HABITAT SUITABILITY MAPPING OF PYGMY BLUE WHALE (*B. m. indica*) IN SRI LANKA USING A GIS-BASED FUZZY AHP ANALYSIS

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ABSTRACT

Sri Lanka is a hotspot for pygmy blue whales. The current blue whales' studies in Sri Lanka depend on boat surveys, which operate seasonally and in only two locations. Therefore, it is essential to model their habitat suitability in the Sri Lankan Ocean using limited survey data and habitat modeling techniques. The study aims to model pygmy blue whales' habitats distribution around Sri Lanka by Fuzzy AHP technique-based GIS. The study area was the ocean around Sri Lanka territory. The study used the data from the years from 2004 to 2019. Bathymetry criteria: slope, distance to shoreline, water depth, and ocean environmental criteria: chlorophyll a (CHL), Sea Surface Temperature (SST), and Sea Surface Salinity (SSS) was used. Six criteria maps were created based on optimum living conditions of pygmy blue whales. The questionnaire data were analyzed using FAHP pair-wise matrix and resulted in normalized fuzzy weights for every six criteria. A spatial model runs in ArcGIS 10.7 to model blue whale habitats' suitability areas. Validation was done by calculation of the ROC curve and the AUC values. The blue whales' habitat map of Sri Lanka (2004-2019) identified the most suitable areas around Sri Lanka, except the Northern part of Sri Lanka, with high accuracy. Highly suitable areas consist of near-to-shoreline regions and along the continental shelf area, displaying optimum productivity. Seasonal movements of pygmy blue whales around Sri Lanka can be visualized as highly suitable, moderately suitable, and less suitable. During the northeast season, whales are highly gathered around the west and south coast; during the First inter monsoon, whales are highly gathered around Sri Lanka and are known as peak season. During Southwest, monsoon whales are highly gathered around the west and northeast coast, and finally, during the Second inter monsoon, whales are highly gathered around Sri Lanka except in northern areas. Therefore, pygmy blue whales' habitats map, based on fuzzy AHP, are accurate and can provide direction for future prospecting.

Keywords: pygmy blue whales, habitat modeling, Google Earth Engine, fuzzy AHP

1 Introduction

Whales are marine mammals belonging to the order *Cetacea*. Sri Lanka is a hotspot for baleen and tooth whales due to the warm tropical climate, abundant annual rainfall, and vibrant coastal waters. Blue whale species around Sri Lanka are identified as specific to the North Indian Ocean (NIO), named pygmy blue whale (*Balaenoptera musculus indica*; *B. m. indica*). It inhabits the warm tropical water year-round and is unique due to short migratory routes and different communication (de Vos *et al.,* 2012). Pygmy blue whales are abundant year-round in the Sri Lankan ocean, the second-highest richness after the Arabian Sea (Afsal *et al.,* 2008; Randage *et al.,* 2014).

The problem of identifying blue whale habitats in Sri Lanka is that data is limited to certain areas where blue whales operations and certain distances from the Sri Lanka coast. Another limitation of blue whales' habitat identification based on boat surveys depends on the ocean's prevailing weather conditions. There is rough weather from May to October. Thus, it has restricted opportunities for whale surveys in all months.

There is high importance of mapping blue whale habitats in the Sri Lankan ocean for future projects in the sea. This is not easy work using limited boat surveys and rough weather in the sea. It is possible to do habitat modeling using new technology such as satellites, spatial technologies, etc.

Therefore, research questions of the study are,

1. How to map highly suitable, moderately suitable, and less suitable areas of blue whales distribution in a poorly understood marine ecosystem with less number survey data using GIS?
2. How pygmy blue whales' habitats are changing in different monsoon seasons?

Habitat models are essential tools for linking whales' sightseeing to habitats preferences variables. Satellite-derived ocean data are readily obtainable in Google Earth Engine (GEE) for geo-spatial analysis and visualization with its fast processing speed facilities. Therefore, ocean environmental parameters can be mapped using daily available satellite images in GEE. Fuzzy AHP based GIS techniques use for modeling different raster layers based on experts' evaluation. This kind of human

judgment, uncompleted judgment, information, and uncertainties can be solved by Fuzzy logic. Fuzzy weights for each habitat parameter can be used for spatial modeling in the model builder in the GIS environment to map whales' distribution. Therefore, as a novel framework, the present study aims to map potential habitats for pygmy blue whales around Sri Lanka (2004-2019) using Fuzzy AHP based GIS.

2 Research Methodology

2.1 The Study Area

The study area is Sri Lankan onshore and offshore areas, located between 5° and 12° of the equator. The area was selected for the study; since blue whales are large animals who move around Sri Lanka, it is important to cover whole Sri Lankan water without confine to one area. The Figure 1 shows the study area and pygmy blue whales' distribution in Sri Lankan water based on boat survey data.

