Managing Water-Related Risks in the Indian Sundarbans:

Policy Alternatives and Institutions

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Abstract

Persistent pressures from water-related threats -- sea level rise, soil and water salinization, and flooding due to embankment overtopping and failure -- have made the West Bengal Sundarbans a challenging place to live, and effects of global climate change will only worsen conditions. Four alternative policy directions are examined: business-as-usual scenario; intensive rural development; short-term out-migration of residents; and embankment realignment and facilitation of voluntary, permanent out-migration. The last of these is the recommended approach. Study findings have informed ongoing deliberations to build consensus on future policy directions for reducing the region's vulnerability to natural disasters.

Key Words: West Bengal, Sundarbans, India, climate change, water-related risks, policy alternatives, institutions.

Introduction

The Sundarbans region, which is formed by the deltas of the Ganges, Brahmaputra and Meghna rivers, contains what is arguably the world's largest remaining mangrove. The forest is home to many endangered species, including the iconic Royal Bengal tiger. About 40% of the region lies within India and the remainder is in Bangladesh. It is bounded on the west by the Bhagirathi-Hooghly River, a tributary of the Ganges, and on the east by the Padma- Meghna River which flows from the Brahmaputra. Although the Sundarbans lies within both India and Bangladesh, this paper treats only the Indian Sundarbans, which is located entirely within the state of West Bengal. (Unless otherwise noted, "Sundarbans" refers to the Indian Sundarbans – see Figure 1.)

Figure 1. Sundarbans Region of India. Figure prepared by the Map Design Unit of The World Bank (see online version for colors).

The total area of the Indian Sundarbans is 9,630 sq. km., of which 4,264 sq. km. consists of wetlands and mangrove (Hazra et al., 2002). While the area was once entirely covered by mangrove, much of it has been converted to other land uses, such as agriculture and aquaculture. Of the 100 or so islands that are currently part of the Indian Sundarbans, 54 are inhabited to varying degrees and the others are forested (Danda, 2007). The population of the Sundarbans rose from nearly 1.2 million in 1951 to almost 3.2 million in 1991 and to 4.4 million people in 2011 (Hazra et al., 2002; Sánchez-Triana et al, 2014).

The Ganges-Brahmaputra-Meghna (GBM) delta, like many other major deltas, is constantly changing as a result of variations in flows and sediment loads. The Sundarbans has lost 100 km^2 in the past 30 years, with effects of erosion felt mainly on the southern shores of islands (Woodroffe et al., 2006). In contrast, the Meghna Delta plain has been experiencing accretion. Allison (1998) reports an average net land accretion rate of rate of 4.4 km^2/yr since 1840 (south of 22.90 N latitude). In 2015, erosion rates in the Indian Sundarbans were reported to be higher than aggradation (Ghosh et al., 2015, Section 6).

This paper summarizes key elements of a World Bank technical assistance study, which included a main report (Sánchez-Triana et al., 2014) as well as 12 detailed, technical reports. Participants in the study are listed in the acknowledgements section, and the 12 reports are listed in the supplemental material. Some of the technical work performed for the World Bank study has appeared in the peer-reviewed literature (e.g., Bhattacharyya, Pethick and Sarma, 2013, and Biller and Sanchez-Triana, 2013), but most of it has not.

Challenges Faced by Sundarbans Residents

This section summarizes major reasons the Sundarbans has become an increasingly difficult place to live.

The region has long been subject to cyclonic storms and severe flooding. Chakraborty (2015) lists the more than 35 cyclones that occurred in the Indian Sundarbans between 1909 and 2009. Cyclone Aila in 2009 provides an instance of a particularly devastating event. It was accompanied by heavy rainfall, flooding and landslides. Wind speeds of 120-140 km per hour were recorded and more than 900,000 houses were damaged, the majority of them in Sundarbans. In addition, more than 500 km of embankments were destroyed (Chakraborty, 2015).

Embankment construction together with forest clearing made extensive human habitation possible in the Sundarbans. The embankment construction process, which started in the late 19th century and continued through to the 20th century, made reclamation possible by preventing saline water from inundating land that was otherwise suitable for cultivation. The associated forest clearing process was extensive. At the end of the 18th century, the mangrove forest extended up to Kolkata (Ghosh et al., 2015); and by 1947, when India gained its independence from Britain, the forest was only 50% of its pre-colonial size (Giri et al., 2007).

Upstream water diversions and other anthropogenic activities have changed the sediment flows to the delta, and creekside erosion together with cyclonic storms have adversely affected the structural integrity of many embankments. Remote sensing data (for 2001-08) indicated the presence of 3638 km of embankments (Hazra et al., 2010). Before Cyclone Aila, 471 km of embankments were considered vulnerable to failure, but that number increased after Aila. According to a preliminary estimate by Hazra et al. (2010), 1000 km of embankments were vulnerable following Aila.

In addition to the effects of creekside erosion in undermining embankments, many of those living behind embankments face frequent challenges associated with embankment overtopping due to storm surges caused by cyclones. For example, in 2005, the western side of Mousuni Island lost about 1.5 km of embankment due to storm surges (Danda, 2007). A study of 600 of the 1550 families in one village (Baliara) on Mousuni Island found that nearly 13% of respondents had been adversely impacted by storm surges on an annual basis (Danda, 2010). Such surges typically take place when very high winds occur simultaneously with spring tides. It is difficult to drain the relatively low lands behind embankments after they are breached or overtopped, and this has led to increased soil salinity with consequent challenges in farming the land (Ghosh et al., 2015; Raha et al., 2013).

Sea level, which has been rising for millennia in the Sundarbans, is predicted to make matters worse. Much recent attention has been given to sea-level rise (SLR), namely global (sometimes called eustatic) sea level rise. Eustatic SLR refers to changes in the mass of the oceans due to the melting of glaciers and other land supported ice, as well as the thermal expansion of sea water as the oceans warm (Ericson, 2006). Changes in salinity also play a small role in global SLR (Antonov, Levitus and Boyer, 2002).

