Modelling Migratory Pinch Points and Connectivity of Pygmy Blue Whale Using Circuit Theory: A Case Study of Savu Sea, Indonesia

Muhammad Shulhan Jihadi[1]*, Muhammad Zainuri[1,2], Virginia Andrews-Goff[3], Rikha Widiaratih[1], Kunarso[1], Elis Indrayanti[1]

[1]Oceanography Department, Faculty of Fisheries and Marine Science, Universitas Diponegoro
Jl. Prof. Jacub Rais, Tembalang, Semarang, Central Java 50275, Indonesia
[2]Center for Coastal Rehabilitation and Disaster Mitigation Studies, Universitas Diponegoro
Jl. Prof. Soedarto SH., Tembalang, Semarang, Central Java, 50275, Indonesia
[3]Australian Antarctic Division, Department of Climate Change, Energy, the Environment and Water
203 Channel Highway, Kingston, Tasmania 7050, Australia
Email: shulhanj@alumni.undip.ac.id

Abstract

Blue whale and their subspecies is an endangered whale species that needs to be conserved by protecting their important habitat and migration corridor. Research about designing and modelling blue whale habitat for marine protected area has been done many times. However, incorporation of connectivity in marine protected areas design and management has been limited due to the complexity of methods used to model connectivity, therefore the implementation among practitioners is inconsistent. An alternative method to model connectivity of pygmy blue whale habitat is discussed through a combination of maximum entropy model and circuit theory. The habitat suitability models were made using satellite-tagged pygmy blue whale data (2012-2016) and oceanographic variables, such as sea surface temperature, chlorophyll, salinity, bathymetry, and seafloor geomorphology for four season that is March-April-May (MAM), June-July-August (JJA), September-October-November (SON), and December-January-February (DJF). The habitat suitability model shows different importance of environmental variables in their preference of habitat in each season, with distance from slope as the most influential parameter during the migration season (54.4% for MAM, 37.8% for SON), mean climatological chlorophyll during winter (31%), and mean climatological sea surface temperature during summer (54.7%). Habitat suitability result were then used to model connectivity, assuming that the whales migrate during MAM and SON. The migration model from Omniscape showed some pinch point, such as Sumba-Sape strait, Alor strait, Rote strait, Ombai strait. These pinch points can be seen as corridors with high potential of pygmy blue whale migration or high connectivity, therefore this area could become priority for conservation.

Keywords: *pygmy blue whale, migration, connectivity, circuit theory, Australia-Indonesia*

Introduction

Blue whale is an endangered species of whale (Cooke, 2018) that needs to be conserved by protecting their important habitat and migration corridor (Lesage *et al*., 2017), as they are also threatened by human activity during their migration such as from ship strikes (Owen *et al*., 2016). Research about blue whale has been done many times (Mustika *et al*., 2006; Double *et al*., 2014; Abrahms *et al*., 2019; Moller *et al*., 2020; Maro *et al*., 2021; Sahri *et al*., 2022). However, incorporation of connectivity in marine protected areas design and management has been limited due to the complexity of methods used to model connectivity, therefore the implementation among practitioners is inconsistent (Balbar and Metaxas, 2019). There are several methods for modeling migration corridors or species movement and gene flow. One commonly used method is the least cost path (LCP). Although this method can provide an overview of the most effective and efficient movement paths, it cannot provide other possible alternative paths that a species might take. The application of circuit theory in modeling migration corridors or species movements can be a solution to the limitations of commonly used methods (McRae, 2008). This theory applies the concept of an electronic circuit which uses components such as resistance (resistors), conductors, currents, and electrical paths (graphs) into a raster layer of the earth's surface or natural features to be modeled into a current map that can depict a potential movement of a species. In circuit theory an electric current flow from a source to a destination through a medium that has a resistance value. The greater the resistance, the smaller the electric current that flows. In modeling species migration, resistance can be thought as the suitability of a location for a species. If a location is more suitable, then the resistances will be smaller, whereas if the place is not suitable, the resistance

*) Corresponding author

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will be greater. Electric current is analogue to the potential for a species to pass through a place. If the resistance is large (the place is not suitable), then the potential for that place to be traversed will be smaller.

