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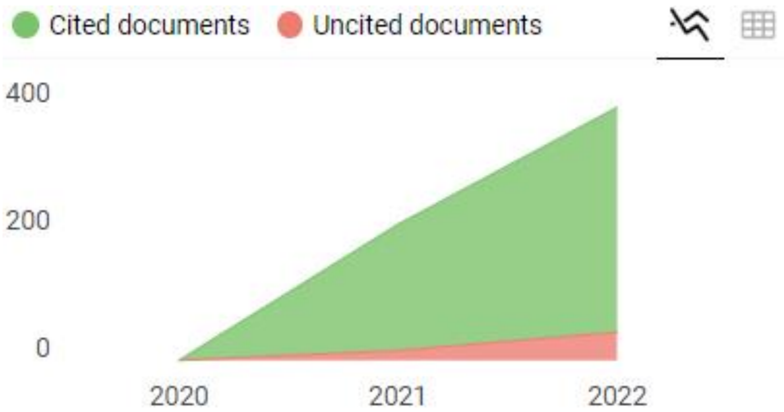

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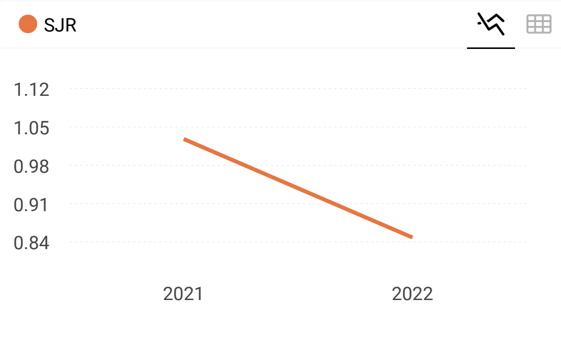

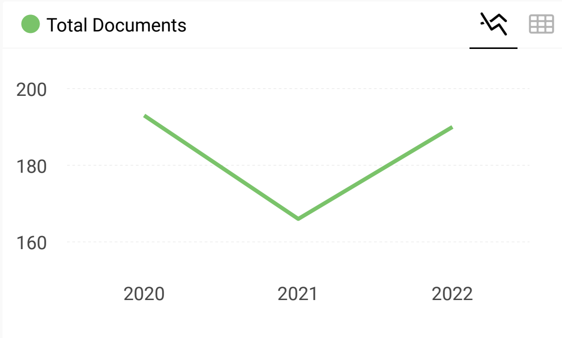

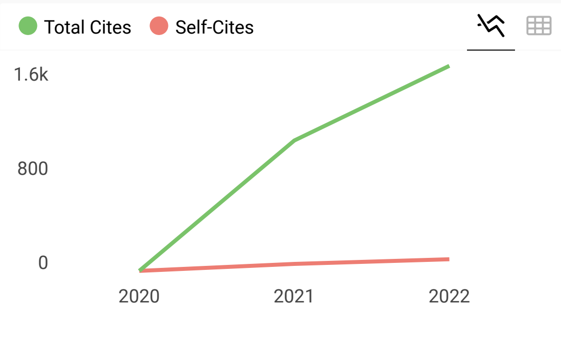

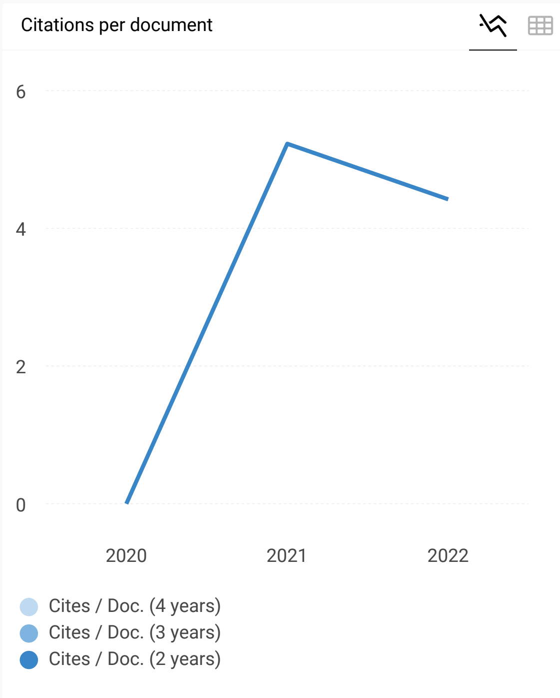

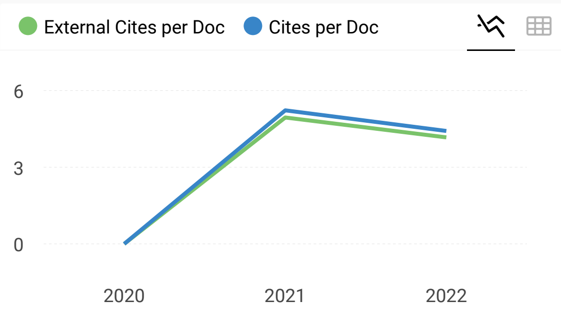

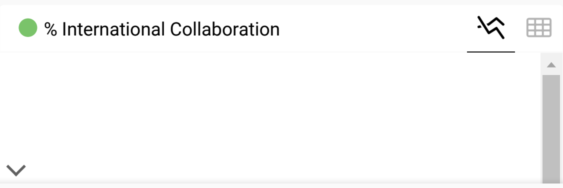

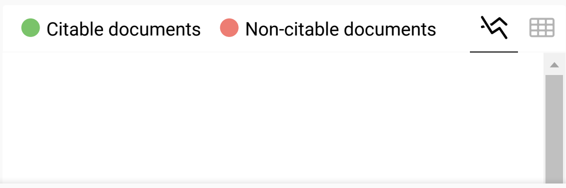

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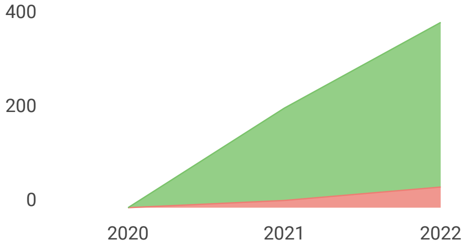

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The Hydrodynamic Model Application for Future Coastal Zone Development in Remote Area

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Abstract

Indonesia is an archipelago country with a wealth of marine resources. However, local communities have not optimally utilized the use of natural resources, including those in the coastal zone of Central Sulawesi, Indonesia. This research goal is to identify the potential coastal areas for future development in the coastal zones, such as grouper floating net cage (FNC) culture, seaweed cultivation, and tourism areas. Thus, it is intended to develop the methodology of the hydrodynamic models for decision support systems (DSS) within the analysis hierarchy process. There are a total of 25 parameters criteria to calculate the potential future coastal zone development, including physics, water quality, and zoning properties. This DSS can serve as the foundation for instruction, knowledge, and application in developing rural coastal regions. Because of its breadth, this research endeavor is still ongoing. After calibration and verification, the initial study of the potential area of approximately 98,000 ha indicates that the model meets the accuracy requirement within the range of the root mean square error of approximately 0.184. Then, the outcomes of the hydrodynamic model simulation in DSS can be used as essential information for maritime development at this location. The outcomes demonstrate that the best areas for grouper FNC cultivation, seaweed cultivation, along with marine tourism are 6,163 ha, 91,000 ha, and 9,024 ha, respectively. It is expected that this research will contribute to sustainable future coastal zone development in the vicinity of Central Sulawesi, Indonesia.

Keywords: Hydrodynamic Model; Central Sulawesi Indonesia; Coastal Potential; Cultivation; Decision Support System.

1. Introduction

Urban coasts can contribute to the city’s identity, improve the area’s visual appeal, and improve residents’ quality of life in general when they are in good condition [1, 2]. Indonesia has already been referred to as a maritime country due to its 5.8 million km² of sea, of which 0.7 million km² are territorial waters and 2.3 million km² are made up of Sea Islands [3]. One of the benefits of having water resources is that, besides having natural resources, they can also support the aquatic ecosystem as well as being an important component of economic development [4–6]. However, researchers and scientists faced some limitations with respect to a lack of measurement data, including physical coastal water, water quality, and coastal zone management. Thus, it is necessary to develop a method that can accommodate and answer these constraints. A decision support system is one of the methods to support the economic development problem [7-9].

Central Sulawesi is one of the islands in Sulawesi that has a lot of possible maritime activities due to its location in a coastal area (see Figure 1). Given that Indonesia is one of the most popular travel destinations worldwide, the tourism

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sector has contributed to raising the nation's overall Gross Domestic Product (GDP) [10]. However, local communities have not optimally utilized natural resources. As a result, communities in Indonesia, especially those in the coastal areas, still live below the poverty line, with a total per capita income still far below the World Bank's standard. There are activities, especially in the coastal areas, to raise economic gains, such as seaweed cultivation, grouper cultivation, and tourism.

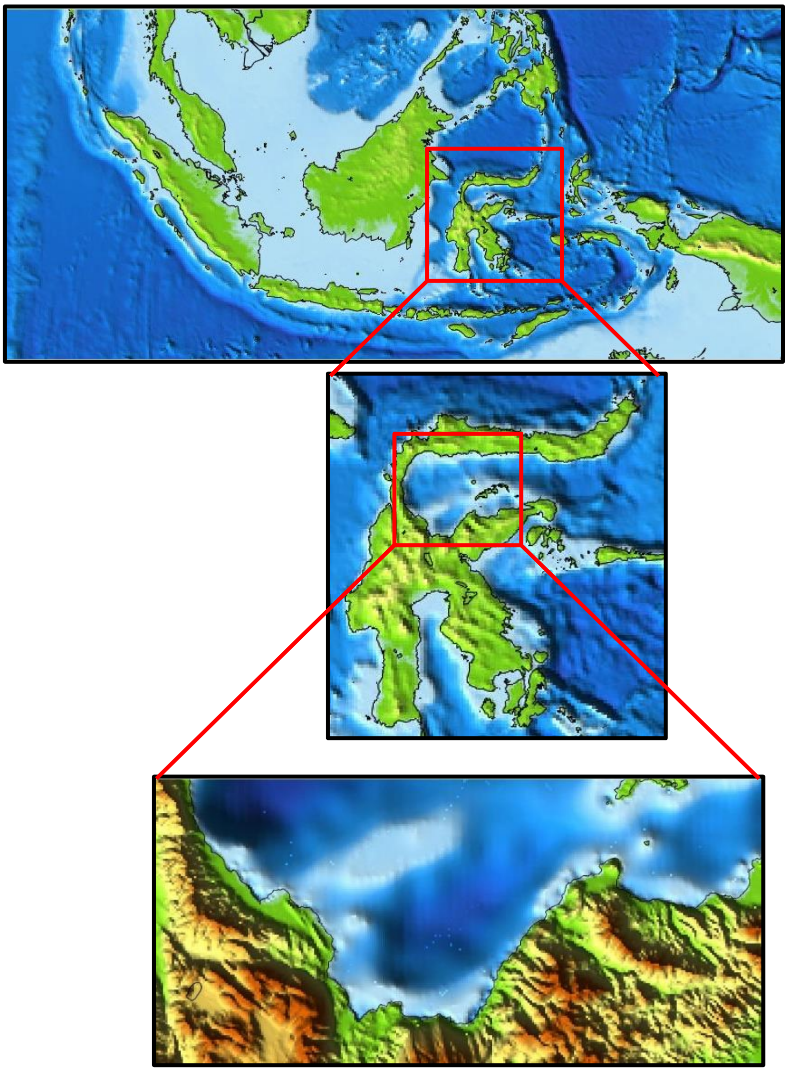

Figure 1. The location of the Central Sulawesi Indonesia

Several studies have been done on the development of the coastal zones. Manca Zeichen et al. [11] conducted a study on geospatial analysis along the Tyrrhenian coast in Tuscany, Central Italy, for fish farming. This study indicates that aquaculture activities require further development to determine zones of the area suitable for aquaculture. Sarker et al. [12] used the Generalized Additive Model (GAM) to describe the study of seaweed distribution in Bangladesh for ecological and economic values. Atzori et al. [13] conducted a study on the effects of climate change on Florida tourism destinations. This study discussed tourists' preferences based on conditional variables such as environmental attributes and weather conditions. Garbossa et al. [14] used a hydrodynamic model to study seaweed dispersion in various environmental conditions in Brazil. Based on simulation parameters, the result indicates that there are variances in seaweed branches ranging from 2 ha to 6 ha. Spencer et al. [15] discussed the tourism industry in the Caribbean, which is possibly threatened by climate change caused by sea level rise. This results in economic losses from tourism, which is required to safeguard the future of Caribbean economies as well as tourism industries.

This research objective is to maximize the potential of natural resources that have not been maximized by the local communities. The area is located in Central Sulawesi, Indonesia, and utilized hydrodynamic models to find out the oceanographic conditions such as wind speed, current speed, water level, and tides. The data obtained from the models are expected to be used as references in the future to determine what activities can be done to advance the coastal areas in terms of mane cultivation, such as seaweed and grouper cultivation, and marine tourism. This research is also expected to have positive impacts such as information, education, and application for the communities around Central Sulawesi, especially the coastal areas, in maximizing the natural resources that have the potential to be utilized.

2. Material and Methods

The hydrodynamic model was used for modeling in this research. The research location was Central Sulawesi, Indonesia. To begin the simulation, statistical data such as bathymetry, wind speed, and water level were required. Delft3D 4.04.02 is a program used to create hydrodynamic models. The Root Mean Square Error (RMSE) technique was then used to compare the validity of the data and verify it. The output of the hydrodynamic model could be utilized to assist the decision support system for an area development opportunity in Central Sulawesi.

2.1. Data

Bathymetry, wind speed, and water level measurements were used to simulate the model. The International Hydrographic Organization (IHO) provides sea level information. Bathymetry data were acquired from the General Bathymetric Chart of the Ocean (GEBCO) (see Figure 2). Bathymetry is the study of water depth, with the information gained useful for seafloor morphology and other sea activities [16, 17]. Figure 2 shows bathymetry data that applies to the research location in the northern parts of North and Central Sulawesi.

