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Land extension analysis for irrigated paddy fields using GIS-based multi-criteria and legacy land data: A case study of the West Sumatra, Indonesia

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Abstract

The demand for food is constantly increasing and becoming a problem in many parts of the world. Therefore, land resources must be optimally utilised to meet food needs and strengthen long-term food security. This research aimed to a) assess land suitability for irrigated paddy using GIS-based multi-criteria and analysing old land data and b) identify priority areas for the expansion of irrigated paddy in West Sumatra. The first phase of this research began with the creation of a geodatabase using GIS-based multi-criteria and old land data. Land suitability was analysed using the matching method. In addition, priorities for land expansion were evaluated based on land suitability, legal status of land, and existing land use. The results showed that 23% of the area in West Sumatra was suitable for irrigated paddy fields (827,065.5 ha). The suitability class consisted of an S2 class of 671,636.4 ha and an S3 class of 155,429.1 ha. The primary priority (P1) for the expansion of new paddy fields is 491,155.2 ha spread over 138,470.6 ha in Pasaman Barat, 99,713.7 ha in Dharmasraya and 57,892.2 ha in Pesisir Selatan. The second most important area (P2) in the area of convertible production forest (HPK) can be developed in Dharmasraya 14,951.0 ha, Pesisir Selatan 9,880.2 ha and Solok Selatan 7,078.2 ha. The limiting factors for suitability are mainly caused by slope factors and root media, such as poor drainage, coarse texture, and shallow soil depth.

1. Introduction

Indonesia has land resources with broad potential, agroclimate, and soil fertility, making it suitable for diverse plant cultivation. Efforts to utilise the potential of land optimally for diverse commodities increased in the 1980s and have continued to evolve up to the present day. Nevertheless, land expansion in Indonesia is predominantly concentrated in the plantation sector, but there is limited progress in expanding lowland rice cultivation. A notable example occurred from 1996 to 1998 when the government embarked on a sizeable project, allocating one million hectares of land in the peatlands of Central Kalimantan for rice cultivation. Unfortunately, this project failed due to inadequate planning, resulting in unproductive and abandoned land (Suriadikarta, 2009). However, the need for food has increased recently, forcing the Government of Indonesia to import 2,250,000 tons of rice in 2018 and 3,000,000 tons in 2023 (BPS, 2024a). The imports are related to the high national rice consumption, where in, the rice consumption reached 30.9 million tons (BPS, 2024b) to meet the 270 million population of Indonesia (BPS, 2020). It was equal to 114.44 kg per capita per year.

Land use optimisation is required to increase production and reduce imports. Various strategies have been attempted in Indonesia, such as improving land intensification, increasing the cropping index (IP), introducing hybrid plant varieties, preventing land conversion through sustainable food land protection (The House of Representatives of The Republic of Indonesia, 2009), as well as financing the protection of agricultural land (The Government of the Republic of Indonesia. 2012). However, those programs have not succeeded in increasing rice production in Indonesia in recent years. Therefore, another effort is needed, such as expanding rice (paddy) fields in potential areas.

One area that has the potential to extend paddy fields in Indonesia is the West Sumatra Province. The province has 42,120 km^2, divided into the mainland part of Sumatra, about 35,667 km^2, and the Mentawai archipelago, about 6,453 km^2. Based on the BPS Sumatra Barat (2021), West Sumatra's rice production is always in surplus every year. The total harvesting area of paddy fields in the province in 2020 was 295.600 ha, with production reaching 1,380,000 tons, while the average annual consumption for its people is only 560,000 tons (Kompas, 2021), meaning that West Sumatra has a surplus of 820,000 tons of rice.

In 2020, the rice productivity in West Sumatra was 4.69 tons/ha (BPS Sumatra Barat, 2021), while in some West Sumatra areas, such as Solok Regency, rice productivity can reach 6.5 tons/ha.

The West Sumatra is abundant in water resources, which are highly required for irrigated paddy fields. Flat topography in the lowlands is essential in reducing soil erosion, facilitating the land accessible for farmers, and expanding the size of new rice fields (Tanaka et al., 2013; Goulart et al., 2020). In addition, the West Sumatra has premium quality rice with a unique texture and taste (Wibawa, 2022). The extension of rice land can be developed in the West Sumatra by opening new paddy fields considering land capability and suitability. The advantage is that besides cultivating rice, the land can also be cultivated for secondary crops and other horticulture during the crop rotation period.

The initial stage of land expansion is carried out by analysing the land suitability based on a developed specific commodity by matching the requirements of plant growth with the topography, soil characteristics, and agroclimate of the targeted area. The stage would result in the distribution of suitable land and not suitable land for the developed commodity (FAO, 1976). Various methods have been introduced in assessing land suitability for certain commodities, such as 1) the matching method developed by FAO (1976); 2) the parametric approach used by Sys et al. (1991), which is a derivative of the Storie index method (Storie, 1978); and 3) the Analytical Hierarchy Process (AHP) processed by using Geographic Information Systems (GIS) known as GIS-based Multi-Criteria Decision Analysis (MCDA) (Akpoti et al., 2019; Tashayo et al., 2020; Orhan, 2021),

The concept of land suitability analysis using the FAO method (1976) is commonly used in many countries, including Indonesia. However, in this study, the matching method (FAO, 1976) was modified by combining the parameters from the new data and the legacy land physical data. Using legacy land data is beneficial as a framework for various current or future studies, especially those used to support land suitability analysis. Besides that, the legacy soil data in Indonesia was available from 1910 to 1996 (Sulaeman et al., 2013) and was documented in soil survey report. The report stores soil database that includes data on the soil morphological, physical, and chemical properties, along with corresponding maps (Sulaeman et al., 2013; Pulittanak, 1990). Since the soil database is outdated, some soil characteristics may not be reliably applicable to current research, especially the soil chemical properties. Therefore, to enhance the accuracy of the study's results, the use of soil database is limited to the characteristics of morphology and soil physics. The properties are also the main determiner in assessing land suitability and land use planning for certain commodities (Hardjowigeno and Widiatmaka, 2007).

