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LAND SUITABILITY MODELING FOR FISHERY RESOURCE ENHANCEMENT IN THE PADANG PARIAMAN REGENCY, WEST SUMATRA, INDONESIA: GIS AND MULTI-CRITERIA EVALUATION APPROACHES

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ABSTRACT

Land suitability analysis is required for successful aquaculture planning. Due to the geographical setting of the Padang Pariaman Regency, aquaculture development is likely hindered by the vulnerable coastal area. The suitability assessment of aquaculture projects is crucial to specify the best method for sustainable development in the study area. This study aims to select the most proper location to be developed as a center of shrimp aquaculture in the Padang Pariaman Regency. This study employed the multi-criteria decision-making (MCDM) and analytical hierarchy process (AHP) approaches, combined with GIS-based analysis to yield the most proper location for aquaculture development. The three sub-models (engineering, water quality, and infrastructure) are overlaid using the weighted linear combination (WLC) technique. The infrastructure sub-model resulted in the highest coverage of highly suitable criteria, with 61.74%. By contrast, the highest percentage of the unsuitable category was found in the water quality sub-model, with 17.67%. Of particular concern, 87.50% of the study area is suitable for aquaculture development. The remaining region is categorized as highly suitable, with 11.93% found in the eastern Padang Pariaman. Thus, we conclude that developing shrimp aquaculture in the study area is possible. Still, the future environmental impacts should be considered beforehand.

KEYWORDS: suitability; aquaculture; Padang Pariaman; GIS; AHP

INTRODUCTION

Seafood consumption in Indonesia nowadays is generally supported by capture fisheries. Nevertheless, a plethora of fishery resources are over-exploited without any awareness of sustainability. It is predicted that fish-catching will be declined by 30% in the future due to the climate change and anthropogenic interventions (Cheung *et al.*, 2016), impacting the aquaculture sector. However, deciding suitable area and resources creates a challenge in conservation in the area with high biodiversity (Abood *et al.*, 2015). The planning system of sustainable aquaculture development requires several considerations in how to decide on the inhabited species and the variability of production systems (Henriksson *et al.*, 2019).

The prospective area for aquaculture in the West Sumatra Province is approximately 7,700 ha scattered in the Pesisir Selatan, Padang Pariaman, Pasaman Barat, and Mentawai Islands where 16.75 ha has been used for pond aquaculture development (0.22% of pond production 312.93 ton). Shrimp aquaculture is promising to develop in the Padang Pariaman Regency (Harisjon *et al.*, 2021). On the other hand, the Padang Pariaman Regency is susceptible to coastal hazards and disasters that may hamper the sustainability of the developed aquaculture (Solahuddin, 2011; Syaharani & Triyatno, 2019).

Several previous studies only focus on aquaculture pond's production efficiency, healthiness, and feed contribution (Aswara *et al.*, 2021; Gusri & Solerena, 2021; Putri & Munzir, 2021). However, a suitable location for aquaculture development has never been discussed. Therefore, a spatial model of a suitable aquaculture areas considering multiparameter criteria is crucial. These techniques are broadly used for identifying a suitable location for aquaculture development (Anand *et al.*, 2020; Bagheri *et al.*,

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2021; Masagounder *et al.*, 2005; Nayak *et al.*, 2018; Seliger *et al.*, 2021; Shunmugapriya *et al.*, 2021). This study aims to determine the perfect location for aquaculture development in the Padang Pariaman Regency based on GIS with a modified multi-criteria technique. It is expected that this study can support future policies regarding aquaculture in the Padang Pariaman Regency with less environmental impact.

MATERIALS AND METHODS

Study Site

The study area is situated in the Padang Pariaman Regency, West Sumatra Province, Indonesia, with a coastline of approximately 41.11 km. Generally, the existing developed area for aquaculture is scattered in the coastal area (Figure 1). The study site has a complex morphology consisting of lowland and hilly areas. Padang Pariaman Regency is composed of six types of soil: alluvial, regosol, organosol, podzolic, latosol, and andosol. Based on the geological data and field survey, the rock texture composition consists of fine sand – medium sand. While in the estuarine area, it is composed of some kinds of silt texture (Kastowo *et al.*, 1996).

Identification of Criteria and Suitability Rating

Deciding the suitable area for aquaculture development relies on many aspects, such as water resource availability, soil quality, salinity, temperature, the distance from pollution provenance, flood inundation, supporting infrastructure, access to significant areas, and markets (Nath *et al.*, 2000; Ponnuchamy & Kaliyaperumal, 2009). This study used 12 criteria to propose the best area for shrimp pond development based on literature review and aquaculture expert consultation. Then, the prepared thematic map (base layer) was classified into three categories: engineering parameters (slope, land use, soil texture, and elevation), water quality and quantity (the distance to the water sources, water temperature and salinity, the distance from pollution sources), and infrastructure parameters (the distance to the main road, markets, processing points, and hatchery).