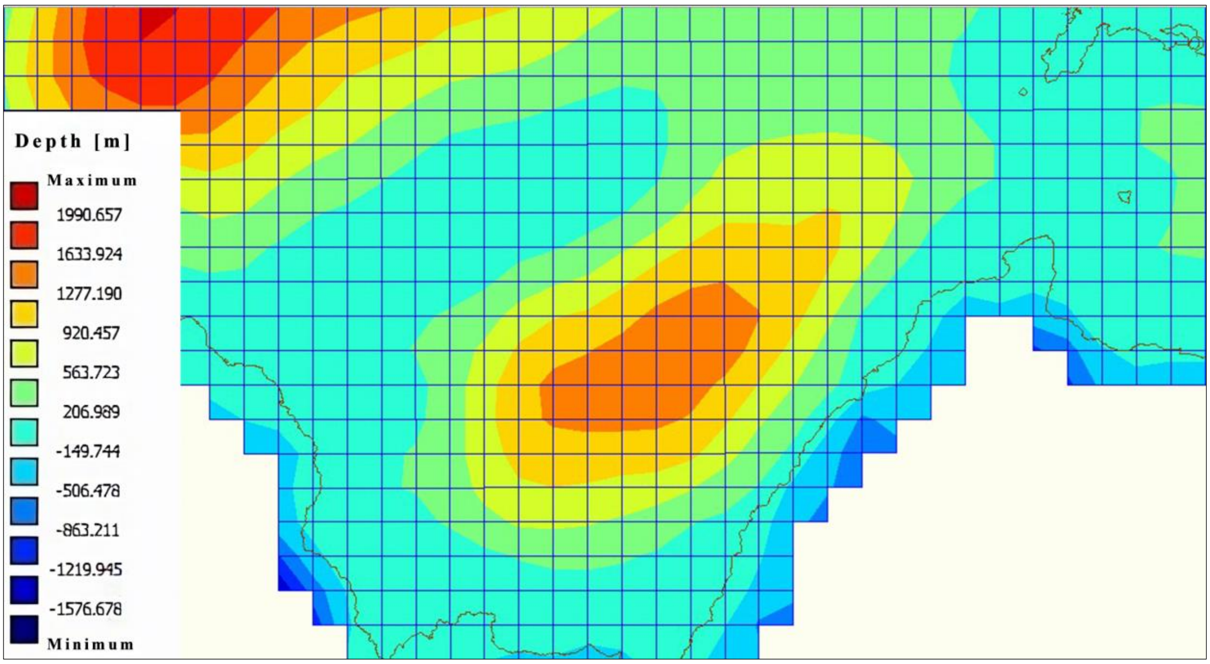

Figure 2. Bathymetry data in Central Sulawesi Indonesia area

Copernicus provides wind speed statistics for the simulation. Copernicus is a program that provides data for observing the Earth's land, air, and sea conditions. The wind data gathered spans the last ten years, from January 1, 2011 to March 31, 2021. The number of measurements obtained is approximately 89,000 data with measurements taken every hour at a height of 10 meters owing to the wind speed being stable at that altitude. After that, the wind data are processed on a table and transformed into a wind rose diagram (see Figure 3). The wind rose shows that the wind in the research location, which is Central Sulawesi, is mostly flowing from the northeast direction.

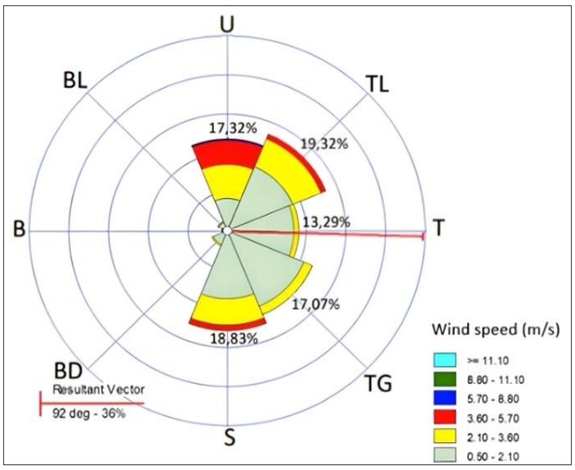

Figure 3. Wind Rose Diagram

2.2. Delft3D for Hydrodynamic Modelling

Deltf3D 4.04.02 is a 3D modeling application used to simulate hydrodynamic movements of bodies of water, such as water qualities, currents, morphology, and sediment transport for estuarine, fluvial, and coastal environments [18]. This application requires other software to operate, such as MATLAB and ArcGIS 10.8. Delft3D 4.04.02 is divided into two main softwares, namely Delft3D Flow and Delft3D Wave. Delft3D-Flow calculates the unsteady flows and phenomena brought on by meteorological stress and tidal forces on a curved boundary-fitted grid [19]. Delft3D Flow is also used to determine the shallow water equation (SWE), also known as the current water equation, calculated using velocity and height variables. To get the result of the currents and tides from the model, the Navier-Stokes equation is used in the Deltf3D calculation. The Navier-Stokes equation is as follows [20]:

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\rho x}+\frac{\partial(\rho v)}{\rho y}+\frac{\partial(\rho w)}{\rho z}=0 \tag{1}$$

where *x, y, z* are Observation location coordinates, *u, v, w* are Speed component variables, and ρ is Sea water density.

The equation used in Delft3D-Flow is formulated in orthogonal curvilinear coordinates. Delft3D-Flow offers two vertical grid systems: the coordinate system and the Cartesian Z coordinate system (Z-model). The hydrodynamic model calculations used in this present study were in the coordinate system. The system was invented by Philips (1957) for atmospheric models. The vertical grid consists of layers bounded by two planes that are not strictly horizontal but follow the bottom topography and free surface. A smooth illustration of the topography is created because the grid is boundary-fitted to both the bottom and the moving free surface [21].

The σ coordinate system is defined as [21]:

$$\sigma=\frac{z-\zeta}{d+\zeta}=\frac{z-\zeta}{H} \tag{2}$$

where z is the vertical coordinate in physical spaces, ζ is the free surface elevation above reference plane (at $z=0$), *D is* the depth below reference plane [m], and *H is* the total water depth, given by [m].

Depth-averaged continuity equation:

$$\frac{\partial \mathrm{V}}{\partial \mathrm{t}}+\frac{U}{\sqrt{G_{\xi\xi}}}\frac{\partial \mathrm{V}}{\partial \xi}+\frac{V}{\sqrt{G_{\eta\eta}}}\frac{\partial \mathrm{V}}{\partial \eta}+\frac{UV}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\sqrt{G_{\eta\eta}}}{\partial \xi}-\frac{U^2}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}}\frac{\partial\sqrt{G_{\xi\xi}}}{\partial \eta}+fu=-\frac{1}{\rho_0\sqrt{G_{\eta\eta}}}P_\eta-\frac{gU\sqrt{U^2+V^2}}{C_{2D}^2(d+\zeta)}+F_\eta+F_{s\eta}+M_\eta \tag{3}$$

where $\frac{\partial u}{\partial t}$ is derivative of u with respect to time, U is depth-average velocity in ξ- direction [m/s], $\sqrt{G_{\xi\xi}}$ is coefficient used to transform curvilinear to rectangular coordinate [m], $\frac{\partial u}{\partial \xi}$ is derivative of u with respect to ξ, V is depth-average velocity in the y- or η-direction [m/s], $\sqrt{G_{\eta\eta}}$ is coefficient used to transform curvilinear to rectangular coordinate [m], $\frac{\partial u}{\partial \eta}$ is derivative of u with respect to η, d is depth below reference plane [m], ζ is water level above some horizontal planes of reference [m], $\frac{\partial u}{\partial \sigma}$ is derivative of u with respect to σ, ρ_0 is reference density of water [kg/m^3], g is acceleration due to gravity [m/s^2], C_{2D} is 2D Chézy coefficient [m$^{1/2}$/s], P_η is gradient hydrostatic pressure in η – direction [kg/(m^{2}s^2)], F_η is turbulent momentum flux in η – direction [m/s^2], $\frac{\partial}{\partial \sigma}$ is derivative with respect to σ, and M_η is source or sink of momentum in η – direction [m/s^2].

Delft3D-Wave was used to simulate the wind-generated waves in coastal water that change over time. The wave module computes wave generation by wind, wind field, wave propagation, non-linear wave-wave interaction, and finite depth [21, 22]. The software can also be used not only for shallow types of water but also for medium and deep types of bodies of water.

Primary data were required to compare results from the hydrodynamic model simulation, in which secondary data were used. The bathymetry data collected using the Deeper Smart Sonar is one of the primary types of data needed. These primary data can be used as a base reference to predict the upcoming current and wave movement in the areas.

2.3. Root Mean Square Error (RMSE)

The Root Mean Square Error (RMSE) is a standard for measuring errors in modeling studies that forecast quantitative data such as meteorology, climate studies, and air quality [23, 24]. The RMSE method is used as a standard statistic by researchers to evaluate how much error the model generates in geoscience activities [25, 26]. Therefore, the hydrodynamic model generated by the RMSE method can be estimated using the RMSE formula:

$$RMSE=\sqrt{\frac{\sum_{i=1}^{N}(Xi-Yi)^2}{N}} \tag{4}$$

where Xi is Predicted value, Yi is Observation value, and n is Data number.

The parameters of RMSE were used to assess the results of the models. If the RMSE value is within or less than 0.1, the modeling can be marked as complete and considered accurate. If the RMSE value is greater than 0.1, the necessary data collection step to allow the simulation must be redone. The data could then be accessed online for future coastal research and growth. ArcGIS 10.8 was used for mapping the suitability of seaweed cultivation, grouper floating net cage cultivation, and tourist development.

2.4. Suitability Criteria

The suitability criteria for future development in grouper floating net cage cultivation, seaweed cultivation, and marine tourism in this study are shown in Tables 1 to 3. The evaluation of the suitability mapping of the Central Sulawesi area for the above opportunities is based on these criteria [9, 27, 28].

Table 1. Floating net cage grouper fish cultivation suitability criteria

Parameters	Unit	Suitable	Not suitable	Parameters
Physical parameters				
Minimum water depth	m	> 8	> 6	< 6
Maximum depth (anchor)	m	< 20	< 25	> 25
Maximum wave height	m	< 0.6	< 1	> 1
Wind speed	m/s	< 10	< 15	> 15
Current speed	m/s	< 0.6	< 1	> 1
Water quality				
Water temperature	°C	27 - 31	20 - 35	< 20 & > 35
Salinity	ppm	26 - 31	15 - 35	< 15 & > 35
Dissolved oxygen	mgO_2/l	> 5	> 4	< 4
Water pH	-log(H+)	7.8 - 8.5	6 - 8.5	< 6 & > 8.5
Water clarity	m	> 5	> 2	< 2

Table 2. Seaweed cultivation suitability criteria

Parameters	Unit	Very suitable	Suitable	Not suitable
Water depth	m	> 2 (low tide)		< 2
Current speed	m/s	0.2 - 0.4	0.1 < x < 0.2	< 0.1 & > 0.4
Water temperature	°C	32 -26	26 - 20	< 20 & > 32
Salinity	mg/l	35 - 32	32 -28	< 28 & > 35
Dissolved oxygen	mgO_2/l	8 - 3	3 -1	< 1

Table 3. Marine tourism suitability criteria for coastal area category

Parameters	Unit	Very suitable	Suitable	Not suitable
Water depth	m	0 - 3	> 3 - 6	> 6 -10
Type of coast	-	White Sand	White Sand, Less Coral	Black Sand, Coral, Steep
Coast width	m	> 15	< 10 - 15	3 - <10
Water base material	-	Sand	Sandy Coral	Muddy Sand
Current speed	m/s	0 - 0.17	0.17 - 0.34	0.34 - 0.51
Coast slope	°	< 10	10 - 25	> 25 - 45
Water clarity	%	> 10	> 5 - 10	3 - 5
Coast land closure	-	Coconut, Open Field	Shrubs, Low, Savannah	Tall Bush
Dangerous biota	-	None	Jellyfish and Sea Urchins	Sea Urchins and Stingrays
Fresh water availability	km	< 0.5	> 0.5 - 1	> 1 -2

Table 1 shows the grouper floating net cage cultivation criteria, consisting of physical parameters and water quality. The physical parameters consist of minimum water depth, maximum depth (anchor), maximum wave height, wind speed, and current speed. Water quality consists of water temperature, salinity, dissolved oxygen, pH, and clarity. Table 2 shows the seaweed cultivation suitability criteria consisting of water depth, current speed, water temperature, salinity, and dissolved oxygen. Table 3 shows the marine tourism suitability criteria. The parameters consist of water depth, type of coast, coast width, water base material, current speed, coast slope, water clarity, coast land closure, dangerous biota, and freshwater availability. One of the parameters of grouper floating net cage cultivation, namely the minimum water depth, shows that if an area has a depth of more than 8 meters, the area is very suitable for grouper cultivation. If the depth is more than 6 meters, it is suitable for group farming, but if the depth is less than 6 meters, the area is not. All development needs to meet the parameters shown in the table below.

2.5. Analysis Hierarchy Process (AHP)

Suitability mapping areas are processed using the Analysis Hierarchy Process (AHP) technique for each growth sector based on the suitability parameters. The Analytic Hierarchy Process is a decision-making process that entails identifying and categorizing judgment goals, criteria, and constraints into a hierarchy, as well as evaluating comparisons between elements at all levels of the hierarchy [29]. The value was estimated using an analytic scheme described in Figure 4 [30]. The measurement data were then divided into three categories: very suitable, suitable, and not suitable. The re-classifications were added together and re-analyzed against the prior parameters, and the final suitability area was created.

