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)

INTERIM LITERATURE REVIEW REPORT-1

JUNE 2019

Bangladesh Water Development Board
Coastal Embankment Improvement Project, Phase-I (CEIP-I)
Long Term Monitoring, Research and Analysis of Bangladesh Coastal Zone
Office: Flat #3/B, House #4, Road #23/A, Banani, Dhaka 1213, BANGLADESH Phone +880 1307 693299

Project Management Unit
Coastal Embankment Improvement Project, Phase-I (CEIP-I)
House No.15, 4tn Floor, Road
No.24(CNW) Gulshan, Dhaka-1212

24 June 2019

Att: Engr. Md. Habibur Rahman, Chief Engineer & Project Director

Dear Mr Habib,

1st Interim Literature Review Report, June 2019

The literature review has been on-going for the last several months. Nevertheless the review is not yet complete. However, as the review will be very useful to the varied group that comprises our team, we have printed a 1st Interim Literature Review Report for distribution to team members. I am happy to enclose two copies of this report for your information.

The 2nd Interim Literature Review Report will be distributed in December 2019.

Yours sincerely

Dr Ranjit Galappatti
Team Leader

Encl: Two copies of 1st Interim Literature Review Report

Copy: Zahirul Haque Khan, DTL'

Soft copies: PD and aAll Team member

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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, river bank 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 are carrying out comprehensive literature review of published research papers and reports. Based on the literature review consultants will produce critical analyses of lessons learnt from completed initiatives, identify research and data gaps, and provide 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 of 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 change in morphology;

All these will help the modeller and researcher to correctly dragonize the problems to deal with the study and come out with the best solution. This component will be carried over a long time 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 this Interim Literature Review Report are:

- GEOLOGY, SUBSIDENCE AND DELTA BUILDING
- MORPHOLOGY AND SEDIMENTATION
- RIVER BANK EROSION
- POLDER DRAINAGE AND MANAGMEMENT
- CLIMATE CHANGE AND SEA LEVEL RISE
- SALINITY.
- ENVIRONMENTAL AND SOCIAL

The publications related to each topic area of knowledge are described in the chapters from Chapter 2 through Chapter 8.

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 the list in second section are summarized in the following section given with the reference number.

2 GEOLOGY, SUBSIDENCE AND DELTA BUILDING

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 favorable 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 (Figure 4) 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, built during the reign of Raja Paratapaditya, the last King of Jessore, before his conquest by the Mughals in 1611 CE 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.

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 deltaplain will be extended over the next decade as part of the greater initiative to improve embankment stability through the Coastal Embankment Improvement Project.

2.1.3 Delta Building

The delivery and retention of sediment to fill accommodation generated by relatively sea level rise (including subsidence, discussed above) is key to building and maintaining delta plains. This means that sediment flux plays a primary role in the construction and maintenance of the >100,000 km^2 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 landforms in 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., 2016). 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 delta plain, constructed principally by the big rivers, (ii) the coastward fluviotidal delta, in which tidal processes overprint and rework the fluvial deposits of the big rivers, and (iii) the tectonically sequestered Sylhet basin, which is also characterized by big river(s) but contributes little sediment flux to the broader delta.

The fluvial fan delta plain

The 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., in review). The Brahmaputra River has also changed position throughout the Holocene, at an estimated avulsion timescale of ~2 ka (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.

The Fluvio-tidal delta

Avulsions of the river(s) redirect sediment and allow for the construction of new land at new depocenters, while abandoned depocenters 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).

Sylhet basin

Sylhet basin, in the northeast portion of the GBMD, is a tectonically active basin that is constrained by the Madhupur Terrace to the west, Shillong Massif to the north, and the Indo-Burman Foldbelt to the east. It was occupied throughout the mid- to late- Holocene by older paths of the Brahmaputra River (Pickering et al., 2014; Sincavage et al., 2018) and is also presently occupied by the Meghna River; sediment within the basin is relatively coarse-grained due to this big river input and 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.

2.2 List of Publications Reviewed

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.

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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.

A.1.21 Satyabala, S.P., 1998. Subduction in the Indo-Burma region: Is it still active? Geophys. Res. Lett. 25, 3189-3192.

A.1.22 Satyabala, S.P., 2000. Reply to comment on “Subduction in the Indo-Burma region: Is it still active?” Geophys. Res. Lett. 27, 1067-1068.

A.1.23 Satyabala, S.P., 2003. Oblique plate convergence in the Indo-Burma (Myanmar) subduction region. Pure Appl. Geophys. 160, 1611-1650, doi: 10.1007/s00024-003-2378-0.

A.1.24 Singh, A., K. Bhushan, C. Singh, M.S. Steckler, S.H. Akhter, L. Seeber, W.-Y. Kim, A.K. Tiwari, R. Biswas, Crustal structure and tectonics of Bangladesh: New constraints from inversion of receiver functions, Tectonophysics, doi: 10.1016/j.tecto.2016.04.046, 2016.

A.1.25 Sikder, A.M., Alam, M.M., 2003. 2-D modelling of the anticlinical structures and structural development of the eastern fold belt of the Bengal basin, Bangladesh. Sediment. Geology 155, 209–226.

A.1.26 Sloan, R.A., J.R. Elliott, M.P. Searle and C.K. Morley (2017) Chapter 2 Active tectonics of Myanmar and the Andaman Sea, Geological Society, London, Memoirs, 48, 19-52, 2017, https://doi.org/10.1144/M48.2.

A.1.27 Steckler, M.S., S.H. Akhter and L. Seeber, Collision of the Ganges-Brahmaputra Delta with the Burma Arc, Earth Planet. Sci. Letts., 273, 367-378, doi:10.1016/j.epsl.2008.07.009, 2008.

A.1.28 Steckler, M.S., Mondal, D., Akhter, S.H. Seeber, L., L. Feng, J. Gale, E.M. Hill, M. Howe (2016) Locked and loading megathrust linked to active subduction beneath the Indo-Burman Ranges, Nature

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A.1.29 Steckler, M.S., Stein, S., S.H. Akhter, L. Seeber, The wicked problem of earthquake hazard in developing countries, EOS, 99, doi: 10.1029/2018EO093625, 2018.

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2.3 Summary of Selected Papers

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
(Ref: A.1.1)

Summary

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

Methodology

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

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

Further consideration was given to the origin (epicenter) of the earthqakes, and past large-magitude earthquakes occuring 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 occured in Bangladesh in the past four decades. They show a greater frequency of earthquakes in the interval of 2007-2016 than in the precending 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.

Locked and loading megathrust linked to active subduction beneath the Indo-Burman Ranges

Micahel 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
(Ref: A.1.28)

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 occuring at rates of 13 - 17 mm/yr along the Indo-Burman Ranges, meaning that earthquakes remain a present-day geoharzard.

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 yr time series

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

Key findings & knowledge gaps

This study is noteable 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 occuring 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.

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
(Ref: A.2.4)

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 millenial timescales are fiarly 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 identif 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 thosands 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.

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
(Ref: A.2.6)

Summary

This study estimated land surface subsidence over modern (instrumental) timescales for a portion of the GBMD using Interferometric Synthetic Aperature 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 bredth 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 susidence throughout the delta.

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
(Ref: A.3.1)

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 combiled 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.

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
(Ref: A.3.2)

Summary

There is significant concern in how the populated and poldered islands of coastal Bangladesh may persist under condistions of relative sea level rise. This study assessed the land surface subsidence os poldered islands, showing that elevation loss there is due to a combination of sediment interruption, accelerated comaction, 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-exascerbated 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 MORPHOLOGY

3.1 Introduction and Synopsis

3.1.1 River Sediments

The concentration and distribution of sediment in the river channels 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 across the entire GBMD system, from the upstream portion in India, to the coastal shelf. Both in situ measurements (e.g. Kuehl et al., 1989; Barua et al., 1994; Datta and Subramanian, 1997; Singh et al., 2007) and remote sensing (Islam et al., 2001) methods have been used to make these estimates. 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.

3.1.2 Wash and Suspended Load

Like many fluvial systems, the majority of sediment in the GBMD is transported as either wash or suspended load. Wash load is defined as very fine sediment, which remains in near-constant suspension, even when velocities are negligible or there is slack water. Suspended load is sediment that is transported along with flow or in response to flow turbulence. In all the literature cited here, no distinction is made between these two suspension mechanisms.

Suspended sediment concentration 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 106.0 Mt/yr for the combined system (Datta and Subramanian, 1997). Sediment moves seaward by fluvial forcing, and 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 microns. Median grain sizes sampled in the Meghna Estuary are similarly fine, ranging from 13.8 to 25 microns, or fine to medium silts (Kuehl et al. 1989, Barua et al., 1994).

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).

3.1.3 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 velocities near the bed are high enough to surpass a threshold for motion. In general, bed load makes up a smaller proportion of sediment load than suspended material.

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). 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 References for Key Literature

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B.9 Stummeyer, J., Marchig, V., and Knabe, W. (2002). The composition of suspended matter from Ganges–Brahmaputra sediment dispersal system during low sediment transport season. Chemical Geology, 185(1-2), 125-147.

3.3 Summary of Selected Papers

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
(Ref: B.1)

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).

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
(Ref: B.4)

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 RIVER BANK EROSION

4.1 Introduction and Synopsis

River bank erosion is one of the main concerning issues in Bangladesh. The major three rivers, namely Jamuna, Ganges and Padma have been facing serious bank erosion in the past few decades. Recent study of CEGIS 2018 reveals that the Jamuna, Ganges and Padma rivers have consumed above 150,000 ha of land through erosion since 1973. They described that among the three rivers, the Jamuna devoured 93,302 ha of land along both its banks but returned only 16,603 ha during 1973-2017. Similarly, Ganges and Padma engulfed about 31,421 ha and 37,296 ha of land due to bank erosion, respectively (CEGIS 2018).

River bank erosion occurs mainly due to three processes: fluvial entrainment, sub-aerial erosion and mass failure due to poor strength of the bank materials (Lawler, 1995). One or the combination of these processes is responsible for the river bank erosion, though for a homogeneous river bank erosion is mainly dominated by a single process (Karmaker et al., 2010). The nature of erosion is quite different in cohesive and non-cohesive river bank material. In non-cohesive sediments, bank erosion occurs in shallow slides and through fluvial entrainment of particles (Jurina, 2017). And in case of cohesive bank, the erosion takes place as crumbs of soil rather than individual particles, as they are bound tightly by the electromechanical cohesive forces (Lawler et al., 1997).

In Bangladesh, most of the river bed and banks consist of very fine, loose sand that is easily mobilized and eroded by relatively small flows with the exception of some parts of (i) the Ganges upstream of the Hardinge Bridge and near the Gorai offtake and (ii) the central left or north bank of the Padma River and a short section at the right or south bank near the confluence with the Upper Meghna, which contains some erosion-resistant soils and has been fairly stable over decades (NHC, 2013). Furthermore, the bank materials of Jamuna River mainly consist of loosely packed silt and fine sand with less than 1% clay (Delft Hydraulics and DHI, 1996), and so they are highly susceptible to erosion, which results in a braiding pattern with many islands (EGIS, 2002). ISPAN (1993) and Thorne et al. (1993) found that the right bank of Jamuna was more prone to erosion than the left bank where both erosion and accretion together produced relatively low net movements. On the other hand, the channels of the Meghna system transport predominantly fine to medium grained sands as bed materials, and their banks are composed mainly of silt- mud with little sand, and thickly root penetrated (Alam, 1991).

