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Decision-making framework for identifying best suitable mariculture sites along north east coast of Arabian Sea, India: A preliminary GIS-MCE based modelling approach

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ABSTRACT

Mariculture in open seas particularly, sea cage farming is rapidly expanding all along the territorial waters of the Indian sub-continent. Intensification of such new activities in open waters may lead to issues related to sustainability and spatial usage. Additionally, there could be escalation of ecological apprehensions and other cross sectoral conflicts. Thus, in view of the importance of sustainable and judicious utilization of open waters for mariculture development in the country, a preliminary Geographic Information System (GIS) based decision support model and a spatial framework was developed for site selection of cage farms in the territorial waters of Gujarat state, India along the Arabian Sea. The transit trajectory of 20 km sea space accounting to 23949.33 km^2 area was modelled under the study. Apart from the preferable biological and oceanographic arrays for the culture system and candidate marine fish species; data on maritime aids, sewage, industrial outlets, river mouths, ecologically sensitive locations and other constraints were marked, re-classified, optimized and benchmarked for the decision-making analysis. The developed comprehensive model consisted office sub-models *viz*., topographic, physical, chemical and biological oceanographic and socio-infrastructural models. The model explored and demarcated suitable sea space of 12557.74 km^2 (52.43% of total) for mariculture. Out of the demarcated area, 27.43% was the most suitable and 25.00% was moderately suitable for mariculture development, emphasizing the untapped potential of the available open waters of Gujarat state. The sensitivity simulation indicated that the developed systematic analytical GIS-Multi Criteria Evaluation (MCE) model was effective, stable and delivered an efficient solution for complex spatial challenges for mariculture site selection process. Further, these results demonstrated that the present spatial decision support model, in particular its methodology and framework, allowed identification of the best suitable sites for mariculture along the territorial waters of the country. The model was adaptable to all maritime states of this subcontinent and could be an effective and useful tool to resolve the complex spatial problems associated with the site selection process for mariculture in open seas. It also provides a way forward for policymakers and stakeholders to formulate strategies for mariculture expansion while governing the marine resources in a holistic, cleaner and sustainable manner.

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1. Introduction

India, the second largest aquaculture producer in the world and a major global seafood supplier, earned 7.08 billion USD through seafood exports (MPEDA, 2018). The growing demand for seafood along with limited scope for expanding capture fisheries in India has prompted the Government to explore new fish culture avenues in open seas. Thus, the first sea-based farming system was established in India in 2007 where Asian seabass *(Lates calcarifer)* was successfully cultured in sea cages at Visakhapatnam, in the east coast of the country off Bay of Bengal by the Indian Council of Agricultural Research-Central Marine Fisheries Research Institute (ICAR-CMFRI) (Mojjada, 2015; Rao, 2012). Since then sea-based farming has captured attention among stakeholders and policy makers is even more so than the other prevailing farming systems. The Government of India has also supported the move towards sea-based farming through policy and funding initiatives like the Pradhan Manteri Matsya Sampada Yojana (PMMSY), Fisheries and Aquaculture Infrastructure Development Funds (FIDF), etc. (National Fisheries Development Board, 2020), with the aim of promoting sustainable mariculture for food and nutritional security of the country.

Globally it is well recognised that aquaculture and its subsectors are predicted to be the main supply source of aquatic animal protein in the coming years (Ottinger et al., 2016). However, unplanned and un-scientific expansion of aquaculture system prompted an escalation of bio-ecological concerns, through potential adverse impacts on marine environment (Aguilar-Manjarrez et al., 2010). The most quoted example of this is the unplanned expansion of coastal shrimp ponds in Asia which led to massive environmental impacts in terms of loss of mangroves, nursery areas and resulting crop losses due to diseases in cultured shrimps (Tandel et al., 2017). To overcome such situations an Ecosystem Approach to Aquaculture (EAA) was recommended while developing any new aquaculture practice or venture (Corner and Aguilar-Manjarrez, 2017). EAA emphasizes sustainable aquaculture while ensuring human well-being, ecological well-being and effective governance (FAO, 2017). One of the key aspects that can ensure maximum ecological well-being is scientific site selection of the culture activity as it can greatly affect the overall ecosystem and environment apart from the commercial feasibility, operational and per unit production cost, survival, growth and disease of farmed species in open waters (Beveridge, 1996).

GIS-based suitability models were used for identifying suitable sites, environmental decision making and ecological planning process by taking advantage of Multi-Criteria Evaluation (MCE) methods (Stelzenmuller et al., 2017). Complex spatial decision making can be resolved through the combination of GIS software and MCE techniques by a spatial multi-criteria evaluation (SMCE) process (Kamruzzaman and Baker, 2013; Krois and Schulte, 2014; Voogd, 1982). GIS delivers a suitable framework for the application of spatial analytic tools and the MCE process provides the various means to manage the multi-criteria situations taking into account the expert knowledge of the decision-makers (Carver, 1991). The application of spatial MCE and its models have increasingly been used in diverse sectors like assessment of coastal vulnerabilities (Bagdanaviciute et al., 2015), site selection for economic activities (Van der Merwe et al., 2013), land-use planning (Ceballos-Silva and Lopez-Blanco, 2003), sustainability assessment (Store and Kangas, 2001), environmental decision making, ecological planning (Comino et al., 2016), multi-criteria spatial modelling (Chakharand Mousseau, 2008), etc**.** In aquaculture, GIS-MCE tools have been used for site selection for multiple culture systems and multiple species (Assefa and Abebe, 2018; Landuci et al., 2020; Radiarta et al., 2008) indicating the suitability and adaptability of GIS-MCE tools for aquaculture planning.

Cleaner production (CP) has been variously defined over the years; however, the core of this concept is that it is “preventive” and “minimizes risk to the environment” (Hens et al., 2018). The EAA interestingly echoes the same principles of CP with respect to ecological well-being. Any form of aquaculture will have some impacts on its surrounding ecosystem. However, the use of science-based objective tools like GIS-MCE models can help to identify a suitable sea farming site which is least intrusive to the marine ecosystem. In fact the use of MCE ensures that multiple aspects of the culture system including environmental (physical, biological and chemical) and socio-economic (communities, infrastructure, other users) are included in the decision-making process making it more holistic. Thus development of such science-based tools and their inclusion in aquaculture policies of a country can go a long way in ensuring that the principles of both EAA and CP are met.

India is on the cusp of expanding sea cage farming in the country. However, so far, there have been no definitive objective or comprehensive methods developed in India, to evaluate the suitability of coastal and open sea sites for mariculture with respect to the physical, oceanographic, and biological parameters of the specific territorial locations. Hence we conducted this study with an objective to develop a GIS based geo-statistical model tool to objectively and scientifically identify and earmark potential sea farming areas in territorial waters of Arabian Sea along Gujarat coast of India. Along with the model, we also aimed to develop a site suitability model framework which could be adapted to all maritime states of the country or other countries with incorporation of their region-specific factors/criteria. We expect that with the use of this site selection tool, sea cage farming will be situated in a manner that will ensure sustainability of the production process with minimum disruption to the ecosystem, thereby meeting the goals of EAA and ensuring cleaner production. We have also proposed some recommendations for the sustainable mariculture expansion in territorial waters of the country which can enhance Blue revolution in the country.

2. Materials and methods

2.1. Study area and geo-morphology

The Northern Arabian Sea coast of India, of 1600 km long coastal contour with 20 km transect trajectory of territorial waters of the state of Gujarat, covering an area of 23949.33 km^2 was investigated to locate potential mariculture sites (Fig. 1). The coast was categorised into four geo-morphologically and oceanographically diverse sub-regions. These included Saurashtra coast, South Gujarat coast and two gulfs viz. Gulf of Kutchh and Gulf of Khambhat. Out of the three Gulfs in the country, two are falling in this region and were investigated. The study area covered 63 riverine inflows counting both major and minor rivers. The coastal area studied was one of the intensely industrialized in the state which influenced the coastal sea with terrestrial discharges and run offs in the form of domestic sewage, direct and indirect urban and industrial effluents through riverine discharges.

2.2. Data synthesis

Data on suitability parameters were collected for 3 years from 2017–19 along the state of Gujarat. Monsoon season was exempted from the *in-situ* data collection. Apart from these, secondary data from various scientific literatures were also collected on biological and oceanographic (physical, chemical and biological) parameters. Remotely sensed data were obtained

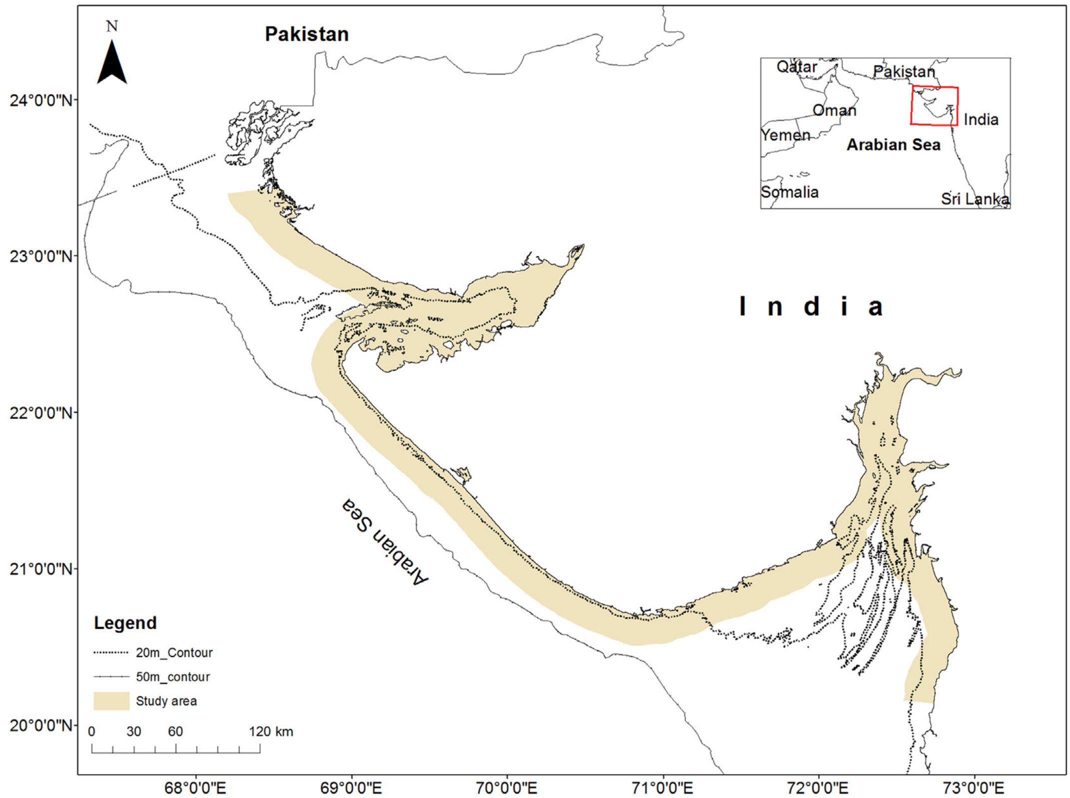

Fig. 1. The study area, North East Arabian Sea coast of Gujarat state, India. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

for some of the oceanographic parameters. Cumulatively, the collected data were cured and error layers were removed. Further, the data was compared with *in-situ* and secondary data sets. The socio-infrastructural data was collected through on-field surveys and the national marine fisheries census data (Ministry of Agriculture et al., 2012). Parameterized data on rescue management and operations were based on consultations with various concerned responsible organizations, institutional experiences, stakeholder's inputs, opinions and prerequisites. The collected data werere-classified as per the requirement of the GIS platform environment.

