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A geospatial assessment of growth pattern of aquaculture in the Indian Sundarbans Biosphere Reserve

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Abstract

Indian Sundarbans Biosphere Reserve (SBR) comprising over 100 estuarine islands and shared by human habitation and mangrove forests is considered to be a potential area for coastal aquaculture. This study, using LANDSAT imageries of the last two decades (1999–2019), delineated the spatiotemporal expansion of aquaculture at the expense of agricultural land, mudflats, and some mangroves. It also estimated a futuristic land transformation to aquaculture using the Cellular Automata-Markov Chain model. From the geospatial analysis, it is observed that (1) the aquacultures are mostly located around 22° 30′N, i.e., far away from the saline seafront, (2) total aquaculture area has increased to nearly 5.82% of the entire SBR in 2019 from 3.59% in 1999 and, (3) cyclone Aila and its surge inundation have influenced in their expansion. This growth of aquaculture took place with the loss of 3.71% (10,536.67 ha) agricultural land, 3.87% (730.40 ha) mudflat, and 0.28% (623.23 ha) mangrove from 1999 to 2009, and 6.02% (13,471.50 ha) agricultural land, 9.98% (1583.64 ha) mudflat, and 0.18% (382.35 ha) mangrove during 2009–2019. According to the predictive modeling, ∼6% of the present agriculture area is prognosticated to be converted to aquaculture by the next decade under a business-as-usual scenario.

1 Introduction

Aquaculture is considered one of the fastest-growing food-producing sectors worldwide. Global production of aquaculture became double from 32.4 to 66.6 million tonnes during the period 2000 to 2012 (FAO, 2014). From the Indian perspective, growth in the aquaculture sector is significant to ensure food security for the growing population, especially when agricultural lands are rapidly declining. After China, India is the second-largest producer of aquaculture resources and contributes approximately 6.3% to

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global aquaculture production (FAO, 2014). In India, carps in freshwater and shrimps in brackish water constitute the major components of aquaculture production (Ghoshal et al., 2019). Brackish water aquaculture (BWA) resources develop mainly in the estuarine area where admixing of fresh water and saline water takes place. India has an estimated total brackish water area of 3.9 million hectares, of which 1.2-million-hectare area has been identified as a potential area for shrimp farming (Handbook of Fisheries & Aquaculture, 2013). During the years 1990 to 1994, there was a substantial increase in brackish water aquaculture all over India. However, due to a huge outbreak of disease from 1995 to 1996, advanced culture technologies were adopted in subsequent years (Panigrahi et al., 2009).

The maritime state of West Bengal has a vast potential for brackish water shrimp farming along its 158 km of coastline. Though there are many freshwater aquacultures in the Sundarbans, a major portion is constituted by the brackish water aquacultures (Hand Book of Fisheries Statistics, 2015–16). The popular species for shrimp farming is the black tiger shrimp, *Penaeus monodon* for its unique taste, high market value, and demand. In West Bengal, scientific farming of the tiger shrimp began during the late 1980s with an area of around 39,000 ha (Mandal & Dubey, 2015). However, since the year 2009, an exotic species *Litopenaeus vannamei* (white-leg shrimp) started drawing the farmers' attention due to its fast growth rate, resilience against the native diseases, and feasibility of culture in a wide range of salinity (Ghoshal et al., 2019). Apart from tiger shrimp and white-leg shrimp, there are other brackish water fishes like sea bass and mullets, which are widely cultured in West Bengal.

There is about 210,000 ha of suitable area for brackish water farming in the three districts of West Bengal viz. North 24 Parganas, South 24 Parganas of the Sundarbans delta, and the East Midnapore (Abraham et al., 2013) on the open coast. Two districts of 24 Parganas have around 46,500 ha area for shrimp farming of which 35,000 ha belonged to North 24 Parganas and 11,500 ha in South 24 Parganas (Mandal & Dubey, 2015). Out of this 46500 ha aquaculture area, a substantial proportion is situated within the 19 administrative blocks of Sundarbans Biosphere Reserve (SBR) (Hand Book of Fisheries Statistics, 2015–16).

Sundarbans (renowned for being the world's largest mangrove forest shared with Bangladesh) comprise a complex network of tidally influenced rivers, creeks, and small islands, where a large number of poor fisherfolks are primarily dependent upon the capture fisheries. Apart from the capture fisheries, brackish water aquaculture production increased significantly in the last decade in this region (Ghoshal et al., 2019). Recently there is a tendency of livelihood shift from agriculture and traditional capture fisheries to brackishwater aquaculture as the economic return in brackishwater aquaculture is many times higher than the two other livelihoods (Ghoshal et al., 2019). However, this sector in Sundarbans faced several issues like natural hazards (severe cyclones, storm surges, etc.), fish disease outbreaks that led to significant yet unpredictable economic loss to the farmers (Annual Report of Marine Product Export Development Authority, 2009–10). On the contrary, soil salinization (DasGupta & Shaw, 2014; DasGupta et al., 2019; Dubey et al., 2017) leads to the unsuitability of agriculture in coastal areas, and it is often believed that brackish water aquaculture (BWA) is becoming more preferred option of livelihood in the time of climate change. Yet some researchers (Chopra et al., 2009) perceive the emergence of BWAs, particularly its more commercial variants as a growing environmental threat to the fragile ecosystem of Sundarbans. The common practice of prawn seed collection in the creeks and rivulets for the BWA farms leads to massive destruction of seeds and even eggs of other fish species (Sarkar & Bhattacharya, 2003).

The present paper therefore investigates the decadal changes of aquaculture area in the SBR between the years 1999 and 2019, with few focused queries like (a) where the aquacultures are located in the Sundarbans delta and where the growth centers are (b) whether cyclone and surge inundations influence the growth/decline of aquacultures in the delta and lastly (c) how the delta would likely respond to the growth of aquaculture under the business-as-usual scenario in the year 2029.

To understand the land transformation dynamics and emergence of aquaculture practice in the coastal region of the delta, both spatial and temporal observations are necessary. Satellite Remote Sensing integrated GIS analysis offers such scope of high-resolution study in large areas. Several studies were carried out by different researchers on aquaculture mapping and change detection around the world (Kapetsky et al., 1988; Aguilar-Manjarrez & Ross, 1995; Arnold et al., 2000; McLeod et al., 2002; Rowe et al., 2002; Salam et al., 2003; Karthik et al., 2005; Longdill et al., 2008), but in the context of Indian aquaculture practice, very few published literature (Gupta, 1995; Jayanthi, 2011; Ramesh & Rajkumar, 1996) is available on the mapping using remote sensing and GIS. However, in the entire SBR, no such literature is available on detailed mapping of the aquaculture area, its change analysis, and transformation from the other land use classes. Only a study by Samanta and Hazra (2012) reported the increasing quantum of brackish water aquaculture area in a small island of Jharkhali in the SBR. In the present study, an indices-based classification approach was applied along with supervised classification using the maximum likelihood classification technique to classify the aquaculture areas with higher accuracy. Using those classifications, detailed mapping of the aquaculture area in the SBR, its decadal change, and area transformation of the different land use classes to and from aquaculture were estimated. Also, the effect of the cyclone Aila on the expansion of aquaculture was studied. Apart from these, a future projection of the aquaculture area in 2029 was given along with a transition probability from different other land use classes.

2 Materials and methods

2.1 Study area

Indian SBR (21° 32′ N–22° 40′ N and 88° 05′ N–89° 51′ E) is located in the southern end of the state of West Bengal. It comprises an area of 9630 km^2 of which core mangrove forest area and Tiger Reserve covers an area of 1700 km^2 (Fig. 1) (Nandy & Kuswaha, 2011). The SBR has102 low-lying islands of which 54 are having human habitation. The islands of entire Sundarbans including both India and Bangladesh are formed by the intricate network of tributaries and distributaries of the rivers Ganges, Brahmaputra, and Meghna. The Indian part is demarcated by river Ichamati-Kalindi-Raimongal on the east, by the river Hugli on the west, by Dampier Hodges line on the north, and the Bay of Bengal on the south. At present, the settlement area of the SBR is located within 19 administrative blocks of which 13 blocks belong to South 24 Parganas and 6 blocks to North 24 Parganas (Chand et al., 2012).