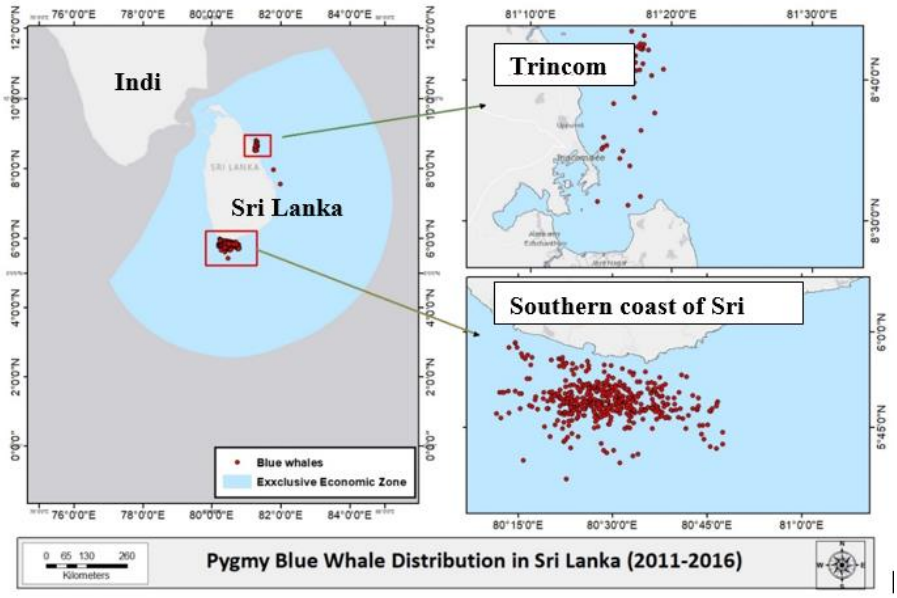

Figure 1: The study area and pygmy blue whales' distribution in Sri Lankan water

2.2 Conceptual framework

The conceptual framework of the study is shown in Figure 2.

2.3 Data and sources

Table 1 shows data and their sources.

Table 1: Data and their sources

Parameter	Unit	Dataset (resolution)	Data period
Depth	m	GEBCO	2020
Slope	degree	GEBCO	2020
Distance from shore	m	GEBCO	2020
CHL	mgm-3	MODIS-Aqua/L3/SMI (daily)	2004-2019
SST	°C	MODIS-Aqua/L3SMI (daily)	2004-2019
SSS	psu	"HYCOM/sea_temp_salinity" (daily)	2004-2019
514 number of whales location	GPS	Russel et al., 2020; Russel and Tilak, 2020; Randage et al., 2014; SL Navy, 2020	2012-2016

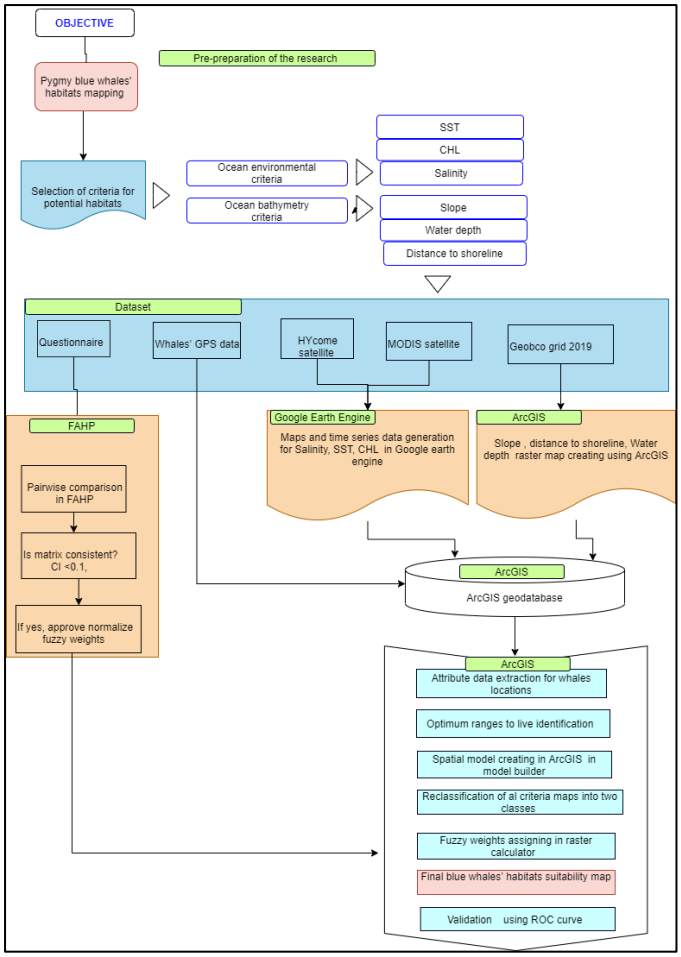

Figure 2: The conceptual framework of the study

2.4 Six Criteria map generation for whales' habitats suitability

2.4.1 Slope

Slope angle is one of the most impacting factors of whales' sightseeing in Sri Lanka. The slope map was prepared from the bathymetry grid: General Bathymetric Chart of the Oceans grid 2020 (GEBCO, 2020) using the 'Spatial Analyst extension' in ArcGIS 10.7 (ESRI, 2011). It was projected into the Sri Lanka Kandawala projection grid to overlap blue whales' observations (Figure 3). The 'Extract values to points' feature in ArcGIS 10.7 was used to extract slope values for blue whales' locations. This slope range was used as the optimum range for blue whales living in Sri Lanka. The slope map was reclassified into two classes (2= highly suitable for whales living, 1= less suitable for whales living) as in Table 1.

