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Original Article

Analysis of Paddy Field Functions for Environmental Conservation in the Noongan and Panasen Sub-Watersheds

Grace Feibe Evangelista Suoth[1*]
[1*]Program Studi Geografi, Fakultas Ilmu Sosial dan Hukum, Universitas Negeri Manado, Indonesia
email: gracesuothgrace@gmail.com

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Corresponding Author*:
gracesuothgrace@gmail.com

Abstract

The Tondano Watershed has experienced significant conversion of irrigated paddy fields, with a loss of 2,966.49 ha between 2002 and 2015, mainly due to the expansion of residential areas (1,434.24 ha) and conversion to other agricultural land (2,279.70 ha). Together with illegal logging in the upstream watershed, these changes have disrupted environmental stability by accelerating soil erosion, reducing water infiltration, increasing sedimentation, and intensifying flood and landslide hazards. This study aimed to evaluate the potential of paddy fields in the Noongan and Panasen Sub-Watersheds for environmental conservation. The research employed a land suitability evaluation based on biophysical characteristics, followed by an assessment of the multifunctional ecological roles of irrigated paddy fields. The analysis identified 4,206 ha (40.11%) of irrigated paddy land as S3 (marginally suitable), distributed across seven districts, indicating their suitability for designation as Sustainable Food Agricultural Land (LP2B). The findings demonstrate that paddy fields provide essential ecosystem services through three dimensions. Direct benefits include rice production, income generation, employment, and household food security. Indirect ecological benefits include soil and water conservation, erosion and runoff control, flood mitigation, sediment reduction, air purification, microclimate regulation, and climate change mitigation. Intrinsic ecological values include biodiversity conservation, environmental education, nutrient cycling, and provision of suitable rooting conditions for vegetation. These findings highlight that conserving irrigated paddy fields is fundamental not only for maintaining food production but also for strengthening watershed resilience, preserving ecosystem functions, and promoting long-term environmental sustainability.

Keywords: Irrigated Paddy Fields; Land Suitability Evaluation; Ecosystem Services; Environmental Conservation; Tondano Watershed

INTRODUCTION

The protection of Sustainable Food Agricultural Land is stipulated in the Regulation of the President of the Republic of Indonesia Number 59 of 2019 concerning the Conversion of Paddy Fields. Chapter II, Article 2 states that the policy is intended to: (1) accelerate the establishment of protected paddy field maps to ensure the availability of paddy land, maintain environmental sustainability, and support national food security; (2) control the increasingly rapid conversion of paddy fields to non-agricultural uses; (3) empower farmers to maintain agricultural land and discourage land conversion; and (4) provide comprehensive information and spatial data on paddy fields as a foundation for determining Sustainable Food Agricultural Land. The Tondano Watershed (DAS Tondano), which extends across Minahasa Regency and Manado City in North Sulawesi, has become a strategic area receiving considerable attention from both the national and provincial governments due to its ecological and socio-economic importance. The watershed encompasses several sub-watersheds, including the

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Noongan and Panasen Sub Watersheds, which constitute the focus of the present study. These two sub-watersheds accommodate the largest concentration of irrigated paddy fields within the Tondano Watershed, making them highly significant for regional agricultural production and environmental management.

Despite their strategic importance, the Noongan and Panasen Sub Watersheds have experienced increasing environmental degradation. Major environmental issues include accelerated soil erosion, sedimentation, recurrent flooding, eutrophication, environmental pollution, and widespread land-use conversion. In many locations, land conversion has occurred without adequate consideration of land suitability, resulting in substantial alterations to river morphology. River channels have gradually developed meandering patterns, while several sections have become constricted, creating hydraulic bottlenecks due to intentional modifications of river courses by land users. These changes are closely associated with the conversion of riparian zones and adjacent paddy fields into non-agricultural land.

The expansion of non-agricultural land uses has been driven by several development activities. First, the rapid growth of boarding houses has been stimulated by increasing demand for accommodation associated with the presence of Universitas Negeri Manado (UNIMA). Second, the construction of the Manado–Bitung Toll Road, which traverses parts of the Tondano Watershed surrounding the lakeshore tourism area, has substantially altered existing land use patterns. Third, the accelerated development of residential infrastructure and public facilities has predominantly occurred on flat agricultural landscapes that were previously occupied by productive paddy fields. These developments have intensified pressure on agricultural land and contributed to the continuing decline of paddy field areas. Evidence of this trend is demonstrated by the findings of Rotinsulu (2018), who reported substantial land-cover changes within the Tondano Watershed. Between 2002 and 2015, the total area of paddy fields decreased by approximately 2,966.49 hectares. This decline was primarily attributed to the conversion of paddy fields into residential land, covering approximately 1,434.24 hectares, and other forms of agricultural land, accounting for approximately 2,279.70 hectares. These findings indicate a significant transformation of land use that poses serious challenges to sustainable agricultural development and environmental conservation.