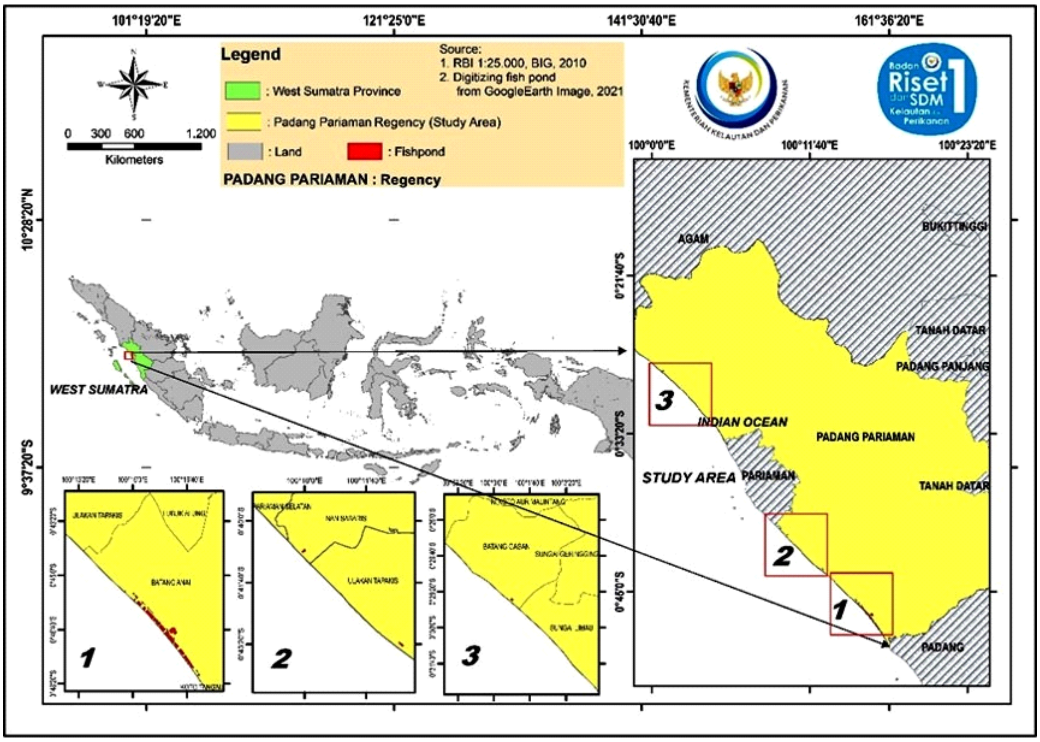

Figure 1. Details of Padang Pariaman Regency and aquaculture ponds distribution in the coastal area

These criteria were then classified based on suitability standard for traditional to semi-intensive pond culture technology. The term "suitability" shows the size of how good unit quality of land area is according to the required formation of land for certain uses (Krasadakis, 2020). The suitability ranks were classified based on FAO (Food and Agriculture Organization) for land suitability of particular use. These ranks were categorized as highly suitable, suitable, moderately suitable, and unsuitable. This study combined the same framework criteria with certain additional parameters, such as social-economy and infrastructure. Moreover, the criteria were standardized using a paired comparison technique, with the standardization value ranging from zero to one. The rank and score of suitability criteria are shown in Table 1.

Table 1. Suitability ranks and scores of engineering, water, and infrastructure parameters adapted from Hadipour *et al.* (2015)

Criteria	Highly suitable	Suitable	Moderately suitable	Unsuitable
Land use type	Aquaculture pond	Poor range, salt farm and here land	Agricultural land	Mangrove forest
Slope (%)	<2	2-5	5-10	>10
Elevation (m)	2-2.5	1-2 or 2.5-4	4-5	>5 or <1
Soil texture (% clay)	>35	18-35	<18	-
Distance to water source (km)	<1	1-2	2-4	>4
Water temperature (°C)	28-32	32-34 or 22-28	34-36 or 15-22	>36 or <15
Water salinity (ppt)	30-40	40-45 or 20-30	45-50 or 10-20	>50 or <10
Distance to pollutant source (km)	>4	3-4	2-3	<2
Distance to market (km)	<3	3-7	7-12	>12
Distance to road (km)	<2	2-3	3-5	>5
Distance to processing plant (km)	<3	3-7	7-12	>12
Distance to hatcheries (km)	<3	3-7	7-12	>12

Construction of Hierarchy and Weighting Procedure

The model structure of shrimp pond exact location was built based on hierarchy structure splitting the entire criteria into other smaller clusters (submodels). To split the hierarchy into smaller clusters, the related element was grouped based on function and property established in several previous studies (Ameen & Mourshed, 2019; Kamaruzzaman *et al.*, 2018). The score for every factor was determined by paired comparison within the context of the AHP method.