2.3. Digitization of hydrographic charts

Hydrographic and nautical charts mapped by the Indian Naval Hydrographic Department (INHD) published by the National Hydrographic Office (NHO), Dehradun, India were used for the present study. A total of 16 different charts, scale, series and numbers (Table 1), digitalised up to the scale were used for the purpose. The charts were intended to meet the specific data requirements on sea routes, commercial shipping navigation channels, contours, depth, nature of sea bottom, wrecks, spoiled grounds, oil and gas pipe lines, notified oil and gas fields, elevations, configuration and characteristics of coast, dangers and aids to navigation, etc. While digitization, the origin, scaleand limits of the hydrographic surveys were used in compiling the charts which were obtained from the source data diagram. Topography details were obtained from Survey of India maps. Positions were obtained from satellite navigation systems which refer to World Geodetic System 1984 datum.

2.4. Conceptual framework for model development

A conceptual frame work (Fig. 2) was designed to organize an on-field/laboratory/data synthesis plan of action to achieve the desired objectives. Since the study area (23949.33 km^2) was very extensive; this frame work fundamentally helped in establishing a path to arrive at the research objectives, by establishing strong technical foundation, analytically, methodologically and scientifically to enhance credibility (Adom et al., 2018). Also, this comprehensively ensured the generalization of the logical constructs while developing the GIS based MCE model for north-east coast of Arabian Sea along Gujarat, India to become a tool to identify the potential mariculture sites along the country's territorial waters.

2.5. Model development and interpretation

2.5.1. Criteria standardization and multi criteria evaluation (MCE)

During the past decade, the Indian Council of Agricultural Research-Central Marine Fisheries Research Institute (ICAR-CMFRI) has conducted several R&D efforts and technology transfer demonstrations on various mariculture technologies throughout the coast with a variety of marine shellfish and finfish species and their farming systems along the region (Damodaran et al.,2017; Mohamed et al., 2010; Mojjada et al., 2012a, 2012b, 2013; Mojjada, 2015) which were considered for determination of culture system criteria for this study (Fig. 3).

The environmental and socio infrastructure criteria were grouped into sub-model factors based on different contexts such as topography, physical oceanography, chemical oceanography, biological oceanography and socio-infrastructure. Each criterion was

Table 1
List of hydrographic and nautical charts digitized for the study Superintendence of Rear Admiral and Chief Hydrographer, 2003-2017.

Hydrography Charts from National Hydrographic Office, India						
Sl. No.	Chart number	Chart series		Scale	Edition	Dated
		Coast	Study location			
1.	IN 201	Coast of Pakistan and India	Gora Chan Creek to Godia Creek	1:150,000 (17°00′)	2010	August 01, 2010
2.	IN 202	India West Coast	Jakhau to Dwarka	1:150,000 (17°00′)	2016	April 30, 2016
3.	IN 203	Arabian Sea-India	Gulf of Kachchh	1:150,000 (22°30′)	2003	June 30, 2003
4.	IN 204	India West Coast	Dwarka to Navibandar	1:150,000 (17°00′)	2003	April 30, 2010
5.	IN 205	India West Coast	Navibandar to Veraval	1:150,000 (17°00′)	2012	March 15, 2012
6.	IN 206	India West Coast	Veraval to Diu Head	1:150,000 (17°00′)	2012	July 31, 2012
7.	IN 207	India West Coast	Diu Head to Gopnath Point	1:150,000 (17°00′)	2012	May 31, 2012
8.	IN 208	India West Coast	Gulf of Khambhat	1:150,000 (17°00′)	2006	July 31, 2006
9.	IN 209	India West Coast	Hazira to Umargam	1:125,000 (17°00′)	2007	June 30, 2007
10.	IN 2039	India West Coast	Gulf of Khambhat Northern Portion	1:75,000 (17° 00′)	2017	September 15, 2017
11.	IN 2044	India West Coast	Gulf of Khambhat (Cambay)- Southern Portion	1:100,000 (21°30′)	2003	August 31, 2003
12.	IN 2068	India West Coast	Gulf of Kachchh Deep Water Route	1:75,000 (22°37′)	2002	March 31, 2002
13.	IN 2079	India West Coast	Approaches to Mundra Port	1:37,500 (17° 00′)	2014	March 15, 2014
14.	IN 2080	India West Coast	Gulf of Kachchh – Eastern Portion	1:75,000 (22°45′)	2011	August 31, 2011
15.	IN 2081	India West Coast	Approaches to Ports Form Diu to Pipavav	1:75,000 (17° 00′)	2017	July 31, 2017
16.	IN 2101	India West Coast	Approaches to Hazira	1:37,500 (17° 00′)	2016	February 29, 2016

Details of common parameters specification.
Depth: Mentioned in meters and reduced to chart Datum, which is approximately the level of Lowest Astronomical Tide.
Heights: Mentioned in meters. All heights are above Mean Higher High-Water level.
Horizontal Datum: World Geodetic System 1984

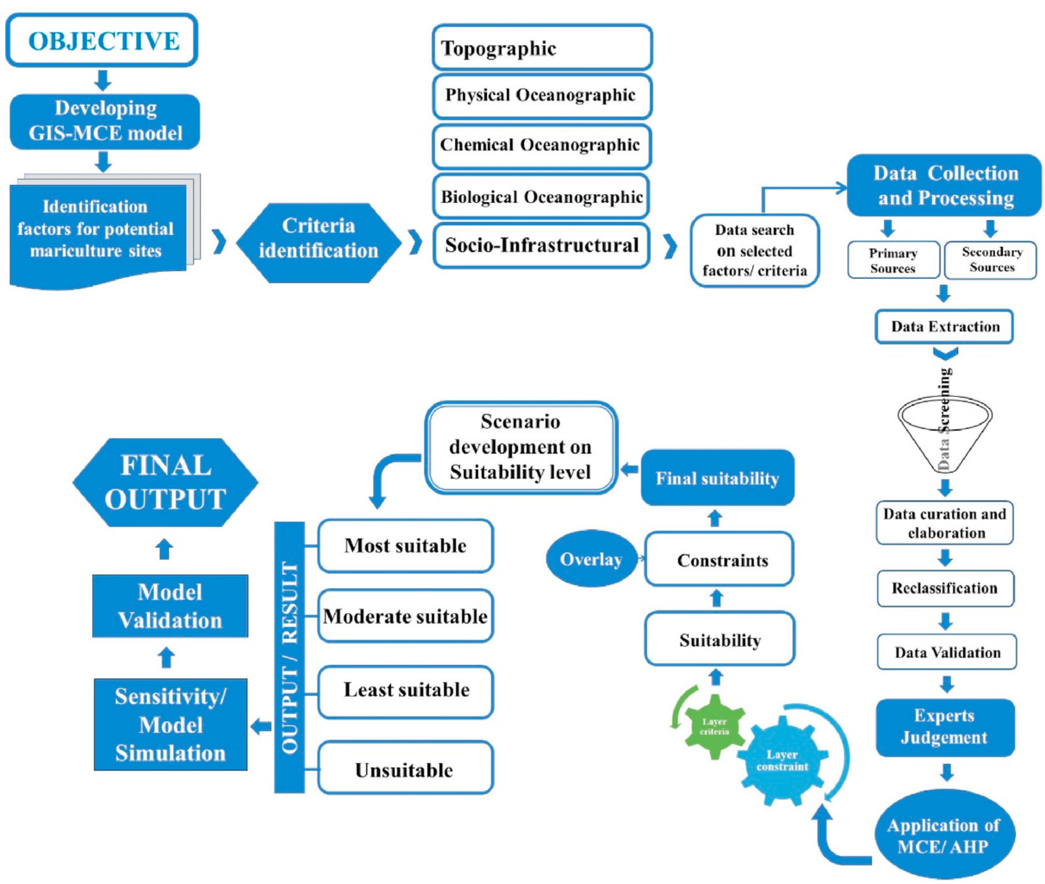

Fig. 2. Conceptual schema designed to develop the decision-making spatial model. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

standardized by suitability levels and scores (Table 2). The layers were re-classified based on the suitability levels from 0 (unsuitable) to 3 (most suitable). The suitability criteria were applied only to environmental parameters. The constraint layers were developed in Boolean format and were excluded from further analysis (either 0 or 1) (Radiarta et al., 2008). The constraint areas were considered as unsuitable for cage culture and other economic activities due to various national legislations and geographic limitations.

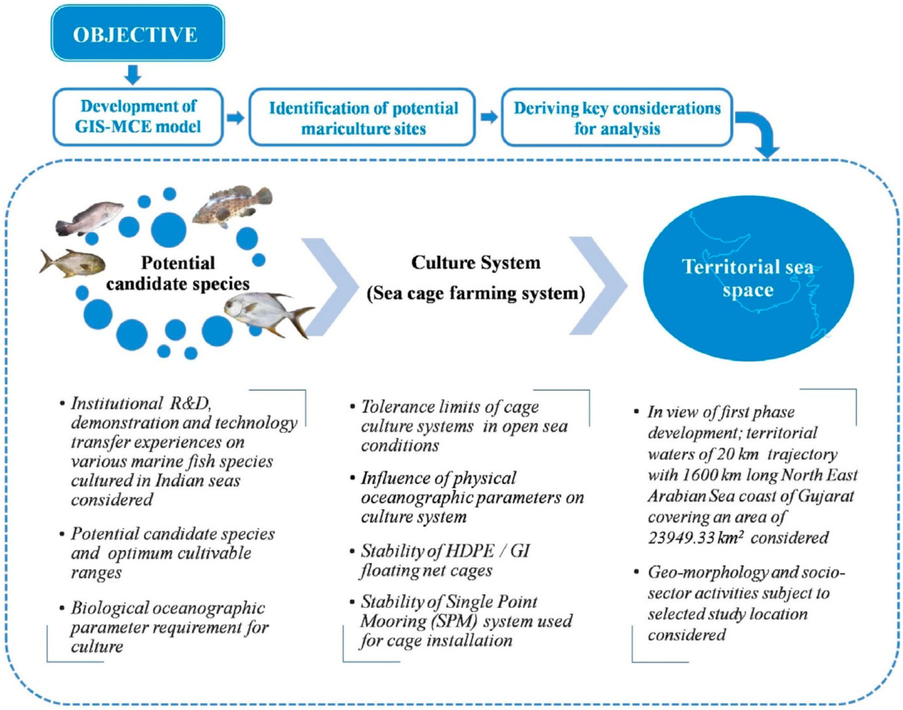

Fig. 3. Schematic representation of factor consideration to locate potential mariculture sites along NorthEast Arabian Sea coast of Gujarat, India. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Criteria applied in the site suitability analysis and its suitability evaluation. Criteria ranges for different suitability levels were assigned for the environmental context of the Gujarat region based on expert judgement.