The largest rivers may have bank line shifts of hundreds of meters per year (Baki & Gan, 2012). CEGIS, 2007 reported in their study that the maximum lateral extent of erosion in Jamuna River can be as high as 2,000 m/y. They found that erosion with a very high rate was more frequent along the left bank than the right bank. The reason for this being that most part of the floodplain along the left bank comprised of newly accreted land. In Ganges River, most part along the left bank is either naturally less erodible or has structural control. As a result, erosion is much higher along the right bank than the left, (CEGIS 2010). The extent of erosion along the left bank was between 300 to 600 m/y whereas along the right bank it was up to 900 m/y. In case of Padma River, the rate of bank erosion along the less erodible floodplain is 0 to 20 m per year and along the highly erodible floodplain it varies 50 m to several hundred meters per year, (CEGIS 2005).

Erosion rates can be quantified by the soil critical shear stress (τ_c). If the critical stress is higher than the effective stress, the erosion rate is zero. In general, fluvial erosion rates depend on the flow strength physical characteristics (soil erodibility parameters) of the bank materials (Khan et al., 2016).

Most bank erosion models rely on near-bank conditions for the bank erosion predictor, see e.g. Mosselman (1995) and Duan (2005). Several authors have reported simulations of plan form developments, such as Nagata et al (2000), Darby et al (2002), Rinaldi et al (2008) and Asahi et al (2013). Asahi et al (2013) also provide a bank accretion model involving a prescribed time-scale over which dry cells become land.

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 crosssection.

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 Asahi, K., Shimizu, Y., Nelson, J., & Parker, G., 2013, “Numerical simulation of river meandering with self-evolving banks”, Journal of Geophysical Research: Earth Surface, 118(4), 2208-2229.

C.3 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.4 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.5 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.

C.6 CEGIS 2010, “Long-term Erosion Processes of the Ganges River”, Prepared for Jamuna-Meghna River Erosion Mitigation Project, Bangladesh Water Development Board, Dhaka, Bangladesh.

C.7 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.8 Crosato, A., 1990, “Simulation of meandering river processes”, Communications on hydraulic and geotechnical engineering, No. 1990-03.

C.9 Darby, S. E., Alabyan, A. M., & Van de Wiel, M. J., 2002, “Numerical simulation of bank erosion and channel migration in meandering rivers”, Water Resources Research, 38(9), 2-1.

C.10 Delft Hydraulics and DHI (FAP 24), 1996. “Bed Material Sampling in Ganges, Padma, Old Brahmaputra and Jamuna”. Special Report No. 8, Prepared for Water Resources Planning Organization (WARPO), Dhaka, Bangladesh.

C.11 Duan, J. G., 2005, “Analytical approach to calculate rate of bank erosion”, Journal of hydraulic engineering, 131(11), 980-990.

C.12 EGIS, 2002, “Developing and Updating Empirical Methods for Predicting Morphological Changes of the Jamuna River”. Technical Note Series 29, Dhaka, Bangladesh.

C.13 Fagherazzi, S., Gabet, E. J., & Furbish, D. J., 2004, “The effect of bidirectional flow on tidal channel planforms”, Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group, 29(3), 295-309.

C.14 Ikeda S, Parker G, Sawai K., 1981, “Bend theory of river meanders. 1. Linear development”, Journal of Fluid Mechanics 112: 363–377.

C.15 ISPAN, 1993, “The Dynamic Physical and Human Environment of the Riverine Charlands: Brahmaputra Jamuna, Geographic Information System”. Prepared for the Flood Plan Coordination Organization (FPCO), Dhaka, Bangladesh

C.16 Jurina. T. O. 2017, “Channel closure in large sand-bed braided rives”, M.Sc Thesis, Delft University of Technology, The Netherlands.

C.17 Karmaker, T. & Dutta, S. 2010, “Modeling composite river bank erosion in an alluvial river bend” River Flow 2010 - Dittrich, Koll, Aberle & Geisenhainer (eds), pp-1315-1322

C.18 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.

C.19 Lawler, D. M., 1995. “The impact of scale on the processes of channel-side sediment supply: A conceptual model. In: Effects of scale on Interpretation and Management of Sediment and Water Quality”, IAHS Publ. 226, Wallingford, U.K.: International Assoc. of Hydrological Science, pp 175-184.

C.20 Lawler, D. M., Thorne, C. R. and Hooke, J. M. 1997. “Bank erosion and stability. In Applied Fluvial Geomorphology for River Engineering and Management”, (Eds.) Thorne, C.R. et al., 137-172. J. Wiely, Chichester, U. K.

C.21 Mosselman, E., 1995, “A review of mathematical models of river planform changes”, Earth Surface Processes and Landforms, 20(7), 661-670.

C.22 Nagata, N., Hosoda, T., & Muramoto, Y., 2000, “Numerical analysis of river channel processes with bank erosion”, Journal of Hydraulic Engineering, 126(4), 243-252.

C.23 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.

C.24 Rinaldi, M., Mengoni, B., Luppi, L., Darby, S. E., & Mosselman, E., 2008, “Numerical simulation of hydrodynamics and bank erosion in a river bend”, Water Resources Research, 44(9).

C.25 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

Modeling composite River Bank Erosion in an Alluvial River Bend

T. Karmaker & S. Dutta
River Flow 2010 - Dittrich, Koll, Aberle & Geisenhainer (eds), Pages 1315–1322
(Ref: C.17)

Summary

Different types of bank erosion processes may occur in a large alluvial river that comprised of composite river bank formation. In the present study an analytical river model has been developed for the composite river bank considering the entrainment and deposition of the sediment particle from the bank surface, basal erosion due to excess shear stress, cantilever mass failure and near bank net sediment transport rate. To demonstrate the model performance, a river bend with active bank erosion rate in the middle reach of Brahmaputra River in India has been considered. The predicted seasonal bank erosion rate by the analytical model is compared with the field measured one. The results show the present analytical model works well for predicting the seasonal extent of bank erosion for the composite bank in a river bend. The model can be used to obtain morphological dynamics of a sand-bed river bend, accounting for variation in the bank material composition.

Methodology

The study site is located along the Brahmaputra river (at Jamuguri, North Lakhimpur), North-East India. The site (26^0 50 ' 08"N, 93^0 46 ' 08"E) is about 70 km upstream of Tezpur town. It is seen from the multi-date satellite imagery (LISS-III) that after 2004 extreme flood, a large river bend has been formed at this location. In this study, a bank erosion model has been used, which includes the basal erosion due to hydraulic force, all possible types of cantilever failure of the overhang soil mass, the erosion of the deposited bank material at the toe of the bank after cantilever failure and the bed degradation. To conduct this study, detailed hydro-graphic and river bank survey was carried out during the moderate flow condition and during high flood condition for the years 2007 and 2008. The survey includes the data collection like bathymetry using GPS aided Echo-sounder, velocity profile through ADCP, river bed and bank soil samples, depth averaged water samples for suspended sediment concentration etc. Different types of soil erosion parameters such as critical shear stress and erodibility coefficients of cohesive layers are also measured by submerged-jet test apparatus. Hence, the seasonal bank erosion rate at a few locations of the bend is measured by repeated field survey using Differential Global Positioning System.

Findings and Research Gaps

From the study, it is found that in case of cantilever stability among the four cases of mass failure, beam type of failure occurred three times and one case is for shear failure. No case of tensile bank failure is found from this simulation. Moreover, the simulated factors of safety fall within the comparable limit for beam and shear type of failure cases. The cumulative bank erosions at the four different monitoring points are also compared with the observed bank erosion rate. Results suggest that fluvial erosion is the key factor prior to the cantilever failure in this model. So, the higher critical shear stress, lower the fluvial erosion and longer cantilever stability is occurred. Apart from the various types of erosion considered in the present model, there may be seepage erosion, which is quite common for composite bank, which needs to be included in the present model in near future.

Riverbank migration and island dynamics of the braided Jamuna River of the Ganges-Brahmaputra basin using multi-temporal Landsat images

A.B.M. Baki, T.Y. Gan

Quaternary International 263 (2012) pages 148-161

(Ref: C.3)

Summary

In this study, using thirteen selected images of Landsat MSS and TM acquired from 1973 to 2003, the riverbank migration patterns and island dynamics of Jamuna River resulted from accretion/erosion processes for 30 years were investigated. For short-term analysis, the migration rate from one Landsat image to the next is estimated. For long-term analysis, the migration rates are based on the difference between the 1973 image as the reference, and subsequent images. For the short-term (long-term) analysis, the average erosion and accretion rates are 227 and 271 m/y (90 and 104 m/y) on the left bank, and 187 and 148 m/y (75 and 50 m/y) on the right bank of Jamuna, respectively. Because of human interventions and the averaging effect of erosion and accretion, the long-term migration rate is lower than that of the short-term migration rate on both banks. From one flood to another, large islands tend to be more stable with little changes, but smaller islands underwent more changes.

Methodology

To investigate the erosion/accretion rate, total of thirteen satellite images covering the whole Jamuna River in Bangladesh were selected for this study. All the images were collected during the dry season. The discharge and water level data of Jamuna River at the Bahadurabad gauging station was collected from Bangladesh Water

Development Board (BWDB). ArcView, a GIS software, was used to estimate the riverbank migration and island dynamics within the study reach of Jamuna River. The short and long-term migrations of both left and right river banks were analyzed. For the short-term analysis, the migration rate was based on differences between two available consecutive images. In contrast, the long-term migration rate was calculated with respect to the earliest image of 1973 as the reference, and the migration rate has been computed for 11 periods only.

Key findings & knowledge gaps

It is found from the study that the Jamuna River has experienced more erosion on the right bank and accretion on the left bank, up to a maximum of 460 m/y, during the last 30 years accretion occurred in large areas, especially at the upstream and downstream reaches of the Jamuna River, along the left bank. On the right bank, almost the full reach length suffered from serious erosion. The mean short-term erosion rate on the left bank is 227 m/y and that on the right bank is 187 m/y. The mean (range) erosion rates of the left bank is 90 (77) m/y, while that of the right bank is 75 (73) m/y, respectively.

In case of chars or islands dynamics, the total area of islands remained approximately constant over the study period but changes only happened to their shape and locations. From the frequency analysis on changes to the islands within the Jamuna River, islands of area bigger than 150 ha are more stable than small islands of area less than 50 ha, which tends to be very unstable and subjected to fairly major changes as observed in this 1973-2003 study period. These new findings about the riverbank migration, and changes to the islands, of the Jamuna River will be useful for implementing any future erosion management plan, or bank protection measures for the river.

