Environmental Evolution of the Indian Sundarbans: Climate, Soil, and Rivers

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Abstract

One such intricate environmental system undergoing rapid change due to anthropogenic pressure and climate change is the Indian Sundarbans, the world's biggest mangrove ecosystem. A study has been conducted of recent research on the environmental development of the Indian Sundarbans, including changes in climate and sea level, soil salinisation, and hydrological variation. The region faces challenges from the sea, including land salinisation and sea level rise (3.14 to 4.0 mm yr−1) that go beyond the bounds of sustainable agriculture, as well as changes in riverine dynamics that impact sediment transport and freshwater supply. Surprisingly, they discovered that during the peak storm seasons, the study area had a higher occurrence of cyclones (17–26%), and that the sea surface water temperature had been rising at an average 27 years at a rate of 0.05°C annually. Much of the soil has high salinity in the region where soil salinity level varies from 8.0 to 20.0 ppt (safe salinity level for rice is 4.0 to 6.0 ppt). The near rivers also present significant 0.75 m per yr bathymetric changes, for maximum annual tidal range, in the past two decades, for the eastern and central rivers. Now, 4.43 million people, who have relied on the ecosystem for their food, face a sweeping change and are scrambling in response. The paper offers a mitigation to the disharmony between the idealized forest nation and a complex assemblage of people who benefit from forests and provides comprehensive environmental indices prepared exclusively for the Sundarban Biosp here reserve, detailed maps of the Sundarban, and areas under administrative jurisdiction that affect nature conservation, etc. It is important to better understand these environmental change processes, if region-specific adaption strategies shall be developed in order to maintain and conserve the long-term sustainability of this UNESCO World Heritage site.

Keywords: Sundarbans; climate changes; soil salinity; sea level changing; environmental evolution; mangrove ecosystem

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1. Introduction

The biggest single block of mangroves in the world (covering nearly 10,000 km²) called The Sundarbans spread into both India and Bangladesh. The Indian part occupies 4,200 km² and is A haven for countless species of jungle fauna, including the renowned Royal Bengal tiger of the Sundarbans (the Indian part is home to both the Bengal tiger and the Indian Sundarban tiger), the country's largest block of forest is also its largest area of halophytic mangrove forest, covering species of plants, according to more recent studies, and a rich variety of bird life, including several species of pelagic birds that vary between terrestrial, arboreal, and aquatic habitats. Mistri & Das's (2020) further investigation of SBR (Sundarban Biosphere Reserve) was place between latitudes 21°32' and 22°40' N and longitudes 88°05' and 89°00' E. The Hooghly River borders it on the west, the Bay of Bengal borders it on the south, and the Ichamati-Kalindi-Raimongal borders it on the east. Sundarbans, its ecosystem, is challenged by the secondary but great threat of climate change, on a back drop of enormously disturbed by man ecosystems resulting making one of the most vulnerable regions in terms of high salinity, sediments and land erosion in the world. The eco-environment of MWR has been increasingly deteriorated in the past decades, and many phenomena surfaced to endanger the survival and development of eco-environment and human well-being.

Sundarbans is a world heritage and therefore monitoring the Ecosystem change here becomes important. It features a unique physiography and geomorphology, the largest contiguous halophytic mangrove forests in the world, as well as a complex system of river and tidal channels, which provide as breeding grounds and habitat for a number of internationally endangered plant and animal species. Blue Carbon Mangroves, along with other related vegetation, store large volumes of ‘Blue Carbon’ considered key to climate preservation worldwide. Ongoing human actions that affect the environment are creating many worrisome trends in such a variety of measures. The downstream water induced anthropogenic threat of climate change is also creating devastating impacts of food security in the Indian Sunderban with high impact cyclonic activities, accelerated sea level rise and changed monsoonal patterns -- a multidimensional effect that is experienced by millions. This paper critically assesses the available information on the environmental changes in the Indian Sundarbans with special reference to: i) climate drivers, and ii) soil and riverine aspects.