Sub-model	Criteria	Unit	Factor Suitability Range (FSR)				
			Most suitable (3)	Moderate suitable (2)	Least suitable (1)	Unsuitable (0)	FSR Source/Reference
Physical Oceanography	Sea Surface Temperature (SST)	°C	25–32	22-25 & 32-33	>33	–	1, 1a, 2–5,12,13, 13a, 13b, 13c
	Wind velocity	m/s	<5.0	5.0–6.5	6.5–10	>10	3,15, 16, 22,13c
	Current velocity	m/s	<1.5	1.5–2.0	2.0–2.5	2.5	3, 6–9, 15, 16, 22
	Tidal Amplitude	m	<4.0	4.0–5.0	5.0–7.0	>7.0	3,13,13c, 15
Chemical Oceanography	pH	–	7.5–8.5	8.5–9.0	>7–7.5	<7.0 &>9.0	1, 3, 5,12,13, 13a, 13b,13c
	Salinity	ppt	15–30	30–40	>40	–	1a, 2–5,12,13, 13a, 13b, 13c, 22
	Dissolved Oxygen	mg/L	4.5–7.0	4.0–4.5	<4.0	–	1a, 2, 3, 4,12,13, 13a, 13b,13c,16, 22
	Ammonia	mg/L	<0.5	0.5–0.7	1.0–1.2	>1.2	1a, 3, 4,12, 13a,13b, 15, 22,13c
	Phosphates	mg/L	<70	70–80	80–85	>85	3, 13, 15, 22, 13b
	Nitrates	μm/L	<100	100–200	200–250	>250	1, 3, 13, 13b,13c
	Nitrites	μm/L	<2	2–4	4–4.5	>4.5	1, 3, 12, 13, 13a, 13c
Biological Oceanography	Biological Oxygen Demand	mg/L	>1.5	1.2–1.5	1–1.2	<1	17,18,19,20
	Chlorophyll-a	mg/m^3	3.5–5.0	<3.5	>5.0	–	3, 10
	Shannon Wiener Index	H	1.5–5.0	1.0–1.5	0.5–1.0	0–0.5	24, 25
Topography	Depth	m	8–30	30–50	>50	<8	10, 13, 14, 15, 16, 22,13c
	Slope	°	10	15	20	>25	23, #, 2,13c
Socio-infrastructural	Jetties	km	1–10	10–20	>20	<1	21, #
	Landing Centres	km	1–10	10–20	>20	<1	14, 21, #
	Harbours	km	1–10	10–20	>20	<1	14, 21, #
	Ports	km	1–10	10–20	>20	<1	21
	Safety, Rescue & Monitoring	km	0–10	10–15	>15	–	14, #

1: Damodaran et al. (2017); 1a: Damodaran et al. (2019); 2: Loka et al. (2016); 3: Joseph et al. (2010); 4: Rao et al. (2010); 5: Vijayakumaran et al. (2009); 6: Garton et al. (2013); 7: Lyakhov and Mikheev (1964); 8: Ackerman (2014); 9: Clarke and Mc Mohan (1996); 10: Fanslow et al. (1995); 11: Bagdanaviciute et al. (2018); 12: Philipose et al. (2013); 13: Mojjada et al. (2012a); 13a: Mojjada et al. (2013); 13b: Mojjada et al. (2012b); 13c: Mojjada (2015) 14: Beveridge, M.C., (2004); 15: Gopalakrishnan, A., (2013); 16: FAO. (2015); 17: National Research Council (1993); 18: Chapman and Kimstach (1996); 19: Chattopadhyay et al. (1988); 20: Zweig et al. (1999); 21: Marine Fisheries Census 2010, IORA-Marine Spatial Planning (MSP), 2017; 22: Rao et al. (2013); 23: Hydrographic and nautical chartsNational Hydrographic Office, Dehra Dun, India; 24: Magurran, 2004; 25: Strong (2016); #: On-field survey/based on operational experience/stakeholders input/estimation of time to reach site by helicopter and speed boat.

Table 3
A pair-wise comparison matrix for assessing relative importance of factors in the final suitability model for marine cage farming site selection in Gujarat, North West coast of India.

Factors	SI	TP	PO	CO	BO	Weight
Social-Infrastructural (SI)	1	1.00	0.20	0.33	0.50	0.08
Topographic (TP)	1	1	0.20	0.50	0.50	0.09
Physical Oceanography (PO)	5	5	1	3	2	0.45
Chemical Oceanography (CO)	3	2	0.33	1	1.00	0.19
Biological Oceanography (BO)	2	2	0.5	1	1	0.19
CR	**0.009**					

The MCE approach was applied to calculate the weights for each criterion and factor. The Analytical Hierarchy Process (AHP) using pair-wise comparison matrix developed by Saaty (1977) was used to develop the relative weightage for each criteria and factors in the present study (Table 3a-e). The relative importance of criteria in the factor was evaluated in pair-wise matrix by giving their weights on a continuous scale of 9 points starting from 1 (1 is equal importance and 9 is extreme importance) and the judgments were assessed accordingly (Saaty et al., 1980). At this stage deep knowledge over the subject as well as the study region is critical. Therefore, the present study was carried out with inputs from various experts who had previous experience on marine cage farming and knowledge on coastal and marine environment management.

The pair wise comparison matrix X of n criteria constructed based the order (n × n) as:

$$X = [x_{ij}],\ i, j = 1, 2, 3, \dots, n \tag{1}$$

where X is a matrix with elements x_{ij} and it has the property of reciprocity on the opposite diagonal side of matrix, then $x_{ij} = 1/x_{ij}$.

The matrix X is normalized to created matrix Y as:

$$Y = [y_{ij}],\ i, j = 1, 2, 3, \dots, n \tag{2}$$

where,

$$y_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}}, \quad i,\ j = 1,\ 2,\ 3, \dots, n \tag{3}$$

The AHP to calculate the weightage value for each criterion (w_i) by taking the eigenvector corresponding to the largest eigenvalue of the matrix Y, is computed as:

$$w_i = \frac{\sum_{j=1}^{n} y_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{n} y_{ij}},\ i,\ j = 1, 2, 3, \dots, n \tag{4}$$

The normalized sum of weight value of criterion in the factor to a unity as

$$\sum_{i=1}^{n} w_i = 1 \tag{5}$$

The consistency of the judgments and finalization of weightage distribution for criteria for the factors were assessed on the basis of a consistency ratio (CR). The CR of the matrix evaluated as:

$$CR = \frac{\lambda_{max} - n}{\text{RI}\ (n-1)} \tag{6}$$

where λ_{max} is the largest eigenvalue of the matrix Y and RI (Random Index) was a constant which correspond to the number of criteria n in the matrix.

If CR ≤ 0.10 it was considered as acceptable. If the consistency ratio was >0.10, then the criteria was re-evaluated and corrected in order to complete the AHP process (Saaty and Vargas, 2012).

2.5.2. GIS model for site suitability

The Site Suitability Index (SSI) was constructed using model builder in ArcGIS platform based on MCE procedure and Weighted Linear Combination (WLC) (Malczewski, 2000). SSI was estimated for factors suitability map and overall suitability map using the formula:

$$SSI_i = \sum_{j=1}^{n} w_j v_{ij} \tag{7}$$

where SSI_i is the suitability index for a given area i; w_j is the weight of criterion j; v_{ij} is the suitability score of area i under criterion j and n is the total number of criteria. The pixels corresponding to the greatest calculated SSI values were selected as the best sites. If any pixels of the criteria were evaluated as unsuitable (SSI = 0), area covered by them was eliminated from further assessment despite presence of other favourable criteria values. The remaining pixels (SSI value range 1–3) were classified into three qualitative suitability classes considering classification of equal intervals: least, moderately and most suitable (Bagdanaviciute et al., 2018).

The final site suitability map was generated by applying Boolean constraints layer on suitability map, where all constraint areas were eliminated from the suitable area for marine cage farming.

$$SSI_i = \sum_{j=1}^{n} w_j v_{ij} * \prod c_j \tag{8}$$

where c_j is the criterion score of constraint j.

2.5.3. Sensitivity analysis

The robustness of each criteria weight used in the base run analysis is very important in MCE approach because it is subjected to uncertainty due to various ranges of source that can lead to an anomaly in the final suitability map. In order to analyse the sensitivity of assigned criteria weights, One-At-a-Time (OAT) method was used, where one factor score is changed at a time while all other factors remain fixed to see the effects on the suitability map in output (Chen et al., 2010). To understand the influence of the criterion weights on spatial domain of the suitable sites, forty evaluation runs were conducted on each criteria weightage separately by altered percent increments i.e. ± 1% with range of percent change was 20 from the original criteria weights used in the base run. Total 200 simulation runs were conducted for five criteria i.e. 40 for each. The weight of the other criteria were adjusted proportionally to meet the additive constrain in equation (5), that requires all criteria weight to a sum of one.

3. Results

3.1. Spatial distribution of the model

The developed integrated GIS-MCE model was applied to the defined criteria which spanned an area of 23949.33 km^2 of territorial transit trajectory of Arabian Sea coast, north-west coast of India. The inclusive final model consisted of five sub-models, viz. topographic (Fig. 4), physical (Fig. 5), chemical (Fig. 6), biological oceanography (Fig. 7) and socio-infrastructural (Fig. 13) with different criteria groups subset to fit in to the model in a logical manner. The sub-models were combined to derive the final model for earmarking potential mariculture sites with suitability scenarios (most, moderate, least and unsuitable) based on the degree of site suitability. The output from the suitability model delineated 6569.84 km^2 (27.43%) of the investigated region (Fig. 9 & Fig. 10) were classed as the most suitable for sustainable mariculture development in territorial waters of Gujarat state. Subsequently, the moderate suitable sites derived from the model spanned an area of 5987.903 km^2 (Figs. 9 and 10). The suitability of oceanographic criteria distribution (physical, chemical and biological sub-models) on spatial maps in the two classes (most and moderate suitable) accomplished 88.79% of required range of parameters for the mariculture of finfish and shellfish.

