Chapter 17
Pathways to Build Resilience Toward the Impact of Climate Change on the Indian Sunderban

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Abstract The Indian Sunderban is located in the southern part of West Bengal. Sunderban is known for its precious mangrove ecosystem. Sunderban holds the world's largest mangrove. Mangrove forest provides a huge amount of natural ecosystem services for the people of Sunderban. The mangroves of Sunderban have faced drastic losses, mainly from the impacts of climate change. Climate change plays a significant role, which makes the mangrove community vulnerable to its impacts. The people of Sunderban are highly dependent on the mangrove ecosystem; the loss of mangrove cover makes them vulnerable. The study found drivers and uncertainties of climate change that would destroy the mangrove community in future. The sea-level rise (cyclonic activity, erosion, and accretion), population rise (land cover change), and pollution (obstruct inflow of freshwater) are extreme threats for mangroves in Sunderban. The study shows that the changes need to be addressed through the government's policies and a restructure of

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governance is required. In policymaking, the collaborative action of scientists, governments, and local people should be involved. The lack of local involvement created a gap in government policy, which increased the threat and risk to the mangrove ecosystem. The traditional knowledge of the local people of Sunderban needs to be incorporated into the management strategy of mangroves. Furthermore, in this study, the Sunderban wetland was studied based on the inundation patterns it has seen over the past 30 years. The study makes use of preprocessed Landsat images (1991–2020) to create annual composites from June to September. The composites were subjected to the short-wave infrared (SWIR) thresholding technique to produce inundation maps using Google Earth Engine (GEE).

Keywords Mangrove ecosystem · Climate change · Sea-level rise · Management strategy · Government policy · Governance · Traditional knowledge · Inundation mapping

17.1 Introduction

Sunderban's real meaning in the local language is "beautiful forest," where Sundar means beautiful and ban means forest. Sunderban holds the world's largest mangrove ecosystem; it was designated a "World Heritage Site" by UNESCO and was recognized as the Ramsar Site in 1985. The Sunderban is situated in India and Bangladesh, where 59% fall under Bangladesh. The Indian Sunderban is situated along the coast of West Bengal for around 260 km and extends over the districts of South 24 Parganas and the southern part of North 24 Parganas. The area of Sunderban was 20,000 km^2 in 1885, and now it has shrunk to 9600 km^2, out of which less than 4200 km^2 is mangrove forest (Bose 2004). The mangrove plant is classified into woody trees and thick shrubs that grow in groups in the intertidal zone of the coastal area. The mangroves have the capability to build the connection between ocean water and river water. The mangrove forest is also known as tidal forest; the Sunderban shares the world's largest and most interesting mangrove vegetation. There are three different types of mangrove: these are the black mangrove (*Avicennia germinans*), red mangrove (*Rhizophora mangle*), and white mangrove (*Laguncularia racemosa*), which are finite in tropical and subtropical areas due to their sensitivity to the temperature. The mangrove vegetation is a very adaptive nature in harsh conditions. They are highly salt-tolerant; it excretes the extra salt through the leaves. They have highly complex and shallow root systems, like prop, pneumatophores, and knee, which also help to bring in oxygen in a flooded condition. Each type of mangrove vegetation has distinctive characteristics that adapt to its environment. The mangrove has another surprising feature: it brings life through viviparous germination. Through viviparous germination, the propagule gets detached from the mother plant and grows independently with the contact of soil, and some propagule falls in the ocean, gets back into the soil through ocean current, and grows independently. Mangrove provides shelter to thousands of species found in mangrove areas. Some creatures, like oysters, crabs, mudskippers, and some sucker species, are most common; the mangrove provides a protective and harmless environment for coral fish to develop enough to travel into the ocean. Mangroves play an integral role in maintaining the coastal ecosystem, as they act as a sink for carbon dioxide (CO_2) and atmospheric pollutants, thereby helping the ecosystem cope with climate change-related disasters. It also protects the shoreline from natural hazards by working as a natural filter due to its unique and complex root system. It filters heavy metals, entraps sediments, and has the capability of absorbing excess nutrients to reduce water turbidity. The natural functionality of mangrove is decreasing gradually due to the contiguity of different types of toxic chemicals from agricultural fields, industries, and ports, which change the geochemical composition of the water. At the same time, the rising pollution from surrounding industries and the waste from the city through channels are increasing the risk and making the coastal region vulnerable. Climate change is one of the major influential weapons for destroying the mangroves in the Sunderban. Because the Sunderban is a low-lying coastal area, climate change has an adverse effect on mangroves. The loss of mangroves in the Sunderban area will erase many endemic species from the face of the earth. According to the report, some areas of the western part of Sundarban are most vulnerable to climate change, like Sagar Island, Namkhana, Ghoramara, Dakshin Surendranagar, and Jambudwip. The southwestern island Ghoramara and Supribhanga had been flooded and submerged (Panda 2010). Those displaced people, due to climate change, are escaping to nearer places, like Sagar Island, Bakkhali, which are also vulnerable to climate change. For the record, Ghoramara Island is shrinking day by day due to the rapid rise of sea levels (Goyal and Ojha 2010, 2012). The western adjacent side of Indian Sunderban mangroves is more vulnerable than the core area (Das et al. 2020; Ghosh et al. 2015). The people are usually impoverished, and the loss of mangrove cover due to climate change has multiplied the calamity for local communities in Bakkhali, which lies along the coast of the Bay of Bengal. Whereas the mangroves act as carbon sinks, a further decrease in the mangrove cover over the region will decrease the natural absorption strength to the atmosphere, thus contributing to climate change as well (Khairuddin et al. 2016). The Indian Meteorological Department (IMD), 2013, marked all adjacent areas of Sunderban on the base of the climatic vulnerable zone. The areas (western, northern, and northwestern), which are very close to Sunderban mangroves, are recognized as high-risk zones due to the high density of the population, degradation of mangroves, frequent hits from cyclones, floods, and storms.

