosus canius). Common coastal species include Clupeids and Engraulids including Bigeye shad (Ilisha filigera), Sardinella fimbriata and Tenualosa ilisha, Croakers (Scianidae), Ribbonfish (Lepturacanthus savala), False trevally (Lactarids), Ponyfish (Leiognathids), Halfbeaks (Hemiramphids), Indian Mackerel (Rastrelliger kanagurta), Four-fingered threadfin (Eleutheronema tetradactylum), Silver Pomfret

(Pampus argenteus), Flathead sillago (Sillaginopsis panijus), Bombay duck (Harpodon nehereus), and Terapon perch (Terapon jarbua). The endangered whale shark (Rhincondon typus) also occurs in the coastal areas.

A survey of the invertebrate fauna of the Naaf River estuary from the mid-1980s to early 1990s recorded, among others, 20 species of shrimp and prawns, three species of crab and two species of lobster. In total seven species of crab and two species of lobster are recorded in the coastal waters. Of particular importance is the Indian Horseshoe Crab or King Crab (*Carcinoscorpinus rotundicauda*), which is considered a living fossil and is listed in the IUCN 2015 Red List of Threatened Species. Five species of oyster from natural beds in Cox's Bazaar and Teknaf were also recorded. Molluscan species belonging to 27 genera of bivalves, clams, mussels and oysters are known to occur along the coast (Anon., 1990). Surveys carried out under the CWBMP 2006, 66 species of mollusks were recorded. Some important bivalves are abundant, e.g. *Anadhara rhombia* and *Anadhara granusa*. Two economically important gastropods that are heavily depleted worldwide – *Trochus radiatus* and *Turbo* sp. are also present. A total of 51 species of butterflies were recorded in the Cox's Bazaar and Chittagong Forest Divisions under the NSCIP-1 survey including the coastal areas (MoEF, 2001b).

Shrimp hatcheries are also established at the site – Cox's Bazaar coast is one of three government shrimp centres and a shrimp hatchery zone has been established in Kalotali. Other hatchery zones exist just north of Inani and adjacent to the Teknaf Beach. All the hatcheries have been established either in, or directly adjacent to, sand dunes, adversely affecting nesting turtle habitat. Almost all have direct outlets to the sea to dispose of untreated hatchery water, which is polluted with chemicals and fertilisers.

The Teknaf Peninsula consists of a variety of fish habitats and therefore is subject to a range of fishing practices. The in-shore areas of the Bak-khali River estuary up to Choufaldondi canal are fished using beach seine, stake nets, push nets, cast nets, seasonal brush parks and monofilament gill nets. The Reju Canal estuary is fished using beach seine, cast nets, seasonal brush parks and hand lines. The mangrove-fringed lower Naaf River estuary from Shahparir Dweep to Nyttong Para is fished using the estuarine set bag net (ESBN), stake nets, cast nets, trammel nets and drifting gill net. The fine-mesh seine nets and stake nets used in the estuarine areas are the largest contributors to the destruction of juvenile fishes and other aquatic organisms, especially during the breeding season.

The sandy bottom coast between Cox's Bazaar and Inani is fished using the monofilament and bottom-set gill nets, cast nets and beach seine. The Inani-Baradail sandy/rocky bottom intertidal/coastal area is fished using the bottom-set and monofilament gill-nets, hook and line and wild plant extracts (poison). The Baradail-Shahparir Dweep sandy bottom coast is fished using the beach seine (mostly in winter – November to February), monofilament gill net and cast net. The collection of tiger shrimp fry with bag net and push net using very fine meshed mosquito netting causes massive destruction of fish and shrimp fry species and other aquatic species, especially during summer and the monsoon. Pelagic crabs (including gravid females), juvenile sharks, rays and other invertebrates are particularly at risk. An area of approximately 413 ha in Najiratek, Cox's Bazaar and Badar Mokam, Teknaf along the coast is used for processing dry fish.

Himchari National Park located south of Cox's Bazaar, comprises 1,729.00 acres of evergreen/deciduous forest was declared in 1980 as a protected area for conservation, research, education and recreation. The habitat comprises lush tropical rain forest, grasslands and features a number of waterfalls, the biggest of which cascades down toward the sandy, sun-drenched beach and into the BOB. Himchari is home to a limited number of these majestic animals like the Asian Elephant (*Elephas maximus*), Barking Deer (*Muntiacus muntjak*). Other mammals include Rhesus Macaque, Leopard Cat, Fishing Cat, and Wild Boar. Additionally the Himchari National Park is home to more than 150 bird species, 56 species of reptiles and 13 amphibian species.

Inani National Park, located south of Cox's Bazaar, halfway between Cox's Bazaar and Teknaf along the coast. Comprises diverse habitat of low hillocks, wide beach interspersed inter-tidal areas with rocks and boulders making it an unique habitat providing substratum for algae, mollusks, echinoderms, and fishes.

Teknaf Wildlife Sanctuary is a protected area in the Cox's Bazaar District comprising a hill forest area of 11,615 ha (44.85 sq. mi.). In the east it is bordered by the Naaf River and in the west by the Bay of Bengal. It was established in 1983 as Teknaf Game Reserve under the Bangladesh Wildlife (Preservation) (Amendment) Act, 1974, later declared as Teknaf Wildlife Sanctuary in 2009. This is one of the few places in Bangladesh where Asian elephants can be seen in the wild. This vast sub-tropical forest has several other attractions like Nitong Hill, Kudum Cave, Kuthi Hill, etc. The popular Toinga Peak has an elevation of about 1000 feet. This sanctuary is rich in biodiversity. The coastal area comprises several habitat types - wide sandy beach, rocky inter-tidal zone, and mudflats which are important for the migratory and resident waterfowl, nesting site for the endangered marine turtles, host to several species of crabs, rocky shores act as vanguard against erosion of the coastline, etc. The coastal area is heavily exploited by the shrimp nurseries and fishermen. Recent Rohingya influx has virtually inflicted devastating impact on the forest biodiversity and coastal resources.

St. Martin’s Island located in the Bay of Bengal (BOB), at an aerial distance of 25 km from Teknaf Township and 12 km from southernmost mainland named Gola (Figure 9-14). It is surrounded by boulders and corals. It is unique to harbour coral-associated ecosystem with more than a hundred coral species, several hundred coral fishes, mollusks, crabs and other coral-associated invertebrates.

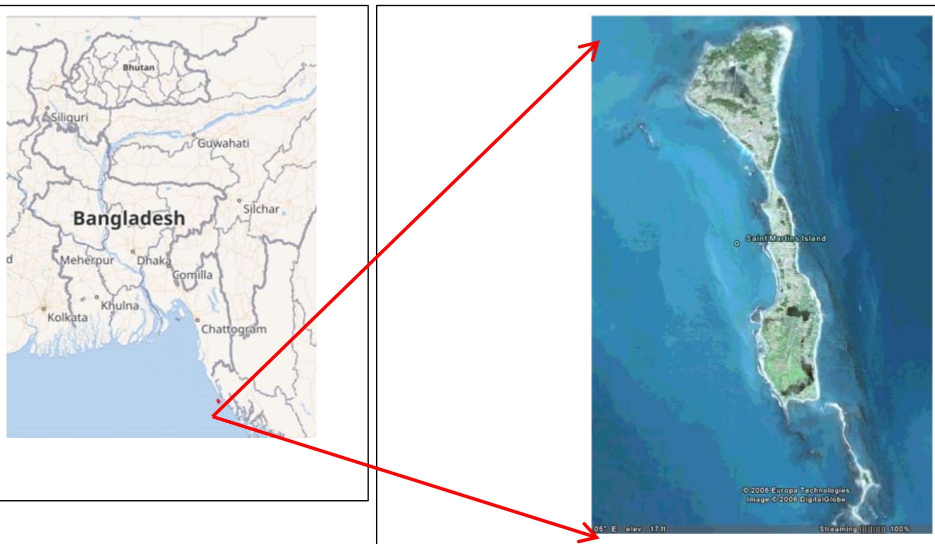

Figure 9-14. Saint Martin’s Island (Narikel-Jinjira) Ecological Critical Area – known for its coral assemblages and marine biodiversity.