The measurement scale for paired comparison starts from 1 to 9. Scale 1 reflects that there is no difference in interest of one criterion to another criterion. In contrast, criteria 9 determines that one criterion is more significant than the others (Table 2) (Wang *et al.*, 2021). The inconsistency of the result relates to the paired comparison matrix. The inconsistency index (CI) and consistency ratio (CR) can be calculated using the formula as follows:

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (1)$$

$$CR = \frac{\bar{CI}}{RI} \quad (2)$$

where:

λ_{max} = the largest eigen value obtained after getting the related eigen factor

n = the amount of matrix column

$\boldsymbol{RI}$ = a random index (consistency index is obtained from a pair randomly yielded from comparison matrix) depending on the compared element

If the value of $\boldsymbol{CR}$ is less than 0.1, it shows a reasonable level of consistency within a paired comparison and if it is more than 0.1, an inconsistency is possible and the AHP method probably did not give a proper result (Saaty, 1980).

The highest level (rank 1) within the hierarchy represents the final objective of the MCDM (Multi-Criteria Decision-Making) analysis. The middle rank of the hierarchy (rank 2) includes relevant evaluation criteria, which are then compared in pairs to examine their relative scores. The lowest level of the hierarchy contains the object of evaluation. The entire criteria influencing the objective and representing the primary data were identified, resulting in a new version of secondary data. Figure 2 shows the suitability analysis of the location chosen for shrimp aquaculture in the Padang Pariaman Regency as a hierarchy structure.

RESULTS AND DISCUSSIONS

Examination Model of Coastal Area Suitability for Aquaculture

The calculation results of the paired comparison matrix and the scores of each criterion are shown in Table 3-6, referred to Hadipour *et al.* (2015). Consistency ratio (CR) ranging from 0 to 0.03 for each parameter, including a ratio less than 0.10, shows that consistency is not accepted. The suitability map is divided into three themes (suitability map of engineering, water, and infrastructure) depicted in Figures 3-5. Two combinations of the overlaid map commonly used are Boolean overlay and weighted linear combination (WLC) (Malczewski, 2004). However, in this study, we only used the WLC model because this

Table 2. Scale of pairwise comparisons

Intensity of importance	Verbal judgment of preference
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance
2, 4, 6, 8	Intermediate values between adjacent scale values

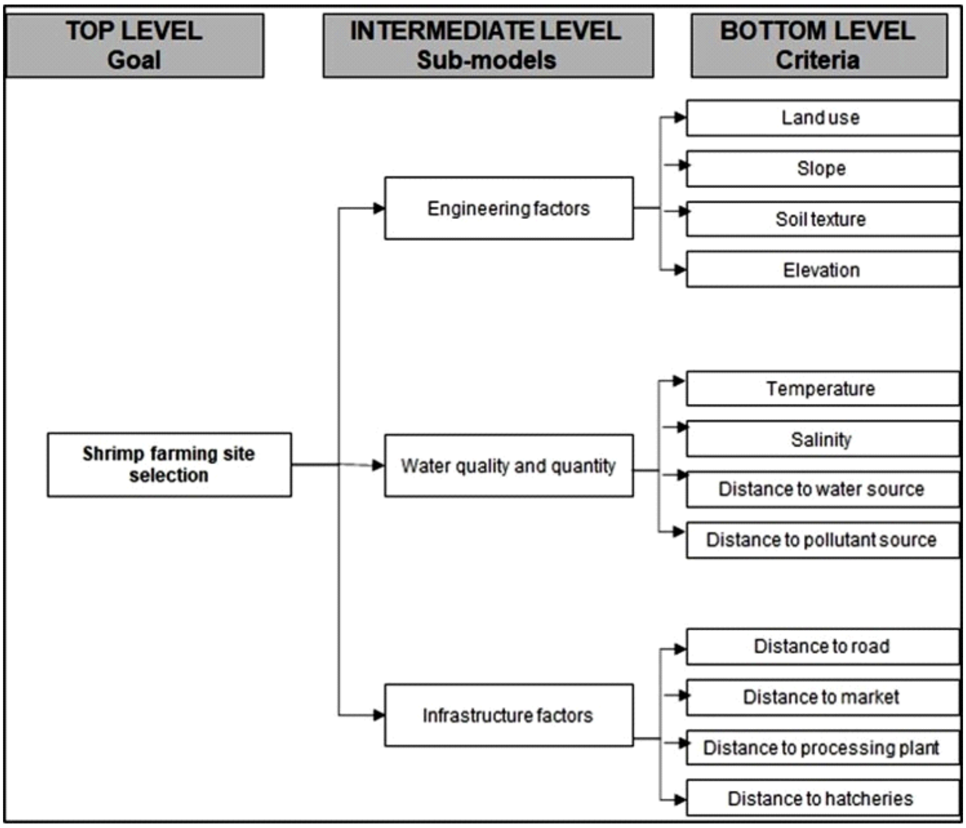

Figure 2. Hierarchical schematic diagram for modelling shrimp farming site selection in Padang Pariaman Regency.

analytical technique can be used when dealing with muti-criteria decision making (MCDM), meaning that more than one attribute should be taken into consideration (Mahini & Gholamalifard, 2006).