17.2 Background

The mangrove ecosystem is growing in the intertidal region that is in-between the average sea-level and the high-tide coastlines of tropical and subtropical regions. The mangrove community apprehends a large variety of species of flora and fauna that play a significant role. Mangrove is subjected to the tidal influence to grow in intertidal regions, and also, the mangrove soil supports a dense and tall mangrove plant (Selvam 2003). Mangrove has a unique quality of surviving under extreme saline conditions, and it requires muddy soil, good rainfall, an average maximum temperature of 34 °C, and a minimum temperature of 13.7 °C. The mangrove community serves ecological and non-ecological values, such as giving protection from floods and storm surges, producing timber and non-timber products, filtering pollutants from coastal water, supporting aquaculture to enhance tourism, and creating aesthetic beauty. FAO estimated the mangrove declined by 14,653 hectares from around the globe. It is estimated that mangrove losses are around 1–2% worldwide per year. Rapid developments near coastal areas, expansion of human settlements, and industrialization are the major causes of the deterioration of mangrove forests, and the deterioration has an impact on the production of fisheries, crustaceans, and mollusks. Mangrove is the only natural buffer system, and it can hold huge amounts of sediments and chemicals to prevent water pollution. The deforestation of mangroves has an impact on fisheries despite the fact that it has a negative impact on adjacent seagrasses and coral reefs because they are interlinked (Arancibia et al.). The mangrove ecosystem plays a crucial role in supporting the livelihoods of humans and creating more economic opportunities that support the economy of the country. Mangrove ecosystem depicts as a fragile ecosystem; it is majorly affected by many extreme weather events and anthropogenic events. The mangrove ecosystem is threatened by sea-level rise, a rise in temperature, and changes in rainfall patterns and intensity, all of which are due to climate change. The Hooghly estuary carries many raw materials from ports and industries and municipal waste from the city of Kolkata, and it directly impacts the Sunderban mangrove area, mainly on the western side, because of southwest and northeast winds that led to southwesterly and northeasterly winds (Sarkar and Naskar 2003). Climate change has an impact globally that leads to the loss of mangrove forests; the width of mangrove forests is becoming narrow, leading to the loss of the island (Nanlohy et al. 2015), and this will change the social and economic life of the local communities. In the current situation, climate change is a highlighted word and a threat to the overall world. The population is rising day by day, which is the cause of the exploitation of nature and natural resources. The growing population is one of the major causes of land cover change. The land is converted from forest land into agricultural land, cultivated land, and a settlement area (Mondal et al. 2010). Due to the setup of various industries by clearing forest land, the air quality gets deteriorated, which increases the level of carbon dioxide, carbon monoxide, CFC, methane, and nitrous oxide in the environment (Mondal et al. 2010). The increasing heat in the atmosphere traps the heat in the earth's atmosphere, which results in global warming and the trapping gas known as greenhouse gas (Poonia et al. 2021; Goyal et al. 2018). The changes in average temperature trends due to global warming. Global warming is caused by anthropogenic activities as well as physical activities, such as ocean circulation, the proportion of water vapor, orbital eccentricity, and differences in cloud cover (Mandal et al. 2009). The man-made activities are not controllable, which results in the high intensity of warming in the atmosphere, but the physical cause is equally responsible, directly or indirectly (Hazra et al. 2002). Since the mid-twentieth century, the high concentration of greenhouse gases has resulted in rising temperature (IPCC 2007). In the last 100 years, the temperature has increased by five times (Mondal et al. 2010). The temperature of India in the coming 50 years will increase by 1 °C. In the next century, greenhouse gas emissions will rise by 3.3° centigrade, as estimated from the scenario of business as usual (IPCC 2007). The conservation of the mangrove ecosystem is another way of an adaptation strategy for climate change, as stated by the Intergovernmental Panel on Climate Change (IPCC 2007), whereas mangrove plantations are disappearing at a high rate. Climate change shows a drastic change due to increasing temperatures over the last three decades (Mondal et al. 2010). Global warming increases the risk of sea-level rise, which affects the coastal zone like the Indian Sunderban. The Indian Sunderban is very vulnerable to climate and weather-related events. The cyclonic events suffered Sunderban and Sunderban's people from many disastrous cyclone events (Mandal et al. 2009). The rising sea surface temperature increases the intensity of cyclone patterns over the time period (Hazra et al. 2002). The sea surface temperature is co-relatable to sea-level rise; the increase in sea surface temperature causes the rise of sea level, or vice versa. It was estimated that due to sea-level rise, storm surges, coastal erosion, natural disasters, and flooding, 1.35 million people are critically venerable from decades ago, and there is also a huge loss of economy and property damage for people in Sunderban. In the last 30 years, 7000 people have been displaced from Sunderban Island by the threat of sea-level rise (Mondal et al. 2010). Sea-level rise forced them to become environment-induced refuges (Mondal et al. 2010). The people of Sunderban have been suffering from constant threats that compromise their basic needs like protection from natural calamities, food security, and socioeconomic security (Hazra et al. 2010). However, the mangrove plays a vital role in preventing climate change through the sequestration of carbon dioxide. The loss of mangrove forest means the loss of carbon dioxide sequestration capacity of mangroves that leads to climate change (Nanlohy et al. 2015), which indicates a reduction of resilience from sea-level rise. In terms of carbon sequestration, the mangrove has a significant and effective role as a carbon sink, either for short- or long-term storage, that performs function globally. The destruction of the mangrove ecosystem affects the blue carbon ecosystem globally. The main loss from mangrove ecosystem loss is climate change mitigation, where emissions are increasing day by day. The mangrove ecosystem serves different types of values, like direct use values and indirect use values. The direct use values considered the values that are directly used by humans, like timber and non-timber products (NTFPs), and indirect use values considered the values that serve the ecosystem but can't be used by humans (Reid et al. 2005). The mangroves are the only natural and efficient way for climate change mitigation worldwide. The coastal population is highly dependent and uses the mangrove ecosystem as a primary source (Saw and Kanzaki 2015) like a collection of timber, honey, fodder, traditional medicine, and food like fish, crabs, and shrimps. The main source of livelihood for communities in the Sunderban is aquaculture (shrimp, prawn, stinging catfish, and mollusk flesh) and agriculture like paddy cultivation, but the impacts of climate change like rising sea level, changes in rainfall patterns, changes in the salinity of soil and water, rising temperature, and increasing frequency of extreme weather events have paused their sources of income, and that affects their contribution to the Indian economy. The mangroves are witnessed many natural disasters, mainly in 1980, 1991, and 2009 in the Sunderban area. Some western coastal islands in the Indian Sunderban, like Bakkhali, Namkhana, Sagar, and Kakdwip, have a very low level of adaptation (Sahana et al. 2019), which means these regions are highly vulnerable to climate change. The extreme events are evidenced by the people, and they were badly affected by the loss of lands, assets, earning options, and livelihood. The coastal people are more vulnerable to climate change, so there is a need to address the problems and prepare them with high resilience to combat climate change (Goyal et al. 2022). The first step to increasing awareness and knowledge in local communities is to involve them in planning and managing their natural resources. The National Action Plan on Climate Change (NAPCC) was enforced in 2008 with the aim of eight missions. The National Action Plan on Climate Change (NAPCC) provides opportunities and identifies risks in key sectors with the help of state action plans. The Government of West Bengal identified climate change as a major threat and assessed key sectors that regulate it through the state action plan (SAP). The National Adaptation Program of Action (NAPA) helps to mark vulnerable areas against climate change and addresses the challenges. In the government's policy, the main focus should be on climate change and managing the Sunderban sustainably. The governance structure is required as an adaptation based on Sunderban, with engaging local people's participation and discussion with different actors.

17.2.1 Objectives

- To identify the drivers and uncertainties for mangrove cover loss over Indian Sunderban
- To understand the inundation patterns the Sunderban wetland has seen over the past 30 years (1991–2020) using Google Earth Engine (GEE)
- To identify the slackness in government policy and governance structure for Indian Sunderban

17.3 Material and Methods

The study takes an exploratory approach to determine the requirements for the completion of the study. Both the qualitative and quantitative data have been taken into consideration in carrying out the study. The secondary data from many sources are the key to meeting all the findings. Secondary sources of data, like research papers (research gate, science direct) and journals (UGC approved), reports (soured from government and nongovernment agencies), data, are used to understand the prime drivers and uncertainties of climate change in the Indian Sunderban as well as identify the gap in government policy and the need to restructure for the protection of mangroves. The quantitative external data and systematic literature review are taken into account to envisage the first objectives. For the next goal, the theme paper of government structure and action from the colonial period will be used to understand the problem and shortcoming and increase resilience toward climate change in the Indian Sunderban. These sources formed the database for the secondary analysis of the Indian Sunderban.

17.3.1 Study Area

The Indian Sunderban lies along the coast of Bay of Bengal in the state of West Bengal, which extends over the districts of South 24 Parganas and the southern part of North 24 Parganas. The Sundarbans delta is formed by the confluence of the Ganga, Brahmaputra, and Meghna Rivers. The geographical location of Indian Sunderban is 21°30′N and 22°40′48″ latitudes and 88°1′48″ E and 89°04′48″ E longitudes. The largest Indian mangrove forest covers 2122.421 sq. km out of 6312.76 sq. km area (Samanta and Hazra 2017). The Sunderban area has constructed miscellaneous types of land like preserved and protected areas, i.e., national park, biosphere reserve, and wildlife sanctuary; inhabited lands; cultivated land; forest land; and agricultural land. The inhabited island is further distributed in-between the northwestern part and the southern part; as already discussed above, the northwestern part is positioned at an upper level from the coast, so it less vulnerable to natural calamities ,whereas the southern part is highly exposed and vulnerable (Fig. 17.1).