An approach to predict the yearly bank erosion rates of Jamuna River: An application of the correlation of bank shear stress and river discharge

M.Khan, M.M.Ali

IJEDR, Volume 4, Issue 2, 2016, Pages 1180–1185

(Ref: C.18)

Summary

In this study hydraulic bank erosion rate has been quantified with the help of analytical formulae and 2-dimensional numerical model. A 2-dimensional morphological model was developed for the selected reach of Jamuna River using the modeling platform MIKE 21C. After calibrating the erosion trends of Jamuna River for 2012, the model was simulated for different hydrologic events to estimate the erosion rates. The erosion rates were used to calculate bank shear stress. Since primary discharge data was not available at different reaches, model simulated discharge for different hydrologic events were utilized to correlate it with bank shear stress. This correlation paved a way to estimate bank shear stresses from the river discharges at respective reaches for the hydrological event of 2013, which in turn offered an opportunity to obtain erosion rate for the same event. The erosion rates thus obtained was compared to that revealed by satellite imagery. The outcome of the comparison represents that the erosion rates calculated by the aforementioned approach was very close to the observed ones.

Methodology

A two dimensional model of the study site (160km reach of Jamuna River from offtake of Teesta River to 70km downstream of Bangabandhu Bridge) has been developed using the modeling platform MIKE 21C. The hydrodynamics & morphology of the model was calibrated and then the model was simulated for different hydrological flood events. Utilizing the outcomes of scenario simulations a relationship between τ_a and discharge was established for five erosion prone reaches. The relationship thus obtained was used to calculate the bank erosion rate from the discharge after the passage of hydrological event 2013. Erosion rates for the year 2013 have been calculated from τ_a of the corresponding model simulated discharges indicated by the correlation equation. The calculated erosion rate was compared to the erosion rate depicted by the satellite imagery to evaluate the fitness of the derived relationship.

Key findings & knowledge gaps

The fluvial bank erosion formula and 2-D model were used to establish relationship between τ_a and discharge at individual reaches. Model simulated bank erosion rates for different hydrologic events were utilized to calculate τ_a for respective hydrological events. From the regression relationships, it is found that simulated boundary shear stress monotonically increases with the average flow discharge. The satisfactory correlations between bank shear stress & average flow over the monsoon, it can be said that bank erosion rate are linked directly to the flow discharge regime. The predicted erosion rates were evaluated by comparing bank erosion rates derived from the correlation with those estimated by remotely sensed imagery. It is evident from the figure that observed & predicted erosion rates fall very close to the 1:1 line for four out of five erosion prone reaches.

Long-term Bank Erosion Processes of the Jamuna River

CEGIS, 2007, Prepared for JMREMP
(Ref: C.5)

Summary

The main objective of this study is to understand the long-term erosion processes of the Jamuna River. To perform the study objectives, time series satellite images (1973-2007) were used to delineated the bankline of Jamuna River. By superimposing the banklines, historical changes in morphology was observed. The total amount of erosion and accretion, erosion pattern, rate of erosion, bankline migration, widening of river, temporal and spatial variation of erosion were mainly analysed in this study. In addition, relation of erosion with discharge and long term prediction of bankline migration were also done on the basis of 1992 bankline. From the analyses, the average rate of erosion in Jamuna River was found about 2,000 ha/y. Though the rate of erosion varies significantly from the left bank to the right, erosion was severe from the downstream of Sariakandi to the upstream of Sirajganj at right bank. On the other hand, the river has penetrated about 2 km during the last 12 years along the left bank near Bahadurabad. The average life span of eroding bend of main channels was also studied here and found that the median life span of different categories of bends varies within a small range from 4 to 5 years.

Methodology

The study area contains about 240 km long reach of Jamuna River starting from the international border of Bangladesh to the confluence with the Ganges River. The primary data source of this study is satellite images. Analyses were done using time series banklines that were delineated on geo-referenced satellite images. Finally after superimposing the banklines with one another, different types of analysis have been carried out.

Key findings & knowledge gaps

From the analysis, it is found that the magnitude and rate of erosion in Jamuna River vary temporally and spatially. From 1970s the mean annual rate of erosion increased and reached its maximum in 1980s. During 1990-2007, erosion along the river has been decreasing rapidly. It has been observed that the annual rate of erosion was at maximum during the two very large floods in 1988 and 1998. The rate of erosion is about 40 to 50% higher along the left bank than that of the right bank. The study also reveals that the annual rate of erosion increases with the annual maximum flood discharge. The rate of erosion along the left bank is much more sensitive to the annual maximum discharge than the right bank.

The rate of erosion along different reaches of the right bank is sensitive to the presence of perennial (main) flanking channels than the left bank. The life span of meandering bends of the main channel varies widely from one year to several years. The average life span of such channels along the right bank is 4 to 5 years, whereas it is about 3 to 4 years for the channels along the left bank. Detailed study can be undertaken to determine the characteristics of the bank materials of both banks of the river in terms of their erodibility.

Numerical simulation of river meandering with self - evolving banks.

Asahi, K., Shimizu, Y., Nelson, J., & Parker, G.
Journal of Geophysical Research: Earth Surface, 2013, 118(4), 2208-2229.
(Ref: C.2)

Summary

The paper presented a computational model based on a 2-dimensional flow and sediment model combined with a planform model that includes bank erosion, land accretion and channel cutoffs. The main achievement of this model is the ability to capture the coevolution of channel sinuosity and width, which is not possible using simpler models that do not consider accretion.

Methodology

Two-dimensional depth-averaged continuity and momentum equations were used in the flow model. Those equations were transformed into a moving boundary-fitted coordinate system. Sediment transport was calculated using a bed-load formula, which included the effect of helical flow and bed slope. The Exner equation was solved to update the bed levels. Bank erosion was calculated from near-bank conditions, including a slump block model. A land accretion model was also included, which was based on a prescribed time-scale over which dry cells become land. The model also included a channel cutoff description based on geometry, i.e. cutoffs occur when the channel crosses its own path, resulting in instantaneous realignment of the channel in the model.

Key findings & knowledge gaps

Several numerical test cases were conducted to demonstrate the importance of the various parameters, especially the temporal variation of the flows and the time-scale for land formation (accretion) versus the time-scale for flooding. Extension of the numerical model from laboratory to field scale will be made possible through the determination of the relevant field-scale input parameters. This represents a challenge for future research.

5 POLDER DRAINAGE AND MANAGEMENT

5.1 Introduction and Synopsis

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.

The construction of the polders has greatly reduced the tidal volume, the flow velocities in the peripheral rivers therefore decreases (unless they carry a significant through-flow) and the size of the peripheral rivers decrease significantly though siltation. As a result the tidal variation diminish and especially low tide levels increases preventing effective drainage of the polders creating widespread water logging 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.

In order to address these challenges, ‘tidal river management (TRM)’ 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.

5.3 Summary of Selected Papers

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).
(Ref: D.1)

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 Sundarban (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.

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 aspect 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 statistical 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.

6.2 List of Publications Reviewed

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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 5.1). 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.

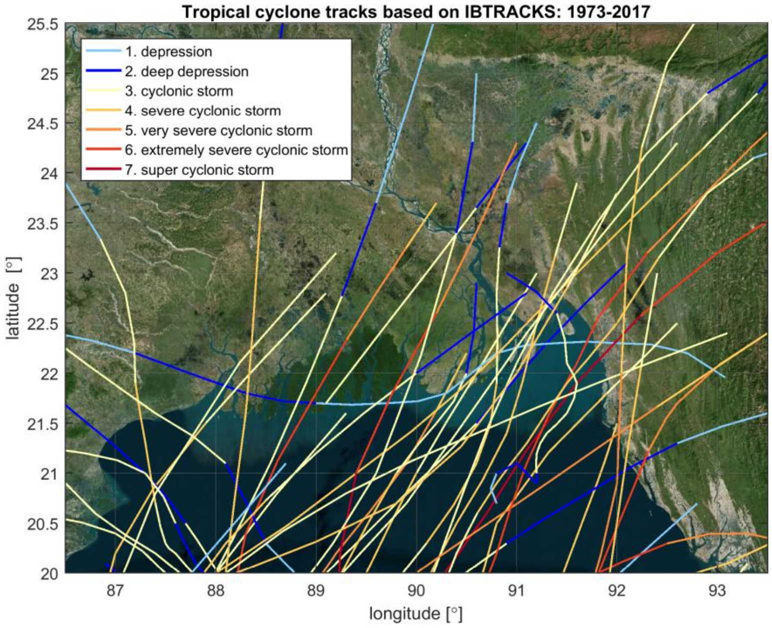

FIGURE 6.1: TROPICAL CYCLONE (TC) TRACKS AND INTENSITY BASED ON THE IBTRACKS DATABASE. HERE THE JOINT TYPHOON WARNING CENTER FOR THE INDIAN OCEAN (IO) WAS USED AS DATA SOURCE. THE TRACKS ARE COLORED-CODED BASED ON THE INDIA METEOROLOGICAL DEPARTMENT (IMD).

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/rain water) 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%.

Brahmaputra basin

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/rain water) are expected to increase.

Table 1 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:

Ganges basin

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.

Brahmaputra basin

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.

Global warming and changes in the probability of occurrence of floods in Bangladesh and implications

M. MonirulQader Mirza
Global Environmental Change
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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 type of paper has been reviewed and tried to fuscous 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 Bagladesh: 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 peakdischarges ofthe 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 of1 987,1987 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 others models. For Bharmaputra 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.

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
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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 analyzed 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 analyzed 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.

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
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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 producechanges 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 topical 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 fresh water 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.

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

(Ref: E.31)

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 analyze uncertain-ties 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 analyzed 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 m^3s^{-1}, which was slightly larger than the average observed stream flow (22,345 m^3s^{-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 decisions. 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 SALINITY

7.1 Introduction and Synopsis

Impact of SLR on salinity intrusion is highly significant in the coastal area of Gorai river network in the South West region of Bangladesh. The sea level rise increases the salinity as well as the salinity intrusion length in the river. 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 Passur River (Bhuiyan 2012). Model simulation results show that the salinity intrusion due to SLR is higher in the western part.

In Barisal, Patuakhali, Barguna and Pirojpur districts enormous amount of freshwater suitable for irrigation of agricultural crops are available throughout the year at present. The quantity is likely to decrease due to the combined effects of external drivers such as inadequate trans-boundary flows, climate change and land use change, which will increase river salinity during the dry season (Z.H. Khan 2015). In 10 years period, 11% of the area suitable for irrigation is likely to be decreased under a moderate climate change scenario (A1B). During the period, even with 22 cm sea level rise, salinity of the rivers in Barisal, Barguna, Patuakhali and Jhalokathi districts will not exceed 2 ppt as there will be high availability of river water for irrigation in these regions. However, this fresh water 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.

7.2 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.

7.3 Summary of Selected Papers

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
(Ref: F.1)

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 21^{0}30'N to 24^{0}00' N and longitude 88^{0}50' E to 90^{0}10' 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 have 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 modeling efficiency index (EF); the goodness-of-fit (R^2) 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 Passur 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.