The consequences of paddy field conversion extend well beyond the loss of agricultural production. Environmental equilibrium has been increasingly disrupted, reducing the watershed's capacity to regulate hydrological processes and maintain ecosystem stability. Areas that historically had little or no exposure to flooding or landslides experienced severe flash floods in early 2014, affecting extensive parts of Minahasa Regency and Manado City. The disaster resulted in substantial economic losses and casualties. Since that event, flooding has become an almost annual occurrence throughout the Tondano Watershed. Environmental degradation has been further exacerbated by illegal logging, which has removed forest cover, diminished soil infiltration capacity, accelerated topsoil erosion, and reduced the effectiveness of natural water retention mechanisms. Within this context, the Noongan and Panasen Sub Watersheds represent environmentally valuable landscapes characterized by extensive paddy field systems that have long been protected through local cultural practices and collectively utilized by surrounding communities. These agricultural landscapes perform not only economic and food-production functions but also provide essential ecological services that contribute significantly to maintaining environmental quality and watershed sustainability. Consequently, preserving these paddy fields constitutes a strategic priority for sustaining ecosystem resilience and supporting community livelihoods.

Considering the complexity of environmental pressures affecting these sub-watersheds, this study addresses the following research question: How do the paddy fields within the Noongan and Panasen Sub Watersheds contribute to environmental conservation? Accordingly, the primary objective of this study is to analyze the potential of paddy fields in the Noongan and Panasen Sub Watersheds in supporting environmental conservation and sustainable watershed management. Beyond their primary role in food production, paddy fields perform a wide range of ecological functions. They serve as temporary water storage systems, reduce surface runoff, mitigate soil erosion and sediment transport, regulate local hydrological processes, and contribute to the maintenance of watershed water balance. These ecosystem services are fundamental to preserving environmental stability and reducing the risk of hydrological disasters. However, these ecological functions remain insufficiently recognized in land-use planning and development policies. The continued reduction of paddy field areas not only threatens

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national and regional food security but also diminishes the watershed's environmental carrying capacity, thereby increasing vulnerability to erosion, flooding, and other environmental hazards. Therefore, strengthening the protection and sustainable management of paddy fields is essential for achieving long-term environmental conservation, watershed resilience, and sustainable development.

MATERIALS AND METHODS

This study employed a field-based research approach integrating land suitability assessment with an evaluation of the ecological functions of paddy fields in supporting environmental conservation. The methodological framework was designed to identify Sustainable Food Agricultural Land (SFAL) through field observations, biophysical land assessment, and a comprehensive review of relevant literature and policy documents. The research was conducted in the Noongan and Panasen Sub Watersheds, located within the Tondano Watershed, North Sulawesi, Indonesia. These sub-watersheds were purposively selected because they contain extensive irrigated paddy fields while simultaneously experiencing increasing pressure from land-use conversion associated with urban development, infrastructure expansion, and population growth. The research procedures were developed in accordance with the provisions of Law of the Republic of Indonesia Number 41 of 2009 on the Protection of Sustainable Food Agricultural Land and the Regulation of the Minister of Agriculture Number 79/Permentan/OT.140/8/2013, which establish technical criteria for identifying and protecting sustainable agricultural land. These regulations provide the legal and scientific basis for assessing land suitability and determining agricultural areas that should be preserved to ensure long-term food security and environmental sustainability. The principal variable examined in this study was the environmental function of paddy fields. In this context, paddy fields are regarded not only as productive agricultural systems but also as providers of essential ecosystem services. Besides producing marketable food commodities, they contribute to carbon sequestration, groundwater recharge, flood mitigation, erosion control, microclimate regulation, biodiversity conservation, and water retention. These ecological functions generate significant public benefits that support environmental quality and watershed resilience (OECD, 2001; Agus & Husen, 2005).

The study consisted of two main analytical stages. The first stage involved a land suitability assessment to determine the capability of the land for sustainable rice cultivation. Land suitability was evaluated using a range of biophysical indicators, including temperature, water availability, relative humidity, soil texture, effective soil depth, peat thickness where applicable, cation exchange capacity, base saturation, soil pH, total nitrogen, available phosphorus, salinity, and slope gradient. Each parameter was assessed using a standardized scoring system based on the criteria established in the Regulation of the Minister of Agriculture Number 79/Permentan/OT.140/8/2013. The resulting scores were integrated to classify land according to its suitability for irrigated rice cultivation. The second stage analyzed the ecological functions of paddy fields in maintaining environmental sustainability. Particular attention was given to their hydrological role in storing rainfall, reducing surface runoff, enhancing groundwater recharge, and mitigating flood risks within the watershed. In addition, the study evaluated the contribution of paddy fields to soil conservation through erosion and sediment control, as well as their capacity to regulate local microclimatic conditions through evapotranspiration. The role of paddy fields as habitats supporting biodiversity was also considered as part of their broader ecosystem services.