2. Study Area and Administrative Framework

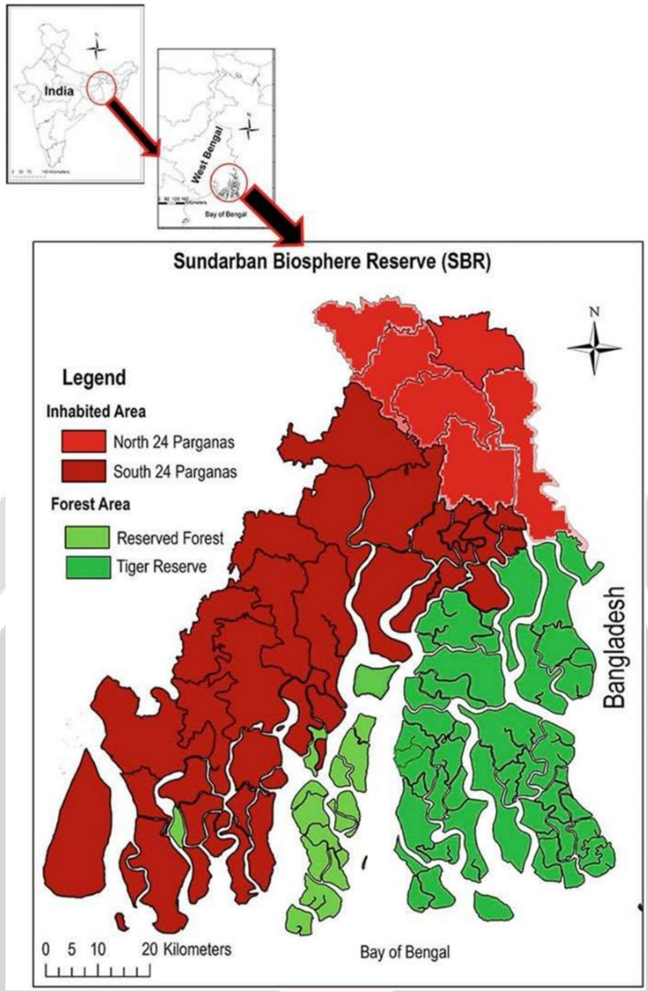
Location and Designations

From the Table1 of the original, it is evident that several designations of Sundarban Biosphere Reserve was done since 1878. It was declared a Protected Forest in 1878 and later as Reserve Forest (4,263km 2) in 1954. km in 1928. The STR, which spans 2,585. km was notified in the year 1973 under Project Tiger and the National Park (1,330.12 sq. km) that was made a UNESCO World Heritage Site in 1987.

Table 1 - Delineated regions and classifications of India's Sundarbans

Year	Legal names	Area
1878	A Protected Forest (PF) designation was given to the region.	——
1928	Itwasdeclaredas a Reserve Forest (RF)	4263sq.km
1973	Under the Project Tiger Scheme, it was one of the first nine Sundarban Tiger Reserves (STR) established.	2584.89 sq. km, which includes 985 sq. km of water and 1600 sq. km of land.
1976	Under the Project Tiger Scheme, it was one of the first nine Sundarban Tiger Reserves (STR) established.	362.42sq.km
1984	The Sundarban National Park (NP) was established as the central region of the Tiger Reserve.	Of the 1330.12 square kilometres of NP, 124.40 square kilometres are kept as a primitive zone to actasagenepool
1987	UNESCO designated the National Park as a Natural World Heritage Site.	1330.10sq.km
1989	The Government of India designated the STR as a Sundarban Biosphere Reserve (SBR), together with the surrounding forest area and human habitat.	9630 sq. km. (4263 sq. km. with forest and 5367 sq. km. with inhabited area)
2001	Under the Man and Biosphere (MAB) program, the SBR was added to the UNESCO World Network of Biosphere Reserves (WNBR).	9630sq.km
2007	newly identified Critical Tiger Habitat (CTH) or STR core	1699.62sq.km
2009	Buffer Zone notification	comprising 362.42 Sajnekhali Wildlife Sanctuary and 885.27 sq. km

The current administrative outlay, according to the map-1 of the source document102 islands (48 barren and 54 inhabited) make up SBR, which includes 19 CDBs dispersed over the West Bengal districts of North 24 Parganas 6-CDMs and South 24 Parganas 13-CDBs.The biosphere equivalent's overall area grows by 9630 square feet. km, including 4,263 sq. km of forest land, with 5,367 sq. km of inhabited area.



Map 1 - A map showing the Sundarban Biosphere Reserve in India, the research region

Administrative Setup

The pyramid of management (Figure 1 at source document) is the expression of the complex governance necessary for such an immense ecosystem. The Field Director is in charge of management. With the help of range officers, deputy field directors and assistant field directors, who have been overseeing four ranges with a total of fourteen beats, the ranks are the same as those of the chief conservator of forests (Table 2).

