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Mapping coastal lagoon characteristics for the aquaculture suitability using multi-criteria decision support (MCDS) spatial analysis: A case study from south-east coast of India

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A large extent of brackishwater resources is yet to be used for aquaculture as the present development stands at only 13% in India. But, growing environmental concerns and crop failures have made site selection a mandatory requirement for cage aquaculture. The case study carried out at Muttukadu Lagoon, India, has used 13 factors to assess cage site suitability, including physical characteristics and environmental conditions. Spatial analysis has integrated the most influencing variables such as depth, turbidity, salinity, temperature, dissolved oxygen, pH, and total ammonia nitrogen using suitability scores and its comparative rank. pH, salinity, temperature, and TAN were in the acceptable range throughout the year. Concerning depth, turbidity, and dissolved oxygen, 12–52%, 30–91%, and 84–91% of the lagoon were found to be suitable at different seasons. Overall, 11% of the lagoon region was found to be fit for cage aquaculture. Water depth was the major limiting factor in cage site selection. From the study, crucial management measures are outlined for successful fish culture and maintain the lagoon's health. This study will serve as a model to make use of the brackish-water regions to support the coastal population's livelihoods.

Keywords. Cage aquaculture; site suitability; coastal lagoon; Geographical Information System (GIS); multi-criteria evaluation; water quality.

1. Introduction

Population growth and fish consumption rates are expected to rise in the future, which force us to look into alternate resources to increase fish production. Coastal land scarcity and growing population make land a major limiting factor for developmental activities. Globally, cage aquaculture in waterbodies such as sea and lakes has contributed to fish production. The zero-footprint brackishwater conditions in the estuaries/lagoons can be used for enhancing aquaculture production. By identifying suitable brackishwater resources and specific locations, there is a great possibility to make cage aquaculture a practice to support the livelihood of coastal populations in developing

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nations. Contamination of water bodies and fish mortality have been reported when scientific methods were not adopted in selecting aquaculture sites (Cao *et al.* 2007). Hence, it becomes imperative to choose appropriate sites before installing cages to reduce the user's conflicts and preserve environmental quality.

The proper site identification is a prerequisite in cage aquaculture as it can considerably indicate the characteristics of the sites and prevents production failures and negative environmental impacts. The fish species requirements, environmental conditions, and other uses of sites are essential to support the stakeholders in planning successful and sustainable cage culture. Also, coastal stakeholders need techniques to assess the threats that aquaculture creates to devise processes that protect the coastal ecosystems (Price *et al.* 2015). The proper site selection and feed management have reduced the adverse impacts in cage aquaculture production (Grøttum and Beveridge 2007). Though marine cage culture is practiced to a considerable extent, brackishwater is not fully used for fish production in cages.

Researchers have used Geographic Information System (GIS) techniques and identified the sites to install cages for marine cages by combining environmental and infrastructure criteria (Pérez *et al.* 2005; Micael *et al.* 2015). But, siting criteria for cages in brackishwater will vary from marine sites due to the shallow water depths, the influence of bar mouth on water quality, the occurrence of algal blooms that kills fishes. Though vast brackishwater resources are unused, placing cages in suitable sites after considering water depth and environmental conditions are necessary for success.

India is bestowed with an 8118 km coastal line, 3.9 million ha of estuaries, and 3.5 million ha of brackishwater areas, which support a vast range of coastal habitats (De-Roy and Thadani 1992). Though brackishwater aquaculture development in the country has used the coastal land areas adjacent to the creeks, its use was less. The present-day brackishwater aquaculture in India is synonymous with shrimp aquaculture, dominated by the Pacific white shrimp, Penaeus vannamei, an export-driven market. The area under aquaculture was 152,595 ha (13%), out of 1.2 million ha of brackishwater in the country (MPEDA 2020). The environmental issues raised over the unregulated growth in the past have made the shrimp aquaculture in regulated and licensing mode through the Coastal Aquaculture Authority Act, 2005 (CAA 2014). The high input cost involved in the shrimp culture and the losses that occurred due to disease outbreaks are prohibitive for the resource-poor coastal population to get into aquaculture.

Besides increasing fish production, cage aquaculture in lagoons and estuaries can serve to support the livelihood of coastal communities, particularly to local fishermen. The factors affecting fish growth include the industrial discharge in the surroundings, the supportive activities of water bodies, the year-round environmental conditions in water bodies, fish seed availability, and sand bar mouth closure. We have seen high turbidity problems, eutrophication in the water bodies due to river mouth closure, and early harvest in cage aquaculture sites due to lack of preplanning and site selection. The lessons learned in the past can be used to make a framework for mapping lagoon characteristics to identify the locations for cage aquaculture through spatial analysis. The riverine and estuarine systems in India have varying environmental conditions and reduced water depth due to sedimentation, which demands an exclusive model for siting cage aquaculture compared to other countries. Hence, this case study was aimed to identify the suitable sites for cage aquaculture in brackishwater lagoon by identifying and integrating influential physical and environmental factors using spatial analysis.

2. Materials and methods

2.1 *Study area*

The Muttukadu Lagoon is close to Chennai city by about 35 km, located in the Chengalpattu district of Tamil Nadu, India's southeast coast. The Muttukadu Lagoon spreads around 15 km in the north–south direction, and its width ranges from 800 to 1050 m and opens into the Bay of Bengal with a width varying from a few to 330 m (Srinivasan and Natesan 2013). A lagoon is a shallow water body, with depth varying from 1 to 3 m (Prasath *et al.* 2014). The elevation of Muttukadu Lagoon region is 19 m above mean sea level. The nautical tourism activities are performed in a portion of Muttukadu Lagoon by Tamil Nadu Tourism Development Corporation. Small scale fishing is being carried out by the fishermen living in nearby villages. The lagoon gets connected to the Bay of Bengal during the north-east monsoon season between October and December, whereas the sand bar divides the lagoon from the sea during the rest of the period. The Buckingham Canal, which runs from the Kakinada, east Godavari District of Andhra Pradesh to Villupuram District of Tamil Nadu, carries fresh water and drains into the Bay of Bengal at Muttukadu. As per India Meteorological Department data, Chennai and its surroundings receive an annual rainfall of 1400 mm. The largest flood in Chennai has occurred in December 2015, which displaced around 1.8 million people. The Muttukadu Bar mouth closure due to siltation was cited as one reason for the Chennai flood. The lagoon is ecologically important as it attracts a variety of migratory birds between November and February.