The SBR, with its pristine mangrove forest and unique biodiversity inhabited by nearly 4.37 million people (2011 census) in the Indian part is considered as one of the most vulnerable areas to climate change (DasGupta et al., 2019). The inhabitants of the delta experience increase in temperature and erratic rainfall, extreme climatic events like cyclones, floods, rapid sea-level rise, saline water intrusion, and habitat loss due
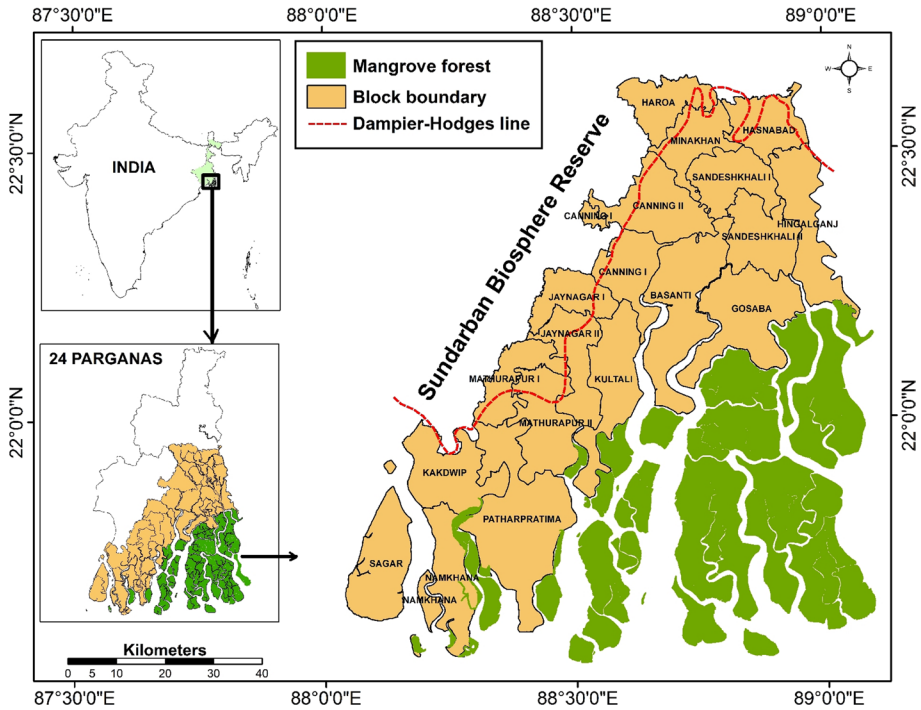
Fig. 1 Map showing the present study area

to high coastal erosion. Daily average air temperature increased 0.1 °C from 1891 to 1970 (Chand et al., 2012). However, the trend of increasing air temperature became prominent after the year 2000 (Mishra, 2010). Mitra et al. (2009) estimated the increase in surface water temperature at an approximate rate of 0.05 °C per year from 1978 to 2008. Hazra et al. (2010) also corroborated the fact by reporting the increase in sea surface temperature (SST) by around 0.0453 °C per year near the sea-facing end of SBR (Sagar Island) during the period 2004 to 2009. This rising SST frequently leads to the formation of high-intensity cyclonic storms over the Bay of Bengal. A changing monsoon pattern has also been observed in Sundarbans (Chand et al., 2012). The region is mainly nurtured by southwest monsoon rainfall. Usually, the middle of June is considered as the onset of the southwest monsoon that continues up-to the first or second week of October with the highest rainfall during August. The average annual rainfall in Sundarbans has been reported as 1625 mm. Sometimes it raises up-to 2000 mm in the heavy rainfall year and may also drop to 1300 mm in the low rainfall years (Chand et al., 2012). However, in the last few decades a delayed onset and recession of monsoon have been observed (Chand et al., 2012). Sea level rise and erosion are two other major problems in Sundarbans. Hazra et al. (2002) reported the sea level rise of 3.14 mm per year from the tide gauge data (1990–2000) near Sagar Island of Sundarbans. In the present century, the rate of sea-level rise was estimated to be as high as 8 to 12 mm per year (Hazra et al., 2016; Pethick & Orford, 2013). A study on the coastal erosion in Indian Sundarbans also revealed the rate of erosion to be in the order of 5.50 sq km per year, particularly on the sea-facing islands, from 2001 to 2009 (Hazra et al., 2010).

2.2 Satellite data

Landsat TM images of the years 1999 and 2009, and OLI images of the year 2019 were used for the present study to delineate the changes in the aquaculture area of the SBR. The spatial resolution of the satellite images is 30 m × 30 m. The aforesaid satellite images were downloaded from the USGS website (http://glovis.usgs.gov). The path/row are 138/44 and 138/45 for the two scenes covering the SBR. The images were projected in the Universal Transverse Mercator (UTM) projection with Zone no. 45 and WGS 84 datum.

Radiometric calibration of the multi-temporal satellite images is the prerequisite of change detection study for the gain and bias corrections (Duggin & Robinove, 1990). The scattering effect is dominant for the Landsat data (Song et al., 2001) and vegetation cover identification. Atmospheric correction is essentially needed to reduce the scattering effect. In the present study, visible and near-infrared (VNIR) bands of Landsat data were atmospherically corrected. The bands were radiometrically calibrated to convert the DN values into the top of the atmosphere radiance (L_{TOA}) using the standard sensor calibration function of Chander et al. (2007). The radiance of VNIR bands was converted to correct surface reflectance based on the image-based atmospheric correction model developed by Chavez (1996). The radiance (L_p) resulted from the interaction with aerosol and atmospheric particles was estimated based on Song et al. (2001); Chavez (1996), and Sobrino et al. (2004).

2.3 Image classification for land use/land cover (LULC) and accuracy assessment

Supervised classification was performed on all three images using the maximum likelihood classification technique. A total of nine LULC classes were considered for the classification based on the authors' knowledge about the study area. The selected LULC classes were—river, mangrove, mudflat, aquaculture, settlement with vegetation, agriculture, brickfield, fallow land, and water body. Training signatures were selected for the land use classes before running the classification. After the classification, the majority spatial filters of kernel size 3 × 3 were applied to each of the classified images to remove the isolated pixels. The accuracy of the classifications was assessed for all three images. Finally, the area transformation matrices were generated from 1999 to 2009 and 2009 to 2019.

2.4 Indices-based classification for extraction of aquaculture and water bodies

In order to specifically extract the water areas including both the aquaculture and other water bodies, different satellite-derived indices viz. Normalized Difference Water Index (NDWI), Modified Normalized Difference Water Index (MNDWI), Water Ratio Index (WRI), and Automated Water Extraction Index (AWEI) were executed upon all the three Landsat images. For this purpose near-infrared was preferred as it is absorbed by the water and reflected by the vegetation and dry soil (Sun et al., 2012). The detailed formulae of the different indices have been given in Table 1.

During the field survey, 35 ground locations of aquaculture plots all over the study area were collected using Garmin eTrex 20 × GPS in the year 2019. Once the water bodies were identified from the indices, knowledge-based classification was performed

Table 1 Satellite derived indices used for the extraction of water body from the Landsat imagery

Index	Equation	Reference
NDWI	$NDWI = (Green - NIR)/(Green + NIR)$	McFeeters (1996)
MNDWI	$MNDWI = (Green - MIR)/Green + MIR)$	Xu (2006)
WRI	$WRI = (Green + Red)/(NIR + MIR)$	Shen and Li (2010)
AWEI	$AWEI = 4 \times (Green - MIR) - (0.25 \times NIR + 2.75 \times SWIR)$	Feyisa et al. (2014)

using those ground locations, and accordingly, the aquacultures were segregated from other water bodies. Accuracy assessment was carried out for the different indices-based classification for segregating aquaculture from other water bodies. Finally, the vectorized aquaculture, water body, and river layers were merged with the previously generated LULC.