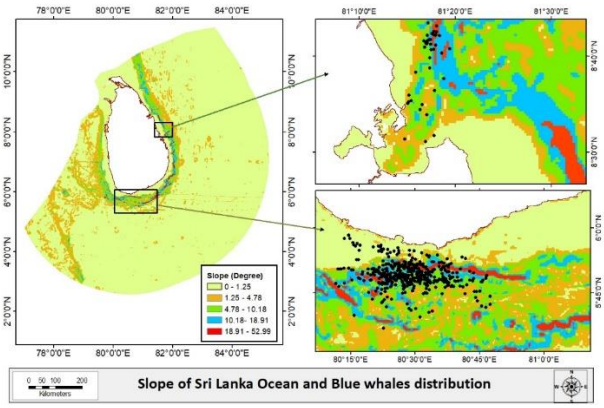

Figure 3: Slope map of Sri Lankan ocean

Table 2: Reclassification of bathymetry criteria for blue whales mapping

Table 2: Data and their sources

Factor	2= Suitable	1= Less suitable
Depth (m)	-30 to -4522	<-30 and >-4522
Distance to shoreline (m)	500 -38 ,000	<500 and >38 ,000
Slope (degrees)	0.1- 45	<0.1 and >45

2.4.2 Water Depth

Water depth is one of the essential bathymetries which cause blue whales aggregation in Sri Lanka. It was mapped from the GEBCO-2020 grid (GEBCO, 2020). It was projected into the Sri Lanka Kandawala projection grid to overlap blue whales' observations (Figure 4). The 'Extract values to points' feature in ArcGIS 10.7 was used to extract water depth values for blue whales' locations. This water depth range was used as the optimum range for blue whales living in Sri Lanka. The water depth map was reclassified into two classes (2= highly suitable for whales living, 1= less suitable for whales living) as in Table 2.

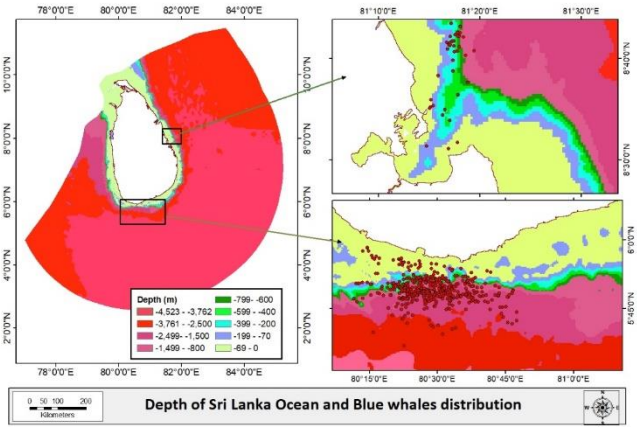

Figure 4: Depth map of Sri Lankan ocean

2.4.3 Distance to Shoreline

Distance to the shoreline is an essential factor to decide whales' suitability in Sri Lanka. Therefore, the distance to coastlines was included for the mapping of blue whales. The data was derived from the GEBCO 2020 grid using the Euclidean distance feature in ArcGIS 10.7. It was projected into the Sri Lanka

Kandawala projection grid to overlap blue whales observations (Figure 5). The 'spatial join tool' feature in ArcGIS 10.7 was used to extract distance to the shoreline values for blue whales' locations. This distance to the shoreline was used as the optimum range for blue whales living in Sri Lanka. Distance to shoreline map was reclassified into two classes (2= highly suitable for whales living, 1= less suitable for whales living) as in Table 2.