The Island, which is 590 ha in area, has been declared an ECA in its entirety. It falls under the jurisdiction of St Martin’s Island Union, Teknaf Upazilla. The site’s northern section is known as Uttar Para, which is connected to the southern part of the Island by a narrow neck of land called Golachipa. The area directly south of Golachipa is termed Madhya Para, followed by Dakhin Para. The southernmost tip of the Island, Cheradia, is separated from Dakhin Para during high tide. The Island is accessible only by boat, from the town of Teknaf.

Lying in a north-south direction, the Island has a wider northern section and a narrower elongated southern section with a constriction between where the sand dunes of the western and eastern shores have almost joined. This narrow neck is gradually being eroded from both sides. Erosion from tides is also evident on the northern coast of Uttar Para where erosion of dunes up to 2 metres was reported in the late 1990s. The average altitude is 2.5 metres with a high point of six metres in Dakhin Para.

The site is particularly susceptible to cyclones. Cyclonic storms develop in the Bay, generally in April-May and October-November, occasionally coming to shore and causing severe damage to human settlements and vegetation. As a result of climate change, sea level rises of up to 43 cm are expected by 2050 and more frequent and extensive cyclones and tidal effects are expected (Alam, 2003). Historical tidal data for the 22 years to 2005 at the Cox’s Bazaar coastal station has shown a sea level rise of 7.8 mm/annum, which is many times more than the mean rate of global sea level rises over the past 100 years (MoEF, 2005a). The effect of sea level rises may be reversed somewhat by uplifting; calculations from the presence of dead coral and microatolls in the intertidal zone suggest that the Island has uplifted 15 cm in the last 150 years and apparently continues to do so (Tomascik, 1997).

From Dakhin Para, an intertidal rocky reef extends about 1.8 km south, supporting three vegetated sand islands known locally as Cheradia. Cheradia is connected to the southern part of the Island during low tide by a narrow sand belt consisting of alluvial sands and littoral carbonates that has accumulated on top of the rocky intertidal reef. Almost the entire coastline of the Island is fringed by a rocky intertidal habitat consisting of small and large boulders, and varying between 100-500 m wide. Coral boulders are also present but are relatively rare. The presence of relatively well preserved dead coral colonies in the upper and middle intertidal zones suggests that the Island has been uplifted in relatively recent times. A coastal embankment has been constructed by piling loose boulders along a considerable length of the east and west coast.

The site’s habitats/communities include sand dunes and beaches, a small mangrove patch, marine habitat including, among others, coral communities and a rocky intertidal zone, and lagoons/wetlands, rocky land and a small mudflat area.

Sand dunes and beaches: The main shoreline habitats are sandy beaches and dunes, with the main sediments being alluvial sands. Beaches and dunes on the southern part of the island have a higher carbonate content compared to the northern Uttar Para beaches. Most carbonates are molluscan shell fragments. The sandy beach in the north and north east stretches over 300-400 m into the sea. The western beach is sandy but the sub-tidal area consists of a bed of boulders. The island’s sandy beaches are reputedly the best nesting sites in Bangladesh for globally threatened marine turtles (Rashid & Islam 1999).

Mangrove: The original mangrove formation at the site was considered quite different from any other mangrove in the country in that it was a pure *Lumnitzera racemosa* formation (GoB/GEF/UNDP, 1999). There is a very small remaining mangrove patch at the site nowadays consisting of *Sonneratia apetala, Acanthus ilicifolius, Avicennia marina* and *Hibiscus tiliceous*, among others.

Marine habitats: The shallow water marine habitats include rocky and sandy intertidal habitats, offshore lagoons, rocky sub-tidal habitats, coral aggregations, seagrass beds, soft coral habitats and offshore soft-bottom habitats. Due to the differences in exposure, benthic communities along the east and west coasts of the island support different benthic communities. However the upper and middle intertidal habitats along both coasts generally support similar communities. A generalised zonation of east coast benthic communities along an inshore-to-offshore gradient starting from the lower intertidal is as follows: intertidal gastropod-algal community, coral-algal community, mixed seagrass-algal community, soft-coral community and soft-bottom (mud) community. The zonation on the west coast is as follows: gastropod-algal community, coral-algal community, algal community and soft-bottom community.

With the exception of the north eastern corner, the Island’s entire intertidal zone is fringed with numerous boulders that extend from a few metres to a few hundred metres to the sub-tidal zone. These boulders of all shapes and sizes originate from the bedrock and provide a diverse microhabitat for numerous marine species sheltering from tidal influences. The upper portion of the rocky habitat is mostly dry during low tide and contains dead coral colonies. The lower intertidal area consists of diversified marine life, including coral, molluscs, echinoderms, reef fishes, barnacles, crabs, algae, etc. It also provides a huge number of rock pools of various sizes where small reef fish forage for the duration of the ebb tide. Depending on the tide, the intertidal zone rocky habitat covers 150-250 ha.

The rocky subtidal habitat from the seaward margin to about 1,000m offshore support a diverse coral community which can be classified as a veneering coral community. Of the 15 reef-building scleractinian coral families, 10 are present on the Island, represented by approximately 22 genera and 66 species. Of these, 39 have been identified as living corals and 14 as soft coral, growing up to a depth of 7 metres. Corals are found around most of the Island, but their abundance and cover is generally low. Small coral aggregations are also found in a number of small intertidal pools of the lower rocky intertidal zone. The coral community also supports associated fish and invertebrate fauna.

Sea grass meadows and algal flora associated with extensive coral reefs were discovered in 1997 by Tomascik and Paiker (MoEF, 2001a). The extensive algal and seagrass beds in the Island's coastal waters are highly productive and diverse and may be important spawning and/or nursery grounds for a number of economically important fish and shell fish species.

There are only a few examples worldwide where coral communities dominate rock reefs; St Martin's Island provides a unique set of environmental conditions (biotic and abiotic) not found elsewhere in Bangladesh and perhaps not in the world (Tomascik, 1997, in GoB/GEF/UNDP, 1999). The co-occurrence of corals, seagrasses and mangroves in the Island represents little known succession of corals in the tropical areas (Welch, 1962, and McCoy & Heck, 1976, in GoB/GEF/UNDP, 1999).

Lagoons/wetlands: Several lagoons/wetlands associated with mangrove and floodplain areas occur at the site, providing habitat for birds. There is a lagoon at Uttar Para, a freshwater wetland at Dakhin Para and sizeable floodplain areas scattered throughout the Island. A 40 ha internal lagoon lies at the south of the main island and within the three small islands comprising Cheradia.

Rocky land habitat: A small area of rocky land exists at Shil Buniya, south of Dakhin Para Morong (lake), and west of the Coast Guard base. The majority of the area is covered with giant boulders similar to that of the intertidal zone, with some lowland pools. The rocky land area covers about 100 ha and is the last remaining habitat for rare species such as the water monitor (*Varanus salvator*), Bengal cobra (*Naja kaouthia*), bush birds, water birds and garden lizards, and native herbs, shrubs and climbers. The rocky ground and shallow water pools provide an excellent terrestrial microhabitat, especially during winter.

Mudflat: There is a small mudflat area (Gaitta Buniya) located at the southern end of the western beach. It provides numerous food sources for shorebirds and a habitat for amphibious sea snakes and crabs.

One hundred and fifty one species of marine algae were identified from specimens collected under the NSCIP-1 in 1996, mainly from the Island's intertidal/littoral zone but some from the sublittoral zone and some as drifted forms.