2.2 *Landuse in and around Muttukadu Lagoon*

Landuse in the surroundings of the water bodies to be selected for cage aquaculture is very important to know the presence of industrial development and effluent discharges, the safety of the sites, and the social issues, if any. Landsat-8, 2017 data having path 142, Row 51 was used to map the landuse. After preprocessing and subsetting, the image was projected to the Universal Transverse Mercator Zone 44N, then classified using supervised classification followed by an on-screen correction. Then, different land classes in the study area were delineated using Arc GIS 10.6. Lagoon, plantation, sea, sand, bare lands, buildings, and aquaculture were mapped using object-based interpretation keys (Lillesand and Kiefer 2000). Ground truth verification using Juno 3B Global Navigation Satellite System (GNSS) was performed to evaluate the accuracy of the land use classification. The methodology flow chart is given in figure 1.

2.3 *Evaluation of critical site selection criteria*

Site selection decides the success and also the sustainability of aquaculture. The factors that influence the site selection for successful cage aquaculture at Muttukadu Lagoon have been identified and scored by scientists from fisheries, engineering, and environmental science. It is not possible to change the water quality characteristics in the lagoon; hence planning must be done to select the suitable sites of acceptable criteria for cage aquaculture (Rao *et al.* 2013). While planning, regulatory, physical, environmental, and logistic factors have to be considered prior to the installation of cages. The Muttukadu Lagoon is not prohibited for aquaculture operations by any regulatory authorities. The lagoon is located within 1-km distance to a state highway, shrimp and finfish hatcheries, and 10 km from the market; hence fulfills all logistical requirements. The water depth and turbidity were identified as important physical characteristics in selection. As cage culture requires suitable water quality for fishes, the physicochemical parameters were assessed throughout the year. The water quality parameters, namely pH, salinity, temperature, dissolved oxygen (DO), total ammonia nitrogen (TAN), turbidity, carbonate, bicarbonate, calcium, magnesium, total alkalinity, total hardness, and water depth, were selected for the assessment. The geographic coordinates of sampling points were measured using Juno 3B Global Navigation Satellite System (GNSS) for spatial interpolation of characteristics. The water samples were collected at a monthly interval from eight sampling points, whereas water depth was measured at 47 points, covering the entire lagoon.

2.4 *Measurement of lagoon water quality characteristics*

Among the water quality parameters, pH, salinity, temperature, and DO were assessed using a multi-water quality meter (Aquaread AP2000D). Turbidity was measured by the Nephelometric method using turbidity meter-Model-ELICO CL52D. TAN, carbonate, bicarbonate, calcium, magnesium, total alkalinity, and total hardness were measured using standard methods adopted by the American Public Health Association (APHA 2005). The water depth was measured using a rope.

2.5 *GIS analysis and verification*

After considering the spatiotemporal variability of water quality parameters, pH, salinity, DO, temperature, TAN, turbidity, and water depth were considered as the most critical factors due to their temporal and spatial variation in the lagoon, hence selected for mapping and spatial analysis. The spatial interpolation of seasonal water characteristics was carried out using Inverse Distance Weighted (IDW) interpolation method. The pairwise comparison matrix was used to assign the weights based on the expert's opinion (Eastman

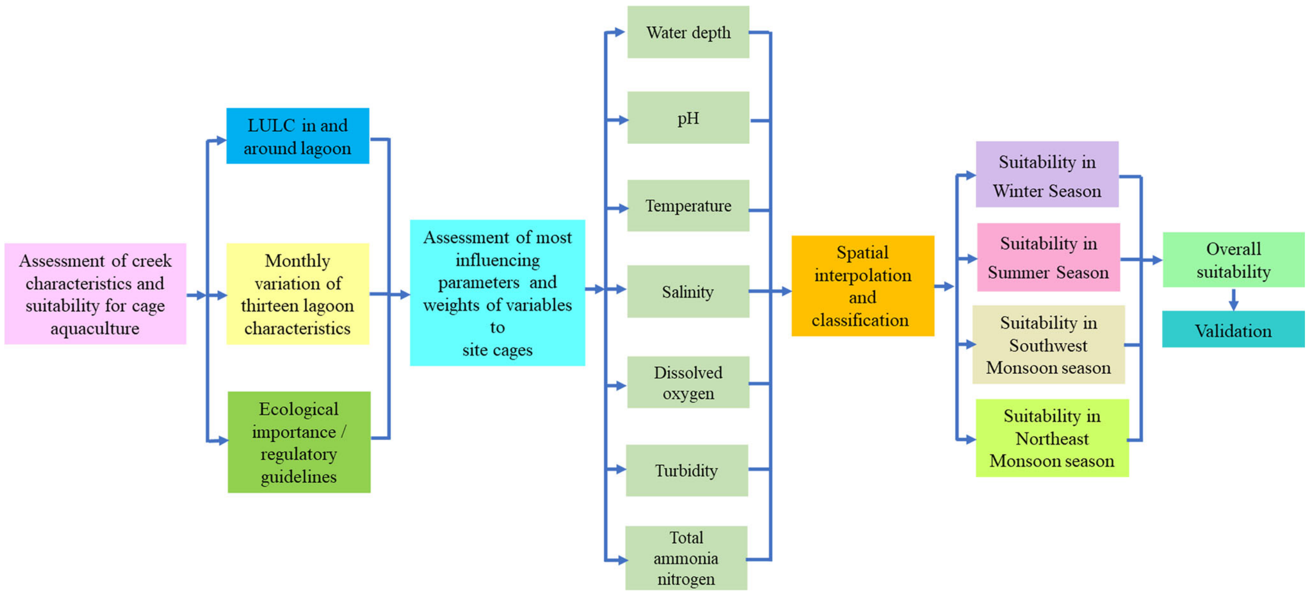

Figure 1. Methodology flow chart for cage aquaculture site selection in brackishwater lagoon.

et al. 1999). The weight of the criteria, consistency index, and ratio were derived based on the relative importance by the standard method described by Saaty (2008). The weighted sum spatial analysis was used to integrate all six variables for four seasons. The raster cell values of each criterion were multiplied by the respective weights and combined to produce an output map. The common suitable regions in all seasons were selected, and then the identified sites were field verified in the lagoon.