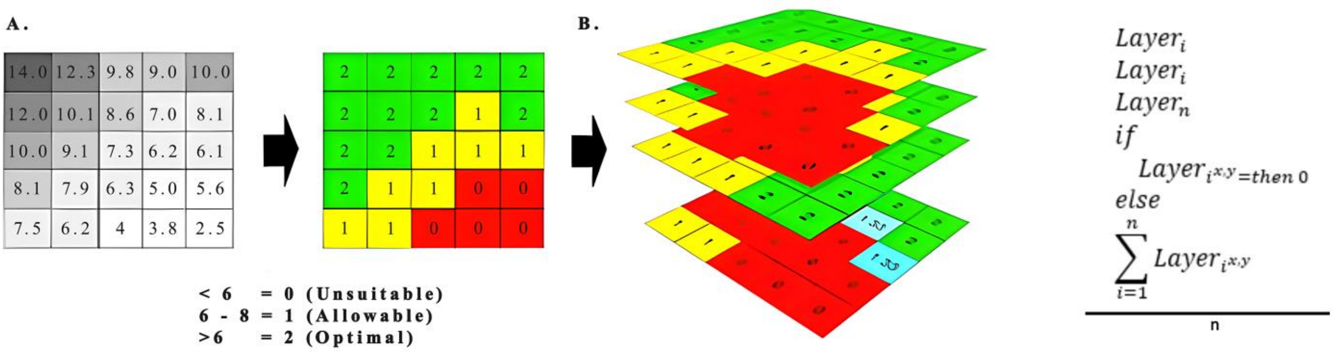

Figure 4. Summation value scheme

2.6. Research Flowchart

The research starts by preparing and studying the location of interest. Primary data collection on location is used to validate the research processes. After collecting primary data, Delft3D software is used to make a hydrodynamic model of the area of interest. Secondary data for the bathymetry data, model setup, and water level data are used to run the simulation. When all secondary data has been collected, Delft3D software can start running the simulation. Results are shown from the simulation and will be validated using the primary data. To validate the data, the RMSE method is used. When the data are validated, the AHP process is used to plot the suitability areas based on each criteria, such as grouper cultivation, seaweed cultivation, and marine tourism. When the results are met, the research process is completed, but secondary data and new models are needed until the RMSE value is met.

Figure 5 shows the flowchart of the research methodology through which the objectives of this study were achieved.

3. Results

3.1. Delft3D for Model Simulation

The model simulation used parameter data such as land boundary, grid, bathymetry, manning roughness, and time step. These data were ultimately be evaluated for compatibility between the simulation mode and the actual condition in the area using trial-and-error technique. The results of multiple trials of the hydrodynamic model simulation using square grid and bathymetry data supplied by GEBCO are depicted in Table 4.

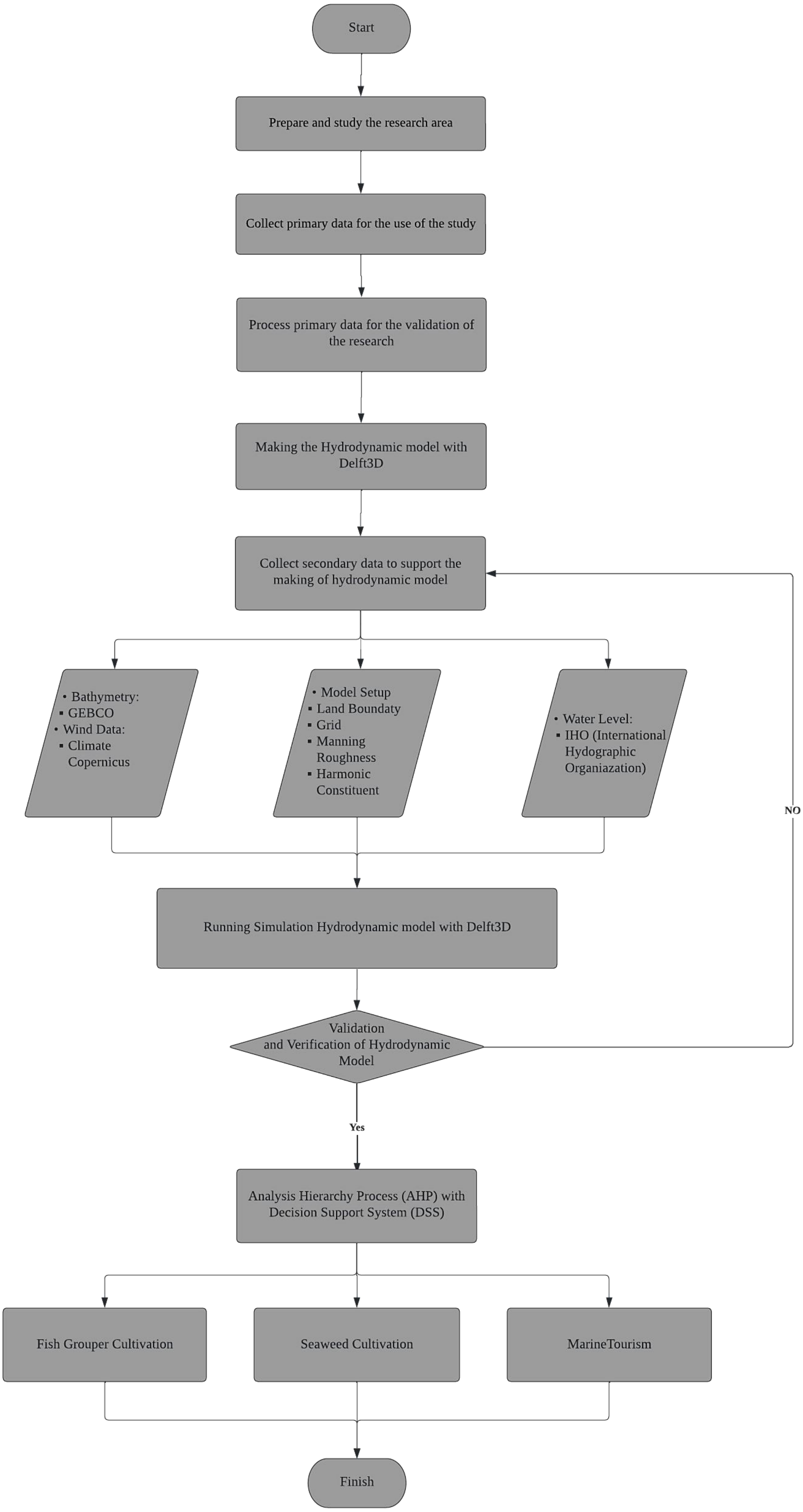

Figure 5. Flowchart of the methodology

Table 4. Simulation model with Delft3D Flow

No.	Models	Grids (meter)	Bathymetry	Manning Roughness	Time Steps	Simulation Durations	Descriptions
1	A	200	GEBCO	0.05	60 minutes	365 days	Failed
2	B	1200	GEBCO	0.05	60 minutes	365 days	Failed
3	C	1600	GEBCO	0.05	5 minutes	30 days	Failed
					30 minutes		
					60 minutes		
4	D	5550	GEBCO	0.05	5 minutes	14 days	Successful
					30 minutes		
					60 minutes		
5	E	5550	GEBCO	0.05	5 minutes	14 days	Successful
				0.033			
				0.025			

As shown in Table 4, failed simulations happened on models A through C. The failures are attributed to small grids and lengthy simulation durations. On the other hand, models D and E showed successful simulations. Model E employed the same grid and simulation time with smaller Manning roughness and time step variations of 5 minutes. Therefore, Figures 6 and 7 illustrate the results for the water level in 2D in Central Sulawesi at a certain time at the observation point. Figure 6 shows the changes in water level from February 13 until February 27. It can be seen that the elevation of the water level on February 15, 2021, at 00:00:00 is 0.45 m. The observation sites indicate that the water level was decreasing and increasing in elevation from that point forward, affecting the directions of the current as shown in Figure 8.