Research that utilises legacy soil data for digital soil mapping has been conducted by several experts, including Mayr et al. (2010), Yang et al. (2022), Minai et al. (2022), and Sulaeman et al. (2013). Similarly, research on the evaluation of rice fields was performed by Aheyu and Besufekad (2015) in Ethiopia using the Analytic Hierarchy Process (AHP) to determine land suitability classes but did not investigate land priority. Therefore, this study aims to assess land suitability and determine priority areas for expanding irrigated paddy fields in West Sumatra using an approach of GIS-based multi-criteria and legacy soil data.

2. Materials and methods

2.1. Study Area

West Sumatra is one of the provinces in Indonesia located in the equator region of Sumatra. The total administrative area of West Sumatra, including its archipelago, is about 4.2 million ha. This research focuses on the mainland of West Sumatra, with an area of 3.5 million ha, as shown in Fig. 1. The average air temperature of the studied area is 25.11°C, with a minimum temperature of 18.41°C and a maximum of 32.3°C. The average humidity in the area is 83.99%. The lowest air temperature and the highest humidity occur in August – December (BMKG, 2023).

Fig. 1. Study area, soil verification and sampling point of the studied area in West Sumatra, Indonesia

The West Sumatra has a diverse range of physiographic groups i.e., Alluvial (A), Marine (B), Peat (D), Hilly (H), Acid Tuff Plain (I), Karst (K), Mountain and Plateau (M), Plain (P), Marine Terrace (T), and Volcanic Group (V) (Buurman and Balsem., 1990). Inceptisols, Ultisols, Oxisols, Andisols, Histosols, Entisols, and Histosols are the dominant soil orders widespread in West Sumatra (Puslittanak, 1990). Irrigated and rainfed rice fields are widespread throughout the region, primarily in the alluvial lowlands with an area of 198,260 ha (LP2B Sumatra Barat, 2019) or around 5.5% of the land of West Sumatra. Farmers ulitised the land for rice cultivation around 2 or 3 times a year, with a water source originating from river flows and dams, distributed through an irrigation network into the paddy fields. In the case of rainfed paddy fields, rice is cultivated during the rainy season and secondary crops are planted in the dry season.

2.2. Framework for building geodatabase

The study was divided into 5 stages, as shown in Fig. 2. The data needed to compile the geodatabase namely agroclimatic data such as rainfall and air temperature (BMKG 2023); topographic data such as slope and elevation; soil physical properties such as soil depth, drainage, texture obtained from the report of legacy soil map (Puslittanak 1990); spatial data of the legal status of lands (DBMCKTR Sumatra Barat, 2023); and hydrology channels (BIG, 2019). All supporting data for this research was processed into spatial data, where slope maps and elevation maps were inherited from DEM data. Rainfall data was processed into an isohyet map using the Inverse Distance Weighing equation in the interpolation process, while temperature data was processed using the Braak (1928) equation. River flow data was processed into buffer zone data.

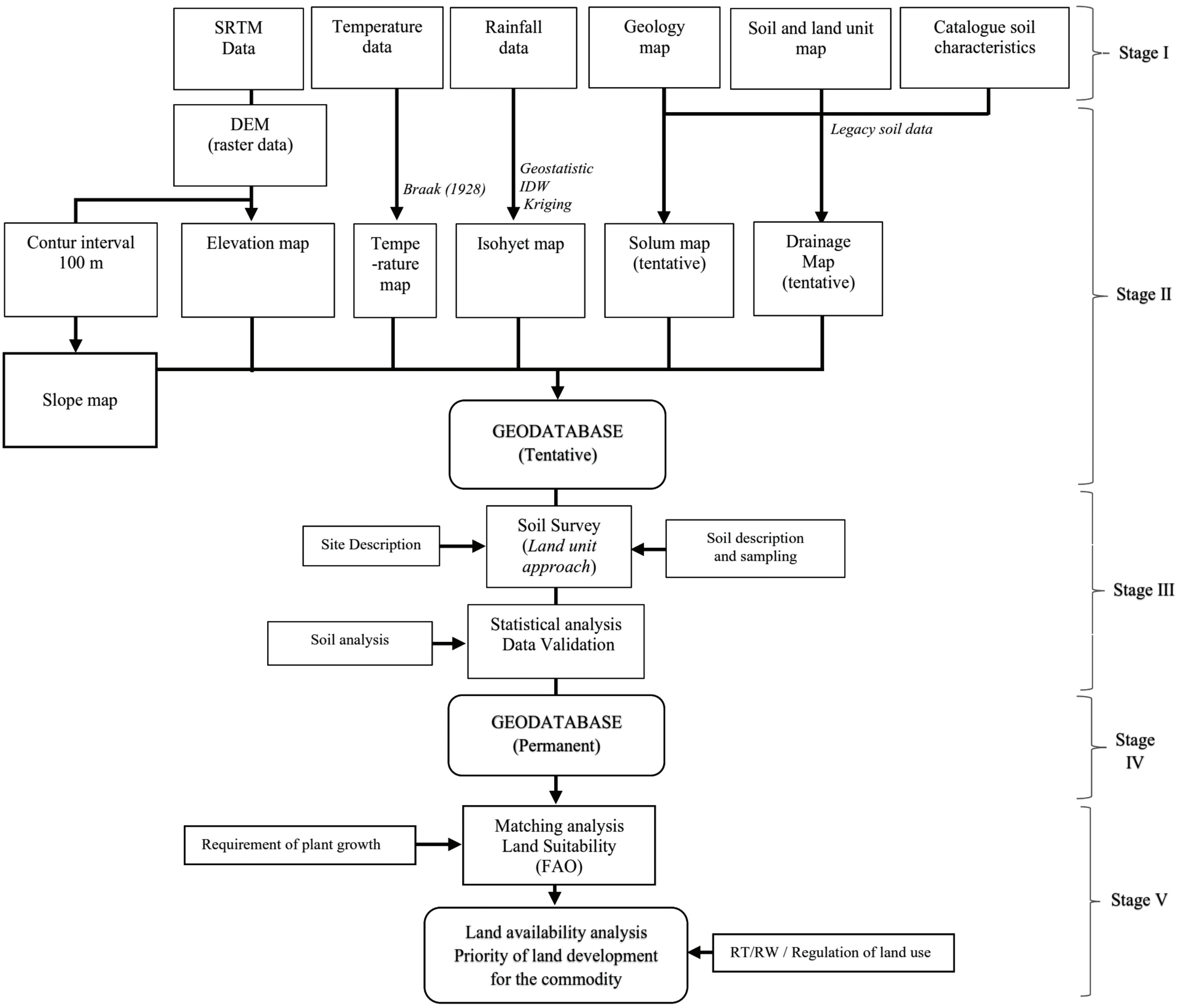

Fig. 2. Framework for assessing land suitability for irrigated paddy fields using GIS-based multi-criteria and legacy soil data analysis