2.5 Prediction of future aquaculture area using Cellular Automata-Markov chain (CA–Markov) model

CA–Markov model is one of the commonly used modeling techniques for prediction of the LULC using the previous trends of Spatio-temporal changes (Nouri et al., 2014; Regmi et al., 2014; Weng, 2002). CA–Markov model is the combination of cellular automata (CA) technique with Markov chain analysis and Multi-Criteria/Multi-Objective Land Allocation (MOLA) land cover prediction procedure that adds an element of spatial contiguity as well as spatial distribution likelihood of transitions to Markov chain analysis. The Markov technique is used for predicting the change of state S at time $t+1$ which is dependent on its previous state at time t and is expressed as a conditional probability (Weng, 2002). Based on this conditional probability and suitability of each pixel for each land cover type produced by multi-criteria evaluation (MCE), the multi-objective land allocation (MOLA) procedure allocates the land from each host land cover category to all other categories. A kernel integral to the Cellular Automata component down-weight the suitability of pixels that are distant from existing instances of the land cover type under consideration. Hence, the pixel must be both inherently suitable and near to existing areas of that class to be a likely choice for land cover conversion. The formula of the CA-Markov prediction model for the land use changes can be expressed as follows:

$$S(t + 1) = S(t) \times P_{ij}$$

where S $(t+1)$, S (t) are the states at times t and $t+1$, respectively, and P_{ij} is the transition probability matrix. Again, the transition probability matrix was calculated according to (Kumar et al., 2014; Sang et al., 2011).

In the present study, the CA–Markov model was applied for developing future projections of the aquaculture area in the year 2029 for SBR. Before predicting the scenario for 2029, the robustness of the model was tested. Initially, LULC for the year 2019 was predicted using the LULC the years 1999 and 2009 followed by the validation with the actual LULC of 2019. Finally, the LULC scenario for 2029 was projected using the LULC of 2009 and 2019. The transition probability matrix between 2019 and 2029 was also

generated. The prediction model was run using TerrSet Geospatial Monitoring and Modeling System.

The year 1999 was chosen because of the enactment of Coastal Zone Management Regulation (1991) from the year 1998 in West Bengal restricting unabated growth of aquaculture (especially brackish water) in an ecologically sensitive Coastal Regulatory Zone-I (CRZ-I) like SBR (CRZ Notification Amendment, 1998). Similarly, the year 2029 was chosen for the future projection as it is the terminal year to achieve the target of sustainable development goals (SDGs) in the delta, particularly SDG 14 and 15, protecting life below water and life on land.

3 Results

3.1 Analysis of indices-based classification

3.1.1 Change detection analysis of aquaculture area in Sundarbans

Changes in total aquaculture area in the SBR have been estimated in the present study for the time window between 1999 and 2019 which indicated a steady increase, often with varying tempo and mode. The total aquaculture area for the years 1999, 2009, and 2019 has been estimated as 3.59% (31,794.02 ha), 4.18% (37,028.54 ha), and 5.82% (51,587.25 ha) of the entire SBR, respectively. Blockwise change in the aquaculture area has also been estimated (Fig. 2). Among the 19 blocks of SBR, Sandeshkhali-I covered the highest aquaculture area (7162 ha in 1999, 7774.81 ha in 2009, and 9460.70 ha in 2019, which were estimated as 39.75%, 43.15%, and 52.51% of the entire block area, respectively) followed by Minakhan (7105.86 ha in 1999, 7608.54 ha in 2009 and 9373.77 ha in 2019, which were estimated as 45.26%, 48.47% and 59.71% of the entire block area, respectively) and Haroa (6491.88 ha in 1999, 6543.57 ha in 2009 and 8251.68 ha in 2019, which were estimated as 41.67%, 42% and 52.97% of the total block area, respectively). In the business as usual scenario, this trend would remain the same in the projected year 2029. Out of the total aquaculture area developed within the last two decades, a major portion (81.24% in 1999, 76.93% in 2009, and 72.98% in 2019, respectively) is concentrated around 22° 30′ North
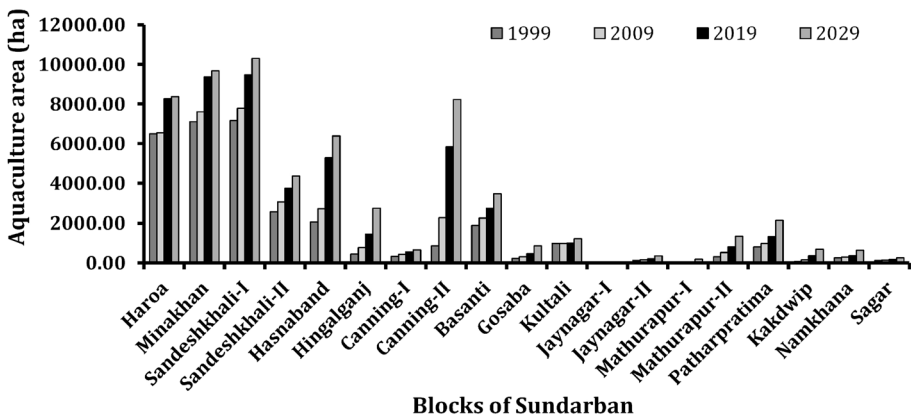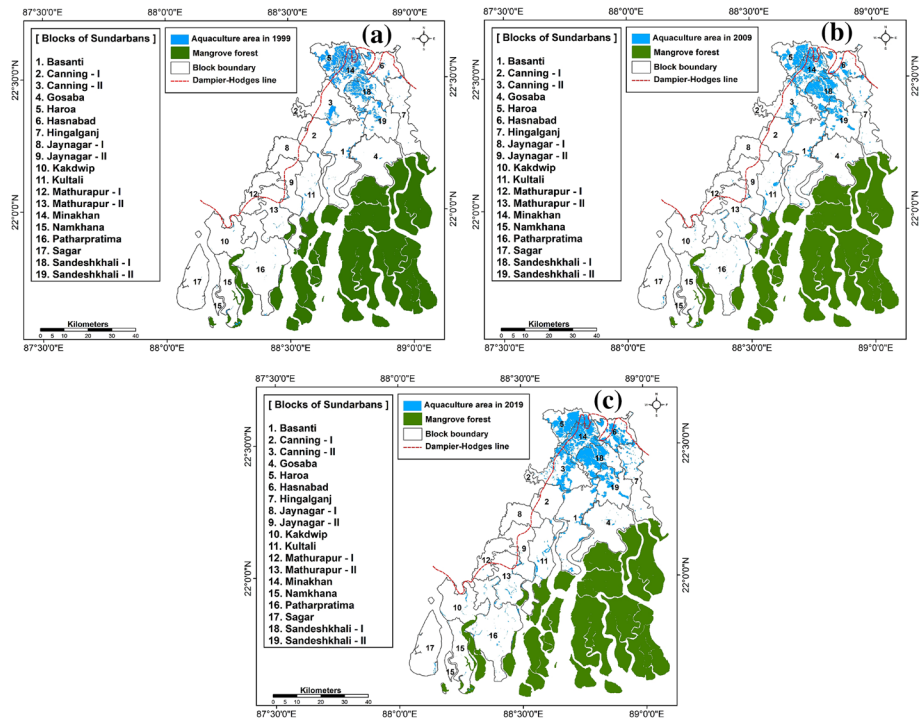

Fig. 2 Block-wise decadal change of aquaculture area in Sundarbans

Fig. 3 Spatial distribution of aquaculture in Sundarbans—a 1999 b 2009 and c 2019

latitude which is far away from the seafront and distributed within the 6 blocks that belong to North 24 Parganas district. Area of aquaculture also increased in all other blocks of South 24-Parganas from 1999 to 2019. The maximum increase was observed in Canning-II (579.21%) followed by Kakdwip (452.21%) and Mathurapur-I (410.66%). The spatial distribution and the changes in the aquaculture area in the SBR are shown in Figs. 3 and 4.