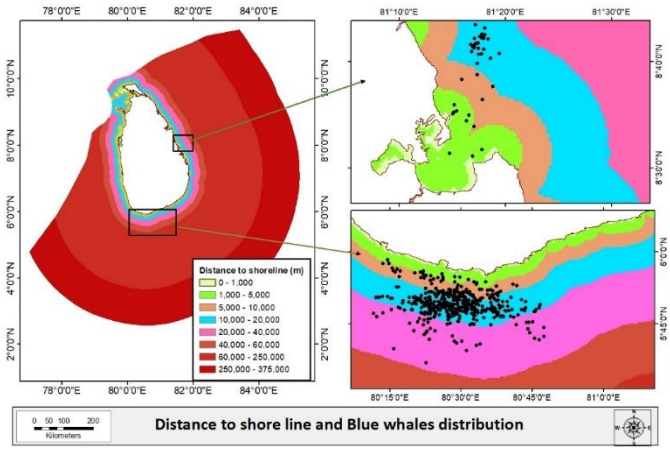

Figure 5: Distance to shoreline map of Sri Lankan ocean

2.4.4 Chlorophyll a (CHL)

CHL plays a vital role in the productivity of blue whales' krill diet. CHL maps were created for 2004-2019 and seasons using MODIS-Aqua/L3/SMI (daily) 500 m resolution products in Google Earth Engine. The 'Extract values to points' feature in ArcGIS 10.7 was used to extract CHL values for blue whales' locations. This CHL range and literature-based optimum range were used as the optimum range for blue whales living in Sri Lanka.

2.4.5 Sea Surface Salinity (SSS)

SSS plays a role in the krill availability and physiology of blue whales. SSS maps were created for 2004-2019 and seasons using HYCOM/sea_temp_salinity in Google Earth Engine. The 'Extract values to points' feature in ArcGIS 10.7 was used to extract SSS values for blue whales' locations. This SSS range and literature-based optimum range were used as the optimum range for blue whales living in Sri Lanka.

2.4.6 Sea Surface Temperature (SST)

SST has effects on blue whale habitats as an indicator of krill availability. SST maps were created for 2004-2019 and seasons using MODIS-Aqua/L3/SMI (daily) 500 m resolution products in Google Earth Engine. Figure 6 shows spatial maps for CHL, SST, and SSS during 2004-2019. The 'Extract values to points' feature in ArcGIS 10.7 was used to extract SST values for blue whales' locations. This SST range and literature-based optimum range were used as the optimum range for blue whales living in Sri Lanka.

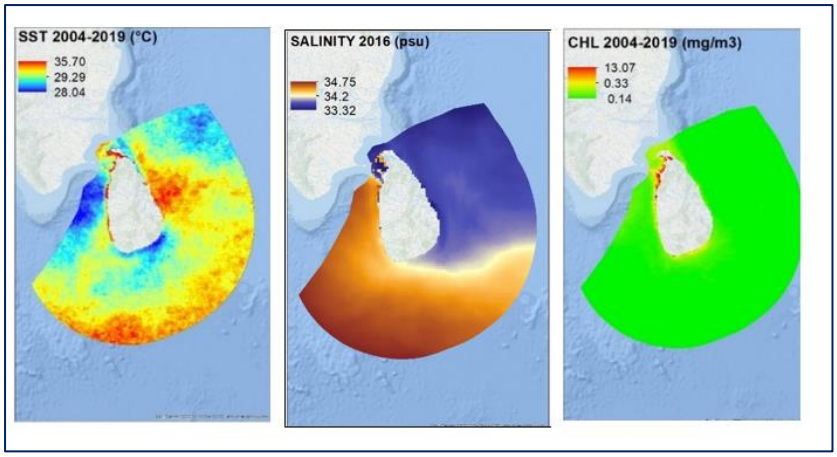

Figure 6: Spatial maps for (A) SST, (B) Salinity, (C) CHL in Sri Lankan ocean (2004-2019)

Reclassification of google earth engine derived CHL, SSS, and SST during 2004-2019 was done into two classes (2= highly suitable for whales living, 1= less suitable for whales living) as shown in Table 3.

Table 3: Reclassification of ocean environmental criteria for habitats suitability maps of 2004-2019

Factor	2= Suitable	1= Less suitable
SALINITY (psu) of 2004-2019	33.5-34.78	<33.5- and >34.78
SST (°C) of 2004-2019	28.037-29.7	<28.037 and >31
CHL (mgm-3) of 2004-2019	0.141-1.99	<0.141 and >1.99

Reclassification of google earth engine derived CHL, SSS, and SST during 2004-2019 in four seasons was done into two classes (2= highly suitable for whales living, 1= less suitable for whales living) in Table 4. Four seasons of monsoon in Sri Lanka are based on rainfall intensity.

- North-east monsoon: NEM season of 2004-2019 (Jan, Feb, Dec)
- First inter monsoon: FIM seasons of 2004-2019 (March, April)
- Southwest monsoon: SWM seasons of 2004-2019 (May, June, July, August, Sept)
- Second inter monsoon: SIM seasons of 2004-2019 (Oct, Nov)

Table 4: Reclassification of ocean environmental criteria for four seasonal habitats suitability maps of 2004-2019