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
(Ref: F.2)

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 fresh water 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. On the basis of current hydrological situation, appropriate mathematical models has 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 modeling 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.

8 ENVIRONMENTAL AND SOCIAL

8.1 Introduction and Synopsis

The Ganges-Brahmaputra-Meghna river basin, which runs from the Himalayas through Bangladesh, is the third largest river basin in the world. Bangladesh, a vast river delta that barely rises above the sea at the best of times, is buffeted by natural forces including flooding rivers and cyclones blowing in from the Bay. Over decades, the country has developed defenses: warning systems, storm shelters, salt-resistant crops, and 139 polders near the coast—a 5700-kilometer network of walls to protect farmland from inundation. But human-made infrastructure is not infallible and can cause problems of its own. That's starkly apparent across the country's polders, which have disrupted a fragile standoff between water and land and are now straining to hold back the water. As climate change compounds that threat with rising seas and stronger storms, Bangladesh Water Development Board who have spent years building barricades is considering what was once unthinkable: letting the water in (Cornwall & Tonmoy 2018). It's resilience by bending, not resisting. And it's tougher to do than it sounds.

The coastal zone is an interface between the land and sea, which comprised of a continuum of coastal land, intertidal area, aquatic systems including the network of rivers and estuaries, islands, transitional and intertidal areas, salt marshes, wetlands, and beaches (Cicin-Sain et al. 1998). Coastal zones are constantly undergoing changes in shape and environment due to natural processes and anthropogenic interventions. These zones are important because much of the world's population inhabit such zones. Additionally, coastal regions are a rich ecosystem with estuaries, mangroves, beaches, tidal flats, and offshore islands providing great biodiversity (Coombes, 2017). Coastal zones change continually because of the dynamic interaction between the oceans and the land. These zones are highly vulnerable to both natural and anthropogenic perturbations. Over exploitation of the abundant natural resources as well as effects of natural disasters like tropical cyclones and associated storm surges have degraded coastal environments almost everywhere. Constant stress and strain from both natural processes and human interference affect the living conditions of the coastal residents, creating physical, socio-economic, and ecological vulnerabilities and challenging their ability to cope, an ability that has evolved over the centuries. Rampant pollution, coastal erosion, changing patterns of land use, and salinization also threaten the resilience of coastal environments, ecology, and the livelihoods of the residents.

The convoluted coastline of Bangladesh exhibit the classic scenario of habitat diversification where the coastline is intersected by thousands of creeks and hundreds of rivers in the southwest including the Sundarban, then east of the Sunderban in the south central there are countless islands, constantly disappearing and emerging, swallowing some and creating new niches for others. Further east of the Ganges-Brahmaputra delta, is a more stable coast that has remained unchanged for a long time (Chowdhury 2019). The 710km coastline has been proposed into four regions to suit the purpose of this project – “Long Term Monitoring, Research and Analysis of Bangladesh Coastal Zone (Sustainable Polders Adapted to Coastal Dynamics”. The regions are 1) Ganges Tidal Plain (west) – includes Sundarban mangrove forest extending from the mid-river/left bank of Raimangal River in the west to Baleshwar River in the east, 2) Ganges Tidal Plain (east) – covers areas between Baleshwar River in the west to Tentulia River in the east, 3) Meghna Deltaic Plain – comprises areas from Tentulia River in the west to east of Hatiya Island and 4) Chittagong Coastal Plain – encompasses coastal areas east of the Hatiya Island to the southern eastern tip of the mainland Badarmokam (in Teknaf). Lowlands along the coast have a crucial function into environmental management because lowlands are able to accommodate and provide water, prevent coastal abrasion, prevent sea water intrusion, oxygen providers and have unique biodiversity.

In the 1960s, 123 polders (low-lying tracts of land enclosed by earthen embankments), including 49 sea-facing polders, were constructed to protect low-lying coastal areas from tidal floods and salinity intrusion in southern Bangladesh. With the dikes surrounding the floodplains, the land is protected from the tides. One-way sluice gates regulate the water flow from the polder area out into the channel. Thus the land within the polder zone is free of waterlogging, salinity intrusion and can be used for farming and other agricultural work. Instrumental in the region’s agriculture development, they have also played a key role in mitigating the loss of life and damage during tidal surges.

Overall, the potential of polders as a barrier to salinity greatly relies on a need for better management and maintenance anticipating future changes of climate, combined with policies ensuring controlled and sustainable management of shrimp farming. But river siltation, outdated sluice gate designs and illegal dike excavation reduced the system's effectiveness. In fact, in many areas, siltation has raised the river or other water channel bed to such levels that the polder region itself effectively lies below the water level. As a result, when sluice gates are opened, instead of water running from the polder lands, outside water rushes in, resulting in long-lasting water logging and flooding (Nowreen et al. 2013).

Inland navigation has always been a principal means of transport, especially in the coastal region. During last 15-25 years, considerable and rapid deterioration has taken place in the river system and navigation routes through massive siltation, instability of rivers and closure of channels for flood control purposes. The coastal embankment project has seriously hampered the local riverine transport system and has been identified as the cause of siltation in the Mongla Port area (WB 2013).

With climate change emerging as the greatest concern for the future in many countries, coastal regions across the globe has received increasing attention from researchers, policy makers, general public, and many others because coastal residents are more vulnerable than anyone in the world to climate change. These residents are on the front lines; because they will be the first victims of climate change–induced sea level rise, which will invariably displace many residents from their ancestral homes. Rising sea levels are likely to inundate large areas of coastal regions particularly in countries located in the tropics and Bangladesh is no exception. Such inundation, among other things, will have severe consequences on coastal water resources; fresh water, for instance, will be less available because of increasing salinity in soil and water. Both will destroy coastal resources, ecology, and the livelihoods of its impoverished residents.

Bangladesh will be among the most affected countries in South Asia, with rising sea levels and more extreme heat and more intense cyclones threatening food production, livelihoods and infrastructure. Cyclone Sidr flooded 3.45 million households. A potential 10-year return cyclone in 2050 could expose 9.7 million people to more than three meters of inundation affecting agriculture and lives (World Bank 2013).

Environmental changes induced by development projects in other sectors has mostly affected the wetlands/aquatic ecosystem including coastal areas and in particular the aquatic resources predominantly the fishery sector and aquatic biodiversity. In the coastal areas, the natural nursery and grazing grounds of many marine and estuarine fishes and prawns have been eliminated by the coastal embankments (Hossain et al. 2013).

The expansion of shrimp cultivation threatens mangroves and increasing soil salinity. In the long term several ill effects of shrimp farming are likely to be felt unless some of the trends are corrected immediately. First, the lure of high income is inducing shrimp farmers, particularly the large ones, to illegally force small landowners to lease their land for shrimp culture (by forcing saline water into their fields) and also to encroach upon mangrove forest land whether legally or illegally, thus initiating a process of self-destruction by breaking the food chain from detritus to shrimp in those forests. If the mangroves vanish, shrimps including many others shall vanish too. Shrimp farming is giving rise to other environmental problems, which include loss of grazing land, loss of sources of fresh water, water pollution, soil quality degradation and a fall in tree cover owing to the rise in salinity. With the spread of salinity there is a reduction in the agricultural crop production.

Although polders were initially constructed to prevent saline water intrusion, this has also become a social issue - the wealthy and influential shrimp-farmers control of the sluice gates in order to allow in saline water for their own business purposes. High salinity is very detrimental to rice crop productivity, generating widespread discontent amongst the more vulnerable rice farmers. Therefore, this ongoing elite capture has important implications concerning the power dynamics in water resource management within the polders (ESCAP 1987).

Problems that arise from the sheer size of each polder and the conflicting interests of those who farm within them are only exacerbated by a lack of clear responsibility and accountability for polder management and maintenance amongst formal government institutions and informal groups (CGIAR 2016).

The trajectory of development in Bangladesh reflects a tight coupling between dynamic environmental conditions such as flood and drought cycles, dry vs. wet season salinization and sedimentation, variable subsidence, and e.g., demographic change and economic growth (Nicholls et al., 2018). Specific to the coastal area, undiversified rural economies and well-being are directly dependent on agriculture and aquaculture, therefore fluctuating environmental conditions mean that income and subsistence are also highly variable from year to year (Adger et al., 2018). For example, crop productivity in the dry season is constrained by soil and pore water salinity (Baten et al., 2015). The accumulation of salts in the soils of agricultural regions occurs progressively when water evaporates from irrigated or flooded fields, leaving residual minerals. Sufficient monsoon rainfall acts to flush salinity that has accumulated during the dry season. However, if total rainfall amounts are below average, or monsoon precipitation is delayed later into the summer, soil salinity remains high and crop production—particularly Aman rice paddy production—will be decreased. This is particularly true for southwest Bangladesh, where the soils are less fertile compared with other agricultural regions of the country (FRG, 2012). Extreme events such as cyclones can also cause inundation of agricultural land both inside and outside of polders with sea water, and typically requires two to three monsoon seasons to return the soils to their pre-inundation salinity levels (Rabbani et al., 2013). The salinity problem is further exacerbated by the move from rice production to brackish water shrimp and fish farming in coastal areas of Bangladesh. Although shrimp production is economically valuable to the land owners, the deliberate inundation of polders with brackish or salt water contaminates soils and groundwater in adjacent areas and causes detrimental effects on both biodiversity and crop production of the region (Kartiki, 2011). In terms of sedimentation, coastal embankments and poorly functioning sluice gates have restricted sediment from entering polders (Auerbach et al., 2015). This has exacerbated rates of subsidence and water logging of the land surface inside polders. Likewise, the embankments have restricted natural soil replenishment that was historically renewed each year during monsoon flooding, resulting in decreased soil fertility and an increase in application of artificial fertilizers (Hossain et al., 2016).

Yet despite past and on-going investments in constructing and maintaining the polder embankments and sluice gates, agricultural productivity is low and poverty is rife. The primary challenge is water management – as a result of the physical environment, the lack of maintenance of the internal polder canals (former natural drains), the conflicting interests surrounding the operation of the sluice gates, and lack of awareness of alternatives (CGIAR 2016).

After more than a decade of meeting the designated objective of increasing productivity in agriculture, the South West coastal polders of Bangladesh have ended up as different man-made disasters. The failure of the polders to deliver the intended outcome is basically attributed to the lack of understanding of their hydro-morphological characteristics, inadequacy in their operation and maintenance, and failure to take into account their social relationship and culture roles. Changes in socioeconomic settings have also forced changes in the designated functions of the polders, but now the emerging context of climate change has become a major issue in rationalizing the coastal polders (Nowreen et al. 2013).

Environmental Impacts of subsidence:

Environmental impacts of subsidence are actually closely connected to other subsidence impacts (i.e., economic and social). Environmental impacts are actually indirect effects of subsidence, and mostly generated by lowering down of land surface and malfunction of river, canal and drainage flow systems due to subsidence phenomena. However, biodiversity, habitat and the ecological services of that particular area are directly impacted. Due to its relatively longer time response, the environmental impacts of subsidence are usually realized after quite sometimes when the impacts are already disrupting our daily activities and ecological services (Viets et al. 1979).

