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Identification of Potential Locations for *Kappaphycus alvarezii* Cultivation for Optimization of Seaweed Production Based on Geographic Information Systems in Spermonde Archipelago Waters, South Sulawesi, Indonesia

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Abstract

Indonesia is the second largest producer of red algae in the world with one of the major Kappaphycus. alvarezii farming areas is in Spermonde Islands, Pangkep Regency, South Sulawesi Province. K. alvarezii production in Pangkep Regency increased every year. However, the availability of natural seaweed can be threatened along with the increasing demand so that seaweed cultivation is necessary. Proper site selection is crucial to guarantee the success of the seaweed farming development. A Geographic Information system (GIS) with geospatial modeling approach was applied for identification of the site selection for K. alvarezii cultivation at the Liukang Tuppabiring District, Spermonde Islands by combining various physical and chemical parameters obtained from in-situ data and hydrodynamics modeling. The parameters are Sea Surface Temperature, salinity, pH, substrate type, current speed, wave height, DO, nitrate, phosphate, and Total Suspended Solid. This research also include the accessibility and the restricted area of shipping lanes for determining the area suitability of K. alvarezii cultivation. This research demonstrates a Geographic Information system with the cell-based geospatial modeling can be effectively used and found the the suitable categorized area for K. alvarezii is 4,546.28 ha, which is the combination of the suitable area of 4,463.08 ha and highly suitable criteria with an area of 83.2 ha. The potential productivity of wet-weight seaweed can reach 56,825 tons per cycle or 113,650 tons per year. This result suggests the GIS with geospatial modeling approach for developing the area of K. alvarezii culture can be applied in other area.

Keywords: *Seaweed production, site selection, geospatial, hydrodynamics modeling*

Introduction

Indonesia is the largest producer of red algae in the world (83% of global seaweed production) followed by the Philippines and several countries (Valderrama *et al*., 2015; Kim *et al*., 2017). Seaweed production in Indonesia comes not only from mariculture, and brackish water ponds but also from natural collections. However, the availability of natural seaweed can be threatened in line with their increasing demand so that seaweed cultivation is completely necessary (Pickering *et al*., 2017). The increasing demand for seaweed was mostly driven by new markets in China, Eastern Europe, Brazil, and others (Bixler and Porse, 2011). Furthermore, Arbit *et al*. (2019) stated that 99.73% of Indonesia's seaweed production comes from cultivation. Therefore, seaweed farming is the best choice for fulfilling market demand.

Site selection is essential in aquaculture development which depends on the species of commodities and applied cultivation methods (Kaiser *et al*., 2010; Junaidi *et al*., 2018). For seaweed, the success of cultivation is intrinsically linked to physical and chemical parameters of seaweed farming areas such as turbidity, temperature, salinity, pH, DO, nitrate and phosphate concentration (Rusliani, 2016;

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Jalil *et al.,* 2020). Hydrodynamic aspects should also be considered in the site selection of *K. alvarezii* farming since the cultivation method uses the longline method which is prone to strong current and wave. One of major *K. alvarezii's* farming areas within the Indonesian seas is in Spermonde Islands, Pangkep Regency, South Sulawesi Province (Jalil *et al.*, 2020). The existence of Indonesian Troughflow along the Makassar Strait (Susanto *et al.,* 2016) and the occurrence of strong upwelling at the southern part of the South Sulawesi during each summer (Setiawan and Kawamura 2011) may influence the hydrodynamics condition in the Spermonde Island. Besides, the existence of small islands among the water area makes the hydrodynamics condition at the Spermonde Islands becomes more complex. This area also has dense shipping activities. Many shipping lanes have lied among these areas which are should be avoided in the mariculture site selection. This shows the complex considerations for conducting site selection of seaweed farming at Spermonde Islands.

In dealing with the complex considerations as mentioned above, the use of the geospatial model which is part of Geographical Information Systems (GIS) becomes an effective solution for determining the proper mariculture site selection (Longdill *et al.,* 2008; Micael *et al.,* 2015). This approach, in general, is an analysis of layers that contains spatial data to evaluate and select a particular area based on its suitability criteria classified according to certain environmental aspects (Malczewski, 2006; Malczewski and Rinner, 2015). GIS utilization in mariculture development has been widely used in various types of commodities including seaweed (e.g., Radiarta *et al*., 2011; Radiarta *et al*., 2012; Sousa *et al*., 2012; Nirmala *et al*., 2014; Teniwut *et al*., 2019) which were mainly used in-situ data and remote sensing data for the input of geospatial modeling. The application of GIS for site selection for aquaculture in the Spermonde Islands has conducted by Arifin *et al*. (2014). However, their analysis was only based on in-situ measurement which cannot represent the temporal change of ocean parameters. In the present study, cell-based geospatial modeling was performed for the determination of sustainable site selection of seaweed cultivation, which integrates various physical and chemical parameters obtained from in-situ data and the hydrodynamic model. The combination of both data becomes the new approach proposed in the present study. Considering that the hydrodynamics aspects for the site selection of seaweed culture is not available in the remote sensing data, a 2D hydrodynamic model was built to represent the hydrodynamic condition in the study area. On the other hand, Indonesia as the maritime continent experiences four-season influenced by monsoon wind (Helmi *et al.,* 2018) which impacts the hydrodynamics conditions. Thus, in-situ and incidental measurements of current and wave cannot represent the hydrodynamics condition in the study area. This issue only can be resolved by performing the hydrodynamics model. Furthermore, the potential productivity of *K. alvarezii* at the selected site is also simulated. This research is expected to become a prototype of a geospatial model to explore the potential aquaculture area in small islands and can be a scientific-based information for local governments, researchers, NGOs, and related stakeholders for planning and developing *K. alvarezii* cultivation in the study area.