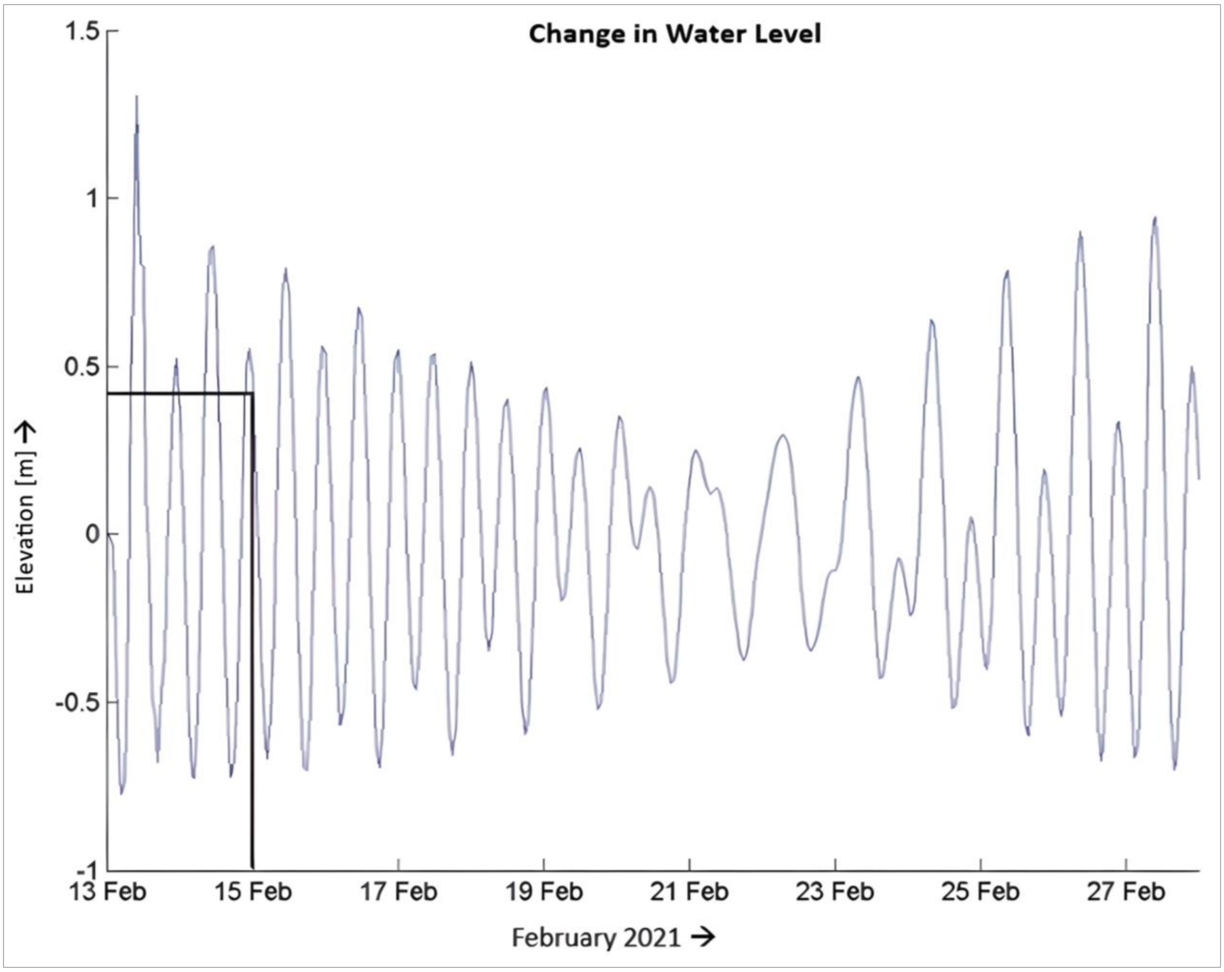

Figure 6. Hydrodynamic model results shown in water level changes

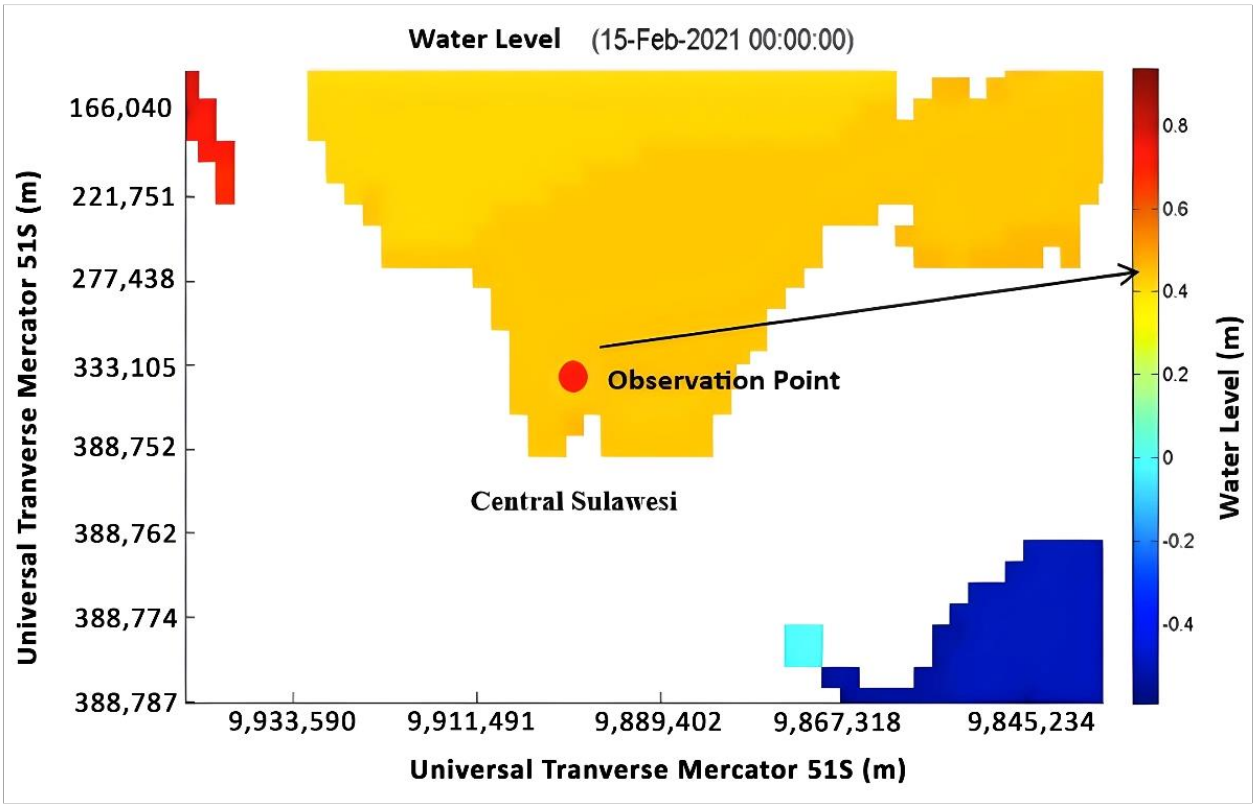

Figure 7. 2D Simulation results on water level changes

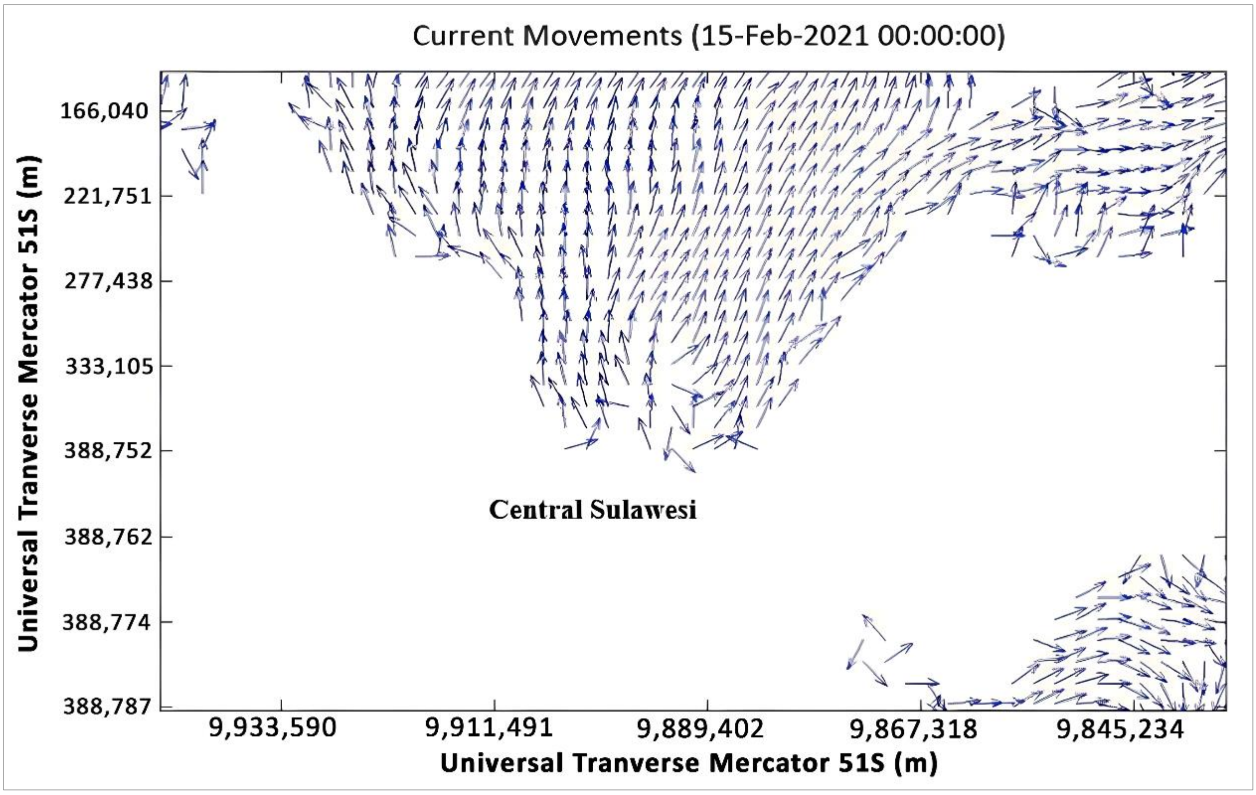

Figure 8. Simulation results of current movements on low tides

Figure 8 shows that the currents are moving away from the coast because of a condition in which the wave shortly experiences a low tide. The current speed at the observation locations is shown in Figure 9.

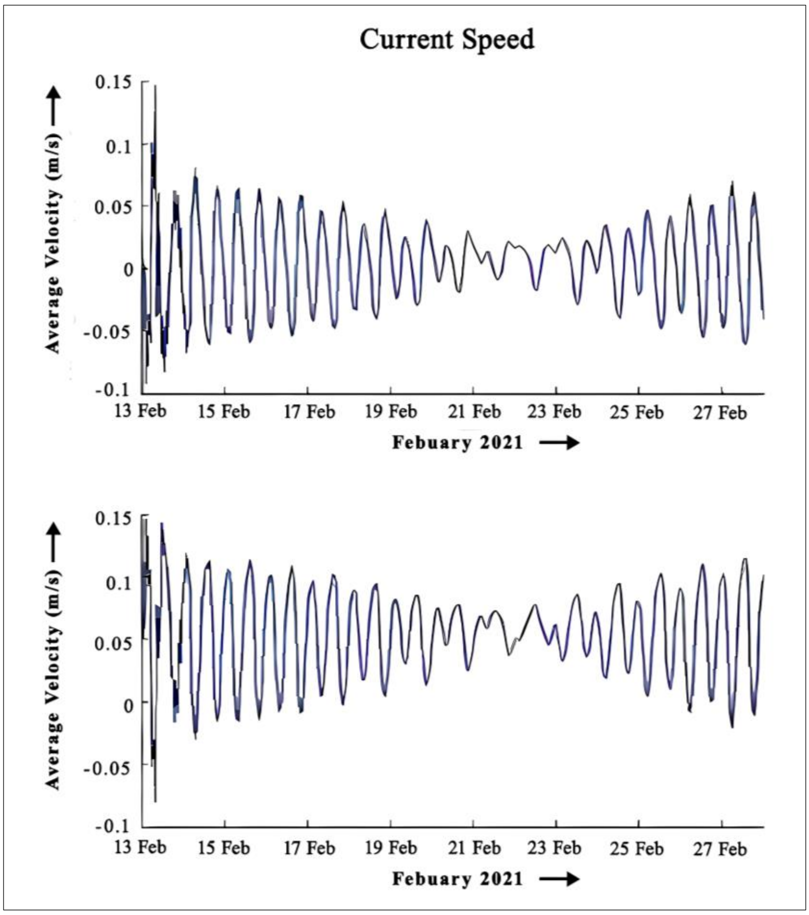

Figure 9. Current speed at observation point

The wave simulation in 2D format is also shown in the hydrodynamic model simulation (see Figure 10). Based on colour indicator on the right side of the figure, the wave heights around the observation point are around 0.1 - 0.2 meters. The model is then validated and verified using RMSE technique.

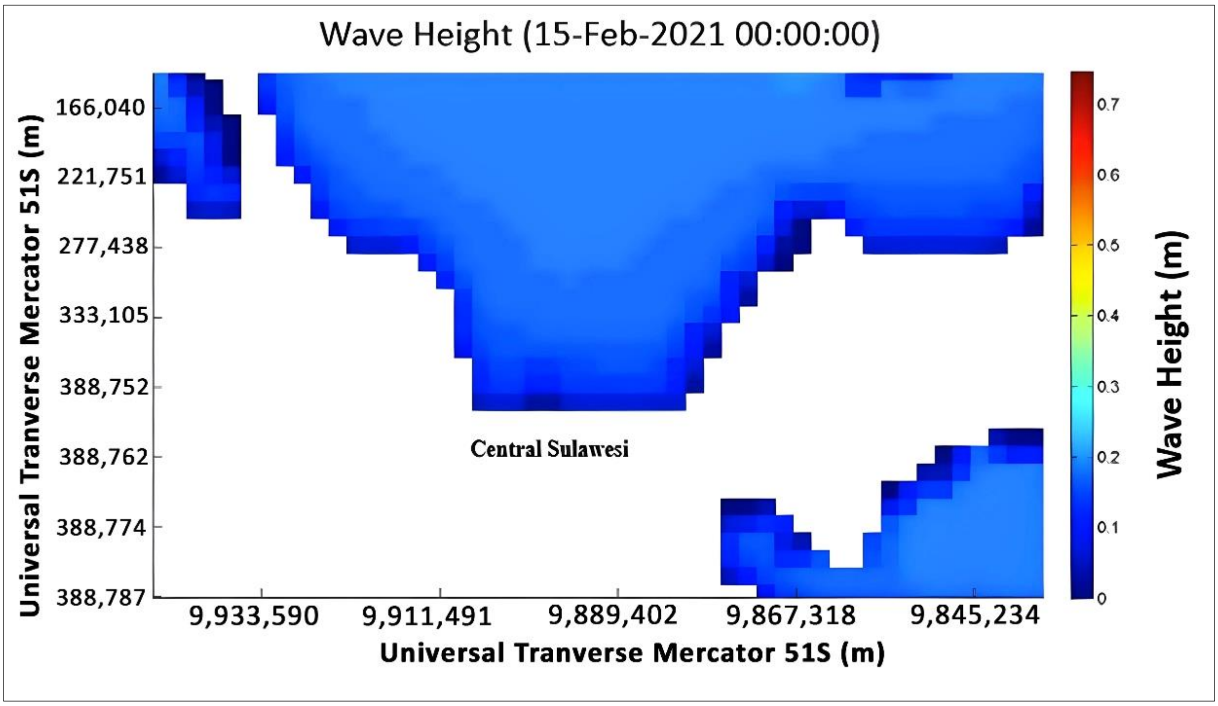

Figure 10. Wave heights on Central Sulawesi coastal area

3.2. Verification and Validation Using RMSE

Root Mean Square Error (RMSE) technique can be used to validate and verify the model between station measurements and simulation findings using Delft Dashboard software. The information on water level elevation is fed into the RMSE formula. Model E is chosen for further study from several model simulations. Three distinct RMSE values are shown for three different Manning roughness results from model E. Data for the research location, namely Central Sulawesi, are derived from the Delft Dashboard software and linked to the International Hydrographic Organization (IHO). Table 5 displays the RMSE for model E with different Manning's roughnesses.

Table 5. RMSE values in Model E Summary

No.	Manning Roughness	RMSE Values
1	0.025	0.296
2	0.033	0.186
3	0.050	0.184

Based on simulation results with three different Manning's roughnesses, 0.05 has the lowest RMSE value of 0.184, indicating that the 0.05 Manning roughness has the lowest error and is the most likely field condition. Figure 11 describes a data comparison of the water level situation between station data and simulation data. The green line shows data from the station, while the blue dotted line shows data from the simulation.

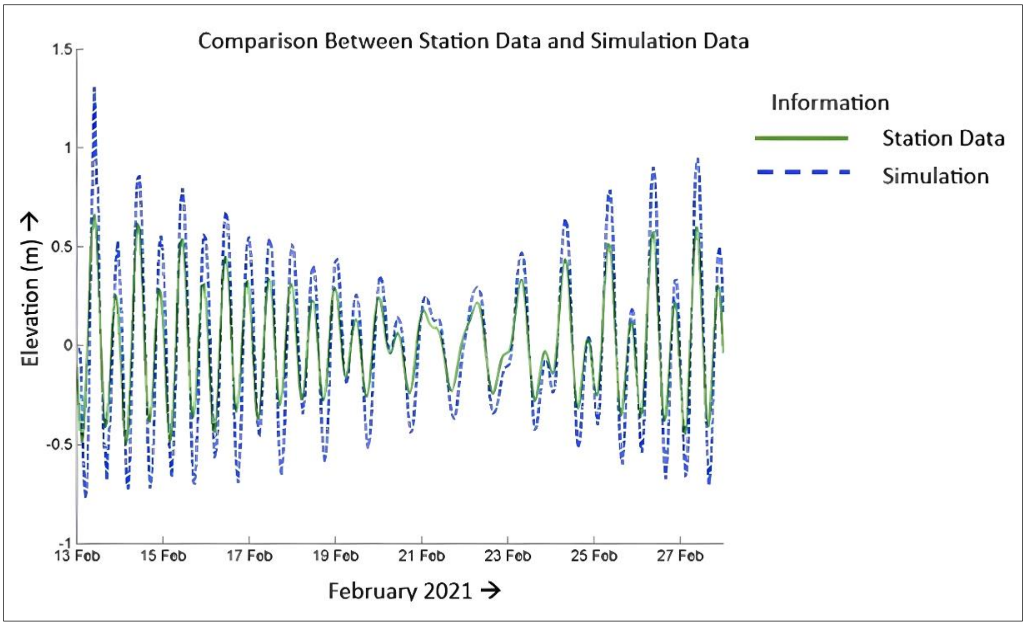

Figure 11. Comparison Water Elevation between Station Data and Simulation Data

Model E with Manning roughness of 0.05 is selected for further investigation because the RMSE value in this model is the highest between those of the three models, close to 0.01, and it is sufficiently accurate to describe the actual field condition of the coastal area in Central Sulawesi. The model is used to map the suitability level of a coastal area in Central Sulawesi with the assistance of the ArcGIS 10.8 application.

3.3. Coastal Area Mapping Development

The hydrodynamic model, as validated with RMSE, can be used as support to complement the online data retrieved and used as suitability mapping data for the coastal area. ArcGIS 10.8 software was used to process the mapping of floating net cages for grouper cultivation, seaweed cultivation, and marine tourism. Mapping was conducted only in the coastal area of Central Sulawesi.

3.3.1. Grouper Cultivation Suitability Mapping Area

The grouper cultivation suitability mapping results are evaluated based on the criteria of the floating net cage for grouper fish cultivation as described in Table 1. Based on the water depth as shown in Figures 12 and 13, most areas have a water depth lower than 6 meters in height and are highlighted in red, which indicates that they are not suitable for grouper farming. Some areas have a water depth of more than 8 meters and are highlighted green, which is very suitable for grouper cultivation.