Circuit theory is a method that has been widely used in modeling migration corridors on land (Poor *et al*., 2012; Jones *et al*., 2015; Algeo *et al*., 2017; Burke *et al*., 2019; D'elia *et al*., 2019; Wieringa *et al*., 2021), but has not been widely used in the marine environment. In Australian and Indonesian waters, the circuit theory method was used by Boussarie (2020) to model the barrier and gene flow of gray reef sharks. Circuit theory also outperformed other modelling methods when creating ecological connectivity model that has a known source and destination (McRae and Beier, 2007; Unnithan Kumar, 2022), therefore, it would be an improvement if applied in the research and conservation of marine biota.

Materials and Methods

The application of circuit theory in migration modeling requires 2 data; the source-destination layer and the resistance layer. The electrical current that flows from the source to the destination is analogues to the blue whale that is migrating between their summers and winter habitat, on the other hand the resistance layer act as a circuit where blue whale is moving towards and from their destination. The degree of how difficult it is for the whale to move is represented by the suitability of the location, with more suitable location has more potential for the whale to traverse to. The source-destination and the resistance layer is created using maxent to model four seasonal habitat suitability, with the assumption that in austral winter (June-July-August or JJA) the pygmy blue whale is in warmer waters (at the equator), and moves southward in September-October-November (SON) to head to waters in southern Australia which have cooler temperatures during the austral summer (December-January-February or DJF). After summer is over, whales move north again in March-April-May (MAM) to head to the equator. The method of combining maxent with circuit theory approach previously been used by Poor *et al*. (2012), Algeo *et al*. (2017), Burke *et al*. (2019), and Wieringa *et al*. (2021).

The suitability model is created using Maxent version 3.4.3, with the configuration of 1000 maximum iterations, 10 replications, and output type of *cloglog*. Pygmy blue whale tagging data from 2009-2012 and 2015-2016 was obtained from Andrews-Goff *et al*. (2018, 2020), and was used as input of species occurrence for creating the suitability model. Chlorophyll and SST variable was obtained from Aqua MODIS and downloaded from NASA Ocean Color (https://oceancolor.gsfc.nasa.gov/). Salinity is downloaded from marine Copernicus website with spatial resolution of 0.0830 (approximately 9 km). Static variable such as bathymetry data was taken from GEBCO with 450 m resolution, and geomorphology data from bluehabitat.org (Harris *et al*., 2014). The data that has been downloaded was then processed that includes resampling, reprojection, map algebra, and data conversion. Resampling is a technique to change spatial resolution of the data so that all of the data has the same spatial resolution. The resolution is changed to 4 km, matching the Aqua MODIS spatial resolution to create an optimal balance of the result quality and the time required to create the model (finer model require smaller spatial resolution and more time to compute). After resampling, the next step was to reproject the data to ensure that each data has the same coordinate system that can be overlayed. Data that have the same coordinate was then processed using R programming language to get the mean climatology and standard deviation for each dynamic variable for each season in the time span of 2009-2016, adjusted to match the availability of the tracking data. The resulting climatology is finally converted to the same ASCII format to be used in the maxent software. Mean climatology is used to describe long term water condition in each pixel, while the standard deviation describe the seasonality, such as used by Abrahms *et al.* (2019).

The application of circuit theory is done using Omniscape package version 0.4.4 in Julia programming language, using the seasonal habitat suitability model as the input. The configuration used is described as follows; 1000 pixel radius adjusting to the macrosensory scale of blue whale (Torres, 2017), and the memory of their migration location (Abrahms *et al*., 2019), and the distance between Indonesia to Australia), with each pixel equal to 4x4 km, and 21 block size (to optimize processing time and the resulting output). For future research, this can be further improved by reducing the block size and more detailed pixel sizes so that smoother output can be produced, although greater processing capacity is also needed. The suitability habitat model of season DJF and JJA were used as a source and destination layer, and MAM and SON were used for the resistance layer. For validation purpose, whale sighting data around the Savu Sea from 2013 to 2021 were used. This sighting data was obtained by Balai Kawasan Konservasi Perairan Nasional (BKKPN) Kupang.

Result and Discussion

The habitat suitability map has an Area Under Curve (AUC) value that represents the accuracy of the model to give accurate prediction. The AUC value ranged from 0 to 1 with values that is closer to 1 is better at creating model or prediction from the field data input. The AUC value for DJF, MAM, JJA, and SON is 0.98, 0.937, 0.966, 0.974, respectively.