3. Results

3.1 *Resource use in and around the lagoon*

LLandsat-8 Operational Land Imager sensor level-one terrain corrected image from the US Geological Survey (http://earthexplorer.usgs.gov) was used to map the land use in and around the surroundings of the Muttukadu Lagoon (figure 2a). The classified land use categories were verified in the field and found to be perfectly matching with 99.9% accuracy. The landuse/land cover in the study area (figure 2b) had buildings (24 ha), bare lands (66 ha), sand (7 ha), lagoon (60 ha), and plantation (22 ha). There were no industries located in close proximity to the lagoon, and so fish culture in the lagoon may not be threatened due to any industrial effluent discharges.

3.2 *Assessment and mapping of water quality characteristics*

The mean values of monthly assessment of water characteristics of the lagoon are indicated in figure 3. The water pH, temperature, salinity in the lagoon ranged from 7.78 to 8.63, 25.87 to 33.08°C, 8.33 to 32.17‰, respectively, within the optimum range for fish culture. The spatially interpolated maps of pH, salinity, and temperature are given in figures 4 through 6. The mean DO values measured at the monthly intervals were between 5.63 and 8.65 mg/l and above the minimum requirement of 5 mg/l. Though mean values were in the acceptable range (3.4–12.4 mg/l), few pockets of the lagoon had below minimum desired DO levels (figure 7). The mean values of TAN ranged from 0.02 to 0.90 ppm, whereas the actual range was from 0 to 1.5 ppm (figure 8). The mean turbidity varied from 10.63 to 31.57 NTU, whereas the range was between 8 and 51 NTU (figure 9). The depth of the water in the lagoon has ranged from 0.2 to 3.6 m, which was the major restrictive class in site selection. The minimum water depth was measured during the summer season (figure 10).

Among the other variables evaluated, total hardness indicates the concentrations of calcium and magnesium, whereas total alkalinity indicates the carbonates and bicarbonates predominantly. The mean values of calcium, magnesium, and total hardness ranged from 200 to 313, 640 to 1032, and 3130 to 5300 ppm as $CaCO_3$, respectively. Also, the

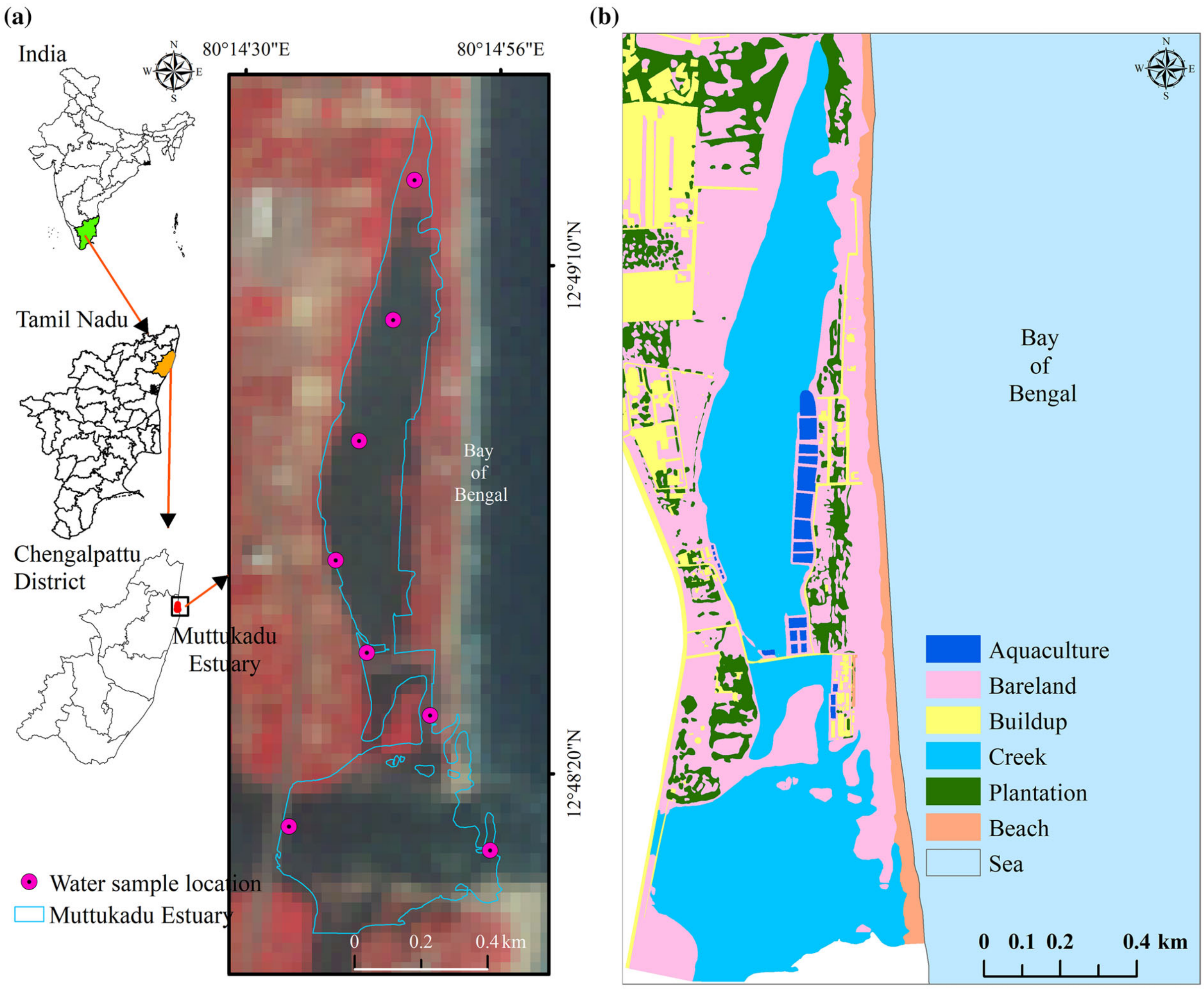

Figure 2. (**a**) Location and satellite view of the study area. (**b**) Land use land cover in and around the lagoon.

values of carbonates, bicarbonates, and total alkalinity ranged from 5.72 to 40.92, 121 to 206, and 132 to 199 ppm as $CaCO_3$, respectively. The acceptable range of total hardness and total alkalinity was 1000–6000 and 50–400 ppm, respectively (Wurts and Durborow 1992).

3.3 *Site suitability investigation*

The pairwise matrix (table 1) indicates the level of influence and its relative importance of the factors in selecting sites for cages. The spatially interpolated and classified maps of pH, salinity, temperature, DO, total ammonia nitrogen, depth, and turbidity were integrated using the weights. The water depth area below 1.5 m during the lowest low tide was eliminated as the regions unsuitable for cage aquaculture. The matrix indicated that the most influencing factor was depth (33%) followed by turbidity (25%), temperature (14%), salinity (8%), pH (8%), DO (8%), and total ammonia nitrogen (4%).