All processed data results were then set into vector data (shapefile). After that, the data was overlaid using the intersection algorithm. The output from the intersection process was cut using the administrative boundaries of West Sumatra. The result of this stage is a tentative geodatabase. The fieldwork was then performed to collect ground truth data and verify tentative data (Fig. 1), including land use, land unit boundaries, solum thickness, drainage, and other soil morphological/physical properties. This survey was employed to improve the data quality and produce a permanent geodatabase. The permanent geodatabase was then used for land suitability, availability, and priority analysis.

2.3. Analysis of land suitability, land availability, and land development priorities

Land suitability analysis used in this research was the matching method by comparing plant growth requirements and land quality (FAO, 1976). The selected land quality parameters were air temperature and elevation (tc); Isohyet map for analysing water availability (wa); rooting media (rc) determined from soil drainage, soil texture, solum depth, and peat thickness and maturity; and erosion hazard/slope (eh). The result was classified into four classes: highly suitable (S1), moderately suitable (S2), marginally suitable (S3), and not suitable (N). The outcome of this stage is referred to as actual land suitability. Lands classified as S2, S3, and N exhibited limiting factors that constrain rice plant growth. To address these constraints, the potential land suitability analyisis was conducted, incorporating recommended land improvements to mitigate limiting factors and enhance suitability for rice cultivation. The criteria used refer to Ritung et al. (2011) and Sys et al. (1993).

An important step after specifying land suitability was the analysis of the land availability and the land extension priorities for paddy fields. Identification of land availability was assessed from 1) land suitability class, 2) the legal status of lands, and 3) existing land use. Land availability was divided into available land and unavailable land. Available land comprises all the existing paddy fields and non-forest areas (APL), which belong to the land suitability class S1, S2, or S3. However, Unavailable land includes areas within protection forest, primary forest, conservation forests (natural reserves, nature conservation area), production forests (limited production forests, permanent production forests, convertible production forests), buffer zone areas, and other land classified as N (not suitable).

The identification of land development priorities was settled based on a priority scale, with classes: Primary Priority (P1), Secondary Priority (P2), and Not Priority (TP). P1 land is all land classified as Available Land. In technical plans for extension paddy fields, the priority land classified as P1 must consider the existing land use. In addition, P2 land is currently unavailable land that is in the conversion production forest (HPK). However, TP land is all included as the protection forest, conservation forests (natural reserves, nature conservation area), primary forests, limited production forests, permanent production forests, and buffer zone areas (The Minister of Agriculture of the Republic of Indonesia, 1980; The Minister of Agriculture of the Republic of Indonesia, 1981).

3. Results and discussion

3.1. Data criteria for building geodatabase for suitability and priority analysis of irrigated paddy fields

Some researchers utilised different numbers and types of criteria to assess land suitability for rice cultivation. Aheyu and Besufekad (2015) studied land suitability in the delta of Lake Tana, Ethiopia, for rice crops using six criteria: slope, soil depth, temperature, rainfall, pH and soil texture (Table 1). Furthermore, Rath et al. (2018) conducted land suitability for rice cultivation in Distrik Khordha using criteria of rainfall, soil depth, slope, soil texture, organic carbon, pH, potassium, phosphorous, and nitrogen. These reports demonstrated that land suitability criteria for rice cultivation varied considerably and were primarily dependent on regional conditions, the specific

Table 1
Land evaluation parameters for rice crop requirements

Parameters	SI	S2	S3	N
Air temperature (°C)	24–29	22–24; 29–32	18–22; 32–35	<18; >35
Elevation (m.a.s.l)*	Suitable for <2000			≥2000
Annual Rainfall (mm)**	>1400	1200–1400	1000–1200	<1000
Oldeman Rainfall classification	B2, B3, C2	A1, A2, B1, C1	C3, C4, D1, D2, D3, D4, E1, E2	E3, E4
Slope (%)	<3	3–5	5–8	>8
Soil drainage	Somewhat poorly drained, slow	Poorly drained, moderate	Very poorly drained, slightly rapid	Well drained, rapid
Soil texture	Fine, slightly fine	moderate	Slightly coarse	coarse
Solum (cm)	>50	40–50	25–40	<25
Peat thickness (cm)	<50	50–100	100–150	>150

Source criteria: Ritung et al. (2011), *The Minister of Agriculture of the Republic of Indonesia (1980), **Sys et al. (1993)

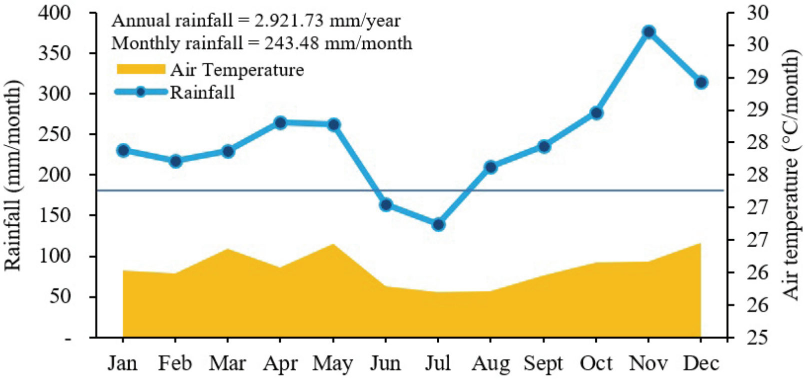

Fig. 3. Monthly rainfall and air temperature of West Sumatra

study area, and the availability of spatial data. It indicated that there are no special standard criteria for the irrigated paddy fields, but the selection of criteria in land evaluation must be relevant to the criteria influencing plant growth and must adopt a mitigation or risk management strategy of land degradation (FAO, 2007).