The summer austral (DJF) habitat is mostly on the southern Australia waters. The most influential variable on this season is SST, with most of the whale occurrence happened on 16^{O}C. This can be understood as their adaptation to look for suitable condition using somatosensory organ that can detect oceanographical parameters such as temperature on the large scale (100-500 km) or macro scale (500 - >1000 km) (Abrahms *et al*., 2019). Research by Ingman *et al.* (2021) also shown that SST has high influence on the migration of blue whale, and affected by El Nino, and other regional or and local pattern such as gyre.

During MAM season, the suitable habitat for the whale is around the west and southern side of Australia. This indicated the movement of the whale to the low latitude or towards Indonesian waters, migrating to the Banda Sea. On that time span, the influential factors is underwater slope, with the average occurrence happened 15 km from slope. This confirms the research of Waite et al. (2007), stating that the western Australian waters are subject to the Leeuwin Current, where the water mass is affected by the ITF and the South Java Current, bringing warm, low-salinity water. Rennie *et al.* (2009) analogue the water on the west side of Australia as a 'high way' for whales that is migrating and doing opportunistic feeding in a highly productive area around Perth Canyon.

In the winter austral or JJA, the suitable habitat for the whale is moved to the north in the Banda Sea, from the previous season location in the Western Australia. Variable with the most influence in this season is mean climatology of chlorophyll, with the average of whale occurrence is recorded on 0,034 mg.L^{-1}. This confirms the previous research from Tristianto *et al.* (2021) stating that chlorophyll content in this season reached its peak on August. This condition is preferred by the marine mammals (Maro *et al*., 2021), because the high chlorophyll can be interpreted as high abundance of phytoplankton and increasing the productivity of the area, which serve as a suitable habitat for the pygmy blue whale.

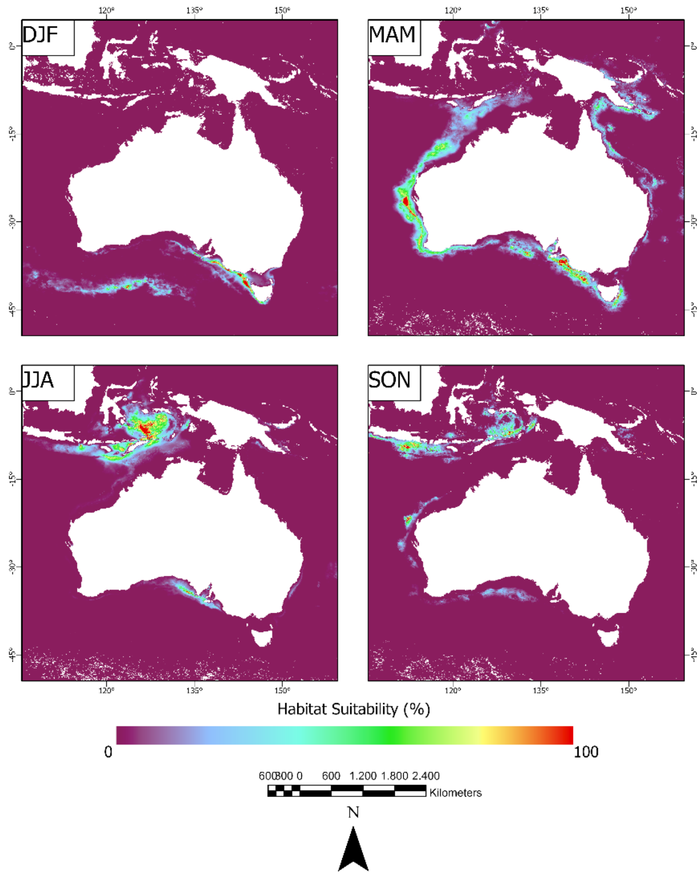

Figure 1. Habitat suitability model for each season; December-January-February (DJF), March-April-May (MAM), June-July-August (JJA), September-October-November (SON).

In the SON period, the suitable location for the whales still located around Indonesian waters, although the intensity decreased. This can be seen on the map where the areas around Banda Sea is darker, while the western Australian waters is become brighter than the previous season, indicating the movement back to the southern Australia. In this period, the influential variable is the distance from slope, where average occurrence happened 24 km from it, this is consistent to their movement that passed the same area on MAM period.