The classified pH (figure 4), salinity (figure 5), and temperature (figure 6) indicated that the total lagoon had a suitable range of these factors in all four seasons. The lagoon area of 11.12 and 3.58 ha had low DO of <5 mg/l during June–September and October–December, respectively (figure 7). TAN has ranged between 0.02 and 1.5 ppm all year round in the lagoon (figure 8), which was within the acceptable range of less than two ppm (table 2). The turbidity values have ranged from 11 to 51 NTU, but the higher values (above 40 NTU) were observed during summer and northeast monsoon season. The acceptable turbidity (10–40 NTU) was observed in 18.04, 54.4, 59.9, and 49.6 ha (figure 9) in winter, summer, southwest monsoon, and northeast monsoon seasons, respectively. The depth of the lagoon (figure 10) indicated that only 24.74, 7.21, 27.59, and 31.09 ha during winter,

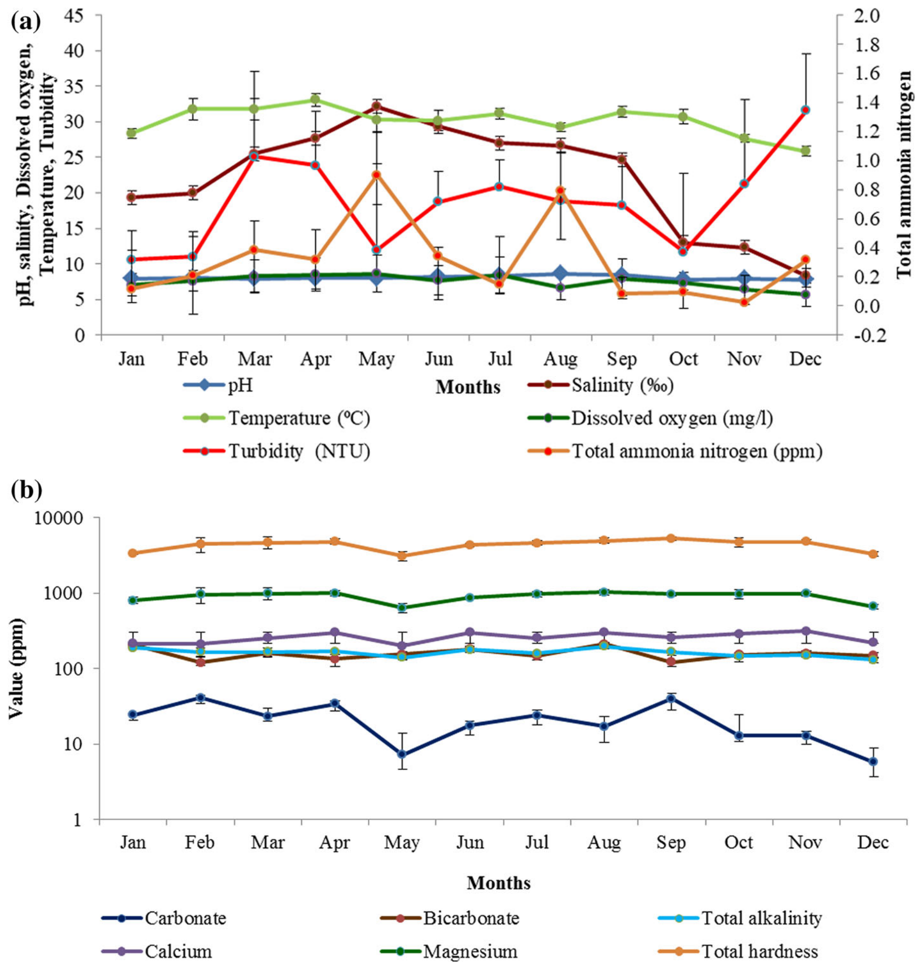

Figure 3. (**a**, **b**) Monthly variations of water characteristics in Muttukadu Lagoon.

summer, southwest monsoon season, and northeast monsoon season was found to be suitable to install the cages. The overall suitability assessment found that 6.65 ha of the lagoon (figure 11), representing 11% of the total area, was suitable for cage culture.

4. Discussion

We have mapped the land use in and around the lagoon and found that there were no conflicting or industrial activities in the surroundings. The suitability of the lagoon in terms of water quality parameters and physical characteristics was assessed at a monthly interval throughout the year. Unlike controlled shrimp farms, it is impossible to change the water characteristics in the cage culture regions of the lagoon. A prior site assessment is mandatory to make sure that the physical and chemical properties of the lagoon will satisfy the requirements of the cage aquaculture. Pollution of different categories is accountable for the high fish mortality in many cage culture projects (Beveridge 2004).

Among the variables, pH, salinity, temperature, TAN, DO, depth, and turbidity were identified as the most critical factors in site selection. Though alkalinity and hardness are both important components of water quality, fish grow well over a wide range of alkalinities and hardness (Saraswathy *et al.* 2015). Of the selected influencing variables, pH, salinity, temperature, and TAN were in the optimum range in all four seasons. The brackishwater pH is mostly in the optimum range, not causing a direct risk to fishes. But the range will vary when changes occur in the quantities of freshwater and seawater (Boyd and Tucker 1998). The average seawater pH is considered to be 8.1; but gradually reducing due to the rise in atmospheric carbon dioxide concentration, causing a higher level of dissolved carbon dioxide in the sea (Boyd 2020). The water pH determines the ammonia toxicity to fishes (Portz *et al.* 2006). If the pH is greater than the suitable range, the algal