Material and Methods

The study area is presented in Figure 1. which is located at the Spermonde islands waters precisely in the Liukang Tupabbiring District, Pangkep Regency, South Sulawesi. The Liukang Tuppabiring District area is 54.44 km2 (4.89% of Pangkep Regency) and consists of 20 islands. The population of this district reached 29,680 inhabitants, generally fishermen and sea farmers. The field stations are located at 4°5'3.98"S - 4°59'51.137"S and 119°18'35.532"E - 119°26'19.849"E. There are 94 sampling points distributed among the island of Bontosua, Sanane, Panjenekang, Pankaiya, Langkadea, Baranglompo, Barangcaddi Island, and reef flat area.

A field survey was conducted for collecting water quality data at 94 points in which the depths are more than 2 meters. Survey site determination was using Garmin 76C GPS. The water quality data collected are presented in Table 1. The in-situ measurements were Sea Surface Temperature, (SST), salinity, pH, and substrate type. For the chemical parameters, such as DO, nitrate, phosphate, and Total Suspended Solid (TSS), the water samples were taken and analyzed. The dynamic and non-dynamic water parameter data were interpolated to obtain a spatial distribution pattern at the time of data retrieval. The data were compiled in a digital form of 5 x 5 meters cell size using spline and classified according to suitability class in Table 2.

Two dimensions (2D) hydrodynamic model was used to simulate current and wave condition at the study area. The data for generating a hydrodynamic model are as follows: (1) High-resolution satellite imagery GeoEye-1 from ESRI online (https://esri indonesia.co.id/arcgis-online); (2) Bathymetry data from Indonesia Geospatial Agency (http://batnas.big.go.id/); (3) Surface wind and wave height data obtained from 6 hourly ERA-interim data with a grid interval of 0.125° from July 2018 to July (Dee *et al.,* 2011); (4) Tidal elevation forecast from July 2018 to July 2019 (https://www.dhigroup.com/download/mike-by-dhi-tools/coastandseatools/global-tide-model).

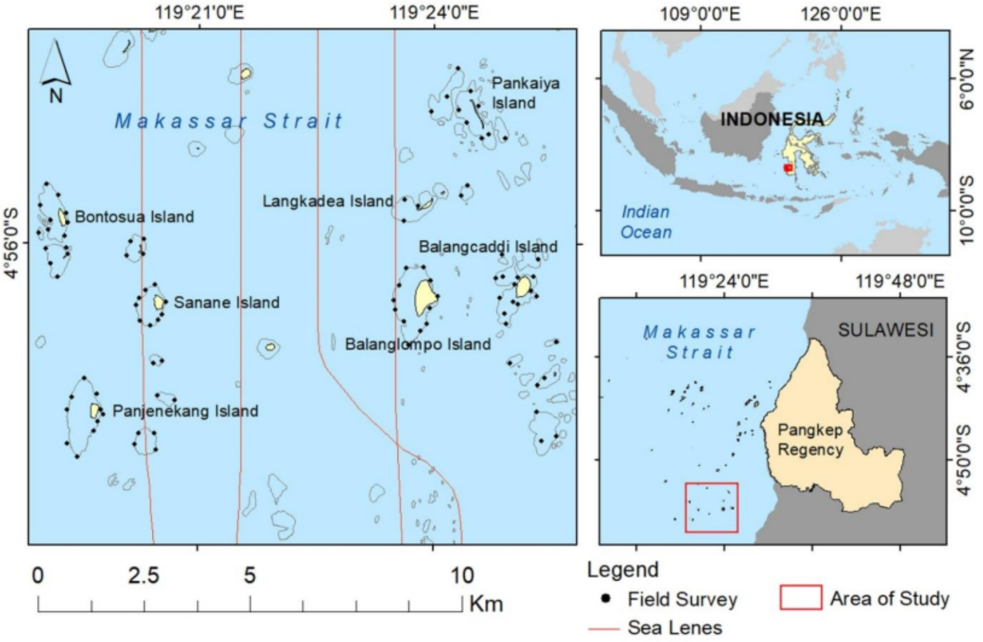

Figure 1. Study area

Table 1. Water quality data collection

No	Variables	Unit	Tools/Methods	Data Retrieval Methods
1	Sea Surface Temperature (SST)	^oC	Thermometer	Insitu
2	Salinity	Psu	Salinometer	In situ
3	pH	-	*Water quality checker*	In situ
4	Dissolved oxygen (DO)	ppm	Winkler method	Laboratory analysis
5	Nitrate	$mg.L^{-1}$	Ascorbic Acid Method	Laboratory analysis
6	Phosphate	$mg.L^{-1}$	Brucine Sulfate Method	Laboratory analysis
7	Total Suspended Solids (TSS)	$mg.L^{-1}$	*Milipore filter*	Laboratory analysis
8	Substrate type	-	Visually observation	In situ
9	Depth	m	Modelled depth from LPI Maps (BIG, 2011) and BATNAS (BIG, 2018) data	Integrating modelled data

The current model was constructed by continuity equations and momentum equations with the average of depth. On-screen digitized coastline from high-resolution satellite imagery GeoEye-1, bathymetry, wind and tidal dynamics were used as an input for generating current model. The initial process was making a mesh, and setting the boundary condition of the model using the mathematical continuity equation as follows:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=S$$