The Sunderban area has a unique and special character that provides the highest aesthetic value in the world. There are some features of the Indian Sunderban, like geology and geomorphology, geohydrology, hydroclimate, and soil that have held the precious mangrove vegetation for decades.

The Indian Sundarban falls between the latitudes 21° 31′ and 22° 31′ North and 88° 10′ and 89° 51′ East longitudes (Fig. 17.2). Table 17.1 describes the climatic and other general information of the Sundarban wetland. As a part of the Indian Sundarban, the West Sundarban Wildlife Sanctuary has its significance in the international context for providing shelter and protection to various species of wildlife included in the Red Data Book (Ramsar 2022).

17.3.2 Geology and Geomorphology

The study area has major geomorphic areas are creeks, mudflat, alluvial plain, channels of the river, sand flat, estuary, and mangrove vegetation (Ganguly et al. 2006). The area formed by the confluence of the three major Ganga, Brahmaputra, and Meghna Rivers, the Ganga delta, is highly dynamic, and the formation of the delta is very rapid (Morgan and McIntire 1959). The tectonic activity has brought

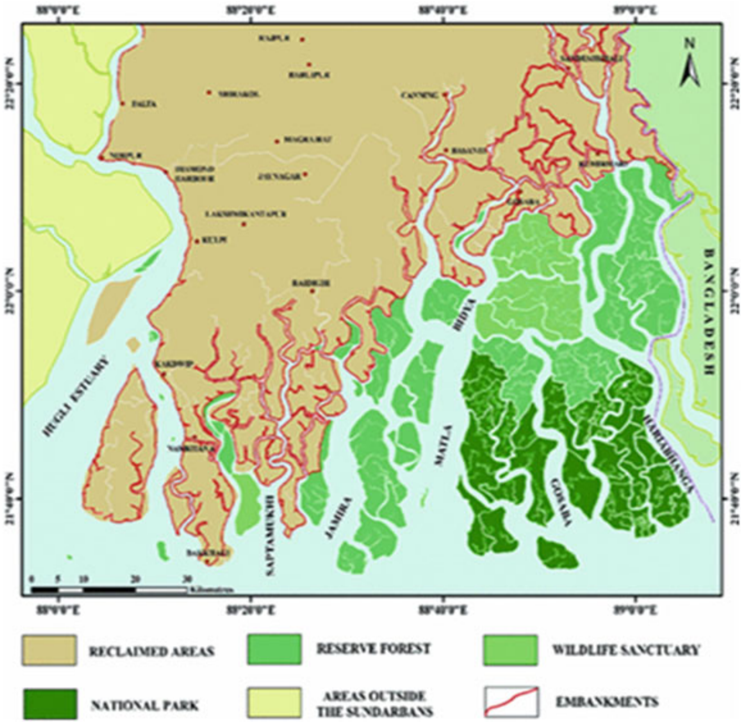

Fig. 17.1 The map of Indian Sunderban (Source: (Rudra 2018))

changes in the geomorphology of the Sunderban, and several river channels carry tons of sediments from its source that help in eroding and accreting.

17.3.3 Geohydrology

The groundwater in the area is neutral to mildly alkaline with a pH range of 7.2 to 8.1. The natural aquifers that contain freshwater are at a depth of 76–360 m, with a thickness of sand and clay beds. The concentrations of magnesium bicarbonate, iron, calcium, and chloride vary from 11–44, 281–640, 0.01–3.4, 14–76, and 14–188 ppm respectively. The groundwater of the area is very suitable for consumption.

17.3.4 Hydroclimate

The Sundarban area has a topical monsoonal climatic condition, whereas the average maximum temperature is 34 °C and the average minimum temperature is 20 °C. The

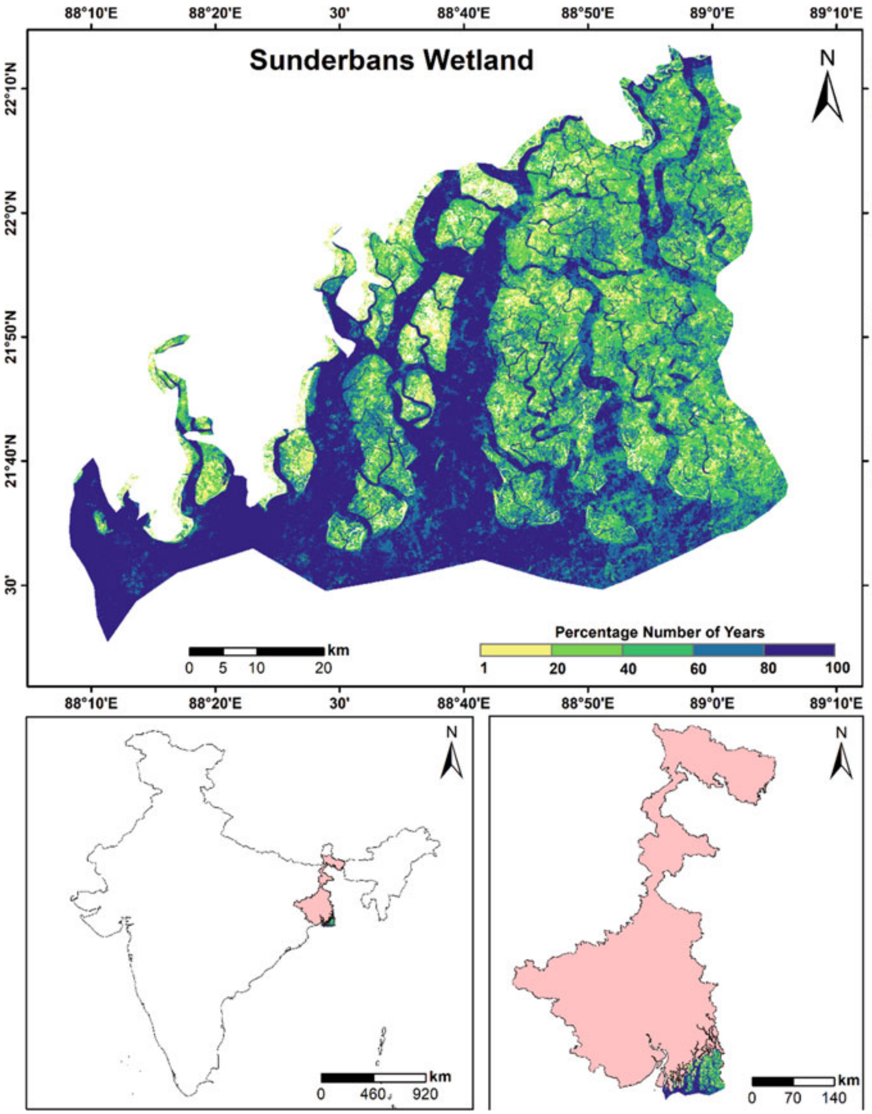

Fig. 17.2 Inundation map of Sundarban wetland. Inundation maps represent the number of years each pixel inundated during the period 1991–2020 (June to September). The legend represents the value of 80–100% (dark blue) of the pixels inundated in all available timesteps and 1–20% (yellow) as not inundated in any available timescale

total rainfall is approximately 1500–2000 mm (Gopal and Chauhan 2006), and the area receives extreme rainfall. The seasonal climate is divided into three phases are pre-monsoon period is between February-May, the monsoon period is between June-September and the post-monsoon period is between October-January (Subramoniam

Table 17.1 Climatic and other general information of the Sundarban wetland

Country	India
Area	423,000 ha
Designation date	30-01-2019
Coordinates	21°46′ N and 88°42′ E
Average precipitation	1904 mm
Maximum temperature	29.8 °C
Mean temperature	26.43 °C

et al. 2022). The relative humidity is about 75–80% over the year due to humid air from the Bay of Bengal. There are mainly two dominant winds that serve the monsoon blowing from the southwest known as the southwesterly and the northeast known as the northeasterly.