3.1.2 Analysis of land use transformation to and from aquaculture

Transformation of different land use classes to aquaculture during the last two decades (1999–2009 and 2009–2019) are shown in Tables 2 and 3. Out of nine land use classes, a remarkable transformation from agriculture to aquaculture [10536.67 ha (3.71% of total agriculture land of SBR) during 1999 to 2009 and 13,471.50 ha (6.02% of total agriculture land of SBR) during 2009 to 2019] was observed. In addition, mudflats, fallow lands, and even some mangrove forest areas were also converted to aquaculture. The establishment of the aquaculture farms at the proximity to the river or creek for easy access to the brackish water resulted in the deforestation of mangrove forests (Tables 2 and 3) in the island fringes. However, within the last two decades, maximum deforestation of the fringe mangroves was observed during the pre-cyclone Aila period of 1999 to 2009 [623.23 ha (0.28% of the total mangrove forest of SBR)] that came down to 382.35 ha (0.18% of the total mangrove forest of SBR) during 2009 to 2019 in the post-Aila period. Apart from this transformation of the different land classes to aquaculture, another noticeable transformation was from aquaculture to brickfields. A major portion of the brickfield areas was
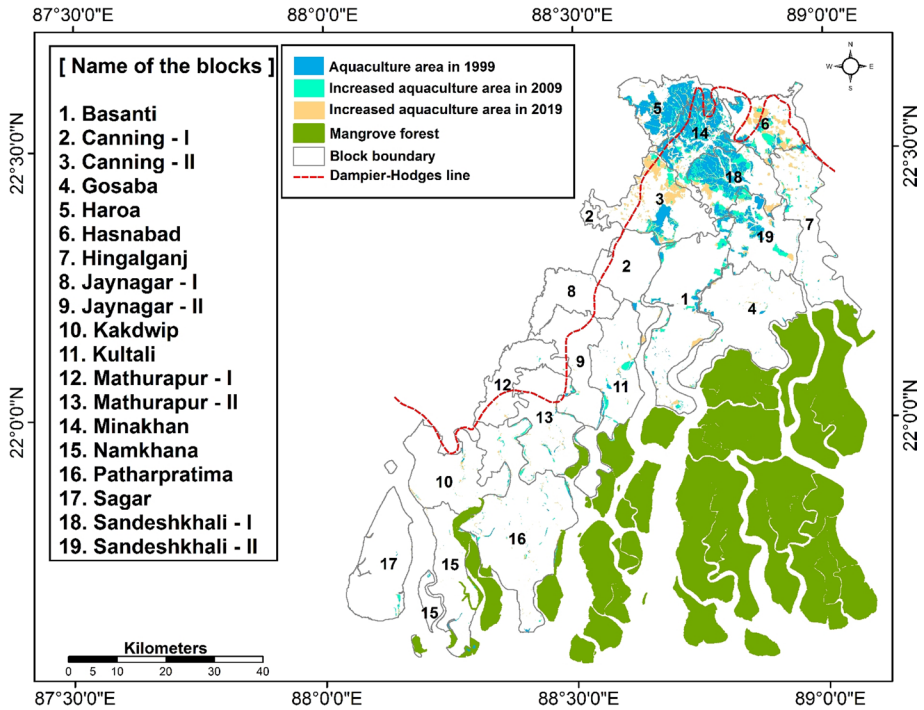
Fig. 4 Increased area of aquaculture in Sundarbans during 1999 to 2019

converted from aquaculture [546.91 ha (1.720% of the total aquaculture area of SBR)] during 1999 to 2009 and 638.53 ha (1.724% of the total aquaculture area of SBR) during 2009 to 2019] during the last two decades. In the Jaynagar-I block, the aquaculture area decreased from 4.59 (in 2009) to 2.63 ha (in 2019) due to conversion to brickfields. With increasing urbanization in the delta, this might be a direction of the possible transformation away from aquaculture and potentially more harmful to the ecosystem unless managed properly. Further, 2124.28 ha aquaculture area was lost due to riverbank erosion from 1999 to 2009 and 235.25 ha from 2009 to 2019.

3.1.3 Changes in aquaculture area after the cyclone Aila

The present study revealed that the difference in the percentage change in aquaculture area between the post-Aila (2009–2019) and the pre-Aila (1999–2009) decades varied between 0.55 and 62.38% in the Aila-affected blocks (Fig. 5). On the contrary, many of the non-Aila-affected blocks, viz. Canning-I, Canning-II, Jaynagar-II, Mathurapur-I, Mathurapur-II, though experienced an increase in the aquaculture area, the percentage of increase in the post-Aila period was much less (4.18–53.40%) than that observed in the pre-Aila period. Jaynagar-I was the only block that experienced a reduction (42.76%) in the aquaculture area (during the post-Aila decade).

Table 2 The land transformation matrix of different land use classes from 1999 to 2009

Land class (area in ha)	2009									
	Agriculture	Aquaculture	Brick field	Fallow land	Mangrove	Mud flat	River	Settlement with veg	Water body	Grand total
1999 Agriculture	221773.76	10536.67	270.62	4001.26	0.00	4140.63	1936.48	40588.11	611.88	283859.39
Aquaculture	6.86	24892.78	546.91	2325.80	207.25	232.44	2124.28	1437.39	20.31	31794.02
Brick field	0.00	0.00	304.29	52.62	0.00	12.96	10.27	10.89	2.61	393.64
Fallow land	1100.30	140.15	20.00	1795.20	1.54	0.00	8.23	301.83	5.11	3372.38
Mangrove	419.17	623.23	0.61	1.44	210687.90	50.18	7156.34	582.11	11.65	219,532.63
Mud flat	129.87	730.40	14.49	99.42	2596.78	8737.66	6553.60	0.00	18.02	18,880.25
River	191.08	22.35	0.53	0.55	875.90	2683.96	235,773.71	108.30	1.22	239,657.60
Settlement with veg	0.00	0.00	0.00	0.00	0.00	0.00	200.25	84,793.20	835.29	85,828.74
Water body	0.00	82.96	0.00	0.00	0.00	0.00	0.00	389.46	1281.89	1754.31
Grand total	223,621.04	37,028.54	1157.44	8276.28	214,369.37	15,857.83	253,763.17	128211.30	2787.98	885,072.94

Table 3 The land transformation matrix of different land use classes from 2009 to 2019

Land class (area in ha)	2019									
		Agriculture	Aquaculture	Brick field	Fallow land	Mangrove	Mud flat	River	Settlement with veg.	Water body	Grand total
2009	Agriculture	161984.51	13471.50	390.62	3543.63	0.00	335.42	3287.31	39781.63	826.42	223621.04
	Aquaculture	10.88	34410.97	638.53	156.79	102.57	40.08	235.25	1406.98	26.48	37028.54
	Brick field	0.00	0.00	962.83	144.82	0.00	0.22	22.77	25.42	1.39	1157.44
	Fallow land	1622.00	1569.86	37.65	4649.77	1.87	0.00	30.72	356.54	7.87	8276.28
	Mangrove	114.96	382.35	0.00	0.13	211676.36	22.94	1586.48	578.90	7.25	214369.37
	Mud flat	137.32	1583.64	52.02	141.97	3126.73	4472.64	6329.17	0.00	14.34	15857.83
	River	162.55	27.62	4.82	0.78	4875.92	1386.77	246709.20	583.43	12.08	253763.17
	Settlement with veg.	0.00	0.00	0.00	0.00	0.00	0.00	748.48	126823.05	639.76	128211.30
	Water body	0.00	141.30	0.00	0.00	0.00	0.00	0.00	562.57	2084.10	2787.98
	Grand total	164032.22	51587.25	2086.47	8637.89	219783.45	6258.07	258949.38	170118.52	3619.69	885072.94

Fig. 5 Comparison between the percentage of change in aquaculture area in Sundarbans during pre and post Aila period. Bracketed blocks were affected during Aila
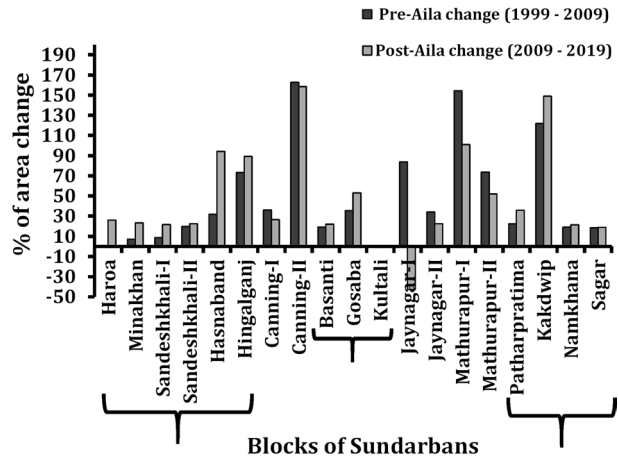
3.1.4 Accuracy assessment of the classification

Tables 4 and 5 depict the classification accuracy of the supervised classification and indices-based classification technique. AWEI was observed to be the most robust index (overall accuracy for the year 1999, 2009, and 2019 was estimated as 93.33%, 94.4%, and 94.03%, respectively) in comparison with others (overall accuracy of NDWI, MNDWI, and WRI for 1999 was estimated as 80.56%, 83.47%, and 74.31% respectively; for 2009, the values were estimated as 80.45%, 86.17%, 76.48% respectively, and for 2019, the values were 84.29%, 89.47%, 81.17% respectively) and therefore was considered with confidence. This classification accuracy of AWEI for the aquaculture and water bodies was much higher than the accuracy assessed for supervised classification. The different LULC generated from the supervised classification exhibited good producer accuracy in all 3 years. However, the producer accuracy for aquaculture, waterbody, and the river was comparatively much higher in AWEI-based classification. Overall kappa coefficient (κ) estimated for supervised classification was 0.8663, 0.8496, and 0.8948 for the years 1999, 2009, and 2019, respectively.