To strengthen the validity of the findings, field observations were complemented by an extensive literature review encompassing scientific publications, government regulations, and previous studies related to land suitability, watershed management, ecosystem services, and sustainable agricultural development. The integration of empirical observations with secondary information enabled a comprehensive assessment of the environmental significance of paddy fields within the Tondano Watershed. This methodological framework provides a robust scientific basis for identifying agricultural land that should be prioritized for long-term protection while supporting sustainable watershed management and environmental conservation.

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RESULTS AND DISCUSSION

A. Evaluation of Paddy Land Suitability

Land suitability evaluation was conducted to determine the potential of land resources for sustainable agricultural development, particularly for irrigated rice cultivation. This evaluation provides a scientific basis for identifying land that is appropriate for food crop production while supporting long-term environmental sustainability. The assessment of land suitability was based on land resource mapping, with the land unit map serving as the primary analytical framework. In this study, a land unit represents a spatial area characterized by relatively homogeneous biophysical attributes, including landform, slope gradient, current land use, and soil type. The land unit map was generated through the overlay of four thematic spatial datasets, namely the landform map, slope map, land use map, and soil type map. The integration of these spatial layers resulted in the delineation of 27 distinct land units, each representing unique combinations of physical and environmental characteristics. These land units formed the basis for subsequent field surveys, laboratory analyses, and land suitability assessments.

Land quality refers to the complex attributes of a land unit that determine its suitability for a specific land use. These qualities are assessed through measurable land characteristics, which describe the physical, chemical, and environmental properties influencing agricultural productivity. In the present study, land suitability for irrigated rice cultivation was evaluated according to the technical guidelines established in the Regulation of the Minister of Agriculture of the Republic of Indonesia Number 79/Permentan/OT.140/8/2013. The evaluation framework consists of ten land quality categories, represented by twenty measurable land characteristics. These parameters provide a comprehensive assessment of the environmental conditions required for sustainable rice cultivation. The first land quality is temperature (tc), represented by the annual average air temperature (°C), which influences crop growth and physiological development. The second is water availability (wa), assessed through relative air humidity (%), reflecting the moisture conditions necessary for rice production. The third land quality is the rooting medium (rc), which includes drainage conditions, soil texture class, coarse fragment content (%), effective soil depth (cm), and peat characteristics, including peat thickness (cm) and degree of decomposition where applicable. These characteristics determine root development, water retention, and soil aeration. The fourth category is nutrient retention (nr), evaluated using soil cation exchange capacity (CEC; cmol kg^{-1}), base saturation (%), soil pH (H_2O), and organic carbon content (%). These indicators describe the soil's capacity to retain and supply nutrients essential for plant growth. The fifth land quality concerns available nutrients (na), represented by total nitrogen (%), available phosphorus (P_2O_5; mg 100 g^{-1}), and available potassium (K_2O; mg 100 g^{-1}). These chemical properties directly influence crop productivity and fertilizer requirements. The sixth category is toxicity (xc), measured by soil salinity (dS m^{-1}), while the seventh category is sodicity (xn), evaluated through exchangeable sodium percentage (ESP), which reflects the degree of soil alkalinity and its potential impact on soil structure. The eighth land quality addresses sulfidic hazards (xs), represented by the depth of sulfidic materials (cm), particularly relevant in peatland and coastal environments. The ninth category evaluates the risk of landslides (eh) using slope gradient (%), an important factor affecting both agricultural management and environmental stability. Finally, the tenth land quality examines flooding or inundation hazards during the growing season (fh), characterized by flood depth (cm) and flood duration (days), which influence crop survival and agricultural productivity.

Field measurements and laboratory analyses were conducted to quantify these land characteristics for each of the 27 land units. The measured values were subsequently compared with the land suitability criteria specified in the Ministerial Regulation. A standardized scoring and classification procedure was then applied to determine the suitability class of each land unit for irrigated rice cultivation. The resulting classification provides the scientific foundation for identifying agricultural land with high potential for sustainable food production while simultaneously supporting environmental conservation and long-term watershed management. The land suitability classification criteria for irrigated rice cultivation are presented in the following table.