The average monthly rainfall of our study is 243.48 mm, and the average air temperature is 26.07°C, with the difference between the dry and rainy seasons being only 0.76°C (Fig. 3). The highest rainfall occurred in November at 376.68 mm and the lowest in July at 139.13 mm. Referring to Oldeman (1977) climate classification system for rice plants, there are ten wet months (>200 mm/month) and two moist months (100–200 mm/month) in the West Sumatra, meaning that the water requirements for rice plants are almost available throughout the year in the West Sumatra.

The spatial results of agroclimate and soil physical properties of the region are presented in Fig. 4 and Fig. 5. West Sumatra has relatively high rainfall, with the average annual rainfall over the last ten years being 2,921.73 mm/year (BMKG, 2023). Approximately, 63% of the West Sumatra has rainfall >2000 mm/yr (Fig. 4a). The rainfall pattern is higher in the western than in the eastern area. However, several regions in West Sumatra have low rainfall, such as the region spread from Singkarak to Sawahlunto city ranging from 1000-1500 mm/year, considered as a rain shadow region. It would be a limiting factor in the development of lowland rice fields in the region unless there is an adequate supply of irrigation.

The Fig. 5b shows diverse elevations of the West Sumatra province. Almost 78% of the area is lowlands, and nearly 38% is an area with 600-2000 m a.s.l (above sea level). The elevation of an area is closely related to its topography. The topography of West Sumatra is diverse, where more than 71% of the area is classed as moderately to steeply sloping (Fig. 5a), located in hills to mountainous areas. In comparison, only 29% of the land is flat to gentle slopes. Regions with flat to gentle slopes are primarily found in the northern coastal areas (Pasaman Barat) and southern areas (Pesisir Selatan) that are grouped as alluvial and or peat/dome physiography (Puslittanak, 1990), and the eastern regions (Dharmasraya) are dominated by tec-

(a) (b)

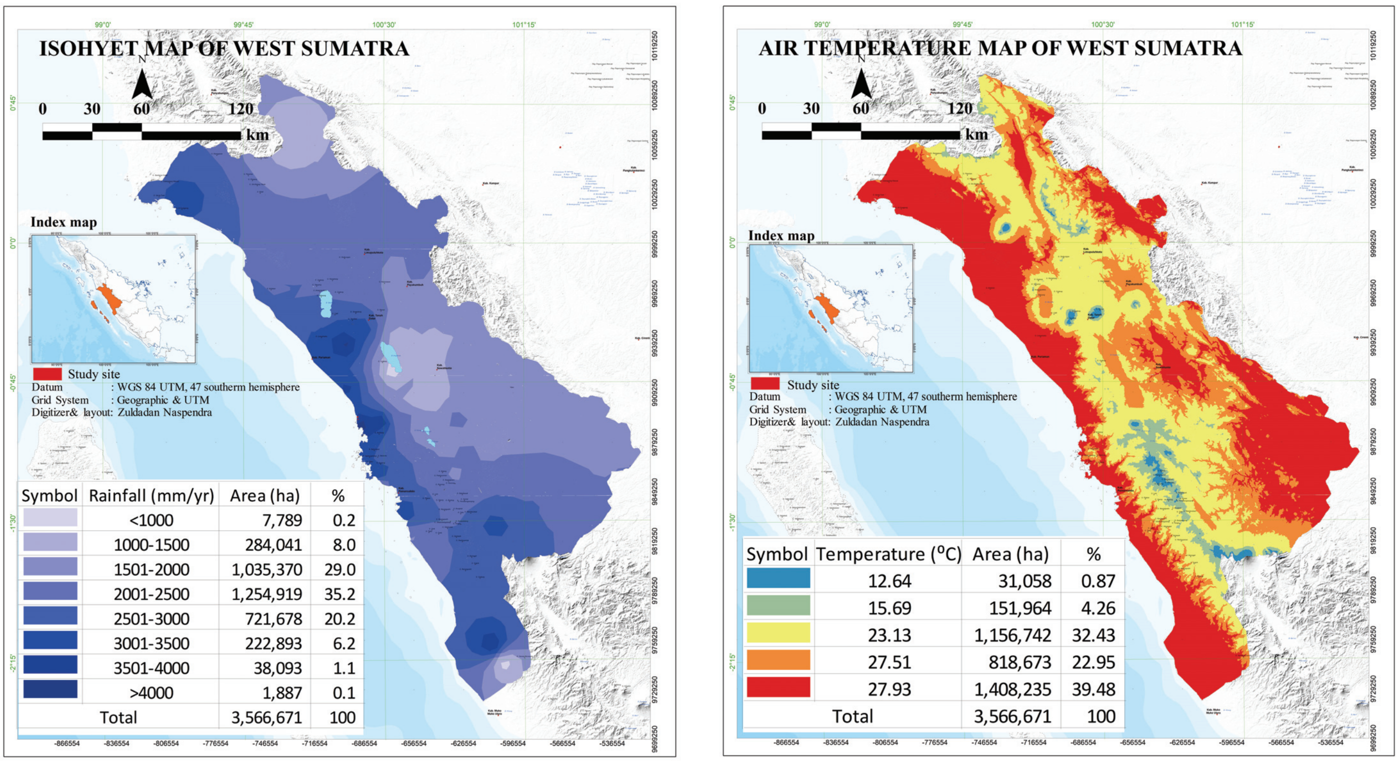

Fig. 4. Isohyet map (a) and Air temperature map of West Sumatra (b)