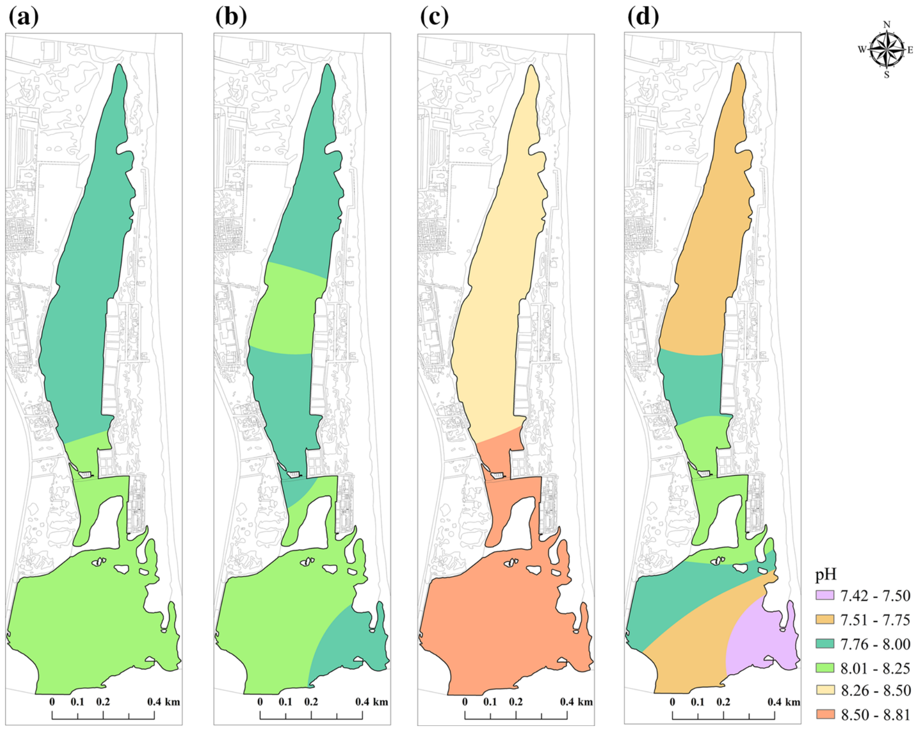

Figure 4. Map depicting seasonal changes of water pH in Muttukadu Lagoon. (**a**) Winter, (**b**) summer, (**c**) southwest monsoon season, and (**d**) northeast monsoon season.

Table 1. *Pairwise comparison matrix to derive the criterion weight in cage aquaculture.*

Criteria	pH	Salinity	Temperature	Dissolved oxygen	TAN	Depth	Turbidity	Weight
pH	1	3/4	1/2	1	2	1/4	1/2	0.08
Salinity	4/3	1	4/5	1/2	2	1/4	1/3	0.08
Temperature	2	5/4	1	2	4	1/2	1/3	0.14
Dissolved oxygen	1	2	1/2	1	2	1/4	1/4	0.08
TAN	1/2	1/2	1/4	1/2	1	1/6	1/5	0.04
Depth	4	4	2	4	6	1	2	0.33
Turbidity	2	3	3	4	5	1/2	1	0.25

bloom can occur and decrease the fish movement due to ammonia build-up.

The brackishwater fishes can withstand a wide range of salinities (10–35‰); however, the optimum range of salinities allows the proper osmoregulation, thereby improves the growth. Temperature is a critical factor in fish cage culture due to its influence on biological activities, which are vital for fish growth. But, the fishes have an enormous thermal acceptance level from 15 to 40°C, commonly farmed at a range of 22 and 35°C (Tucker *et al.* 2002). The temperature beyond the practical range of a fish species triggers a stress reaction that can badly impact immune function (Dominguez *et al.* 2004) and makes the fishes vulnerable to infections (Matanza and Osorio 2018).

Concerning DO, 19% and 6% of the lagoon had low DO between June–September and October–December, respectively. Oxygen is produced in the water bodies due to photosynthesis, where planktons make use of liberated carbon dioxide to make oxygen. The oxygen level may go down due to the increased nutrient load, plankton die off, a large quantity of fish or feed waste deposits and reduced water exchange in the water bodies. Studies indicated that wind-generated tides rise the water mixing in the shallow water lagoon, and increase oxygenation and reduce likely anoxia triggered by eutrophication, which could be harmful to numerous organisms (Kjerfve and Magill 1989; Powers *et al.* 2005). Besides, rain also can affect the nutrient equilibrium of the lagoon by disturbing

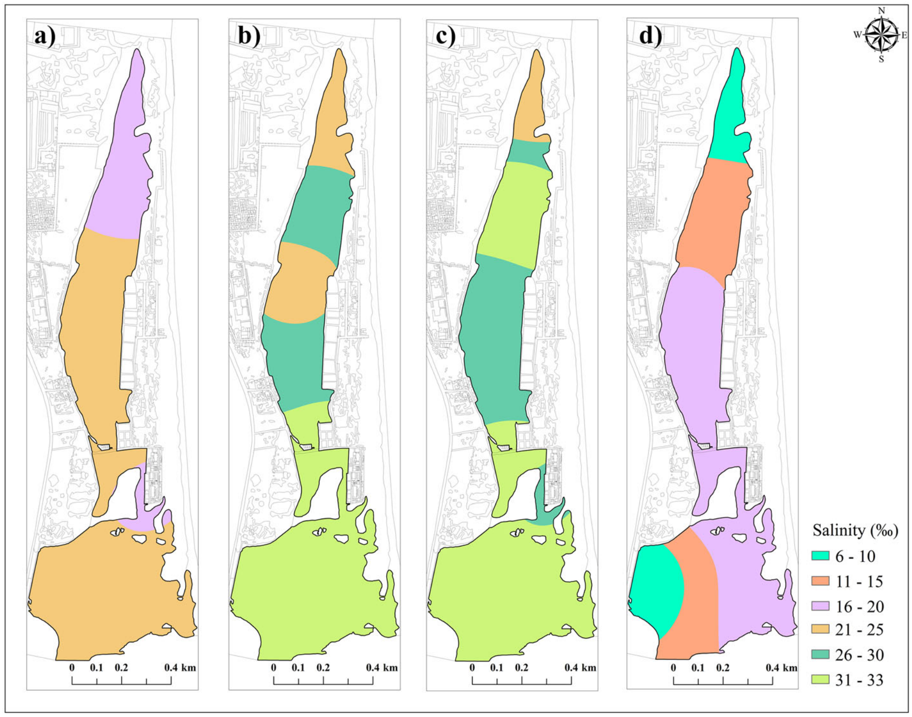

Figure 5. Map of seasonal variation of water salinity in Muttukadu Lagoon. (**a**) Winter, (**b**) summer, (**c**) southwest monsoon season, and (**d**) northeast monsoon season.