Category	Representation of Impact	Level of Impact
Environmental	changes in river canal and drain flow systems	indirect
	frequent coastal flooding	indirect
	wider expansion of flooding areas	indirect
	inundated areas and infrastructures	indirect
	increased inland sea water intrusion	indirect
	deterioration in quality of environmental condition	indirect
	loss of biodiversity, changes in species composition, habitat alteration	direct
Economic	increase in maintenance cost of infrastructure	indirect
	decrease in land and property values	indirect
	abandoned buildings and facilities	indirect
	disruption of economic activities	indirect
Social	deterioration in quality of living environment and life (health, sanitation, waste production, etc.)	indirect
	disruption of daily activities	indirect

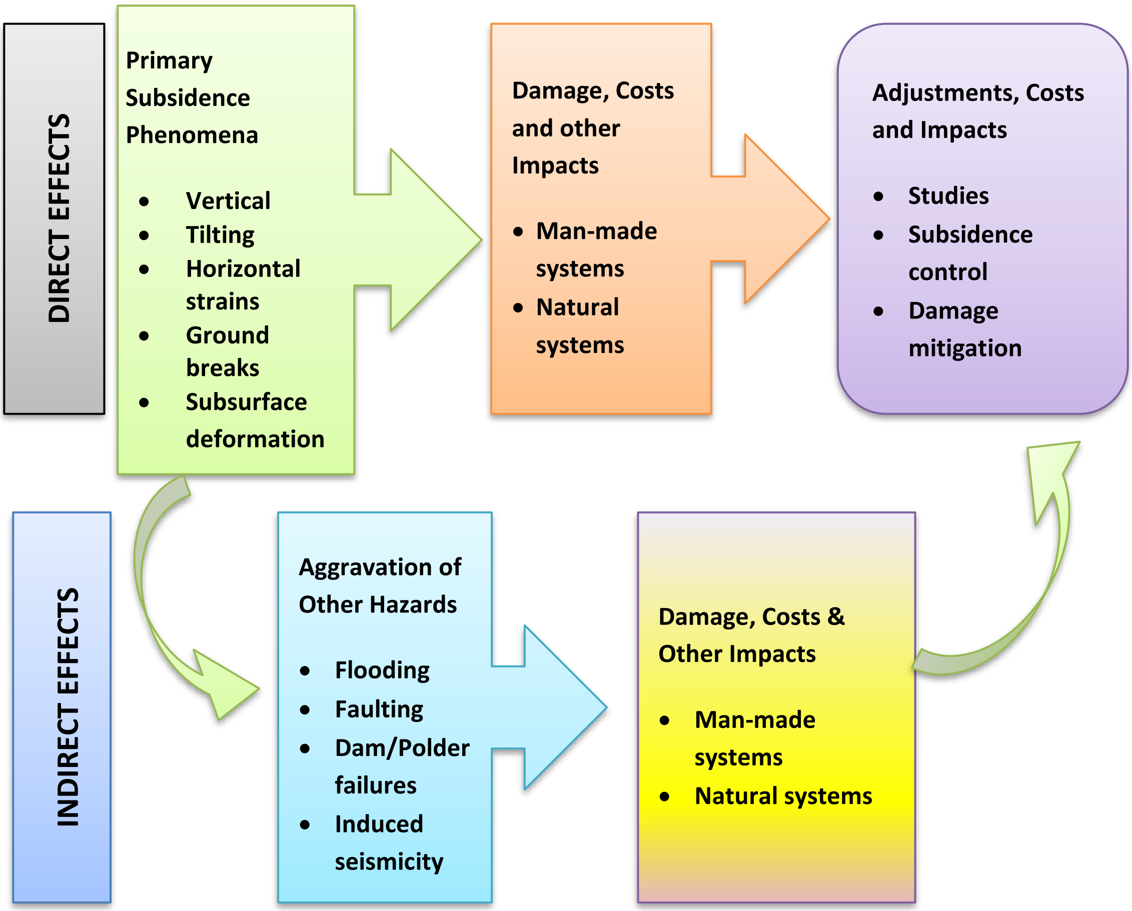

Fig. 8.1: Direct and indirect environmental impacts of subsidence. (Source: Viets et al. 1979)

Summary of operational Environmental Action Plans prepared by the Contractor under CEIP-1.

The Environmental Action Plans (EAP) [prepared by the Contractor for operation during the construction work in the Polders under Package 1, 2 and 3 of CEIP-1 to comply with the respective polder Environmental Impact Assessment (EIA) reports] have stressed in taking actions to prevent any form of pollution on land or in water (coastal, estuary, surface, or groundwater), preservation of flora and fauna, noise pollution, vibrations or dust, solid/liquid waste management, sanitation, embankment protection by plantation/turfing using indigenous plant species and to comply with the Occupational Health and Safety and Public Health and Safety during the course of the works. Moreover, the contractor's operational guidelines will comply with the recommendations of the Department of Environment (DoE), Bangladesh and the Environmental Safeguard Policies of World Bank.

8.2 List of Publications Reviewed

G.1 Abdullah, H. M.; Mahboob, M. G.; and Banu, M. R. 2013. Monitoring the drastic growth of ship breaking yards in Sitakunda: a threat to the coastal environment of Bangladesh. Environ Monit Assess (2013) 185: 3839. https://doi.org/10.1007/s10661-012-2833-4.

G.2 Abu Muhammad Shajaat Ali. 1995. Population pressure, environmental constraints and agricultural change in Bangladesh: examples from three agro-ecosystems. Agriculture, Ecosystems & Environment. Volume 55, Issue 2, September 1995, Pages 95–109

G.3 Adger, W.N. et al. (2018) Ecosystem services, well-being and deltas: current knowledge and understanding. Palgrave Macmillan, p. 3.

G.4 Alam, Mohammad Zahangeer, Lynne Carpenter-Boggs, Shishir Mitra, Md. Manjurul Haque, Joan Halsey, M. Rokonuzzaman, Badhan Saha,and M. Moniruzzaman. 2017. Effect of Salinity Intrusion on Food Crops, Livestock, and Fish Species at Kalapara Coastal Belt in Bangladesh. Journal of Food Quality Volume 2017, Article ID 2045157, 23 pages https://doi.org/10.1155/2017/2045157.

G.5 Ali, A.M.S. (1995) Population pressure, environmental constraints and agricultural change in Bangladesh- examples from three agroecosystems; Agriculture, Ecosystems & Environment, Volume 55, Issue 2, September 1995, Pages 95–109.

G.6 Andres Payo, Anirban Mukhopadhyay, Sugata Hazra, Tuhin Ghosh, Subhajit Ghosh, Sally Brown, Robert J. Nicholls, Lucy Bricheno, Judith Wolf, Susan Kay, Attila N. Lázár, and Anisul Haque. 2016. Climatic Change (2016) 139: 279–291. DOI 10.1007/s10584-016-1769-z.

G.7 Auerbach, L. W., S. L. Goodbred Jr, D. R. Mondal, C. A. Wilson, K. R. Ahmed, K. Roy, M. S. Steckler, C. Small, J. M. Gilligan, and B. A. Ackerly. 2015. Flood risk of natural and embanked landscapes on the Ganges–Brahmaputra tidal delta plain. Nature Climate Change. Volume 5:153–157.

G.8 Baten, M., L. Seal, and K. Lisa. (2015) Salinity intrusion in interior coast of Bangladesh: Challenges to agriculture in South-Central Coastal Zone. American Journal of Climate Change 4: 248–262.

G.9 Brammer, Hugh. 2014. Bangladesh's dynamic coastal regions and sea-level rise. Climate Risk Management (1): 51–62.

G.10 Brown, S., and Nicholls, R. J. 2015. Subsidence and human influences in mega deltas: the case of the Ganges–Brahmaputra–Meghna. Sci Total Environ. 527–528: 362 - 374. doi:10.1016/j.scitotenv.2015.04.124.

G.11 CGIAR. 2016. The Polder Promise: Unleashing the productive potential in southern Bangladesh. CGIAR Research Program on Water, Land and Ecosystems (WLE), International Water Management Institute (IWMI), 127 Sunil Mawatha Pelawatte, Battaramulla, Sri Lanka.

G.12 Chowdhury, S. U. 2017. Mudflats: An unseen world worth preserving. The Daily Star. April 14, 2017.

G.13 Cicin-Sain, Biliana; Robert W. Knecht; Dosoo Jang; and Gregory W. Fisk. 1998. Integrated coastal and ocean management: concepts and practices. Island Press. Virginia, USA. 517 pages. ISBN: 1559636033, 9781559636032.

G.14 Coombes, M. A. 2017. Biogeomorphology. In: Richardson, D., Castree, N., Goodchild, M., Kobayashi, A., Liu, W. and Marston, D. (eds.) International Encyclopedia of Geography: People, the Earth, Environment and Technology. Wiley-Blackwell, Oxford. ISBN: 9781118786352.

G.15 Cornwall, Warren, and Tanmoy Bhaduri. 2018. https://pulitzercenter.org/reporting/sea-levels-rise-bangladeshi-islanders-must-decide-between-keeping-water-out-or-letting-it. Science Magazine. Pulitzer Center.

G.16 Dasgupta S, Islam, M. S., Huq, M., Huque, Khan Z., Hasib, M. R. 2019. Quantifying the protective capacity of mangroves from storm surges in coastal Bangladesh. PLoS ONE 14(3): e0214079. https://doi.org/10.1371/journal.pone.0214079.

G.17 Elizabeth Humphreys 2015, Productive, profitable, and resilient agriculture and aquaculture systems

G.18 ESCAP. 1987. Coastal Environmental Management Plan for Bangladesh. Vol. 1. Summary. Economic and Social Commission for Asia and the Pacific, United Nations. Bangkok, Thailand. 32 pages+Maps.

G.19 FRG. (2012) Fertilizer recommendation guide-2012. Soils publication no. 32. Dhaka: Bangladesh Agricultural Research Council (BARC). https://archive. org/details/ Fertilizer Recommendation Guide 2012_201509.

G.20 Hossain, M.S., J.A. Dearing, M.M. Rahman, and M. Salehin. (2016) Recent changes in ecosystem services and human well-being in the Bangladesh coastal zone. Regional Environmental Change 16 (2): 429–443.

G.21 Hossain, M. S., Uddin, M. J. and Fakhruddin, A. N. M. 2013. Impacts of shrimp farming on the coastal environment of Bangladesh and approach for management. Rev Environ Sci Biotechnol (2013) 12: 313. https://doi.org/10.1007/s11157-013-9311-5.

G.22 Hsiao-Wen Wang, Cheng-Wei Lin, Chun-Yao Yang, Chung-Feng Ding, Hwung-Hweng Hwung and Shih-Chun Hsiao. 2018. Assessment of Land Subsidence and Climate Change Impacts on Inundation Hazard in Southwestern Taiwan. In: Special Issue: Sustainable Development of Tidal Areas: Climate Change and Environmental Impacts. Editors: Prof. Ruey-Chy Kao, Prof. Hsiao-Wen Wang, and Dr. H.P. Ritzema. Irrigation & Drainage. Volume 67, Issue S1: 26 – 37.