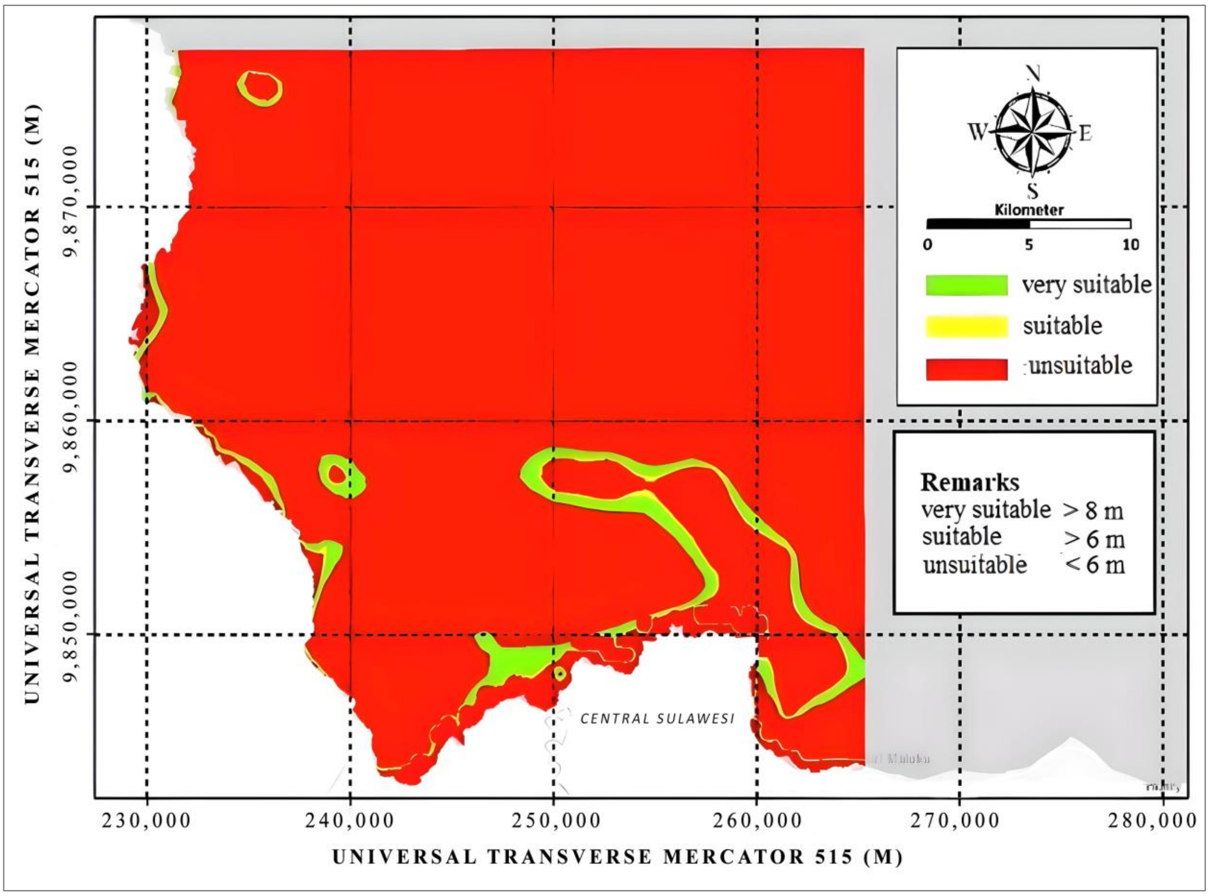

Figure 12. Grouper cultivation suitability area according to minimum water depth

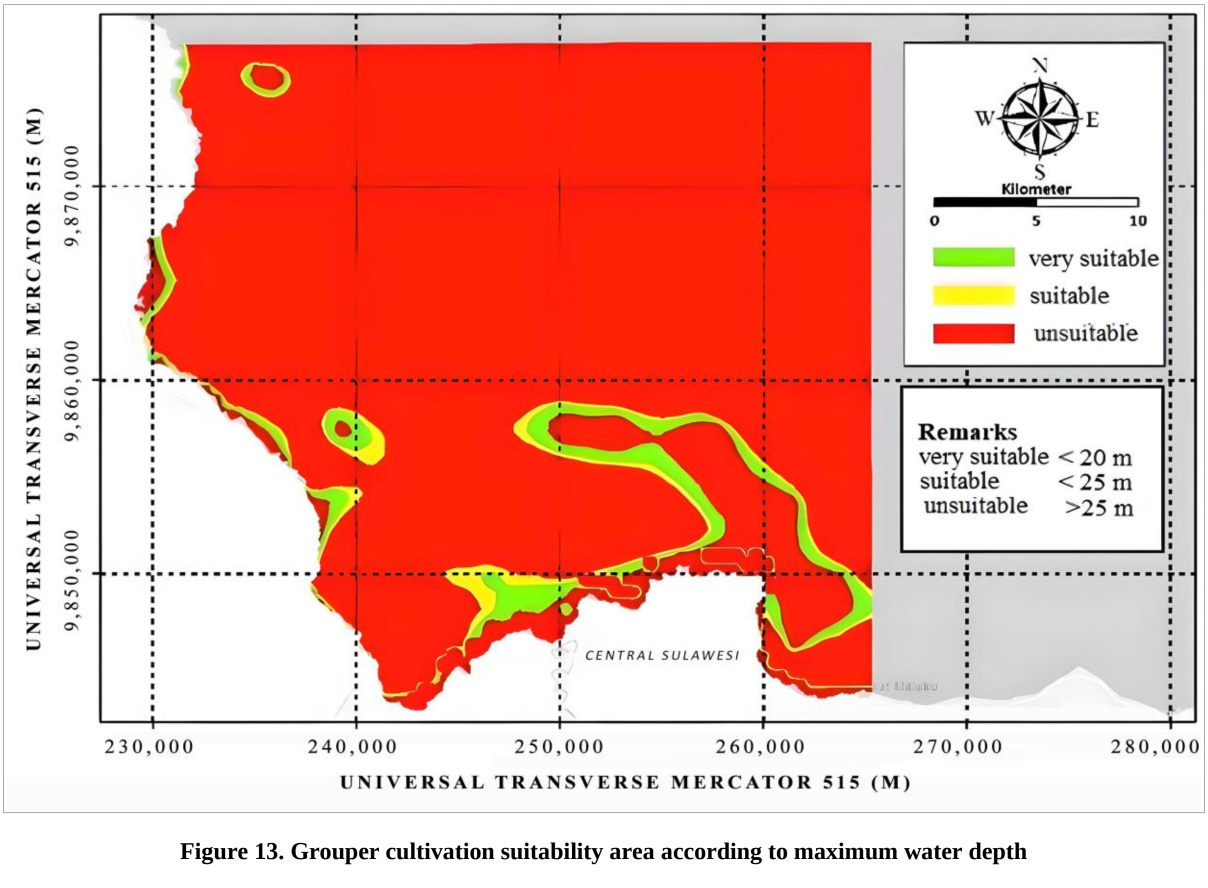

Figure 13. Grouper cultivation suitability area according to maximum water depth

Considering the wave heights, all areas shown in Figure 14 have less than 0.6 meters in wave height and are highlighted green, which indicates that the areas are very suitable for grouper cultivation.

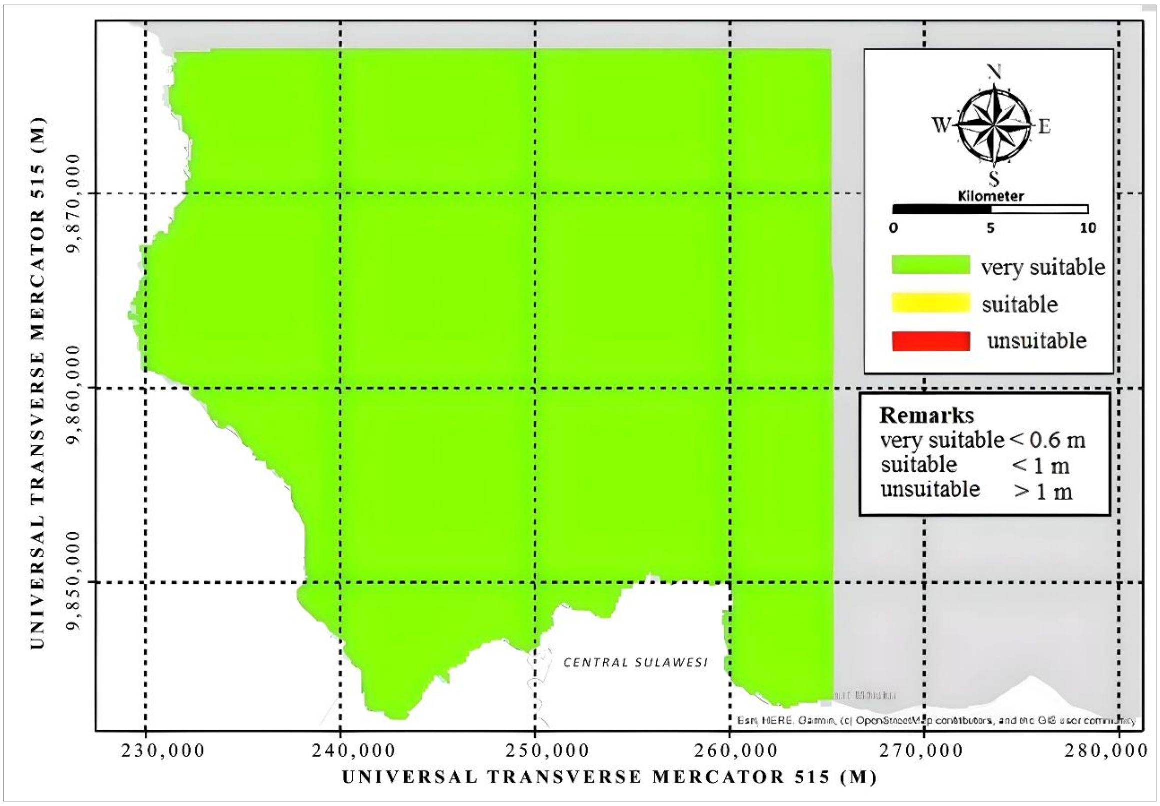

Figure 14. Grouper cultivation suitability area according to wave height

Considering the current speed in Figure 15, most areas have lower than 0.6 m/s in current speed and are indicated green which shows that the areas are very suitable for grouper cultivation.

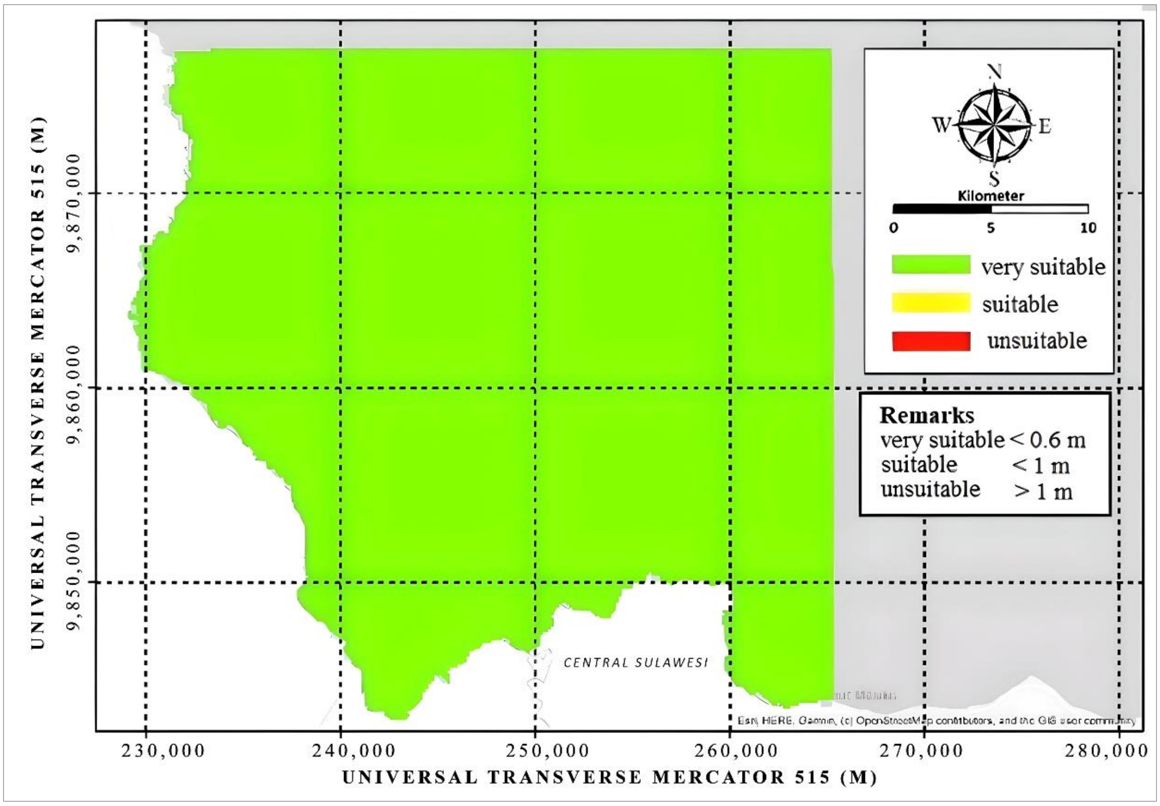

Figure 15. Grouper cultivation suitability area according to current speed

Considering the wind speed, Figure 16 shows that all areas are marked green and have wind speed lower than 10 m/s which indicates that the areas are very suitable for grouper cultivation.

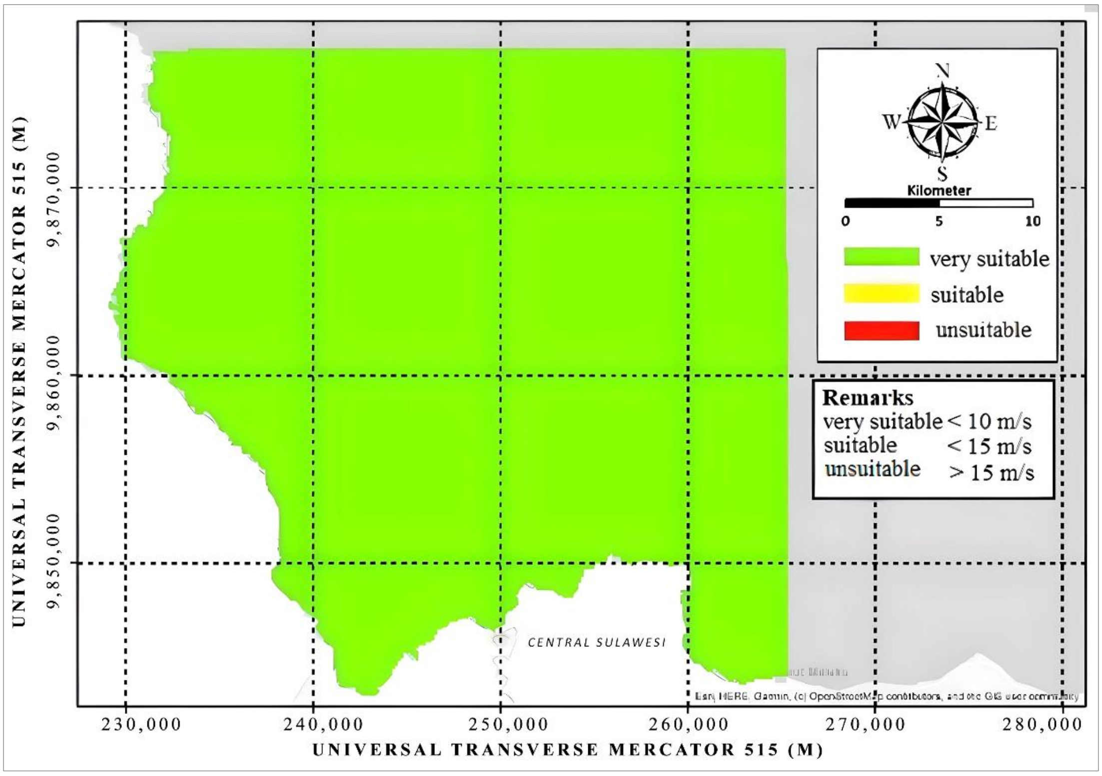

Figure 16. Grouper cultivation suitability area according to wind speed

Considering the water quality in Figure 17, all areas are marked green, and all parameters are suitable which shows that the areas are very suitable for grouper cultivation.