The mangrove includes the following associated mangrove species: Acanthus ilicifolius, Hibiscus tiliceous, Excoecaria agallocha, Avicennia marina and Clerodendrum inerme. Salt-secreting mangrove, Aegialitis rotundifolia, an early coloniser, has disappeared from the Island. Pandanus odoratissimus and Ipomea pescaprae, in association with grasses Panicum repens, Passpalum vaginatum and sedges Cyperus spp. and Fimbristylis spp., constitute the vegetation of the sand dunes. Streblus asper and Vitex trifoliata are also found among the crevices formed by rocks, adjacent to a swamp supporting the young mangrove formation. A number of liverworts and mosses and one fern species (Adiantum philippense) have also been recorded at the Island.

Marine plant diversity is yet to be exhaustively explored in Bangladesh. Limited explorations have been done by far on the open sea waters. According to Volumes 3 and 4 of Encyclopedia of Flora and Fauna of Bangladesh (Ahmed 2008, 2009) there are 50 species of brown algae (Order: Laminariales, also known as kelp), 82 species of red algae (Class: Rhodophyceae), and 26 species of green algae (Class: Cholorophyceae). Almost all seaweed species are found on St. Martin's Island. In Bangladesh, five species have so far been reported from Bangladesh coast, namely Halodule uninervis, Halophila beccarii, Halophila decipiens, Halophila pinifolia and Ruppia maritima (Kamal and Short, 2009).

A total of 19 species of mammals were recorded from the Island during the NCSIP-1 survey, of which none of the land-based mammals are carnivorous. Among the cetaceans Finless Porpoise (Neophocaena phocaenoides), Common Dolphin (Delphinus delphis), Irrawaddy Dolphin (Orcaella brevirostris), spinner dolphins (Stenella longirostris), (Stenella attenuta) can be seen in the surrounding waters. Pest species include dogs, domestic cats and field rats (Bandicota bengalensis, Mus musculus, Rattus norvegicus, Rattus rattus).

The site lies on the East Australasian Flyway and Central Asian Flyway and provides a stepping stone for several globally threatened migratory waders. A total of 120 species of birds have been recorded from the Island (77 resident species and 43 migratory species) of which 18 species may be classified as locally threatened. Two species, the grey-headed lapwing (Vanellus cinereus) and Black-bellied Tern (Sterna acuticauda), are listed in the 2015 IUCN Red List of Threatened Species.

The Island supported a total of 27 reptile species, of which 11 are locally threatened. All five species of marine turtle known to occur in Bangladesh have been reported in the area including Lepidochelys olivacea (Olive Ridley Turtle), Eretmochelys imbricata (Hawksbill Turtle), Chelonia mydas (Green Turtle), Dermochelys coriacea, Caretta caretta (Loggerhead Turtle) and Dermochelys coriacea (Leatherback Turtle). Three species – the Olive Ridley, Hawksbill and Green turtles – are known to nest at the site (Rashid, 1986). Of these, the Olive Ridley and Green turtles are listed Endangered, and the Hawksbill as Critically Endangered. Other reptiles include, among others, monitors, five species of terrestrial snakes and six species of sea snakes, lizards and four species of freshwater turtle.

The Island supports four amphibian species, including a toad (Duttaphrynus melanostictus) and three frog species – Skipper Frog (Euphlyctis cyanophylctis), the Bull Frog (Hoplobatrachus tigerinus) and Tree Frog (Polypedates maculatus).

A total of 234 species of fish have been identified from the site, 89 of which are coral-associated fish species and only 16 of which are freshwater fish. Though coral reefs have not developed, the coral community supports fish fauna characteristic of coral reef environments. The most abundant coral or reef-associated herbivores are the Pomacwentridae (damsel fish), Scaridae (parrot fish) and Acanthuridae (surgeon fish). Important coral or reef-associated predators are Serranidae (groupers), Lutjanidae (snappers) and Lethrinidae (emporers). Five species of the common butterfly fish (Chaetodontidae) were recorded on the Island, as was one species of angel fish (Pomocanthidae). Croakers (Sciaenidae) are also present.

Of the 68 species of living corals identified from the Island, the Porites, Favites, Goniopora, Cyphastrea and Goniastrea genera are the most abundant. The soft corals include Sinularia sp., Lobophyton sp., Anthelia Dendronephthya, Palythoa, Nemanthus, Telemectius and Discsorna sp. The taxonomy of a good portion of corals occurring around the island remains unknown. A total of 187 species of molluscs have been recorded at the Island. Of these, 44 species are gastropods and the rest are bivalves. Some important gastropods are abundant, e.g. Conus striatus, Conus textile and Conus geogrphes, and two economically important gastropods that are heavily depleted worldwide - Trochus niloticus and Turbo marmoratus - are also present at the Island. Four species of sea urchin, one species of sea star, a number of brittle stars and one species of sea cucumber have been recorded. A number of colourful nudibranchs have been recorded in the shallow subtidal rocky reefs. Seven species of crabs and six species of butterflies have been recorded from the Island.

9.5 Climate Change Impact on Coastal Biodiversity

Impacts on coastal systems are among the most costly and most certain consequences of climate change (Figure 9-15). As temperature increases and rainfall patterns change, soil moisture and runoff to the coast are likely to be altered. As sea level rises, coastal shorelines will retreat, enhance erosion and land loss, and low-lying areas will be inundated more frequently, if not permanently, by the advancing sea. The salinity of estuaries, coastal wetlands, and tidal rivers will increase, thereby restructuring coastal ecosystems and displacing them further inland. Tropical cyclones will increase in intensity and frequency, as projected by many studies, shoreline retreat and wetland loss along the low-lying coastal margins will accelerate further (Burkett et al. 2008).

Climate change increases challenges by the abundance, distribution, recruitment, and migration of various aquatic species including invertebrates, fish, sea turtles, and cetacean species. Currently, attention to environmental sustainability and climate change impacts in the biodiversity sector is limited and has not been translated into practical adaptation and livelihood transformation solutions. Yet, climate change can adversely impact the productivity of marine and coastal biodiversity including fisheries, affecting future catch levels and rates of recovery for fisheries, due to shifts in the availability of food, habitat, and appropriate ocean conditions for fish stocks.

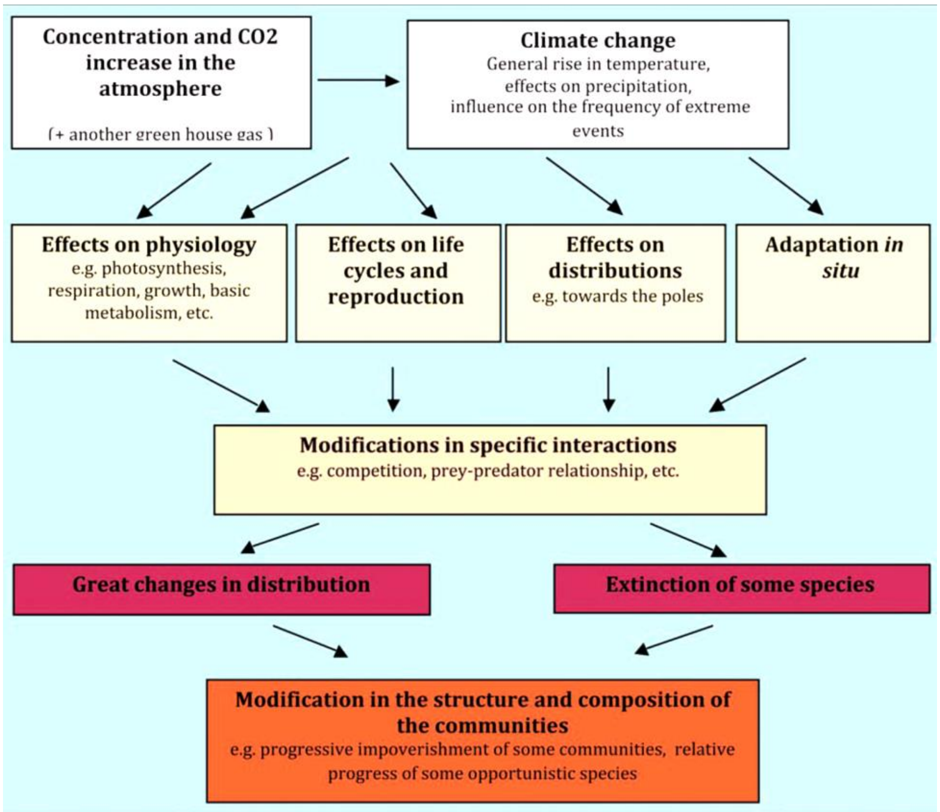

Figure 9-15. Impact of climate change on biodiversity (according to Hughes (2000), TREE). Source: UNEP-MAP-RAC/SPA, 2010.