However, eustatic SLR is only one component of relative sea-level rise; i.e., the rate of apparent sea-level change relative to the land surface. In addition to eustatic sea-level rise, relative SLR in the Indian Sundarbans is influenced primarily by land subsidence, e.g., from auto-compaction, tectonic activity and anthropogenic processes, including ground water withdrawals (Bhattacharyya, Pethick and Sarma, 2013). Further information on land subsidence contributing to SLR, as well as challenges resulting from the limited relevant data in the Sundarbans is given in the supplemental material.

As detailed later in this paper, the embankment system that was intended to protect the Sundarbans from the sea is not working well, and many km of embankments are vulnerable to breaches and overtopping due to storm surges. Based on extensive modeling studies, Kay et al. (2015) predicted that flooding due to storm surges during increasingly high tides will be an even more significant risk for residents of the GBM delta, which includes the Sundarbans.

Changes in salinity in the estuaries of the Indian Sundarbans are another concern. Owing to higher freshwater flows in the Hooghly Estuary, salinity has decreased in that zone. As a consequence, fish species of low commercial value, particularly hilsha *(Tenualosa ilisha), have* increased significantly, but the commercially important taxa have become less abundant. (Ghosh 2015; Sinha, Mukhopadhyay, and Mitra, 1997). The situation is different in the central portion of the Sundarbans. Salinity has increased in that area because connections to meltwater sources have been eliminated due to heavy siltation of the Bidyadhari Channel (Banerjee, 2013).

Although net forest lands have not diminished much in recent decades, the changes in the mix of tree species has been notable (Giri et al., 2007). Part of this shift in species is explained by forest replanting programs and by shifts to salt tolerant mangrove in areas of rising soil and water salinity (Giri et al., 2007, Hazra et al., 2010). Also, increases in pollution and soil salinization has caused top dying disease of *Heritiera fomes* (commonly known as sundri), the once dominant and economically most important mangrove species in the Sundarbans (Ghosh et al. 2015). Of special concern are the central portions of the forest where levels of salinity have increased (Banerjee et al., 2012a). In addition, remote sensing studies for 2001-2008 show continued land conversion, with agricultural lands being converted to dense settlement areas and aquaculture ponds; the area of agricultural lands in that period dropped from 2149 km^2 to 1691 km^2 (Hazra et al. 2010).

The drop in lands suitable for cultivation has been accompanied by an increase in shrimp farming, and many residents are supplying tiger shrimp seeds for aquaculture. This was the case for 20% of the 243 households surveyed by Danda (2007). However, seed collection practices result in significant aquatic ecosystem disruptions as a result of bycatch: the target species *(P. monodon*) accounts for at most one percent of the total catch brought from the sea during seed collection, and almost of all the remaining portion is discarded on beaches or tidal mudflats (Danda, 2007). Capture of aquatic species caught unintentionally during shrimp seed collection together with overexploitation of shrimp fry are severely limiting the numbers of fully grown shrimp in natural waters (Knowler et al., 2009).

Pollution from Kolkata has increased, as evidenced by heavy metal contamination of Hooghly Estuary. For example, Samanta et al. (2005) found levels of Cd, Cu and Pb at levels high enough to disturb the aquatic life process in the portions of the Hooghly near Haldia. In addition, Guzzella et al. (2005), found poly-chlorinated biphenyls and other persistent toxic pollutants in sediments along the lower stretch of Hooghly Estuary. Much of this pollution has been linked to sources in Haldia and Kolkata (Samantha et al., 2005; Banerjee et al., 2012b)

Other challenges in the Sundarbans concern increases in human-animal conflicts. In the case of tigers, this is because of habitat loss and the encroachment of humans into tiger territories. Das (2014) conducted household surveys in villages adjacent to the mangrove forest and identified 237 incidents of tigers straying into those villages during 1995–2010. In the context of that survey, the vast majority of incidents involved predation on livestock, followed by injury to people. There were also 7 cases of human death and 12 cases in which villagers killed tigers.

Rationale for the Proposed Strategy

This section summarizes the approach used to develop a strategy for reducing risks faced by Sundarbans residents and conserving biodiversity, and subsequent sections of the paper highlight elements of the strategy.

The World Bank study that provides the basis for this paper was conducted from 2009 to 2012. The study team included World Bank staff and consultants who prepared 12 different background papers across a broad range of subjects: livelihoods dependent on aquaculture, agriculture, and ecotourism; education; health; water and sanitation; energy; transportation; and household air pollution from use of solid fuels. Also, a survey of 2,188 households in the Sundarbans was conducted to provide a demographic and economic profile of households and information on patterns of migration in response to extreme-weather events (Ortolano, et al., 2016). A study dealing with weather-related hazards identified cyclonic storm trends. A study on coastal geomorphology looked at changes in erosion and accretion in tidal channels and consequent effects on the integrity of embankments. Furthermore, studies were conducted of the effectiveness of existing disaster risk management systems and government subsidies for Sundarbans' residents (Sánchez-Triana, et al., 2014).

Literature reviews informed all aspects of the study, although several reports involved primary data gathering. In the context of this paper, primary data gathering was done by Bhattacharyya, Pethick and Sarma (2013) for the geomorphological modeling studies summarized herein. In addition, the household survey, which was conducted by Economic Information Technology, with participation by Professor Guatam Gupta of Jadavpur University in Kolkata, also involved primary data gathering. The survey results were detailed in an unpublished study, and key aspects of the results (as well as information on the household sampling strategy) were summarized by Ortolano et al. (2016).

