

Social, hydro-ecological and climatic change in the southwest coastal region of Bangladesh

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Abstract This study investigates the historical development of the southwest coastal region of Bangladesh through the lens of human-delta co-evolutionary system. The change process of social and hydro-ecological systems is described based on the drivers–pressure–state–impact–response (DPSIR) framework. The multiple physical and socio-economic drivers such as climatic change, upstream development, geologic process, land

use change-affected river flow, salinity, water logging and cyclones are creating adverse impacts on ecology (e.g. mangrove forest) and society (e.g. population migration). Existing management practices such as the Coastal Embankment project (CEP) also created adverse impacts on social–ecological system. In addition to the geology of this region that plays the major role in the delta development process, human interventions such as large coastal development projects have intervened the land formation processes. The trends and impacts of these changes along the coast unfold the necessity of integrated management approach such as Integrated Water Resources Management (IWRM) and Integrated Coastal Zone Management (ICZM). Comprehensive understanding of social and hydro-ecological system in southwest coastal region through DPSIR approach presented in this study can provide effective solution for implementing ongoing management strategies.

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Introduction

The coastal regions of the world contain social and ecological systems (SES) in which complex biophysical and socio-economic processes mutually interact in a resilient and sustained manner (Redman et al. 2004). However, the vulnerabilities of coastal deltas to various natural and geological processes such as land subsidence, coastal flooding, cyclones, climate change and sea-level rise (SLR) are widely recognized (IPCC 2014). In addition, human populations are concentrated along coasts, and as a consequence, coastal ecosystems are amongst of the most impacted and altered worldwide (Adger

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et al. 2005). One of the main drivers causing environmental degradation and socio-economic deprivation worldwide is infrastructure development (MEA 2005), such as construction of coastal polders (generally a piece of low-lying land reclaimed from the sea or a river and protected by dykes) and road networks. The combined effect of these natural as well as anthropogenic activities is playing a major role in altering the coastal environment. Environmental management of these complex systems requires integration such as Integrated Water Resources Management (IWRM) (e.g. Rouillard et al. 2014) and Integrated Coastal Zone Management (ICZM) (Cicin-Sain 1993). A systematic assessment of trends of social and ecological processes and understanding their interconnectivity is therefore essential for coastal adaptation planning within IWRM and ICZM approaches.

Bangladesh (Fig. 1), part of one of the largest low-lying deltas known as the Ganges–Brahmaputra–Meghna (GBM) delta, is frequently quoted as one of the most vulnerable nations due to impacts of climate variability and change (e.g. Auerbach et al. 2015). More specifically, the country's embanked southwest coastal area is often cited as the zone of major hazards and disasters such as cyclones, SLR, salinity intrusion, extreme monsoon rainfall, water logging and river flooding (Brammer 2014, Matin and Taylor 2015). This part of the coast is, however, ecologically highly valuable and extremely fertile accompanied with large, variable hydrological and geomorphological subsystems featuring densely populated human habitats and rich biodiversity. The region is the home to about 22 million people (see Supplementary Information (SI) for detail description of the region). Various anthropogenic and development activities such as construction of coastal polders, upstream water withdrawal at Farakka barrage (it is a barrage across the Ganges River, located in the Indian state of West Bengal, roughly 16.5 km from the border with Bangladesh), land use change through intensification of shrimp aquaculture, deforestation, pollution and changes in chemical fluxes have contributed to accelerated changes in the coastal zone (e.g. Hossain et al. 2016a, b).

Several recent studies (e.g. Shameem et al. 2014, Matin and Taylor 2015, Khan et al. 2015) assessed the vulnerability and resilience of rural livelihoods in southwest coastal area due to tropical cyclones, land use change and salinity intrusion. The construction of Farakka barrage and its effect on freshwater flow (Gain and Giupponi 2014), salinity (Mirza 1998) and biodiversity (Gain et al. 2007, 2008) in the area have also been studied. Swapan and Gavin (2011) assessed the impact of commercial saltwater shrimp farming on rural livelihood patterns in southwest Bangladesh using participatory methods. Auerbach et al. (2015) assessed the impacts of polder constructions on sediment deposition and distribution. However, these studies do not provide a comprehensive picture of SES of the southwest coastal area. Most recently, Hossain et al. (2016a, b) made an

attempt to provide an integrated picture on the interrelationship between ecosystem services and human well-being in the area, rather than focusing on social and ecological processes considering dominant drivers and its impacts. A scientific understanding of socio-economic and ecological functioning and their changes is still a major gap in the southwest coastal area in support of integrated coastal zone management.

The objective of this study is to provide a historical perspective on physical, social and development change of complex social ecological system that contributes to the understanding of the “change process” of southwest coastal region of Bangladesh. The change process of SESs is described based on the drivers–pressure–state–impact–response (DPSIR) framework. The DPSIR is a useful adaptive management tool for analysing and identifying solutions to SESs (Gari et al. 2015). Recently, Hossain et al. (2015a, b) applied DPSIR framework for exploring the integration of ecosystem services and climate change adaptation in coastal wetlands in Bangladesh. We have applied DPSIR framework to provide a comprehensive overview of social ecological system in southwest coastal area. The information from the DPSIR analysis can be used to develop integrated management decision (within ICZM and IWRM framework) in the study area.

Conceptual framework

The DPSIR framework is developed by the Organization of Economic Cooperation and Development (OECD) and the European Environment Agency (EEA) for the adaptive management of social ecological systems (EEA 1999). According to the DPSIR framework, there is a chain of causal links: “driving forces” such as social and economic developments exert “pressures” on the environment (e.g. pollutants) and, as a consequence, the “states” (physical, chemical, biological) of the environment changes. This leads to “impacts” on e.g. human health, ecosystems and materials that may elicit a policy “response” that feeds back on the driving forces, on the pressures or on the state or impacts directly, through adaptation.

The implementation of this framework (Fig. 2) for the southwest coastal area highlighted the specific features of each DPSIR element: (i) the assessment of drivers provides the identification of the major driving forces affecting the area, (ii) the pressures highlight the ways that these drivers are actually expressed, (iii) the state provides the current socio-economic and environmental status of the system, (iv) the impacts identify the causative effects on ecosystem and society, and (v) the response is the evaluation of management practises and the policy measures for sustainable socio-economic development of the area.