The broad categories of climate change impacts which will affect the coastal areas of Bangladesh are changes in temperature and rainfall patterns, sea-level rise, change in frequency and intensity of cyclones, storm surge, changes in river and soil salinity.

Moreover, salinity affects land and water in the coastal areas. With the consequence of climate change, it gradually extends towards inland water and soil. This scenario of gradual salinity intrusion into the coastal areas of Bangladesh is very threatening to the primary production system, coastal biodiversity and human health. The total amount of salinity affected land in Bangladesh was 83.3 million hectares in 1973, which increased up to 102 million hectares in 2000 and the amount has risen to 105.6 million hectares in 2009 and continues to increase (Soil Resources Development Institute, SRDI). In the last 35 years, salinity increased around 26 percent in the country, spreading into non-coastal areas as well.

Changes in river salinity and the availability of freshwater will affect the productivity of fisheries. It will adversely affect the wild habitats of freshwater fish and giant prawn. In addition, the salinity increase may induce a shift in the Sundarbans mangrove forest from Sundari (the single most dominant and important species, with the highest market value) to Gewa and Goran.

Due to the rise in soil salinity, Chittagong and Khulna districts are likely to witness the highest within-district additional migration, estimated between 15,000 and 30,000 migrants per year ("Coastal Climate Change, Soil Salinity, and Human Migration in Bangladesh", International Food Policy Research Institute (IFPRI) and the Ohio State University. 2018).

Societies throughout the whole world have always tried to adapt and to reduce their vulnerability to the consequences of weather and climate phenomena such as flooding, droughts or storms. Additional adaptation measures will however be necessary on a regional and local scale to reduce the nefarious effects of the anticipated evolution and variability of the climate in addition to the ample mitigation measures which will be set up in the next twenty or thirty years (IPCC report, 2007). Adaptation on its own will surely not be enough to offset all the anticipated effects of climate change, especially in the long term as there is a clear trend that most of the repercussions are being amplified. There are numerous adaptation possibilities, but it is vital for the action already engaged in to be intensified if vulnerability is to be attenuated in view of the climate change taking place. There are obstacles, limits and costs involved which are not always truly grasped.

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H.36 WCS. 2015. Proposal to establish a marine protected area in the Swatch-of-No-Ground submarine canyon and surrounding coastal waters in the Bay of Bengal. Wildlife Conservation Society. Bangladesh Cetacean Diversity Project. https://www.cbd.int/doc/meetings/mar/ebsaws-2015-01/other/ebsaws-2015-01-gobi-submission6-en.pdf.

H.37 Zöckler, C., Syroechkovski, E. E. and Bunting, G. 2008. International Single Species Action Plan for the conservation of the Spoon-billed Sandpiper Calidris pygmeus on behalf of BirdLife International for the CMS. Bonn: Convention on Migratory Species.

9.7 Summary of Selected Papers

Project Document, Coastal and Wetland Biodiversity Management at Cox's Bazaar and Hakaluki Haor Project (BGD/99/G31).

GoB/GEF/UNDP. 1999. Dhaka, Bangladesh.
(Ref: H.12)

Summary

In recent years, Bangladesh has demonstrated increased determination and commitment to address the challenges of ensuring sustainable use and conservation of its natural resources, including its biodiversity. A number of specific policies, laws, action plans and strategies have been developed in this regard. A major current challenge is to ensure the effective implementation of the 1995 Environmental Conservation Act, which includes a key provision providing the Department of Environment (DoE) with broad powers for conservation of sites that it determines to be Ecologically Critical Areas (ECAs). In the context, Department of Environment has taken the crucial step of nominating the first six ECAs, all within the country's highly significant coastal, marine and freshwater wetland ecosystems. The overall objective of the project was to establish and demonstrate an innovative system for management of ECAs in Bangladesh that will have a significant and positive impact on the long-term viability of the country's important biodiversity resources. The project supported DoE efforts to operationalize the ECA concept at two main sites: one site (which included three ECAs - Sonadia Island and Cox's Bazaar-Teknaf sea beach) within the country's long and biodiversity-rich coastal zone and the second at one of the largest and most important of the country's many inland freshwater wetlands (Hakaluki Haor). Through a combination of Global Environment Facility (GEF) incremental cost financing and co-financing, conservation and sustainable use of these sites was demonstrated. This demonstration created important opportunities for replication in coastal, freshwater wetland and other ecosystems throughout the country, including sites recently nominated as ECAs.

Methodology

Detailed baseline studies on the biodiversity covering fisheries, aquatic and terrestrial wildlife plants were conducted between 2005 and 2007 which still serve as a reference for all studies and projects in the said areas. Species of national and global significance were identified, their habitats and extent of occurrence determined for their protection and future conservation initiatives. The DOE appointed ECA Management Officers (ECAMO) to oversee and coordinate the project activities. Seventy two (72) Village Conservation Groups (VCGs) through gazette notification were formed in the three ECAs, comprising of different-profession members from the ECA localities for guarding and monitoring the biodiversity within each of the ECAs. ECA Cell was formed within the DOE to enhance the capacity of the DOE staffs to manage ECAs, monitor the activities and to exchange knowledge gathered from the ECAs.

Findings and Gaps

The important achievement of the project was the development of Conservation Management Plans (CMP) for the three ECAs based on which the GOB undertook some future initiatives and projects. The formation of National, District, Upazilla and Union-level ECA Committees was notified through gazette notification which was a step in the right direction for the conservation and management of the natural resources within the ECAs. Unfortunately the ECA Cell within the DOE and the ECA Committees formed at the national and local government levels have remained inactive since the project ended. Similarly the VCGs have either been abolished or are inactive. Lack of sustainability of such initiatives combined with the non-implementation of the recommendations is the major gap in natural resources conservation and management.

Review: Conservation and research on marine turtles in Bangladesh.

Rashid, S. M. A. and Islam, M. Z.
In: Shanker, K. and Chowdhury, B.C. (eds) Marine Turtles of the Indian Subcontinent, GOI/Wildlife Institute of India, UNDP. Universities Press, India. 2006. pp 200-216.
(Ref: H.28)

Summary

Sea turtles belong to the most ancient line of living reptiles. However, there is a lack of up-to-date information on the regional status and conservation efforts of sea turtles on the subcontinent. Addressing this gap, Marine Turtles of the Indian Subcontinent documents the results of surveys carried out under the Sea Turtle project sponsored by the Indian government and the United Nations. With contributions from leading experts from a variety of disciplines, the book provides up-to-date information on the regional status and conservation efforts of sea turtles on the subcontinent. The book records the status of sea turtles along the east and west coasts of the Indian mainland, the Lakshadweep archipelago, and the Andaman and Nicobar Islands and surveys their status in Sri Lanka, Pakistan, and Bangladesh.