A combined value of the most suitable and moderately suitable sites evaluated indicated that 52.43% (12557.74 km^2) of the studied area was suitable for mariculture activity. The unsuitable sites (Figss. 9and 10) amounted to10065.64 km^2 (42.03%) due to various factors like their biological unsuitability for fish farming, structural stability levels for the culture system, topographic, socio-infrastructural unsuitability or various other constraints (Fig. 10). The constraint area covered was 1325.95 km^2 which formed 5.54% of total investigated area (Figs. 8 and 11). The potential sites in terms of overall culture feasibility (culture systems and species) were mostly located along the Saurashtra region and maximum unsuitable sites were found along the Gulf of Khambhat region (South Gujarat).

3.2. Sensitivity analysis

Topography and socio-infrastructure had the highest sensitivities and physical oceanography had the lowest sensitivity among the factors. The other two factors showed nearly similar degree of sensitivity in weightage (Fig. 12). Topography significantly influenced suitability class which changed from the most suitable to moderate suitable when the weight changed greater than +10% and from moderate suitable to most suitable when the weight changed less than −6%. Similarly, for socio-infrastructure, the suitability class changed from moderate suitable to most suitable when the weight changed greater than +16% and less than −10%. The moderate and most suitable classes were found most sensitive to criteria weight changes where considerable cell variation was noted.

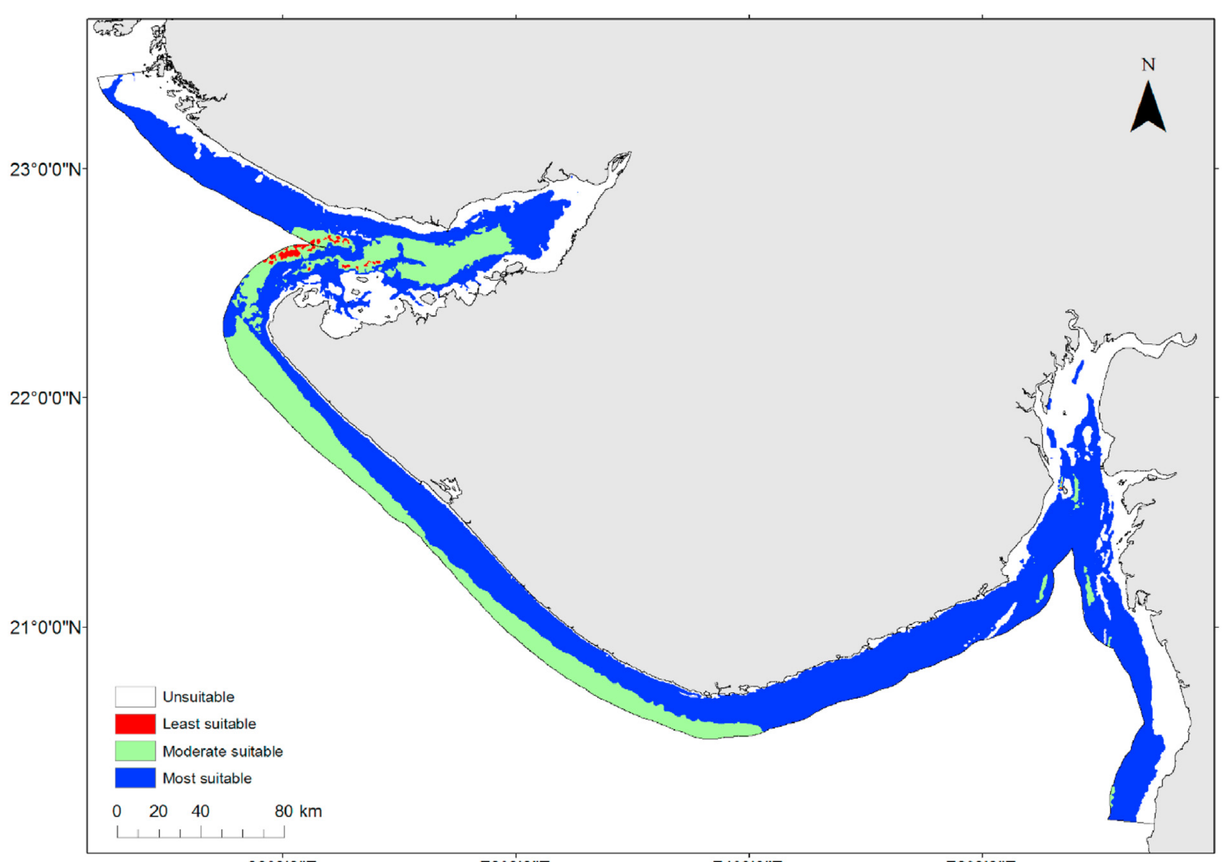

Fig. 4. Topographic suitability map. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

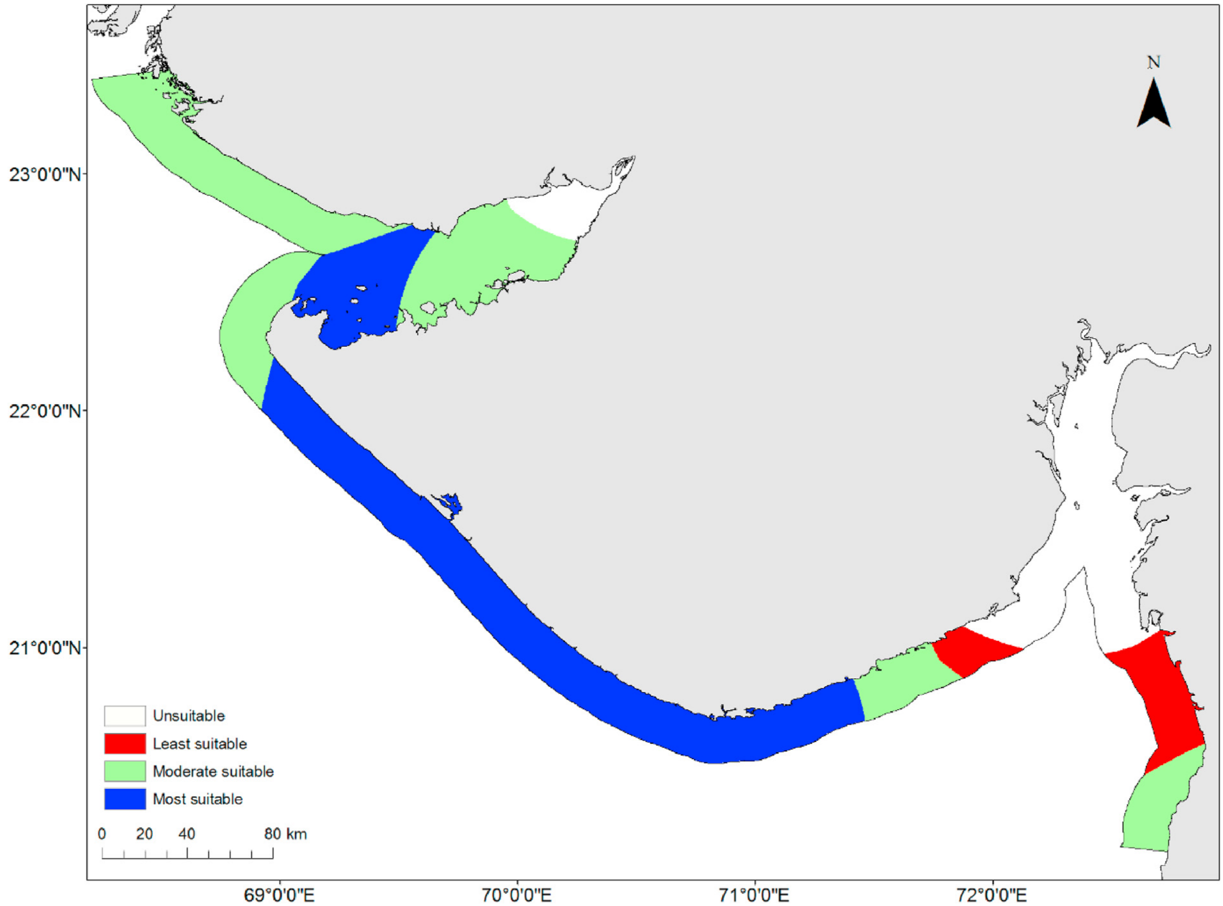

Fig. 5. Physical oceanographic parameter suitability map. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Discussion

This study has demonstrated the potential use of GIS for mariculture site selection through MCE approach in the Indian subcontinent. The study focused on locating suitable mariculture sites along one of the most industrialized maritime states of the country namely, Gujarat, where discharges of large rivers, industrial effluents and domestic sewage occur into the near shore sea. Sea cages are operated in an open environment; hence it is unrealistic to control the water quality in established sea cage farming sites. Hence, prior to the installation of cage farms, proper examination of potential sites must be conducted so as to assess the possibilities of acceptable water quality ranges for fish farming (Perez et al., 2005). The significance of the GIS based MCE model, is that it can assimilate multiple environmental, biological and socio-infrastructural criteria within a framework, which reflects diverse priorities and spatial scenarios. Through the developed model, the best possible mariculture sites for marine fish farming were identified within the range of territorial limits (12 nautical miles) for Gujarat coast along the Arabian Sea.

Even a modest growth in cage farming can generate substantial blue economy through seafood production (Lester et al., 2018). Anticipating a modest growth in cage farming in India, we deployed our model to assess potential cage farming sites within a 20 km range of marine space from the present existing shore. To achieve such modest development in the mariculture sector in this region, policy makers and implementing agencies essentially need to put their efforts on a high priority basis with an industry-enabling futuristic approach by adhering to the concepts of Ecosystem Approach to Aquaculture (Aguilar-Manjarrez et al., 2017) along with the essence of ecological, socio-economic and industrial point of views (Dapueto et al., 2015). In such scenarios where one sector is yet to take off, having a model which can assess potential sites based on multiple criteria would be of great use for policy makers and coastal zone managers for the successful governance of the venture from initial stage itself.