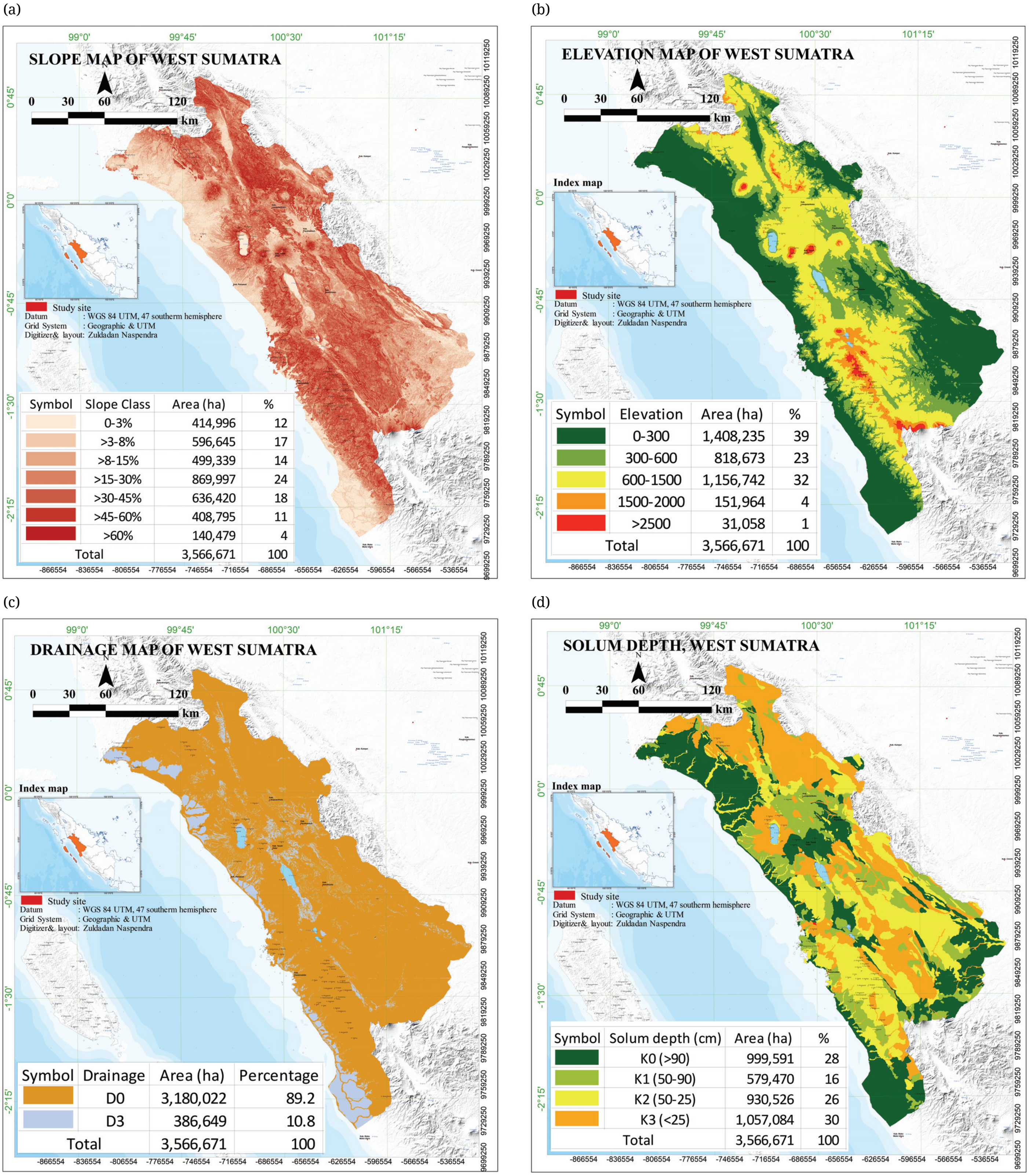

Fig. 5. Slope map (a), Elevation map (b), Drainage map: D0 = well drainage, D3 = Poorly drainage (c), and solum depth map of West Sumatra (d)

tonic and alluvial plains with flat to wavy topography. According to physiography and land use patterns, most of which are dry land. Our analysis shows that more than 89% of the area is well drained, and only 11% has poorly drained soils. The poorly drained soils are found in paddy fields, with an area of about 198,260 ha (Table 2).

The shallow solum depth would affect plant root penetration and limits the land use for growing rice plants. Ritung et al.

Table 2
Poorly drainage soils based on land use and physiography in West Sumatra

Land unit code	Description	Area (ha)
Af.1.2.1	Flood plain and meandering river	34,845.50
Au.1.1.1	Swamp; open, low vegetation, or grass	21,257.00
Au.1.1.2	Swamp; mixed vegetation, mainly swamp forest	20,948.65
Bfq.5.5	cultivated back swamp	24,655.29
Bu.4.3	Tidal flat	776.80
D.2.1.2	Oligotropic, fresh water peat with thickness 0.5–2 m	42,821.34
D.2.1.3	Oligotropic, fresh water peat with thickness >2 m	77,329.50
Sawah	rainfed and irrigation paddy field/sawah	198,260.00
Total		420,894.07

(2011) stated that the most suitable soil depth for rice plants is more than 50 cm, Meanwhile, a soil depth of less than 25 cm is not suitable for rice plants because it will inhibit root penetration. The Fig. 5d shows that the area with a solum depth >90 cm in the West Sumatra is around 28% (999,591 ha). The area is highly suitable for rice plants. The difference in solum depth is influenced by weathering rate, type of parent material, and slope (Soil Science Division Staff et al., 2017; Buol et al., 2011).

3.2. Actual land suitability of rice plants

Land suitability analysis is an essential process that must be conducted before assessing land availability and establishing land extension priorities. This process ensures that land designated for extension is situated in areas suitable for rice cultivation. Table 3 shows that about 23% of the area is suitable for irrigated paddy fields in West Sumatra, with classes of S2 and S3 covering an area of 827,065.5 ha (Table 3). Meanwhile, land with S1 class does not exist in West Sumatra. It is due to the presence of a higher limiting factor that restricts plant growth such as slopes and rooting media.

The primary limiting factor for rice cultivation in West Sumatera is slope (N.eh), which affects an area of up to 1.4 million ha (Table 4). According to Ritung et al. (2011), the maximum suitable slope for irrigated paddy fields is 8%. Given the topography of the region, which is predominantly hilly and mountainous, slopes pose a significant barrier to the suitability of land for rice cultivation (Fig. 5a). The steep slopes accelerate soil erosion, leading to a decline in soil quality and an increased risk of land degradation (Lal, 2001; Aflizar et al., 2010).