A pioneering and comprehensive study was conducted by the Centre for Advanced Research in Natural Resources & Management (CARINAM) in Bangladesh during 1996 to 1998 at the Saint Martin's Island and later along the total coastline to assess the nesting habitat of the marine turtles, identify species utilizing the beaches for nesting, nesting frequency and address threats to the species like stealing and selling of turtle eggs, and conservation awareness initiatives.

Methodology

Local people, involved in turtle eggs stealing, were hired as a measure to provide them with a source of livelihood. They were directed to monitor the beaches and look for any nesting turtles on a daily basis, particularly at night during high tide as nesting was influenced by high tide, full moon and windy conditions. Once any nesting turtle was found, it was allowed to lay the eggs and later the eggs were marked, measured and removed following some protocols to the beach hatchery, established for this purpose for ex-situ hatching. The turtles were also marked to determine the inter-clutch period as it is known that the turtles lay multiple clutches of eggs during the nesting season.

Findings and Gaps

This study was the pioneering study in Bangladesh on the marine turtles. The major finding was that the turtles used to nest round the year. The frequency of nesting peaked during the winter season (November – January) for Olive Ridley turtles, while it was August-September for the Green Turtles. Moreover, the species used different beach conditions for nesting, Olive Ridleys used to nest in the gradual sloping areas with smooth sand while the Green Turtles used steep slopes with coarse sand for nesting. The incubation period for the Olive Ridleys was between 55-60 days and 60-65 days for the Green Turtles. The third species found to nest was the critically endangered Hawksbill Turtle.
The major gap found during the study was the lack of awareness among the local fishermen and the concerned authorities.

The Impacts of Climate Change on the Livelihoods of Coastal People in Bangladesh: A Sociological Study

Joydeb Garai

In: W. Leal Filho et al. (eds.), International Perspectives on Climate Change, Climate Change Management, DOI: 10.1007/978-3-319-04489-7_11, © Springer International Publishing Switzerland 2014: Pg. 151 - 163.
(Ref: H.11)

Summary

The study attempted to assess the impacts of climate change on the livelihoods of coastal people in the south-western part of Bangladesh. This study was conducted by using quantitative method with semi-structured interview questionnaire for data collection in purposive manner. The paper examined the impacts of climate change on agricultural productivities, food securities and institutional challenges that the coastal people face. This paper finds that the frequency and severity of natural disasters have increased in recent years, that threat on food securities by inundating low agriculture land, restricting economic activities, decreasing employment opportunities, expanding different health diseases, destructing houses, crops and other infrastructures in Bangladesh. The findings indicate that the most climate change induced vulnerable and risky people are women, children, elderly and disabled people as they cannot easily cope with the unfavorable environment during disasters. There has not much empirical research conducted about the impacts of climate change, so policy makers can get comprehensive view about this concern by this study and implement policy for the survival of the climate change induced affected coastal people.

Methodology

The study is quantitative in nature. A semi-structured interview questionnaire was used to obtain quantitative data from eight villages in Shyamnagar Upazila of Satkhira district in Bangladesh. With an aim to arrange this work in a representative manner, 400 samples were selected purposively from the study area. Each male and female (age 15–85) who lived in the selected polder area was the unit of the study. Statistical analysis (SPSS Windows Program, version 17.5) was used to process the data. Relevant information was also collected from secondary sources. The study also delved into the climate change-induced risk and vulnerability of coastal people especially on women, children, elderly and disabled people.

Findings and Gaps

The important finding of the work is that climate change affects severely to the lives and livelihoods of coastal people in terms of agricultural productivities, food securities and people's vulnerabilities. Due to climate change, floods, tidal surges and cyclones have become a common phenomenon in the lives of coastal people and to minimize the loss and cope with the situations coastal people use their own strategies. However, the work indicates that to cope with the hazard situations coastal people should emphasize on taking disaster management training, be aware about their responsibilities and utilizing and preserving existing resources, so as to achieve sustainable livelihoods in the coastal area of Bangladesh.

Moreover, salinity mainly affects land and water in the coastal areas. With the consequence of climate change, it gradually extends towards inland water and soil. This scenario of gradual salinity intrusion into the coastal areas of Bangladesh is very threatening to the primary production system, coastal biodiversity and human health

Impact of climate change on marine and coastal biodiversity in the Mediterranean Sea: Current state of knowledge.

S. Ben Haj and A. Limam
UNEP-MAP-RAC/SPA, 2010. Tunis: 1-28.
(Ref: H.35)

Summary

Despite an uneven contribution to greenhouse gas emissions, all the countries will be faced with the effects of climate change and will therefore have to deal with the serious perturbations which will affect their natural heritage.

Today it is quite clear that the effects of climate change are perceptible at all levels; human health, animal health, water resources, biological resources, quality of the environment and economic activities (agriculture, industry, transport, insurance, etc.) and will become even more amplified and throughout the whole world they will have particular impacts on supply and demand, the future quality of water resources and will modify the frequency, spatial distribution and intensity of droughts and flooding.

The challenge is a prioritary one for the marine and coastal areas so that the first adaptation and mitigation measures should be urgently undertaken. The coasts of the whole earth which are already under various types of pressure already have a concentration of 60 % of the human populations on a 60 km wide belt. Littoral waters represent 14 to 30 % of the ocean primary production and 90 % of the fish catch. Bangladesh is no exception and is particularly sensitive to the effects of climate change which are an additional burden on littoral biodiversity.

Some consequences of climate change will in any case be irreversible with no possibility of adaptation. This concerns in particular those activities which depend on marine biodiversity (fishing, aquaculture, recreational activities). In the long term the major challenge will probably be to succeed in forecasting the future of our biodiversity, the future composition of fisheries and other aquatic life, submarine landscapes and to adapt ourselves to these changes in consequence.

This new emerging problem is highly complex and unevenly documented so that it is absolutely vital to expand the existing basic knowledge especially on the physical and biological aspects, effects of climate change on ecosystems and biodiversity and in particular the cross-over effects of climate change and other sources of disturbance. In view of the various future scenarios, it is important to set up models pertaining not only to species but specifically also to the mechanisms regulating the ecosystems so as to evaluate their resistance and resilience capacity. These models could surely contribute to define a range of cross-cutting and sectoral adaptation and mitigation strategies in order to face the different climate change scenarios.

No decision should therefore be left pending until perfect and illusory knowledge is gathered in order to undertake ideal adaptation measures for a given coastal zone. What is needed on the contrary is to learn how to cope and manage with this incertitude on the basis of often incomplete scientific data. Adaptation or at least mitigation can be envisaged in as far as the ecosystems are often already fragilized by pollution, fragmentation of habitats, biological invasions and can thus be highly sensitive to climate change with diminished adaptation capacity. The response to existing or potential impacts of climate change can be an indirect one by reducing the nuisances which can be tackled by the human society. One of the things that could be done is to multiply the marine and coastal protected areas as well as the dedicated areas and if the ecological corridors are taken into consideration then this would reinforce the resilience and resistance capacity of the ecosystems and species.

10 Lessons Learnt

10.1 Summary, Gaps, and Lessons Learned

10.1.1 Delta Tectonics and Subsidence

- Subsidence of the land surface is a composite response to many processes operating at different spatial and temporal scales. From large-scale to small, these processes include flexural loading of earth's crust, growth of tectonic structure (folds and thrusts), deep sediment compaction (>5 m; dewatering), and surface sediment compaction (< 5 m; edaphic [soil] factors).

- Flexural loading and deep compaction rates are difficult to separate but combine to yield long-term (>1000 years) rates of 0.5 to ~3 mm/yr on the lower GBMD (e.g., Grall et al., 2018). These rates are best measured by radiocarbon and GNSS approaches. However, deep compaction can be greatly enhanced by anthropogenic fluid extraction, as shown by Dhaka's accelerated subsidence >12 mm/yr (Akther et al., 2010).