The horizontal momentum equation for component x is as follows (DHI, 2010) :

$$\frac{\partial u}{\partial t}+\frac{\partial u^2}{\partial x}+\frac{\partial vu}{\partial y}+\frac{\partial wu}{\partial z}=fv-g\frac{\partial h}{\partial x}-\frac{1}{r_0}\frac{\partial p_a}{\partial x}-\frac{g}{r_0}\int_z^h\frac{\partial r}{\partial x}dz-\frac{1}{r_0 h}\left(\frac{\partial S_{xx}}{\partial x}+\frac{\partial S_{xy}}{\partial y}\right)+F_u+\frac{\partial}{\partial z}\left(v_t\frac{\partial u}{\partial z}\right)+u_sS$$

While the horizontal momentum equation for component y is as follows (DHI, 2010):

$$\frac{\partial v}{\partial t}+\frac{\partial v^2}{\partial y}+\frac{\partial uv}{\partial x}+\frac{\partial wv}{\partial z}=-fu-g\frac{\partial h}{\partial y}-\frac{1}{r_0}\frac{\partial p_a}{\partial y}-\frac{g}{r_0}\int_z^h\frac{\partial r}{\partial y}dz-\frac{1}{r_0 h}\left(\frac{\partial S_{yx}}{\partial x}+\frac{\partial S_{yy}}{\partial y}\right)+F_v+\frac{\partial}{\partial z}\left(v_t\frac{\partial v}{\partial z}\right)+v_sS$$

Note: x, y, z = cartesian coordinates of x, y, and z direction; t= time; u= water particle speed of direction x; v= water particle speed of direction y; w = water particle speed of direction z; η= water surface elevation; d= sea depth; h= total depth of the sea; f= coriolis parameter (f= 2ω sinØ); Ω= ratio of earth revolution; Ø= latitude coordinates; g= acceleration of gravity; S_{XX}, S_{XY}, S_{YY}, S_{YY} = component of radiation stress tensor; vt= vertical eddy viscosity; pa= atmospheric pressure; ρ0= sea density; S= debits due to sources; us= particle velocity of air sources direction x; and vs= the particle speed of air sources direction y.

Wave modeling used directional decoupled parametric and fully spectral formulations based on wave eternity movements with the input data of on-screen digitized coastline from high-resolution satellite imagery GeoEye-1, bathymetry data, wind speed and direction and wave data. Parameterization was created in the frequency domain by introducing the 0 and 1st moments of the wave spectrum as a variable (Azhar *et al.,* 2011). The arranger equation was the equilibrium wave force in cartesian coordinate formulated as follow (DHI, 2010):

$$\frac{\partial N}{\partial t}+\frac{\partial}{\partial \varphi}C\varphi N+\frac{\partial}{\partial \lambda}C\lambda N+\frac{\partial}{\partial \sigma}C\sigma N+\frac{\partial}{\partial \theta}C\theta N=\frac{S}{\sigma}$$

Source energy, S, shows the superposition of surface functions in various styles (Azhar *et al*., 2011).

$$S=S_{in}+S_{nl}+S_{ds}+S_{bot}+S_{surf}$$

Note: $N_{x,\sigma,\theta,t}$= power density, φλ= coordinate spherical, C= speed of propagation of four-dimensional wave group, S= energy source, S_{in}= formation by wind, S_{nl}= energy transfer, non-linear, S_{ds}= wave energy due to white capping, S_{bot}= by bottom friction, S_{surf}= dissipation due to the depth-induced breaking.

The maximum value of the current speed and wave height were taken in each grid that comes from 4 seasonal patterns characteristics, that is the west monsoon (December), transition 1 (May), east monsoon (July), and transition 2 seasons (October). The results of the 2D hydrodynamic model form the patterns of current speed and wave height every season were interpolated with a spline method with a cell size of 5 x 5 meters and analyzed using cell statistics to obtain the maximum value of current speed and wave height. The results of the distribution map were classified according to suitability class in Table 2.

Determination of area suitability criteria

The determination of the weighting and scoring was done to provide value in each criterion for supporting the feasibility of seaweed cultivation. The weight determination of each criterion was based on the literature research and later on was used to weight the variables by priority. The variable that is very influential for the growth of seaweed got a high score. The determination was based on the defined suitability matrix as shown in Table 2. The total score multiplication and weight in table 2 were used to determine the class of water suitability of seaweed cultivation with quantitative analysis using the following equation:

$$Y = \Sigma\, ai\, .\, Xn$$

The range of suitability cultivation area of *K. Alvarezii* was adjusted to use the following equation:

$$I = \frac{(\Sigma ai.Xn)\text{-}(\Sigma ai.Xn)min}{k}$$

Note: Y= The final value, ai= weight per parameter, and X_n= score of suitability level, I= interval of suitability class, k= number of suitability class.

Finally, the suitability interval was divided into 5 classes, *i.e.* 1) highly suitable (HS) is in the range of the value 42-50, 2) suitable (S) is in the range of 33-41; C) moderately suitable (MS) is in the range of 24-32; 4) less suitable (LS) are in the range of 15-23; and 5) not suitable (N) had the value of <15. Each parameter in Table 2 was transformed in digital format using a spline interpolation method with a cell size of 5 x 5 meters resulting in an index map of water suitability.

Distance suitability analysis

Distance suitability analysis was also carried out as the other limiting factors out of the water parameters. Those were the distance to shipping lanes or sea lanes and the distance to a settlement which are arranged in a digital format of 5 x 5 -meter cell-sized using the buffer and the euclidean distance method to consider the accessibility and disruption of marine traffic. These criteria are described in Table 3. The suitability of distance to the settlement was compiled using the data of inhabited island, namely Bontosua, Sanane, Panjenekang, Baranglompo, and Barangcaddi Islands, while the shipping lanes data used was inter-regional shipping routes. The results of the analysis were integrated with a water suitability index map.