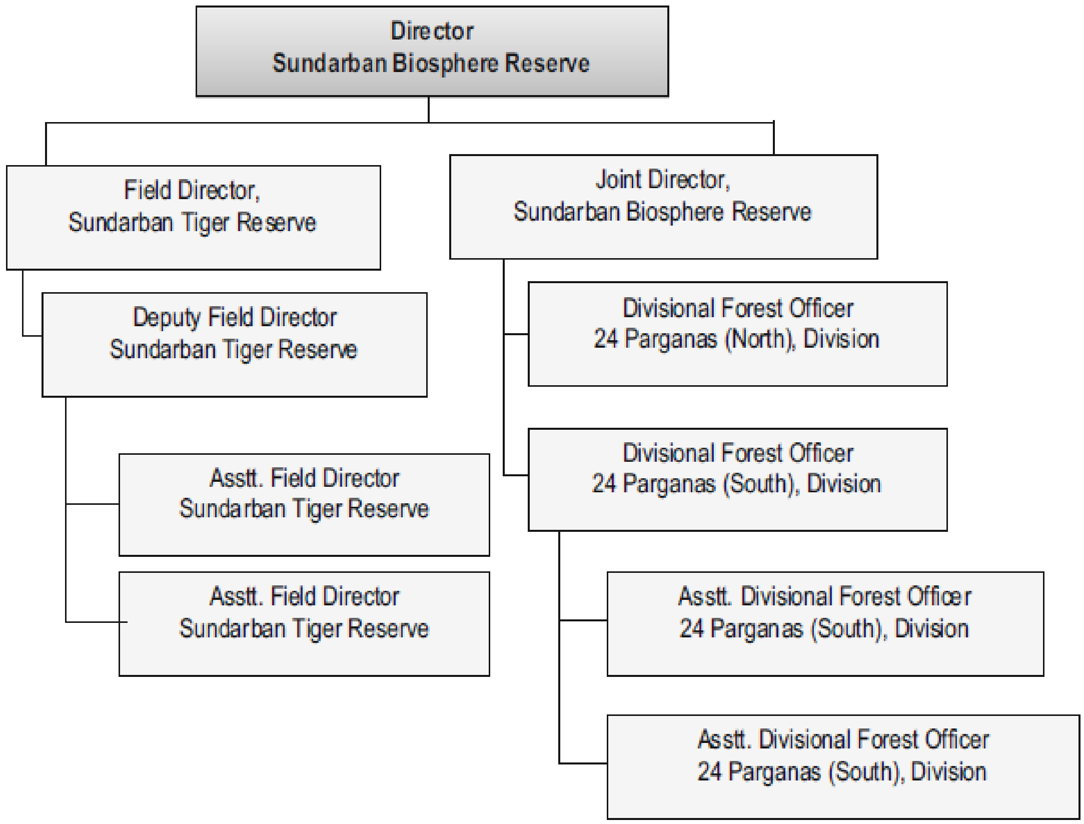


Figure 1- Administration of SBR (Forest part)

Table 2- STR's administrative divisions in India

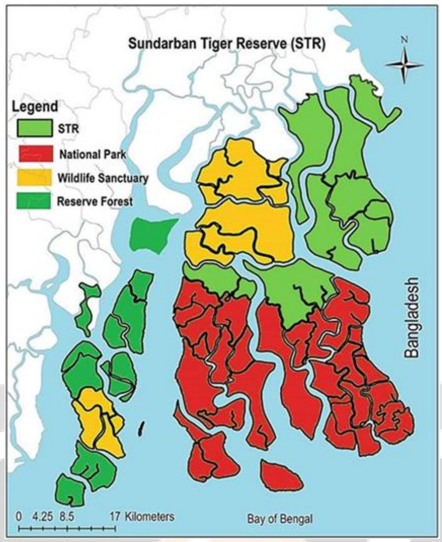
Ranges	Beats
Basirhatrange	Jhingekhali, Khatuajhuri, Burirdabri, Bagna, and Harinbhanga (in Harikhali)
Wildlife Sanctuary at Sajnekhali	Dobanki,SajnekhaliandDuttar
NationalPark(east)	Bhagmara, Chandkhali, and Chamta (new)
NationalPark(west)	Kendo, Haldibari, and Netidhopani

Table 3 (head-wise spread) provides the district level administrative procedure for North 24 Parganas (1 sub-division, 6 blocks) and Parganas South 24 (4 sub-divisions, 13 blocks). Map 2 shows the STR lay out by type of protected area and Map 3 casting on regional planning zoning of the land used in the nuclei of the forest community.

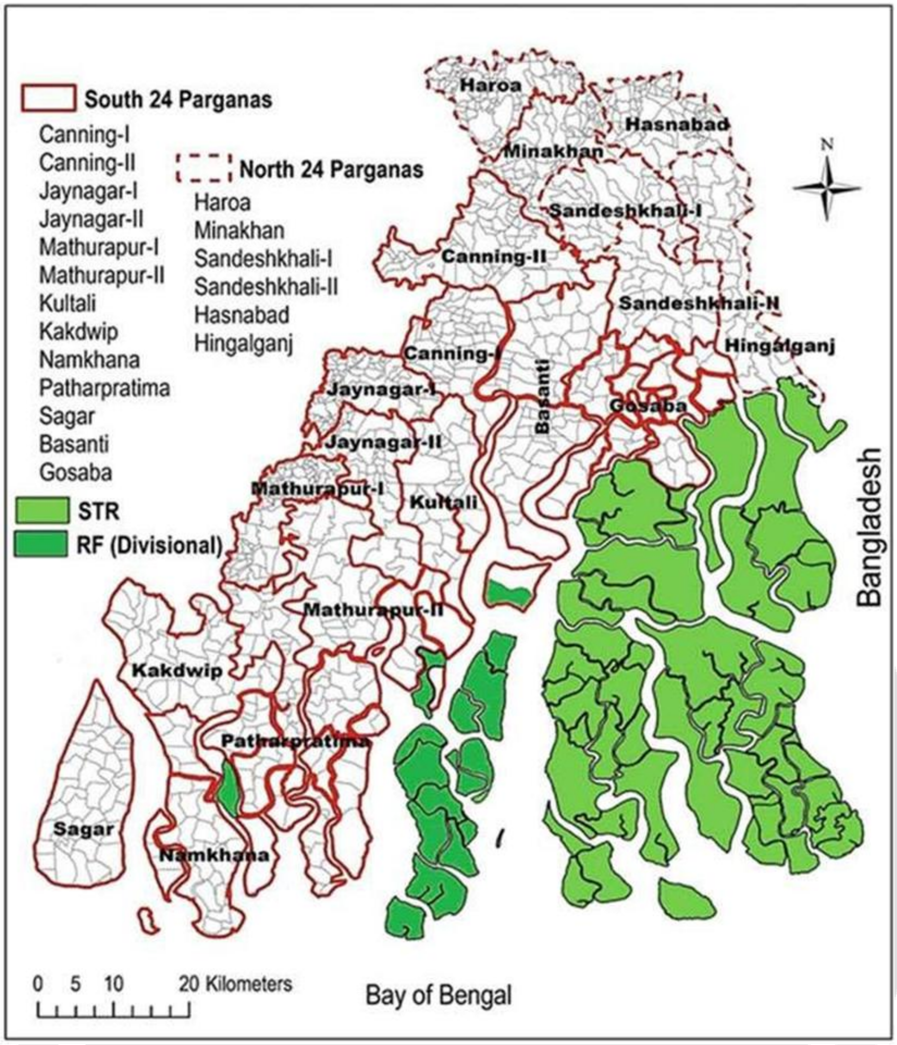
Table 3- Administrative units, inhabited areas of Sundarban, India