- The growth of tectonic structures can be an important driver of uplift and subsidence (~mm/yr), but such structures are restricted to the delta at or east of modern river mouth. In particular, the tops of anticlines buried <50 m below surface have been identified beneath Bhola Island (current CEIP drilling data), Raipur/Chandpur, and Sandhip Isand. Such subsurface structures are poorly mapped and their growth rates are not well known – this is a particular knowledge gap for the eastern delta region.

- In all, observations of mean, long-term (>1000 yrs) subsidence rates rarely exceed 4-5 mm/yr, with a mean of 3.5 mm/y and median of 2.0 mm/yr in the lower GBMD (Brown and Nicholls, 2015). Currently, the map of Grall et al. (2018) presents the most accurate magnitude and distribution of long-term subsidence rates. Nevertheless, the principal knowledge gap remaining for long-term subsidence is a more precise understanding of its spatial distribution.

- In contrast to the reasonable understanding of long-term subsidence patterns, there is great uncertainty for the rates, distribution, and even causes, of short-term subsidence (<1000 years). The compilation by Brown and Nicholls (2015) yields mean and median short-term subsidence rates of 8.8 and 7.4 mm/yr, respectively, with a large standard deviation of 7.5 mm/yr. These averaged rates are more than double those of the long-term background rates of subsidence.

- Two main causes of rapid short-term subsidence include anthropogenic fluid extraction (groundwater or petroleum) and shallow compaction caused by natural and anthropogenic processes. The extraction of groundwater for rural irrigation and urban water supplies has increased manifold in the last two decades and represents a likely major source of increased subsidence, although measurements remain few. Land use and environmental change are another potential source of short-term subsidence by affecting shallow soil processes.

- The Brown and Nicholls (2015) compilation suggests that subsidence rates may be twice as fast in areas of heavy irrigation (ie., high groundwater extraction) vs. rainfed agricultural areas. Although existing data is limited and groundwater extraction not yet explicitly linked to higher rates in the irrigated areas, the correlation is very plausible. Determining the impact of crop irrigation on local subsidence rates remains a major knowledge gap that warrants further attention.

- Many observations of locally high, modern subsidence rates have been made using InSAR (Higgins et al., 2014), RSETs (Wilson, this study), and direct elevation measures (Auberbach, et al., 2015). These short-term rates of 5-15 mm/yr (or higher) are often 2-5 times faster than nearby long-term measurements. Where these rates are not caused by groundwater withdrawal, they instead appear to be associated with soil processes in the upper 10 m of sediments.

- Shallow soil compaction in the GBMD is typically associated with newly formed lands (chars, coastal islands, infilled channels) or land-use changes where wetland environments are deforested or drained for conversion to agriculture. The effects that contribute to subsidence include the drying and compaction of soils, degradation of organic biomass, removal of wood (stumps and roots), and the loss of bioturbation by burrowing animals.
- The concern about shallow compaction is that rates can be very high (>10 mm/yr), but they also may not persist for more than a decade or two before stabilizing. This assertion needs to be tested, however. Overall, the rates and extent of shallow compaction are not well known and represent an important knowledge gap regarding that stability of local land-surface elevation.

10.1.2 Delta Morphology and Sediment Supply

- Geomorphology of the GBMD is among the better studied aspects of the delta system, owing to the relative accessibility of surface environments and the application of remote sensing to landforms patterns and dynamics. Broadly speaking, there is extensive geomorphic literature on the channel braidbelts (e.g., Ashworth et al., 2000; Dewan et al., 2017) and delta morphology (e.g., Allison 1998; Allison et al., 2003; Wilson and Goodbred, 2015)
- Current research needs on GBMD geomorphology are related to morphodynamics and geomorphic response to environmental change, such as work began with the Meghna Estuary Study (e.g., Ali et al., 2007; Sokolewicz et al., 2008) and continue with modeling efforts of the current CEIP study.
- A sediment load of 1 billion metric tons per year (10^{12} kg) is the commonly accepted value for combined GB sediment delivery to the GBMD. Rahman et al. (2018) take the 10 or so measurements of sediment discharge in the last 50 years to suggest that the mean sediment load has been declining at ~10 Mt/yr or rate of 1% annually. However, there remains insufficient data to confirm this trend or to assess the role of ENSO and other climate variables in controlling GB sediment discharge.
- Recent model studies have explored possible impacts of climate change on sediment supply to the delta. Darby et al. (2015) uses IPCC scenarios to drive the model Hydrotrend, with results suggesting that a stronger monsoon could drive sediment load increases of 16% to 18% in the Ganges and 25% to 28% for the Brahmaputra, by 2050. These increases could double to 34-36% and 52-60% by 2100.
- River engineering projects, however, could offset the possible sediment increases related to climate change. Higgins et al. (2018) explore the potential effect of India's proposed River Linking Project that would divert water from wet northeast rivers to more water stressed regions in west and central India. The model results suggest a potentially major impact of 39–75% reduction in Ganges annual suspended load and 9–25% reduction for the Brahmaputra.
- The monitoring and further understanding of riverine sediment supply variability should be a priority research area. Such knowledge provides an essential baseline for understanding how external factors such as climate change and proposed engineering projects will affect the essential delivery of sediment to the GBMD.

10.1.3 Riverbank Erosion

Bank erosion rate is very significant in Bangladesh. The sediment regime appears to be the main reason for the variation. Hasegawa (1989) found that the highest bank erosion rates are found for medium to coarse sand, while the lowest erosion rates are found for finer (cohesive) or coarse (gravel) material. This suggests a clear correlation between the erodibility of the bank material and bank erosion.

Since gravel is essentially non-existent in Bangladesh, we must consider two regimes when modelling bank erosion in the rivers of Bangladesh:

- Sandy banks
- Cohesive banks

The rivers in the southwest region are dominated by cohesive banks and will therefore exhibit much smaller erosion rates than the river in the southeast region (Lower Meghna and Sangu).

Flow regime needs to be considered in addition to the sediment regime although they are related. Most of the tidal rivers have significant cohesive sediment influence, while most of the fluvial systems have very little cohesive sediment influence on the morphology.

The apparent inability to predict (anticipate) the imminent occurrence of serious bank erosion had caused much concern and unplanned cost overruns in the CEIP-1 within a short space of time after completion of construction. Thus, the modelling of bank erosion processes. Identification of critical reaches, inclusion of protective or avoidance measures in the original design has become a major priority in the next phases of CEIP.

River bank erosion in coastal area in Bangladesh:

In Bangladesh polder construction was started aimed to boost up the agricultural production mainly rice. Main components of these polders are construction of embankment to prevent saline water intrusion form the peripheral rivers and construction of sluice gate to drain the accumulated rainwater to the river. During planning and construction embankments were constructed keeping sufficient set back distance from the rivers. At that time riverbank erosion problems were not severe there. Rivers had sufficient depth to accommodate the flood water within its regime during monsoon. As such bank protection work were not needed. On the other hand, previously upland flow volume was higher than present volume. Naturally silt deposition rate at the river mouth was less due to outward thrust of inner water flow. But due to decrement of upland flow silt deposition rate at the river mouth is higher than the previous rate. Moreover, construction of polders are another reason for silt deposition in the river bed. This phenomenon reduced the overall cross-sectional area of the river at the river mouth near sea. Due to Decrease of depth of these rivers, monsoon flood water can be accommodated with in the river and passing water hits the banks causing bank erosion. The decrement of depth is not always uniform on the riverbed, somewhere it is less and somewhere it is high forming chars at river mouth. These formations of chars also divert the water to higher depth region causing oblique flow which hits the bank. Overall due to different reason bank erosion problem is higher than previous rate in coastal area in Bangladesh.