This study assumes that the complex and dynamic regional and local changes in the socio-ecological processes of this coastal zone are co-determining and interacting at various



Fig. 1 Southwest coastal region of Bangladesh. Red circles indicate river discharge and salinity measuring stations. Green circles indicate location of major administrative areas known as district (Color figure online)

levels, although the linkages between the processes are yet not fairly understood. Thus, the application of the DPSIR model requires an appropriate list of indicators “site-specifics” in order to describe the complex ecological and socio-economic processes in the studied area. Reviewing the literature (Sebesvari et al. 2016), a number of several indicators are

available mirroring the anthropogenic stressors and the quality of the river basins. The long-term changes in the co-evolutionary coastal system of southwest Bangladesh was investigated based on available peer-reviewed literature. However, in order to support our findings, we have used time series data for the following variables: temperature, rainfall,

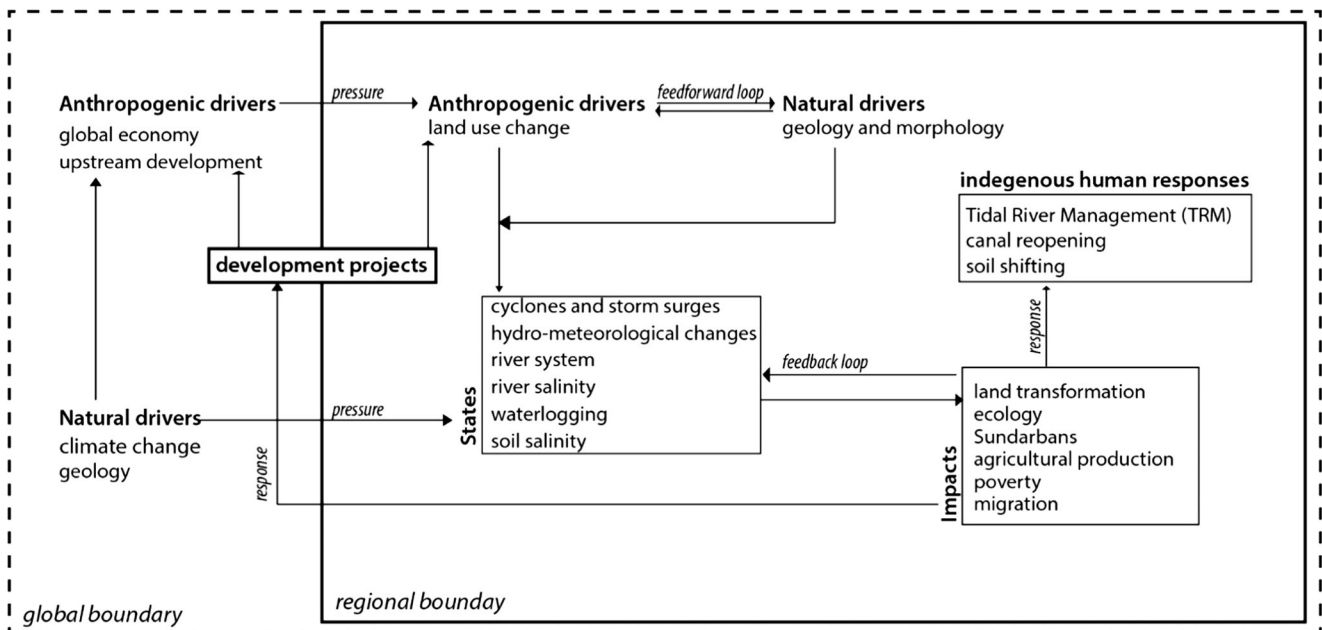


Fig. 2 Conceptual framework of study

discharge, SLR, river sinuosity, waterlogging, river salinity, coverage of shrimp culture, soil salinity, ground water level, land use change and modification, land subsidence, cyclones and diversity in the Sundarbans (mangrove forest). Details of the time series data, their time span and sources are summarized in Table 1. In order to observe past changes for these primary data, we have analysed trends in time series with the application of parametric and non-parametric statistical methods (see [Electronic Supplementary Information](#) for details).

Historical perspectives on drivers, pressures, states, impacts and responses

Drivers and pressures

Both natural and anthropogenic driving forces such as climate change, upstream development, geological process, land use change and global economy play important roles for the changes in the SESs in southwest coastal area. Table 2 presents a summary of the spatio-temporal changes in the drivers

Table 1 Time series of environmental change observations in SW Bangladesh

Data	Time period	Source
Meteorological (8 stations)	1948–2014	Bangladesh Meteorological Department (BMD)
Tide gauge/discharge	1937–2010	Bangladesh Water Development Board (BWDB), Halcrow et al. (1993)
Sea-level rise (SLR)	1968–2010	BWDB, Pethick and Orford (2013)
River sinuosity	1963–1992	Halcrow et al. (1993); Landsat image analysis
Waterlogging	1980–2010	Gain et al. 2017, Roy 2004, Satkhira Upazilla Office (2014)
River salinity	1975–2010	BWDB
Shrimp and agriculture	1983–2007	Datta et al. 2010
Soil salinity	1973–2009	Soil Resource Development Institute (SRDI)
Land use and modification	1830–2013	Maitra (1914), BBS (1975, 2002, 2011); Halcrow et al. (1993), Khan et al. (2015); Field work (2012–2014)
Groundwater level	1985–2010	BWDB
Land subsidence	Last 300 years	Syvitski et al. (2009); Goodbred and Kuehl (2000a, 2000b); Stanley and Hait (2000); Allison and Kepple (2001); Hanebuth et al. (2013); Higgins et al. (2014)
Sundarbans diversity	1926–2010	Iftekhar and Saenger (2008); Aziz and Paul (2015)
Cyclones	1877–2014	Islam and Peterson (2009), BMD

Table 2 Summary of spatio-temporal changes found within the regional boundary of the southwestern coastal zone

Drivers	Temporal changes	Spatial trend
Temperature and rainfall	Annual temperature and post-monsoon rainfall increasing	Wide variation in rainfall and temperature trends. More erratic along the sea-facing regions
River sinuosity and sedimentation	Sinuosity and sedimentation have increased in the 30 recent years; otherwise, Gorai has been stable over last 100 years or so before the recent changes	Upper part of Gorai is now stable, while the lower part is showing remarkable changes, losing transport energy in the process
Fresh water flow and river salinity	Fresh water flow is decreasing, and salinity is increasing at a sharp rate	Salinity in the tidal rivers has increased about threefold in recent three decades. Saline front is pressing north and spreading towards northwestern parts
Tidal range	Both tidal maxima and minima are increasing	Tidal range is getting higher in the poldered region compared to the estuarine regions
Sea-level rise (SLR)	Increasing	Effect varies over topography, felt much higher in the poldered region
Soil salinity	Increasing at a lesser rate compared to last three decades, changes occurring from lower salinity class to higher salinity class.	Soil salinity is not expanding spatially, but higher salinity class is prograding northward
Waterlogging	Increasing in terms of area and time duration	Waterlogged areas are expanding towards western regions
Groundwater level and water quality	In most cases, ground water table is rising, and seasonal variation is quite high. Water quality has not changed much	There is no spatial trend
Coastal changes	Delta is active and prograding; accretion is higher than erosion	Small local erosion towards western region; western region appears to be moribund while eastern region is active
Land subsidence	The delta is sinking	Rate of subsidence is higher in the inland than that of the Sundarbans
The Sundarbans	Areal extension appears stable, threatened due to rising salinity; rate of accretion appears to have kept pace with SLR	–
Delta development process and human interventions	Extensive intervention over last 200 centuries; delta has responded accordingly	Coastal part of the region is more intervened by humans rather than the northern parts

and pressures within the regional boundary of southwest coastal region.