In addition, workshops and consultations were held with representatives of multiple levels of government. At the national level, this included Government of India (GoI) National Disaster Management Authority, Ministry of Surface Transport in Kolkata, Ministry of Shipping, Inland Waterways Authority of India, and National Highway Authority of India. At the Government of West Bengal (GoWB) level, those consulted included the Department of Planning, Sundarbans Development Board (SDB) and members of the West Bengal Legislative Assembly representing local constituencies. Other consultations were with local research institutions (e.g., Department of Oceanography, Jadavpur University); non-governmental organizations (NGOs) such as the World Wildlife Fund (WWF); and individual residents. Interactions with stakeholder were used to identify issues to be addressed in individual studies and to discuss findings from the studies as they emerged. These interactions also informed creation of the proposed strategy.

The study team was motivated to develop a strategy for risk reduction and biodiversity conservation for the following reason. The Indian Sundarbans has become increasingly hazardous and high levels of material poverty have been evident for generations. For centuries, large parts of the forest have been extensively exploited for timber, fish, shrimp seeds or converted for agriculture and aquaculture. Upstream water diversions and other anthropogenic activities have changed the landform in the delta and the structural integrity of embankments. The region's population growth has led to degradation of the mangrove forest, unsustainable extraction of natural resources, and an increase in the number of people exposed to significant and recurring flood risks. Pollution from Kolkata has increased. In addition, the absence of adequate physical infrastructure in the region contributes to low standards of living. Increased salinity and waterlogging has imperiled agriculture and shrimp farming practices have been ecologically unsustainable. Moreover, the frequency of human-animal conflicts has increased because of habitat loss.

The portion of the Sundarbans in which residents face particularly high risks and hardships, referred to herein as the "transition zone," is between the part of the Sundarbans on the mainland (the "stable zone") and the "core zone." The latter is defined herein as the contiguous legally protected areas of the Sundarbans, which includes the Sundarbans National Park and Tiger Reserve, one of the three wildlife sanctuaries in the region, and the Sundarbans Reserve Forest (SRF). The three zones are shown in Figure 2.

Figure 2. Map of the West Bengal Sundarbans, showing the core, transition, and stable zones. Figure prepared by the Map Design Unit of The World Bank (see online version for colors).

The people within the transition zone suffer from a shortage of livelihood opportunities. They also lack the economic, human and social capital needed to make permanent out-migration to urban job centers successful in the short term. Job training would be a necessary precondition, for successful out-migration.

The study team considered four approaches to improve the condition of transition zone residents: business-as-usual; intensive rural development; short-term out-migration of residents; and embankment realignment and facilitation of voluntary, permanent out-migration. The business-as-usual approach is a continuation of the current low-intensity rural development strategy with influxes of aid following disasters. It does nothing to effectively address the region's challenges and will only perpetuate the ongoing cycle of poverty. A more intensive rural development approach was considered and rejected because it would attract migrants from outside the Sundarbans and thereby put more people at risk; it would also put additional pressure on the mangrove forest. The third of the approaches examined involved short-term migration of residents out of the transition zone. This was ruled out because there would not be sufficient time to allow residents to obtain the training and other resources needed to migrate successfully and the approach would entail massive social disruption.

Based on its analysis, the team recommends a fourth strategy, one that reduces both human and ecosystem risks by encouraging the gradual, voluntary movement of transition-zone residents to the stable zone and urban areas outside of the Sundarbans that offer increased safety and improved employment opportunities. This strategy recognizes that transition zone residents will continue to face stresses, such as embankment overtopping, and that some existing livelihood options are unsustainable. In addition, major investments in transport networks and electricity in the transition zone would be economically inefficient because projected SLR is likely to make parts of the transition zone uninhabitable in coming decades.

The proposed strategy rests on measures to build the economic, human and social capital residents require to migrate permanently outside the transition zone into relatively safe urban areas in the stable zone and beyond. With appropriate planning in urbanized areas, there would be improved options for health care, education and employment. Transition-zone residents have generally not pursued permanent out-migration as an option, in part because they lack the economic, human and social capital required for successful out-migration. In order to buy time while the needed capital is being created (e.g., using job training programs) and to reduce risks for those who choose not to migrate voluntarily away from high-risk areas, the study team proposed measures to improve the integrity of the embankment system and the effectiveness of the disaster risk management system; and it also suggested actions to improve the sustainability of livelihood options for those who choose to remain.

At first glance, it may appear to be internally contradictory to encourage out-migration from the Sundarbans and at the same time reduce water-related risks within the Sundarbans. However, the approach is internally consistent once time scales are taken into account. It will take time to equip transition zone residents who choose to migrate with the economic, human and social capital needed to take advantage of the greater employment and other opportunities within lower-risk urbanized areas. While this capacity building process is ongoing, residents will continue to be exposed to considerable risk and thus risk-reduction measures are appropriate: realigning embankments gradually and systematically; allowing mangrove to occupy land vacated by realignment of embankments; and improving the emergency management in response to cyclones and floods (e.g., improving disaster warning systems and building additional shelters).

The remainder of this paper emphasizes the dimensions of the proposed approach most closely tied to reduction of hazard in the transition zone caused by sea level rise and cyclonic storms. Four aspects of the proposed approach were developed by the team:

- Modify embankment system and reduce disaster risk -- It is infeasible to eliminate exposure to hazards for transition-zone residents, but risks can be reduced by improving disaster risk management programs and modifying the embankment system.
- Enhance the capacity of residents to migrate outside the transition zone – Steps can be taken to improve the ability of transition-zone residents to migrate successfully and incentives can be provided for out-migration.
- Conserve biodiversity – Biological conservation measures can provide opportunities for reducing *both* hazard exposure (via ecosystem service provision) and vulnerability (by creating new revenue streams that support building the capacity of transition-zone residents to migrate successfully).
- Strengthen institutions – Improvements can be made in the ability of government agencies to implement elements of the proposed strategy.