We were able to assess the relative importance of various criteria among the factors for generating sub-models in pair-wise matrix through allotting their weights over a continuous scale from 1 to 9 (1 was equated for equal importance and 9 for very high importance) (Saaty et al., 1980). The method applied by various researchers (Bagdanaviciute et al., 2018; Gimpel et al., 2015; Gorsevski et al., 2012; Jiang and Eastman, 2000) were also employed in our model development with necessary modifications in ordered weightage criteria. Pair wise matrix equated with analytical hierarchy process (AHP) enabled us to evaluate the weightage of each criterion under consideration by setting priorities for each one. This method has been effective in the site selection process for co-location farming (Gimpel et al., 2015), by fuzzy membership measures in multi-criteria evaluation model (Jiang and Eastman, 2000) and also in other sectors like site suitability for land fill and site for waste management (Gorsevski et al., 2012). There are findings that even minor deviations in the weighted coefficients can lead to a significant impact over the results while performing the suitability analysis (Radiarta et al., 2008). Therefore, we have cautiously allotted and ordered the weightages through logical thinking, scientific debate through gained practical experience and expertise on various parameters applied while judging the criteria. The score and weights allocated to the factors were rarely accepted unanimously (Falconer et al.,

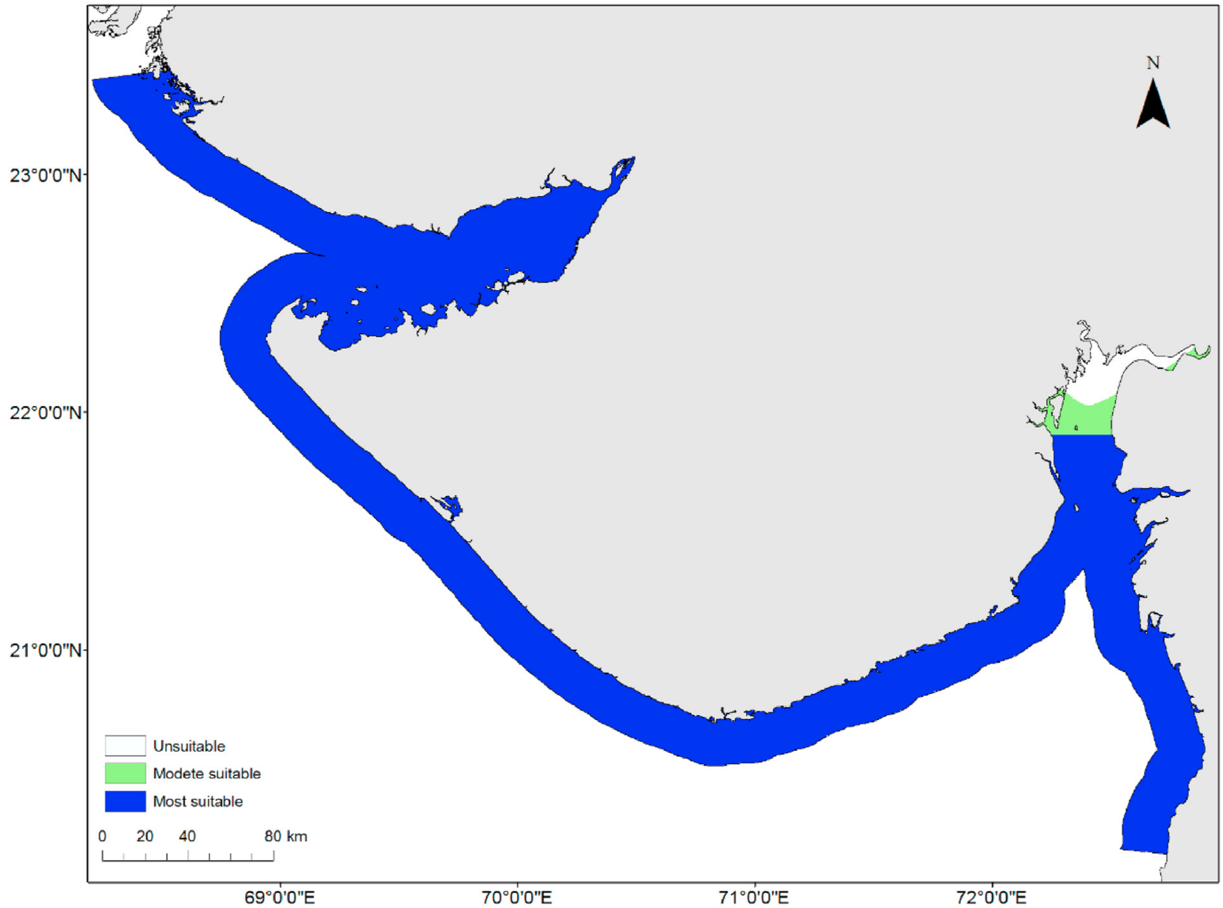

Fig. 6. Chemical oceanographic parameter suitability map. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2016). Hence, on-site practical feasibility was considered as a key point while finalizing the assigned weights. This may vary in future due to the need-based priorities of the stakeholders and logistic developments by the decision makers. The value of weights to the sub-factors/criteria often remains subjective (Bagdanaviciute et al., 2018). Scores and weightage distribution among the sub-factors we developed were consistent (Table 3). The consistency values deviated slightly between each sub-factor. This was attributed to the experts' familiarity with the coast, thorough knowledge of mariculture technologies and their decision-making ability on various criteria presented.

The major advantage of using the MCE model was that it helps to highlight both the advantages as well as challenges for propagating the venture. The major advantage for the state was the ideal depth and slope along the study region. The coast of Gujarat state has a moderate slope of 0–5° and depth range of 20–78 m (Mojjada, 2015) (Fig. 4) which was considered highly suitable for seabed-based installations (Beveridge, 1996). Such slopes are very much favourable for the mooring, erection and positioning the anchors of sea cages or any other open sea mariculture system installations. In particular, deadweight/block anchors would have an extra advantage due to the seabed topography which would facilitate a solid grip of sea cages on the seafloor. The CR of the criteria justified the requirement for positioning the seabed mounted mariculture system where the seabed was highly consistent in this region.

The physical oceanographic sub-model (Fig. 5) mainly focussed on SST, Wind and Current velocity and Tidal Amplitude (TA). This particular sub-model was distributed into four classes (Most (34.56%), Moderate (34.38%), Least (6.88%) and Unsuitable (24.18%)). Out of the three gulfs in the country, two namely, Gulf of Kutchh and Gulf of Khambhat fell within our study area and presented unique challenges to this study. The Gulf of Kutchh was more sensitive with the Marine National Park (MNP) which was distributed over 457.92 km^2 with diverse flora and fauna ("Principal Chief Conservator of Forest & Head of the Forest Force (HoFF) Gujarat forest department. 2015, Government of Gujarat", 2020). The Gulf of Khambhat was spread over 3000 km^2 (Badrinaryan, 2005) was very much industrialized with diverse sectors. In fact, it was one of the difficult and most complicated areas under our investigation. It had a current velocity record up to 9.26 ms^{-1} and tide ranges up to 12 m (Badrinaryan, 2006). The sea was often subjected to severe winds resulting in very rough conditions. Several major rivers including the Tapti, Narmada, Chathranji, Sabarmathi and Mahi drains into this gulf, which resulted in high levels of turbidity. No suitable sites were found along the Gulf of Khambhat, for sea farming activity, due to the TA, which dragged the mean water level of this region to very low depths during the neap tide. A low depth range was not much advisable for the cage installation and biological activities like fish culture (Beveridge, 1996). Further, the industrial and sewage discharge in this Gulf region was also a grave concern.

The wind and current data for the physical oceanographic sub-model were obtained from secondary source and satellite remote sensing data and the values were extrapolated to the locations which were data poor in the region. Obtaining data on these parameters were challenging in particular to territorial waters. GIS

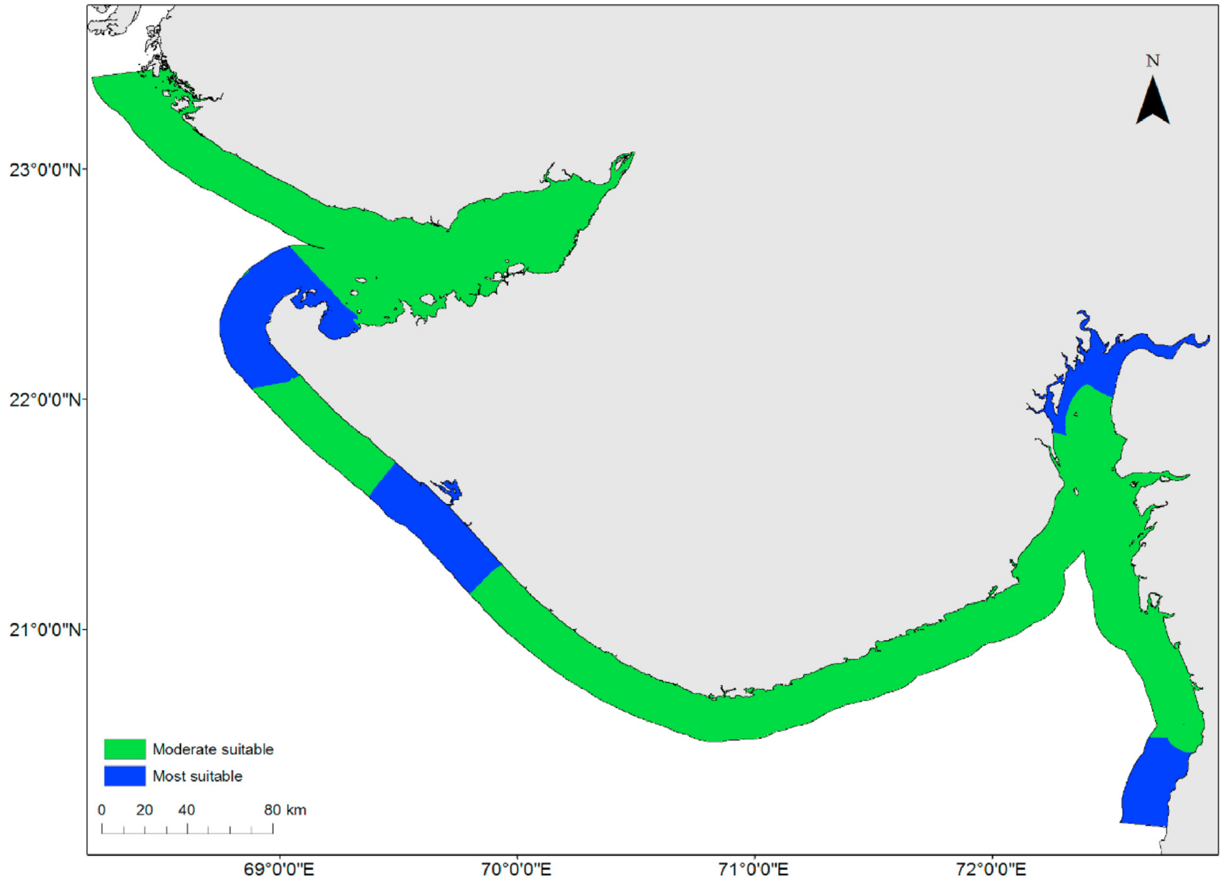

Fig. 7. Biological oceanographic parameter suitability map. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

was useful in such data scare situations. In future, data accuracy on physical oceanographic parameters may be improved by incorporating real-time on-site data with more randomised samples for deriving greater accuracy for the maps and further improvement of the present model.