17.3.5 Soil

The soil of the Sundarbans has unique characteristics and is different from that of other islands, which are habitats for thousands of species. The soil structures are sandy loam, silt, or clay loam, and pH ranges from 5 to 8. The soil is also called "mangrove soil" (Mandal and Ghosh 1989; Banerjee 2013). The content of sodium and calcium is low in eastern, organic matter ranges 4–10% and the salinity of the soil varies from high to moderate; the land is inundated with saline water. This soil character supports the unique mangrove community, which plays an initial role in the atmosphere.

17.4 Results and Discussion

The precious mangrove cover is slowly depleting from nature. There are some main genesis factors, including climate change in the context of sea-level rise, pollution, and population growth, behind the evanescence of mangrove from the Indian Sunderban over decades. The study was found the mangrove forest cover decreased from the year 1986 to the mangrove cover 2246.839 sq.km afterward in 1996 it was 2201.41 sq.km. Then, in 2001, it was 2168.914 sq.km., and in 2012, it was 2122.421 sq.km. (Hazra et al. 2017). Some islands, like Gosaba, Dulibhasani, Dalhousie, Bhangaduni, and Jambudwip, have witnessed a great loss of mangrove forest cover (Fig. 17.3) (Table 17.2).

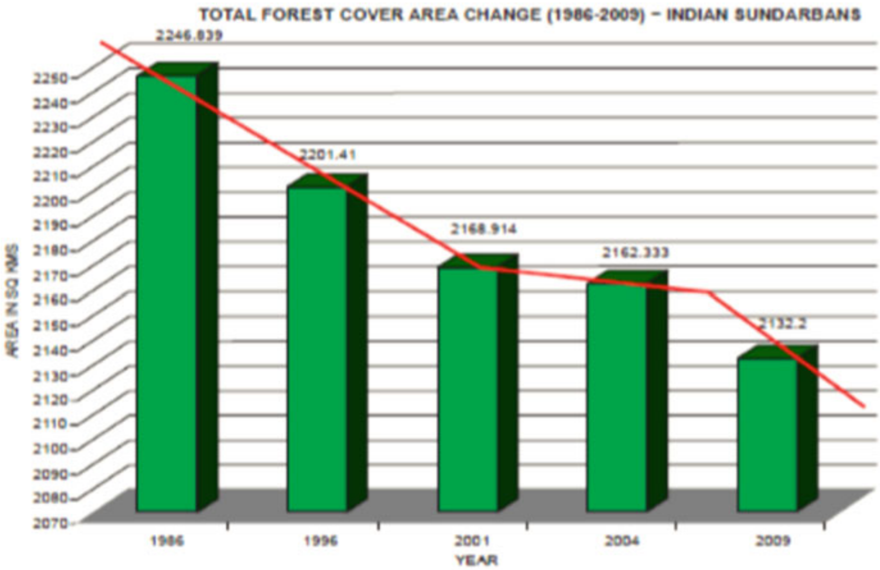

Fig. 17.3 The decrease in forest cover in the Indian Sunderban (Source: Danda 2010)

Table 17.2 The reduction of mangrove covers in 1986–2012

Years	Reduction in mangrove forest cover in sq.km.
1986–1996	45.429
1996–2001	32.5
2001–2012	46.493

17.5 The Main Drivers and Uncertainties of Climate Change

17.5.1 Climate Change and Sea-Level Rise

Climate change plays the main role in the drastic sea-level rise and changes in ocean circulation in the Indian Sunderban. The sea-level rise has an expansive relationship with surface air temperature. With the rising sea level over the past few decades, the air temperature has increased by 0.019 °C per year. The melting of glaciers globally has an adverse effect on local areas like the Indian Sunderban. Several areas in Sunderban, like Namkhana, Jambudwip, Ghoramara, Sagar, Mousuni, Bulchery, Dalhousie, and Dhanchi, were predicted to be vulnerable and cause 68% land loss in the future (Hazra et al. 2010). Since the mid-twentieth century, the Sagar Island has shrunk by 20 square miles, and three islands – Lohachara, Suparibhanga, and Bedford – were covered by mangrove species (Schwartzstein 2019), but now these islands have disappeared due to sea-level rise. The vanishing of the mangrove ecosystem and rising sea level will make the surrounded areas of Sunderban, like

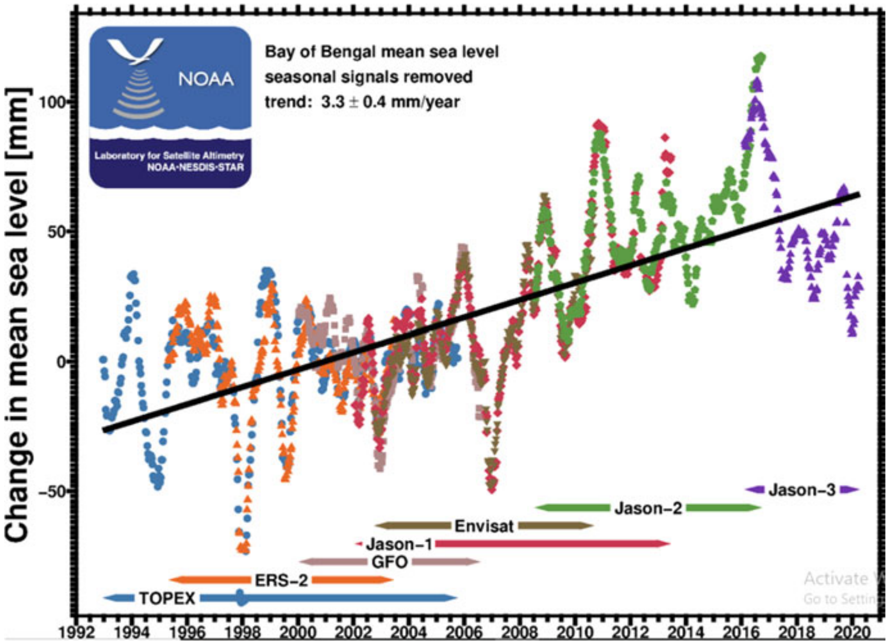

Fig. 17.4 The rising of mean sea-level over the Bay of Bengal (Source: NOAA)

Kolkata, more vulnerable to cyclones, floods, and storm surges (Ghosh and Lalitha 2017) (Fig. 17.4).

The gradual increase in annual sea levels in the Bay of Bengal has effects globally. The highest peak in those years (from the image), which indicates the excess level of water in the system, was due to El Niño phenomena and contribution of the highest amount of rainfall during monsoon periods. Hazra et al. estimated that without seasonal disturbance, the mean sea level would rise by 1.62 cm in 5 years. In the current scenario, the relative sea-level rise will 3.14 mm per year, and by the year 2050, the sea-level elevation will be approximately 1 m. The study found that the mean sea-level rise of 2.6–4 mm per year from 1985 to 2010 influenced tidal creeks along the shoreline. Already, some islands, such as Lohachara and Ghoramara, have fully drowned, and now the Sagar Island is at risk position from constant sea-level rise. The people living on those islands get displaced and travel to other islands of Sunderban, which is badly affects the resources of the island and increases the pressure and conflict between people. The constant, gradual sea-level rise will cause the disappearance one of the most precious and unique mangrove communities in the future. Climate change and sea-level rise result in increasing temperatures, changes in cyclone occurrence, and changes in precipitation. The sea-level rise is also responsible for some associated changes like erosion and accretion patterns on Sunderban Island, which cause land use and land cover change and also changes in the occurrence of storms, cyclones, and floods that result in seasonal variation.