Looking from the habitat suitability model, it can be inferred that pygmy blue whale tends to prefer location that is not too far from underwater slope. Furthermore, the SST and chlorophyll variable is also important factor influencing their preferred habitat. According to Abrahms *et al.* (2019), blue whale aside from using their sensory organ to migrate, is also using their long term memory to define their migration corridor. On this context, the long term memory is on the form of mean climatology of several years.

There are differences on the significance of the variables on building the suitability habitat model (Table 1). The most influential parameters for modelling pygmy blue whale suitable habitat for the season DJF, MAM, JJA, and SON respectively are SST (16 ^{0}C-18 ^{0}C), distance from slope (0-100 km), chlorophyll (0.002-0.003 mg.L^{-1}), and distance from slope (0-400 km). The use of oceanographic parameters such as on the table has also been used by the previous research by Bedriñana-Romano (2018); Abrahms *et al.* (2019); Bedriñana-Romano *et al.* (2021); Sahri *et al.* (2022); Guzman (2024), and Kampf (2024). However, other research by Barlow *et al.* (2021) also states that there is spatial and temporal lag of chlorophyll and SST with the correlation of blue whale occurrence. The lag might be caused by winds that relates to the upwelling phenomena in the local area. Climate pattern such as ENSO, El Niño and La Niña are also influencing the distribution of the pygmy blue whale. Truong and Rogers, (2022) found that the presence of pygmy blue whale calls in the southern Australia waters was higher during La Niña years compared to neutral or El Niño years.

The resulting connectivity model shows that the brighter color indicated higher connectivity or higher potential to be a migration corridor. The corridor is translated as the preferred location that is more likely to be passed during their migration process. There are some areas on Savu Sea that have high potential corridor that is located on the straits of East Nusa Tenggara islands such as Sumba-Sape strait, Alor strait, Rote strait, and Ombai strait, shown on Figure 2 and 3.

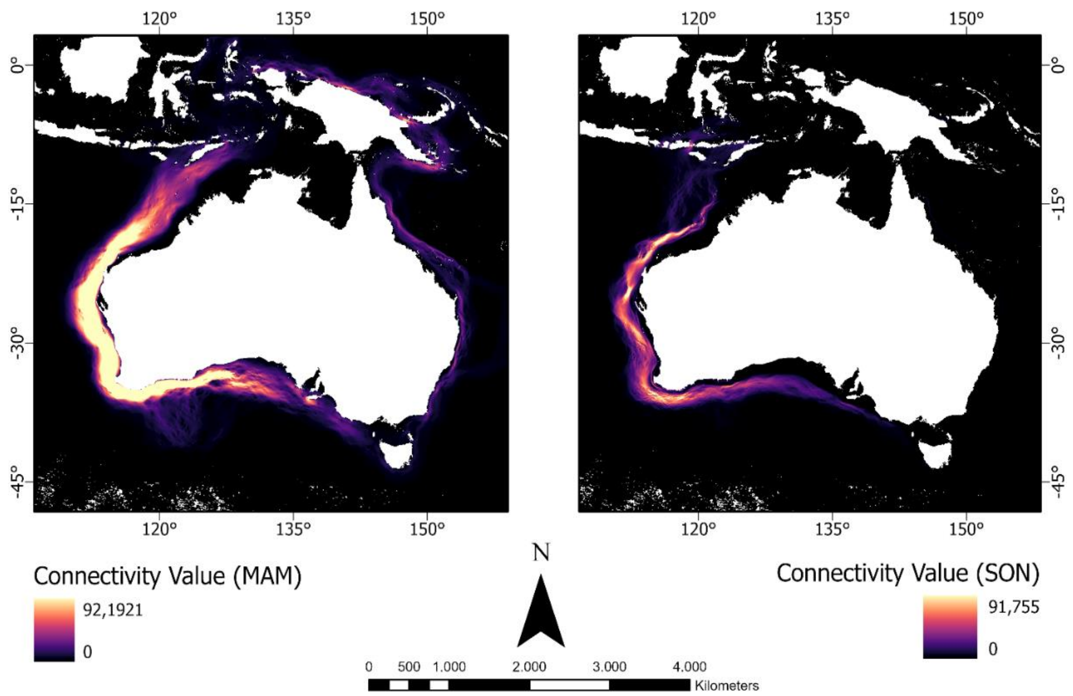

Figure 2. Connectivity model for migration season; March-April-May (MAM) on the left and September-October-November (SON) on the right.