3.2 Future expansion of aquaculture area

Probability matrices for the transformation of various land classes during the 2019 to 2029 time period (Table 6) indicated that 6.06% of agricultural land, 3.89% fallow land, 3.44% mudflat, and 2.82% water bodies are likely to get converted into aquaculture by 2029 in the business as usual scenario. The predictive modeling showed that the total aquaculture area in SBR in the year 2029 could be 61,914.24 ha. Among the 19 administrative blocks, maximum conversion to aquaculture is predicted to take place in Sandeshkhali-I (10,305.02 ha) followed by Minakhan (9680.79 ha) and Haroa (8365.13 ha). However, a significant increase in aquaculture in the Canning-II, Kakdwip, and Gosaba blocks is predicted as well (Fig. 6).

Table 4 Accuracy assessment of the maximum likelihood classification generated LULC for the year 1999, 2009 and 2019

Land use classes	1999		2009		2019	
	User accuracy (%)	Producer accuracy (%)	User accuracy (%)	Producer accuracy (%)	User accuracy (%)	Producer accuracy (%)
River	87.5	87.5	86.3	87.5	88.8	93.3
Mangrove	81.3	86.4	88.8	88.9	88.3	89.8
Mud flat	86.4	88.3	86.2	89.8	86.6	89.7
Aquaculture	86.9	88.9	87.1	89.3	87.2	88.5
Settlement with vegetation	90.9	93.33	80.1	82.6	90.9	83.3
Agriculture	86.9	89.9	84.1	83.7	84.5	87.1
Brick field	85.6	88.32	86.2	88.5	88.2	88.6
Fallow land	81	88.88	85	86.1	90	87.8
Water body	82.3	87.7	87.9	89.4	90.3	86.8
Overall classification accuracy (%)	87.13		86.42		88.66	
Kappa coefficient (κ)	0.8663		0.8496		0.8948	

Table 5 Accuracy assessments of the land cover classification using AWEI for1999, 2009 and 2019

Land use classes	1999		2009		2019	
	User accuracy (%)	Producer accuracy (%)	User accuracy (%)	Producer accuracy (%)	User accuracy (%)	Producer accuracy (%)
Water body	91.8	94.7	92.6	96.6	94.3	94.3
Aquaculture	92.9	93.9	94.1	94.3	93	94.5
River	92.8	94.12	94.26	95.69	92.47	94.2
Overall classification accuracy (%)	93.33		94.4		94.03	
Kappa coefficient (κ)	0.9026		0.9142		0.9138	

Table 6 Transition probability matrix of different land use classes between 2019 and 2029

Land class		2029								
		River	Mangrove	Mud flat	Aquaculture	Settlement with veg.	Agriculture	Brick field	Fallow land	Water body
2019	River	0.9238	0.0529	0.0143	0.0023	0.0018	0.0008	0.0030	0.0010	0.0001
	Mangrove	0.0282	0.9335	0.0123	0.0034	0.0203	0.0022	0.0000	0.0000	0.0002
	Mud flat	0.4617	0.2124	0.2615	0.0344	0.0000	0.0200	0.0032	0.0029	0.0039
	Aquaculture	0.0103	0.0042	0.0019	0.8837	0.0615	0.0166	0.0153	0.0005	0.0060
	Settlement with veg.	0.0086	0.0000	0.0000	0.0000	0.9836	0.0000	0.0000	0.0000	0.0077
	Agriculture	0.0141	0.0068	0.0016	0.0606	0.2255	0.6687	0.0018	0.0171	0.0038
	Brick field	0.0374	0.0000	0.0005	0.0000	0.0478	0.0000	0.8902	0.0204	0.0038
	Fallow land	0.0033	0.0002	0.0000	0.0389	0.0367	0.8898	0.0010	0.0293	0.0008
	Water body	0.0000	0.0000	0.0000	0.0282	0.2695	0.0000	0.0000	0.0000	0.7023
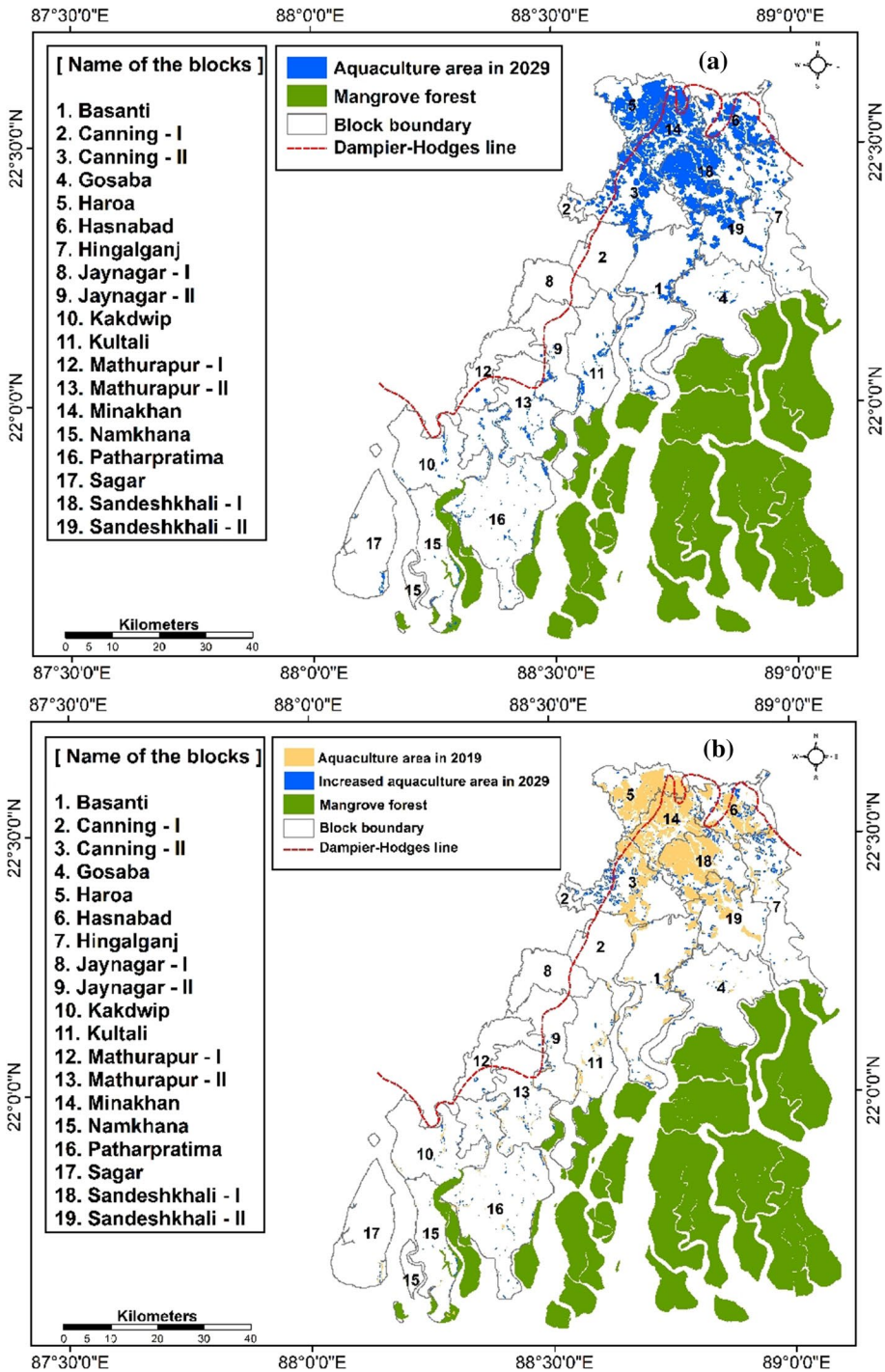
Fig. 6 **a** Future projection of spatial distribution of aquaculture area in Sundarbans for 2029 **b** additional area likely to be converted to aquaculture in 2029

4 Discussion

The present investigation on the location and growth of brackishwater aquaculture in the SBR area could not have been accomplished without the application of advanced geospatial analysis techniques. Four different indices were used in this study for extraction of the water features as every individual index has specific limitations. For instance, the extracted water features by NDWI or MNDWI, often get mixed with the built-up areas, and thus it is often overestimated. On the contrary, AWEI can eliminate the built surfaces of the urban areas (Rokni et al., 2014). The aquaculture farms in several locations of the present study area also developed in a close association with the settlements. That is why AWEI could provide better accuracy than the three other indices. However, all four indices were used individually for the classification to check the accuracy of the indices of which the results of the AWEI were taken into the consideration.