Suitability Maps of Engineering Sub-Model for Shrimp Aquaculture Development in The Padang Pariaman Regency, West Sumatra

Agriculture-related uses mainly covered the study area with an approximate cover of 63% of the entire study area, categorized as moderately suitable for aquaculture. The other land use types are bare lands and aquaculture ponds situated throughout the coastline of Padang Pariaman Regency, categorized as suitable for aquaculture.

In the study area, most of the soil texture is clay, with approximately <18% coverage, categorized as moderately suitable for aquaculture. In contrast, clay texture predomination is more significant in the coastal area, with a percentage of 18-35% (suitable). These states correspond to the regional geological map where the coastal area is covered by alluvial deposits containing sand, silt, and clay sediments marked by swamp deposits (Kastowo *et al.*, 1996). The remaining areas are categorized as highly suitable, with a clay percentage of >35% situated behind the coastal zone.

On the other hand, intensive and semi-intensive aquaculture systems rely on the local slope. An area with a uniform slope is very suitable for aquaculture

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Table 3. A pairwise comparison matrix for assessing relative importance of engineering factors for shrimp farming site selection in Padang Pariaman Regency (numbers show the rating of the row factors relative to the column factor)

	Land use type	Slope	Elevation	Soil texture	Weight
Land use type	1	2	5/2	2	0.41
Slope	1/2	1	2	1/2	0.19
Elevation	2/5	1/2	1	1/2	0.13
Soil texture	1/2	2	2	1	0.27

Table 4. A pairwise comparison matrix for assessing relative importance of water quality and quantity factors for shrimp farming site selection in Padang Pariaman Regency (numbers show the rating of the row factors relative to the column factor)

	Distance to market	Distance to road	Distance to processing plant	Distance to hatcheries	Weight
Distance to market	1	2/5	2	2	0.25
Distance to road	5/2	1	5/2	3	0.46
Distance to processing plant	1/2	2/5	1	3/2	0.16
Distance to hatcheries	1/2	1/3	2/3	1	0.13

Table 5. A pairwise comparison matrix for assessing relative importance of infrastructure factors for shrimp farming site selection in Padang Pariaman Regency (numbers show the rating of the row factors relative to the column factor)

	Distance to market	Distance to road	Distance to processing plant	Distance to hatcheries	Weight
Distance to market	1	2/5	2	2	0.25
Distance to road	5/2	1	5/2	3	0.46
Distance to processing plant	1/2	2/5	1	3/2	0.16
Distance to hatcheries	1/2	1/3	2/3	1	0.13

Table 6. A pairwise comparison matrix for assessing relative importance of land use requirements for shrimp farming site selection in Padang Pariaman Regency (numbers show the rating of the row factors relative to the column factor)

	Engineering	Water quality and quantity	Infrastructure	Weight
Engineering	1	2/5	2	0.25
Water quality and quantity	5/2	1	5/2	0.46
Infrastructure	1/2	2/5	1	0.16

Consistency ratio (CR) = 0.00

development where it is only 9% of the area with uniform slope scattered in Batang Anai, Ulakan Tapakis, and Nan Sabaris Sub-districts. In contrast, the area with a steep slope (unsuitable) covered 83% of the entire study area. The rest areas (8%) are categorized as suitable for aquaculture development. The declivous slope is categorized as suitable due to considering water supply toward the aquaculture pond (FAO, 2017; Hossain *et al.*, 2009). Concerning the land elevation, the study area is predominated by a moderately suitable category (elevation of 4-5 m), covering 85% of the entire area. The remaining categories are 2% suitable, 14% unsuitable, and 1% highly suitable (elevation 2-2.5

The result of the overlaid aquaculture suitability based on the engineering sub-model is shown in Figure 3. Overall, 92.74% of the study area is categorized as suitable for aquaculture development. Of particular concern, the coastal area of Batang Anai Sub-district is highly suitable, while the other coastal zones are categorized as moderately suitable. Therefore, we can say that Padang Pariaman Regency is suitable for aquaculture development based on the engineering sub-model assessment.

Suitability Maps of Water Quality and Quantity Sub-model for Shrimp Aquaculture Development in the Padang Pariaman Regency, West Sumatra

The temperature data were measured from existing ponds and surrounding rivers, ranging from 28.6 to 39.4ºC. Generally, the water temperature in the existing pond is highly suitable (18-31ºC). However, in the shrimp ponds in the Ulakan Tapakis Sub-district, the temperature is categorized as suitable (32-34ºC) for aquaculture.