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Table 1. Land Suitability Classification Criteria for Irrigated Rice (*Oryza sativa* L.) Cultivation

No	Land Use Requirement/Land Characteristic	Land Suitability *)			
		S-1	**S-2**	**S-3**	**N**
	Temperatur (tc)				
1	Annual Average Temperature (°C)	24 – 29	22 - 24 29 - 32	18-22; 32-35	< 18; >35
	Water Availability (wa)				
2	Humidity (%)	Irigated 33-90	Irigated 30-33	Irigated < 30; > 90	- -
	Rooting Medium (rc):				
3	Drainage	Modeately impeded to moderate	Impeded or well-drained	Very poorly drained or moderately rapid	Rapid
4	Soil Texture	Fine, moderately fine	Medium	Moderately coarse	Coarse
5	Coarse Fragment (%)	< 3	3 - 15	15 - 35	> 35
6	Soil Depth (Cm)	> 50	40 - 50	25- 40	< 25
7	Peat Characteristics: - Thickness (cm) - Maturity	< 40 Sapric	40 – 100 Sapric-Hemic	100 – 140 Hemic	>140 Fibric
	Nutrien Retention (nr)				
8	Cation Exchange Capacity (cmol/kg)	>16	5,0 - 16	< 5	-
9	Base Saturation (%)	5,5 – 7,0	4,5 - 5,5	< 0,8	-
10	Soil pH (H_2O)	> 1,2	0,8 - 1,2		
11	Organic Carbon (%)	-	-	Very Low	-
	Available Nutrient (na)				-
12	Total Nitrogen (%)	Moderate	Low	Very Low	
13	P_2O_5 (mg/100 g)	High	Moderate	Very Low	
14	K_2O (mg/100 g)	Moderate	Low	4 - 6	> 6
	Toxicity (xc)				
15	Salinity (dS/m)	< 2	2 – 4	30 – 40	>40
	Sodicity (xn)				
16	Exchangeable Sodium Percentage/ESP (%)	< 20	20 – 30	40 - 75	< 40
	Sulfidic Hazard (xs)				
17	Sulfidic Layer Depth (cm)	> 100	75 – 100	8 - 30 (terracing) moderate	> 30 rigorous
	Landslide Hazard (eh)				
18	Slope (%)	< 3	3 - 8 (terrace) light	50-75; 7 - 14	> 75; >14
	Flooding Hazard During Growing Season (fh)				
19	-Flood Depth (cm) -Duration (days)	25 None	25 - 50 < 7		

Source: Adapted from the Regulation of the Minister of Agriculture of the Republic of Indonesia No. 79/Permentan/OT.140/8/2013.

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B. Actual Land Suitability and Evaluation of Land Quality Characteristics

The determination of the actual land suitability class for irrigated rice cultivation was carried out by matching the land characteristics of each land unit with the crop growth requirements established in the land suitability classification criteria. Each land characteristic was evaluated individually to identify the degree of suitability and the principal limiting factors affecting rice production. The assessment results for each parameter are presented as follows.

1. **Temperature (tc)**. Mean Annual Temperature (°C). Air temperature was estimated based on the mean annual temperature recorded for each land unit. The evaluation indicated that Land Units 1, 2, 11, 12, 13, 15, 16, 18, 19, 20, 21, 22, 23, 24, 25, and 27 were classified as S2 (moderately suitable), indicating the presence of moderately severe limitations for irrigated rice cultivation. In contrast, Land Units 3, 4, 5, 6, 8, and 9 were categorized as S3 (marginally suitable) because temperature conditions impose more significant constraints on crop growth and productivity.
2. **Water Availability (wa).** Relative Humidity (%). Water availability was evaluated using relative humidity as the principal indicator. The assessment revealed that all land units exhibited average annual relative humidity ranging from 85% to 90%, based on the Minahasa Regency Statistics (2020). According to the established land suitability criteria, all land units were classified as S1 (highly suitable) with respect to water availability, indicating that atmospheric moisture conditions are highly favorable for irrigated rice cultivation.
3. **Rooting Medium (rc).** (1) Drainage: The rooting medium was first evaluated based on soil drainage conditions. The results indicated that Land Units 1 through 26 possess well-drained soils, corresponding to the S2 (moderately suitable) class. Land Unit 27, however, exhibits moderately impeded drainage, which falls within the S1 (highly suitable) category for irrigated rice cultivation because rice performs optimally under conditions of moderate water retention; (2) Soil Texture: The evaluation of soil texture demonstrated considerable spatial variability among the land units. Land Units 1, 2, 15, 20, 23, and 26 were classified as S1 (highly suitable). Land Units 7, 11, 12, 13, 14, 16, 17, 18, 19, 21, 22, 24, 25, and 27 were categorized as S2 (moderately suitable). Land Units 4, 5, 8, 9, and 10 were classified as S3 (marginally suitable), whereas Land Units 3 and 6 were assigned to the N (not suitable) category because their soil texture does not adequately support sustainable irrigated rice cultivation; (3) Coarse Fragments (%): The assessment of coarse fragment content indicated that all land units contained less than 2% coarse fragments, thereby satisfying the requirements for S1 (highly suitable) classification. This finding suggests that coarse materials do not constitute a limiting factor for root development or soil water retention within the study area; (4) Effective Soil Depth (cm): Effective soil depth exceeded 60 cm across all land units, resulting in their classification as S1 (highly suitable). The considerable soil depth provides favorable conditions for root penetration, nutrient uptake, and water storage, thereby supporting sustainable rice production.
4. **Nutrient Retention (nr)**. (1) Cation Exchange Capacity (CEC): Nutrient retention was initially evaluated using soil cation exchange capacity (CEC). Laboratory analyses recorded 90 samples with low CEC, 197 samples with moderate CEC, and 609 samples with high CEC, yielding a total of 897 observations. Overall, all land units exhibited CEC values exceeding 16 cmol kg^{-1}, qualifying them for the S1 (highly suitable) category. These results indicate that the soils possess a high capacity to retain and exchange essential nutrients required for rice growth; (2) Base Saturation (%): The evaluation of base saturation revealed substantial variation among the land units. Land Units 10, 12, 13, 14, 15, 16, 17, 20, 21, 22, 24, and 25 exhibited base saturation values greater than 50% and were therefore classified as S1 (highly suitable). Land Units 6, 11, 18, 23, 26, and 27 recorded base saturation values ranging between 35% and 50%, corresponding to the S2 (moderately suitable) category. Meanwhile, Land Units 2, 3, 4, 7, 8, 9, and 19 showed base saturation values below 35%, resulting in their classification as S3 (marginally suitable) due to reduced nutrient availability; (3) Soil pH (H_2O): The assessment of soil pH demonstrated that all land units (1–27) possessed pH values ranging from 5.5 to 7.0, corresponding to the S1 (highly suitable) class. Soil pH within this range is considered optimal for irrigated rice cultivation because it promotes nutrient availability while minimizing adverse