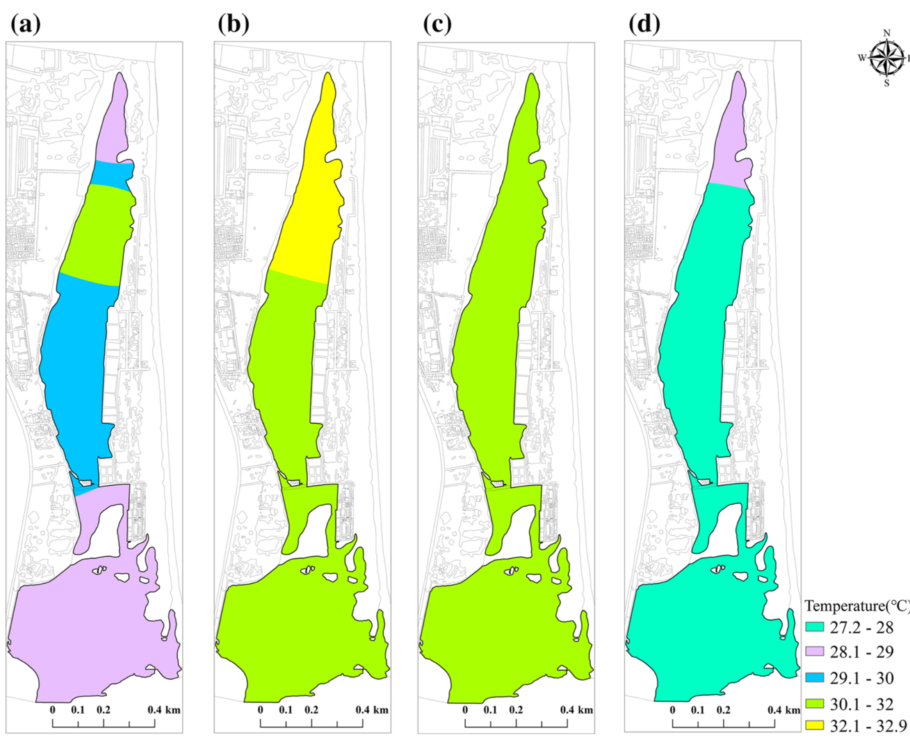

Figure 6. Water temperature map of Muttukadu Lagoon at different seasons. (**a**) Winter, (**b**) summer, (**c**) southwest monsoon season, and (**d**) northeast monsoon season.

the association with the ocean (Mendoza-Salgado *et al.* 2005).

The turbidity was beyond the suitable range in 70%, 9.1%, 17% of the lagoon during winter, summer, and northeast monsoon season, respectively. Depth is a major limiting factor for planning cage culture in the Muttukadu Lagoon as the minimum water depth of minimum 1.5 m in

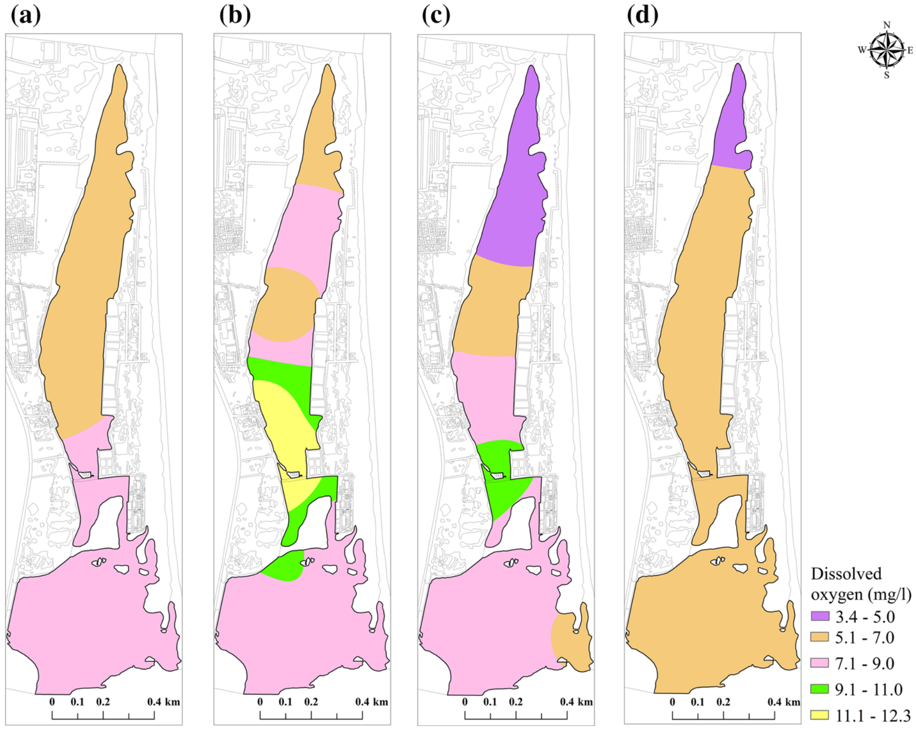

Figure 7. Changes in dissolved oxygen in Muttukadu Lagoon at different seasons. (**a**) Winter, (**b**) summer, (**c**) southwest monsoon season, and (**d**) northeast monsoon season.

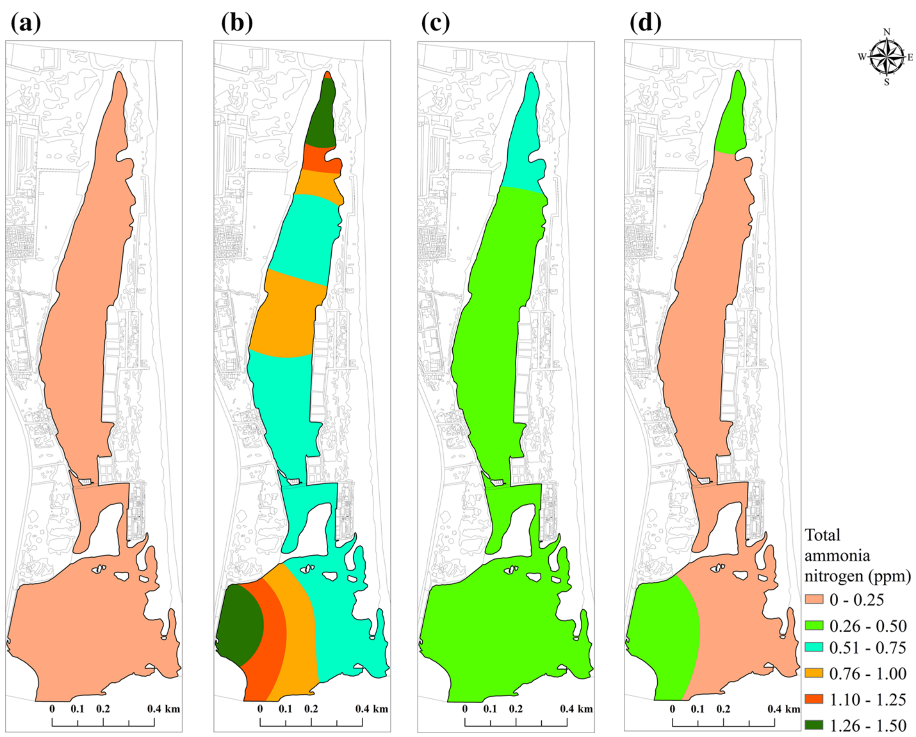

Figure 8. Presence of total ammonia nitrogen in Muttukadu Lagoon across the seasons. (**a**) Winter, (**b**) summer, (**c**) southwest monsoon season, and (**d**) northeast monsoon season.