On the other hand, the pond's salinity ranges from 18.7 to 27 ppt. Salinity values categorized as suitable for aquaculture ranging from 20-30 ppt were observed in Batang Anai and Nan Sabaris Sub-districts. A moderately suitable category (10-20 ppt) is identified in Ulakan Tapakis and Nan Sabaris Sub-districts. Generally, based on salinity value, no areas are categorized as highly suitable for aquaculture development (30-40 ppt).

Generally, the existing shrimp ponds in the Padang Pariaman Regency are categorized as highly suitable where the seawater source is less than one km from the pond area. However, several areas are categorized as unsuitable and moderately suitable due to the buffer system, with more than four and 2-4 km distance from the coastline.

The primary pollutant sources in Padang Pariaman Regency are husbandry, factories, and residential waste from the dense settlement. The number of factories and husbandry is still limited, and thus, based on the distance to pollutant sources, it is categorized as highly suitable for aquaculture, with more than 4 km from the pollutant source. Nevertheless,

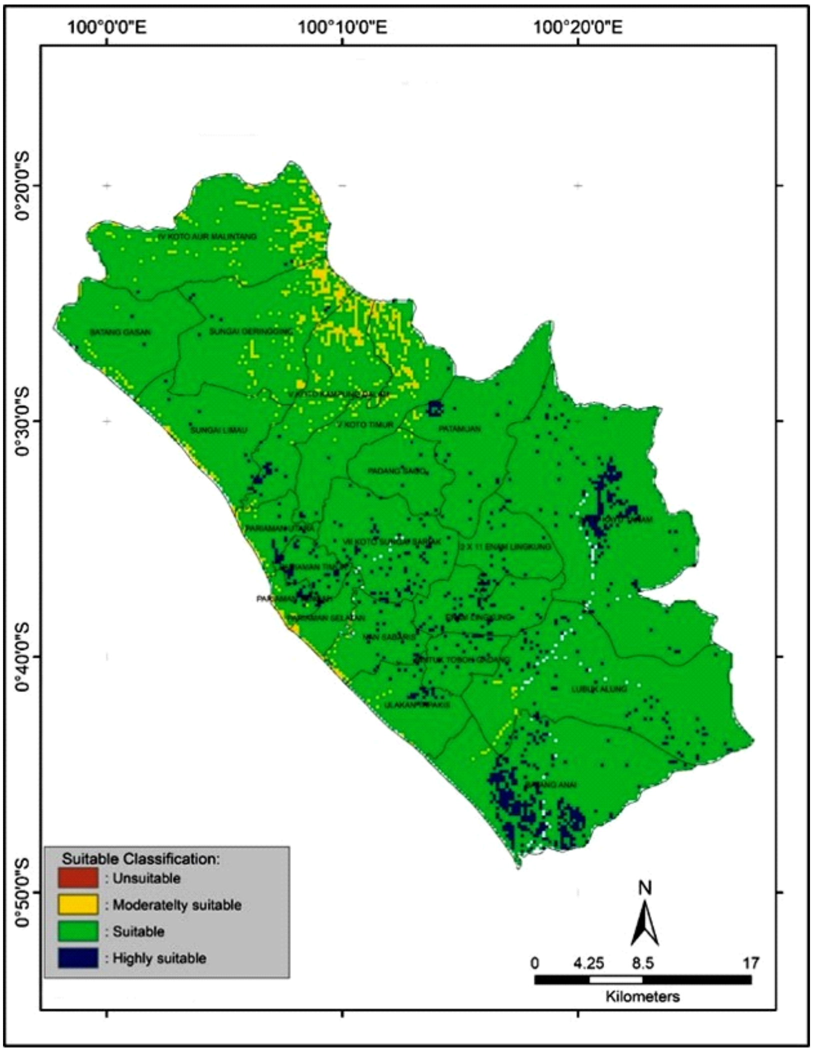

Figure 3. Suitability map of engineering sub-model for shrimp aquaculture development.

in several areas in the surrounding pollutant source (factory, husbandry, and residential area), it is categorized as unsuitable, with a distance from the pollutant source of fewer than 2 km.

Overall, the suitability map based on the water quality sub-model shows four categories where the highly suitable category is predominant in the study area, whereas toward the sea, the category is gradually transformed into unsuitable (Figure 4). The primary factor determining the suitability of aquaculture development area based on the water quality sub-model is influenced by the distance to water and pollutant sources.

Suitability Maps of Infrastructure Sub-Model for Shrimp Aquaculture Development in the Padang Pariaman Regency, West Sumatra

Based on the distance to the main road, 83% of the entire area of Padang Pariaman Regency is categorized as highly suitable for aquaculture development. The other categories are unsuitable (3.39%), suitable (4.61%), and moderately suitable (5.17%). The close distance between the aquaculture area and the main road ensures the easiness and safety of transportation and production processes (Yakubu *et al.*, 2022).