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effects on plant roots and soil microorganisms. Previous studies have demonstrated that soil pH values between 6.0 and 7.5 exert minimal negative effects on plant growth and microbial activity (Smith & Doran, 2000; Winarso, 2005). Moreover, the observed pH values fall within the optimum range for the majority of soil microorganisms, generally reported to be between 5.0 and 8.0 (Winarso, 2005), thereby supporting favorable biological processes essential for maintaining soil fertility and agricultural productivity.

5. **Available Nutrients (na).** (1) Total Nitrogen Content (Total N, %): The availability of nitrogen was evaluated based on the total nitrogen (Total N) content of the soil. The analysis revealed that Land Units 3, 4, 5, 6, 7, 8, 9, 10, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, and 27 were classified as S1 (highly suitable), with total nitrogen concentrations ranging from 0.21% to 0.50%, corresponding to a moderate nutrient status. Land Unit 11 was assigned to the S2 (moderately suitable) category, with a total nitrogen content of 0.18%, indicating a relatively low nitrogen status. In contrast, Land Units 1 and 2 were classified as S3 (marginally suitable) because of their very low total nitrogen content (0.01%), which constitutes a significant limitation for sustainable rice production; (2) Available Phosphorus (P_2O_5; mg 100 g^{-1}): Available phosphorus was assessed using the concentration of P_2O_5 in the soil. The results indicated that all land units (1–27) were classified as S3 (marginally suitable), with available phosphorus concentrations of less than 152 mg 100 g^{-1}. These findings suggest that phosphorus availability represents one of the principal limiting factors for irrigated rice cultivation throughout the study area and may require appropriate nutrient management interventions to sustain crop productivity; (3) Available Potassium (K_2O; mg 100 g^{-1}): The evaluation of available potassium demonstrated considerable spatial variability among the land units. Land Units 10, 12, 13, 20, and 27 were classified as S1 (highly suitable), with soil potassium concentrations exceeding 196 mg K_2O 100 g^{-1}. Land Units 1, 7, 14, 16, 23, 24, and 25 were assigned to the S2 (moderately suitable) category, exhibiting potassium concentrations ranging from 90 to 196 mg K_2O 100 g^{-1}. Meanwhile, Land Units 2, 3, 4, 5, 6, 8, 9, 11, 15, 17, 18, 19, 21, 22, and 26 were classified as S3 (marginally suitable) because their available potassium concentrations were below 90 mg K_2O 100 g^{-1}, indicating insufficient potassium availability for optimum rice growth.
6. **Soil Toxicity (xc).** (1) Soil Salinity (dS m^{-1}): Soil toxicity was evaluated using electrical conductivity (salinity) as the principal indicator. The assessment demonstrated that all land units (1–27) exhibited salinity values below 2 dS m^{-1}, thereby qualifying for the S1 (highly suitable) category. These results indicate that salinity does not constitute a limiting factor for irrigated rice cultivation within the study area.
7. **Landslide Hazard (eh).** (1) Slope Gradient (%): Landslide hazard was assessed based on slope gradient, which represents one of the primary determinants of terrain stability and erosion susceptibility. The analysis showed that Land Units 14, 16, and 27 were classified as S1 (highly suitable), with slope gradients of less than 3%. Land Units 7, 8, 10, 11, 15, and 17 were categorized as S2 (moderately suitable), exhibiting slopes between 3% and 8%. Land Units 5, 6, 9, 12, 13, and 18 were assigned to the S3 (marginally suitable) class because their slopes ranged from 9% to 30%, reflecting moderate topographic constraints. In contrast, Land Units 1, 2, 3, 4, 19, 20, 21, 22, 23, 24, 25, and 26 were classified as N (not suitable), as their slope gradients exceeded 30%, indicating a high susceptibility to erosion and slope instability that significantly limits sustainable rice cultivation.
8. **Flooding and Inundation Hazard During the Growing Season (fh)**. (1) Flood Depth (cm): The assessment of flood hazard indicated that flooding within the Tondano Watershed is primarily associated with extensive land-use conversion in downstream areas, where productive paddy fields have increasingly been transformed into residential settlements and commercial developments, including restaurants and other built-up areas. These land-use changes have substantially altered the morphology of the lower Tondano River, resulting in the formation of numerous meanders and hydraulic bottlenecks. Consequently, river discharge is significantly constrained during periods of intense rainfall, reducing channel conveyance capacity and causing prolonged inundation across adjacent lowland agricultural areas. Major flooding events have been particularly evident in the agricultural landscapes surrounding Lake Tondano and