In the chemical oceanographic sub-model (Fig. 6), the common criteria taken for this analysis were laid down in only two classes (most suitable and moderate suitable). The water quality parameters like salinity, pH, DO, ammonia and nitrates ranged optimal in 22 873.25 km^2 (95.51%) area. However, there is a correlation between the growth of fishes and salinity as a compound function (Altinok and Grizzle, 2001). Due to the broad tolerance array of the candidate species, like the silver pompano *Trachinotus blochii* (Jayakumar et al., 2014), Indian pompano *Trachinotus mookalee* (Ranjan et al., 2018), snapper (*Lutjanus* spp.) (Murugan et al., 2016), grouper (*Epinephelus* spp.) (Cheng et al., 2013; Ranjan et al., 2017) and Asian seabass (*Lates calcarifer*) (Loka et al., 2016), the derived sub-model had only minimal classes of suitability needs.

The biological sub-model also consisted of only two classes (Moderate (80%) and Most (20%) (Fig. 7) because the cultured species attributes had a wide range of acceptability of critical parameters in culture conditions. The culture system suitability, operational feasibility, rescue operation conveniences and farm maintenance activities were also assessed during the site suitability assessment. Despite locating the most and moderate suitable sites through the defined criteria for optimum fish growth, other important factors like coastal tourism, recreation, water sports, and other seaside activities (Radiarta et al.,2008) were also considered in order to integrate every potential use of the suitable sites while developing location specific models as per the observations. This was based on examples from around the world, namely, the co-existence of sea cages for finfish mariculture with tourism industry in the Canary Islands in Australia (Perez et al., 2003) and the development of spatial modelling framework for integrating wind farms and aquaculture of marine finfish, crustaceans, bivalves, seaweed and IMTA in German EEZ by using ordered weighted average (OWA) implemented with fuzzy membership function on GIS (Gimpel et al., 2015). With our work, we were able to demonstrate that such integration can be applied to the Indian context as well.

The socio-infrastructure sub-model was distributed (Fig. 13) into four classes. Among them the combined value of 5398.08 km^2 (22.54%) consisting of most suitable (294.43 km^2 (1.23%)) and moderate suitable (5103.65 km^2 (21.31%)) areas showed that the coast already had considerable infrastructure support for launching immediate needs for mariculture development. These locations (most & moderate) covered the criteria such as rescue of the stakeholders in emergencies, onsite farm operations and management. The available levels of most suitable socio-infrastructure would be sufficient enough to achieve modest development of mariculture in the territorial waters of this region. It would be ideal to plan for integrated mariculture parks/clusters close to the most suitable (socio-infrastructural) locations during the initial phases. Such locations may be given first priority for the implementation of mariculture developmental plans (MDP), through intervention of government/decision-makers and stakeholders. The infrastructure can be developed in a phased manner in future of along the least 18327.06 km^2 (76.52%) and unsuitable 224.1839 km^2 (0.94%) sites

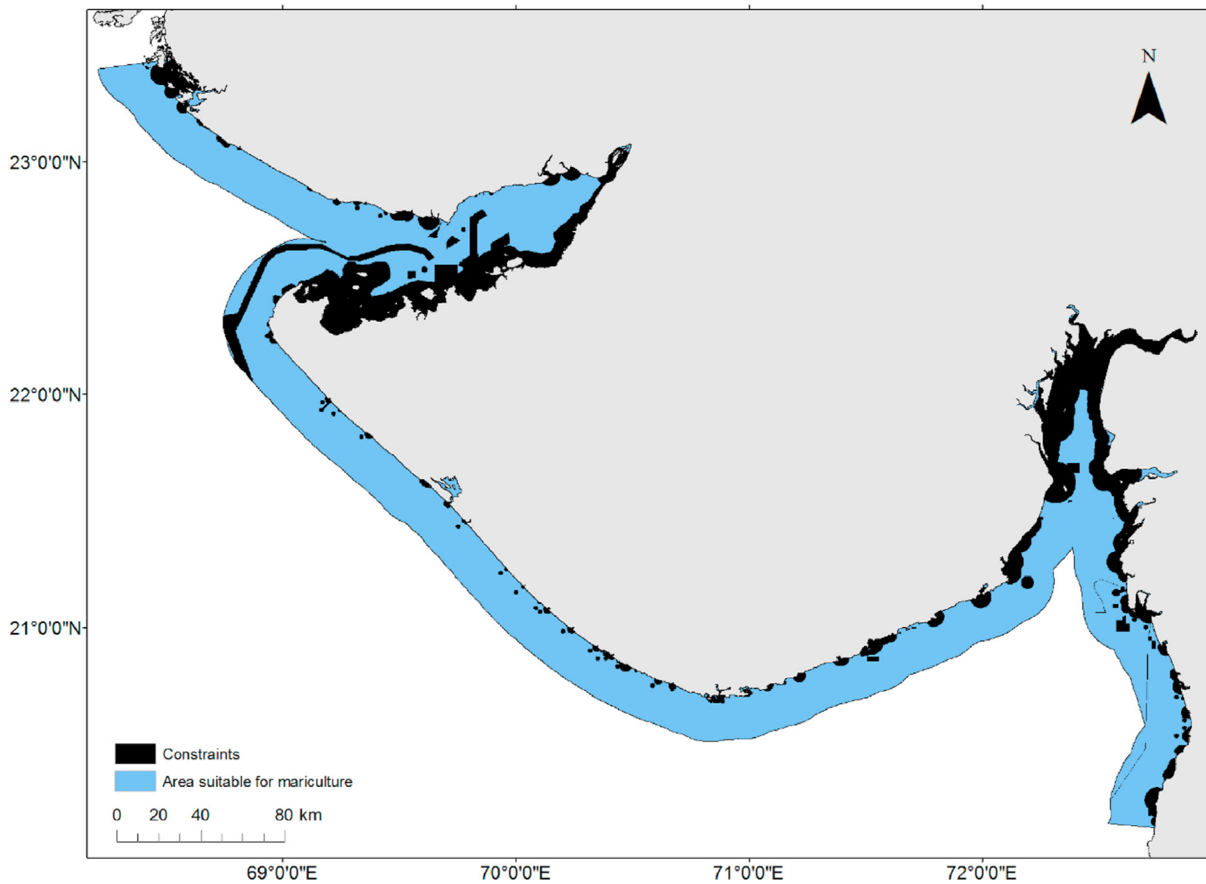

Fig. 8. Constraint area along the investigated site. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

too, where farming parameters were found suitable.

In some cases, the suitability for fish culture was overlapping with one or more other activities at one particular site based on the intended uses of the site. In such circumstances the ecosystem-based approach (EAA) as recommended by Aguilar-Manjarrez et al. (2010) and Aguilar-Manjarrez and Ross (1995) was used as the thumb rule. The best use of the site was selected based on environment sustainability as the prime concern than any other commercial activity. Therefore, the priority was given on the basis of the environmental impact of the particular activity or sector on the earmarked suitable sites (Aguilar-Manjarrez et al., 2010; Soto et al., 2008). Decisions based on the ecosystem-based approach principle can ensure that future site uses need not lead to habitat degradation, and potential conflicts among multiple users. Different uses of the same site are often a concern for management and providing a consistent idea behind the decision-making process which will ensure maximum benefit with least ecosystem disturbance.

The constraints identified and mapped were the artisanal fishing locations (which are most sensitive or fragile in terms of socio-political aspect), defence sensitive/operational areas, depth and slope distribution pattern, landing centres and harbours, industry/sewage discharge outlets, Marine Protected Areas (MPA) (including marine national park (MNP), bird sanctuary, mangrove wetland, seagrass bed, dugong location, etc.), navigational channels/commercial shipping sea routes, oil and gas fields (active as well as demarcated fields for future development), underwater pipelines (Seawater, Oil and Gas), river mouths, restricted pilgrim zones (security sensitive temples), port areas and country border (Government of Gujarat, 2017).

Though the consistency ratio among the sub-factors and criteria were agreeable at this point, in future it may vary with changing coastal water usage scenarios according to future developments and needs of the stakeholders of the diverse sectors operating in the region. In the present study variability in expert's decisions were effectively prevented by comprehensive knowledge of the environment and species culture conditions and tolerance limit of culture system which were derived from the institutional work experience along the Indian peninsula. Involving a wide array of experts (Bagdanaviciute et al., 2018), such as scientist, NGOs, coastal communities, conservation biologists, along with the cross-sector stakeholders would be beneficial while defining the model criteria. Refinement of the criteria obviously enhances the accuracy of the assessments (Bagdanaviciute et al., 2018), by broadening the involvement of various field of experts and stakeholders. We too deployed similar strategies while deriving the model through the present study.

This study highlighted the significance of on-field experience on species, expertise on various culture systems, location and long-term interactions, discussion and opinion exchange with the fisher/aquaculture farmers and other maritime stakeholders along with the experts while judging the hierarchy among the criteria which was a critical step in model development. Region-specific familiarity through physical and on-board surveys over a period of time enabled us to weigh several criteria in a meaningful manner. Therefore, the developed model combined with experience has the immense applicability to assist the site selection process by providing options to the stakeholders and policy makers