Climate change and sealevel rise Turner and Annamalai (2012) reviewed climate change in South Asia and found that the Indo-Pacific oceanic warm pool has warmed up over last 50 years and potentially supplied increased amount of moisture during the monsoon in the region although observation suggests that monsoon rainfall has not been increased. A more recent study by Loo et al. (2015) further explained the phenomena as, 1970s onwards, there is a westward shift of Indian summer monsoon, which leads to a delay of few days the onset of the monsoon and a 15-day delay of the onset of the monsoon in the future is predicted. Based on 22 years (1977–1998) measured sea-level data, the meteorological research council of the South Asian Association for Regional Cooperation (SAARC) found that the rate of SLR at the coast of Bangladesh is much higher (from 4 mm year⁻¹ at western part to 19 mm year⁻¹ at eastern part) than the global rate of 1.0–2.0 mm year⁻¹ in the last century (Brown and Nicholls 2015).

Geological activity The study area is located in the lower reaches of the Ganges–Brahmaputra–Meghna (GBM) river basin, which is geologically one of the youngest and tectonically most active denudation regimes of the world. The GBM river system carries the world's highest annual sediment load ($\sim 1 \times 10^9 \text{ t a}^{-1}$) (Goodbred and Kuehl 2000a, b). Therefore, sediment deposition historically played a major role of developing the area. Over the past several thousand years, eastward migration of Ganges (due to geologic process) has led to effectively cut off fluvial sediment and a major share of freshwater flow in the southwest coastal area (Allison et al. 2003, Hore et al. 2013). Land subsidence due to crustal movement and compaction of the recent sediment also contributed to SLR. Hanebuth et al. (2013) observed that in last 300 years, the Sundarbans region is sinking at a rate of $5.2 \pm 1.2 \text{ mm year}^{-1}$, while Brown and Nicholls (2015) recently reported that the average subsidence rate in the region is about 8.8 mm year⁻¹ over last 1000 years, which actually has doubled over last 10,000 years. The erosion and accretion also played an important role in coastal changes. Rogers et al. (2013) estimated the recent annualized accretion rates as about 1.1 cm year⁻¹. Allison (1998) observed that the whole delta front is active and prograding at a rate of 7 km year⁻¹ over last 200 years. However, the western front of the southwestern region is at a state of small net erosion as the sea-facing shoreline has retreated about 3–4 km since 1792 while the eastern front is showing small net accretion since 2000 (SI Fig. S6).

Upstream development Since the study area is located in the downstream of the GBM river basin, upstream development activities such as construction of barrages, dams and

reservoirs in India, China, Nepal and Bhutan have significant implication on freshwater and sediment flow in the study area. Most importantly, the commissioning of Farakka barrage in India in 1975 to withdraw Ganges water during dry season played a major role on freshwater supply and sediment deposition in the southwest coastal region (Mirza 1998; Gain and Giupponi 2014).

Land use change and other human interventions

Conversion of agriculture and mangrove forest to brackish water aquaculture has been one of the most evident drivers of changes in southwest coastal area (Datta et al. 2010; Islam 2014). Being a traditional practice, shrimp culture was usually restricted between the levees and the river channels. However, driven by the foreign demand, over the last three decades (post-1980s), such practice has increased in spatial coverage within the polder systems. Using 13-year (1999–2012) remote sensing data, Khan et al. (2015) found an overall 30% increase in shrimp culture, while 48% decrease in agricultural land. Since the late nineteenth century, other human intervention, for example, reclamation work (i.e. closing small channels) also contributed to change in coastal processes (Hunter 1877, Williams 1919).

Global economy Due to global increasing demand of shrimp and its higher economic return, aquaculture is undertaken largely in southwest coastal region of Bangladesh (Datta et al. 2010). The lands were utilized for paddy cultivation before shrimp culture activities commenced in early 1980s.

States

Hydro-meteorological changes Analysis of eight meteorological stations (i.e. Khulna, Jessore, Barisal, Satkhira, Faridpur, Mongla, Patuakhali and Bhola) over southwest Bangladesh reveals that the average annual temperature is increasing significantly at a rate varying from 0.006 to 0.024 °C per year since 1948. This increasing trend has intensified since the post-1990s (0.05–0.1 °C year⁻¹). In contrast, annual rainfall varies widely in the region and shows no stable trend over the time except for Jessore, Faridpur and Barisal. However, it is found that cumulative post-monsoon (September–November) and winter (December–February) rainfall is increasing in the region as a whole (SI Figs. S1 and S2). This increasing trend in post-monsoon and winter rainfall is possibly associated with the occurrences of post-monsoon cyclones rather than pre-monsoon cyclones (Kandalgaonkar et al. 2005).

Cyclones and storm surges Over the period of 1877–2014, about 123 cyclones and tropical depressions (TD) made landfall in Bangladesh. Examination of the time series data suggests that about 60% of those cyclones and TDs made landfall

in the southwest coastal region. Trend analysis reveals that severe cyclonic storms with hurricane intensity have increased over the Khulna coast since 1980 (SI Fig. S8). This intensification of severe cyclones is likely to be linked with the increasing sea surface temperature and high enthalpy flux exchange with available moisture content during post-monsoon over the Bay of Bengal (Vissa et al. 2013).