Districts	Subdivisions	C.D. Blocks
South24 Pargana	Kakdwip	Namkhana, Kakdwip, Patharpratima, and Sagar
	Diamond Harbour	Mathurapur-I,Mathurapur-II
	Baruipur	Jaynagar-I, Jaynagar-II, Kultali
	Canning	Basanti, Gosaba, Canning-I, Canning-II
North24 Parganas	Basirhat	Sandeshkhali-I, Sandeshkhali-II, Haroa, Minakhan, Hingalganj, and Hasnabad.

Total	5(4+1)	19(13+6)



Map 2- Indian divisions of the Sundarban Tiger Reserve (STR)



Map 3 - Sundarban Biosphere Reserve's administrative arrangement in India

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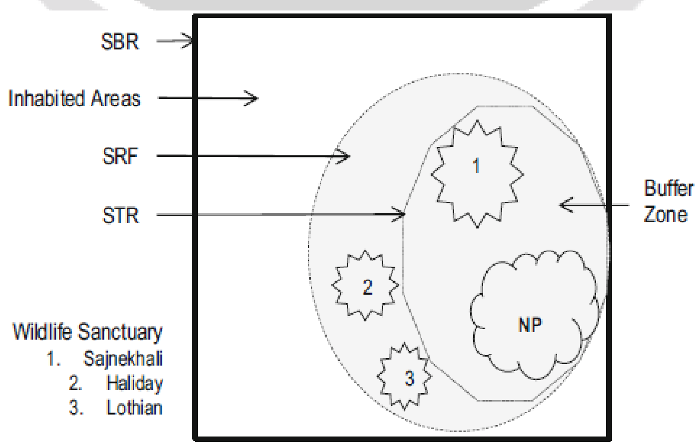

Figure 2- Graphical representation of SBR, India

Department of Sundarban Affairs (DoSA) and Sundarban Development Board (SDB) is been looked after co-ordination with other development activities of economy and the Border Security Force is been looked after trans-border crimes etc. with Bangladesh. It's a complex multi-layered bureaucratic mechanism intended to deal with the challenges of managing a dynamic ecosystem amidst the exacerbating environmental woes of a sprinting ahead society.

3. Climate Evolution and Variability

3.1 Sea Level Rise Dynamics

The Sundarbans' rising sea level is above the global norm and is turning into a highly potent environmental indicator. Analysing observational data at different stations reveals unsettling information. Based on four sites in the Hooghly estuaries Sagra, Gangra, Haldia, and Diamond Harbour it has been noted that the rise in sea level has fluctuated between 3.82- and +4.85-mm yr-1 between 1937 and 2006. The mean sea level rose 3.14 mm annually on average between 1985 and 1998, according to Sagar Island's tidal statistics. The trends in mean annual sea level rise (4.0 mm yr^{-1}) at Hiron Point (1977–98) were thought to be caused by rising sea surface temperature and monsoon rain. These trends were also observed in the BD-S (BD-S-MP). These rates are far higher than the Indian scale rate of 1.0 mm/year (mutual) and the global scale rate of 1.8 ± 0.5 mm/year from 1961 to 2003 (GM). If sea levels rise faster than expected, the consequences will be dire. The flooded area could increase to 40-918 km^2 by 2100 (from 1-23% of land area) due to the SLR found among the various scenarios. With peak elevations ranging from 0.90 to 2.11 meters above mean sea level, the Sundarbans are particularly susceptible to floods.

3.2 Temperature Trends and Thermal Evolution

Surface water temperature observation shows that SUT is warming in most part of the Sundarbans. Between 1980 and 2007, the Indian Sundarbans' multi-deltaic complex saw an average rise in surface water temperature of 0.5°C every decade, or 0.54°C, this was nine times higher than the 0.06°C per decade global norm. The average annual surface water temperature rose by 0.05°C between 1980 and 2007, reaching a range of 28 to 29°C. The eastern and western Sundarbans, as well as the northern and southern Sundarbans, differ locally. The average water temperature rose 6.12% in the eastern Sundarbans and 6.14% in the western Sundarbans between 1980 and 2007. Temperature trends in the Indian Sundarbans near Kuralikhali from 1985 to 1998 Warm advection from the water tended to increase the temperature in the Bangladesh Sundarbans around Hiron Point study by approximately 1.0°C (0.071°C year1) in May and by approximately 0.5°C (0.036°C year1) in November. The variations in air temperature are far more pronounced. Warming rate, the rate of change of the annual mean Ts has recently accelerated to 0.1058 °C year −1 for 2002–2009, or 1.0 °C per decade. This anomalous warming could be attributed to local heat (especially because of the industrialization around Sundarbans as well as the expansion of Kolkata Urban Agglomeration).