Table 1. Percentage of Variables Influence on Modelling Habitat Suitability of Pygmy Blue Whales

Predictor	DJF	MAM	JJA	SON	AVG
Distance from slope	13.3	54.4	23.2	37.8	32.175
SST mean	54.7	16	10.9	20.7	25.575
CHL mean	3	2	31	11.9	11.975
Bathymetry	17.9	7.6	7.8	9	10.575
Salinity standard deviation	3.4	5.8	13.3	10.8	8.325
SST standard deviation	5.7	5.9	3.6	1.9	4.274
Salinity mean	0.2	3.9	5.8	5.2	3.775
CHL standard deviation	1.8	3.2	3	0.3	2.075
Slope	0.1	1.1	1.3	3	1.375

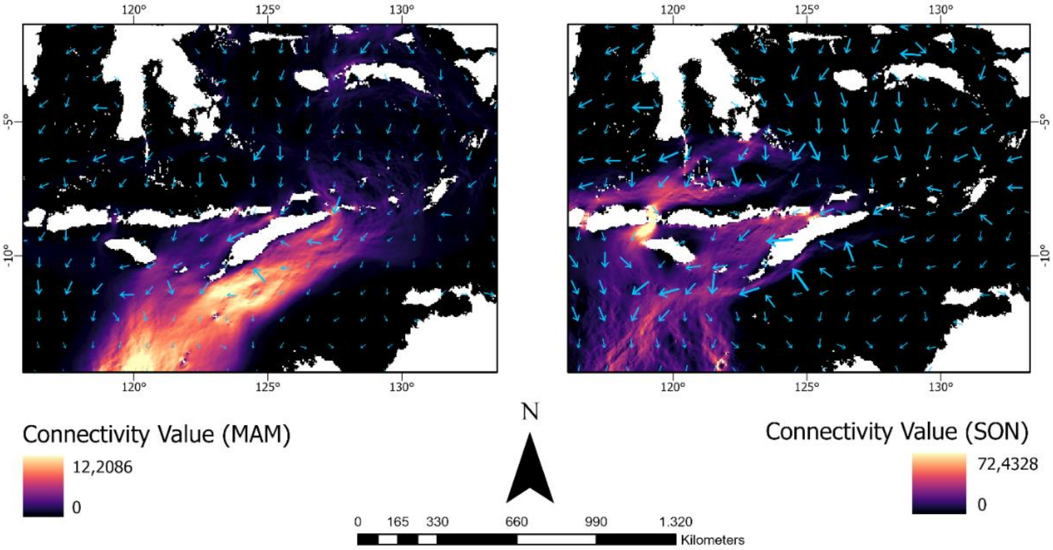

Figure 3. Connectivity model around Savu Sea during migration season, overlayed with the ITF current direction

The migration of pygmy blue whale along the western coast of Australia has been confirmed by previous study (Garcia-Rojas *et al.*, 2018), even when using different method such as passive acoustic sound detection (McCauley *et al.,* 2018; Jolliffe *et al.,* 2019; Truong and Rogers., 2022), genetics assessment (Attard *et al.*, 2018), and stranding record (Foord *et al.,* 2019; Mustika *et al.,* 2022). The behavior of blue whale is affected by upwelling and thermal fronts, in which the phenomena operate to attract krill that feed on phytoplankton (Bedriñana-Romano *et al.*, 2021). In southern Australia the whales usually gather around convergence zone and the Great Southern Australian Coastal Upwelling System, and Bonney upwelling region (Kampf, 2024), on the other hand the gathering location of pygmy blue whale in Indonesia is around Savu and Banda Sea which are known to have thermal fronts (Jatiandana and Nurdjaman, 2020; Syah and Sholehah, 2021). The importance of surface temperature in monitoring whale migration has been stated in other research by Szesciorka *et al.* (2020), where the relation of SST with the climate change was also observed.

The connectivity map shows different connectivity value for MAM and SON, with relatively higher connectivity value on the eastern side of Savu Sea (east of Timor Island) on MAM, while on SON the connectivity is higher on the western side of Savu Sea through the Sape Strait. However, the overlayed maps with ITF current (Figure 3) show that the ocean current velocity has difference of magnitude on both migrating seasons, with slightly different direction.