Spatial modelling

The spatial modelling in this study used cell-based modelling by integrating all oceanographic and water quality parameters based on the suitability classification according to Table 2 with the following modelling algorithms develop from Danish Hidraulic Institute (2010):

$$WS = (T_i \times 0.5) + (pH_i \times 0.5) + (S_i \times 1) + (DO_i \times 0.5) + (N_i \times 1.5) + (F_i \times 1.5) + (B_i \times 0.5) + (HS_i \times 1.5) + (CS_i \times 1.5) + (TSS_i \times 0.5) + (SB_i \times 0.5)$$

Note: WS= Water suitability, T_i= temperature index map, pH_i= pH index map S_i= salinity index map, DO_i = Dissolved Oxygen index map, N_i= Nitrate index map, F_i= phosphate index map, B_i= bathymetry index map, HS_i= significant wave height index map, CS_i= current speed index map, TSS_i= TSS index map, SB_i= seabed index map

The result of this modeling is continued by determining the classification of water suitability based on a class of suitability presented in Table 2. Then, integrating the results of water suitability above with the result of distance suitability analysis was conducted according to Table 3 using cell statistics analysis.

Estimating productivity

After obtaining the distribution of classes areas for all variable, the seaweed production is estimated only by considering the area which is suitable or highly suitable. Longline method of seaweed cultivation unit was designed as 25 × 50 meter per unit, the distance between the rope was 1 meter and the planting distance of each tied seaweed was 25 cm (WWF, 2014). The initial weight of the seedlings was approximately100 grams per bunch (Parakkasi *et al.*, 2020) with the wet weight crop was 500 grams per tie. The cultivation of seaweed with a floating rope/longline system produces an excellent product and can gain a weight up to four to five times from the initial weight of the seedlings (100 g) in a period of cultivation time. The number of the allocated cultivation units was estimated to be 5 units.ha^{-1}. The distance correction between units is 10 m in width

Table 2. Table of suitability criteria for seaweed *Kappaphycus alvarezii* cultivation

Variables	Level of conformity (score)					Weight	Sources
	HS (5)	S (4)	MS (3)	LS (2)	N (1)		
SST (°C)	28-30	24-27 or 31-32	22-23 or >32	21 or >34	<21 or >36	0.5	Modification of Noor (2015); Rahmayanti *et al.* (2018)
pH	7-8	6.5-7 or 8-8.5	6-6.4 or >8.5	4-6	<4 or >9	0.5	Modification of Kautsari and Ahdiansyah (2015); Noor (2015)
Salinity (psu)	28-31	26-28 or 31-33	<26 or ≥ 34	18-25 or 35-36	<18 or >37	1	Modification of Kautsari and Ahdiansyah (2015); Rahmayanti *et al.* (2018); Utama and Handayani (2018)
DO (mg.L^{-1})	>6	5-6	4-5	2-4	<2	0.5	Modification of Afandi and Musadat (2018)
Nitrate (mg.L^{-1})	0.04-0.07	0.02-0.03	0.01 or >0.1	<0.01 or >0.5	>1	1.5	Modification of Kautsari and Ahdiansyah (2015); Afandi and Musadat (2018)
Phosphate (mg.L^{-1})	0.051-0.1	0.02-0.04	0.01-<0.02 or >0.2-1	<0.01 or >1	>2	1.5	Modification of Patty *et al.* (2015)
Depth (m)	3-10	2-3 or 11-13	1-2	>13-15	<1 or >15	0.5	Modification of Radiarta *et al.* (2012); Kautsari and Ahdiansyah (2015); Yulianto *et al.* (2017)
Wave height (m)	0.2-0.3	0.1-0.19	>0.3	<0.1 or >0.4	>0.5	1.5	Modification of Rahmayanti *et al.* (2018)
Current speed (m.s^{-1})	0.25-0.3	0.2-0.24 or 0.31-0.4	0.1-0.19 or >0.4	<0.1 or >0.45	>0.5	1.5	Modification of Utama and Handayani (2018)
TSS (mg.L^{-1})	<25	25-50	50-100	100-400	>400	0.5	Modification of Yulianto *et al.* (2017)
Seabed	Coral, Rubble	Sand	Reefs	Muddy Sand	Mud	0.5	Modification of Noor (2015); Yulianto *et al.* (2017)

Note : HS: Highly suitable, S: suitable, MS: moderately suitable, LS: less suitable, and N: not suitable (twice longer than the average length of the fishing boat) for fishing traffic. This amount represents 62.5% of the maximum number of units i.e., 8 units.ha^{-1}. To estimated production is the multiplication between the number of cultivation units (from the total suitable area) and once crop yields per unit with the following equations:

$$Ye = N \times Cy$$

Note: Ye= estimated yield per cycle (tons), N= number of cultivation unit, Cy= crop yield per cycle (tons). Briefly, the research method is summarized in the flowchart presented in Figure 2.