3.3 Precipitation Patterns and Monsoon Dynamics

Monsoon precipitation variation in the basin resulted from the drought or flood of this region, and the monsoon precipitation anomaly was the principal monsoon precipitation effect of the anomalous procedure of the overall hydrological cycle such as run-off, evaporation et al. The short-term average rainfall is 1920 mm 5 and the rains have become erratic and unpredictable. Monsoon precipitation has also been enhanced significantly 0.0041 mm/h over 2001–2008. Climate: South west monsoon (June-September) is the main source of the precipitation with a rainfall of 1500-2500 mm per annum and monsoon (80%) annually. But the intensity and the distribution of rainfall here too are very diverse, spatially and in terms of time.

3.4 Cyclonic Activity and Storm Intensification

Increasing frequency of cyclonic activities due to climate change has cost the Indian Sundarbans delta millions of hectares of land and hundreds of hectares of land have been submerged under seawater. Statistical analyses reveal that the majority of cyclones are generated during the months May--October and May--November; most of the cyclonic storms achieve their peak intensity in October--November. The number of tropical cyclonic storms over the entire NI in November was about double the no. of that in the last 122 years (1877–1998). During November, the frequency of tropical cyclones which reached its cyclone stage had increased by 17% (to reached the cyclone stage) and by 26 % had increased to reach the SCS stage at the last 129 years at the BoB. Table 4 in the cited source reports the full list of cyclonic events which demonstrate a progressive increase in frequency and in intensity. Some of the catastrophic events are Cyclone Aila of 120 km/h wind speed with 10–15 m water surge in year 2009 devastated Sunderbans and affected more than 800,000 people and also damaged crops.

Table 4- Northern Bay of Bengal tropical cyclones from 1999 to 2018

Name	**Date of occurrences**	**Knots of speed (1 knot = 1.852 km/h)**	**Category**
——	28October1999	>140	Supercyclonicstorm
——	28October2000	<40	Cyclonicstorm
——	19May2003	<60	SCS
——	17May2004	<60	SCS
——	2October2005	<40	Cyclonicstorm
Mala	24April2006	>120	Supercyclonicstorm
Notgiven	13May2007	<60	SCS
Sidr	15November2007	>120	Supercyclonicstorm
Notgiven	28June2007	>120	Supercyclonicstorm
Rashmi	26October2008	>40	Cyclonicstorm
Nargis	27April 2008	<120	VerySCS
Bijli	16April2009	<60	SCS
Aila	24May2009	<60	SCS
Giri	19October2010	<120	VerySCS
Phailin	4October2013	<120	VerySCS
Komen	31July2015	<40	Cyclonicstorm
Titli	11October2018	<119	Very severe cyclonic storm

4. Soil Dynamics and Salinization Processes

Salinity Crisis and Agricultural Implications

One of the prime problems facing in the coast is the salinity and it creates drawbacks with reference to the crop production and people sustenance. Salinity of soil in the Sundarbans has crossed safe level of cultivation. The soil salinity of 8.0 ppt and above were recorded in north (Nalkata) region of south compared to south western (Bay side) were 8.0 - 20.0 ppt is mentioned over and above safe high of 4.0 - 6.0 ppt for rice. Agriculture production system has been devastated due to cyclonic storms namely ‘Aila’ in 2009 and ‘Amphan’ in 2020 through the increase of acidity and salinity. All soil salinity irrespective of the average salinity was up to 1.5 m bts (5.0 foot below topsoil) for post Aila assessment and all were increased 2-3 years not growing any crop. The shallow tube well's level of 28 ppt and the pond/canal's salinity rising to 30 ppt caused major losses in agriculture and fishing.

Spatial and Temporal Salinity Variations

Salinity intrusions are one of the major problems in the coastal belts which adversely affect the crop cultivation and the life style of the people. Soon, the soil salinity has been consolidated to farming hazard at the Sundarbans. Soil salinity in the northern GHYAVA is 8.0 ppt, and it is higher (8.0 to 20.0 ppt) near the Bay of Bengal, which exceeds the safe level (4.0 to 6.0 ppt) for rice. The agriculture production system is also adversely affected during the post-cyclone storms, such as in Aila 2009 and Amphan 2020, owing to acidic ph and salinity. Post-Aila evaluation showed that water pan soil salinity was soil salinity (salinity) to subjective discharge and mitigate the reflection of the reflection of the depth of 1.5 m bts ((5.0 feet) no crop grew in 2-3 years apartment stall, 1.5 m bts (5.0 feet). Canal water of the pond carrying salt was 30 ppt and shallow tube well (shallow tube well water sites) 28 ppt salinity and its devastating impact on fisheries and agriculture.

Soil Chemistry and pH Dynamics

The pH of surface water is also a promising data series for monitoring atmospheric CO 2 budget and ocean acidification. The measured pH (S) at Sundarbans throughout 1980–2007 varies from 8.25 to 33 above the global average pH 8.17. Sanjappa, 2018) pH trend estimation The Western Sundarbans shows a negative linear pH trend at 0.015 per decade, which may be a reflection of the direct intake of the remaining atmospheric CO_2 from the top water. Alterations in soil chemistry affect distribution of mangroves and agricultural productivity. Recent studies have advocated that development of salt tolerant crops and intensive agriculture technologies are able to breathing with the salinity problem. Land sculpturing FYM application and RWHS have emerged as a sound control measures for salinity.