Changes in river system River Gorai is the principal distributary of the Ganges and major source of fresh water in the region. Historical average annual discharge records (1934–2007) show that the Ganges flow is decreasing significantly at a rate of $\sim 19 \text{ m}^3 \text{ s}^{-1} \text{ a}^{-1}$ at Hardinge Bridge (10 km upstream to origin) especially after late 1950s (SI Fig. S9). The Gorai, as a consequence, is losing its flow at a rate of ~ 5.2 and $\sim 8.2 \text{ m}^3 \text{ s}^{-1} \text{ a}^{-1}$ measured at Gorai Railway bridge (~ 10 km from origin) and Kamarkahali (~ 50 km from origin), respectively. There is a major shift of trend after 1981 (avg. $\sim 10 \text{ m}^3 \text{ s}^{-1}$, measured at Gorai Railway Bridge) where the river lost about an order of a magnitude of its annual minimum flow compared to that of the 1960s (average $\sim 110 \text{ m}^3 \text{ s}^{-1}$). The decreased river flow is attributed to the combined effect of upstream development such as construction of Farakka barrage (Mirza 1998; Gain and Giupponi 2014) and geological activity such as eastward migration of Ganges due to neotectonic movement in the southwest (Hore et al. 2013). Over the course of time, Gorai–Madhumati system has shown increased sinuosity (measured as the actual path length divided by the shortest path length of a curve, with a value ranges from 1 (case of straight line) to ∞ (case of a closed loop)) in the recent hundred years which ranges between 1.1 and 1.3 (Halcrow et al. 1993) with the lower half of the channel representing higher sinuosity (1960–2010 avg. = ~ 2.3) than that of the upper half (1960–2010 avg. = ~ 1.3) (SI Fig. S3 and S4). Due to increase of energy loss and decrease of channel slope, Gorai's ability of transporting water and sediment in the upper reaches is getting impaired with time. As a consequence, the major river system draining southwest became disconnected from its source during 1950s and lost fresh water supply and energy to carry sediment along the course.

Tidal range and ESLR

Tide gauge analysis of Bhairab–Rupsha River system (in Khulna) over the period 1937–2010 indicates that the maximum tidal height is increasing at a rate of $\sim 18 \text{ mm a}^{-1}$ while the minimum tidal height is decreasing at a rate of $\sim 8 \text{ mm a}^{-1}$ (SI Fig. S5). Pethick and Orford (2013) observed that relative mean sea-level rise (RMSL) ranges from 8.8 mm a^{-1} at the mouth of the Passur estuary to 2.8 mm a^{-1} at Khulna, some 120 km from the mouth. However, they argued that the spatial trend of effective sea-level rise (ESLR), which takes land subsidence, tidal amplitude, eustatic sea-level and freshwater input into account, tends to be the opposite of RMSL: being low

at the mouth of estuary (10.9 mm a^{-1} in Hiron point at the coast), higher at the origin of the estuary (14.5 mm a^{-1} at Mongla) and highest at the poldered region (17.2 mm a^{-1} at Khulna). They attributed this phenomenon to construction of coastal polders.

Changes in river salinity All the downstream stations that exhibit tidal characteristics show significant upward trends in salinity—Jhikargacha $\sim 231 \mu\text{S cm}^{-1} \text{ a}^{-1}$, Paikgacha $\sim 2160 \mu\text{S cm}^{-1} \text{ a}^{-1}$, Khulna $\sim 83 \mu\text{S cm}^{-1} \text{ a}^{-1}$ and Mongla $\sim 1007 \mu\text{S cm}^{-1} \text{ a}^{-1}$. Decreased river discharge as well as SLR and intensive aquaculture is responsible for changes in river salinity (Bhuiyan and Dutta 2012; Shaha and Cho 2016).

Waterlogging Waterlogging has become evident in the region over last three decades especially in the areas adjacent to the coasts of Jessore, Satkhira and Khulna Districts. Analysis indicates that in Jessore region, waterlogging has expanded to $\sim 600 \text{ km}^2$ since 1980 at a rate of $\sim 20 \text{ km}^2$ per year. The rate for Satkhira is $\sim 25 \text{ km}^2$ per year since 1980 ($\sim 755 \text{ km}^2$ area under waterlogging in 2014) (SI Table S1). As a whole, waterlogging is expanding from northeast to southwest. The intensive water logging is attributed to the intensive shrimp farming, sedimentation in the river bed and unplanned human activities.

Soil salinity Soil salinity data over the period of 1970–2009 shows that area under saline soil is increasing rapidly in the region at a rate of $5875 \text{ ha year}^{-1}$. Although salinity classes exhibit temporal variation, it is evident that since 1970, areas are transforming into high soil salinity class ($\text{EC} > 15 \text{ ds m}^{-1}$) at a rate of $7044 \text{ ha year}^{-1}$. While area under slight ($\text{EC} < 4 \text{ ds m}^{-1}$) and slight to moderate ($\text{EC} = 4\text{--}8 \text{ ds m}^{-1}$) class salinity is decreasing, area under moderate to high ($\text{EC} = 8\text{--}15 \text{ ds m}^{-1}$) and high ($\text{EC} > 15 \text{ ds m}^{-1}$) is increasing in this region (SI Table S2).

Impacts

The changes of states of different variables due to climatic, manmade and geologic drivers have created different order effects on society and economy in southwest coastal area.

Land use change and coastal aquaculture have multifarious consequences to the social–ecological system of the study area. Deb (1998) found that the labour requirement for on-farm activities in shrimp farming is only one fourth to that of traditional agricultural activities. Therefore, shrimp culture and water logging negatively affected agro-based labour force for the coastal communities, causing outward seasonal migration and even permanent migration, in extreme case (Ackerly et al. 2015). Roy et al. (2009) reported existence of human-made breaches in the polders attributed to shrimp farming and linked the event of embankment failure during cyclone Aila

(hit southwest coast on 25 May 2009). Several analyses have also linked shrimp farming with weakening embankments and thereby increasing the risk of embankment failure in the face of storm surges (Vivekananda et al. 2014). Besides, the increasing number and magnitude of hazards/disasters are affecting the land use pattern, which in turn degrading the community resources and capacities (Huq et al. 2015), and have consequences on agricultural production as it increases soil salinity (Worland et al. 2015) as well as degrades the availability of fresh water as well as biodiversity. Similar findings have been confirmed by Hossain et al. (2016a, b) as they have reported that rice production has reduced poverty alleviation and increment of gross domestic product (GDP) growth, whereas deteriorated water quality impacted on economic growth.

The people of Bangladesh have improved their ability to cope with disastrous events, like cyclone, river bank erosion, flooding or even waterlogging and salinity. For example, the death toll of cyclone Gorkey in 1991 was 130,000 whereas the similar kind of cyclone Sidr of 2007 was 3400 deaths. Disasters often has caused displacement or forced migration in the region. According to the International Organization for Migration (IOM) (IOM 2009), many people have migrated from the coastal zones of Bangladesh to urban low-income areas due to frequent cyclones, storm surges, river erosion and other environmental occurrences. Mallick (2014) described that the process of disaster-induced rural–urban migration had been dramatic in 1970, when a strong cyclone hit the coastal regions of the country with a subsequent death toll of ~300,000. In 2007, 2008 and 2009, three severe cyclones—Sidr, Nargis and Aila—hit the southern coastal region of Bangladesh. During cyclone Aila in 2009, an estimated 40,000 people were displaced (Roy et al. 2009). This number, including forced migration, may have reached up to ~120,000 due to prolonged waterlogging until 2010 and with many households deciding to migrate to other locations (Mallick and Vogt 2013). Mallick and Siddiqui (2015) indicated that people in the vicinity are forced to change their original agrarian occupations to non-agrarian occupations, thus creating lack of job opportunity, unemployment and migration. Hasan et al. (2013) have mentioned that over 35 million people will have to leave the coastal areas (southeast and southwest of Bangladesh) due to an anticipated 45 cm SLR by 2050. All these facts indicate that there is a close relationship between extreme climate events, water logging and coastal aquaculture (i.e. shrimp farming requires one-fourth labour force of rice production, therefore, during shrimp season, a huge number of poor income people seasonally migrate in nearby places for alternative income sources), immediate displacement and long-term migration patterns.