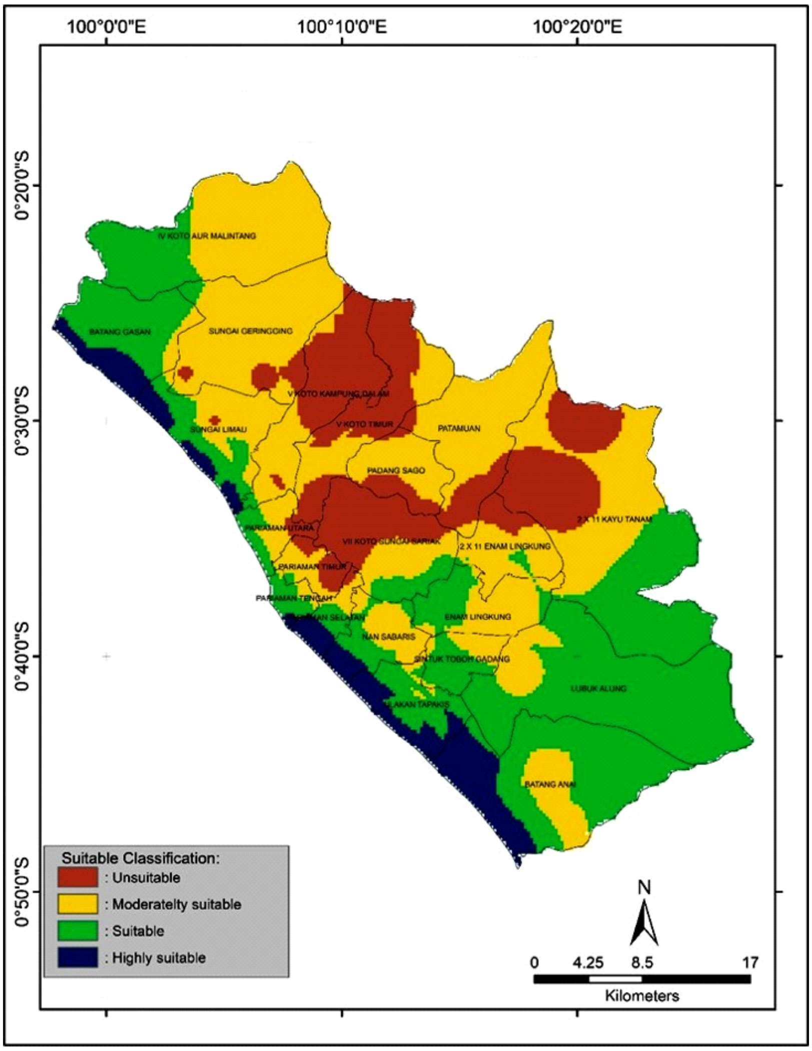

Figure 4. Suitability map of water quality and quantity sub-model for shrimp aquaculture development.

On the other hand, the distance to the market becomes one significant parameter in aquaculture classified from <3 km up to >12 km. Thirty-one market points are scattered in the Padang Pariaman Regency, so we considered the distance buffer for every point in this assessment. Based on this parameter, 46% of the entire study area is categorized as highly suitable. The other categories are suitable (33.96%), moderately suitable (15.68%), and unsuitable (4.36%).

There is only one processing plant over Padang Pariaman Regency situated in the Ulakan Tapakis Subdistrict. Based on the distance to processing plant classified from <3 km to >12 km (Table 1), 83.2% of the study area is categorized as unsuitable. In contrast, the suitable and highly suitable categories covered only 4.67% and 1.23%, respectively.

In the study area, four hatcheries are scattered in the Ulakan Tapakis and Batang Anai Sub-districts, where these areas are the center of fishery production (BPS, 2021). Based on this parameter, 50.18% of the area is categorized as unsuitable for aquaculture development. The remaining categories are highly suitable (6.63%) and suitable (16.85%). In addition, the distance to hatchery relates to the time travel required from the aquaculture pond to reach the hatcheries. However, since we could not precisely estimate the travel time to hatcheries. This aspect was not considered to be assessed in the model. Therefore, estimating the travel time from the aquaculture pond to hatcheries within the AHP modeling is worthy studied.