Result and Discussion

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Distribution of water quality parameters

Spatial distributions of the suitability of water quality parameters are shown in Figure 3. It can be seen that the water quality conditions based on the variable of SST, and pH, are highly suitable for seaweed cultivation in the study area. SST is the important l31ting factor for marine organisms (Wirasatriya *et al*., 2019). The range of measured SST in the study area is very narrow *i.e*., only around 30°C. According to BSN (2015) the optimal temperature for this acti8y is 26-32°C, so the temperature in this site is still suitable for seaweed cultivation. The high temperature of the water causes death on seaweed while low water temperatures cause damage to protein and fat membranes and is very influential in the seaweed life cycle. Photosynthesis on seaweed generally lasts at a maximum temperature of 23°C-30°C (Msuya, 2011; Ding *et al*., 2013). Seawater has an enormous support ability to prevent pH fluctuation. The condition of pH that is very acidic or alkaline will endanger the survival of organisms because it led to metabolic and respiration disorders. The pH range at the study site is 7.26-7.63. Whereas, optimal seaweed growth requires a pH value range of 7.5-8.5 (BSN, 2015; Radiarta *et al*., 2018). Moreover, Noor (2015) stated that a suitable pH range for *K. alvarezii*

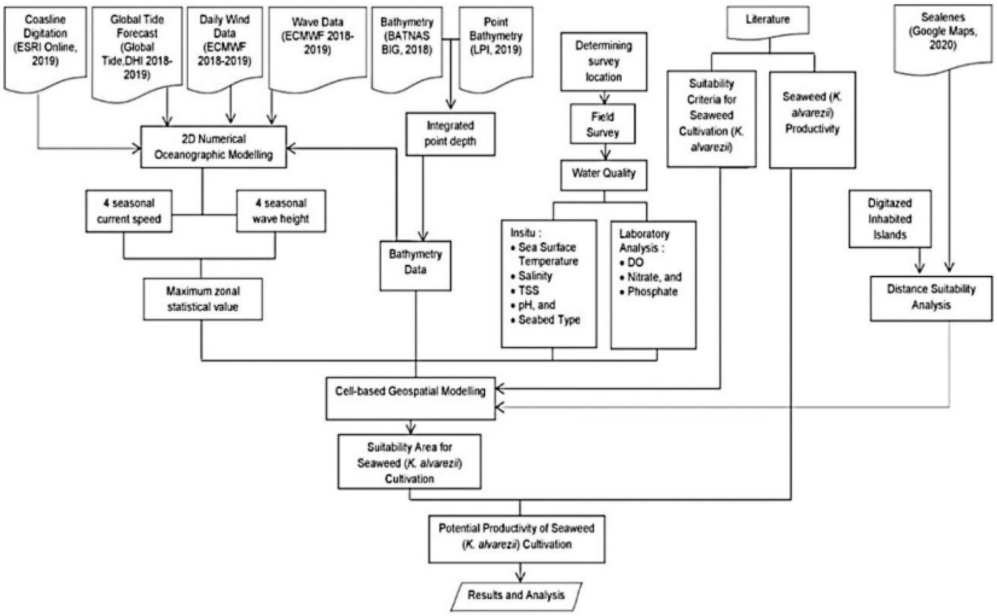

Figure 2. Research Flowchart

Table 3. Distance suitability analysis

Parameters	Suitability Level (Score)					Sources
	HS (5)	S (4)	MS (3)	LS (2)	N (1)	
Shipping lanes (m)	> 500	-	-	-	≤ 500	Ariyanto *et al.* (2018)
Distance to settlements (km)	4	4-5	5-6	6-7	>7	Modification of Radiarta *et al.* (2012)

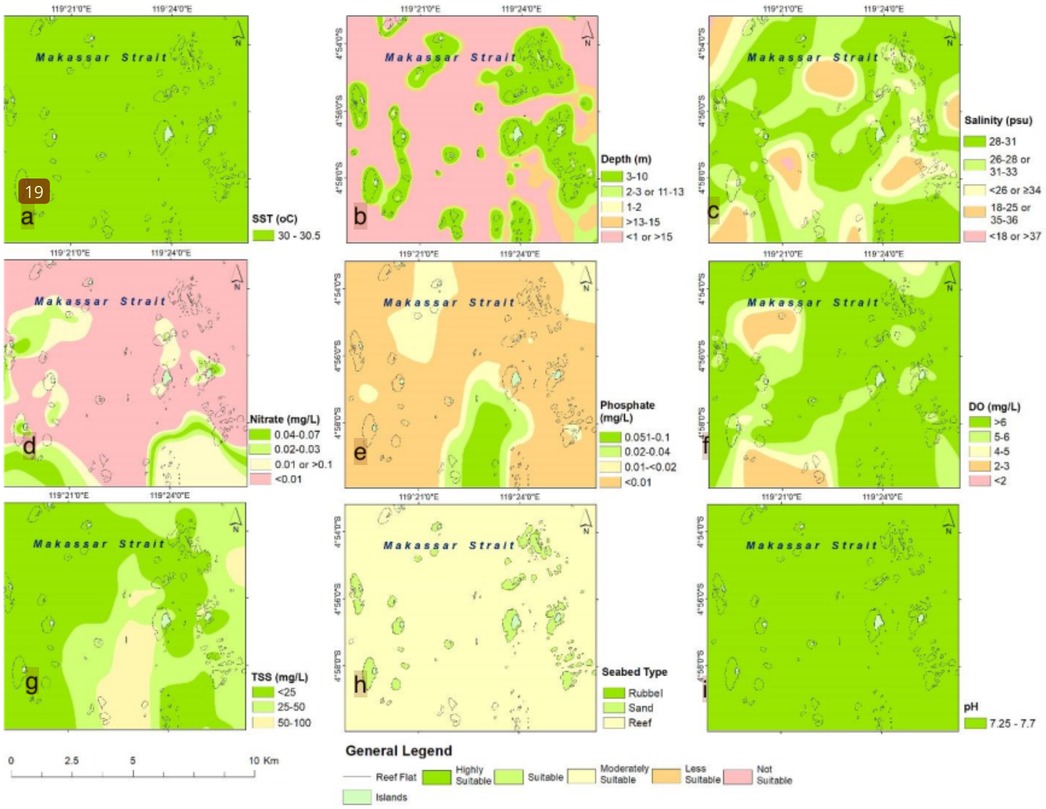

Figure 3. Distribution of physical and chemical parameters: a) SST (Sea surface temperature); b). Depth; c). Salinity; d).Nitrate; e). Phosphate; f). DO (Dissolved Oxygen); g).TSS; h: seabed type; i): pH

cultivation is in normal and disposed alkaline level. Therefore, these values of pH of this area are feasible for seaweed cultivation (Rahman *et al*., 2019).