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across large sections of Tondano City, especially in areas located north of the lake that encompass portions of the Noongan and Panasen Sub-Watersheds. These flood-prone areas are predominantly underlain by lacustrine deposits characterized by an extremely gentle surface gradient of less than 1:900. Furthermore, fluctuations in the lake water level frequently exceed 2 m, resulting in extensive inundation of broad, low-lying plains surrounding the lakeshore. These hydrological conditions have adversely affected local communities through diminished access to clean water and deteriorating public health conditions. In the southern part of Lake Tondano, several irrigated paddy fields within the Noongan Sub-Watershed also experience recurrent flooding caused by riverbed aggradation resulting from sediment accumulation around the intake weir and channel constrictions at bridge crossings. Previous studies have further demonstrated that landslide susceptibility within the Tondano Sub-Watersheds is distributed across five hazard classes, extending throughout Eris, Kakas, and East Tondano Districts. According to Helena Sri Sulastriningsih et al. (2018), landslide susceptibility is classified into low (<2.5), moderate (2.5–3.5), and high (>3.5) hazard categories; (2) Duration of Inundation (days): Records from the Public Works Agency (Dinas Pekerjaan Umum) indicate that a major flood affected Minahasa Regency and Manado City in 2014. During this event, floodwaters reached depths of approximately 2 m in several locations, while inundation persisted for approximately three days before receding. The flood caused substantial economic losses, extensive damage to public infrastructure and private property, and severe disruption to the livelihoods and well-being of local communities, highlighting the increasing vulnerability of the Tondano Watershed to hydrological hazards associated with land-use change and environmental degradation.

Based on the comprehensive assessment of land quality and its associated biophysical characteristics, the actual land suitability classes for irrigated paddy fields were determined as the basis for proposing areas to be designated as Sustainable Food Agricultural Land (LP2B). The land suitability evaluation integrated all relevant land quality indicators, including climatic conditions, soil physical and chemical properties, topographic characteristics, and environmental constraints, to identify agricultural land with the greatest potential for long-term protection and sustainable utilization. The analysis revealed that 4,206 ha, representing 40.11% of the total study area, were classified as S3 (marginally suitable) for irrigated rice cultivation. These agricultural lands are distributed across seven districts, namely North Langowan, South Langowan, East Langowan, West Langowan, Tompaso, Remboken, and Kakas. Although categorized as marginally suitable, these paddy fields remain productive and constitute strategically important agricultural resources that warrant protection under the LP2B framework, particularly considering their significant contribution to regional food security and environmental sustainability. The largest contiguous area of actual paddy land was identified within Land Unit 15, which extends across Tompaso, West Langowan, East Langowan, and South Langowan Districts. In contrast, the smallest area of actual paddy land was recorded in West Langowan District, covering 311.42 ha, equivalent to 2.97% of the total study area. The spatial distribution of the actual land suitability classes derived from this study is presented in the land suitability map shown in the following figure.