Challenges for bank protection:

1) It is observed that in the affected area near bank, depth of water is very high and therefore cost for protection is very high.
2) Through holistic approach proper study is needed for determination of appropriate length of protection.
3) For long length protection we have to go for phase wise protection and what will be the sequence of the phases that should be properly determined.
4) Implementation of riverbank work in a proper way is very difficult. Because there are some variables which mostly control the quality of protective work. Such as in tidal river, direction of river current is always reversible in eight hours, water level is continuously changing, water velocity is also changing continuously. Considering all these factors implementation of quality protective work is very difficult in traditional method.
5) For sustainable riverbank protection after implementation close monitoring and proper maintenance is very necessary. This cost for monitoring and maintenance should be allocated.

Riverbank protections work in Bangladesh:

Cost of riverbank protection work in coastal is very high in Bangladesh. Due higher cost proper bank protection measure against erosion were not taken. Sometimes locally affected areas with little measures were taken but no measures were taken in a holistic approach. But from last decade Government of Bangladesh moved forward to protect the riverbank in vulnerable areas in a holistic approach. Some major projects are mentioned below.

1) West bank of Meghna river in Bhola District, Polder no 56 and polder no. 57. Nearly 100 km length is vulnerable, of which nearly 55 km protection work is done and the rest reach will be done in the near future. Condition of implemented works are still good except some little damages. Actually, close monitoring and maintenance is very necessary for long lasting protection work.
2) East bank of Meghna river in Laxmipur district, polder no. 59/2. Nearly 38 km length is suggested for protection. Out of it 6.27 km is already implemented. For the rest length government has allocated fund and implementation will start very soon.

Besides the above-mentioned projects government also gave attention for riverbank protection work in Chittagong division. In Chittagong district at Bashkahali, Miershari, Anwara protection works are running.

Lesson learning and suggestion:

Bangladesh Water development Board implemented above mentioned projects recently, up till now no severe damages observed except some little incident which are very natural. Government should allocate special operation and maintenance fund for this implemented works for the sustainability in future. With the development of the polders, now a huge population live in this area, huge investments are there. Government should move forward for protection of this population and their property. To get fruitful benefit by expending this hard eared money, government should move in a holistic approach in determining appropriate length of implementation phases. After implementation, at least next 3 years close monitoring and maintenance is very necessary and for this purpose necessary fund should be included in DPP.

10.1.4 Polder Drainage and Management

The three main causes of drainage congestion problems in the coastal polders as recognized are:

Poor maintenance of the drainage structures and siltation of drainage canals (khals) inside the polders and lack of proper operation of the facilities. The proposed interventions in CEIP-1 (CES-JV, June 2013) underlines: In 16 of 17 polders replacement of existing sluices were recommended while re-excavation of khals were proposed in all 17 polders.

Diminishing freshwater flow from upstream due to construction of Farakka Dam and freshwater abstraction at large-scale irrigation schemes were thought to cause siltation of peripheral rivers.

The construction of the polders has greatly reduced the tidal volume, the flow velocities in the peripheral rivers therefore decreases and the size of the peripheral river decrease significantly through siltation. As result, the tidal range diminishes in some peripheral rivers reducing the drainage capacity of previously effective drainage structures.

In the western part of the delta the freshwater flow has been negligible even before the construction of the coastal polders, hence here the reduced tidal volume is the main reason of siltation, while in the south-central region the diminishing flow through the Gorai River may play a larger or additional role. Further east towards Meghna River the freshwater flow is abundant, and siltation of peripheral river seems to less of a problem there.

In areas where siltation of peripheral rivers have been identified as the main cause of drainage congestion, 'tidal river management (TRM)' (Gain et al, 2017) has been identified as a comprehensive approach for sustainably managing polder drainage. Tidal river management involves breaching of the embankments to one or more polders for a period of time (few years). This has two beneficial effects: 1) the tidal volume will increase and thus flow velocities will increase in the peripheral rivers that will erode and restore original size; and 2) the water entering the polders will carry a high silt load that will accelerate land accretion.

TRM is a solution applicable only to carefully selected polders or groups of polders which are allowed to be flooded to enable simultaneously the erosion of the seaward tidal channels running from the tidal ocean towards the polder. The production of flooded polders selected for land building would have to be voluntarily interrupts for a number of years.

10.1.5 Climate Change and Sea Level Rise

UNDP (2004) has identified Bangladesh as the most vulnerable country in the world to tropical cyclones and the sixth most vulnerable country to floods. Relative sea level rise is one of the major concerns for this low-lying country. The predicted average sea level rise by 2100 range roughly between 50 and 90 cm. Estimates for the North Indian Ocean, based on models, suggest an increase in frequency of all TCs (tropical cyclones) for all categories and, in particular, for the most extreme ones. The projection data indicate increases in monsoon and post-monsoon precipitation over the basin, a decrease in pre-monsoon precipitation, and a shift in the timing of peak monsoon precipitation. There has been a consistent increase in temperature over the last 40 years in the basin and the temperature is likely to increase further under climate change.

The effects of climate change on temperature, sea level rise, frequency, and intensity of tropical cyclones, rainfall, flood etc. as stated above should necessarily be considered in the planning and design of engineering projects and infrastructures for ensuring safety, sustainability, and economy of the country.

It must be kept in mind that allowing for climate change and other changes in the delta as it evolves is computed on the basis of present knowledge and understanding of processes.   The future planning should include the possibility that, in additional variations induced by climate change, the delta will be strongly influenced by development in the upstream river systems in China and India while the climate change trajectory will be influenced by large economies which are responsible for generating huge amounts of greenhouse gases.

10.1.6 Hydrodynamics and Salinity

- While the negative hydrodynamic impacts of poldering has been recognised, the enormous socio-economic benefits that have resulted from the construction of the coastal embankments far outweigh these negative impacts. It is however necessary to fully understand and quantify these negative impacts to be able to minimise them through improved design and management. The reduction of dry season Ganges flows have reduced the supply of fresh water through the right bank distributaries, particularly the Gorai reiver. While this reduction has increased saline intrusion into the Southwestern delta, it would be a mistake to siltation resulting from mainly the distortion of the tidal dynamics due to the construction of polders.

- The possibilities of reducing saline intrusion by constructing the Ganges Barrage has been demonstrated and this benefit must be recognised, also as a mechanism for mitigating the increases in saline intrusion due to sea level rise.

10.1.7 Groundwater Salinity

- Groundwater and surface water salinity are closely interlinked. Larger scale effects of climate change such as sea level rise, higher storm surge frequency and reduced river freshwater discharges will affect the boundary conditions at local scale polders. Solutions in polder water and salinity management must be found within these changing boundary conditions.

- The individual polder infrastructure in terms of embankments and drainage infrastructure as well as water management play key roles in preventing or controlling salt intrusion. Reducing storm surge influx of saline water and maintaining a well-functioning drainage network allowing discharge of excess salt is important in order to avoid long term accumulation.
- Mobilisation of saline groundwater by excessive pumping, use of brackish or low salinity water for irrigation and mixing with saline drainage flows may add further to the increasing groundwater salinity trend. Poor drainage, waterlogging and restrictions with respect to gate operation increase salinity problems in low lying polder areas.
- Improved management requires site specific monitoring and data collection aimed at supporting integrated analysis at the individual polder level. The hydrogeological conditions and groundwater salinity concentrations within polders are highly variable. Continuous monitoring of salinity in soils, surface water and groundwater at multiple locations will be required to manage in accordance with local thresholds.

10.1.8 Coastal & Marine Biodiversity

Coordination

The coastal areas are rich in the biological diversity and renewable resources that demands intensive monitoring and coordination among the various agencies implementing projects in the coastal areas. The BWDB is engaged in the restoration of the polders that alters and restricts the natural hydrological flow of the tides on which the coastal ecosystem is dependent. The impact on the biological resources due to the physical alteration needs to be monitored in coordination with the agencies responsible like the Forest Department, Department of Fisheries, LGED, and Department of Environment. Emphasis is being given to the agricultural production at the cost of the ecological services and biodiversity. The use of chemical fertilizers in the polders is rampant and runoffs from the agricultural fields to the wetlands (canals, ditches, etc.) blends with the regulated tidal waters. In addition, the chemical pollutants also seep into the groundwater within the polders rendering it risky for the users in the long-term. [CHECK FOR FERTILIZERS].