Factor	2= Suitable	1= Less suitable
NEM season of 2004-2019 (Jan, Feb, Dec)		
SALINITY (psu)	33.5-34.5	<33.5 and >34.5
SST (°C)	28.03-29.5	<28.03 and >29.5
CHL (mgm-3)	0.17-1.54	<0.17 and >1.54
FIM seasons of 2004-2019 (March, April)		
SALINITY (psu)	33.6-34.34	<33.6 and >34.34
SST (°C)	28.92-30.14	<28.92 and >30.14
CHL (mgm-3)	0.13-0.3	<0.13 and >0.3
SWM seasons of 2004-2019 (May, June, July, August, Sept)		
SALINITY (psu)	33.7-34.8	<33.7 and >34.5
SST (°C)	27.5-29.5	<27.5and >29.5
CHL (mgm-3)	0.17-1.9	<0.17 and >1
SIM seasons of 2004-2019 (Oct, Nov)		
SALINITY (psu)	34.59-34.78	<34.59 and >34.78
SST (°C)	27.44-29.67	<27.44 and >29.67
CHL (mgm-3)	0.18-1.99	<0.18 and >1.99

2.5 Fuzzy AHP Data Analysis

Firstly, a questionnaire-based interview was done with marine biologists, conservationists, and researchers with expertise in blue whales in Sri Lanka to determine the importance of different factors based on AHP, Saaty's model (1996). The selected data were calculated as in Putra et al. (2018) and normalized fuzzy weights, as mentioned in Table 5.

Table 5: Normalized mean fuzzy weights for each criteria

Criteria	Normalized fuzzy weights	Ranking
SST	0.274	2
Salinity	0.027	6
Chl	0.414	1
Depth	0.086	4
Distance to shoreline	0.069	5
Slope	0.131	3

2.6 Spatial Modelling of Habitats Suitability Map

The blue whale's habitat suitability model was created in model builder in ArcGIS 10.7, as shown in Figure 7. The six criteria maps reclassified into two classes were calculated with fuzzy normalized weights in the raster calculator. Final suitability maps for the 2004-2019 period and four seasons (2004-2019) were created and reclassified into three classes (1= less suitable, 2= moderately suitable, 3= highly suitable) based on histogram and manual reclassification (Table 7). To determine the statistical reliability of the results, the area under the AUC curved was employed for all suitability maps by plotting the Relative Operating Characteristics (ROC) curve. The AUC value is a good indicator to evaluate the model's prediction performance, and the largest AUC, from 0.7 to 1.0, is the most ideal model (Yilmaz, 2010).

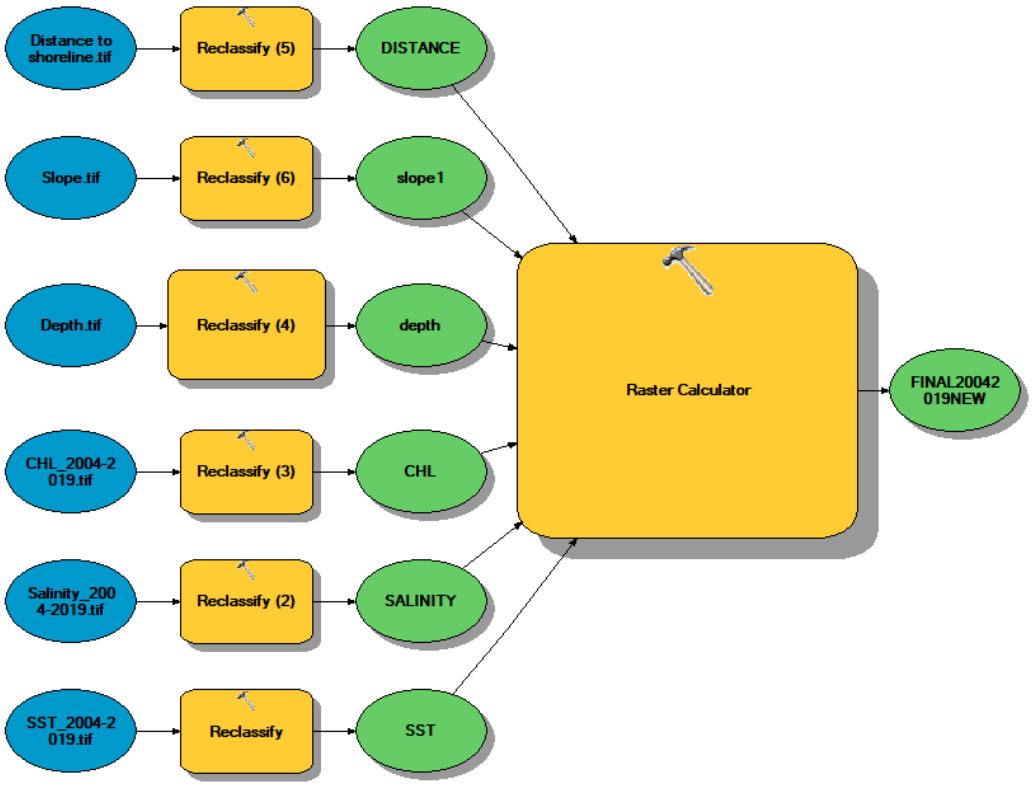

Figure 7: Pygmy Blue whales habitats suitability model in model builder

Table 6: Reclassification of final whales' habitats maps

Map	Less suitable	Moderately suitable	Highly suitable
2004-2019	1-1.77	1.77-1.93	1.93-2.11
NEM season	1-1.47	1.47-1.75	1.75-2.2
FIM season	1-1.34	1.34-1.85	1.85-2.14
SIM season	1-1.68	1.68-1.93	1.93-2.24
SWM season	1.2-1.6	1.6-1.9	1.9-2