Changes in river discharge and salinity have created a major impact on Sundarbans, the world's largest single tract mangrove forest. It provides a wide range of ecosystem services

and contributes to socio-economic development of the neighbouring communities. According to Maitra (1914), the Sundarbans was naturally measured around 16,000 km² sometime around 1770s. Given its current extent (10,000 km² of which ~60% is in Bangladesh), Sundarbans has lost about one third of its original extent. Aziz and Paul (2015) analysed Landsat imagery over 1989–2010 to find formation of numerous small creeks and channels prior to 2000, which actually reduced ~28% of *Heritiera fomes* (locally known as Sundari tree) cover in the extreme northern part of the mangrove. Iftekhar and Saenger (2008) reported a decline in both *H. fomes* and *Excoecaria agallocha* (locally known as Gewa)-dominated forest cover at a rate of 0.23–0.27% a⁻¹ over the period of 1926–1997. Chowdhury et al. (2008) estimated that *H. fomes* trees are affected by “top-dying” diseases and its coverage has declined by 76% since 1959. They also reported evidences of dramatic declines in other mangrove species. *H. fomes* is economically a high value tree that is used for paper pulp and known to grow along the freshwater dominant areas of the tidal zones. These impacts are associated with decreases in fresh water flow, SLR, geologic land subsidence, coastal aquaculture and shrimp farming. Sarkar et al. (2016) claimed that Ganges's freshwater flow into the Sundarbans has dropped from 3700 to 364 m³ s⁻¹ since the commissioning of the Farakka barrage in India in 1975.

Transformation in land use from rice cultivation to shrimp farming affected different populations differently. This process exacerbated inequalities amongst people in poverty (Ackerly et al. 2015). The most vulnerable are those who depend on day wages and those who face a family crisis, like daughter's marriage, sudden death of earning member, health crisis and costly diseases. (Ackerly et al. 2015), and sometimes, they need to choose seasonal or temporary migration to nearby cities and/or communities as an alternative livelihood option (Mallick 2014).

Despite the presence of waterlogging and salinity, agricultural (crop and fisheries) production and GDP have increased and poverty has been reduced in the region. Evidences show that since 1961, rice production has been rising steadily in the southwest Bangladesh, which intensified post-1995 (Hossain et al. 2016a, b). The reason behind increased agricultural production is the use of high-yielding varieties (HYV) replacing the local varieties. Similarly, the production in inland fishes, marine fish catches and shrimp production have also been increased between 1980 and 2010 (Hossain et al. 2016a). The continuous and increasing inflow of foreign remittances is also a great contributor to the GDP increment. As an outcome, GDP is increased and poverty is declined ~17% across the coastal zone since 1995 (Hossain et al. 2016b). However, future projections suggest that due to SLR, agriculture production can be reduced and

hence this will negatively affect the GDP and poverty (de Araujo Barbosa et al. 2016).

Response

Development projects Both natural and human interventions have shaped the southwestern coastal region over centuries. As discussed earlier, literatures that go back up to sixteenth century suggest that, while geology has played a major role in the delta development process, human interactions have also contributed towards modification of delta development. Over the time, humans on this delta have responded to these changes, whether the changes inflicted by nature or themselves. As a result, in recent times, this coastal region has also seen many development projects related to water management: for example, Coastal Embankment Project (CEP) (1968 onwards), Small-Scale Water Resources Sector Project (1996–2002), Gorai River Restoration Project (1998–2007), Integrated Planning for Sustainable Water Management (IPSWAM) (2003–2008), Coastal Zone Development Program (CZDP), Coastal Embankment Rehabilitation Project (CERP) (1996–2002) and Khulna–Jessore Drainage Improvement Project (1994–2002). These projects have significantly modified the land use pattern as well as morphological processes in the region (Nandy et al. 2007). For example, the main objective of CEP was to convert the seasonally flooded coastal wetlands into reclaimed land for permanent agricultural as well as to establish human settlement protected from saline intrusion, cyclones, and tidal waves, (Gain et al. 2017). A series of 37 polders with 1566-km-long embankment and 282 sluice gates were constructed under CEP (Halcrow et al. 1993). During the construction, numerous channels were cut-off, modified and closed. The system worked fine for the first decade as crop production raised twofold to threefold, but improper operation, poor management and failure to take the topography and regional sedimentation pattern into account led the polder malfunction (Kibria 2006). The construction of the CEP has caused a major change to the transitional processes that were already in place in the region prior to 1960s. After the 1960s, the volume of tidal over spill has greatly reduced, which is resulting in insufficient tidal ebb discharge to sustain pre-polder channel cross sections and subsequently contributing to rapid silting up of the both sides of the polders (Awal 2014).

Indigenous human responses While institutional responses to the changes in this coast have been thorough development projects, community-wise people have responded to the changes in their own ways. Before polders, building temporary earthen embankments alongside rivers to prevent high waters was a common practice amongst coastal people. After the implementation of the CEP, which introduced permanent embanking system that led to short supply of sediment (and source of crop nutrition) inside the polder, communities

responded with the idea of river basin management, known as the tidal river management (TRM) (Gain et al. 2017). The idea basically revolves around letting high water in to deposit sediment carried by it through intentional breaching of the polder at points close to river (Roy 2004). Although such idea has been proven to have social and technical difficulties (for example, it causes erosion and population displacement), a few successful experiments exist. Another recent response has been identified as reopening former channels that were closed during polderization. This technique efficiently brings tidal excess tidal spill inside the polder and reintroduces fresh sediment inside. Shifting of shrimp to rice to avoid salt-water intrusion, cropping alongside the river levees outside polder system, excavating and transporting riverside soil inside polders to grow vegetables, etc. have been of indigenous responses lately (last decade or so). Beside, with the aid of government and non-government agencies, communities in the southwest coast are responding to the monsoon shift, increasing temperature, lack of freshwater flow and sediment through crop rotation, crop alteration, water conservation during post-monsoon, river born soil shifting and many other locally adopted techniques.