Monitoring

Long-term plans for monitoring the biological resources should be an integral component of all the polder-related projects. The pre- and post-changes need to be documented for comparison and future assessment of the biological resources. Results from the monitoring should be periodically reviewed and actions taken to mitigate and adverse impacts as well as to restore the affected resources.

Biodiversity

The government advocates for the conservation and protection of the biodiversity to comply with the Convention on Biological Diversity, as well as fulfilling the targets under Goal 14 (Life below Water) and Goal 15 (Life on Land) of the Sustainable Development Goals. Article 18A of the Constitution of Bangladesh also advocates for the protection and improvement of environment and biodiversity. Yet in practicality, the implementing organization and the persons involved completely overlook and forget about the biodiversity and ecosystem. This has to be changed. The contractors should mention about the protection and conservation of biodiversity during every day's morning briefings (see Fig. below) and BWDB has to monitor it that they actually do it. For this purpose of project authorities should educate the workers, answer their questions, and inform them about potential impacts of surveillance technology on disadvantaged groups. The Forest Department has response teams then will help address the biodiversity issues. The important thing is to get organized before the guests arrived.

Species Inventory

Establishing the baseline information is very important for a project to start with. Very little time is being provided to establish the baseline. It is recommended that a reasonable adequate time be provided to the contractors/consultants to establish the baseline including species inventory.

Appendix: Comments on Interim Literature Review Report-1 and Responses by the Consultants

WB's Comments	Consultant's Response
Comments Literature Review - interim report In general, it is appreciated that this is an interim document. Hence, comments below can be used for further finetuning this literature review. The expectation based on the TOR language is that the Consultant will deliver a thorough, coherent and readable literature review covering relevant topics (within each of the themes now listed) deriving important insights from the literature into the physical functioning of the coastal system (e.g. to either use for validating models or to check the system behavior in the models), provide lessons learned from past interventions and pilots (successes, failures from both technical but also institutional ones), also identification of key gaps which will partly be addressed in this LT study but probably also require further (beyond this LT study) and key information feeding into the LT study in general (e.g. for polder design aspects etc.). All in all, I think that this literature review is a start but needs much more work to make it valuable for the study as such and in general for BWBD and Bangladesh.	We do appreciate that the language of the ToR goes beyond what we have delivered in the Literature Review - interim report. However, this is indeed an interim report thus work in progress. We have added a paragraph in the Introduction underlining that this is work in progress and acknowledged that subsequent deliverables will be expanded and met the ToR.
A brief synopsis in each chapter of the key findings is a good idea (as stated in Chapter 1); some chapters, however, do not contain a synopsis (chapter 2 have many pages under this header), others do this very well (e.g. chapter 6); what also strikes me is that some chapters have no clear structure or start nor and end; my suggestion for further structuring the literature review would be to have a clear and coherent set of questions/topics to be answered from the literature review within each theme; important topics seem missing (e.g. what about observed changes in tidal water levels/extreme water levels in the system?); in other cases, there is a lot of room for topics which may not be that relevant for the coast, e.g. why elaborating very extensively on river bank erosion whereas the study is about the coastal belt/tidal river system? What about the observed erosion issues along the coast? What about bank protection efforts and their successes/failures in the coastal zone? What are the lessons learned etc. I think that the literature would add value if the review is more focused/structured in this way to feed into the rest of the study; Chapter 6 is an exception in that it very clearly answers questions relevant for this study like what changes in relevant climate parameters (rainfall, Sea level, cyclones etc.) can be expected based on the literature review; that chapter can serve as an example in my view for others;	All chapters have been updated attempting to use Chapter 6 as a model: • Chapter 2 and 3 have been reorganised and chapter 3 expanded to reflect on coastal sediments. • Chapter 4 has been refocused to bank erosion in estuaries • Chapter 5 expanded slightly • Chapter 6 is unchanged • Chapter 7 reformulated and expanded with issues related to groundwater salinity
Chapter 3 covers the topic of morphology but the chapter itself only covers sediment characteristics and sediment fluxes (and not morphology); there is a focus mainly on	• Reorganized sections 2 and 3 by editing and moving Delta Building section to

the GMB rivers, there is hardly any mention of the coastal sediments and transport/redistribution along the coast which seems also relevant for this long-term study of the coastal area; the distinction in this chapter between wash/suspension/bed load seems also to reflect the "river" focus of this chapter; sediments that are transported as wash load in the rivers are part of the sediment bed in the very downstream area in the coastal belt; I think it would be much better if this chapter would describe the sediment characteristics and the sources and sediment transport paths of these sediments based on a literature review; this will also be needed for setting up/calibrating numerical models;	better represent the requested Delta Morphology section. • Significantly expanded and updated the Sediment Supply section to include (a) nearshore and coastal sediments and (b) current and future sediment delivery to the delta. Roughly doubled the number of papers presented for sediment supply. • Text was updated to refer to more issues related to CEIP efforts. • Several new publications were added and discussed in the text.
Chapter 4 focuses very much on river bank erosion and references to Jamuna etc.; also the selected papers are all related to river situations; what about bank erosion in the coastal zone where tides dominate the behavior? There is one sentence at the end of the synopsis about this; what about bank protection schemes in the coastal zone and the lesssons, etc.?	The synopsis has been rewritten now with focus on bank erosion in the coastal zone and differences in erosion rates from fluvial environment to the coastal zone. Selection of references has been updated accordingly. Information on protection schemes in the coastal zone will await fielding/approval of the Polder Design/Embankment Design Expert
Chapter 5 is very short whereas the polder is a core element in the study in that the long-term study shall result in improving design/management of the polder system; also the construction of the polders is now suggested as the one cause for siltation of the peripheral river system; however, there are also papers suggesting that the diminishing fresh water inflow has had a large effect (especially in the SW); that is not mentioned here, why not?; this chapter shall contain also reviews of earlier feasibility studies, and polder improvement initiatives etc. (see also TOR) with a thorough analysis of these reports;	The synopsis has been updated and it is clearly stated what the focus of the review is and what will be included in subsequent deliverables (e.g. various polder management issues, discussion of earlier feasibility studies). Discussion of causes of siltation of siltation of peripheral rivers discussed further.
Chapter 7 discusses salinity; shouldn't there be a chapter discussing the hydrodynamic behavior including salinity? Salinity changes are driven by freshwater inflow changes (especially in the SW) and tidal changes and these are not covered in the review; is the salinity modeling referenced done with well-calibrated models for salinity throughout the system? Any weaknesses in the modeling approach? E.g. do all the salinity models assume static sediment bed? So with 59 cm SLR but no changes in the morphology? I would think that if the morphology will someway adapt to the SLR, then the salinity effect is also different.	A chapter on hydrodynamics will be included in subsequent deliverables. Discussion of surface water salinity in the synopsis expanded. Also groundwater salinity discussed.
Chapter 8 is strongly related to Chapter 5, so integration? Also Chapter 8 seems to have a very different writing style and voices strong opinions about certain issues with the polders; I would recommend to integrate and break this down into various subtopics to make this more readable and useful and also provide backup of strong statements/conclusions with references; the Table at page 50 is not very clear to me; BDP2100 has some cause-effect relationship diagrams that may be useful to consider in this report about topics like waterlogging etc.;	We have faced problems getting input from relevant experts to update this section of the report due to the suspension of the project, re-staffing issues and the COVID-19 plan. We have therefor taken this section out of this interim report and plan to include an updated an expanded version of the section in the next interim report.