In addition to slopes, rooting media, such as drainage and solum depth, is another significant limiting factor for the extension of irrigated paddy fields in the West Sumatra. Table 2 indicates that approximately 420,894 ha of land with poor drainage are primarily found in back swamps and flood plains within the alluvial physiography, predominantly located in Pasaman Barat, Pesisir Selatan, and Dharmasraya. Poorly drained soils are advantageous for rice cultivation as they reduce infiltration and percolation, leading to water conservation (Lin et al., 2013; Kukal, 2002; Kirchhof et al., 2000). Hardjowigeno and Widiatmaka (2007) added that the main constraints of rooting media include poor drainage, coarse soil texture, shallow soil depth (40–50 cm), and/or peat depth (0–50 cm).

Table 4 presents the land suitability subclasses by district in West Sumatra, with Pasaman Barat and Dharmasraya exhibiting the largest areas classified as suitable compared to other regions. In Pasaman Barat, the primary limiting factors for the S2 class are slope, rooting media, and temperature (S2.eh.rc; S2.rc; S2.tc.eh). In Dharmasraya, the S2 class is predominantly limited by erosion hazards, rooting media (S2.eh.rc), and slope (S2.rc). Conversely, Pesisir Selatan has the largest area classified as S3 class, with constraints including rooting media (S3.rc) such as drainage, medium texture, and shallow soil depth (40–50 cm). Although the limitations of S2 and S3 classes can generally be mitigated (Hardjowigeno and Widiatmaka, 2007), the S3 area require greater investment for improvement due to more severe limiting factors. Despite these limitations, both S2 and S3 areas are suitable for irrigated paddy fields, though they may affect crop productivity, profitability, and input requirements (FAO, 1976).

Table 3
Land suitability class for rice plants based on districts/cities in West Sumatra

District/City	Area (ha)			
	S1	S2	S3	N
Agam	–	44,989.3	30,886.7	137,646.1
Bukittinggi	–	1,415.7	–	695.7
Dharmasraya	–	141,157.9	711.0	155,933.6
Limapuluh Kota	–	35,476.6	18,394.3	274,594.4
Padang	–	14,387.2	–	50,527.0
Padang Panjang	–	807.9	35.7	1,054.8
Padang Pariaman	–	37,508.5	10,030.1	86,687.8
Pariaman	–	2,553.5	1,034.8	2,516.7
Pasaman	–	30,225.3	9,973.0	350,050.2
Pasaman Barat	–	149,933.8	28,161.5	191,467.4
Payakumbuh	–	5,640.3	12.3	1,873.6
Pesisir Selatan	–	70,999.5	33,426.4	498,399.0
Sawahlunto	–	576.7	1,449.9	21,781.4
Sijunjung	–	34,812.9	6,241.1	263,112.8
Solok	–	21,696.7	3,722.1	302,268.5
Solok Selatan	–	54,680.7	3,940.7	301,930.8
Tanah Datar	–	24,773.9	7,409.6	99,065.9
Total	–	671,636.4	155,429.1	2,739,605.8
Percentage	–	19	4	77

Table 4
Subclasses of land suitability for rice plants and their limiting factors based on districts/cities in West Sumatra

Limiting Factor	Luas (ha)																	Total
	Agam	Bukit-tinggi	Dharmas-raya	50 Kota	Padang	Padang Panjang	Padang Pariaman	Paria-man	Pasaman	Pasaman Barat	Paya-kumbuh	Pesisir Selatan	Sawah-lunto	Sijunjung	Solok	Solok Selatan	Tanah Datar	
S2.eh.rc	–	–	94,122.4	4,881.2	8,265.4	3,056.5	–	–	17,868.5	80,454.4	–	35,854.4	10.7	16,395.6	15,403.7	37,449.1	–	313,761.9
S2.rc	13,027.7	400.6	46,190.1	9,455.6	6,121.7	141.5	10,889.0	763.7	10,099.5	60,641.7	2,298.2	34,303.0	52.5	10,166.7	5,207.8	11,238.3	2,934.4	223,932.0
S2.tc.eh	31,961.6	1,015.1	–	21,139.8	–	666.5	23,563.1	1,789.8	2,257.3	8,837.7	3,342.2	–	513.5	8,250.6	1,085.2	–	21,839.5	126,261.7
S2.tc.eh.rc	–	–	743.7	–	–	–	–	–	–	–	–	726.4	–	–	–	5,405.2	–	6,875.3
S2.tc.rc	–	–	101.7	–	–	–	–	–	–	–	–	115.8	–	–	–	588.1	–	805.6
Subtotoal	44,989.3	1,415.7	141,157.9	35,476.6	14,387.2	3,864.4	34,452.0	2,553.5	30,225.3	149,933.8	5,640.3	70,999.5	576.7	34,812.9	21,696.7	54,680.7	24,773.9	671,636.4
S3.rc	30,886.7	–	711.0	18,394.3	35.7	–	10,030.1	1,034.8	9,973.0	28,161.5	12.3	33,426.4	1,449.9	6,241.1	3,722.1	3,940.7	7,409.6	155,429.1
Subtotal	30,886.7	–	711.0	18,394.3	35.7	–	10,030.1	1,034.8	9,973.0	28,161.5	12.3	33,426.4	1,449.9	6,241.1	3,722.1	3,940.7	7,409.6	155,429.1
N.eh	66,158.3	695.7	133,303.5	125,224.6	39,301.0	265.7	53,395.3	876.9	82,816.9	77,671.3	1,518.1	293,598.4	9,103.5	170,597.4	154,125.9	177,164.0	46,478.7	1,432,295.3
N.eh.rc	51,794.5	–	14,679.8	132,475.8	6,844.7	690.4	22,781.4	104.1	237,053.2	63,638.4	14.5	72,202.0	11,769.7	85,211.6	88,616.9	90,076.7	42,117.7	920,071.3
N.rc	12,750.5	–	7,061.1	9,280.2	3,305.9	98.7	10,169.0	1,535.7	11,963.5	45,052.9	341.0	80,644.8	908.2	7,160.7	3,556.3	7,301.0	3,020.6	204,149.9
N.tc	63.7	–	3.1	19.6	14.9	–	1.8	–	12.1	11.7	–	621.5	–	–	4,665.1	366.7	26.1	5,806.4
N.tc.eh	6,364.2	–	720.8	3,299.6	1,060.6	–	340.2	–	2,330.7	2,880.4	–	44,104.7	–	143.1	36,247.1	23,917.6	7,093.9	128,503.0
N.tc.eh.rc	510.4	–	165.4	4,221.1	–	–	–	–	15,707.2	2,014.5	–	7,129.3	–	–	14,850.6	3,066.2	312.8	47,977.4
N.tc.rc	4.5	–	–	73.4	–	–	–	–	166.6	198.2	–	98.4	–	–	206.6	38.6	16.2	802.5
Subtotal	137,646.1	695.7	155,933.6	274,594.4	50,527.0	1,054.8	86,687.8	2,516.7	350,050.2	191,467.4	1,873.6	498,399.0	21,781.4	263,112.8	302,268.5	301,930.8	99,065.9	2,739,605.8
Total	213,522.1	2,111.5	297,802.6	328,465.3	64,949.9	4,919.2	131,169.9	6,105.0	390,248.5	369,562.6	7,526.2	602,824.9	23,807.9	304,166.8	327,687.3	360,552.2	131,249.5	3,566,671.4