17.5.2 Cyclone and Storm

According to records, the number cyclonic storm has increased by 26% over the Bay of Bengal in the last 120 years (Singh 2009), and coastal erosion is dominant over the southwestern islands (Hazra et al. 2010). From 1891 to 1961, the cyclones occurred 56 times in Sunderban (Fig. 17.5).

The rising intensity of cyclones is possible due to sea-level rise (Hazra et al. 2002). When it was analyzed over the last 120 years, the frequency and intensity of cyclones appeared to be very high (Singh 2007). Over the last 120 years, 26% of intense cyclonic events occurred over the Bay of Bengal, mainly in post-monsoon seasons. With the rising sea level over the past two decades, the intensity of storms and cyclones increased in the past, and the frequency of their occurrence decreased, which is due to global warming. The rising sea level also causes decadal change. Before, the intensity and frequency of cyclones were very high, but now, according to the present study, the intensity of cyclones has increased and the frequency of cyclones has decreased. The increase in the intensity of cyclones and storms influences the rate of precipitation over the Bay of Bengal. From the table, after many years, the disastrous cyclone Aila came on May 25, 2009, in West Bengal. It

Type of Hazard	***Year of Occurrence***	***Blocks affected***	***Impact on Life***	***Impact on Livestock***
Flood	1978	All blocks	Severe	Affected to a great extent
	1986	1. Kultali	Severe	In some areas affected to a great extent
		2. Joynagar-II	Moderate	
		3. Canning-I	Moderate	
		4. Gosaba	Severe	
		5. Basanti	Severe	
		6. Mathurapur-II	Moderate	
		7. Kakdwip	Severe	
		8. Namkhana	Severe	
		9. Sagar	Severe	
		10. Patharpratima	Severe	
Drought	1998-99	1. Kakdwip	Moderate (5 mouza)	Affected to a great extent
		2. Basanti	Do (6 mouza)	
		3. Caning-II	Do (5 mouza)	
		4. Gosaba	Do (23 mouza)	
		5. Mathurapur-I	Do (6 mouza)	
		6. Patharpratima	Do (2 mouza)	
Cyclone	1999	1. Kultali	Severe	Affected to a great extent
		2. Joynagar-II	Moderate	
		3. Canning-I	Moderate	
		4. Gosaba	Severe	
		5. Basanti	Moderate	
		6. Mathurapur-II	Moderate	
		7. Kakdwip	Severe	
		8. Namkhana	Do	
		9. Sagar	Do	
		10. Patharpratima	Do	
Cyclone (Aila)	2009	Almost all the blocks of Sundarban	Severe	Affected to a great extent in most of the blocks

Fig. 17.5 List of natural disaster occurrences over the decades (Source: UNDP 2009)

was one of the climatic disasters that hit the Indian Sundarbans. In a few minutes, it made 4000,000 people homeless, thousands of villages disappeared, and killed thousands of people. With that, it destroyed livelihood patterns and the economy (Mondal et al. 2010).

17.5.3 Erosion and Accretion Patterns

It was estimated that the geomorphic characteristics of Sunderban over 32 years (1980–2012) varied with the interaction of the external variable, sea-level fluctuation (Ghosh et al. 2015), and the outcomes showed a reduction in the land, an increase in salinity, changes in the pattern, and degradation in the mangrove (Fig. 17.6).

The above image shows the erosional and accretion areas over three decades. The erosional area is dominant over the southern and western parts of Sunderban, and the estimated erosional area is 162.879 km^2 (Ghosh et al. 2015), which also indicates those lands are more vulnerable and situated along shorelines. The sea-level rise directly or indirectly changes the size, shape, and structure of islands. Some parts of land, like Mousuni, Namkhana, Gosaba, Chuksardwip Island, and Jambudwip Island (from the image), are strongly or moderately related to the erosion in the context of sea-level rise. It was noticed that the accretion is partially related to sea-level rise, and in the accretion area, adding layers of mud and excess siltation influence sea-level rise gradually (Hazra et al. 2012). Erosional plays a highly powerful role

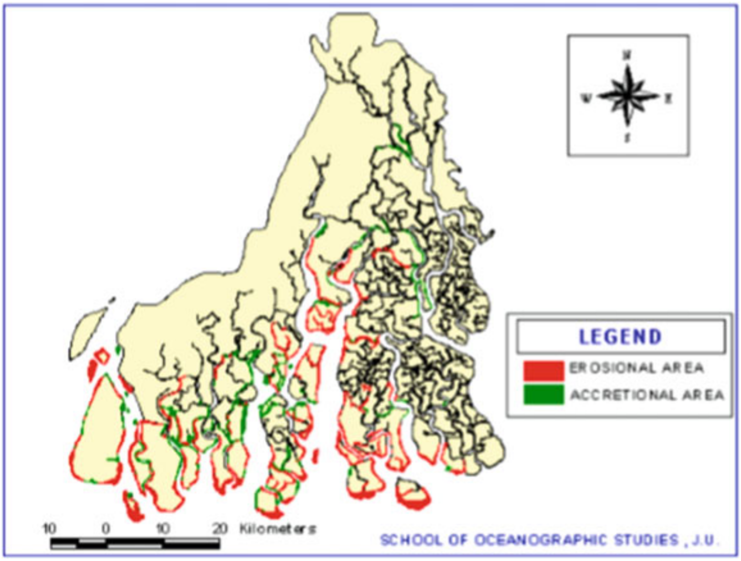

Fig. 17.6 The changes in area through erosion and accretion over Sunderban (Source: Hazra et al. 2002)

that results in the disappearance of Lohachara Island, which was 6.212 km^2 (Ghosh et al. 2015). The accretion area was estimated at 82.505 km^2 over three decades (Ghosh et al. 2015). The study also found there is a direct correlation. The analysis showed that not only erosion but also accretion have a relationship with the fluctuation of sea level (Ghosh 2012). From the analysis, in the Sunderban, the sea-level rise is strongly related to the erosion and accretion rate, or accretion contribute to sea-level rise, which ultimately makes the area vulnerable and increases the pressure for people on the island.

The rate of erosion and accretion has been the primary cause of land-use change for decades. Climate change and sea-level rise are indirectly involved in land-use change pattern, and the change in land use has impacted the whole system. The land loss affects the mangrove cover in the coastal zone, where the settlement largely extends near the shoreline, and their activity for their livelihood is changing the land-use system. The settlement along the shoreline is to be affected more by erosion and accretion from sea-level rise. The reserved and protected forest or area is badly affected by sea-level rise. The major natural parameters like erosion, accretion, and geomorphic changes and anthropogenic parameters like population rise, growing urbanization, and resource utilization (agricultural land, aquaculture, and construction) affected the land-use change over two to three decades by 66% and some inexplicable anthropogenic changes by 2% in the Sunderban Island.

17.5.4 Rise in Population

The Indian Sunderban consists of an area of 9630 sq. km out of that 4264 sq. km of wetland and mangrove reserve forest and 5366 sq. km for human settlement that is divided into 19 blocks: 13 blocks are Jaynagar-1, Jaynagar-2, Kultali, Canning-1, Canning-2, Basanti, Gosaba, Kakdwip, Namkhana, Mathurapur-1, Mathurapur-2, and Patharpratima in South 24 Parganas, and 6 blocks are Haroa, Hasnabad, Hingalganj, Sandeshkhali-1, Sandeshkhali-1, Sandeshkhai-2, and Minakhan in the North 24 Parganas (Hazra et al. 2002). In 1901, the population was 487,377, whereas in 1931, the population increases by 55%, a rise of 755,434. In the partition time, the population was 11,70,922 in 1951. According to the 1991 census, the average density of all the block is 690 persons per sq. km, and the population differs for each block from 120,000 to 250, 000. The population of the Sunderban rose by 18% over one decade, according to the 2011 census. According to the 2011 census, the sex ratio was comparatively high (955 females per 1000 males) in the state West Bengal and India, which shows the population of male children is high than the population of female children. The mangrove forest cover of the Indian Sunderban is more than 5000 km^2 and has been designated as a reclaimed area due to the growing population over the last two centuries (Naskar et al. 2004). The study shows the population marginally decreased by 19.1% over a decade, and it was found that the population growth rate decreased for the previous five decades (Ghosh 2018). From

Table 17.3 The population rise over decades in the Indian Sunderban

Year	Population in numbers	Rise in percent
1901	4,87,377	55
1931	7,55,434	55
1951	1,170,922	160
1991	3,044,397	18
2011	3,738,417	–

the previous decade, in the last decade (2001–2010), the working population rose by 28%, according to the 2011 census (Table 17.3).