CA–Markov-based prediction of LULC offers a broad understanding of the complex nature of the spatial system. CA–Markov model was used by several researchers for simulation and prediction of land-use changes (Eastman, 2006; Hamad et al., 2018; Megahed et al., 2015; Regmi et al., 2014). In the present study, robustness of the model was tested by predicting the land use of 2019 using the land use map of 1999 and 2009 and validated against the actual land use map of 2019. The accuracy of the model can be expressed with [M(m)] which is the agreement between the reference map and the unmodified comparison map. It is the proportion of grid cells classified correctly, which is the most commonly used measure of agreement between maps. However, for the present prediction, the model accuracy [M(m)] was estimated as 0.90 or 90%. It also indicates the reliability of the land use classification.

The geospatial analysis of location and growth of brackish water aquaculture area brings out three salient observations—(1) the aquaculture farms are concentrated around 22° 30′ North latitude and far away from the seafront; (2) aquaculture area has grown significantly over the last two decades at the expense of agriculture and mangrove area within the biosphere reserve area despite legal embargo over such conversion in the ecologically sensitive Coastal Regulatory Zone-I area; and (3) cyclone and surge inundation have a definite role in the expansion of aquaculture in the SBR area. The first observation does not support the fact that location and expansion of aquaculture have a strong relation to salinity ingress in the delta, as the aquaculture farms grew and concentrated far away from the saline front. During the 1960s, the said area remained as a meander cutoff and a marshy area close to the East Kolkata Wetlands, a Ramsar site (Chakrabarti, 1991, 1995). Even in neighboring Bangladesh, prolific development of aquaculture may be observed along the same latitude with the Indian side of Sandeshkhali—Hingalganj block with large aquaculture farms. The location and proliferation of aquaculture at the margin of Dampier Hodges line or Kakdwip-Bashirhat-Dhaka lineament (Chakrabarti, 1991) (which is spatially the northern limit of saline tide ingress) indicate that geomorphic control plays a decisive role rather than the effect of salinity behind the expansion of aquaculture in the SBR.

Fishery resources play a pivotal role in the economy of Sundarbans. Due to the favorable environment in terms of suitable biophysical conditions, Sundarbans act as the nursing ground for various commercial aquatic species (Dutta et al., 2017). Brackish water species are cultured in the swampy coastal areas by developing the artificial enclosure, locally named as 'Bheri' (Chand et al., 2012). The current study indicates that more than 70% of the total aquaculture area in Sundarbans is distributed in the 6 blocks that belong to the North 24 Parganas district. This expansion of aquaculture in this district started after

a severe flood that took place in the year 1967 during which the river banks of the Kulti river got affected and farmlands became inundated (Naskar & Guha Bakshi, 1987). Later, the Irrigation Department established a ring dyke in a distant location landward from the river. As a result, many low-lying agricultural lands left in between the dyke and the bank became unsuitable for agriculture. The poor landowners were exclusively dependent upon these lands, and to maintain livelihood, they started allowing the ingression of the brackish water for the rearing of seeds of different fishes and river shrimps. Later with increasing population and non-availability of agricultural land, this practice became very popular as it was proved to be profitable, often more than agriculture (Naskar & Guha Bakshi, 1987). This brings out the explanation for our second observation that why the aquaculture area has grown significantly over the last two decades at the expense of agriculture.

Expansion of aquaculture in tidally affected Sundarbans delta and conversion of different land use classes to aquaculture especially from the agriculture was also been reported by several other researchers (Chopra et al., 2009; DasGupta & Shaw, 2014; Johnson et al., 2016; Sánchez-Triana et al., 2018; DasGupta et al., 2019). However, the present study has significantly differed by indices-based extraction of aquaculture area that could provide a more accurate estimation. Moreover, this study has provided a recent estimation of the change in aquaculture area at the block level and established the effect of cyclone Aila behind the aquaculture growth. Apart from the decreasing agricultural productivity, several other socio-economic aspects resulted from this expansion. There is around a 1.6% increase in the population of Sundarbans every year. Moreover, the fewer livelihood opportunity due to natural and geographical hindrances led to a consistent flow of out-migration in search of livelihood opportunities (Chopra et al., 2009; DasGupta & Shaw, 2014; DasGupta et al., 2019). Despite having several investments and development programs by the Government, the people have to struggle with poverty and isolation due to the passive approach of the local government for socio-economic development (DasGupta et al., 2019). This desperation of people might have led to the expansion of aquaculture despite having many legislative inhibitions by the government. In addition, market demand, particularly after the globalization in the 1980s, contributed further to the growth of brackishwater aquaculture in Sundarbans to meet the demand of domestic as well as international market (Sánchez-Triana et al., 2018). This recent expansion of aquaculture and changing livelihood pattern from traditional agriculture to aquaculture can be attributed to the comparative economic profit of aquaculture in comparison to the traditional agriculture and fishing activities (Dubey et al., 2017; Sarkhel, 2015). The transformation of the mangrove forest to aquaculture, in violation of the Coastal Zone Management Regulations in India, is the result of the illegal encroachment of the people to get easy access to the required water for aquaculture farm from river or creek. In addition to this, the perception of the common people to consider mangrove forests to have an insignificant monetary return in comparison with aquaculture is another reason for the transformation in this fragile ecosystem (Chopra et al., 2009).

Climatic extremes like Cyclone Aila of 2009 and associated surge inundation are observed to play an important role in the huge expansion of aquaculture area in Sundarbans in the last decade. Out of the 19 blocks of Sundarbans, 13 blocks viz. Haroa, Minakhan, Sandeshkhali-I, Sandeshkhali-II, Hasnabad, Hingalganj, Basanti, Gosaba, Kultali, Patharpratima, Kakdwip, Namkhana, and Sagar were severely affected by the cyclone. The cyclone and over 2-m surge of saline water inundated agricultural land closer to creeks contaminated freshwater ponds with salt water (Ali et al., 2018). As a result, farmlands became unproductive for years due to a rise in soil salinity and ponds became unsuitable for culturing freshwater fishes (DasGupta & Shaw, 2014; Johnson et al., 2016;

Sánchez-Triana et al., 2018). This could be one of the major reasons for the transformation of different land use classes to aquaculture especially the agricultural lands and water bodies closer to the creeks in the administrative blocks affected by the storm surge. The blocks of Sundarbans that were severely affected demonstrated a higher percentage of land transformation to aquaculture during the post-Aila period. Embankment breaching and saline water inundation in the agricultural lands resulted in the damage of the standing crops and ceased the possibilities of agricultural activities for a coming couple of years due to an immediate increase in soil salinity (Sphere India report, 2009). As a consequence, the conversion of agricultural land to brackishwater aquaculture was considered an alternate livelihood opportunity for some people.

The overall culture practices involved in the brackish water aquaculture inflict different environmental impacts viz. degradation of the mangrove habitat, pollution of the coastal waters, salinization of the soil and water, depletion of the wild stock of the shrimps, and depletion of other wild varieties due to the destruction which occurs concomitantly during seed collection (Chopra et al., 2009). Among all these impacts, the most serious threat is the destruction of mangroves. It is also true that the mangrove ecosystem in Sundarbans itself is the reason for this expanding shrimp culture as mangroves act as the nursery for the shrimp seeds and various other aquatic biodiversities. Apart from that, mangroves also act as the coastal bio-shields where aquaculture farms are also protected. So, it can be well understood that the farmers have to suffer a lot if the continuous deforestation of mangroves continues. Aquaculture at the expense of agriculture and mangrove forest in coastal areas poses a serious challenge to SDG 14 and 15, which needs to be addressed in separate research.