Generally, the overlaid of those previous assessments showed four suitability categories for shrimp aquaculture development. A highly suitable category is observed in the Batang Anai and Pariaman Tengah

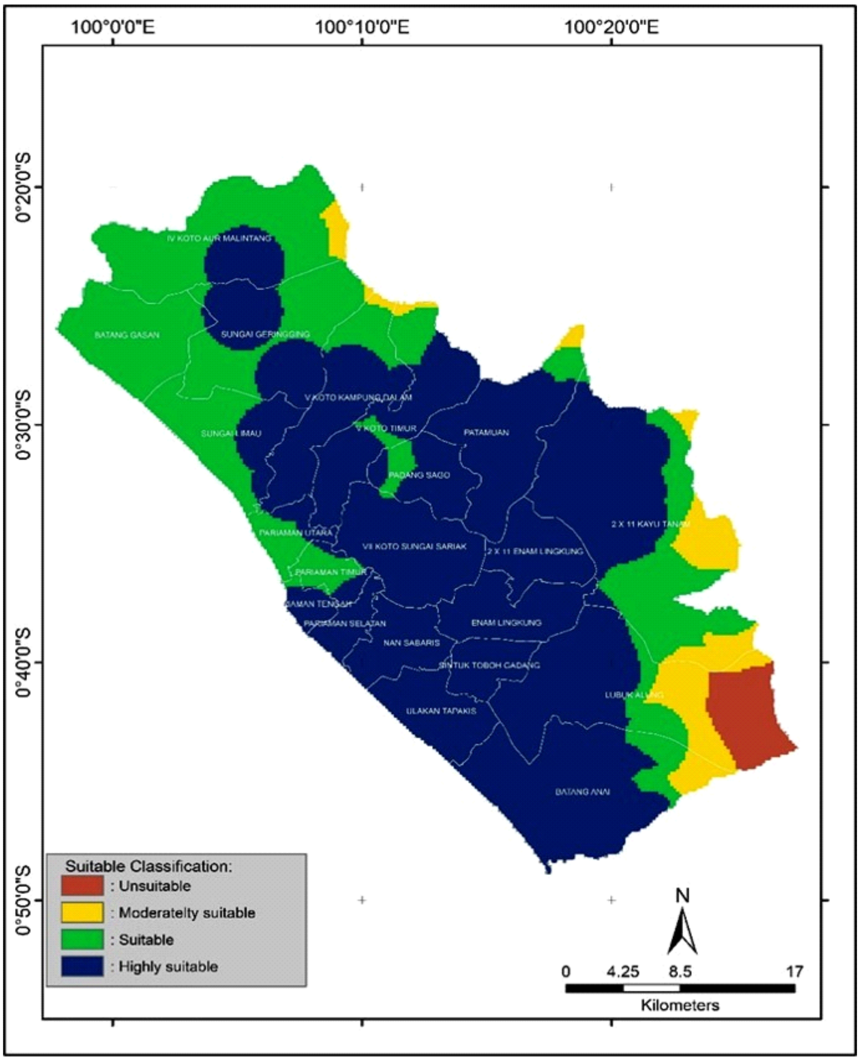

Figure 5. Suitability maps of infrastructure sub-model for shrimp aquaculture development.

Sub-districts, with a suitability of 62.74%. A suitable category can be found in the Sungai Limau and Batang Gasan Sub-districts, with 29.95%. The remaining categories are suitable and unsuitable, with respective percentages of 5.80% and 2.51%, identified in the Kayu Tanam Village, Lubuk Alung Sub-district (Figure 5).

Classification of Land Suitability for Aquaculture Development in the Padang Pariaman Regency, West Sumatra

The top level of the hierarchy model is the suitability map shown in Figure 6. This top-level was yielded from the combination or overlaying of intermediate level, consisting of engineering, water quality, and infrastructure factors. The result of these combinations is the overall site selection map prepared by applying the WLC model for selecting shrimp aquaculture sites in the Padang Pariaman Regency, West Sumatra Province.

Based on three sub-models in the intermediate level, it shows that the highly suitable category is yielded from engineering and water quality sub-models, with 62.74% and 5.88%, respectively. At the same time, the suitable category has resulted from the assessment of all sub-models, whereby the engineering sub-model shows the highest percentage, with 92.74%. The remaining sub-models show lower values, with 34.94% and 29.95% for water quality and infrastructure factors (Figure 7). The following categories are moderately suitable (41.51%) and unsuitable (17.67%), found only in the water quality sub-model. While the percentage of the other sub-models is less than 10%. These conditions indicate that water quality and quantity parameters play a significant role in determining the area of aquaculture development in the Padang Pariaman Regency.