The people's livelihood options are very limited, mainly agriculture, aquaculture, timber, and non-timber products, such as honey and medicinal plants. Their inelastic way of running their existence and abject poverty are very deficient due to a lack of alternatives and opportunities. The miserable and woeful condition may not be uprooted because, according to the census of 2011, one of the reasons for population structure is that half of the population belongs from the Scheduled Castes and Scheduled Tribes, and another half of the population belongs to the landless laborers, farmers, fishermen, and honey collectors. And another reason for the harsh condition of physical infrastructure and road construction is lack of communication, infrequent electric supply (mainly in the southern area of Sunderban), and transport (Ghosh et al. 2018). The constant rise of the population is one of the major factors for mangrove loss due to cutting trees, an increase of settlement areas, and over-exploitation of forest resources (Banerjee 2013). In 1991, the table shows 3,044,397, which reflects a havoc rise of 160% due to the reason for the partition of India after independence. In 1991, the population rise for the major reason is industries. The surrounding areas of the Indian Sunderban, such as Haldia, have a large scale of industries, like metal, chemical, fertilizer, leather, etc. The people from the surrounding area and neighboring countries like Bangladesh were in search of food, shelter, and other living opportunities during that period. In Sunderban, migrant people can suffice at a minimum cost rather than living in a big city like Kolkata, and also, the border area is very close to the Indian Sunderban (Sen and Bhadury 2017). In the different years, many migrants and climate-induced migrants came to the Indian Sunderban after partition between Bangladesh and India. The geomorphic feature and land-use change have also been regulated by the population in Sunderban for decades. Indeed, because of exigency and barriers, the people of Sunderban are constantly suffering and struggling from natural calamities, and contrarily at some extent, the people of Sunderban are responsible for bringing them into jeopardy. The population of Sunderban is highly dependent on natural resources, and at the same time, people have been under constant threat from natural calamities, climate change, poverty, disempowerment, and socioeconomic security trade for decades. The vital role of the mangrove ecosystem is loss in daily life with the deterioration of mangrove vegetation.

17.5.5 Pollution

The mangroves of Sunderban Island act as a wall between freshwater and ocean water; without the supply of freshwater, the mangrove vegetation could not grow in Sunderban. The Ganga water from the Himalayas flows through the Hooghly River in terms of freshwater, which gives service to the Sunderban mangrove through the Hooghly-Matla estuarine system. This river has a length of 260 km and also passes from the city of Kolkata, which also covers the Haldia Port and Kolkata Port (Estuaries of India 2002). The last estuary channel is connected through Diamond Harbour, which extends and spreads over more than 20 kms and mixes in the Bay of Bengal. The soil types, geology, and climate of Sunderban and Hooghly are similar (Sadhuram et al. 2005). The Hooghly River is surrounded by many types of industries, like jute mills, pulp, and papers, plastic, rubber, and thermal power plant (Biswas et al. 2007). All the toxic material and wastewater are directly delivered into the Hooghly River for decades, and the municipal waste from the surrounding cities is delivered into the river. The Haldia Port and the Kolkata Port activities are equally responsible for discharging waste materials into the Hooghly River (Bhattacharya et al. 2008) (Fig. 17.7).

The Hooghly estuary act as a huge waste disposal sink (Hazra et al. 2015). Over the past decades, the water quality has highly deteriorated and been impacted by anthropogenic activities, which also increase the threat of environmental degradation. The freshwater from Hooghly River enters through the lower part of Sunderban, facing toward the Bay of Bengal, where the mangrove vegetation lies. According to the study, the western part of Sunderban is more affected and vulnerable to the discharge of toxic chemicals. These toxic chemicals reach the mangrove through wind and ocean circulation, which is the main cause of destruction of the mangrove's unique characteristics and increases the threat to the mangrove community. These toxic chemicals suppress the natural function of mangrove; the toxic and heavy metals penetrate through the roots system of mangrove, blocking the entry of oxygen (Singh 2009). The waste material and garbage in the river reduce availability of freshwater and the supply of sediments (Hazra et al. 2015) to the mangrove community. Whereas the mangrove vegetation needs the minimum inflow of freshwater, if not, the mangrove succession is replaced from freshwater-loving to salt water-loving, but the inflow of freshwater is required for the growth of wealthy and rich mangrove. Being a forested area, the mangrove vegetation not only serves ecosystem service but is also a habitat for numerous species. The eternal changes and threats, both naturally and anthropogenic, put the mangrove plantation in such an extremely vulnerable condition that, one day in near future it will obliterate one of the oldest and most unique World Heritage sites since 1985.

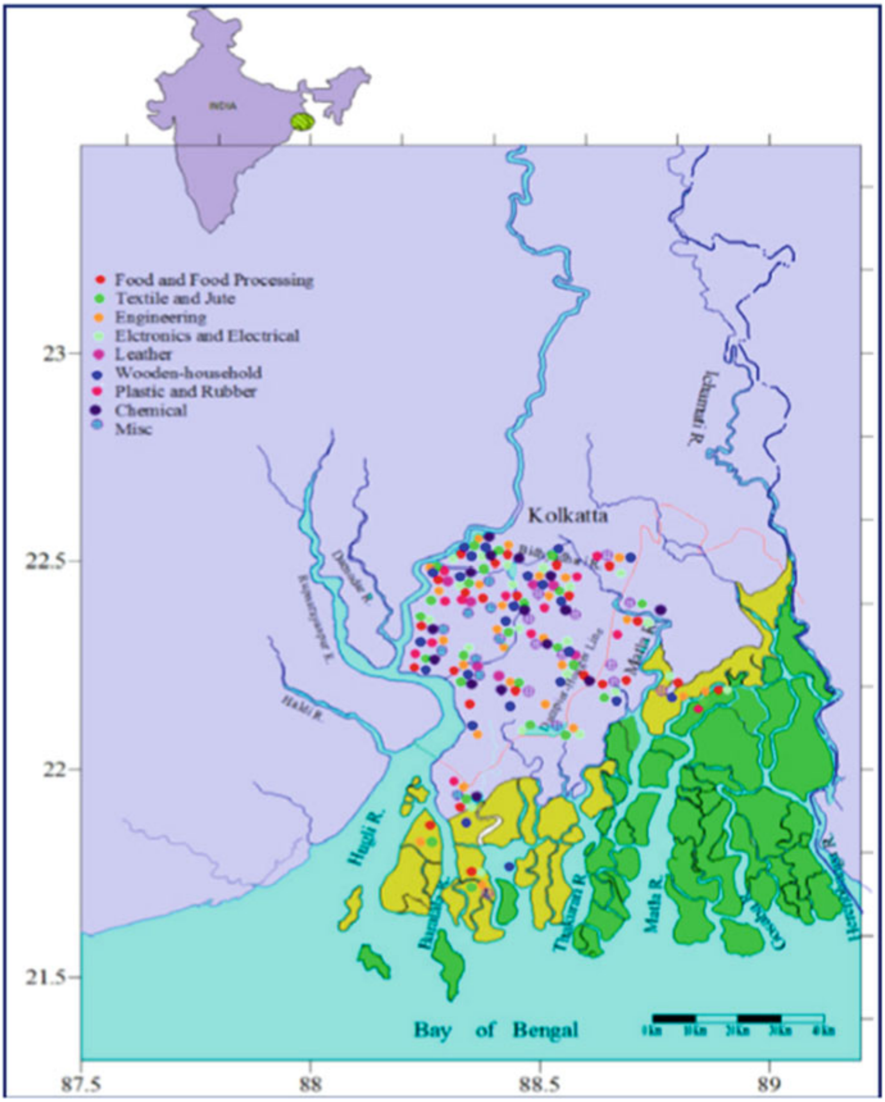

Fig. 17.7 The industrial area surrounded by Sunderban (Source: (Singh 2009))