G.23 Islam, Md. Feroz, Biswa Bhattacharya, and Ioana Popescu. 2019. Flood risk assessment due to cyclone-induced dike breaching in coastal areas of Bangladesh. Nat. Hazards Earth Syst. Sci., 19, 353–368, 2019 https://doi.org/10.5194/nhess-19-353-2019.

G.24 Islam, F., M. Rahman, S. S. A. Khan, B. Ahmed, A. Bakar, and M. Halder. 2013. Heavy metals in water, sediment and some fishes of Karnofuly River, Bangladesh. Poll Res. 32 (4): 715-721.

G.25 Kartiki, K. (2011) Climate change and migration: a case study from rural Bangladesh. Gender and Development 19 (1): 23–38.

G.26 Linta Rose and Prasad K. Bhaskaran. 2015. Tidal Prediction for Complex Waterways in the Bangladesh Region. Aquatic Procedia 4 (2015): 532 – 539. https://www.sciencedirect.com/science/article/pii/S2214241X1500070X.

G.27 Nicholls, R.J. et al. (2018) An integrated approach providing scientific and policy-relevant insights from Southwest Bangladesh. Palgrave Macmillan, p. 54.

G.28 Nowreen, Sara; Rashed Jalal, Msa Khan. 2013. Historical Analysis of Rationalizing South-West Coastal Polders of Bangladesh. January 2013. Water Policy 16(2). DOI: 10.2166/wp.2013.172.

G.29 Rabbani, G., A. Rahman, and K. Mainuddin. (2013) Salinity-induced loss and damage to farming households in coastal Bangladesh. International Journal of GlobalWarming5(4):400–415.

G.30 Viets, V. F., C. K. Vaughan, and R. C. Harding. 1979. Environmental and economic effects of subsidence. Earth Sciences Division, Lawrence Berkeley Laboratory, University of California. Report prepared for the U.S. Department of Energy by EDAW-Earth Sciences Associates, Palo Alto, California. 251 pages.

G.31 Wang, Hsiao-Wen, Cheng-Wei Lin, Chun-Yao Yang, Chung-Feng Ding, Hwung-Hweng Hwung and Shih-Chun Hsiao. 2018. Assessment of Land Subsidence and Climate Change Impacts on Inundation Hazard in Southwestern Taiwan. In: Special Issue: Sustainable Development of Tidal Areas: Climate Change and Environmental Impacts. Editors: Prof. Ruey-Chy Kao, Prof. Hsiao-Wen Wang, and Dr. H.P. Ritzema. Irrigation & Drainage. Volume 67, Issue S1: 26 – 37.

G.32 Wilson, Carol A., and Steven L. Goodbred Jr. 2015. Construction and Maintenance of the Ganges-Brahmaputra-Meghna Delta: Linking Process, Morphology, and Stratigraphy. Annual Review of Marine Science. Vol. 7: 67-88 https://doi.org/10.1146/annurev-marine-010213-135032.

G.33 World Bank. 2013. Turn Down the Heat: Climate Extremes, Regional Impacts, and the Case for Resilience. Executive Summary. A Report for the World Bank by the Potsdam Institute for Climate Impact Research and Climate Analytics. The World Bank, 1818 H Street NW, Washington, DC 20433, USA. viii + 21pp.

8.3 Summary of Selected Papers

Monitoring the drastic growth of ship breaking yards in Sitakunda: a threat to the coastal environment of Bangladesh.

Abdullah, H.M., Mahboob, M.G., Banu, M.R. 2013. Environ Monit Assess (2013) 185: 3839.
https://doi.org/10.1007/s10661-012-2833-4.
(Ref. G.1)

The vast coastal and marine resources that occur along the southern edge of Bangladesh make it one of the most productive areas of the world. However, due to growing anthropogenic impacts, this area is under considerable environmental pressure from both physical and chemical stress factors. Ship breaking, or the dismantling and demolition of out-of-service ocean-going vessels, has become increasingly common in many coastal areas. To investigate the extent of ship breaking activities in Bangladesh along the Sitakunda coast, various spatial and non-spatial data were obtained, including remote sensing imagery, statistical records and published reports. Impacts to coastal and marine life were documented. Available data show that ship breaking activities cause significant physical disturbance and release toxic materials into the environment, resulting in adverse effects to numerous marine taxonomic groups such as fish, mammals, birds, reptiles, plants, phytoplankton, zooplankton and benthic invertebrates. Landsat imagery illustrates that the negatively impacted coastal area has grown 308.7% from 367ha in 1989 to 1,133ha in 2010. Physicochemical and biological properties of coastal soil and water indicate substantially elevated pollution that poses a risk of local, regional and even global contamination through sea water and atmospheric transport. While damage to the coastal environment of Bangladesh is a recognized hazard that must be addressed, the economic benefits of ship breaking through job creation and fulfilling the domestic demand for recycled steel must be considered. Rather than an outright ban on beach breaking of ships, the enterprise must be recognized as a true and influential industry that should be held responsible for developing an economically viable and environmentally proactive growth strategy. Evolution of the industry toward a sustainable system can be aided through reasonable and enforceable legislative and judicial action that takes a balanced approach, but does not diminish the value of coastal conservation.

Tidal Prediction for Complex Waterways in the Bangladesh Region.

Linta Rose and Prasad K.Bhaskaran. 2015. Aquatic Procedia. Volume 4, 2015, Pages 532-539.
(Ref. G.26)

The navigational aspects of marine transport and its maneuverability require precise knowledge on tides. Information on time varying water levels, magnitude and direction of tidal currents is quite critical in coastal waterways and estuarine environment. Real-time water levels along with other hydrodynamic parameters are used in almost all major ports for effective operations throughout the year. Also various coastal engineering projects require precise information on site-specific water level elevations. There is a rapid expansion of coastal infrastructure in the recent times, and therefore it is very essential to have reliable water level prediction system that caters the need for coastal engineers, port and harbour activities etc. The Sea Level Processing Package (SLPR2) developed by the University of Hawaii Sea Level Center in collaboration with National Oceanographic Data Center (NODC) provides reliable estimate of location specific sea level information. SLPR2 performs three primary tasks that include tidal analysis and prediction, quality control, and filtering. Harmonic tidal analysis using linear least square produces the relevant tidal constituents of a specific region. High frequency data (preferably one-hour duration) for a minimum duration of one complete year would suffice the tidal analysis phase in SLPR2. The tide prediction algorithm used in the present study uses a maximum of 68 harmonic constituents. The region of interest is the head Bay of Bengal region located along the east coast of India. Preliminary analysis of measured sea level data indicate that tide gauges located along Bangladesh has research quality data, and therefore used in this study. Station data from seven locations viz; Hiron Point, Khepupara, Charchanga, Chittagong, Khal No.10, Cox's Bazaar, and Teknaf all located in Bangladesh were used for tidal analysis, and thereafter the predictive capability of SLPR2 for one-year period was investigated. There are exceptions at two stations, Teknaf (comprising of 87% observed data) and Khal No.10 (99% of observed data), and remaining five stations are free from data gaps. In a hydrographic perspective, the Bangladesh region has complex network of waterways, and bottom topography have several detached shoals. Tides enter the Bangladesh coast through two submarine canyons, reaching Hiron Point and Cox Bazaar at almost the same time. Amongst the principal constituents, dominant modes are exhibited by M2 and S2 whose natural oscillation periods are 12h 25min, and 12h respectively. The results from SLPR2 indicate considerable seasonal variation in water level prediction during the monsoon season, attributable to meteorological reasons and excess river discharge, at stations Cox Bazaar and Charchanga. The locations Hiron Point and Khepupara show elevated predicted tides after the onset of monsoon, indicating the presence of seasonal signature resulting from large amplitude of the annual tidal component ‘Sa’. Residual time series produce the de-tidal water level variations attributed due to meteorological effects such as wind, atmospheric pressure and river discharge. Inspection of residual can help to quality control measured data such as datum level correction, and replacement of data voids. The effective shallow nature in North-Eastern Bay produces partial reflections thereby increasing the tidal range. In addition, the seasonal effects of meteorological forcing along with non-linear shallow water interaction can result in number of higher harmonics. Finally, the correlation of tidal prediction between SLPR2 and measurement show a reasonably good match.

Projected changes in area of the Sundarban mangrove forest in Bangladesh due to Sea Level Rise by 2100.

Andres Payo, Anirban Mukhopadhyay, Sugata Hazra, Tuhin Ghosh, Subhajit Ghosh, Sally Brown, Robert J. Nicholls, Lucy Bricheno, Judith Wolf, Susan Kay, Attila N. Lázár, and Anisul Haque. 2016.
Climatic Change (2016) 139: 279–291. DOI 10.1007/s10584-016-1769-z.
(Ref. G.6)

The Sundarbans mangrove ecosystem, located in India and Bangladesh, is recognized as a global priority for biodiversity conservation and is an important provider of ecosystem services such as numerous goods and protection against storm surges. With global mean sea-level rise projected as up to 0.98 m or greater by 2100 relative to the baseline period (1985–2005), the Sundarbans – mean elevation presently approximately 2 m above mean sea level – is under threat from inundation and subsequent wetland loss; however the magnitude of loss remains unclear. Remote and field measurements, geographic information systems and simulation modelling were used to investigate the potential effects of three sea-level rise scenarios on the Sundarbans within coastal Bangladesh. The paper illustrates how the Sea Level Affecting Marshes Model (SLAMM) was able to reproduce the observed area losses for the period 2000–2010. Using the calibrated model and assuming that mean sea-level is a better proxy than the SLAMM assumed mean lower low water for Mangrove area delineation, the estimated mangrove area net losses (relative to year 2000) were 81–178 km2, 111–376 km2 and 583–1393 km2 for relative sea-level rise scenarios to 2100 of 0.46 m, 0.75 m and 1.48 m, respectively and net subsidence of ±2.5 mm/year. These area losses were very small (<10%of present day area) and significantly smaller than previous research has suggested. The simulation also suggested that erosion rather than inundation may remain the dominant loss driver to 2100 under certain scenarios of sea-level rise and net subsidence. Only under the highest scenarios did inundation due to sea-level rise become the dominant loss process.

Brown and Nicholls (2015) reviewed net subsidence (i.e., difference between sedimentation, isostatic rebound and subsidence) rates in the Ganges–Brahmaputra–Meghna delta, reporting 205 measurements based on a range of methods and timescales. Subsidence can result from natural processes of geology and soil compaction, as well as anthropogenic effects due to extraction of water and is also affected by the available sediment supply carried by the river system. Compared with other land uses in the delta (e.g., urban or croplands), the Sundarbans reported the lowest mean (2.8 mm/year) and median (2.0 mm/year) rates of net subsidence. Overall, they found the median rate of subsidence preferable to the mean, as a few single large measurements of subsidence skewed results. Brown and Nicholls (2015) also state that the more recent and shorter term measurements reported higher rates of subsidence, either due to anthropogenic influences or as a result of partial measurement. Thus to reflect these differences, a representative value of −2.5 mm/year of net subsidence in the Sundarbans is used in the SLAMM simulations and assumed to be valid to 2100. Simulations are also run using 0 mm/year and +2.5 mm/year to assess the sensitivity of the results to the uncertainty on net subsidence rate.