5 Conclusion

Present investigation with advanced application of geo-informatics has indicated the direction of the changing trend of aquaculture in Indian Sundarbans. Among the nine different land use classes, agricultural lands have undergone the maximum transformation. However, a large area of the fallow land, mudflat, and mangrove forest have also been transformed which is a serious environmental challenge to the policymakers towards sustainability of the aquaculture in this fragile ecosystem of Sundarbans. However, the introduction of some governance policies regarding land conversion to aquaculture, strict implementation of the existing policies regarding mangrove forest protection, and establishment of state-of-the-art hatcheries to stop the collection of post-larvae from the wild can help toward achieving sustainability in the Sundarbans.

Author contributions All the authors contributed significantly during the present work. Material preparation, data collection and analysis were performed by Sandip Giri, Sourav Samanta, Partho Protim Mondal, Oindrila Basu and Samiran Khorat. The first draft was written by Sandip Giri and Abhra Chanda. Sugata Hazra critically reviewed the results and discussion before finalization of the manuscript. All the authors read and approved the final manuscript.

Data availability Source of the satellite data used in this study has been properly cited in the manuscript, and field data were collected by the authors.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical statement We the authors declare that we have stringently followed all the rules and all the accepted principles of ethical and professional conduct. While carrying out the present research, no animals were harmed or used as subjects of experiment. There was no involvement of human beings in this research and hence there is no question of sharing any private or personal information without informing the persons concerned. We also declare that all the authors have strictly complied with the authorship principles furnished by the journal.

Informed consent All the authors have provided consent to communicate the manuscript to 'Environment, Development and Sustainability,' and the institutions of the respective author have no objection in this regard.

References

Abraham, T. J., Sasmal, D., Dash, G., Nagesh, T. S., Das, S. K., Mukhopadhayay, S. K., & Ganguly, S. (2013). Epizootology and pathology of bacterial infections in cultured shrimp Penaeus monodon Fabricius 1798 in West Bengal India. *Indian J Fish, 60*(2), 167–171.

Aguilar-Manjarrez, J., & Ross, L. G. (1995). Geographical information system (GIS) environmental models for aquaculture development in Sinaloa State Mexico. *Aquaculture International, 3*(2), 103–115. https://doi.org/10.1007/BF00117877

Ali, M. I., Imran, A., Syed, I. M., Islam, M. J., & Mallik, M. A. K. (2018). A comparative study of storm surge phenomenon associated with the tropical cyclone Aila over the Bay Of Bengal using NWP models. *Journal of Engineering, 9*(2), 33–40.

Annual Report of Marine Product Export Development Authority. (2009–10). Ministry of Commerce & Industry, Government of India.

Arnold, W. S., White, M. W., Norris, H. A., & Berrigan, M. E. (2000). Hard clam (*Mercenaria* spp.) aquaculture in Florida, USA: Geographic information system applications to lease site selection. *Aquacultural Engineering, 23*(1–3), 203–231.

Chakrabarti, P. (1991). Morphostratigraphy of coastal quaternaries of West Bengal and Subarnarekha delta Orissa. *Indian Journal of Earth Sciences, 18*(3–4), 219–225.

Chakrabarti, P. (1995). Evolutionary history of the coastal quaternaries of the Bengal plain, India. *Proceedings, Indian National Science Academy, 61A*(5), 343–354.

Chand, B. K., Trivedi, R. K., Dubey, S. K., & Beg, M. M. (2012). *Aquaculture in changing climate of Sundarbans: Survey report on climate change vulnerabilities, aquaculture practices & coping measures in Sagar and Basanti blocks of Indian Sundarbans* (p. 198). West Bengal University of Animal & Fishery Sciences.

Chander, G., Markham, B. L., & Barsi, J. A. (2007). Revised Landsat-5 thematic mapper radiometric calibration. *IEEE Geoscience and Remote Sensing Letters, 4*(3), 490–494. https://doi.org/10.1109/LGRS.2007.898285

Chavez, P. S. (1996). Image-based atmospheric corrections-revisited and improved. *Photogrammetric Engineering and Remote Sensing, 62*(9), 1025–1035.

Chopra, K., Kapuria, P., & Kumar, P. (2009). Biodiversity land use change and human well being: A study of aquaculture in the Indian Sundarbans. OUP Catalogue.

CRZ Notification Amendment. (1998). S.O. 334 (E) dated 20th April 1998, Ministry of Environment & Forests. Government of India.

DasGupta, R., & Shaw, R. (2014). Role of NGOs and CBOs in a decentralized mangrove management regime and its implications in building coastal resilience in India. In R. Shaw & T. Izumi (Eds.), *Civil society organization and disaster risk reduction.* Springer.

DasGupta, R., Hashimoto, S., Okuro, T., & Basu, M. (2019). Scenario-based land change modelling in the Indian Sundarban delta: An exploratory analysis of plausible alternative regional futures. *Sustainability Science, 14*(1), 221–240. https://doi.org/10.1007/s11625-018-0642-6

Dubey, S. K., Trivedi, R. K., Chand, B. K., Mandal, B., & Rout, S. K. (2017). Farmers' perceptions of climate change, impacts on freshwater aquaculture and adaptation strategies in climatic change hotspots:

A case of the Indian Sundarban delta. *Environmental Development, 21*, 38–51. https://doi.org/10.1016/j.envdev.2016.12.002

Duggin, M. J., & Robinove, C. J. (1990). Assumptions implicit in remote sensing data acquisition and analysis. *Remote Sensing, 11*(10), 1669–1694. https://doi.org/10.1080/01431169008955124

Dutta, S., Chakraborty, K., & Hazra, S. (2017). Ecosystem structure and trophic dynamics of an exploited ecosystem of Bay of Bengal, Sundarban Estuary India. *Fisheries Science, 83*(2), 145–159.

Eastman, J. R. (2006). *IDRISI Andes tutorial*. Clark University, Worcester, MA.

FAO. (2014). The State of World Fisheries and Aquaculture. Opportunities and Challenges. Food & Agriculture Organization of the United Nations (FAO), Rome.

Feyisa, G. L., Meilby, H., Fensholt, R., & Proud, S. R. (2014). Automated water extraction index: A new technique for surface water mapping using Landsat imagery. *Remote Sensing of Environment*, *140*, 23–35.

Ghoshal, T. K., De, D., Biswas, G., Kumar, P., & Vijayan, K. K. (2019). Brackishwater aquaculture: opportunities and challenges for meeting livelihood demand in Indian sundarbans. The Sundarbans: A disaster-prone eco-region, Springer.

Gupta, M. C. (1995). Brackish water aquaculture site selection using techniques of geographical information system (GIS). Space Application Centre, ISRO.

Hamad, R., Balzter, H., & Kolo, K. (2018). Predicting land use/land cover changes using a CA-Markov model under two different scenarios. *Sustainability, 10*(10), 3421.

Handbook of Fisheries and Aquaculture. (2013). Indian Council of Agricultural Research (ICAR), India. Handbook of Fisheries and Aquaculture. (2013).

Handbook of Fisheries Statistics. (2015–16). Department of Fisheries, Government of West Bengal, India.

Hazra, S., Mukhopadhyay, A., Mukherjee, S., Akhand, A., Chanda, A., Mitra, D., & Ghosh, T. (2016). Disappearance of the New Moore Island from the Southernmost Coastal Fringe of the Sundarban delta-a case study. *Journal of the Indian Society of Remote Sensing, 44*(3), 479–484. https://doi.org/10.1007/s12524-015-0524-7

Hazra, S., Samanta, K., Mukhopadhyay, A., & Akhand, A. (2010). Temporal Change Detection (2001–2009) Study of Sundarbans. Unpublished report. WWF-India http://glovis.usgs.gov. Surfed on 4th April, 2020.

Hazra, S., Ghosh, T., DasGupta, R., & Sen, G. (2002). Sea level and associated changes in the Sundarbans. *Science and Culture, 68*(9-12), 309–321.

Jayanthi, M. (2011). Monitoring brackishwater aquaculture development using multi-spectral satellite data and GIS-a case study near Pichavaram mangroves south-east coast of India. *Indian Journal of Fisheries, 58*(1), 85–90.