The intensity of connectivity value in SON is higher with narrower corridor, while the MAM model shown a lower intensity of connectivity, but more distributed corridor across the Indonesian sea and straits. From the spatial pattern of ITF direction and magnitude, the broader corridor might be explained as the effect of the lower current velocity in the area, and the higher current velocity hindering the whale movement resulted in narrower corridor and higher intensity. Although, this need more clarification as in this research we did not include current velocity and direction as these variables could be biased if used as inputs in the omniscape algorithm. As omniscape employed omni-directional modelling of the species movement (McRae *et al*., 2008)

The migration of pygmy blue whale is driven by the changing season that is influencing the presence of prey such as krill and plankton. This is also affected by oceanographic factors such as SST, chlorophyll, and salinity, or geomorphological factors such as slope and bathymetry. A water column or water mass with some volume will be carried by ocean current movement that is related to the season. This explain why the whale is moving according to the direction of the direction of the water mass that is following ITF current. A water mass that is carried by ITF current tends to have dynamic hydro-oceanographic characteristics that support the lives of marine biota. This condition is driving biota that have the ability adapting to the dynamic environment to follow the movements of that water body. This is confirmed by the research of Ismail and Taofiqurohman (2020), where they found that water mass following ITF current has little dynamics of water quality parameter (SST, salinity) with narrow range. This narrow range is giving an opportunity for the trophic productivity to be more stable and provide abundance of food for any biota that migrate in it.

From the modelled migration corridor, the pinch points location can be known. Pinch point is a narrow corridor between two barriers but have minimal resistance, this can be found on several strait in Savu Sea area. This is corresponding to the ITF current pattern on the period of 2009-2016, that have a suitable water quality to support pygmy blue whale life (Maro *et al*., 2021). Comparison between suitable habitat and migration corridor can also interpreted that, even though one location had low suitability, they can still be a potential location to be traversed by the blue whale during migration. This prove that habitat suitability analysis is not enough on the conservation steps, so there need to be an additional step to give a picture of important corridor migration (Balbar and Metaxas, 2019).

On the validation of the output, the model is overlayed with the sighting data from BKKPN Kupang, from 25 sighting data, 5 are above 75th percentile, and 19 are above the 50th percentile for SON, while there only 1 data recorded in the MAM season that is above 25th percentile. The lack of data is causing the validation not optimal; this should be considered for the future research.

The presence of the blue whale migration corridor along the western coast of Australia to Banda Sea in Indonesia is also posing the risk of vessel strikes (Sahri *et al.,* 2022). Incidents of vessel strike on large whale in Australian waters is recorded by Peel *et al.* (2018) with up to more than 100 records in 2010. In Indonesia, the records of marine mammal stranding is recorded by Mustika *et al.* (2022), with 525 single stranding events, and 43 mass stranding events. From these evidence of ship collision and stranding events, circuit theory model can be used to avoid overlapping areas of the migration corridor and the vessel traffic path. Moreover, this migration corridor modeling can combine with other method such as one developed by Barlow and Torres (2021), that can predict future ecological environment for further enhancing capabilities to employ dynamic spatial management, and lowering ship strikes incidents. The spatial management could be in the form of dynamic MPA, that is a moving protected area that shift according to the needs and condition (Lewison *et al*., 2015; Gilman *et al*., 2019). On this context, the implementation could be a temporary protected on the migrating season so that the migration is not disturbed by human activities. Application of this method to model species migration corridor can also be used in other migrant species. Furthermore, with knowing the migration corridor, important location such as pinch points that is prevalent along the corridor can be a target of conservation effort.

Conclusion

Pygmy blue whale migration on seasonal basis is driven by several oceanographic factors such as mean climatology chlorophyll, SST, and distance from underwater slope. The weight of this factors is depended on the season. On DJF, the highest contributing factors is SST by 54,7%, on MAM and SON the most influential is distance from underwater slope by 54,4% and 37,8% respectively, while on JJA the most significant factor is chlorophyll by 31%. Circuit theory can be an alternative to model migration corridors for migrating-marine fauna. The model is affected by the suitability layer that is used as resistance layer in omniscape algorithm. For species that is migrating on seasonal basis, the resistance layer should also be created seasonally. This is because the migration that is done periodically may have different oceanographic parameter on each period. The area around Savu and Banda Sea can be an important location for pygmy blue whale migration, that can be seen on the connectivity model, especially on the strait around East Nusa Tenggara Islands such as Sumba-Sape strait, Alor strait, Rote strait, and Ombai strait, indicating a pinch point that is vital for pygmy blue whale migration.

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