All aspects of the proposed approach are considered below, but emphasis is on reduction of hazard in the transition zone caused by sea level rise and cyclonic storms.

Reducing Exposure to Climate-related Hazards

The proposed approach employs two main types of interventions to deal with the flood-related disasters in the transition zone: short-term measures that extend India's disaster management activities, and a long-term program of large-scale embankment realignment.

Disaster preparedness

The aforementioned survey of 2,188 households illustrates particular challenges concerning flood warnings. Among households affected by a major cyclone or flood during the 2006-11 period, only 3.6 % of households were notified of the event beforehand (Ortolano et al., 2016). This was the case even though the extreme-weather events in question caused 55.4% of surveyed households to evacuate their homes. Of the residents who faced evacuation only 2.2% went to shelters (and 26.0% relocated to schools). Moreover, 42.8% of those who were evacuated went to the nearest embankments or elevated roads, which are among the most exposed places during cyclonic storms.

The World Bank study also examined the adequacy of the existing shelter system. It assumed that one cyclone shelter serves 2,000 residents, which is typical for the region. Thus, to serve the more than 4.4 million people in the Sundarbans, at least 2,000 shelters would be needed. However, as of 2010, only 315 shelters were located in the coastal areas of North and South 24 Parganas (which includes the Sundarbans) and Midnapore East (Basu, 2010).The study recommended a substantial increase in the number of shelters as well as improved cyclone/flood warning systems and increased inter-agency and agency-NGO communication during cyclone and flood disasters.

Improvements are being made. The West Bengal Disaster Management Department and Sundarbans Affairs Department are putting in place cyclone shelters, cyclone resistant buildings, and communication networks to improve response to extreme weather events. In 2015, West Bengal took actions consistent with those suggested by the study team by joining the National Cyclone Risk Mitigation Project (partially funded by the World Bank). This will provide GoWB with resources needed to build more shelters and enhance its capacity to respond to disasters (National Disaster Management Authority, 2015).

Embankment system challenges

A major effort to reduce hazard exposure in the Indian Sundarbans involves flood protection measures using embankments, but the embankment approaches currently in use are not working as planned. The vulnerability of the Sundarbans to damaging surges linked to effects of cyclones and SLR is made clear by events associated with Cyclone Aila in May 2009. Storm surges of 2–3 m swept through the region, more than 400 km of embankments were breached, and the entire Sundarbans biosphere reserve was inundated with 2–6 m of water for several days. Damages were estimated at about US$550 million and 2.5 million people were affected (Chatterjee et al., 2013).

Similar outcomes were observed in the Bangladesh Sundarbans. For example, as reported by Auerbach, et al. (2015), during Cyclone Aila, there were several breaches in the embankment at Polder 32. The breaches, which occurred in several places, apparently resulted because of undercutting of embankment foundations by erosion. As a consequence of embankment construction, land elevation inside Polder 32 was more than a meter below the elevation of adjacent land outside the polder, and this elevation difference contributed to damages resulting from the embankment breaches.

Based on their assessment of data for the Indian Sundarbans, Bhattacharyya, Pethick and Sarma (2013) estimate that considering the *combined* effects of subsidence and eustatic SLR, relative sea level in the Sundarbans is rising at between 3 mm/yr and >8 mm/yr, depending on the location. Higher rates have been observed at the landward edge of the delta (the Kolkata tide gauge) and lower rates at the seaward edge (Sagar Island gauge). Bhattacharyya, Pethick and Sarma reported the period of record for both gauges as 1932 to 1999.

Many others have examined the effects of sea level rise in the region and results generally point to significant challenges in the future. For example, modeling studies by Kay et al. (2015) estimated that sea level could rise in the GBM Delta by 0.63 to 0.88 m by 2090, with predictions by others being 0.5 m higher if potential melting of the West Antarctic ice sheet is included. The modeling results led to the conclusion that “climate change could lead to large areas of land being subject to increased flooding, salinization and ultimate abandonment in West Bengal, India, and Bangladesh” (Kay, et al. 2015: 1311).

Based on field visits after Cyclone Aila, Bhattacharyya, Pethick, and Sarma (2013) observed that overtopping and wave erosion were not responsible for most breaches in the Indian Sundarbans. Instead, the breaches were caused by mass failures that occurred because of: (1) over-steepening of embankment faces as a result of long-term channel erosion; and (2) seepage during surge events, which led to increased pore pressure within the clay structure. These researchers found that channel erosion undercutting of embankment intertidal footings plays a key role in failures because it steepens slope angles, thereby increasing embankment instability during storm surges when pore pressures within the embankments are high.

One component of the World Bank study consisted of modeling conducted by Bhattacharyya, Pethick and Sarma (2013). This work employed a regime modeling approach developed for use in estuaries as detailed by Wallingford, ABPmer, and Pethick (2006). In this context, “regime” refers to the *equilibrium* morphology of an estuary channel in response to a tidal discharge. An estuarine channel that neither erodes nor deposits sediments, over a long period of time, is said to be in equilibrium. The central idea in the modeling study was to determine whether particular estuaries in the Sundarbans were wider or narrower than their equilibrium values so that judgements could be made about the suitability of existing embankment locations. Channels that were narrower than their equilibrium widths could be expected to erode as they approached equilibrium; in contrast, channels wider than equilibrium widths could be expected to accommodate the deposition of sediments. The modeling effort is summarized in the supplemental material.