5. Riverine Systems and Hydrological Evolution

River Network Dynamics

The unique characteristic of Sundarbans mangrove ecosystem is that its natural habitat is hydrological regime and it cannot survive without an in depth knowledge of its hydrological status and human interference on it. The Indian Sundarbans Estuary is home to seven major rivers (source table), including the Hoogly, Matla, Bidyadhari, Gosaba, Gomar, Passur and Balari which are described in Table X of the source paper. Results Based on studies, a pronounced dynamic differentiation between the west and east part of Sundarbanic tidal rivers, and the north and the south part is evident. The stability of tidal channels depends on geological structure, geomorphological features, and hydrological factors such as tidal amplitude, sediment supply, response to seasonal discharges, frequency of high flow and velocity profiles.

Tidal Range and Estuarine Dynamics

Over the past 20 years, observations indicate that the annual maximum tidal range for the eastern and central sectors has increased at a pace of about 0.75 m. For over six weeks out of the year, about 60% of those places are in a high (>20 ppt) salinity state, which has detrimental effects on the freshwater supply and the health of freshwater and aquatic ecosystems. And seduced by its multicausal network pattern of tidal channels, mudflats, and mangrove cays, the basin is `alive' in, so much as it can alter its shape through erosion and accretion. Maximum erosion rates took place between 1973 and 1979 (23.2 km^2 $year^{-1}$ of land loss), and recent ones on average exhibit a retreat of the shoreline.

Water Quality and Pollution Patterns

Features of hydrology Quality of water Temporal and spatial variations in some physical-chemical and biological parameters of the river system of the Sundarbans are presented in Figure 2, 3 with their probable ranges given in Table 2, 3. Average DO of water bodies is 5.99mg/L, the organic pollution of the major water bodies is somewhat of an alarming trend and is fit for Environmental Quality Standard. The Total Ammonia, NO_3- N and PO_4- P are all with in the non-lethal levelate ranges for aquaric life survival in all the storage water except that on the Lead and chromium exceeds in the Western inflow and the inflows are concentrated along the major barge routes. The varying trend in the riverine mediated sediment discharge and water quality in the basin is strongly modulated by the monsoon-driven shifts in hydroclimatic regimes.

Sediment Flow and Morphological Changes

The most significant human intervention had been the Farakka dam in India that was commissioned in 1975, and the retaining of 1133 m^3/s of the silt laden flow, and then more silt reduction to the Bangladeshi coast of the Sundarbans. The scarcity of those sediments is essential for the development of the deltas and the coast. According to the media, the mangrove is threatened by a number of factors, including pollution, storms, growing salinity, and a decrease in the flow of fresh water into the delta as a result of India's Farakka Barrage on the Ganges. The altered sediment regime is currently interfering with the natural deposition processes that, if we had managed them properly in the past, could have offset sea level rise with the addition of deltaic land.

6. Environmental Indicators and Ecosystem Health

Mangrove Forest Dynamics

Sundarbans is well known for its beautiful collection of flora and fauna; over 220 bird species, 250 fishes, 56 reptiles, 40 mammals, and more than 84 mangroves and their associates. Yet the signals of ecosystem health are alarming. According to recent studies, as salinity rises in the central and eastern Sundarbans, mangrove species, in particular, Nypa fruticans (Golpata) and Heritiera fomes (Sundari) are declining. The conservation status of the Sundarbans species is described on the IUCN Red List. The estuary crocodile, the Ganges and Irrawaddy dolphins, and the Royal Bengal Tiger are among the animals that are threatened worldwide. Two rare species can be found in this region: the critically endangered (CR) River Terrapin (Batagur Baska) and the vulnerable (VU) King Cobra. Many extinct species, like the Javan rhinoceros, water buffalo, and Indian muntjac, can be found in the Sundarbans. The Indian Sundarbans was assessed as endangered under the IUCN Red List of Ecosystems in 2020. Map 2 in the source book is of the Sundarban Tiger Reserve's map and the complex patch work quilt of protected area pieces that have been attached to secure this biodiversity hot spot.

Land Use and Land Cover Changes

Information on environmental modifications is provided in Table 5 from the original document source. The dense forest cover area leveled off at 1,651.3 km², while degraded forest cover area declined from 404.9 to 332.0 km². Contrariwise to the saline nulls also the saline blanks grew from 38.9 to 74.8 km2 expressing the salt and saline land not suitable for plant species establishment.

Table 5- Changes in SBR's land cover and land use (sq. km) between 2001 and 2009

Sl.no	Classes of land cover and land use	Year 2001	Year 2009
1	Dense forest	1655.878	1651.3275
2	Degraded forest	404.887	332.0008
3	Saline blanks	38.93	74.7965
4	Settlement with vegetation	1226.334	1666.43
5	Agricultural land	2149.615	1691.246
6	Aquaculture farm	603.603	649.1
7	Waterbody	232.888	250.6531
8	Mudflats	23.897	12.6135
9	Sand (dunes and beaches)	8.0835	8.7664
10	Reclaimed land from forest	14.512	12.644
11	Swamp	14.847	20.41
	Total	6373.4745	6369.9878

Vegetation space that recorded farmland, settlement increased from 1226.3 km² to 1666.4 km², 2149.6 km² to 1691.2 km², which reflected land use pattern change and environment pressure. The area of wave overtopped by sea water increased from 60,936 to 101,079 km2 from 1970 to 2000, and from 603.6 to 649.1 km2 in aquaculture area, demonstrating the adaptation to new environmental conditions.