Johnson, F. A., Hutton, C. W., Hornby, D., Lázár, A. N., & Mukhopadhyay, A. (2016). Is shrimp farming a successful adaptation to salinity intrusion? A geospatial associative analysis of poverty in the populous Ganges–Brahmaputra–Meghna Delta of Bangladesh. *Sustainability Science, 11*(3), 423–439. https://doi.org/10.1007/s11625-016-0356-6

Kapetsky, J. M., Hill, J. M., & Worthy, L. D. (1988). A geographical information system for catfish farming development. *Aquaculture, 68*(4), 311–320. https://doi.org/10.1016/0044-8486(88)90245-1

Karthik, M., Suri, J., Saharan, N., & Biradar, R. S. (2005). Brackish water aquaculture site selection in Palghar Taluk, Thane district of Maharashtra, India, using the techniques of remote sensing and geographical information system. *Aquacultural Engineering, 32*(2), 285–302. https://doi.org/10.1016/j.aquaeng.2004.05.009

Kumar, S., Radhakrishnan, N., & Mathew, S. (2014). Land use change modelling using a Markov model and remote sensing. *Geomatics, Natural Hazards and Risk, 5*(2), 145–156. https://doi.org/10.1080/19475705.2013.795502

Longdill, P. C., Healy, T. R., & Black, K. P. (2008). An integrated GIS approach for sustainable aquaculture management area site selection. *Ocean & Coastal Management, 51*(8–9), 612–624. https://doi.org/10.1016/j.ocecoaman.2008.06.010

Mandal, B., & Dubey, S. K. (2015). Present status and prospects of black tiger shrim p farming: A case study in maritime state of West Bengal, India. Perspectives in Animal Ecology and Reproduction. Daya Publishing House

McFeeters, S. K. (1996). The use of the Normalized Difference Water Index (NDWI) in the delineation of open water features. *International journal of remote sensing, 17*(7), 1425–1432.

McLeod, I., Pantus, F., & Preston, N. (2002). The use of a geographical information system for land-based aquaculture planning. *Aquaculture Research, 33*(4), 241–250. https://doi.org/10.1046/j.1355-557x.2001.00667.x

Megahed, Y., Cabral, P., Silva, J., & Caetano, M. (2015). Land cover mapping analysis and urban growth modelling using remote sensing techniques in greater Cairo region—Egypt. *ISPRS International Journal of Geo-Information, 4*(3), 1750–1769.

Mishra, S. (2010). Abar Kharar Kabale Paschim Banga. *Saar Samachar, 48*(3), 11–30.

Mitra, A., Gangopadhyay, A., Dube, A., Schmidt, A. C., & Banerjee, K. (2009). Observed changes in water mass properties in the Indian Sundarbans (Northwestern Bay of Bengal) during 1980–2007. *Current Science, 97*(10), 1445–1452.

Nandy, S., & Kushwaha, S. P. S. (2011). Study on the utility of IRS 1D LISS-III data and the classification techniques for mapping of Sunderban mangroves. *Journal of Coastal Conservation, 15*(1), 123–137. https://doi.org/10.1007/s11852-010-0126-z

Naskar, K., & Guha Bakshi, D.N. (1987). Mangrove swamps of the Sundarbans. Naya Prokash.

Nouri, J., Gharagozlou, A., Arjmandi, R., Faryadi, S., & Adl, M. (2014). Predicting urban land use changes using a CA–Markov model. *Arabian Journal for Science and Engineering, 39*(7), 5565–5573. https://doi.org/10.1007/s13369-014-1119-2

Panigrahi, A., Sundaray, J. K., Ghoshal, T. K., De, D., & Ravichandran, P. (2009). Bio-Secure Zero water exchange system technology of shrimp farming for better monitoring of coastal ecosystem. *Journal of Indian Society of Coastal Agricultural Research*, *27*, 50–53.

Pethick, J., & Orford, J. D. (2013). Rapid rise in effective sea-level in southwest Bangladesh: Its causes and contemporary rates. *Global and Planetary Change, 111*, 237–245. https://doi.org/10.1016/j.gloplacha.2013.09.019

Ramesh, R., & Rajkumar, R. (1996). Coastal aquaculture site selection and planning in Tamil Nadu using remote sensing and GIS. *Asian-Pacific Remote Sensing and GIS Journal, 9*(1), 39–49.

Regmi, R., Saha, S., & Balla, M. (2014). Geospatial analysis of land use land cover change predictive modeling at Phewa Lake Watershed of Nepal. *International Journal of Current Engineering and Technology, 4*, 2617–2627.

Rokni, K., Ahmad, A., Selamat, A., & Hazini, S. (2014). Water feature extraction and change detection using multitemporal Landsat imagery. *Remote Sensing, 6*(5), 4173–4189.

Rowe, D. K., Shankar, U., James, M., & Waugh, B. (2002). Use of GIS to predict effects of water level on the spawning area for smelt, Retropinna retropinna, in lake Taupo New Zealand. *Fisheries Management and Ecology, 9*(4), 205–216. https://doi.org/10.1046/j.1365-2400.2002.00298.x

Salam, M. A., Ross, L. G., & Beveridge, C. M. (2003). A comparison of development opportunities for crab and shrimp aquaculture in southwestern Bangladesh, using GIS modelling. *Aquaculture, 220*(1–4), 477–494. https://doi.org/10.1016/S0044-8486(02)00619-1

Samanta, K., & Hazra, S. (2012). Landuse/landcover change study of Jharkhali Island Sundarbans, West Bengal using remote sensing and GIS. *International Journal of Geomatics and Geosciences, 3*(2), 299–306.

Sánchez-Triana, E., Ortolano, L., & Paul, T. (2018). Managing water-related risks in the West Bengal Sundarbans: Policy alternatives and institutions. *International Journal of Water Resources Development, 34*(1), 78–96. https://doi.org/10.1080/07900627.2016.1202099

Sang, L., Zhang, C., Yang, J., Zhu, D., & Yun, W. (2011). Simulation of land use spatial pattern of towns and villages based on CA–Markov model. *Mathematical and Computer Modelling, 54*(3–4), 938–943. https://doi.org/10.1016/j.mcm.2010.11.019

Sarkar, S. K., & Bhattacharya, A. K. (2003). Conservation of biodiversity of the coastal resources of Sundarbans, Northeast India: An integrated approach through environmental education. *Marine Pollution Bulletin, 47*(1–6), 260–264. https://doi.org/10.1016/S0025-326X(02)00475-7

Sarkhel, P. (2015). Flood risk, land use and private participation in embankment maintenance in Indian Sundarbans. *Ecological Economics, 118*, 272–284. https://doi.org/10.1016/j.ecolecon.2015.08.003

Shen, L., & Li, C. (2010). Water body extraction from Landsat ETM+ imagery using adaboost algorithm. In 18th International Conference on Geoinformatics, IEEE, pp 1–4.

Sobrino, J. A., Jiménez-Muñoz, J. C., & Paolini, L. (2004). Land surface temperature retrieval from LANDSAT TM 5. *Remote Sensing of Environment, 90*(4), 434–440. https://doi.org/10.1016/j.rse.2004.02.003

Song, C., Woodcock, C. E., Seto, K. C., Lenney, M. P., & Macomber, S. A. (2001). Classification and change detection using Landsat TM data: When and how to correct atmospheric effects? *Remote Sensing of Environment, 75*(2), 230–244. https://doi.org/10.1016/S0034-4257(00)00169-3

Sphere India Report. (2009). Interagency multisectoral assessment report, Cyclone Aila – 2009.

Sun, F., Sun, W., Chen, J., & Gong, P. (2012). Comparison and improvement of methods for identifying waterbodies in remotely sensed imagery. *International Journal of Remote Sensing, 33*(21), 6854–6875. https://doi.org/10.1080/01431161.2012.692829

Weng, Q. (2002). Land use change analysis in the Zhujiang Delta of China using satellite remote sensing, GIS and stochastic modelling. *Journal of Environmental Management, 64*(3), 273–284. https://doi.org/10.1006/jema.2001.0509

Xu, H. (2006). Modification of normalised difference water index (NDWI) to enhance open water features in remotely sensed imagery. *International journal of remote sensing*, *27*(14), 3025–3033.