The key prediction from the modeling effort is the theoretical, time-independent, equilibrium value of channel width; not all estuarine systems under study were expected to be in equilibrium as they might be either be eroding or accreting. Creeks that are eroding are of particular concern since embankments are located at or near creek edges. Bhattacharyya, Pethick and Sarma (2013) used model results to categorize the estuaries based on whether their widths were smaller or larger than their equilibrium values under prevailing conditions; model runs were also performed for hypothesized future increases of 1 and 2 m in sea level. The estuaries under study were categorized by Bhattacharyya, Pethick and Sarma as follows:

- Oversized— These estuaries could accommodate future sea level rise because reclamation of intertidal lands together with removal of headwater creeks from tidal flow (using flap sluices) had cut tidal prism volumes.
- Equilibrium -- Channel widths for these estuaries have kept pace with past SLR, but they contain minimal space to accommodate future increase in sea level, and thus collapse of existing embankments along these channels is expected.

- Undersized—These estuaries are undersized as a result of previous SLR and a recent increases in tidal flow to and from aquaculture ponds. The recent rapid increase in aquaculture acts to reverse the process of reclamation. Given that accommodation space in these estuaries is already negative, response to future SLR is expected to be severe.

The above-mentioned modeling results suggest that retreating many embankments away from tidal channels can prevent channel bank erosion from undercutting their foundations; this embankment realignment strategy was also highlighted in related studies in the Bangladesh portion of the Sundarbans (Pethick and Orford, 2013). Results from these modeling studies, as elaborated in unpublished technical reports by Pethick (a consultant on the World Bank study) and summarized by Sánchez-Triana et al. (2014), were used in making specific recommendations to GoI regarding the need for systematic retreat of selected embankments. In some cases, the recommendation was to accommodate future sea level rise by moving embankments back by as much as 100–300 meters (or 50–150 meters from each bank of a channel) over the next 20 years and raising the height of a number of embankments.

The managed realignment of embankments near the edges of eroding channels would require that existing embankments be maintained while new ones are constructed further from those channels. In relocating embankments in danger of being undermined by erosion, the land between old embankments (eventually to be abandoned) and new (retreated) embankments will become unprotected. As noted by Bhattacharyya, Pethick and Sarma (2013), using an additional set back distance of 30–50 m would allow mangrove to regenerate in these areas, thereby providing a buffer to dissipate the energy of tidal currents and storm-driven winds.

Incentivizing Out-Migration

Sea level rise, salinization of soil and water, cyclonic storms and flooding have combined over the past century to render the Sundarbans one of the most hazardous parts of the Indian subcontinent. Natural stresses have been compounded recently by human-induced stresses, which include reductions in fresh-water flows to many parts of the delta and an expansion in tidal water aquaculture. The predicted changes associated with global climate change will exacerbate these problems: intense cyclonic storms coupled with continuing sea level rise will further increase exposure to hazards of the local population.

In the long term, trying to address these challenges by following a business-as-usual development scenario will make matters worse because huge numbers of Sundarbans' residents will remain in harm's way. Moreover, increasing residents' income or building extensive infrastructure throughout the region will only attract more people to areas that are fundamentally in decline and hostile to human habitation. In the long term, voluntary, permanent out-migration out of the transition zone appears to be the most viable option.

The suggested measures for improving the disaster response system and realigning embankments will reduce risk in the short and medium term, but these measure will not eliminate risk. Given the hazard risks, increasing numbers of transition-zone residents are likely to view permanent out-migration out of the area as a desirable option. This is reflected in increased out-migration during the last few years from inhabited parts of the Sundarbans closest to the sea; e.g., parts of Sagar Island (Eaton, 2015). The prospect of increased out-migration to cities outside the transition zone is beginning to be discussed by West Bengal officials (Ghosh, 2015).

In recent years, much of the out-migration from the Sundarbans has been temporary. A portion of the aforementioned 2011 household survey probed the migration issue and found that that 31.7% of residents in surveyed households moved in search of work after Cyclone Aila; and more than 98% of those who migrated did so on temporary basis in search of employment (Ortolano et al. 2016). These findings are consistent with findings of Penning-Rowsell et al. (2013) from focus groups in rural Bangladesh: unless a place becomes permanently uninhabitable, people may migrate temporarily in response to cyclones and other natural disasters, but they frequently return to their villages.

While involuntary out-migration could be achieved within a few years, the approach recommended by our study would be socially less disruptive as it would encourage the gradual, voluntary and permanent out-migration of residents living close to the SRF boundary and other high-risk places to cities in the stable portions of the Sundarbans and beyond that are relatively safe and have greater economic opportunities. Encouraging residents living near the SRF to seek opportunities elsewhere will also reduce the number of resident residents who illegally exploit the forest's resources.

Most transition-zone residents lack the education and social capital to obtain attractive employment elsewhere and many are aware of the challenges of life in urban slums. Under the circumstances, what would encourage those residents to migrate? Certainly, providing additional information to residents about the worsening hazardous conditions and the unsustainability of shrimp farming and other current livelihood options would provide some incentive to leave. Out-migration could also be incentivized by re-evaluating the existing post-disaster government and

NGO aid programs since they encourage residents to rebuild their dwellings and remain in hazardous areas.

Other incentives to leave the transition zone relate to the attractiveness of opportunities in cities for increased employment and improved healthcare and education. Projections by McKinsey Global Institute (2010) show that the bulk of India's growth in both population and GDP during the coming decades will occur in urban agglomerations. We propose use of small subsidies to reduce the risks associated with moving to an unknown place on a journey with uncertain outcomes. The effectiveness of small subsidies to encourage out-migration in rural Bangladesh was illustrated by Bryan, Chowdhury, and Mobarak (2013).

Incentives to migrate will not be enough. There also needs to be a program of education and skills development to enhance the likelihood of success of migrants to new locations. In many such locations, there are opportunities for plumbers, electricians, mechanics, skilled masons, etc. Improved education and vocational training is a prerequisite for labor market success.