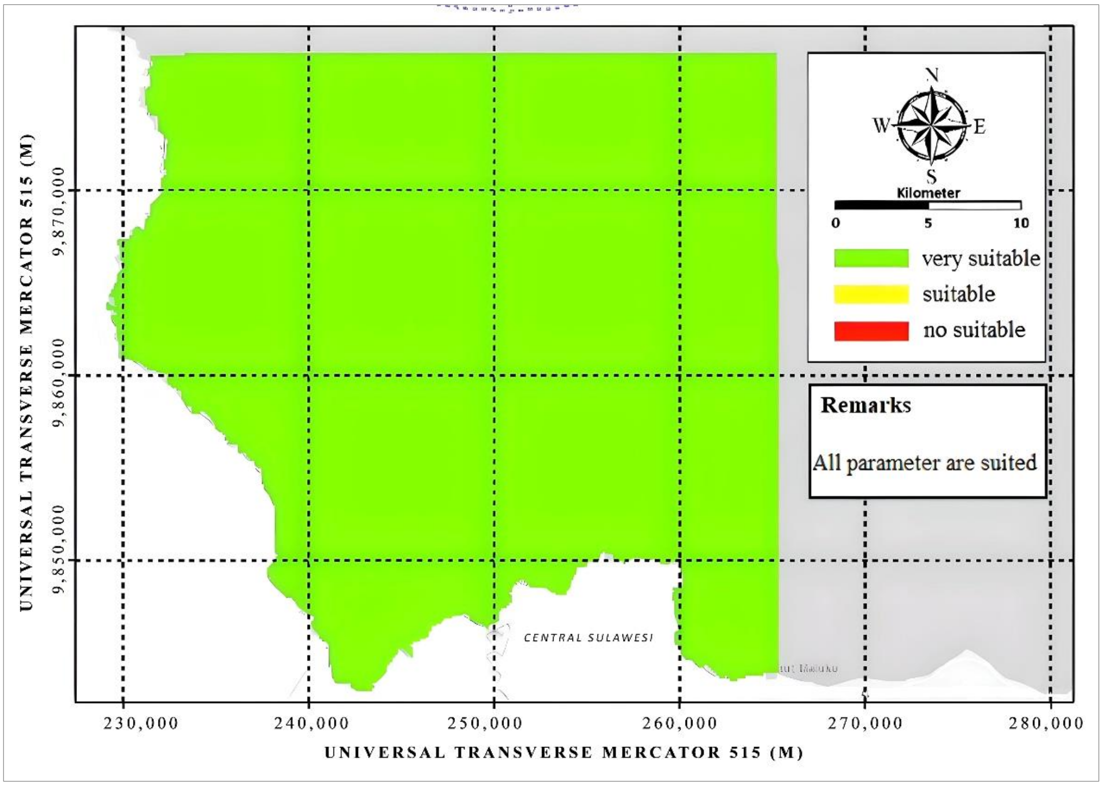

Figure 17. Grouper cultivation suitability area according to water quality

3.3.2. Seaweed Cultivation Suitability Mapping

The results of seaweed cultivation suitability mapping are based on Table 2 as specified in SNI 7579.2:2010 to regulate the cultivation of Cottoni seaweed (*Euchema Cottoni)* using long-line method. Based on the water depth as shown in Figure 18, most areas marked green have water depth of more than 2 meters, which indicates that the areas are very suitable for seaweed cultivation. Some areas highlighted red have lower than 2 meters in water quality, which indicates that it is not suitable for seaweed cultivation.

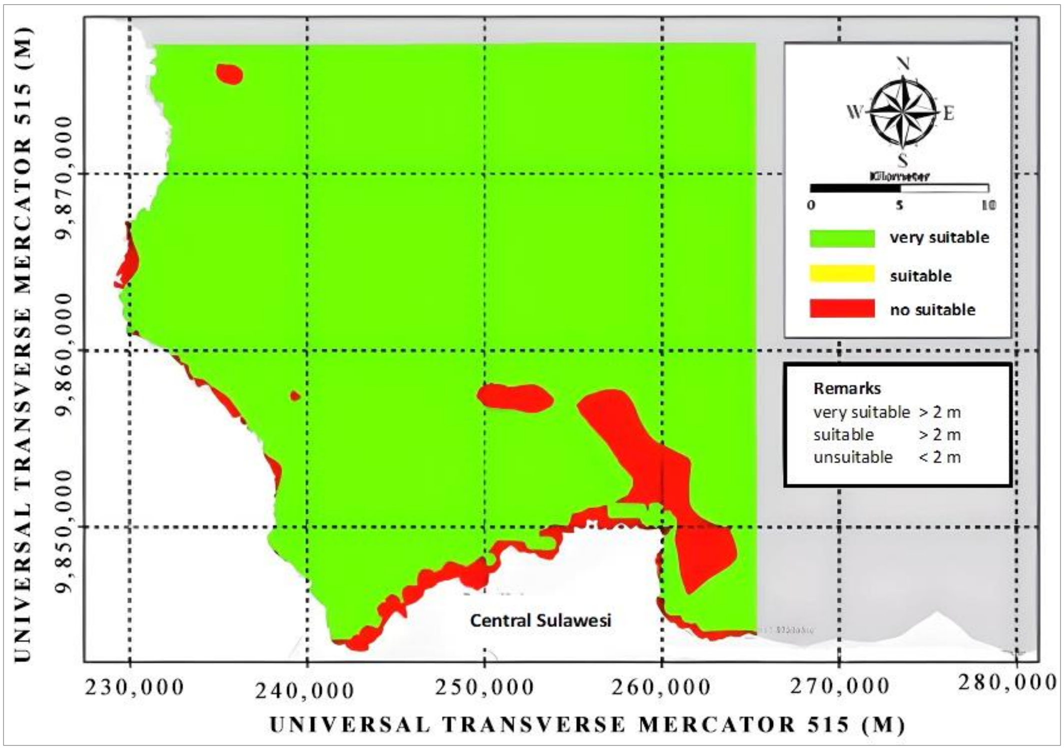

Figure 18. Cottoni seaweed cultivation suitability area according to water quality

Based on the current speed, most areas highlighted in red have ranges of less than 0.1 m/s and more than 0.4 m/s in current speed, which are not suitable for seaweed cultivation. Some areas highlighted in yellow have a range of 0.1–0.2 m/s, which indicates that those areas are suitable for seaweed cultivation (Figure 19).

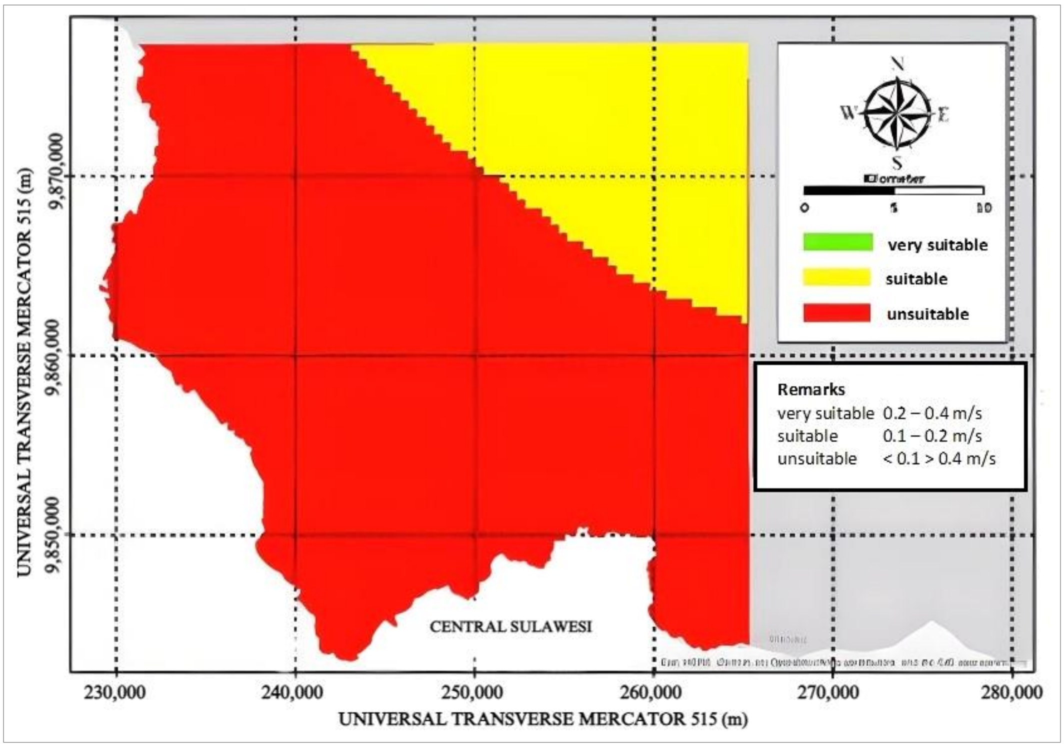

Figure 19. Cottoni seaweed cultivation suitability area according to current speed

Based on the water temperature shown in Figure 20, all areas have water temperatures ranging from 26 to 32 °C and are highlighted green, which indicates that those areas are very suitable for seaweed cultivation.

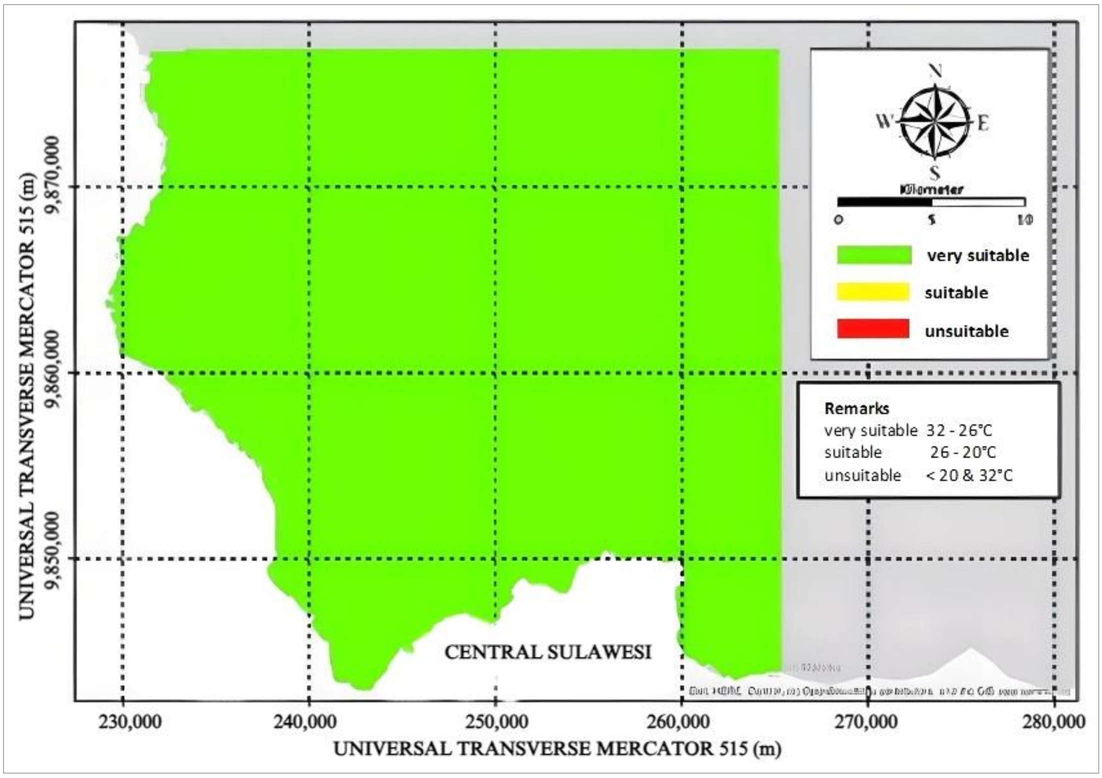

Figure 20. Cottoni seaweed cultivation suitability area according to water temperature

Based on the water quality in Figure 21, all areas are highlighted green, and all parameters are suitable, which indicates that the areas are very suitable for seaweed cultivation.