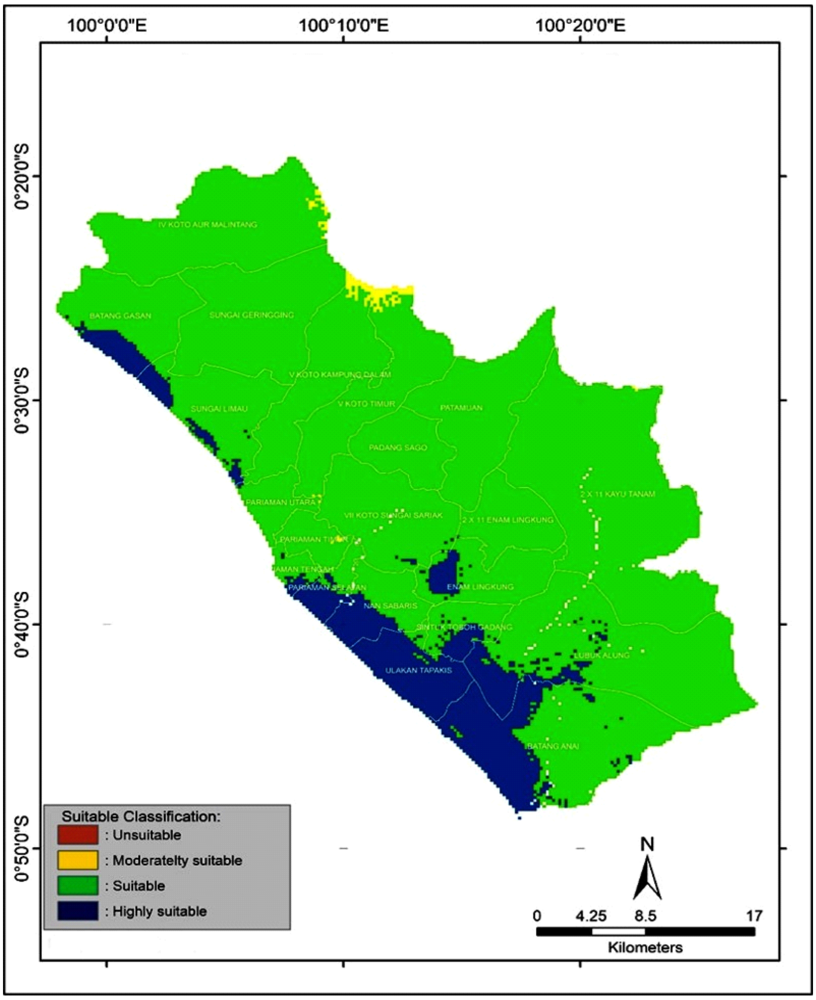

Figure 6. Overall site selection map prepared by the application of WLC model for selecting shrimp aqua culture sites in the Padang Pariaman Regency, West Sumatra Province.

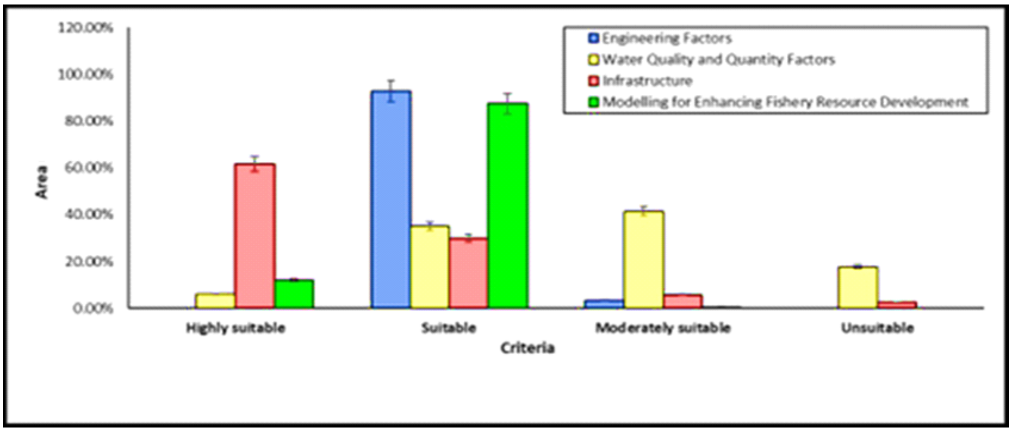

Figure 7. Diagram of the percentage of each sub-model category for determining the suitability of aqua culture development in the Padang Pariaman Regency

The matrix calculation of paired comparison considering the three sub-models was overlaid in a suitability map shown in Figure 6. The highly suitable area for aquaculture development (11.93%) is found in Batang Anai, Ulakan Tapakis, Pariaman Selatan, Sungai Limau, and Batang Gasan Sub-districts. However, the suitable category is predominant, with a percentage of 87.50%, covering the entire study area. The lowest percentage belongs to the moderately suitable category, with 0.57%.

CONCLUSION

Based on the assessment of the three sub-models using WLC technique, the highest prioritized area is categorized as highly suitable for aquaculture, with 11.93% cover area situated throughout the Padang Pariaman coastline. However, the suitable category is predominant, with 87.50% coverage area (1,239.18 km^2). While the moderately suitable category only covered 0.57% (8.02 km^2) of the entire study area. The suitability map from this study is expected to be a basis for future decision-making and policy relating to aquaculture development in the Padang Pariaman Regency. The other things that should be considered to create the final decision are socio-economic factors. Direct verification in the field is also recommended, even though it will take time. However, this approach is needed to validate the GIS modeling result in identifying the most proper area for aquaculture development.

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AUTHORS CONTRIBUTION

WAG and UJW are considered as the main contributors of this article. All authors have read and agreed to the published version of this manuscript.

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