The suitability distribution for TSS and substrate type are moderately suitable or more in the study area. A substrate is dominated by reef almost at entire study area which is categorized as moderately suitable. The suitable condition is located around the small islands with the sand as the substrate type. Seaweed will grow optimally when the cultivation site is in coral, rubble, sand-based substrate, or a mixture of all those three. The most optimum substrate type for seaweed cultivation is a hard substrate like the rocky coral then followed by sandy corals (Parakkasi *et al*., 2020). Waters with a fractional substrate of coral to sand are usually passed by the current that was suitable for the growth of seaweed. However, cultivating seaweed with a longline method is not overly influenced by the substrate type. For TSS, the eastern part of the study area is highly suitable while the western part is moderately suitable. This indicates that the further distance from the mainland the lower TSS is observed. TSS is insoluble sedimentation which increases the turbidity of water (Nurdin *et al*., 2019). High turbidity due to the suspended material impedes light penetration into water column and affects seaweed growth. Thus, TSS indicates water pollution as *K. alvarezii* lives optimally in transparent oligotrophic waters (Hayashi *et al*., 2011). According to Ministry of Environment R.I (1998), the recommended TSS value is <25 mg.L^{-1}, although up to 80 mg.L^{-1} is allowed for marine cultivation. The TSS levels in the study area range between 3.6-57.6 mg.L^{-1} which means that the waters are suitable for the growth of *K. alvarezii*. TSS concentration is probably due to the absence of re-suspension from bottom substrate and no input of the coastal sediment.

For DO and salinity values, the suitability distributions vary from less suitable to highly suitable. Based on the DO criterion, the study area is mostly highly suitable for seaweed cultivation, with only 2 spots in the study area which are less suitable. The water circulation among small islands plays an important role in high DO level. In open water, the low concentration of oxygen in a natural condition is rarely found (Diaz *et al.,* 2013). The optimal dissolved oxygen for seaweed cultivation is in the range of 3-7 mg.L^{-1} (Rahman *et al.*, 2019). For salinity, the less suitable classes are spread in some areas and even the class at the eastern part of Sanane Island is not suitable for seaweed cultivation. The stability of salinity becomes an important factor for seaweed because seaweed is a stenohaline organism that cannot resist the high fluctuation salinity (Reis *et al.*, 2010; Aris *et al.,* 2021). The extreme salinity changes can lead to ice-ice disease. Salinity can affect the osmoregulation process of marine biota including seaweed (Aris *et al.,* 2021). Because *K. alvarezii* can grow optimally in the range of salinity values of 29-34 ppt (Doty,1987), therefore, most of the area is still feasible for seaweed cultivation.

Nitrate and phosphate concentrations as indicators of water fertility are relatively low in this region. This may be related to the absence of big rivers in the small islands of the study area as the nutrient sources. Nitrate is a limiting factor for seaweed growth and one of the nutrients needed for the growth of seaweed. The result shows that nitrate concentrations in the study area range between 0.001-0.12 mg.L^{-1} which is relatively low. According to Kautsari and Ahdiansyah (2015), the feasible nitrate concentration for seaweed cultivation ranges from 0.01 mg.L^{-1} to 0.07 mg.L^{-1}, while the concentration of <0.01 mg.L^{-1} and > 0.1 mg.L^{-1} are not suitable for seaweed cultivation. Phosphate can be a limiting factor due to the source limitation. In the study area, phosphate concentration ranges from 0.001 mg.L^{-1} to 0.062 mg.L^{-1} which indicates low to insufficient fertility levels. Phosphate concentration for the fertile water should range from 0.051 mg.L^{-1} to 0.1 mg.L^{-1}. Besides, phosphate concentration also controls the growth (Nursidi *et al.*, 2017) and the carrageenan content of seaweed (Patty *et al*., 2015).

The depth of the study area ranges from 2 m to 39.2 m. The longline method can be applied at the 1 m depth from the lowest tide or below (WWF, 2014). The sufficient depth provides seaweed to be submerged. Nevertheless, noted that the deeper waters will increase the cost of constructing seaweed cultivation. Thus, the areas with a depth of more than 15 m are categorized as not suitable for seaweed cultivation.

The distribution of physical and chemical parameters at the seaweed site is highly determined by the wave and current. These aspects play a pivotal role in the water movement for algae growth (Gaylord *et al.,* 2007; Kregting *et al.*, 2013; Nursidi *et al.*, 2017). The variability of current speed and wave height is distinguished by four different characteristics of the west monsoon; transition 1; east monsoon; and transition 2 based on the results of 2D hydrodynamic modeling (Figure 4 and Figure 5). During west monsoon and transition 1 (east monsoon and transition 2), strong current speed appears at the northwestern (southern) part of the study area. The strongest current speed occurs during the transition 1 season. The pattern of the surface current in the study area is influenced by the current pattern of breaking waves in the small islands waters and the surrounding shallow area; and the influence of wind and tidal conditions in these waters. Based on the criteria shown in Table 2, the study area is categorized as highly suitable (dark blue color) to less suitable (light blue color). For the wave height, almost entire study areas are categorized as suitable and highly suitable for seaweed cultivation except during east monsoon. During west monsoon transition 1 and transition 2, the blue and dark blue colors mean that the wave height ranges from 0.1 m to 0.3 m. During east monsoon, the wave higher than 0.3 m occurs at almost the entire study area which makes it less suitable for seaweed cultivation.