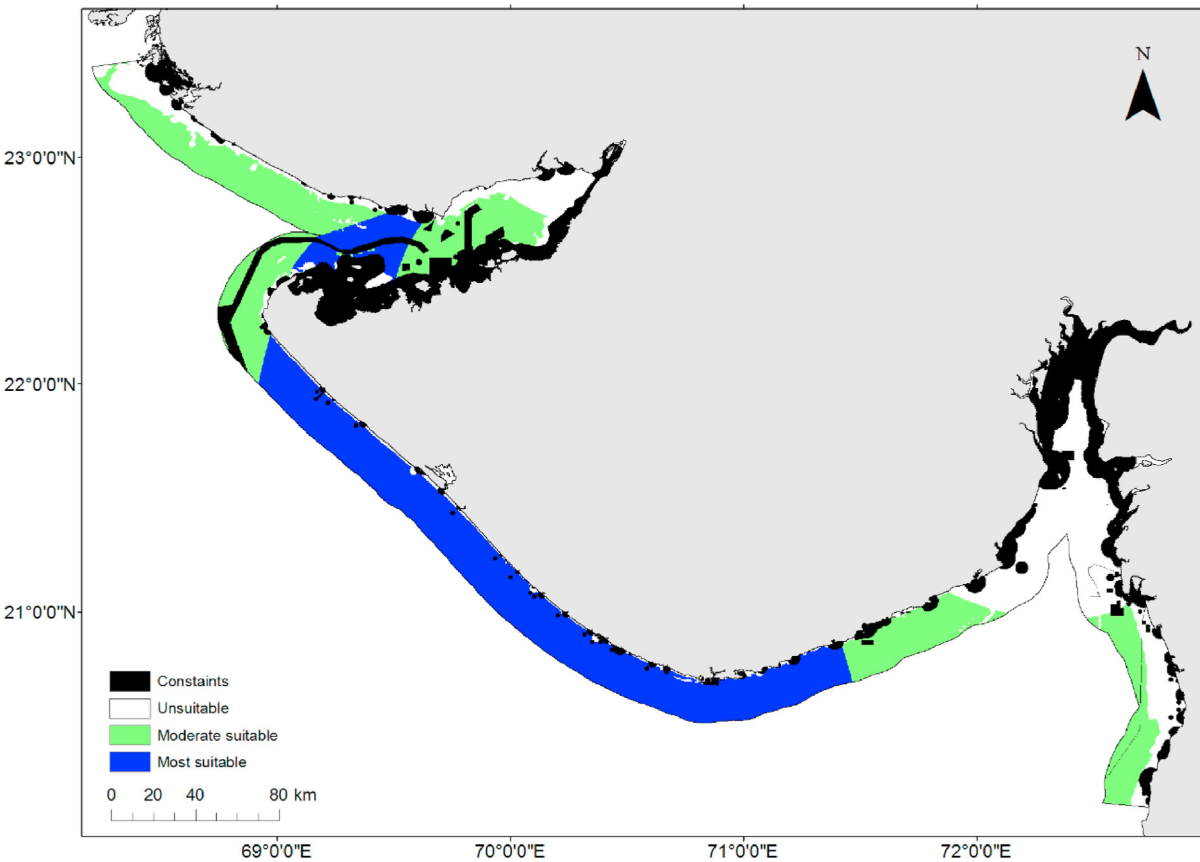

Fig. 9. Final suitability map for potential sites for mariculture development. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

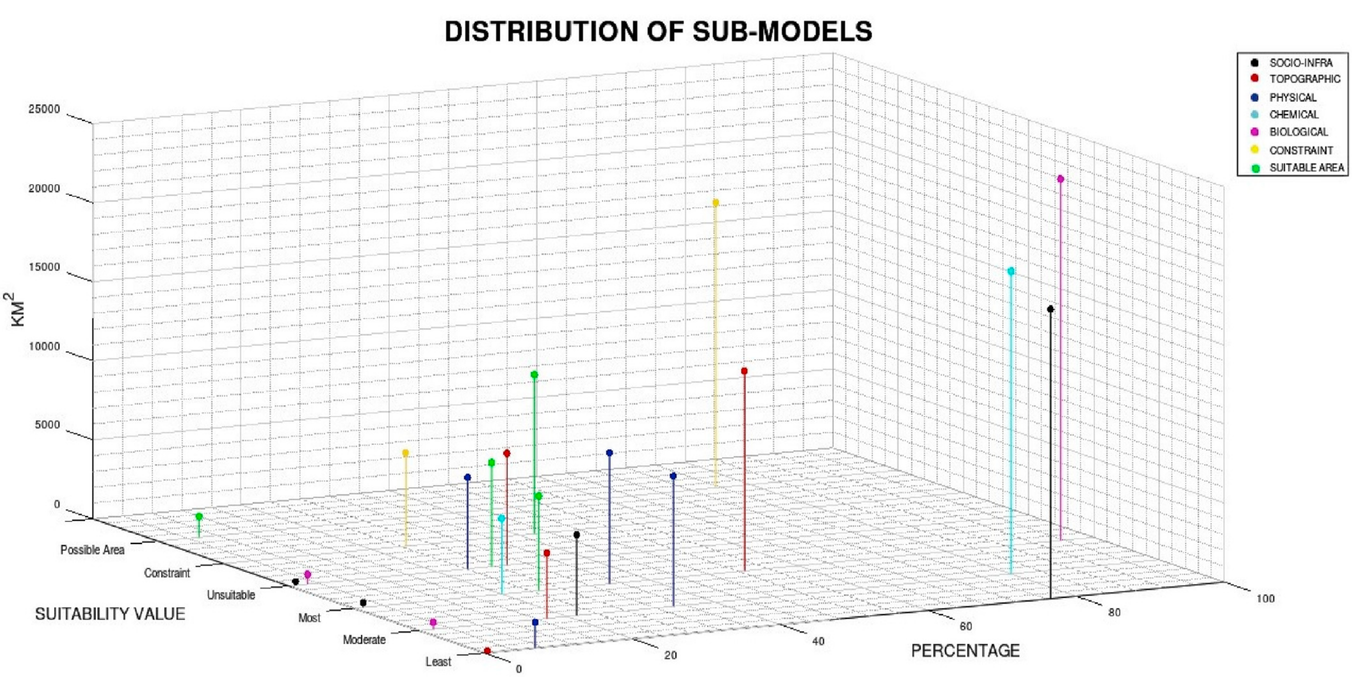

Fig. 10. Distribution of suitability levels in sub-models. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

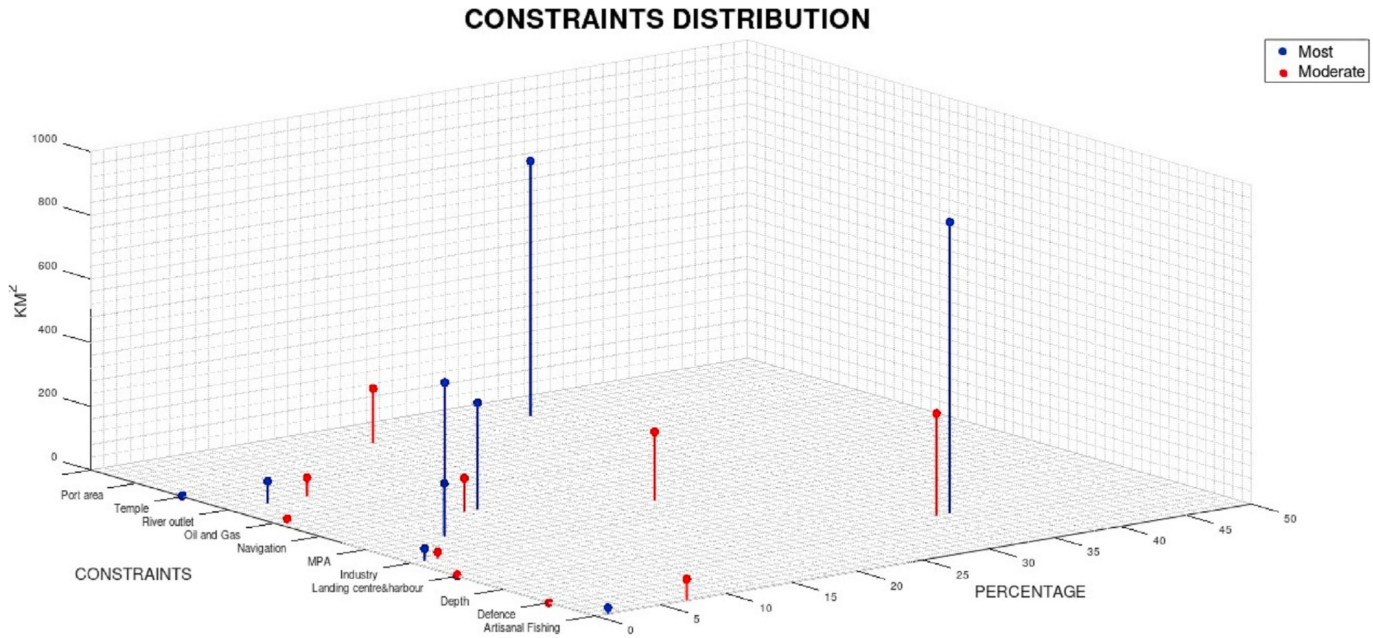

Fig. 11. Constraints distribution in potential areas. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

for the future sustainability developments in the field of mariculture. Location specific individual biological models or an ecosystem-based consideration will be essential for holistic future research and development (Brigolin et al., 2017).

At present there are no standardized set of criteria and suitability indicators for coastal aquaculture, although there exists a need for their establishment and implementation (Frankic and Hershner, 2003; Kapetsky and Aguilar-Manjarrez, 2007). Remotely sensed data is an important and cost-effective approach for developing countries and data-poor regions for site selection processes. The use of satellite data for aquaculture planning has been emphasized by many studies (Aguilar-Manjarrez et al., 2010; Longdill et al., 2008; Radiarta et al., 2008). Improved methods for data access, particularly remotely sensed data, will enable better spatial coverage for site selection studies with fewer and scattered in-situ measurements, especially in developing countries where there is a scarcity of these.

Potential sites identified through the final model, had all appropriate topographic, oceanographic (physical, chemical, biological) and socio-infrastructural parameters. The developed submodels mainly focused on the areas of maximum interest for development of mariculture of commercially important fish species in various culture systems which were demonstrated in India by ICAR-CMFRI along the sub-continent. The model well assessed the culture feasibility of available candidate species in the country i.e., Asian seabass, *(Lates calcarifer)*, Cobia *(Rachycentron candum)*, Silver pompano *(Trachinotus blochii)*, Indian pompano *(T. mookalee)*, Spiny lobster, *(Panulirus polyphagus)*, Grouper *(Epinephelus coioides)*, etc.

Use of science-based decision making tools is necessary for sustainable aquaculture (Samuel-Fitwi et al., 2012). Our model not only used science-based techniques but also used social knowledge for selecting sites, thus incorporating the intangible knowledge of the primary stakeholder in the decision making process. This combination of science and field experience led us to develop a model that ensures sustainable aquaculture production with minimum impacts on the ecosystem while integrating other potential uses for the selected sites. The lack of environmental considerations in aquaculture has been quoted as a major barrier for the development of environmentally sustainable production (Luna et al., 2019). As mentioned earlier, consideration for environment has been used in the biological selection criteria where the choice was made based on sustainability of the environment with a motto of cleaner and sustainable production. Moreover, onus has been to select sites which are closer to moderately developed infrastructure which could promote effective utilization of existing facilities rather than creating new ones thereby reducing impacts on the ecosystem.

5. Conclusions

The methodological approach presented in this paper demonstrated the development of region-specific GIS-MCE models for identifying the most suitable sites for mariculture development in Indian territorial waters of Gujarat state. We developed a GIS-MCE model that included multiple aspects of the ecosystem (topographic, physical oceanographic, chemical oceanographic, biological oceanographic and socio-infrastructural) as well as inputs of stakeholders and experts to identify “most”, “moderate” and “least” suitable sites for cage mariculture. The model we developed had a framework with an objective set of criteria which can be adapted not only for the region or for the country but also for those countries located in similar agro-climatic conditions too. This study was a novel and first attempt for Indian waters and systems. Our study can be seen as the first step towards providing a scientific tool for marine spatial plan (MSP) for the region which so far is still in its infancy in the country.