3 Results and Discussion

3.1 Pygmy Blue Whales Habitats Map (2004-2019) in Sri Lankan Ocean

The blue whales' habitats map of Sri Lanka for 2004-2019 identified highly suitable areas all around Sri Lanka except the northern part of Sri Lanka (Figure 8). Highly suitable areas consist of near-to-shoreline regions and the continental shelf area. The migration of blue whales around the north part of Sri Lanka is unlikely to do due to the Palk Straight being so shallow with less than 100 m depth (Hydrographic Office, 2007). The AUC value for the Pygmy blue whales habitats map of the 2004-2019 year period in the Sri Lankan ocean is 0.891. Thus, the model is highly accurate.

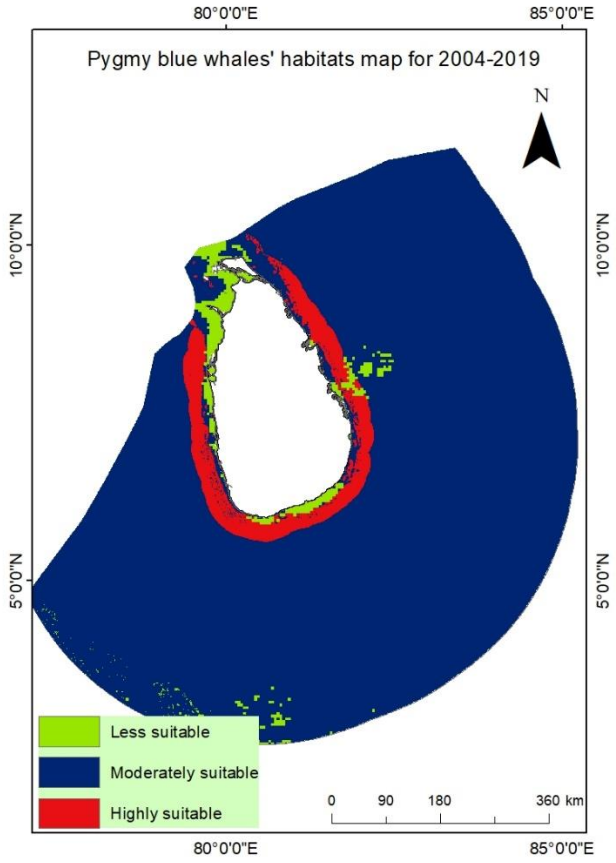

Figure 8: Pygmy blue whales habitats map (2004-2019) in Sri Lankan ocean

3.2 Pygmy Blue Whales Habitats Map for NEM (2004-2019)

Northeast monsoon (NEM) includes from December to February months. Highly suitable areas for blue whales can be identified on the western coast and south of Sri Lanka during NEM season (Figure 9). The model accuracy is 0.71. From the model by Redfern et al. (2017), the west coast of Sri Lanka has been identified as a blue whales gathering area during NEM. During NEM, after the SWM, there is a disperse of blue whales' highly suitable regions in Figure 9. This is due to weak upwelling current and whale aggregate where high productivity available. De Vos *et al.* (2014) proved this, whales' feeding areas become wider and disperse during NEM than congested.

There is an absence of blue whales in the northeast during NEM, according to Nanayakkara et al. (2014), due to strong onshore winds. During NEM, there are fewer chlorophyll concentrations than SWM but, there is a high aggregation of whales on the south coast during NEM (De Vos *et al.,* 2014). During NEM, the southern coast and west coast are highly suitable. This might due to blue whales travel from the south coast to Bengal Bay offshore in south Sri Lanka and migrate from the Maldives to Sri Lanka during NEM (Charles et al., 2012).