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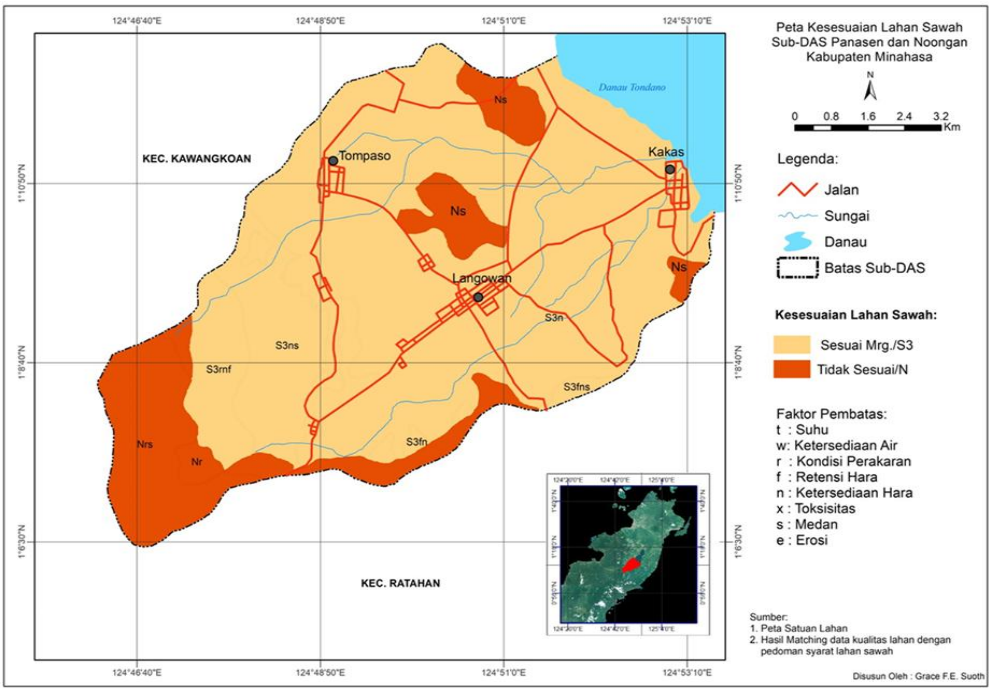

Figure 1. Actual Land Suitability Classification Map for Irrigated Paddy Fields

C. Multifunctionality of Paddy Fields in Maintaining Environmental Balance

Paddy fields constitute a public good because they generate substantial ecological, economic, and social benefits that extend beyond individual landowners and contribute to the welfare of society as a whole. In addition to serving as the primary source of rice production, paddy fields provide a wide range of ecosystem services that are indispensable for sustaining environmental quality and supporting human well-being. The present study classifies the multifunctionality of paddy fields within the Noongan and Panasen Sub-Watersheds into three interrelated categories: direct benefits, indirect benefits, and intrinsic (inherent) benefits. Collectively, these functions play a fundamental role in environmental conservation and the long-term sustainability of watershed ecosystems.

1. **Direct Benefits**. The direct benefits of paddy fields comprise both marketed outputs and non-marketed social benefits. Marketed outputs include:
   a) Rice grain production as the principal food commodity;
   b) Income generation for farming households and contributions to regional and national economies; and
   c) Employment opportunities throughout agricultural production and related value chains.

   Non-marketed benefits include:
   a) Recreational functions;
   b) Social and cultural functions;
   c) Regulation of urban expansion through the preservation of agricultural landscapes;
   d) Contributions to public health and environmental quality;
   e) Promotion of social cohesion and community solidarity; and
   f) Preservation of rural landscape aesthetics while providing spaces for social interaction among farming communities.
2. **Indirect Benefits**. Paddy fields also provide numerous indirect ecosystem services that support environmental stability and watershed resilience, including:
   a) Soil and water conservation;
   b) Air purification and microclimate cooling;
   c) Regulation of watershed water balance;
   d) Erosion control;
   e) Reduction of river sedimentation;
   f) Flood mitigation;

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   g) Recycling and natural assimilation of organic waste;
   h) Reduction of landslide susceptibility and mitigation of landslide impacts; and
   i) Mitigation of increasing air temperatures through enhanced evapotranspiration and vegetation cover.
3. **Intrinsic Benefits**. The intrinsic ecological values of paddy fields include:
   a) Conservation of biodiversity and ecological habitats;
   b) Environmental education and ecological awareness;
   c) Provision of water and essential nutrients for crop growth; and
   d) Maintenance of a suitable rooting environment that supports plant establishment and development.

D. Ecological Functions of Paddy Fields

Paddy fields perform a broad spectrum of ecological functions that are essential for maintaining environmental integrity. These functions include flood regulation, runoff reduction, erosion and sediment control, microclimate regulation, pollution mitigation, biodiversity conservation, improvement of local climatic conditions, decomposition and recycling of organic residues, provision of habitats for diverse flora and fauna, preservation of socio-cultural values and rural landscape aesthetics, generation of employment opportunities, and reinforcement of household food security among farming communities. A growing body of scientific evidence has demonstrated that agricultural land, particularly irrigated paddy fields, exerts a significant influence on surrounding environmental conditions. Destouni and Prieto (2018) reported that irrigated agriculture moderates daily maximum air temperature while increasing minimum air temperature, thereby reducing the diurnal temperature range and stabilizing local climatic conditions. The magnitude of these microclimatic effects varies according to crop growth stage and rice cultivar, reflecting differences in plant physiological characteristics.