the lowest low tide is compulsory for successful aquaculture. We could see the suitable water depth in 12% of the lagoon during the summer. The weighted overlay spatial analysis in GIS found that 11% of the lagoon area is suitable for cages. GIS spatial techniques have been explored and widely accepted in aquaculture site selection (Ross *et al.* 1993; Nath *et al.* 2000; Pérez *et al.*

Table 2. *Seasonal variation of lagoon water characteristics and its extent.*

		Extent at different seasons (ha)			
Parameter	Range	Winter	Summer	Southwest monsoon	Northeast monsoon
pH	7.42–7.50				4.52
	7.51–7.75				14.81
	7.76–8.00	26.98	47.74		27.92
	8.01–8.25	32.88	12.12		12.60
	8.26–8.50			26.76	0
	8.51–8.81			33.1	0
Salinity (‰)	6–10				10.31
	11–15				18.44
	16–20	12.39			31.11
	21–25	47.47	11.54	2.97	
	26–30		15.05	17.29	
	31–33		33.27	39.60	
Dissolved oxygen (mg/l)	3.43–5.0			11.12	3.58
	5.1–7.0	26.31	10.44	11.45	56.27
	7.1–9.0	33.55	36.66	33.75	
	9.1–11		6.07	3.54	
	11.1–12.3		6.68		
Temperature (°C)	27.2–28				55.70
	28.1–29	33.37			4.16
	29.1–30	18.51			
	30.1–32	7.98	48.01	59.85	
	32.1–32.9		11.84		
TAN (ppm)	0–0.25	59.86			47.41
	0.26–0.50			55.52	12.44
	0.51–0.75		31.74	4.34	
	0.76–1.00		15.42		
	1.10–1.25		6.24		
	1.26–1.50		6.44		
Depth (m)	0.50–1.0	8.50	27.39	8.17	7.05
	1.10–1.5	26.64	25.28	24.11	21.71
	1.51–2.0	14.46	7.211	15.66	15.42
	2.10–2.5	6.74		7.68	8.85
	2.51–3.0	3.54		4.25	4.35
	3.10–3.6				2.47
Turbidity (NTU)	8–10	41.82			
	11–20	18.04	41.19	44.66	46.20
	21–30		9.72	15.19	1.82
	31–40		3.46		1.58
	41–51		5.49		10.25

2003; Esmaeilpour-Poodeh *et al.* 2019; Jayanthi *et al.* 2020). Physical characteristics play a major role in providing a conducive environment and keeping the health of the lagoon. The bar mouth closure is another biggest problem as it blocks the movement of water between the sea and lagoon, which increases the turbidity and reduces the DO. The dredging to open the bar mouth of the lagoon can bring welcome changes due to tidal water exchange and also reduce the turbidity, algal bloom, etc. Moreover, the groyne barrier constructed near Muttukadu Beach in the recent past has reduced the beach width considerably. Recent reports by the media indicate that the groyne has altered geodynamics and usual sediment transmission, quickening sea erosion from a natural occurrence to a rapidly-unfolding artificial disaster that has damaged about 3 km

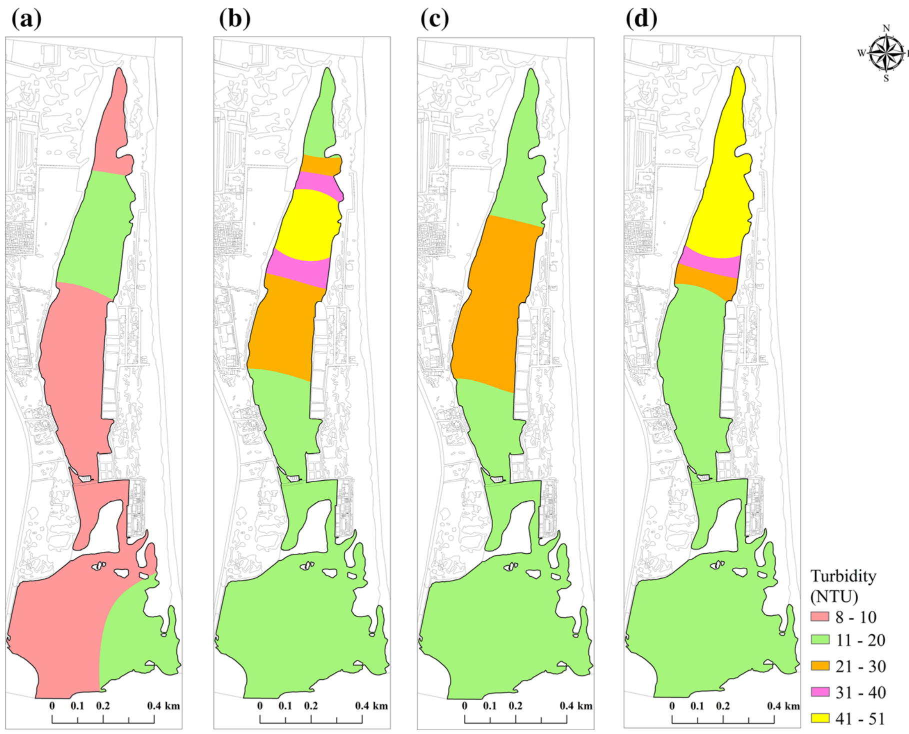

Figure 9. Levels of water turbidity in Muttukadu Lagoon at all seasons. (**a**) Winter, (**b**) summer, (**c**) southwest monsoon season, and (**d**) northeast monsoon season.