Note: S2 = Moderately Suitable, S3 = Marginally Suitable, N = Not Suitable, Pasbar = Pasaman Barat
tc = temperature, eh = erosion hazard, rc = root media

3.3. Potential land suitability of rice plants

The evaluation of potential land suitability aims to predict the expected conditions following the implementation of targeted land improvements, considering varying levels of management intensity. Table 5 presents the limiting factors associated with the S2 and S3 land suitability classes, along with alternative land improvement recommendations feasible for farmers operating at moderate to high management levels, such as those related to slopes and rooting media. In contrast, factors like temperature and soil texture are inherently permanent and difficult to modify. Even if technical modifications are possible, they would require substantial investment and may not be practical to implement at the farm levels.

Table 5
Alternative land improvement for irrigated paddy fields based on limiting factors in classes S2 and S3

Land Suitability Class	Limiting factor	Area (ha)	Type of improvement
S2.eh.rc	Erosion hazard:	313,761.86	
	– Slope		– Constructing terraced paddy fields followed the natural contours at various levels; creating paddy fields closer with increasing slope.
	Root media		
	– Drainage		– Building irrigation and drainage channels.
	– Soil texture		– No improvement.
	– Effective depth		– Remove the pan layer if it is thin or slightly hard; stones, and separated boulders could be moved and arranged as a barrier to paddy fields.
	– Peat thickness		– Arranging drainage canals and cultivate tolerable rice plant varieties.
S2.rc	Root media	223,931.98	
	– Drainage		– Building irrigation and drainage channels.
	– Soil texture		– No improvement.
	– Effective depth		– Remove the pan layer if it is thin or slightly hard; stones, and separated boulders could be moved and arranged as a barrier to paddy fields.
	– Peat thickness		– Arranging drainage canals and cultivate tolerable rice plant varieties.
S2.tc.eh	Air temperature	126,261.70	– No improvement.
	Erosion hazard		
	– Slope		– Constructing terraced paddy fields followed the natural contours at various levels; creating paddy fields closer with increasing slope.
S2.tc.eh.rc	Air temperature	6,875.30	– No improvement.
	Erosion hazard:		
	– Slope		– Constructing terraced paddy fields followed the natural contours at various levels; creating paddy fields closer with increasing slope.
	Root media		
	– Drainage		– Building irrigation and drainage channels.
	– Soil texture		– No improvement.
	– Effective depth		– Remove the pan layer if it is thin or slightly hard; stones, and separated boulders could be moved and arranged as a barrier to paddy fields.
	– Peat thickness		– Arranging drainage canals and cultivate tolerable rice plant varieties.
S2.tc.rc	Air temperature:	805.61	– No improvement.
	Root media		
	– Drainage		– Building irrigation and drainage channels.
	– Soil texture		– No improvement.
	– Effective depth		– Remove the pan layer if it is thin or slightly hard; stones, and separated boulders could be moved and arranged as a barrier to paddy fields.
	– Peat thickness		– Arranging drainage canals and cultivate tolerable rice plant varieties.
S3.rc	Root media	155,429.15	
	– Drainage		– Building irrigation and drainage channels.
	– Soil texture		– No improvement.
	– Effective depth		– Remove the pan layer if it is thin or slightly hard; stones, and separated boulders could be moved and arranged as a barrier to paddy fields.
	– Peat thickness		– Arranging drainage canals and cultivate tolerable rice plant varieties.
Total		827,065.59	

Table 5 demonstrates that land improvement strategies for the S2 and S3 suitability classes are largely similar; however, interventions for the S3 class necessitate considerably higher resource investment due to the more pronounced limiting factors. Soil and water conservation techniques are critical for mitigating erosion and sustaining soil productivity. An effective approach involves constructing terraced paddy fields aligned with natural contours (Chen et al., 2017) and optimising field density on steeper slopes to reduce soil erosion.

The restriction factor of plant root media can be mitigated by constructing irrigation channels to regulate water flow and repositioning stones to create physical barriers in paddy fields. Additionally, Subiksa et al. (2011) stated that peatland rice cultivation requires drainage networks to control water table depth and selecting rice varieties tolerant to these conditions

3.4. Priorities for the development of irrigated paddy fields in the West Sumatra

During the land suitability analysis, the distribution of land suitability classes, associated limiting factors, and potential improvement alternatives have been identified. However, land availability status has not yet been considered, leaving the priority areas for expanding rice paddy fields undefined. Therefore, an assessment of priority areas for the expansion of irrigated paddy fields is necessary.