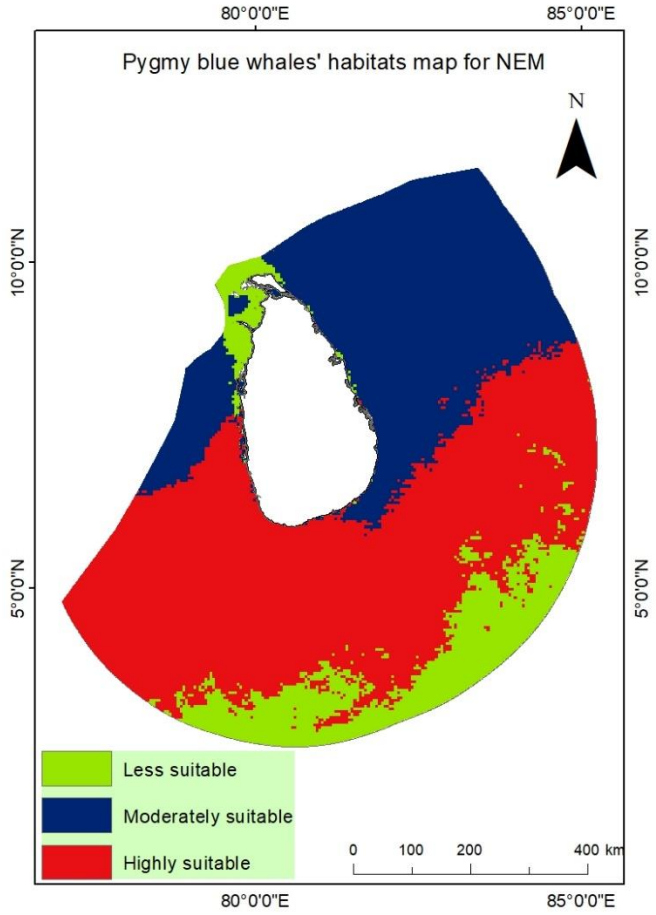

Figure 9: Pygmy blue whales habitats map for NEM (2004-2019) in Sri Lankan ocean

3.3 Pygmy Blue Whales Habitats Map for FIM (2004-2019)

First Inter Monsoon (FIM) includes from March to April months. The blue whales' habitat map for the FIM season (2004-2019) year in the Sri Lankan ocean shows that blue whales' suitability areas are around Sri Lanka. (Accuracy = 0.97). According to de Vos *et al.* 2014, during FIM, blue whales are around the East, South, Northeast of Sri Lanka. Many whales were sighted on the East coast during FIM season (Charles *et al.,* 2012). Priyadarshana et al., 2014 identified the FIM season as a high peak for sightseeing on the south coast of Sri Lanka. Charles et al., 2012 found that whales are highly visible in Sri Lanka (northeast, east, and south) during FIM than in other seasons.

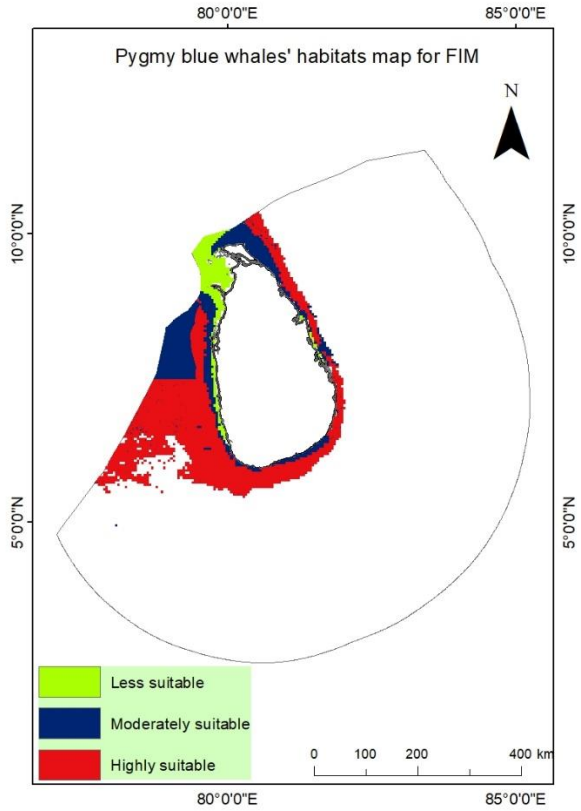

Figure 10: Pygmy blue whales habitats map for FIM (2004-2019) in Sri Lankan ocean

3.4 Pygmy Blue Whales Habitats Map for SWM (2004-2019)

South West Monsoon (SWM) included from May to September months. There is a high suitability for blue whales during SWM in Sri Lanka, west coast and north east coast, than south coast (Accuracy = 0.96, Figure 11). This is due to high upwelling and increased productivity for food for whales (de Vos et al., 2014a; Afsal et al., 2018). During SWM, blue whales show localization and movement based on strong upwelling currents (Anderson *et al.,* 2012). Anderson et al., 2012 and Charles *et al.,* 2012 identified the west coast of Sri Lanka as a whales-gathering area during SWM. There are highly suitability for whales inn northeast and east coast also. This might due to whales are moving from the Northeast coast to the south via the east coast of Sri Lanka to move to the Arabian sea (Charles *et al.,* 2012). Therefore, the Sri Lanka coast in the north, east, south, and west are highly suitable areas for blue whales during SWM as their local feeding or movement to another site.

3.5 Pygmy Blue Whales Habitats Map for SIM (2004-2019) in Sri Lankan Ocean

Second Inter Monsoon (SIM) includes from October to November. Blue whales habitats are highly abundant around Sri Lanka during SIM (accuracy= 0.93, Figure 12).