Discussions and conclusion

We examined how the coastal processes may interact with the existing human interventions through DPSIR framework. Our findings suggest that current coastal management (see “Response” section) such as implementation of CEP is not sustainable which again negatively contributed to drivers, pressures, states and impacts. The presented framework is highly useful in structuring and prioritizing information needs in support monitoring design for integrated management in southwest coastal area.

Recently, tidal river management (Dewan et al. 2015; Gain et al. 2017; Hossain et al. 2015a, b), river basin management (Gain and Schwab 2012) and delta plan (<http://www.bangladeshdeltaplan2100.org/>) are ongoing management strategies of the government of Bangladesh in southwest coastal area. Evaluating each of these management options by using DPSIR framework presented here can provide a comprehensive picture of the study area. For example, successful implementation of tidal river management can reduce water logging and enhance river flow, which can provide positive impact on agricultural production and other higher-order impacts. However, unplanned and poor design could lead to erosion and population displacement as happened in the *Pakhimara Beel* this year. Effective transboundary cooperation through applying river basin management approach with India and other upstream countries can ensure freshwater supply during dry season, which can

reduce salinity in the southwest coastal region. This will create positive impact on biodiversity and forest ecosystem (Gain et al. 2008). Thus, reliable information and knowledge on changes in the social–ecological systems and comprehensive causes of those changes can be effectively analysed through the approach presented here, which can support decision making southwest coastal area.

The human history of intervention and socio-ecological changes in the southwestern coast of Bangladesh are inseparable. The application of DPSIR framework suggests that the region is already facing severe problems that might be worsening at an accelerated pace. This study synthesizes the historical biophysical and human intervention database to explore the ways that the people and nature here are interconnected and mutually co-existed. It also gives us the understanding that the dynamism of the southwest coast demands detailed, long-term and site-specific information to comprehend the mechanisms in play. To negotiate such situation, we need to be prepared with knowledge, proper plan and economic strength.

It is essential to make site-specific detail assessments of socio-ecological integrity of this region in relation to the future threats of SLR, salinity, waterlogging, cyclones and storm surges and displacements. Monitoring institutions that provide biophysical information need to be updated and strengthened. Institutional and political arrangements that are to implement the coastal planning and management are to be equipped with scientific knowledge, awareness and manpower and to be blessed with local people's experience and cooperation. A range of studies are needed to develop such integrated coastal management plans in Bangladesh. Putting all the pieces together is the utmost step towards integrating the ideas of river basin management into a complete coastal zone planning. A holistic approach is therefore required to adjust delta changes.

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References

- Ackerly B, Anam M, Gilligan J (2015) Environment, political economies and livelihood change. In: Mallick, Etzold (eds) Environment, migration and adaptation—evidence and politics of climate change in Bangladesh. AHDPH Publication, Dhaka, pp 27–40
- Adger WN, Hughes TP, Folke C, Carpenter SR, Rockström J (2005) Social-ecological resilience to coastal disasters. *Science* 309:1036–1039. doi:10.1126/science.1112122
- Allison MA (1998) Historical changes in the Ganges–Brahmaputra delta front. *J Coast Res* 14(4):1269–1275. URL:<http://www.jstor.org/stable/4298887>
- Allison M, Kepple E (2001) Modern sediment supply to the lower delta plain of the Ganges–Brahmaputra River in Bangladesh. *Geo-Mar Lett* 21:66–74. doi:10.1007/s003670100069
- Allison MA, Khan SR, Goodbred SL Jr, Kuehl SA (2003) Stratigraphic evolution of the late Holocene Ganges–Brahmaputra lower delta plain. *Sed Geol* 155:317–342. doi:10.1016/S0037-0738(02)00185-9
- Auerbach LW, Goodbred SL Jr, Mondal DR, Wilson CA, Ahmed KR, Roy K, Steckler MS, Small C, Gilligan JM, Ackerly BA (2015) Flood risk of natural and embanked landscapes on the Ganges–Brahmaputra tidal delta plain. *Nat Clim Chang* 2015:153–157. doi:10.1038/NCLIMATE2472
- Awal MA (2014) Water logging in south-western coastal region of Bangladesh: local adaptation and policy options. *Science Postprint* 1(1):e00038. doi:10.14340/spp.2014.12A0001
- Aziz A, Paul A (2015) Bangladesh Sundarbans: Present status of the environment and Biota. *Diversity* 7(3):242–269. doi:10.3390/d7030242
- BBS (1975, 2002, 2011) Bangladesh statistical year book. Bangladesh Bureau of Statistics, Dhaka, Bangladesh
- Bhuiyan MJAN, Dutta D (2012) Assessing impacts of sea level rise on river salinity in the Gorai river network, Bangladesh. *Estuar Coast Shelf Sci* 96:219–227. doi:10.1016/j.ecss.2011.11.005
- Brammer H (2014) Bangladesh's dynamic coastal regions and sea-level rise. *Clim Risk Manag* 1:51–62. doi:10.1016/j.crm.2013.10.001
- Brown S, Nicholls RJ (2015) Subsidence and human influences in mega deltas: The case of the Ganges–Brahmaputra–Meghna. *Science of The Total Environment* 527–528(2015):362–374. doi:10.1016/j.scitotenv.2015.04.124
- Chowdhury MQ, Schmitz N, Verheyden A, Sass-Klaassen U, Koedam N, Beeckman H (2008) Nature and periodicity of growth rings in two Bangladeshi mangrove species. *IAWA J* 29:265–276. doi:10.1163/22941932-90000185
- Cicin-Sain B (1993) Sustainable development and integrated coastal management. *Ocean Coast Manag* 21:11–43. doi:10.1016/0964-5691(93)90019-U
- Datta D, Roy K, Hassan N (2010) Shrimp culture: trend, consequences and sustainability in the south-western coastal region of Bangladesh. In: Ramanathan AL, Bhattacharya P, Dittmar T et al (eds) *Manag. Sustain. Dev. Coast. Zo. Environ.* Springer Netherlands, pp 227–244. doi:10.1007/978-90-481-3068-9_15
- de Araujo Barbosa CC, Dearing J, Szabo S, Hossain S, Binh NT, Nhan DK, Matthews Z (2016) Evolutionary social and biogeophysical changes in the Amazon, Ganges–Brahmaputra–Meghna and Mekong deltas. *Sustain Sci*. 11:555–574. doi:10.1007/s11625-016-0371-7
- Deb AK (1998) Fake blue revolution: environmental and socio-economic impacts of shrimp culture in the coastal areas of Bangladesh. *Ocean Coast Manag* 41(1):63–88. doi:10.1016/S0964-5691(98)00074-X
- Dewan C, Mukherji A, Buissonc M (2015) Evolution of water management in coastal Bangladesh: from temporary earthen embankments to depoliticized community-managed polders. *Water Int.* 40:401–416. doi:10.1080/02508060.2015.1025196
- EEA (1999) Environmental indicators: typology and overview. Technical report No 25. European Environment Agency (EEA), Denmark
- Gain AK, Benson D, Rahman R, Datta DK, Rouillard JJ (2017) Tidal river management in the South West Ganges–Brahmaputra delta: moving towards a transdisciplinary approach? *Env Sci Pol* 75: 111–120. doi:10.1016/j.envsci.2017.05.020
- Gain AK, Giupponi C (2014) Impact of the Farakka dam on thresholds of the hydrologic flow regime in the Lower Ganges River Basin (Bangladesh). *Water* 6:2501–2518. doi:10.3390/w6082501
- Gain AK, Schwab M (2012) An assessment of water governance trends: the case of Bangladesh. *Water Policy* 14:821–840. doi:10.2166/wp.2012.143