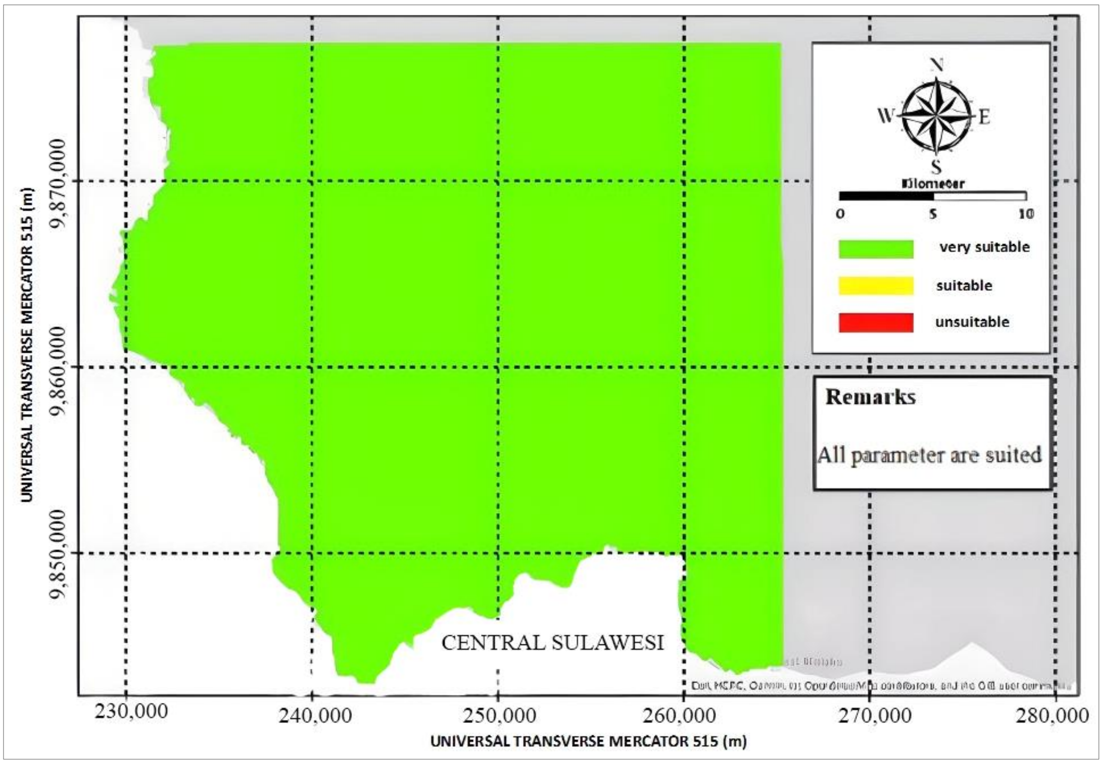

Figure 21. Cottoni seaweed cultivation suitability area according to water quality

3.3.3. Marine Tourism Suitability Mapping

The results of marine tourism suitability mapping were evaluated based on the described criteria in Table 3. The coastal marine tourism mapping in this research covers water depth, water clarity, current velocity, and coastal slope, as these data are provided by the hydrodynamic model. The most optimal results for coastal marine tourism have not yet been achieved. Based on the water depth as shown in Figure 22, most central areas are highlighted red and have a range of 6–10 meters in water depth, which indicates that they are not suitable for marine tourism, while some areas near the coastal area have a range of 0–3 meters in water depth and are highlighted green, which indicates that those areas are very suitable for marine tourism.

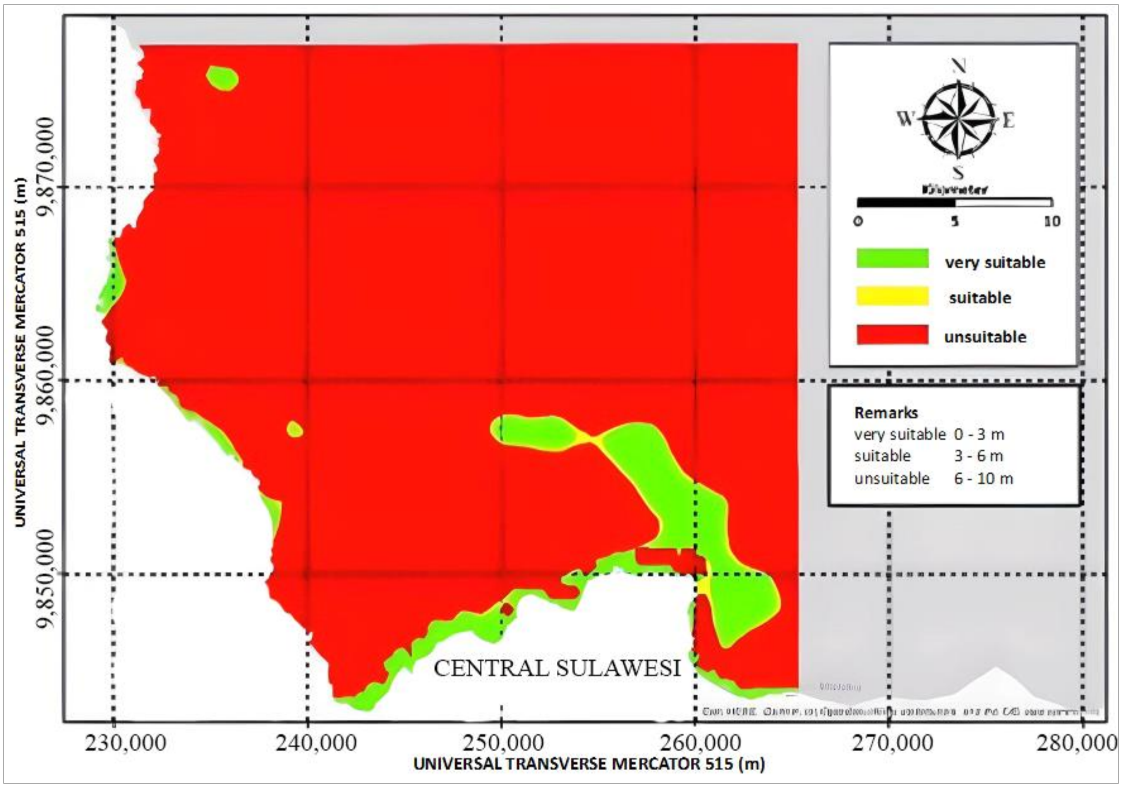

Figure 22. Marine tourism suitability area according to water depth

Based on the current speed in Figure 23, all areas have a current speed ranging from 0 – 0.17 m/s and are highlighted green, which indicates that those areas are very suitable for marine tourism.

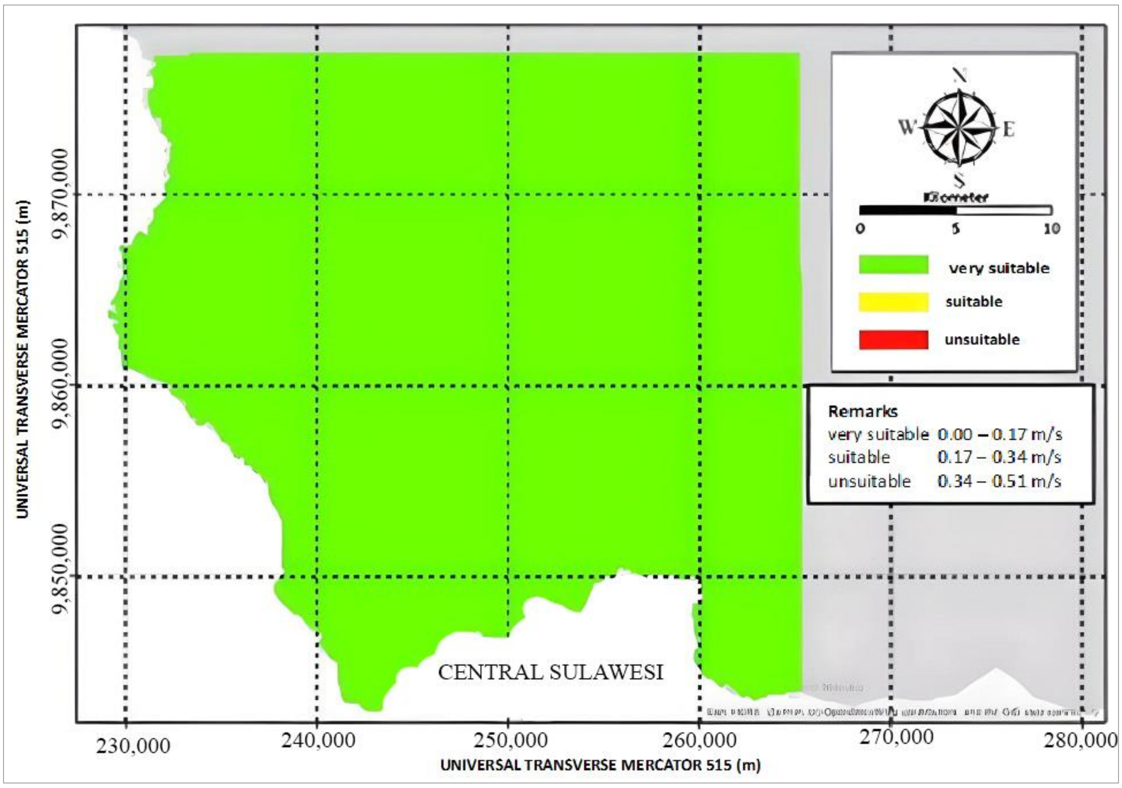

Figure 23. Marine tourism suitability area according to current speed

Based on the coastal slope shown in Figure 24, all areas are highlighted green and have a coastal slope of less than 10°, which indicates that all areas are very suitable for marine tourism.

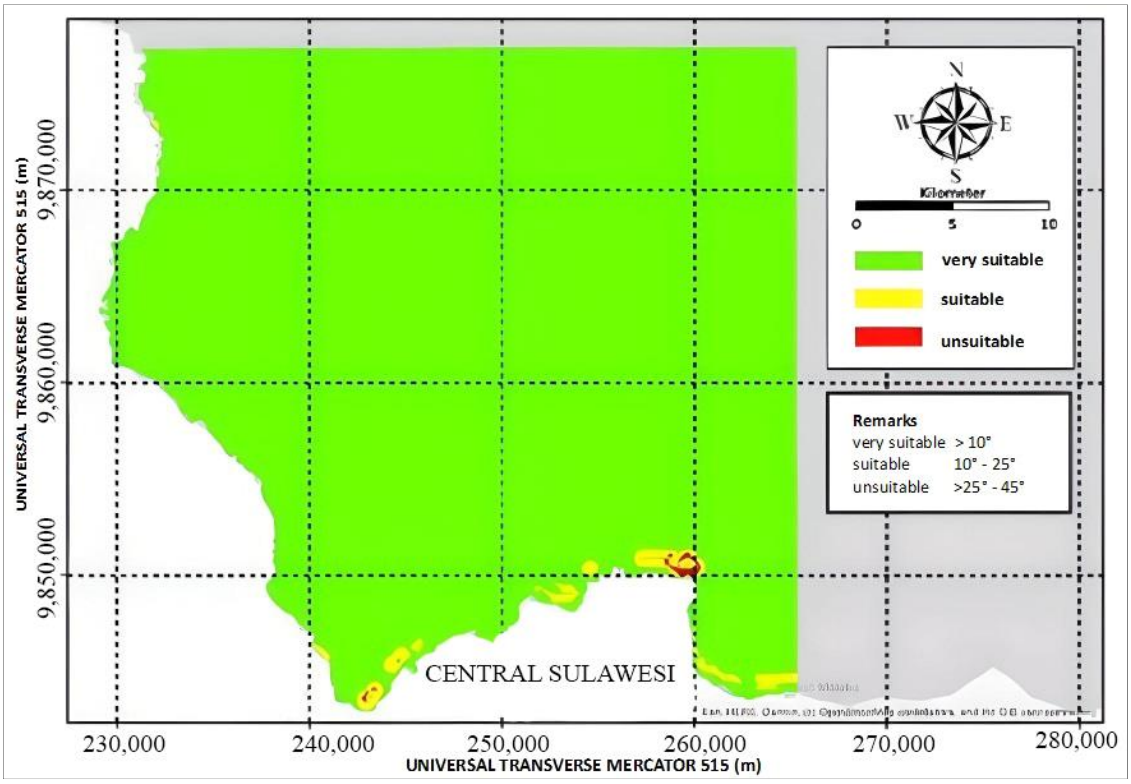

Figure 24. Marine tourism suitability area according to coastal slope

Based on the water clarity shown in Figure 25, most areas have a water clarity of 3–5% and are highlighted red, which indicates that they are not suitable for marine tourism. Some areas are highlighted yellow and have water clarity ranging from 5–10%, which indicates that those areas are suitable for marine tourism. A small area shown has water clarity ranging from more than 10% and is highlighted green, which indicates that those small areas are very suitable for marine tourism.

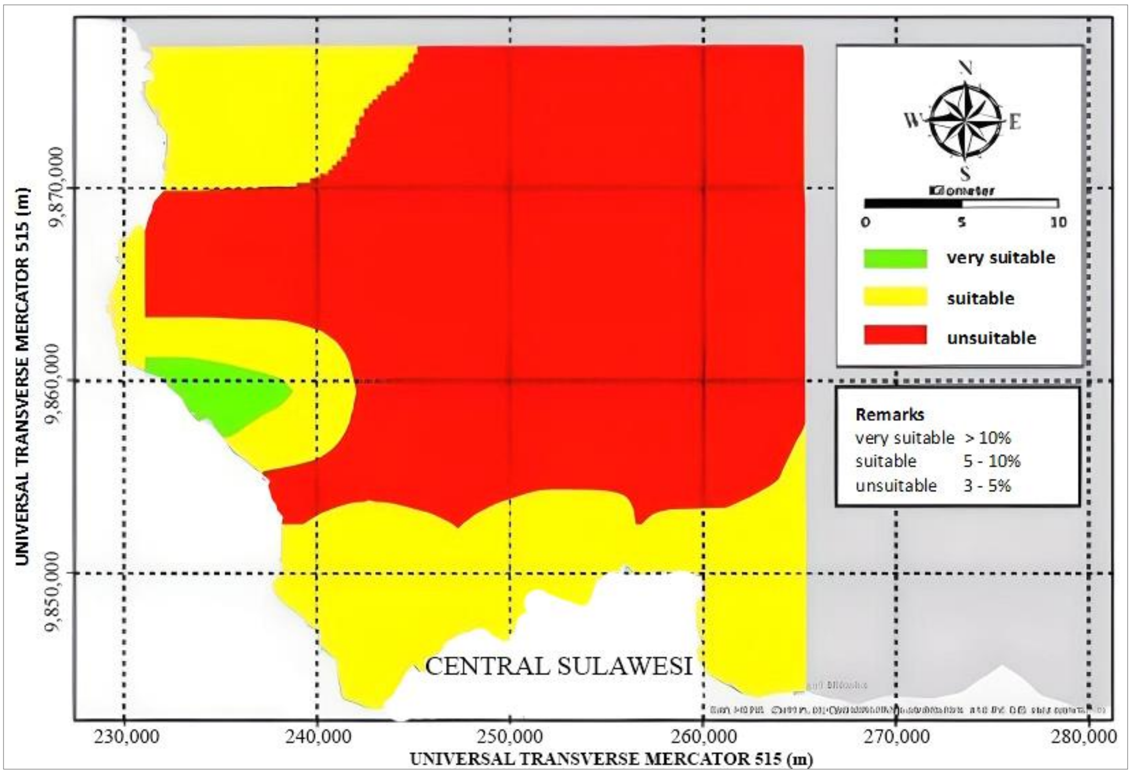

Figure 25. Marine tourism suitability area according to water clarity

3.3.4. Suitability Mapping Results

Based on all parameters that have been mapped based on each development sector, an estimated extent of the area is then determined to produce the suitability area for grouper floating net cage cultivation, seaweed cultivation, and marine tourism, as shown in Figures 26 to 28, respectively.