Water Transparency and Productivity

Between 1980 and 2007, the water's transparency dropped from 7.0 to 9.0 cm (cycle) per ten years, harming both fish output and phytoplankton development. According to a recent study, low-cost monitoring systems for this extensive mangrove ecosystem may be created to gauge the water quality and health of nearby fisheries using satellite data and machine learning techniques. Low water transparency and a high concentration of suspended sediment are the results of erosion-accretion-generating processes, which both function as turbulent forces. Overall, the Eastern Sundarbans have more transparency than the wet western Sundarbans, which seems to be caused by regional variations in freshwater influx and sediment dynamics.

7. Environmental Risk Assessment and Adaptation Challenges

Climate Risk Perception

Community perceptions Based on the perception studies, the current vulnerabilities are part of a dynamic response from the socio-ecological system in the Sundarbans and the climate change policies have implication for health and well-being of the residents in the Sundarbans. Early age families (5–7) and economic families with members who earn between \$18.45 and \$36.88 per month are the most exposed to climate change, according to the report. The respondents mostly used rainfall (67.3%), as opposed to dry leaves (65.4%) and fish by Sondorbon (80.6%). The largest percentage is impacted by disasters (66.7%), water-borne illnesses, and water logging and salinity (65.05%), indicating a negative correlation between environmental change and human vulnerability.

Adaptation Strategies and Management Responses

Nature-based solutions, and integration in precision agriculture, are promising strategies that are sustainable, in the long term, to alleviate soil salinization by its ecosystem services reestablishment. Salt adaptation technologies already exist, including the planting of salt-tolerant crop species and the development of land re-levelling, organic fertilization or rainfall harvesting systems. A Case for Adaptation: 'Ring Bandh' in the Sundarbans the act of 'Ring Bandh' is an important facet of the Sundarbans as an adaptation in Face Box 1 ('Ring Bandh'): in text box 2 in the original paper is intertidal regions where local evidence of it is a raised embankment). It is a local nomenclature of the newly formed arch shaped or hill type mud embankments in place of completely broken embankment. Then, occasionally, but not always, when a levee breaks and ravages, and new one is not re-erected, at least lo, and behold, in the same immediate vicinity, because a certain number of acres, some scape, had already been given over to that “river grasp,” if you will, as evidenced by the comings and goings of house-hold transplants.

Feature Box 1: Ring Bandh

'*Ring Bandh*' is a local term which refers to the newly constructed arching shaped mud-built embankment in the Sundarban. After breakdown of an embankment, a new one is constructed away from the previous position. The landward erosion and extreme river current erode the base of the broken embankment and try to merge with the riverbed. To construct a *ring bandh*, a substantial amount of land has to leave for river grasp result in certain number of households is displaced. Plate 1 portraits the broken embankment wiped out by the water surge of Aila in 2009, and Plate 2 shows '*ring bandh*' erected after Aila leaving some amount of agricultural land to the river grasp.

Plate 1 The broken embankment by the storm surge of SCS, Aila in 2009

Plate 2 Ring Bandh' after Aila

Feature Box 1 'Ring Bandh' with Plate 1 and Plate 2

Plates 1 and 2 illustrate an example of a storm-tide breached embankment (cyclone Aila 2009) and the "Ring Bandh" constructed following Aila where a "rice bowl" of alluvial productive land has been sacrificed to the river system. The Institutional Response to Environmental Challenge is given in Table 3 and administrative aspect in source document is presented in table 2. Nested scales of governance, from the village level committees to the encompassing state-level departments, also suggests a recognition of the complexity of environmental issues, which often have a multi-scaled, or multi-level character.

Loss and Damage Assessment

Four islands of Indian Sundarbans, Bedford, Lohachara, Kabasgadi and Suparibhaanga (Sagar) have sunk in the past 25 years displacing over 6,000 families. Lohachara was the world's first inhabited island to be lost to sea level rise, and its neighbor Ghoramara is already half-submerged. Economic valuation puts the annual costs to environment (damage) and health at Rs 1290 cr (appx US$ 250 mn) at 10% of GDDP of Sundarban 2009. Factors such as rising sea level which is rendering the entire region unsuitable for human habitation any longer, the wood value of the forest, the migration of about 1,5 million people who will possibly have to be moved out of the Sundarbans permanently.

8. Discussion

Integrated Environmental Assessment

Development of environmental indices showed gradual degradation in various sectors in Indian Sundarbans. The eustatic SLR rates are 3.14–4.0 mm/year, while the LLS rates are 5–15 mm/year, which made the RSLR rates in the 10–15 mm/year range in diverse areas. And that's extremely fast by the standards of the planet as a whole, and a direct threat to low-lying nations right now. The increased temperatures that are on the increase (0.05°C yr^{-1} in the case of surface water and 0.1058°C yr^{-1} for air temperature) are among the highest reported anywhere in the world. These are thermodynamic changes that can set of any number of cascading events, including changes in rainfall and evaporation and in species distribution. The economy of 4.43 million people can thus be threatened exactly by salinity levels that went farther beyond their carrying capacity. On the BSB, basal saline blanks increased from 2001-2009 over an area of 38.9 to 74.8 km^2, suggesting that the signals of environmental change are gaining momentum to the extent that they could exceed human capacity to adapt.