Several studies have further examined the relationship between paddy cultivation and greenhouse gas dynamics. Methane emissions generated during rice cultivation have been shown to influence the surrounding atmospheric environment, with emission rates largely regulated by rainfall patterns, irrigation practices, and crop phenology (Kim et al., 2006; Kim et al., 2016; Wu et al., 2019; Wang et al., 2019). Likewise, different rice cultivars exhibit varying methane emission potentials, resulting in distinct thermal and atmospheric responses within tropical paddy ecosystems (Bharali et al., 2017; Fang et al., 2019). Previous research has therefore emphasized the importance of paddy fields in modifying local climatic conditions through their influence on air temperature, atmospheric humidity, and greenhouse gas exchange (Minamikawa et al., 2016; Katayanagi et al., 2017; Begum et al., 2018).

In semi-arid environments, the expansion of irrigated paddy fields transforms previously water-limited land surfaces into moist agricultural landscapes during the growing season. This transition substantially increases latent heat flux through enhanced evaporation and evapotranspiration, resulting in higher atmospheric humidity and lower near-surface air temperatures (Kueppers & Snyder, 2012). This phenomenon, commonly referred to as the "cooling–humidification effect," contrasts sharply with the "warming and drying effect" associated with wetland degradation and agricultural land loss (Anderson et al., 2003; Erwin, 2008). Together, these opposing processes contribute to the spatial heterogeneity of land–atmosphere interactions and increase the complexity of local and regional climate systems. Liu et al. (2019) further demonstrated that converting alkaline soils into irrigated paddy fields substantially improves soil physicochemical properties while enhancing local ecological and landscape functions. Continuous inundation during the irrigation phase significantly reduces land surface temperature through intensive evaporative cooling. Conversely, during the drainage phase, rapid vegetative growth enables rice plants to achieve nearly complete canopy cover, thereby altering surface albedo and energy exchange processes. Reduced surface albedo enhances the absorption of incoming shortwave radiation, producing localized surface warming despite the continued cooling effects associated with evapotranspiration.

Moreover, increased soil moisture resulting from irrigation promotes greater evapotranspiration, which elevates atmospheric water vapor content. This additional moisture can stimulate cloud formation, enhance atmospheric convection, and increase downstream precipitation, thereby influencing regional hydrological processes. Beyond climatic regulation, paddy fields provide critical hydrological services by controlling soil erosion, surface runoff, and sediment transport. Soil erosion is

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primarily governed by topography, soil texture, runoff intensity, vegetation cover, and land-use practices. Among agricultural landscapes, terraced paddy fields located within upper and middle watershed regions perform particularly important environmental functions. These include temporary floodwater storage, groundwater recharge, water purification, sediment retention, and substantial reductions in soil erosion. The findings of the present study indicate that terraced irrigated paddy fields provide the highest level of soil and water conservation within the study area. Their conservation function can be further strengthened through appropriate maintenance of terrace embankments and by increasing bund height, thereby enhancing water retention capacity, reducing runoff velocity, and improving the long-term ecological resilience of the watershed.

CONCLUSION

This study demonstrates that the evaluation of land quality and biophysical characteristics provides a robust scientific basis for identifying irrigated paddy fields suitable for designation as Sustainable Food Agricultural Land (LP2B). The land suitability assessment revealed that 4,206 ha (40.11%) of the study area are classified as S3 (marginally suitable), indicating that although certain environmental limitations exist, these areas remain strategically important for sustainable rice production and should be prioritized for long-term agricultural protection. The spatial distribution of these paddy fields across seven districts highlights their significant contribution to regional food security and landscape sustainability within the Tondano Watershed.

Beyond their agricultural function, the findings confirm that irrigated paddy fields constitute multifunctional ecosystems that generate substantial ecological, economic, and socio-cultural benefits. Their ecosystem services encompass food production, livelihood support, biodiversity conservation, soil and water conservation, flood mitigation, erosion and sediment control, regulation of watershed hydrology, microclimate moderation, and enhancement of environmental quality. The study further demonstrates that irrigated and terraced paddy fields improve local ecological processes by regulating surface energy exchange, increasing evapotranspiration, moderating air temperature, and strengthening watershed resilience against environmental degradation and climate-related hazards.

These findings underscore that the conservation of irrigated paddy fields should not be viewed solely as an agricultural policy aimed at maintaining food production. Rather, it should be recognized as a comprehensive environmental management strategy that simultaneously safeguards ecosystem services, enhances climate resilience, and promotes sustainable watershed governance. Therefore, integrating scientifically based land suitability assessments with LP2B planning is essential for protecting productive agricultural land while preserving the ecological functions that underpin long-term environmental sustainability and regional resilience.

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