Given that Sundarbans residents in the transition and stable zones will need training to fill jobs offered in livelihood clusters and more densely populated parts of the stable zone as well as in urban areas outside the Sundarbans, education and skill building programs could be created (in the stable zone) to train the labor force for new manufacturing and service sector jobs (e.g. hotel workers). These can be targeted to transition area residents who would be willing to relocate to seek better jobs.

Notwithstanding the challenges facing migrants in Kolkata and other large cities, those areas offer better opportunities for employment and education compared to the transition zone. Moreover, over multiple generations, descendants of the rural poor who seek employment in urban areas are often better off than they would have been if their families had remained as rural residents (Glaeser, 2011; Narayan, Pritchett and Kapoor, 2009; Ravallion, 2007). In addition, urban economic growth can positively impact the living standards of those who remain in rural areas not only because of remittances sent by family members in cities, but also because fewer people are left in those areas to compete for already scarce jobs.

Out-migration can also be incentivized using conditional cash transfers in the form of health and education vouchers usable in cities in India outside the transition zone. Some results of the aforementioned 2011 household survey suggest that this approach could be successful: many respondents expressed willingness to send their children outside the Sundarbans for educational opportunities (86%) or to participate in training programs in Kolkata or other parts of West Bengal (78%).

GoWB and local governments could prepare for the anticipated increase in rural-to-urban migration by promoting rational urban land-use and building needed infrastructure (particularly in transport and energy) to accommodate growing economic activity in the manufacturing and services sectors. Moreover, local governments could redouble their efforts to deal with the pollution problems that plague many Indian cities. Government interventions in urban centers could also include improvements in delivering education, housing and other urban services. Local governments could also create social networks and support systems to help migrants integrate into local labor markets.

Information could be disseminated to transition-zone residents on how they could improve their livelihoods, health and education by migrating to more urbanized areas. Such information could highlight research showing positive effects of rural-urban migration on income (e.g., Young, 2013). Information dissemination campaigns could also be used to discourage potential migrants from entering the transition zone. In-migration cannot be stopped by government edict, but it can be discouraged by providing information to potential migrants using a mass education program regarding dangers associated with life in the transition zone. Potential in-migrants could be reached by disseminating information in locations known (via the 2011 household survey) to be common departure points for in-migrants.

Social scientists have not yet developed complete explanations for why people migrate from rural to urban areas (Bryan, Chowdhury and Mobarak, 2014). Thus implementation of elements of the voluntary out-migration program we propose should be treated as small-scale experiments designed such that data can be gathered to assess effectiveness. Results can be used to modify subsequent efforts to influence out-migration decisions.

In the long term, residents in the transition zone will leave because of the challenges associated with living there and this may offer opportunities to augment the mangrove forest. An expanded forest will provide enhanced opportunities for conserving biodiversity and serve as a bio-shield to protect Kolkata and other inland cities from the high winds associated with cyclonic storms over the Bay of Bengal.

The proposed out-migration approach would require a relatively long time frame, during which those living in the transition zone would face increasing risks. Thus, during this time interval, there is a need to reduce potential threats by undertaking embankment realignment and upgrading, and mangrove bioshield restoration, as well as to strengthen early warning systems, emergency preparedness, and cyclone shelters investments to address more effectively the treatment of disasters when they do occur. These measures are complementary to initiatives that encourage out-migration, and would be phased out as the population in the most exposed areas of the transition zone decreases.

Conserving Biodiversity

One element of the proposed approach to conserving biodiversity concerns improved coordination on forest management procedures between India and Bangladesh. Although our study concerned the Indian portion of the Sundarbans, the study team recommended that the Sundarbans ecosystem be managed by having both Bangladesh and India create an integrated policy for conservation and development, or at least adopted a harmonized policy that could be implemented by each country individually. Steps toward bilateral cooperation on biodiversity conservation were advanced in 2011 when the Governments of India and Bangladesh entered into cooperative agreements that facilitate information sharing and increased coordination in the context of managing the Sundarbans forest (Ortolano et al., 2016).

Biodiversity conservation could also be furthered by the previously mentioned activities involving mangrove restoration in new land areas created by realigning existing embankments to prevent embankment failure due to tidal creek erosion. Other measures aimed at conserving biodiversity involves generating revenues to benefit local residents, thereby giving them a stake in forest conservation (Biller and Sanchez-Triana, 2013). One approach to revenue generation involves payment for ecosystem services (PES) programs (Pattanayak, Wunder and Ferraro, 2010). Services provided could include the previously-mentioned use of the forest as a bio-shield to protect Kolkata and other inland areas from damaging winds. Also, an innovative revenue-generation approach that can be further explored involves creating property rights on non-timber forest products, such as honey, fruit and other extracted products and non-extractive use functions (e.g., tiger viewing). Moreover, by preserving the mangrove it will be possible to access revenue streams that have been (and will be) created as part of carbon financing programs intended to manage greenhouse gas emissions. New revenues generated in the aforementioned ways could provide benefits for residents, such as programs to equip transition-zone residents with training needed to access jobs in the stable zone and outside the Sundarbans.

Another biodiversity conservation measure involves establishing privately-funded hatcheries for use in shrimp aquaculture and improving shrimp seed collection methods while hatcheries are being developed. Aquaculture in the Sundarbans could be made more sustainable if state-of-the-art hatcheries were promoted and if the Food and Agricultural Organization's Code of Conduct for Responsible Fisheries were adopted.

Institutions

Government programs for the region's development are driven largely by GoWB agencies. The Department of Sundarban Affairs and the Forest Department have the broadest administrative influence over the Sundarbans. When the Department of Sundarban Affairs was created in 1994, it subsumed the SDB, which had been created to address the socio-economic challenges of the region. A report by WWF clarifies the political challenges faced in planning for the region: "The original mandate of SDB was to coordinate activities of the various sectoral departments operating in the ecoregion. However, the SDB has since morphed into a parallel implementation agency with a range of divisions mirroring the departmental mandates of different state departments …." (Danda, et al., 2011, p.22).