Quantifying the protective capacity of mangroves from storm surges in coastal Bangladesh. (G.16)

Dasgupta S, Islam, M. S., Huq, M., Huque, Khan Z., Hasib, M. R. 2019. PLoS ONE 14(3): e0214079.
https://doi.org/10.1371/journal.pone.0214079.
(Ref. G.16)

Mangroves are an important ecosystem-based protection against cyclonic storm surge. As the surge moves through the mangrove forest, the tree roots, trunks, and leaves obstruct the flow of water. Damage to adjacent coastal lands is attenuated mainly by reducing (i) surge height, which determines the area and depth of inundation and (ii) water flow velocity. But the extent of mangrove protection depends on the density of tree plantings and the diameter of trunks and roots, along with an array of other forest characteristics (e.g., floor shape, bathymetry, spectral features of waves, and tidal stage at which waves enter the forest). Making efficient use of mangroves' protective capacity has been hindered by a lack of location-specific information. This study helps to fill that gap by estimating reduction in storm surge height and water flow velocity from mangroves at selected sites in cyclone-prone, coastal Bangladesh. A hydrodynamic model for the Bay of Bengal, based on the MIKE21FM system, was run multiple times to simulate the surge of cyclone Sidr (2007) at the Barisal coast. Estimates of surge height and water flow velocity were recorded first without mangroves and then with mangroves of various forest widths and planting densities, including specific information on local topography, bathymetry, and Manning's coefficients estimated from species' root and trunk systems. The results show a significant reduction in water flow velocity (29–92%) and a modest reduction in surge height (4–16.5 cm). These findings suggest that healthy mangroves can contribute to significant savings in rehabilitation and maintenance costs by protecting embankments from breaching, toe-erosion, and other damage.

Three study areas (a total of seven sites) with existing polders in Bangladesh's southwest coastal region were selected for this hydrological analysis. These sites are located in Bagerhat and Barguna districts, where recurrent cyclones in recent years have been cited as a major reason for high incidence of poverty. The study was conducted primarily with secondary data from the study areas, which did not include protected areas or private land and did not involve endangered or protected species. The three areas selected for the analysis are located (i) at the foreshore of polder 35/1, (ii) adjacent to polder 40/2, and (iii) at the southern foreshore of polder 40/1 in the Sundarbans and central coast. Selection of these three areas was based on storm-surge vulnerability and tidal characteristics (e.g., mud flat accretion/erosion and availability of adequate mangrove afforestation area in the foreshore of the coastal polders)

Effect of Salinity Intrusion on Food Crops, Livestock, and Fish Species at Kalapara Coastal Belt in Bangladesh.

Alam, Mohammad Zahangeer, Lynne Carpenter-Boggs, Shishir Mitra, Md. Manjurul Haque,
Joan Halsey, M. Rokonuzzaman, Badhan Saha,and M. Moniruzzaman. 2017.
Journal of Food Quality Volume 2017, Article ID 2045157, 23 pages https://doi.org/10.1155/2017/2045157.
(Ref. G.4)

Salinity issues constrain both the agricultural and economic development. Salinity causes a hostile environment for the normal crop production throughout the year in the coastal belt of Bangladesh. The organic matter content of the coastal soils is pretty low (1.0–1.5%). Nutrient deficiencies of N and P are quite common in saline soils. Micronutrients such as Cu and Zn are both widespread. As a result, the reduction of food crop production in the coastal region has significant impact on the national economy of Bangladesh. This threat is elevated because of the reduction of fresh water flow from upstream tidal flow and groundwater discharge. The Kalapara coastal belt is one of the nearest areas to the Bay of Bengal in Bangladesh. This bay is one of the greatest sources of saline water. The electrical conductivity is an indicator of this saline water. This conductivity increases the salt in soil and water across the coastal belt in Bangladesh. This salt water from the Bay of Bengal increases many ions in the soil and water in this coastal region such as chloride (Cl−), sulfate (SO4), sodium (Na+), potassium (K+), calcium (Ca2+), magnesium (Mg2+), bromide (Br−), phosphate (PO4), nitrite (NO2), nitrate (NO3), and sulfate (SO4).

Salinity has caused significant negative effects on agricultural production. This research is focused on the vulnerabilities of soil and water salinities on crop, fish, and livestock production across the Kalapara coastal belt of Bangladesh. Several parameters were measured as indicators of salinity. The electrical conductivity of water was found to be significant with TDS, F−, Cl−, SO4, Na+, K+, Ca2+, Mg2+, NO2, and PO4. Chloride was found to be identical with Na+, K+, Ca2+, Mg2+, Br−, and Electrical conductivity, F−, Cl−, Na+, K+, and Mg2+ were all found to be higher than the recommended values. Similarly, soil conductivity was found significant with TDS, Cl−, SO4, Na+, F−, NO2, NO3, and PO4. Chloride in soil samples was found statistically identical with SO4, Na+, NO3 and PO4. About 200 ha fodder crops areas are affected each year due to salinity. Ninety-two percent of the areas were found to be salinity affected in the 36 current cropping patterns. Twelve percent of marine fish and 25 percent of shrimp species have disappeared as a result of salinity. The negative impact of soil and water salinity on crops, fish, and livestock has been increasing in this coastal belt.

Table: Methods for the determination of salinity indicators in soil and water samples across the Kalapara coastal belt in Bangladesh.

Samples	Chemical properties	Methods/instrument for chemical analysis
Water	Salinity %	Salinity meter (Model: HACH SensION 156)
	Conductivity (µS/cm)	Conductivity meter (Model: HANNA HI-8633)
	TDS, mg/l	TDS meter (Model: HACH SensION 156)
	pH	Glass electrode pH meter (Model: Metrohm 906 Titrande)
	Fluoride (F^-), mg/l	Ion chromatography (Model: Dionex ICS-1600)
	Chloride (Cl^-), mg/l	Ion chromatography (Model: Dionex ICS-1600)
	Nitrite (), mg/l	Ion chromatography (Model: Dionex ICS-1600)
	Bromide (Br^-), mg/l	Ion chromatography (Model: Dionex ICS-1600)
	Nitrate (), mg/l	Ion chromatography (Model: Dionex ICS-1600)

	Phosphate (), mg/l	Ion chromatography (Model: Dionex ICS-1600)
	Sulfate (), mg/l	Ion chromatography (Model: Dionex ICS-1600)
	Sodium (Na$^+$), mg/l	Flame emission spectrophotometry (Model: Jenway, PFP7)
	Potassium (K$^+$), mg/l	Flame emission spectrophotometry (Model: Jenway, PFP7)
	Calcium (Ca^{2+}), mg/l	Atomic Absorption Spectrophotometer (AAS) (Model: AA-7000, Shimadzu)
	Magnesium (Mg^{2+}), mg/l	Atomic Absorption Spectrophotometer (AAS) (Model: AA-7000, Shimadzu)
Soil	pH	Glass electrode pH meter
	TDS, g/kg	TDS meter
	Conductivity (mS/cm)	Conductivity meter (Model: HACH SensION 156)
	Salinity %	Salinity meter (Model: DDSJ-308A)
	Fluoride (F$^-$), mg/kg	Ion chromatography (Model: Dionex ICS-1600)
	Chloride (Cl$^-$), mg/kg	Ion chromatography (Model: Dionex ICS-1600)
	Nitrite (), mg/kg	Ion chromatography (Model: Dionex ICS-1600)
	Bromide (Br$^-$), mg/kg	Ion chromatography (Model: Dionex ICS-1600)
	Nitrate (), mg/kg	Ion chromatography (Model: Dionex ICS-1600)
	Phosphate (), mg/kg	Vanadomolybdophosphoric yellow color method
	Sulfate (), mg/kg	Turbidimetric method
	Sodium (Na$^+$), mg/kg	Flame emission spectrophotometer (Model: Jenway, PFP7)
	Potassium (K$^+$), mg/kg	Flame emission spectrophotometer (Model: Jenway, PFP7)
	Calcium (Ca^{2+}), mg/kg	Atomic Absorption Spectrophotometer (Model: AA-7000, Shimadzu)
	Magnesium (mg^{2+}), mg/kg	Atomic Absorption Spectrophotometer (Model: AA-7000, Shimadzu)

Flood risk of natural and embanked landscapes on the Ganges–Brahmaputra tidal delta plain.

Auerbach, L. W., S. L. Goodbred Jr, D. R. Mondal, C. A. Wilson, K. R. Ahmed, K. Roy, M. S. Steckler, C. Small, J. M. Gilligan, and B. A. Ackerly. 2015. Nature Climate Change. Volume 5:153–157.
(Ref. G.7)

The Ganges–Brahmaputra river delta, with 170 million people and a vast, low-lying coastal plain, is perceived to be at great risk of increased flooding and submergence from sea-level rise. However, human alteration of the landscape can create similar risks to sea-level rise. This paper reports that the islands in southwest Bangladesh, enclosed by embankments in the 1960s, have lost 1.0–1.5 m of elevation, whereas the neighboring Sundarban mangrove forest has remained comparatively stable. This elevation loss is attributed to interruption of sedimentation inside the embankments, combined with accelerated compaction, removal of forest biomass, and a regionally increased tidal range. One major consequence of this elevation loss occurred in 2009 when the embankments of several large islands failed during Cyclone Aila, leaving large areas of land tidally inundated for up to two years until embankments were repaired. Despite sustained human suffering during this time, the newly reconnected landscape received tens of centimeters of tidal deposited sediment, equivalent to decades' worth of normal sedimentation. Although many areas still lie well below mean high water and remain at risk of severe flooding, elevation recovery may be possible through controlled embankment breaches.

- Conducted 2200-household ethno-survey for high-quality data on household adaptations to patterns and changes in environmental conditions, and related migration events. Surveys included 320 surveys of migrant households in destination cities. Ethno-survey integrates with physical data observations and will provide input for agent-based modeling.
- Constructed regional remote-sensing vegetation phenologies with resolution down to local scale (10^1-10^2m); Database provides sub-annual to decadal patterns in land cover variation through a 12-year MODIS EVI time series; Strong trends in shifting shrimp and agricultural land use; Dataset a principal basis for next phase of up-scaling ground-based studies and observations.
- Inter-annual changes in agricultural phenology throughout the lower delta suggest stepwise expansion of aquaculture to the west of Polder 32 and increasing agricultural intensification to the northeast. Several of the polders, including 32, continue to show little large scale aquaculture and only wet season agriculture.