The protected area is determined by several types of physical conditions such as current velocity, and wave height. The influence of strong current and ocean waves will drag and damage the cultivated seaweed and its system. The maximum value of the distribution of current speeds and wave height for 4 seasons is described in Figure 6. Based on the results in Figure 6, the current speed and wave height around the study of the water are mostly at the range of moderately suitable to highly suitable for seaweed cultivation. The less suitable areas for the current speed (wave height) category appear mostly in the northeastern (northern) part of the study area. There is no area with a current speed of more than 0.5 m.s^{-1} and the wave height more than 0.5 m which makes the area is not suitable for seaweed cultivation. The absence of strong current and wave may correspond to the morphology of the study area which is categorized as coral waters with a lot of shallow/reef flat area located within the small islands that protect the area from the high wave and strong current. As mentioned by Sulma *et al.* (2008), the types of protected waters are bays, caps, straits, lagoons, and reef flat. Furthermore, Helmi *et al.* (2017) also stated that the coral reef is a shoreline protector.

Potential areas for seaweed culture development and production

Various suitability criteria as limiting factor of site selection for seaweed cultivation include physical and chemical parameters and distance suitability for accessibility and restricted area inside the shipping

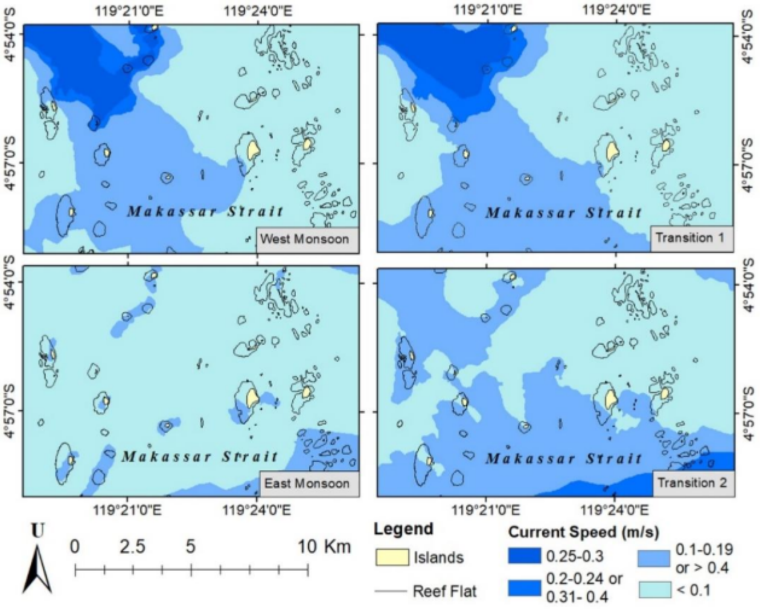

Figure 4. Distribution of current speed (m.s-1) based on 2D hydrodynamic model in each season

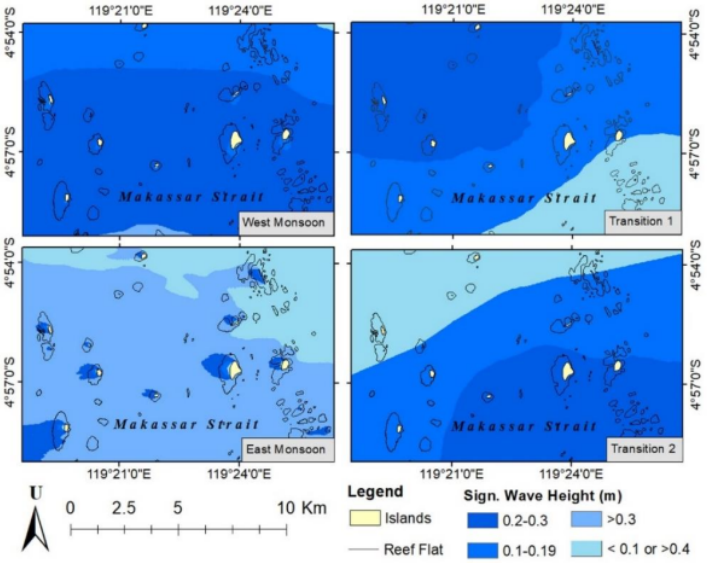

Figure 5. Distribution of significant wave height (m) based on 2D hydrodynamic model in each season

lanes has been determin[illegible] into 5 highly suitable classes (HS), suitable (S), moderately suitable (MS), less suitable (LS) and not suitable (N).