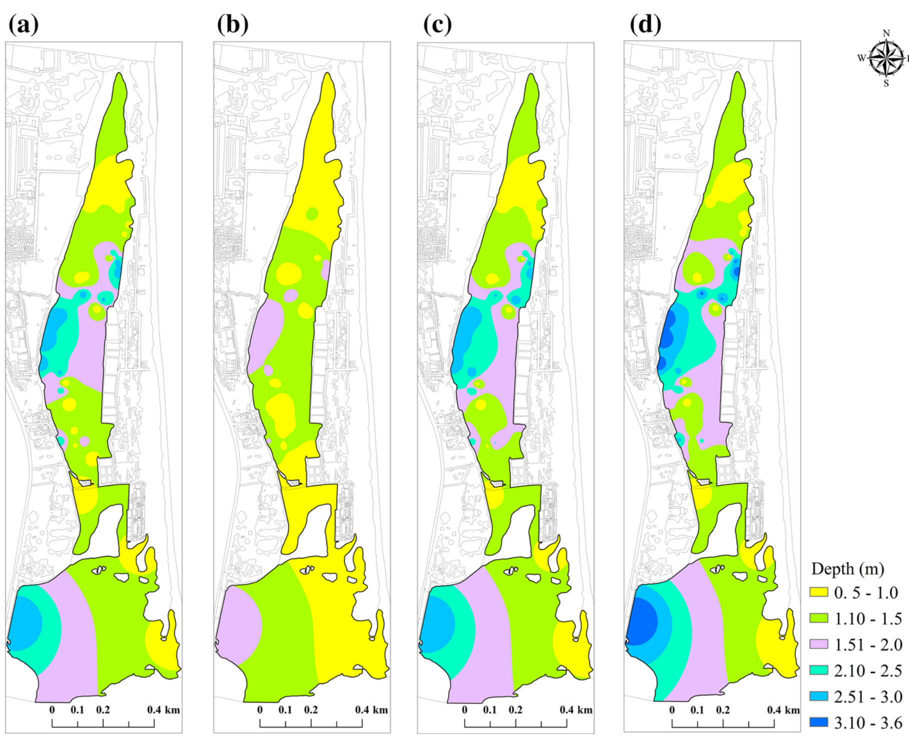

Figure 10. Water depth in Muttukadu Lagoon at different periods in a year. (**a**) Winter, (**b**) summer, (**c**) southwest monsoon season, and (**d**) northeast monsoon season.

of beach. This indicates the need for detailed impact assessment before planning any structural modifications to change natural phenomena on coastal stretches.

While planning for cage aquaculture, the potential impacts on the lagoon need to be taken into consideration. Water quality worsening may happen due to the release of solid wastes such as

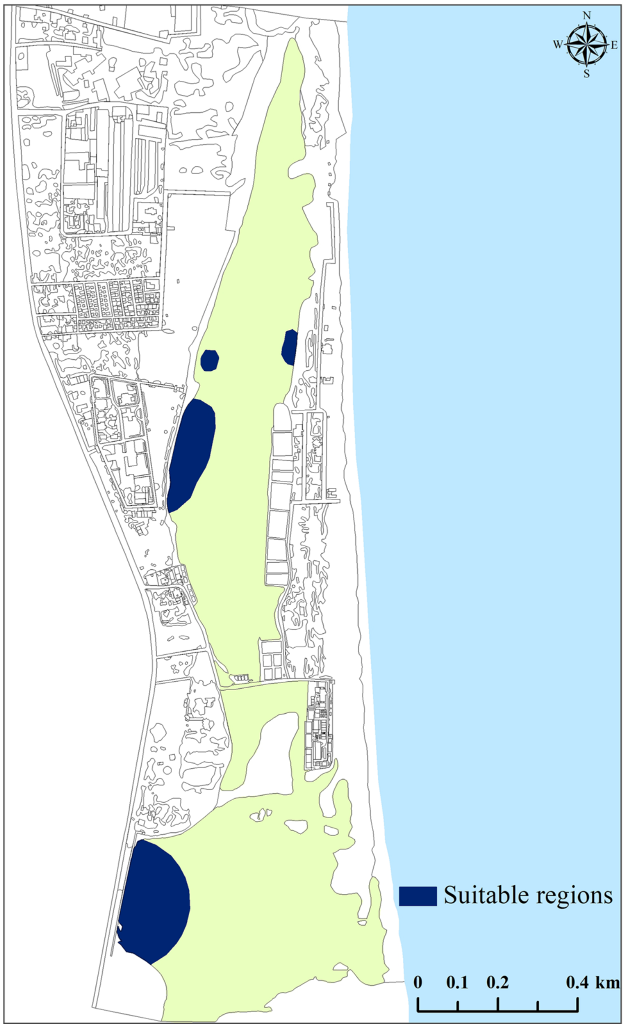

Figure 11. Suitable regions for cage aquaculture in Muttukadu Lagoon.

excess feed, and fish faeces (Dias *et al.* 2011), that can lead to eutrophication (Demir *et al.* 2001). Also, algal blooms and changes in zooplankton community structure (Dias *et al.* 2011), and disease impacts from the caged fish (Mangaliso *et al.* 2011) can occur. These impacts can affect environmental health and natural fish growth. Though we have identified only 12% of area as suitable, it is important that cage aquaculture should be backed by a strong environmental monitoring system and suitable management measures to retain the environmental quality of lagoon. Overall, the study has framed a method that can be used to identify and lease out suitable brackishwater regions for cage aquaculture. By adopting this model, vast unused brackishwater resources can be put to good use in terms of increasing fish production and also support the livelihood of the coastal poor.

5. Conclusion

The present study demonstrates the method to assess suitable regions to develop cage aquaculture in the coastal lagoon by integrating the resource quality and availability. It is established that the spatial techniques will be crucial in aquaculture decision making and identifying the prospects, from preplanning to resource allocation. The spatial variability of the physical characteristics of the lagoon has played a major role in limiting the sites for cages. Management measures and strategies are needed to protect the environmental conditions of the lagoons before planning the developmental projects. The study will serve as a model and provide information to expand brackishwater aquaculture in lagoons, estuaries, and other shallow waterbodies to offer livelihood opportunities to coastal communities.

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Author statement

M Jayanthi: Conceptualized the research work, planned the experiments, carried out the data analysis, and prepared the manuscript. M Samynathan: Conducted the experiments and mapped the variables using GIS. S Thirumurthy: Conducted the experiments and GIS analysis. P Kumararaja: Conducted experiments and water analysis. M Muralidhar: Contributed to the fund acquisition and manuscript review and K K Vijayan: Supervised the project.

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