17.5.6 History of Sunderban

The name of Sunderban Day was mentioned in the Puranas (Sarkar 2011). At very fast speed, the Sunderban land, when it came to marking the land, was originated mainly by Portuguese and Burmese (Sarkar 2011). In the era of the British ruling period, the land of Bengal, Bihar, and Orissa was given on lease in 1765. After that, in 1785, the small portions of land in Sunderban were given a lease to zamindars for many years. At the time of partition between India and Bangladesh, a large Hindu population and Muslims entered from Bangladesh districts. Many came as laborers in search of work from the neighboring district of West Bengal, Midnapur. The Sunderban formed with the main four major communities (Jalais 2010). First are the tribal communities in colonization who were clearing the forest; the second population of people were designated as OBC; the third are Muslim immigrants from Bangladesh; and the fourth are Hindu immigrants who came from Bangladesh as refugees (Jalais 2010). At a slow pace, the land of Sunderban mixed with a different socio-culture atmosphere, which helped to develop a threat to nature.

17.6 Methodology for Inundation Mapping Using Google Earth Engine (GEE)

The schematic flowchart of the methodology is shown in Fig. 17.8.

- **Cloud-masking:** Clouds and cloud shadows are present in the Landsat sceneries, and they need be masked to generate proper composites to enhance accuracy of the inundation maps. The pixels classified as cloud or cloud shadow on the Landsat cloud mask band were masked for each scene using a gap-filling method (Yin et al. 2016). The pixels were then filled with the median value for the pixel from a year before or after the scene's date.
- **Landsat composites:** A gap-filling method was afterward used to cloud masked images. The SWIR band (B7) was chosen for each scenario. Each year's composites are made using all the scenes available from June to September. A median of the corresponding pixel values from all the scenes of that year is evaluated and

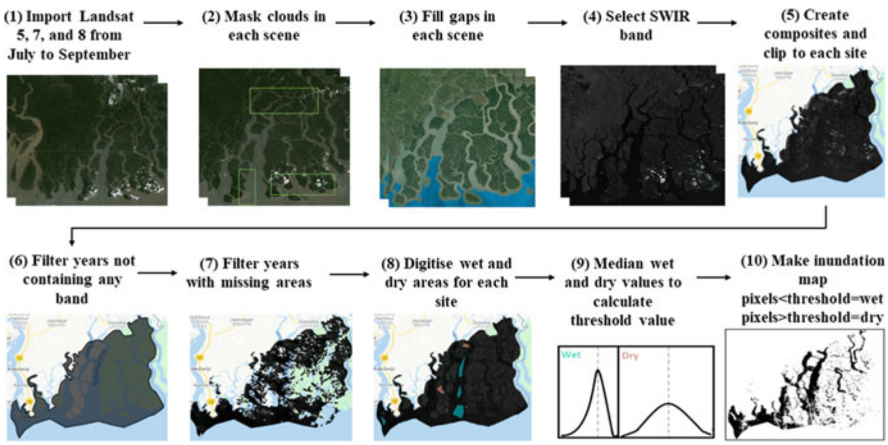

Fig. 17.8 Schematic flowchart of the methodology

designated as the value of the corresponding pixel in the composites to be generated for each pixel in the study area.

- **Filtering bad composites:** The SWIR band was missing for some of the composites created. Those composites were manually filtered by removing them from the image collection. Most of the cloud masking is done via the cloud masking algorithm. However, there were some regions in almost all the coastal sites, where the pixels were classified as a cloud most of the time. The masking algorithm made the pixels transparent in these circumstances. A filtering algorithm was used to filter these pixels. This resulted in a set of composites without even a single masked pixel.
- **Creating inundation maps from the composites:** The inundation maps are made from composites by thresholding the SWIR band pixel values. We manually assessed and digitized permanent wet (e.g., the lake's central region and permanent channels) and dry areas (like barren land or hill region near the wetland) for each site. The median SWIR values for wet ($SWIR_{wet}$) and dry ($SWIR_{dry}$) inundated areas for each composite were calculated using these digitized areas, and a composite specific $SWIR_{threshold}$ (to account for the dynamic seasonal and annual nature of the inundation patterns in wetlands) value was calculated using eq. (17.1) (Wolski et al. 2017).

$$\mathrm{SWIR_{threshold}} = \mathrm{SWIR_{wet}} + 0.3\left(\mathrm{SWIR_{dry}} - \mathrm{SWIR_{wet}}\right) \tag{17.1}$$

The classifier compares each pixel's SWIR value to its $SWIR_{threshold}$ for each composite. The pixels having SWIR values less than or equal to $SWIR_{threshold}$ are classified as inundated, while pixels having SWIR values larger than or equal to $SWIR_{threshold}$ are classified as dry. As a result, each pixel with a particular SWIR value is classified and transformed into one of two values: 0 for dry pixels and 1 for inundated pixels, and an inundation map is generated using these changed pixels.