Although GIS-MCE model is useful as a site selection tool, the final suitability map was limited by some level of uncertainty in extracting more accurate maps. The criteria judged in the present study may change in future based on the perspectives and priorities of the stakeholders and decision makers. Therefore, the present model may need further fine tuning through supplementary additions or even better refinements based on such mentioned aspects. We suggest that the long-term regional/location specific

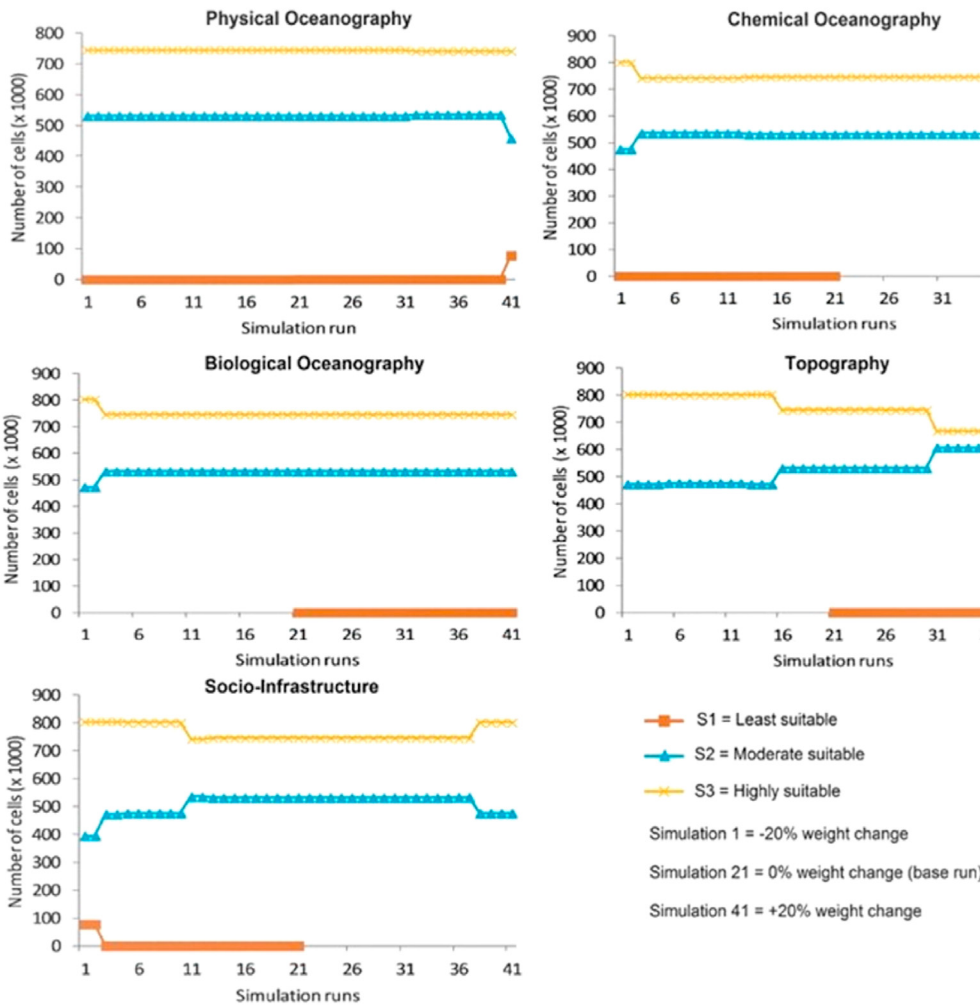

Fig. 12. Number of cells changed from simulation runs in sensitivity analysis (40 runs for each criteria). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

working experience, familiarity with the coast and stakeholder's interaction has great importance in judging the factors to support the decision-making process for the development of the most viable spatial model for mariculture. This is particularly imperative for developing countries where socio-political issues play a decisive role in decision making, than rest other factors of site suitability.

6. Recommendations

The study offers an efficient method for marine cage site selection in the territorial waters of the Indian sub-continent. Our study could able to successfully integrate expert knowledge, experience in the field, remotely sense data of the environment and stakeholder's views in a systematic manner for arriving at a suitable model for site selection procedures for marine cage culture. These preliminary modelled potential sites along Gujarat coast can be zoned by addition of necessary need based supplementary data or experimentation or applying novel models. Ultimately, an integrated comprehensive marine spatial plan (MSP) in combination with inter-sector maritime space users is the need of the hour at regional and national levels. We recommend a similar modelling exercise for other sites along the Indian coastline to study the adaptability and efficiency of the model as well as potential modifications if required as and when to this model.

The Government of India under its Blue Revolution initiative has placed high emphasis on cage culture along the Indian coast (NFDB, 2020). Our model would be an ideal tool for site selection for the forthcoming expansion of cage culture in the country. Most of the Indian coastal stretch will fall into the criteria which we have used for building the base model. In fact, our study site of Gujarat coast is one of the most diverse and challenging in India including a sensitive international boundary, major river mouths, wetlands, gulf areas, marine protected areas, marine fisheries and coastal industries. The evaluation criteria, matrix development and benchmarking the parameters for analysis which were used for sea cage structural influences and biological requirements for fish culture used are applicable to the whole Indian coast. This model applied with necessary region-wise modifications can extract the best suitable locations for mariculture development along territorial waters of other states in the country. The model can be adjustable to any new criterion and can be incorporated to the base model which reflects the elasticity of the developed model.

For the eco-system based marine space management by balancing multiple sector activities, India must initiate MSP similar

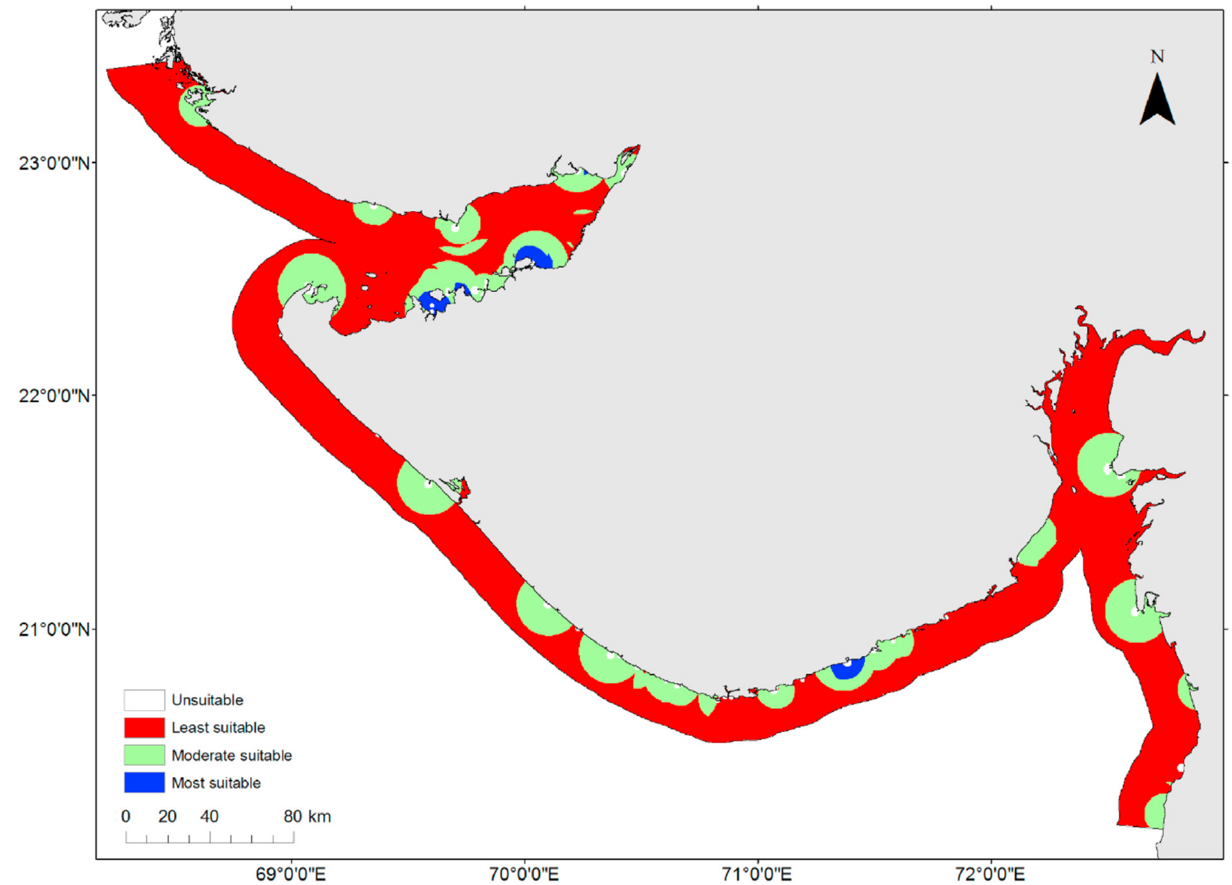

Fig. 13. Socio-Infrastructural suitability model. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

to European Union (European MSP Platform, 2009), Indian Ocean Rim Association (IORA-MSP, 2017), Australia (Ehler and Douvere, 2009), Japan (Nakornchai et al., n. d.), etc. to achieve the sustainable development goals (SDG's) in particular to SDG-14 (Life below water) which is one of the key goal which influences most of the other goals directly or indirectly of Global Agenda (2030) through a holistic approach.

CRediT authorship contribution statement

Damodaran Nair Divu: Funding acquisition, Project administration, Conceptualization, Investigation, Supervision, Resources, Methodology, Data curation, Writing - original draft, Writing - review & editing. **Suresh Kumar Mojjada:** Conceptualization, Methodology, Investigation, Formal analysis, Validation, Visualization, Supervision, Project administration, Writing - original draft, Writing - review & editing. **Abdul Azeez Pokkathappada:** Data curation, Formal analysis, Software, Validation. **Kapil Sukhdhane:** Investigation, Data curation, Formal analysis. **Muktha Menon:** Visualization, Resources, Writing - original draft, Writing - review & editing. **Ramesh Kumar Mojjada:** Software, Methodology, Formal analysis, Validation, Visualization, Resources. **Mayur Shivdas Tade:** Data curation, Methodology, Formal analysis, Validation, Resources. **Hiralal Mepabhai Bhint:** Investigation, Data curation, Resources. **Achemveettil Gopalakrishnan:** Resources, Funding acquisition, Project administration, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.124760.

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