Systemic Interactions and Feedback Mechanisms

Through that dynamic, environmental changes in the Sundarbans figure as a kind of complex back-and-forth's, feedback loops. Elevation of sea level and seawater intrusion, soil salinization and fresh water availability are also among indicators of these impacts. These effects are compounded by decreased input from upper reservoir impoundment, synergistic losses that exceed the total of the consequences of each individual disturbance. These days, climate change exacerbates the impacts of cyclonic activity, with higher storm surges and salt water penetrating further inland. Post cyclone recovery periods bring to focus the contagion effect of the environmental stress; the soil salinity influence tends not to fade out even at 2-3 years after the shocks unveiled at stages like Cyclone Aila. When mangrove ecosystems are ailing, we lose nature's defenses against storms and erosion, "positive feedback loops" that viscerally accelerate environmental decay.

Implications for Sustainability and Management

Recent ecosystem perturbations in the Sundarbans suggest the current management paradigms would have to change substantially to keep pace with that rate of change. The administrative structure in Figure 1 and Map 3 of the source document is institutional-oriented and interlinkage between levels and sectors is minimal. Primary engineering responders such as banks appear less able to cope with the range of stressors. "Ring Bandh" Sidebar 1 in the source document is not addressing the actual problem but trying to surrender land to erosion. Ecosystem-based adaptation interventions offer some source of hope, but they need to operate at landscape levels that transcend jurisdictions. As shown in Figure 2, the UNESCO Biosphere Reserve mode is a model of integrated management, but which fails in operation since conservation needs in no way relate to development needs.

9. Methodology

This systematic review was based on the contemporary literature (2020 2024) and encapsulated peer-reviewed manuscripts on environmental transformation in the Indian Sundarbans. Data were sourced from the seminal study "The Sundarban and Its Environment", by Mistri and Das (2020) (which comprises comprehensive information relating to environmental knowledge and background of the population. DATABASES Main search strategies the search in AGORA, INFONET, Medline complete and other related institutional literature was performed in the main scientific database such as Google scholar, Web of Science and Scopus Scientific database combined with key words (Sundarbans; Climate Change; Environment Change; Soil Salinity; Sea Level Rise, Hera; River system) Preference was of substantive empirical research with quantitative environmental datasets with long-term monitoring. It had geographic analysis with original maps and geographic data e.g. map (1) map (2) map 3. The spatial frames were to serve as contextual paths to explore regional-scale patterns of environmental change in general. Table 1, Table 2, Table 3, and Figures 1 and 2 display administrative and organizational characteristics that were typical of the establishment's periphery. Tables 4 and 5 were distance to a point of environmental change. Environmental forced at different spatial scales, from local, through regional, to global scales. The emphasis was on finding threshold-values and -tipping points of environmental systems; limits of salinity of arable soil and rates of sea-level-rise which are too fast to adapt to by itself have been inferred.

10. Conclusions

The coevolution of the Indian Sundarbans has been a highly complex development in these not-so-slowly changing world, which has put the ecology and the livelihood of the people in peril simultaneously. The conclusions are that there are intelligent environmental indicators that surpass the level of the sustainable with a deteriorating tendency of most important from these, as the sea level is increasing, the temperature is growing, the penetration of salt to the soils, change of the water and supply. RSLR of 3.14–4.0 mm yr^{-1}, when added to land subsidence, equates to a relative rise rate of 10–15 mm yr^{-1}, a value that may not be realistic for natural settings. The temperature of the water has been rising by 0.05°C year, whereas air temperature has increased at 0.1058°C per year, some of the highest growth rates globally, triggering downstream changes in all levels of the food web. Salinity levels vary from 8.0 to 20.0 ppt with increasing soil salinity being more than the limit of 4.0- 6.0 ppt for rice production in most of the areas. At least 60 per cent of the region is salted up for more than 1.5 months a year, and even the farming-mothered heart of local economies is in peril.

Catchments are also changed strongly -apart from changing e.g. the grain size parameters, e.g.: 20 year annual max tidal range increases by 0.75 m reservoir constructions upstream change the sediment and, and, and. These hydrological modifications have implications for landscape-level freshwater supply and ecosystem productivity. As described in Tables1-2, Figures 1-2 of this paper, this management system has institutional capacity in managing HR, but it should be adjusted to a dynamically changing environment. The UNESCO Biosphere Reserve model of balanced conservation and development befit for the matter at hand. New programs should be focus on the observation of monitor of the components capable of capture the interaction climate-soil-hydrological system. Improved knowledge on such thresholds and tipping points will benefit adaptive management design. Longitudinal monitoring studies will be important to feed evidence-based policy, using both traditional and newer tools (e.g. satellite-based assessments). The environmental changes reported in this study are additional contributors, and amplifications, of the impacts from the Sundarbans to other coastal deltaic system worldwide. Learning from Sundarbans about the shifting ecosystem and management response could be the best source of learning to the climate related response of other such vulnerability ecosystem of the world. The long-term survival of the Indian Sundarbans, after all, depends upon putting in place a comprehensive management plan to address the drivers of environmental change and to enhance the adaptive capacity of external natural and of human systems per se. The window of opportunity to act on these issues is closing fast and there is a pressing need to act to protect the future security of this globally significant ecosystem".

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