17.6.1 Governance Structure and Policy

In colonial times, when they get to know about the revenues from the forest, the colonial administration announced the Sunderban forest as "protected forest" in 1878 (Chakraborty et al. 2009). The announcement of mangrove forests as "protected forest" sparked the struggle of people who were highly dependent on mangrove forests because of the regulation for using the forest. The Forest Department earned an advantage by being designated as "protected forest" rather than "reserved forest." They have the option for lease, converting land from forest to agriculture and timber production (Ghosh and Lalitha 2017). At that period, the mangrove forest has suffered from threats due to man-made activities. In 1943, the tidal forest reclassified as "reserved forest" from "protected forest." In 1987, the Sunderban National Park was designated a World Heritage Site, giving it a high level of protection. The Forest Department suppressed their regular activity in forest protection that further inhibited the opportunities for research. Due to the remaining slackness in the protection of mangrove forests, the National Forest Policy (NFP), in 1988, was redrafted to enhance and improve the condition of the forest, socioeconomic values, and sustainable issues (Bandopadhyay and Nandy 2011). The new changes in National Forest Policy emerged with two specific guidelines for the management of the Sunderban tidal forest, which was earlier led by Joint Forest Management in 1990 through the Government of West Bengal. The specific guidelines are for, first, mangrove forest areas of Sunderban and, second, national park and sanctuaries of the state (Ghosh et al. 2011). Under the 11th 5 years, the State Planning Board of 2007 introduced a specific policy for community participation and involvement. Under this notification, 51 forest protection committees (FPC) and 14 eco-development committees (EDC) were developed to work more specifically in national park and sanctuaries, which are adjoining to villages, and also to increase the involvement of the local community in forest management and distribute the equal benefits (Ghosh et al. 2011) according to the Supreme Court order. But this could not run long enough to further decrease the management of mangrove forest and make the communities receive unequal benefits, rise difficulties, and detach from forest management, which also increases the corruption (Ghosh et al. 2011). In 1973, the Sunderban Development Board (SDB) was controlled under the Planning Department of Government of West Bengal. The Sunderban Development Board mainly focused on the socioeconomic development and development of mangrove plantations in Sunderban area, and the functions were the preparation of an integrated program for utilization, coordination with developmental plans for execution, supervision of the execution of the developmental project, and the evaluation of the progress with reviewing the policies and measures (Bramhachari et al. 2018). The Sunderban Development Board formed the Sunderban Affairs Department (SAD) in 1994, which is under the control of the State Minister to continue the development of the Sunderban. The Sunderban Affairs Department focused on the social, economic, and cultural aspects of people residing in Sunderban (Bramhachari et al. 2018). The Sunderban Affairs Department measures the development of irrigation and agriculture system, provides balance in ecosystem, and preserves them. Some of its main functions are forestry, disaster risk management, water supply, and sanitation, with the help of following government (Bose et al. 2018). After that, the Sunderban Affairs Department was created to manage the governance structure and support people living in climate-vulnerable areas. The Green Bench of Kolkata enforced strict norms for the protection of wetland as Sunderban is one of the Ramsar site, but the Green Bench of the Kolkata was also unable to perform at a time decree in terms of changes in policy for adaptation and translation in development to simplify their use of local communities (Bose et al. 2018). The West Bengal, according to Disaster Management, 2005, proposed disaster management policy and framework in three forms: pre-disaster measures, disaster phase, and post-disaster response (Department of Disaster Management 2005). In the past 10–15 years, transformational changes have been observed in policy due to the introduction of the new structure of governance in West Bengal. The political vibrancy could not protect the implemented plans and program because the plans were made without taking into account the voices of locals in respect to needs in Sunderban (Bose et al. 2018). Efforts were taken from the government to give protection of mangrove forests and adapt to climate change over the pasts, but the results are vague due to lack of communication. The problem was detected by the local people who were living in the land of Sunderban, and they had better knowledge regarding the problems of Sunderban than outsiders. With implementation of plans and programs by a government institution, the locals don't know about the purpose, functions, and use of the plans. The findings also show the scientist have significant roles in policymaking to set purposes according to research and findings through the government (Ghosh 2018). At the local level of an institution like Gram Panchayat and self-help group, structure and initiatives were lacking and fuzzy due to a lack of uniformity (Ghosh 2018). It appears there is a scarcity of scientific knowledge from experts to protect mangrove vegetation, which raises uncertainty in various departments and mainly at the grassroots level and also suffers from a lack of compatibility and motivation. The governance structure is not well defined to meet the goals of plans and programs. The governance requires an authority to design it, and it also needs the body of governance either run by the public and private institution or the cooperation of two formal and informal institutions. The rising disparity between the views of policymakers and local level of institution increases the risk and threat of climate change and introduces new challenges to the people living in the Sunderban area and to others (Ghosh et al. 2018). The policy having a lack of clarity and awareness for the local people to combat for coping strategies of climate change. The lack of institutional linkages has made it impossible to inquire about their basic needs and demands to run their livelihood, and this has also deprived them of the traditional knowledge and experiences (Bose et al. 2018). The traditional knowledge is an auspicious tool for the locals to sustainably manage the mangrove plantation. The people of Sunderban are highly dependent on the natural resources of the forest, and the forest act as a natural wealth for them. Their traditional knowledge and participation are not incorporated into the government policy, which has shown many lack of communication between government and locals for the protection of mangrove forests (Karmakar 2018). The ethnic identity of local communities is needed to be preserved, so their involvement will give a sustainable result in mangrove conservation, but the inconsistency of policy acts as a barrier to community participation. It is essential to raise the awareness and understanding among locals about mangrove destruction from decades ago because many people don't have the idea about the climate change that can uproot the mangrove vegetation in the near future. There is a need for traditional knowledge as well as scientific knowledge with the help of sustainable policy to conserve the precious tidal forest. There is a need for a distinct change in policy and governance structure that has the capacity to cope in harsh conditions (Gleditsch et al. 2007). If the present policies continue, the Indian Sunderban will face inviolable challenges from climate change and population rise. There is a strong need for the intervention of all different actors (national, state, district, and local) for the management. WWF gave a vision as a long-term perspective by 2050 for Indian Sunderban to protect the land from natural and anthropogenic loss; it also aimed to reduce the risk from weather events, restore mangrove plantations, and raise socioeconomic status in the future. There is a need of an interdisciplinary and collaborative approach, which can help Sunderban restore the mangrove plantation in a sustainable way that would propagate a large amount of economic activity from the forest in the future, so that not only national institution but also international institution will take part in raising the finance.

17.7 The Governance Structure Needs to Restructure the Sunderban Land in Future

In the structure, the level of governance comprises a three-tier mechanism, and all the actors are equally important for participation. The Sunderban area is divided into parts for different functions. The area which lies near the shoreline would not permit a settlement area. Understanding the capacity building of the population is necessary for the shoreline area. The increasing population has already expanded in the danger zone area, which enhances the vulnerability. The area, like Gosaba, Basanti, and Patharpratima (Hazra et al. 2011), would be covered by mangrove plantations, which would act as a good adaptation strategy. The initiative the institution would take for the living population of these areas would give them some alternative, or they could access other areas. In this way, the land can restore mangrove vegetation in the future. These areas have active tidal creeks, which can submerge in the ocean. If these islands are not taken into consideration, then it increases the risk in the surrounding areas, like Namkhana and Sagar Island having, which have a large population. The physical infrastructure development would take into account the department of natural disasters because of the intensity of cyclones, floods, and all-weather events in Sunderban. All areas should not be considered for physical development, which results in the clearance of mangrove forests. If the restoration program of mangrove plantations continues in this way, then it would be possible to return to sustainable development in Sunderban. The mangrove cover benefits not only the surrounding areas of Sunderban also the neighboring city of Sunderban. It was estimated that healthy mangroves earn as an ecosystem service in the range of US$ 2000 to 9000 per hectare yearly (Spalding et al. 2010).

17.8 Conclusion

The study shows that the mangrove ecosystem is highly vulnerable to climate change issues. Climate change and climate-induced changes like sea-level rise have pose a threat to the Indian Sunderban for decades. The major divers of climate change are sea-level rise, population rise, and the increase in pollution levels in Sunderban. Over the Bay of Bengal, the sea surface temperature is increasing by 0.019 °C annually, which enhances the effect of sea-level rise of 3.14 mm annually (Hazra et al. 2002). The sea-level rise introduces many changes, like changes in cyclonic activity, erosional, and accretion patterns. It was noticed from the past the intensity of cyclone increase than the frequency of cyclone appears on Indian Sunderban. The changes in erosional and accretion patterns result in changes in land cover. The population rising is one factor that influences sea-level rise by clearing mangrove vegetation and also climate change and sea-level rise impacts the population of Sunderban. The pollution is directly impacted and can destroy mangrove plantations. The climate change and its associated changes are suffering the mangrove ecosystem and slowly destroying its natural precious ecosystem service. The living people of Sunderban are and will always be highly dependent on mangrove service regardless of any alternatives. In the current situation, the changes cannot alter the situation, but changes in the government policy and governance could control the loss of mangrove cover from a long-run perspective. All types of actors are needed, from international to district levels, for the restoration of mangrove in the Indian Sunderban. As we know, the Sunderban has the largest number of mangroves that meet the human needs until death. There is a need for a bottom-up approach that focuses on the grassroots level. Indigenous knowledge is a special tool in terms of mangrove protection. The lack of communication from ground level is unable to bring change in the restoration of mangroves. More community participation, local involvement, and discussion with scientific knowledge are needed in policymaking, which can function successfully and sustainably in the future. Education and empowerment skills are necessary for locals to combat climate change, and they need to understand the uncertainties of climate change in Sunderban, which would ruin their future. The small-scale adaptation program would increase the resilience of mangroves againts natural calamity. The interdisciplinary collaboration needs to develop through policies that address the conservation of mangroves in the Indian Sunderban.

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