Figure 7 shows that most of the study areas are moderately suitable and suitable for seaweed cultivation. The area which is not suitable is only located along the shipping lane. Figure 8 summarizes the area size of each criteria asfollows: the highly suitable (HS) is 83.2 ha (0,42%); suitable (S) is 4,463.08 ha (22.21%); moderately suitable (MS) is 9,983.52 ha (49.68%); less suitable (LS) is an area of

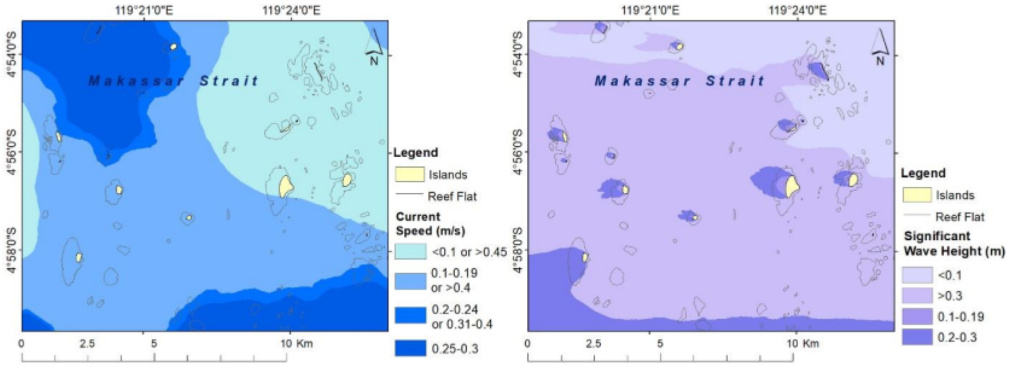

Figure 6. Maximum statistical value of current speed (left) and wave height (right) for all season

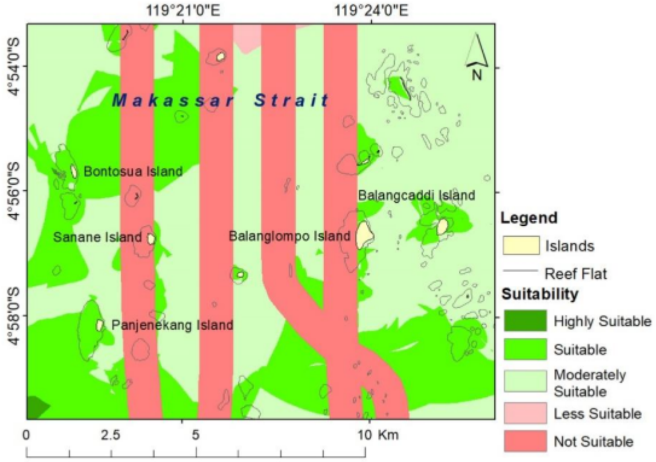

Figure 7. Suitability distribution for cultivation area of *K. alvarezii*

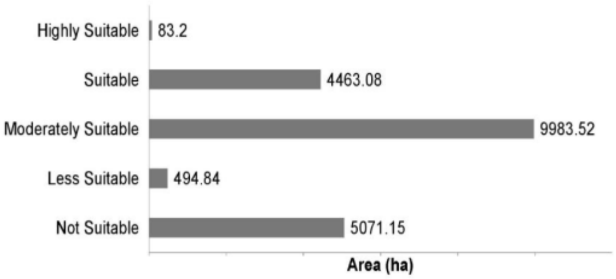

Figure 8. Potential area for *K. alvarezii* cultivation in each

494.84 ha (2.46%); and not suitable (N) is 5,071.15 ha (25.23%). The potential area for seaweed cultivation development reaches 4,546.28 ha as the sum area of highly suitable and suitable criteria. This result is more than obtained by Arifin *et al.* (2014) which only found 1,963.6 ha area suitable and highly suitable for *K. alvarezii* cultivation in the same study area. This indicates that our method can optimally classify the potential area for *K. alvarezii* cultivation. Furthermore, this potential area can be utilized for 22,730 cultivation units with seaweed production reaching about 56,825 tons of wet weight per crop, or within a year (2 times of harvesting) can reach about 113,650 tons. This amount is only about one-third of the total seaweed production in Pangkep Regency in 2018. However, it is important to be noted that, there are some limitations in the present study which should be considered. For example, the present study did not include the longterm climate variability which may also influence the physical and chemical parameters in the study area. As reported by Msuya *et al.* (2014) and Kunarso *et al.* (2019), the climate variability influences the oceanographic condition which then affects fisheries activity such as aquaculture and fish catch. The present study also did not consider the risk analysis which was able to disturbed the cultivation process as shown by Castelar *et al.* (2015). Furthermore, to maintain the carrying capacity of the study area, the potential area that might be utilized for the expansion of *K. alvarezii* cultivation is about 50% (covering 2,273.14 ha) of the total suitable area accordingly. The result of the present study indicates the effectiveness of Geographic Information Systems with geospatial modeling for developing the area of *K. alvarezii* culture which can be applied in the other area.

Conclusions

Physical and chemical parameters as well as the accessibility and restricted area of shipping lanes were used to define the suitability criteria for K. alvarezii cultivation. The result is SST and pH are categorized as highly suitable for *K. alvarezii* cultivation in the whole study area. A substrate is dominated by reef type almost at the whole study area which is categorized as moderately suitable. TSS levels in the study area range between 3.6-57.6 mg.L^{-1} which means that the waters are suitable for the growth of *K. alvarezii*. For DO and salinity, the suitability distributions vary from less suitable to highly suitable. Nitrate and phosphate concentrations mainly are too low which are not suitable for *K. alvarezii* cultivation. The depth at the study area ranges from 2 m to 39.2 m. The area with a depth more than 15 m is categorized as not suitable for *K. alvarezii* cultivation. The current speed and wave height around the study area are mostly at the range of moderately suitable to highly suitable for seaweed cultivation. After summarizing all criteria according to their weighting score, the suitable for seaweed cultivation at the study area is 4,546.28 ha, which is the combination of the suitable (S) area of 4,463.08 ha and highly suitable criteria (HS) with an area of 83.2 ha. The potential production per crop can reach 56,825 tons per cycle and 113,650 tons per year.

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