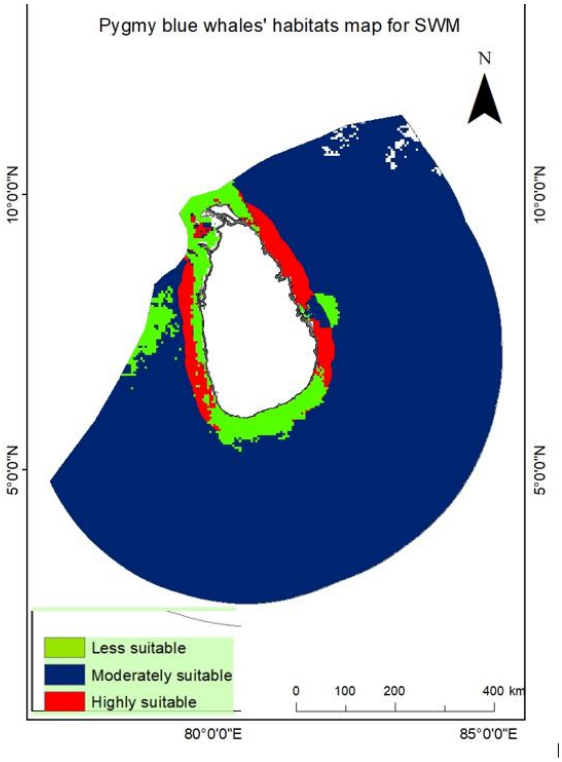

Figure 11: Pygmy blue whales habitats map for SWM (2004-2019) in Sri Lankan ocean

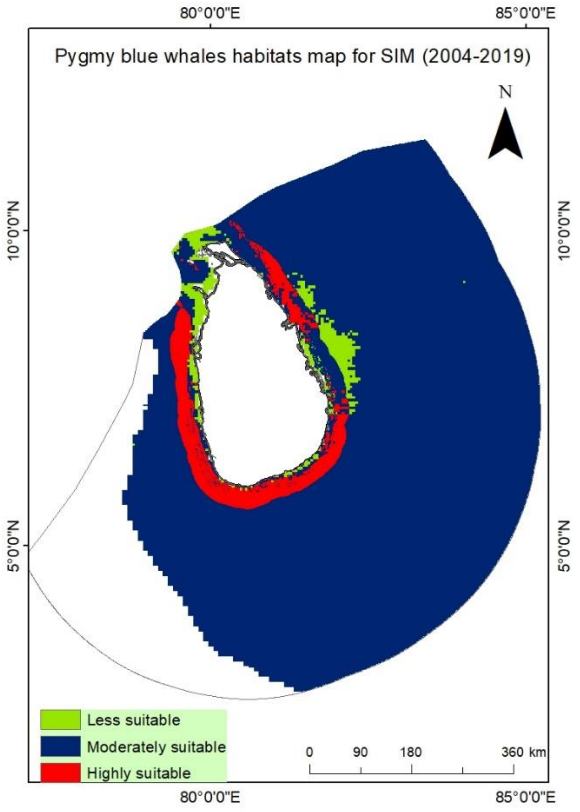

Figure 12: Pygmy blue whales habitats map for SIM (2004-2019) in Sri Lankan ocean

4 Conclusions

The main outcome of the research is the pygmy blue whales' habitats suitability model in Sri Lankan water. The map can use for future ocean projects' planning and conservation purposes. Other outcomes are four seasonal maps of pygmy blue whales' habitats, which indicate their movement during the year. At the beginning of the year (during NEM season, December to February), pygmy blue whales' habitats are highly suitable on the south coast and west coast. This might whale move from the Maldives to Sri Lanka during this season. After NEM, during FIM season (March to April), blue whales' highly suitable areas are around Sri Lanka, except the northern part. This season is known as a peak season in different regions of Sri Lanka to sightseeing whales. After FIM, during the SWM period (May to September), current blue whales are localized in few areas based on high upwelling. Now, the North east area is not highly suitable and south coast near the shoreline due to strong winds. During SWM, whales move from northeast to south via the east coast. Also, during SWM, the west coast is a highly suitable area. After SWM, during SIM season (October to November), blue whales show again around Sri Lanka before starting NEM within a month.

In Sri Lanka, there are fewer recorded blue whales during SWM due to rough weather around Sri Lanka. Also, there is no study covering four seasons and all Sri Lankan water to understand pygmy blue whales' habitats. Therefore, this study is essential. The limitation of this research was related to FIM and SIM seasons due to the absence of MODIS satellite data daily to cover the whole study area.

Finally, the present research concludes that GIS-based Fuzzy AHP in blue whales' habitats modelling is possible with fewer blue whales' data. These maps can be used for future environmental assessment of the proposed ocean-related projects and conservations.

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