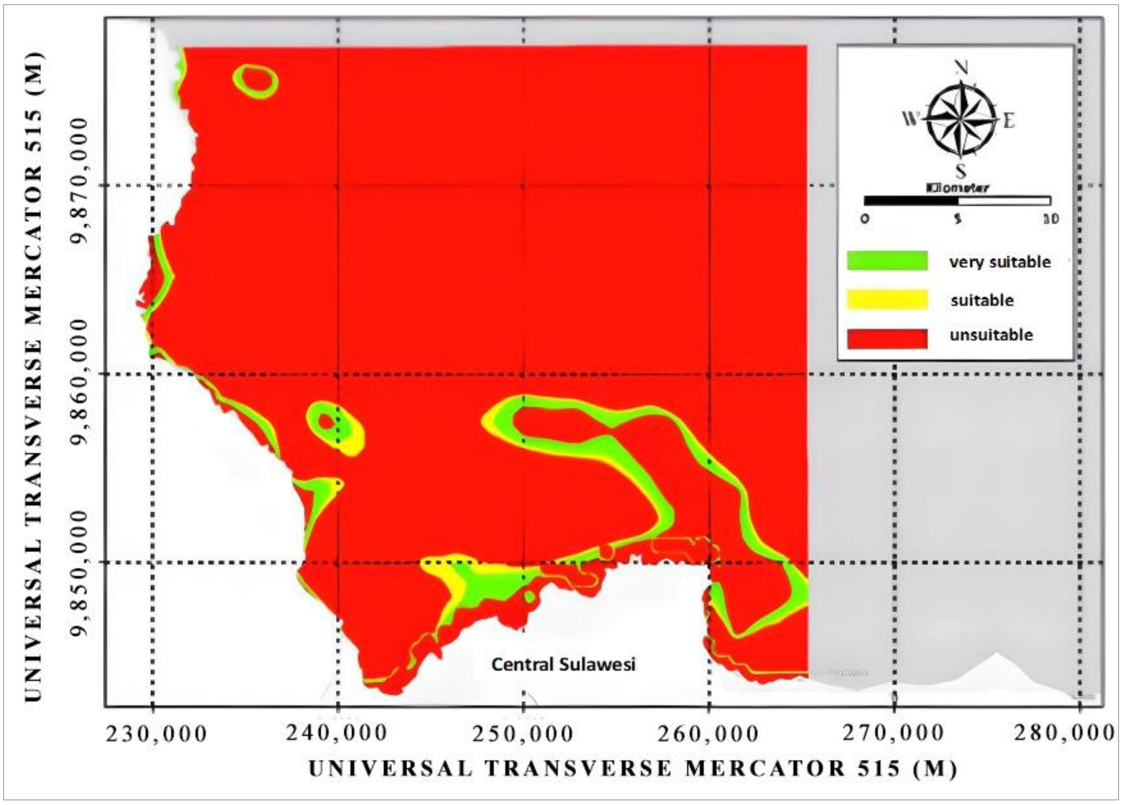

Figure 26. Grouper cultivation suitability area

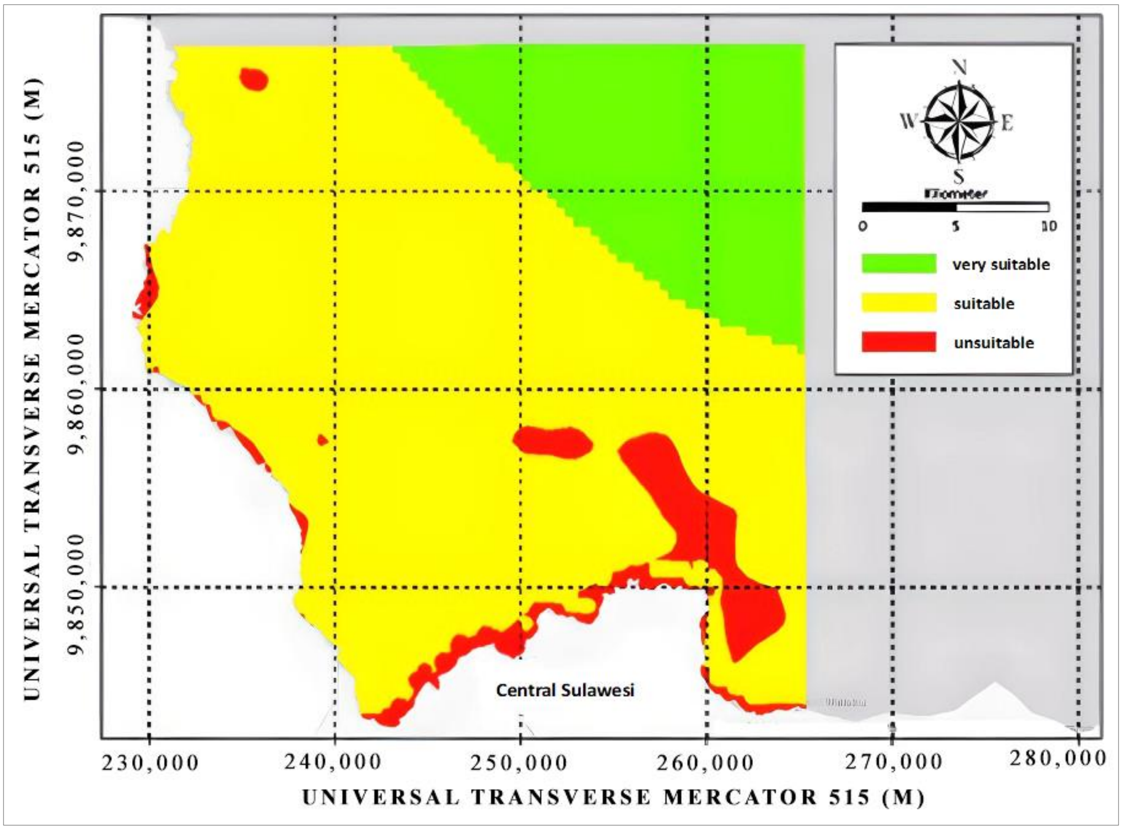

Figure 27. Seaweed cultivation suitability area

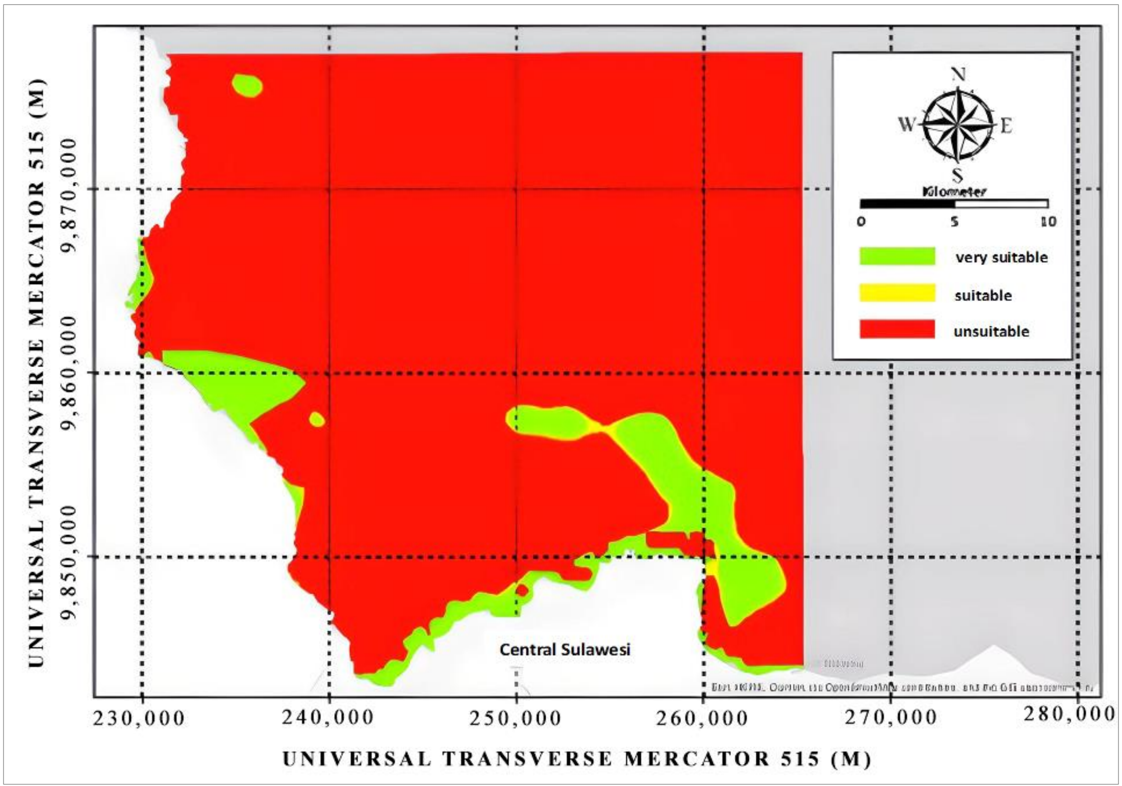

Figure 28. Marine tourism suitability area

The extent of the areas for grouper cultivation mapping shows that 4,161 ha fell into the very suitable area category, while 2,000 ha fell into the suitable area category. From the Cottoni seaweed cultivation map, it can be observed that an area of 20,685 ha shows a very suitable area, while 70,316 ha shows a suitable area. In the marine tourism map, 7,979 ha of the areas fell into the very suitable area category, and 1,045 fell into the suitable area category. However, the results of the suitability map for each development sector are not optimal because several parameters or criteria are not fulfilled, as the observation in this research is based on the hydrodynamic model scope.

4. Discussion

The suitability map for all contents, which are grouper cultivation, seaweed cultivation, and marine tourism, may vary based on each parameter required. The use of a hydrodynamic model may help the coastal area's water simulation in areas that have a lot of potential but are yet to be developed. Parameters such as grid sizes and time steps taken are important to determine the accuracy of the model. The first model simulation was model A with a 200-meter grid size and 0.05 Manning roughness; the duration of the simulation was 365 days, and the simulation failed. The model B was modified to use a bigger grid, which is 1,200 meters, but the model still experienced errors. With the next model, model C was modified by increasing the grid size to 1,600 meters with three different time steps and a simulation duration of 30 days. However, model C encountered some errors when the simulation was running. The next model, namely model D, was modified by increasing the grid size to 5,550 meters and the simulation duration to 2 weeks with the same variables as model C, and the simulation result was successful. Model E was created based on the parameters used by model D, but with three different Manning roughnesses, the result turned out successful. Model E was used because the grid size and time step are rather good and show no errors when simulated using 3 different Manning roughnesses, and model E had a RMSE value of nearly 0.1, namely 0.184. With the result of RMSE, it can be concluded that model E was the most accurate to describe the conditions of the waters in Central Sulawesi. The simulation data are then applied to ArcGIS software for the AHP processes to determine the suitability map for each sector.

Based on the results from the AHP processes for each development sector, results vary due to differences in seasons, locations, and conditions. The average temperature of seaweed cultivation in Brazil was around 22.17 $^{\circ}$C in a growing region and 17.11 $^{\circ}$C in the coldest month [7], while the results for the Central Sulawesi region's average temperature was 32–36 $^{\circ}$C based on the parameters, Central Sulawesi has a better area to cultivate Cottoni seaweed. The research in Florida shows that it is important for beach size, water clarity, and types of sand for a coastal area to be suitable for a marine tourism spot [6]. Wave height in Italy ranges around 0.01–0.4 m [14], which is relatively similar to the conditions in Central Sulawesi for fish cultivation. The results show that different locations have different conditions for each cultivation sector. Areas located in tropical areas have different parameters, such as wind speed, water temperature, and area size, than areas located in sub-tropical areas.

5. Conclusion

The utilization of hydrodynamic model simulation in decision support systems can be a method that benefits remote development in the vicinity of coastal areas. The implementation of the decision support system, which utilizes the Analysis Hierarchy Process (AHP), can compute the suitability area of the potential area of 98,466 ha for future development in Central Sulawesi, Indonesia. The outcomes determine that 6,163 ha of areas are suitable for grouper cultivation, 91,001 ha of areas are available for seaweed cultivation, and 9,024 ha of areas are available for marine tourism. However, the marine tourism suitability maps, which require more data, such as substrate mapping and mapping of dangerous animals, are not available. Data needed to be researched further to get more accurate suitability mapping. Primary data gathering by the local government is one of the solutions for data gathering. This research uses only 4 out of 10 factors, namely current speed, coastal slope, water clarity, and water depth, to determine the suitability map. As a result, it is anticipated that this research will serve as the starting point for the development of more precise suitability mapping for choosing the right coastal marine tourism destination in Central Sulawesi, Indonesia.

During this research, the lack of measurement data highlighted the main challenge for coastal researchers and developers in Indonesia. Thus, for future research, it needs to deploy instruments for seawater measurement of the primary data due to physics, water quality, and coastal management. The utilization of the Decision Support System (DSS) proves that it can solve the complexity (physical, water quality, and coastal zone management) of the potential seawater information data for future coastal zone development in remote areas of Indonesia. Recently, there have been limiting studies about the practice of the DSS with respect to Indonesia's coastal waters, especially in remote areas of central Sulawesi. Thus, this manuscript contributes to new knowledge application in the special domain (remote area) along with delivering information on one of the potential areas for the decision-maker and government for future development.

6. Declarations

6.1. Author Contributions

Conceptualization, S.H. and D.B.; methodology, S.H.; software, J.F.; validation, S.H., E.M., and J.E.P.; formal analysis, S.H.; investigation, S.H.; resources, D.B.; data curation, J.F.; writing—original draft preparation, S.H.; writing—review and editing, J.F.; visualization, J.E.P.; supervision, S.H.; project administration, J.E.P.; funding acquisition, S.H. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in the article.

6.3. Funding

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6.4. Acknowledgements

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6.5. Conflicts of Interest

The authors declare no conflict of interest.

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