The results include:

- Establishment of an Integrated Social, Environmental, and Engineering (ISEE) framework for conducting trans-disciplinary research on human-environment coupling and its social influences and impacts.
- Identified key issues linked with observed rapid changes in the physical landscape and human communities within tidal delta plains of southwest Bangladesh – (1) embankment (polder) construction and management; (2) growth of shrimp farming and related influences; (3) water resources, their management, and household water security; (4) livelihood diversity and associated migration strategies.
- Completion of an in-depth, interdisciplinary social-physical study of the causes and consequences of a cyclone-induced embankment failure and 2-years of uncontrolled tidal flooding on a 40 km^2 island; 10,000 households were displaced during this time, with an estimated 25% out-migration; This work provided a detailed understanding of physical environment vulnerabilities and diverse narratives of community strategies for coping with long and short-term stressors.

Construction and Maintenance of the Ganges-Brahmaputra-Meghna Delta: Linking Process, Morphology, and Stratigraphy

Wilson, Carol A., and Steven L. Goodbred Jr. 2015. Annual Review of Marine Science. Vol. 7: 67-88
https://doi.org/10.1146/annurev-marine-010213-135032.
(Ref. G.32)

The Ganges-Brahmaputra-Meghna Delta (GBMD) is best characterized as a composite system, with different regions having morphologic and stratigraphic attributes of an upland fluvial fan delta; a lowland, backwater-reach delta; a down-drift tidal delta plain; and an offshore subaqueous-delta clinoform. These distinct areas of upland and lowland fluvial reaches and tidal dominance vary in time and space and is distinguished as late-Holocene phases of delta construction, maintenance, and decline like delta-lobe cycling in other systems. The overall stability of the GBMD landform, relative to many deltas, reflects the efficient, widespread dispersal of sediment by the large monsoon discharge and high-energy tides that affect this region. However, we do identify portions of the delta that are in decline and losing elevation relative to sea level owing to insufficient sediment delivery. These areas, some of which are well inland of the coast, represent those most at risk to the continued effect of sea-level rise.

Assessment of Land Subsidence and Climate Change Impacts on Inundation Hazard in Southwestern Taiwan

Hsiao-Wen Wang, Cheng-Wei Lin, Chun-Yao Yang, Chung-Feng Ding, Hwung-Hweng Hwung and Shih-Chun Hsiao. 2018. In: Special Issue: Sustainable Development of Tidal Areas: Climate Change and Environmental Impacts. Editors: Prof. Ruey-Chy Kao, Prof. Hsiao-Wen Wang, and Dr. H.P. Ritzema. Irrigation & Drainage. Volume 67, Issue S1: 26 – 37.
(Ref. G.22)

Excessive extraction of groundwater resulting in serious land subsidence as well as intensified rainfall and storm surges due to climate change have complicated the flooding problems in southwest Taiwan. A coupled set of different models was proposed to analyze the effect of inundation risk considering land subsidence and climate change. Three models, including the groundwater flow model, land subsidence model, and the physiographic drainage–inundation model, were used in this study, enabling simulations of different considerations. The results revealed that more severe flooding would result from land subsidence and climate change. The findings of a 21% increase in flood area with an inundation depth greater than 1.5m for 200-yr return period events clearly showed more severe flooding would result from land subsidence. The flooding in those severely subsiding areas would increase in a range from 3.4 to 21.5% when further considering climate change.

While the simulation results revealed that the flood area could be decreased by as much as 50% taking into account the implemented policies, the coastal region would still be exposed to a high risk of being flooded. It thus suggests that policies focusing on infrastructure would be insufficient, and river basin management as well as spatial planning should be investigated further.

Productive, profitable, and resilient agriculture and aquaculture systems

Elizabeth Humphreys ,Manoranjan Mondal, Michael Phillips m.phillips, To Phuc Tuong t.tuong,
K. Kabir ,M. Rafiqul Islam, Md. Ruhul Amin Sarker, Nirmal Sharma, M.A. Rahman,
Priya Lal Chandra, Sukanta Sarangi, Subhasis Mandal , Asutosh Deo, Jitendra Sundaray
G2 closure report, page 1-53
(Ref: G.17)

Summary

This project (G2) sought to contribute to this goal through developing and introducing more productive, diversified, and resilient agriculture/aquaculture production systems in the brackish-water coastal zones of the Ganges delta in Bangladesh and India. The project conducted on-farm experiments and demonstrations in low, medium and high salinity locations on 3 polders in the coastal zone of Bangladesh and didn,t applicable for the whole Bangladesh. To achieve this goal improved water management will require a change in mindsets to treat each polder as an integrated water management unit, with a single entity responsible for co-ordination.

Methodology

Farmers relying on rice-based and aquaculture-based production systems. In this project they use improved varieties (rice, fish etc.) and technologies in productive and diversified agriculture and aquaculture systems. For households, with focus on women they use Adapt integrated farming systems and new technologies in homestead. This study focus on crop and aquaculture seed producers (GOs, NGOs, private) they use seed suppliers on provision of high-quality seeds of improved rice varieties and aquaculture species. In this Study promoting new technologies, training farmers, and taking ownership of the technologies disseminated and provide microfinance for inputs of new technologies; Increase loans to farmers who apply new technologies and also on enabling directives and policies for seed production and adoption of new technologies.

Findings and Research Gaps

The project mainly focused on improvements in agriculture and aquaculture systems that raise cropping intensity, diversity and productivity. However, the researchers proposed to explore for two or three crops per year in less saline area. Where, in areas with medium salinity levels, integrated rice-aquaculture systems are likely are suggested. In areas with higher salinity levels, it was recommended to focus on, risk management in aquaculture. It was also proposed by study to use, higher yields, are short-maturing salt tolerant crops in coastal area, as numerous salt-tolerant and submergence-tolerant varieties of rice are now available to prove their adaptation and suitability to replace the low-yielding rice. The results of the variety trials suggest that in situations where there is fresh water year-round, such as in polder 43/2/F, it is possible to intensify to 3 high yielding crops per year (3 rice or 2 rice and 1 rabi crop) using shorter duration HYV. In medium salinity situations, 2 high yielding and/or high value crops per year (aman-boro or aman-rabi) are possible.

It is evident from the study, achievement of crop diversification is suggested by the introduction of non-rice upland crops such as short-duration mung bean, maize, or sunflower, with enhanced tolerance to submergence and salinity. The production systems were designed from the “cropping systems perspectives” where annual benefits are more important than those from individual crops. The interactions between germplasm and resource management and trade-offs among component crops was analysed. Risk minimization and avoidance was considered in coping strategies for calamities such as typhoons.

Project findings indicates, that the water resources of the coastal zone have largely been misconceived and under-utilized. There is tremendous scope for increasing the productivity, profitability and resilience of agricultural and aqua-cultural production systems in the Ganges coastal zone, through adoption of improved germplasm and management, cropping system intensification and diversification. However, achieving this will require improved water management, and in particular drainage management. Changing current water management practices requires a change in mind-sets to treat each polder as an integrated water management unit, with a single entity responsible for coordination. It will also require significant investment in polder infrastructure, within the polders as well as around the perimeters, zonation and synchronization of production systems.

This research is only applicable for the 3 polder in Bangladesh. Integrated study will be required for proper agriculture and aqua culture management.

Population pressure, environmental constraints and agricultural change in Bangladesh: examples from three agro-ecosystems

Abu Muhammad Shajaat Ali
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Summary

Cultural ecology theory of agricultural change on the basis of a 40 year (1950-1990) data has been examined here in this study. Data were collected from 130 farmstead households living in three villages in Bangladesh. The villages represented xeric, wetlandand transformed irrigated rice agroecosystems. In 1950s, cropping intensity and land productivities were less than national average in all three villages. Over time, the farmers adopted strategies like land level adjustments, change in cropping schedules, adoption of new cultivars to suit the environment and Green Revolution technological changes. These new strategies helped increasing the agricultural production. Population pressure forced farmers to intensify agriculture, but underconditions of severe environmental constraints, population growth alone was not the only factor to cause desired agriculturalchange. Farmers' technological capabilities to reduce the environmental constraints have played a key role in agricultural growth.Water control technology like low-lift pumps for irrigation and flood control played a key role in increased production, dry season cultivation of high yielding variety (HYV) of rice and to increasing cropping intensity and yields.

Methodology

The three villages examined in this study are locatedin three districts of Bangladesh: Bhatshala in the north-eastern district of Kishoreganj, Surjapur in Chapai Nawabganj district in the northwest, and Khazanagar in the southwestern district of Kushtia. Data collection period for this study were 1984-85 and 1989-90. The time series data set for 1950, 1960, 1970, 1985, and 1990 were collected at the household level from the three villages. Data were collected on the basis of farm size; samples were drawn from large holder (> 3 ha), medium holder (1-3 ha), small holder (0.2-1 ha), and landless farmsteads (< 0.2 ha). A total of 130 households, which includes 50 households from Bhatshala, 30 from Surjapur, and 50 from Khazanagar, were selected for this study. Collected data included farm size, family size, farm land amount in different land levels, area affected by flooding and drought, labor use in farming tasks, land used for different crops, uses of technology and fertilizer inputs, and output of rice and non-rice crops. Each sample household was visited three times over a 1 year period, and the farm owner was interviewed by using a pretested questionnaire. Temporal data were obtained by memory recall, checking old family records, consulting village elders, and checking published government documents. Other types of data like land use, cropping schedule and cropping patterns were obtained for the entire village through detailed plot to plot land use surveys in each village. These data were used to describe the village agroecosystems. The physiologic density, which refers to the number of people per unit area of arable land, was taken as a measure of the population pressure. The percentage of total land affected by floods and droughts was considered as an indicator of the environmental constraints.

Findings and research Gaps

This study has examined and supported the cultural ecology theory of agricultural change by investigating the relationships between population pressure, environmental constraints and agricultural change in three environmentally constrained agroecosystems in Bangladesh. Each of the three study villages had lower population pressure and high environmental constraints in 1950. Monsoon flooding in Bhatshala, and drought in Surjapur and Khazanagar significantly set the limits of agricultural growth. Without some major adjustments in the physical quality of the land, and changes in cultivation and water control practices, those constraints could not be overcome. In order to cope with these situations, farmers have adapted several strategies which included changes and adjustments in the physical environments, introduction of new crops and inputs all aimed at the reduction of the limiting effects of the environment and increasing agricultural production. Water control technology like low-lift pumps for irrigation and flood control played a key role in increased production, dry season cultivation of high yielding variety (HYV) of rice and to increasing cropping intensity and yields. Thus the study demonstrates that human adaptations to environmental constraints such as flood and drought have been the key to success in agricultural growth and change in Bangladesh. Therefore, strong flood and drought control measures should be given the top priority in agricultural development planning. High monsoon rainfall, rapid deforestation in the upland Himalayan mountains in Nepal and India, and riverbed siltation are the most important causes of floods in Bangladesh. Reforestation in the Himalayan Nepal, combined with large scale dredging in the rivers may help reduce the dimension of floods. Storage of rain and flood water, conservation and management of underground water resources are crucially important to facilitate dry season irrigated rice cultivation. Emphasis has to be given to population control and planning initiatives to reduce poverty over the long-term.