- Gain AK, Aryal KP, Sana P, Uddin MN (2007) Effect of river salinity on crop diversity: a case study of south west coastal region of Bangladesh. *Nepal Agric Res* 8:29–37. doi:10.3126/narj.v8i0.11576
- Gain AK, Uddin MN, Sana P (2008) Impact of river salinity on fish diversity in the south-west coastal region of Bangladesh. *Int J Ecol Environ Sci* 34:49–54
- Gari SR, Newton A, Icely JD (2015) A review of the application and evolution of the DRSIR framework with an emphasis on coastal social-ecological systems. *Ocean Coast Manag* 103:63–77. doi:10.1016/j.ocecoaman.2014.11.013
- Goodbred SL, Kuehl SA (2000a) Enormous Ganges-Brahmaputra sediment discharge during strengthened early Holocene monsoon. *Geology* 28:1083–1086. doi:10.1130/0091-7613(2000)
- Goodbred SL, Kuehl SA (2000b) Large sediment supply, active tectonism, and eustasy on margin sequence development: Late Quaternary stratigraphy and evolution of the Ganges-Brahmaputra delta. *Sediment Geol* 133:227–248. doi:10.1016/S0037-0738(00)00041-5
- Halcrow W, DHI, EPCL, SSL (1993) Final Report, Vol. 3, Morphological studies (a), Vol. 4, Coastal studies (b), Vol. 9, Impact studies (c), Southwest Area Water Resources Management Project, FAP-4, People's Republic of Bangladesh, Ministry of Irrigation, Water Development and Flood Control, FPCCO, UNDP, ADB, Sir William Halcrow and Partners in association with DHI, EPCL and SSL
- Hanebuth TJJ, Kudrass HR, Linstädter J, Islam B, Zander AM (2013) Rapid coastal subsidence in the central Ganges-Brahmaputra Delta (Bangladesh) since the 17th century deduced from submerged salt-producing kilns. *Geology* 41:987–990. doi:10.1130/G34646.1
- Hasan Z, Akhter S, Ahmed S, Kabir A (2013) Challenges of integrating disaster risk management and climate change adaptation policies at the National Level. Bangladesh as a case. *Glob J Human Soc Sci Geogr Geo-Sci Environ Dis Manag* 13(4):55–65
- Higgins SA, Overeem I, Steckler MS, Syvitski JPM, Seeber L, Akhter SH (2014) InSAR measurements of compaction and subsidence in the Ganges-Brahmaputra Delta, Bangladesh. *J Geophys Res: Earth Surf* 119(8):1768–1781. doi:10.1002/2014JF003117
- Hore SK, Sarker MH, Ferdous MR (2013) Study of the off-take dynamics for restoring the Gorai River. 4th International Conference on Water & Flood Management, Dhaka
- Hossain MS, Hein L, Rip FI, Dearing JA (2015a) Integrating ecosystem services and climate change responses in coastal wetlands development plans for Bangladesh. *Mitig Adapt Strateg Glob Change* 20: 241–261. doi:10.1007/s11027-013-9489-4
- Hossain F, Khan ZH, Shum CK (2015b) Tidal river management in Bangladesh. *Nat Clim Chang* 5:492. doi:10.1038/nclimate2618
- Hossain MS, Eigenbrod F, Johnson FA, Dearing JA (2016a) Unravelling the interrelationships between ecosystem services and human well-being in the Bangladesh delta. *Int J Sust Dev World Ecol*. doi:10.1080/13504509.2016.1182087
- Hossain MS, Dearing J, Rahman MM, Salehin M (2016b) Recent changes in ecosystem services and human well-being in the Bangladesh coastal zone. *Reg Environ Chang* 16:429–443. doi:10.1007/s10113-014-0748-z
- Hunter WW (1877) A statistical account of Bengal. Trübner & Company, London
- Huq N, Hunge J, Boon E, Gain AK (2015) Climate change impacts in agricultural communities in rural areas of coastal Bangladesh: a tale of many stories. *Sustainability* 2015(7):8437–8460. doi:10.3390/su7078437
- Iftekhar MS, Saenger P (2008) Vegetation dynamics in the Bangladesh Sundarbans mangroves: a review of forest inventories. *Wetlands Ecol Manage* 16(4):291–312. doi:10.1007/s11273-007-9063-5
- International Organization of Migration (IOM) (2009) Migration, climate change and the environment. International Organization for Migration, Geneva
- IPCC (2014) Summary for policymakers. In: Edenhofer O, Pichs-Madruga R, Sokona Y, Farahani E, Kadner S, Seyboth K, Adler A, Baum I, Brunner S, Eickemeier P, Kriemann B, Savolainen J, Schlömer S, von Stechow C, Zwickel T, Minx JC (eds) *Climate change 2014: mitigation of climate change*. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge
- Islam MS (2014) *Confronting the blue revolution: industrial aquaculture and sustainability in the global south*. University of Toronto Press
- Islam T, Peterson RE (2009) Climatology of landfalling tropical cyclones in Bangladesh 1877–2003. *Nat Hazards* 48(1):115–135. doi:10.1007/s11069-008-9252-4
- Kandalgaonkar SS, Tinmaker MIR, Nath A, Kulkarni MK, Trimbake HK (2005) Study of thunderstorm and rainfall activity over the Indian region. *Atmósfera* 2005:91–101. URL: <http://www.scielo.org.mx/pdf/atm/v18n2/v18n2a02.pdf>
- Khan MMH, Bryceson I, Kolivras KN, Faruque F, Rahman MM, Haque U (2015) Natural disasters and land-use/ land-cover change in the southwest coastal areas of Bangladesh. *Reg Environ Chang* 15:241–250. doi:10.1007/s10113-014-0642-8
- Kibria Z (2006) Of deception and destruction: Social and environmental impacts of ADB-financed Khulna-Jessore Drainage Rehabilitation Project (KJDRP) in Southwest Coastal Region in Bangladesh. In *Untold Realities: How ADB safeguards have been violated in Bangladesh, India, Lao PDR and Pakistan*. NGO Forum on ADB. Retrieved from <http://www.forum-adb.org/docs/Untold-Realities.pdf>
- Loo YY, Billa L, Singh A (2015) Effect of climate change on seasonal monsoon in Asia and its impact on the variability of monsoon rainfall in Southeast Asia. *Geosci Front* 6(6):817–823. doi:10.1016/j.gsf.2014.02.009
- Maitra SC (1914) *History of Jessore and Khulna* (Translated English title), Vol. 1. Reprinted in 2006, Lekhak Samabay Dhaka
- Mallick B (2014) Cyclone-induced migration in southwest coastal Bangladesh. *ASIEN* 130:60–81
- Mallick B, Siddiqui T (2015) Disaster-induced migration and adaptation discourse in Bangladesh, in Hillmann, F. et al. (eds.) *Environmental change, adaptation and migration—bringing in the region*. Palgrave Macmillan. pp. 164–185
- Mallick B, Vogt J (2013) Population displacement after cyclone and its consequences: empirical evidence from coastal Bangladesh. *Nat Hazards* 73(2). doi:10.1007/s11069-013-0803-y
- Matin N, Taylor T (2015) Emergence of human resilience in coastal ecosystems under environmental change. *Ecol Soc* 20(2):43. doi:10.5751/ES-07321-200243
- MEA (2005) *Ecosystems and human well-being: current state and trends, volume 1. Millennium Ecosystem Assessment (MEA)*. Hassan, R, Scholes, R, Ash, N (eds.) Island Press
- Mirza MMQ (1998) Diversion of the Ganges water at Farakka and its effects on salinity in Bangladesh. *Environ Manag* 22:711–722. doi:10.1007/s002679900141
- Nandy G, Ali S, Farid T (2007) *Shrimp and popular economics: who gains and who pays*. ActionAid, Dhaka, p 144
- Pethick J, Orford JD (2013) Rapid rise in effective sea-level in southwest Bangladesh: its causes and contemporary rates. *Glob Planet Change* 111:237–245. doi:10.1016/j.gloplacha.2013.09.019
- Redman CL, Grove JM, Kuby LH (2004) Integrating social science into the long-term ecological research (LTER) network: social dimensions of ecological change and ecological dimensions of social change. *Ecosystems* 7:161–171. doi:10.1007/s10021-003-0215-z
- Rogers KG, Goodbred SL, Mondal DR (2013) Monsoon sedimentation on the “abandoned” tide-influenced Ganges-Brahmaputra delta plain. *Estuar Coast Shelf Sci* 131:297–309. doi:10.1016/j.ecss.2013.07.014