The number of poorly adapted initiatives that have been used in the Sundarbans over the past decades makes it evident that there are no effective incentives for government agencies to cooperate or coordinate their programs in the region. Numerous examples exist. For instance, aquaculture development has contributed to tidal creek erosion that undermines embankment stability. Another example is the complete ban on mangrove cutting, which reduce the incentives for communities to manage them well and have in fact turned pursuit of some potentially sustainable uses of the forest into a crime.

Although the Department of Sundarban Affairs is intended to coordinate all efforts in the region, tackling the high-priority issues could be improved by enhancing the cooperation and coordination between selected pairs of responsible GoWB departments. For example, cooperation between the Forest Department and the Irrigation and Waterways Department is essential given the current and future needs to encourage mangrove growth along areas that become available for restoration as a result of embankment realignment. There is a need to ensure that areas created by retreat of embankments are immediately planted with appropriate mangrove species and maintained. This requires the Irrigation and Waterways Department to: (a) plan and implement the embankment realignment activities sequentially, and engage in mangrove planting at the time embankments are retreated; and (b) hand over jurisdiction of land vacated as embankments are realigned to the Forest Department without any opportunities for other land uses to occupy that land. The Department of Panchayat and Rural Development should also be a part of an enhanced coordination effort, given its capacity to improve community efforts in social forestry.

Another example involves coordination between the Irrigation and Waterways Department and the Department of Fisheries and Aquaculture. Much of the current embankment erosion in the eastern delta is related to the location of aquaculture ponds and the timing of pond refilling activities. The Department of Fisheries and Aquaculture should promote aquaculture practices in ways that do not negatively impact embankment investments undertaken by the Irrigation and Waterways Department. Enhanced cooperation and communication between these two departments could reduce the undesirable effects associated with the location and operation of aquaculture activities. For example, both departments should take steps to prohibit pond operators from operating their sluices at the same time to let water in to flush the ponds on the high spring tides because this causes a major discharge.

The study team presented its recommended strategy to officials in GoI and GoWB, and the recommendations are feeding into meetings and consultations aimed at arriving at a consensus among stakeholders regarding next steps in managing the Sundarbans. This consensus building process is ongoing and thus complete government policies for dealing with the water-related issues described herein are still being formulated.

Definitive policy making is ongoing in a number of domains, such as promoting transboundary management of protected areas, strengthening the mandate of the Sundarbans Development Board, and augmenting the budgetary resources for conservation and improvement of community livelihood options. In addition, many of the study team's recommended actions are already being pursued. As an example, the Irrigation and Waterways Department's program of embankment reconstruction has been modified in ways consistent with the study team's geo-morphological modeling results. The Department's US$1 billion of funding from GoI is being used to realign damaged embankments in the transition zone. Other examples include: construction of 200 cyclone shelters under World Bank financed projects, construction of additional cyclone shelters using financing from NGOs; and mangrove planting by private sector actors to earn carbon credits under the Clean Development Mechanism of the United Nations

Framework Convention on Climate Change. These activities rely directly or indirectly on local capacity, which has been informed or strengthened by the study team's efforts.

Conclusions

Persistent pressures from water-related threats -- sea level rise, soil and water salinization, and flooding due to embankment overtopping and failure -- have made the Indian Sundarbans a challenging place to live, and effects of global climate change will only worsen conditions. Attempts at poverty alleviation in high-risk areas will involve an endless and unavailing struggle, even in the absence of future climate change impacts.

The study team's recommended approach involves striking an effective balance between long-term risk avoidance via voluntary out-migration and risk reduction measures for those who remain in the high-risk transition zone. As mentioned, this approach of facilitating voluntary out-migration and enhancing risk reduction is not internally contradictory once the time scales involved are considered. Time will be required to equip those who choose to out-migrate with the economic, human and social capital needed to migrate successfully to safer areas with greater opportunities. Measures to assist with the out-migration include: improve interagency collaboration; invest in key areas, such as the creation and operation of job training centers for migrants; augment services in nearby urbanized areas in the stable zone and beyond so that those areas are better able to receive migrants; and implement incentives to encourage out-migration (e.g., information dissemination campaigns to alert residents regarding increasing risks or remaining and improved options elsewhere) and to discourage in-migrants.

During the time interval needed to prepare for successful voluntary out-migration, measures to cut risks (e.g., embankment re-alignment and enhanced disaster management systems) will be needed because the population will continue to be exposed to considerable risk.

A number of additional recommendations concern biodiversity conservation (e.g., creation of revenue streams to give residents living near the SRF incentives to conserve the forest).

Acknowledgements

The findings, interpretations, and conclusions expressed in this paper do not necessarily reflect the views of the Executive Directors of The World Bank or the governments they represent. The World Bank does not guarantee the accuracy of the data included in this work. The boundaries, colors, denominations, and other information shown on any map in this work do not imply any judgment on the part of The World Bank concerning the legal status of any territory or the endorsement or acceptance of such boundaries.

Many thanks are due to members of the study to team. In addition to the authors, the study team included: Anupam Joshi, Cecilia Belita, Charles Joseph Cormier, Dan Biller, Ghazal Dezfuli, Jack Ruitenbeek, John Pethick, Jean-Noel Guillossou, Nalin Jena, Priti Kumar, Rahul Kanakia, Ana Luisa Gomes, Ramachandran R. Mohan, Roshni Sarah John, Ruma Tavorath, Sanjay Gupta, Santiago Enriquez, Shakil Ahmed Ferdausi, Snehashish Raichowdhury, Soumya Kapoor, and Surbhi Goyal. Additional background papers and analyses were produced by Anurag Danda, Anna C. O'Donnell, Bjorn Larsen, Chandreyee Das, Christine Heyniger, Damanjit Singh Minhas, D.M. Mohan, Elena Strukova Golub, Gautam Gupta, Ishtiaque Ahmed, Juan Luna-Kelser, Kakoli Sen Sarma, Lidvard Gronnevet, Nirmala Banerjee, Peter Webster, Pranabes Sanyal, Priyanka Roy, Ratul Saha, Samir Mehta, Samuel Taffesse, S.C. Rajshekar, Somenath Battacharya, Subimal Roy, the Institute of Environmental Studies and Wetland Management, Economic Information Technology, IMRB Consultants, Jadavpur University, Sundarban Rural Development and Training Centre, West Bengal Green Energy Department Corporation, and the Worldwide Fund for Nature-India. We are also grateful to Dinesh Kumar, Cecilia Tortajada, John Pethick, and two anonymous reviewers for helpful comments on an earlier draft**.**

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Annex 1
Reports Prepared for World Bank Study

1. Historical Overview and Current Trends in Development in the Sundarbans
2. Effective Forecasting Systems for Reducing the Impacts of Cyclones and Extreme Weather Events
3. Disaster Risk Management for Addressing Immediate Needs
4. Management Practices in Addressing Sea Level Rise, Floods, and Erosion
5. Policies and Programs in the Sundarbans
6. Environmental Risks and Measures to Reduce Their Costs
7. Spatially Blind Policies to Promote Human Development
8. Enhancing Livelihood Opportunities
9. Spatial Transformation and Increased Economic Growth Opportunities
10. Spatially Based Approach to Infrastructural Development in the Sundarbans
11. Regulatory Instruments and New Market-Based Incentive Mechanisms to Preserve Biodiversity
12. Institutional Approaches for Addressing Priority Challenges in the Sundarbans

Annex 2

Sea Level Rise

The information below provides details on subsidence in the Sundarbans as well as the modeling studies performed by Bhattacharyya, Pethick and Sarma (2013) as part of the World Bank study (Sánchez -Triana et al., 2014).

Information on rates of subsidence in the Sundarbans is incomplete and data that exists is highly variable. This is demonstrated by the work of Brown and Nicolls (2015), who analyzed all available published and unpublished data for the GBM delta: 205 point measurements from 24 studies. They reported an overall mean value of 5.6 mm/yr, median value of 2.9 mm/yr, and a standard deviation 7.3 mm/yr. The variability in the data was much lower for 36 point measurements of subsidence in the Sundarbans: mean value of 2.8 mm/yr, median value of 2.0 mm/yr, and a standard deviation 2.0 mm/yr. The Sundarbans measurements ranged from a low of 0.7 mm/yr to a high of 7.1 mm/yr (Brown and Nicholls, 2015).

The causes of the high variability of land subsidence measurements in the GBM delta are not completely understood. Brown and Nicholls (2015) report significant differences in data quality, methodology and period of measurement, with radio-carbon dating being the most common of the ten different measurement methods employed in the 24 studies.

The significance of subsidence as a key cause of relative SLR has also been noted by Nicholls and Cazenave (2010). For coastal areas experiencing subsidence (e.g., the GBM delta), they found that the rate of relative SLR due to local variables is often more pronounced than sea level rise due to global climate change. The importance of local factors in contributing to relative SLR is also highlighted by Syvitski et al. (2009).

The analytic work that was a part of the World Bank study reported on in this paper included a modeling effort by Bhattacharyya, Pethick and Sarma (2013). Their work is summarized briefly here to make it possible for readers to understand the general approach they followed without having to access their original paper. The modeling performed by Bhattacharyya, Pethick and Sarma was based on use of a semi-empirical equilibrium equation in the form of a power functions relating tidal prism and equilibrium values of inlet cross-section area: $A=kP^n$, where P is the tidal prism on a spring tide, A is the cross sectional area below mean sea level at equilibrium, and k and n are empirically determined parameters (Gao and Collins, 1994). This relationship dates back to studies by O'Brien (1931 and 1969). As detailed by Wiegel and Saville (1996) and D'Alpaos et al. (2010), the work started by O'Brien has been extended and refined by many others.

Bhattacharyya, Pethick and Sarma (2013) proceeded by employing the aforementioned equation with values of k and n determined from the literature (e.g., Gao and Collins, 1994). The modelers calculated values for tidal prisms for each estuary under study based on a combination of remote sensing data, a bathymetric field survey, and tidal range information from field deployment of tide gauges; tidal prisms were calculated in 250 m increments. Using values for tidal prisms together with the values of k and n from the literature, Bhattacharyya, Pethick and Sarma (2013) estimated equilibrium cross sectional areas along an estuary using $A=kP^n$. They also calculated equilibrium channel depths using equations developed by Lacey (1930), which used information on sediment grain size distributions of channel beds and banks. Predictions of equilibrium channel widths along an estuary were then made based on the cross sectional area and depth estimates.

The modeling involved the following tidal water bodies: the Saptamukhi system (including, Kalchara, Gobadia, Ghughudanga Gang and Banstala Gang); the Matla Estuary; and the Bidya system (including Pathanakhali Nadi) and the Raimangal system (including Bagna Khal/Jhila River). As described by Bhattacharyya, Pethick and Sarma (2013), the models were verified using standard procedures, and verification results were considered acceptable for purposes of the study.

Tide gauge data for the Sundarbans is very incomplete, but there is more on the Bangladesh side (Pethick and Orford, 2013) in comparison to the Indian portion, where the only permanent tide gauge is at Sagar Island. The water level at Sagar is measured using a visual staff record method, and data is only recorded during daylight hours. There are also challenges in using the data from Sagar Island to characterize the circumstances in the interior of the

Sundarbans. A more comprehensive data base that can be used in making management decisions related to embankments is needed, particularly as regards tidal and surge information.

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