- Rouillard JJ, Benson D, Gain AK (2014) Evaluating IWRM implementation success: are water policies in Bangladesh enhancing adaptive capacity to climate impacts? *Int J Water Resour Dev* 30:515–527. doi:10.1080/07900627.2014.910756
- Roy K (2004) Water logging in the southwest coast. Climate Information Center-CIC, CDP, December, 2004. CDP-CARE-RVCC-CIDA
- Roy K, Kumar U, Mehedi H, Sultana T, Ershad DM (2009) Initial damage assessment report of Cyclone AILA with focus on Khulna District. Unnayan Onneshan-Humanity Watch- Nijera Kori, Khulna, Bangladesh, June 23, 2009
- Sarkar SK, Reeve R, Thompson J et al (2016) Are we failing to protect threatened mangroves in the Sundarbans world heritage ecosystem? *Sci Rep* 6:2016. doi:10.1038/srep21234
- Satkhira Upazilla Office (2014) Personal communication with Upazilla Nirbahi Officer (UNO), Satkhira, Bangladesh
- Sebesvari Z, Renaud FG, Haas S, Tessler Z, Hagenlocher M, Kloos J, Szabo S, Tejedor A, Kuenzer C (2016) A review of vulnerability indicators for deltaic social–ecological systems. *Sustain Sci* 11:575–590. doi:10.1007/s11625-016-0366-4
- Shaha DC, Cho Y (2016) Salt Plug Formation Caused by Decreased River Discharge in a Multi-channel Estuary. *Scientific Reports* 6(1). doi:10.1038/srep27176
- Shameem MIM, Momtaz S, Rauscher R (2014) Vulnerability of rural livelihoods to multiple stressors: A case study from the southwest coastal region of Bangladesh. *Ocean Coast Manage* 102:79–87. doi:10.1016/j.ocecoaman.2014.09.002
- Stanley D, Hait K (2000) Holocene depositional patterns, neotectonics and Sundarban mangroves in the western Ganges-Brahmaputra delta. *J Coast Res* 16:26–39. doi:10.1007/s00334-008-0203-5
- Swapan MSH, Gavin M (2011) A desert in the delta: participatory assessment of changing livelihoods induced by commercial shrimp farming in Southwest Bangladesh. *Ocean Coast Manage* 54:45–54. doi:10.1016/j.ocecoaman.2010.10.011
- Syvitski JPM, Kettner AJ, Overeem I, Hutton EWH, Hannon MT, Brakenridge GR, Day J, Vörösmarty C, Saito S, Giosan L, Nicholls RJ (2009) Sinking deltas due to human activities. *Nature Geoscience* 2(10):681–686. doi:10.1038/ngeo629
- Turner AG, Annamalai H (2012) Climate change and the South Asian summer monsoon. *Nat Clim Chang* 2:587–595. doi:10.1038/nclimate1495
- Vissa NK, Satyanarayana ANV, Kumar BP (2013) Intensity of tropical cyclones during pre- and postmonsoon seasons in relation to accumulated tropical cyclone heat potential over Bay of Bengal. *Nat Hazards*. 68:351–371. doi:10.1007/s11069-013-0625-y
- Vivekananda J, Schilling J, Mitra S, Pandey N (2014) On shrimp, salt, and security: livelihood risks and responses in South Bangladesh and East India. *Environ Dev Sustain* 16:1141–1161. doi:10.1007/s10668-014-9517-x
- Williams A (1919) History of the rivers in the Gajetic delta, 1750–1918, Bengal Secretariat Press, 1919, reprinted by East Pakistan IWTA, 1966
- Worland SC, Homberger GM, Goodbred SL (2015) Source, transport, and evolution of saline ground water in a shallow Holocene aquifer on the tidal delpalain of southwest Bangladesh. *Water Resour Res* 51:5791–5805. doi:10.1002/2014WR016262