The Fig. 6b illustrates the priority areas for expanding irrigated paddy fields, while Table 6 provides a breakdown of each prioritised area by district in West Sumatra. The Primary Priority (P1) covers 689,415.1 ha, although this includes 198,260 ha of existing paddy fields. It means that the actual extension of paddy fields is 491.155.2 ha or about 14% of the total area of West Sumatra. The expansion P1 area is located within the Non-Forest Area (APL). Based on the district, the most significant prospect for developing new irrigated paddy fields in the P1 class is Pasaman Barat, with 138,470.6 ha, followed by Dharmasraya (99,713.7 ha) and Pesisir Selatan (57,892.2 ha). While APL land is available for expansion, the technical project must consider current land uses, as APL areas are also utilised for plantations, settlements, forests, and other purposes.

Table 6 also presents the Secondary Priority (P2) areas for expanding irrigated paddy fields, located within the Convertible Production Forest (HPK). Our analysis indicates that the total area of HPK classified as S2 and S3 is 45,929.5 ha. Based on the district, the largest P2 class for expanding irrigated paddy fields is in Dharmasraya, covering 14,951.0 ha, followed by Pesisir Selatan (9,880.2 ha), and Solok Selatan (7,078.2 ha). Although the Convertible Production Forest belongs to the Unavailable Lands, the P2 can potentially be converted to non-forest area by applying all activities to prevent land degradation and obeying zoning regulations as land use control instruments (The Minister of Forestry of the Republic of Indonesia, 2014). Areas classified as S1 to S3 should be prioritised with the P2 areas considered only after optimal utilisation of the P1 areas.

Changing land use for specific purposes requires in-depth study considering land suitability and availability to mitigate the risk of land degradation. This includes the expansion of paddy

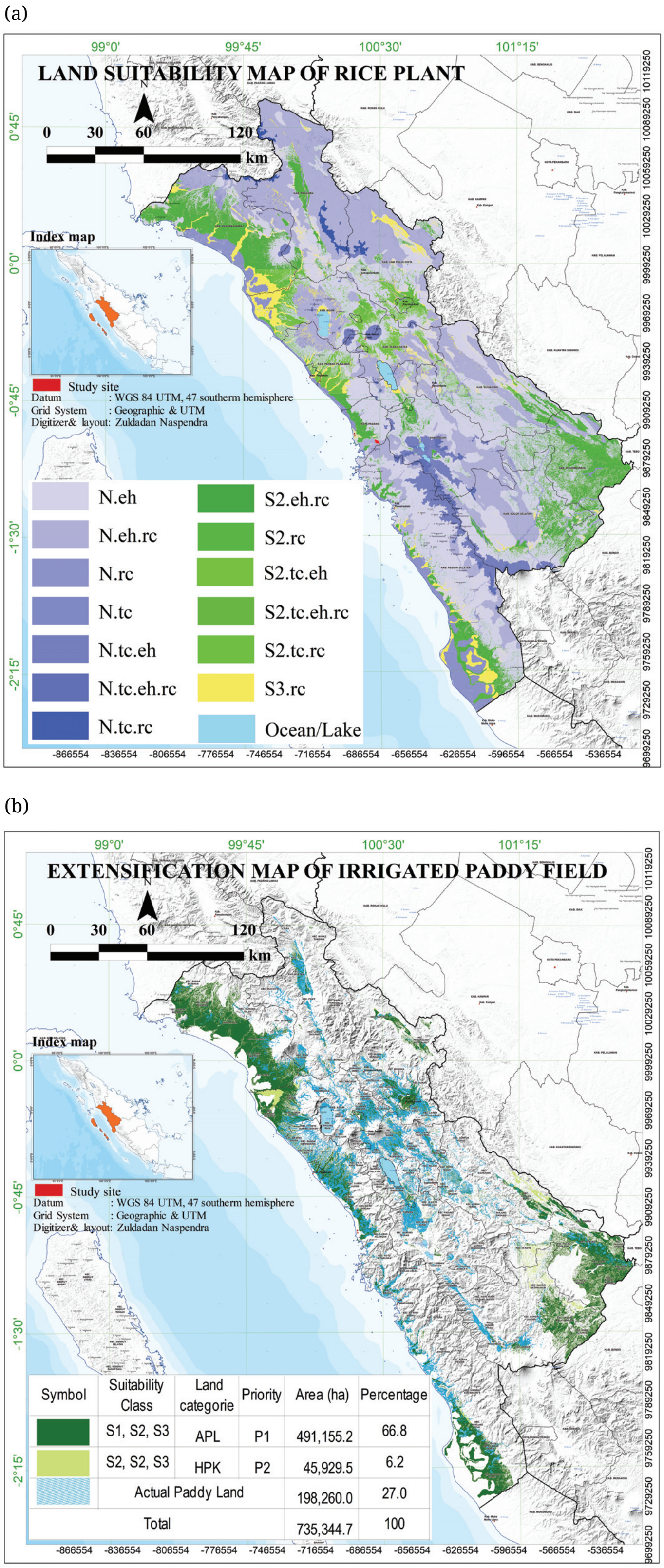

Fig. 6. Land suitability map (a) and land priority map for extension irrigated paddy fields in West Sumatra (b). S2 = moderately suitable, S3 = marginally suitable, N = not suitable, eh = slope, rc = rooting media, tc = temperature, APL = non-forest area, HPK = Convertible Production Forest

Table 6
Land extension priority of irrigated paddy fields in West Sumatra

Land Classification	Land Suitability	District/City	Availability	Priority	Area (ha)
Non Forest Area (APL)	Suitable (S2, S3)	Agam	Available	P1	40,890.2
	Suitable (S2, S3)	Bukittinggi	Available	P1	1,040.8
	Suitable (S2, S3)	Dharmasraya	Available	P1	99,713.7
	Suitable (S2, S3)	Lima puluh Kota	Available	P1	25,961.6
	Suitable (S2, S3)	Padang	Available	P1	8,999.8
	Suitable (S2, S3)	Padang Panjang	Available	P1	318.0
	Suitable (S2, S3)	Padang Pariaman	Available	P1	22,720.7
	Suitable (S2, S3)	Pariaman	Available	P1	2,411.4
	Suitable (S2, S3)	Pasaman	Available	P1	12,607.4
	Suitable (S2, S3)	Pasaman Barat	Available	P1	138,470.5
	Suitable (S2, S3)	Payakumbuh	Available	P1	5,445.3
	Suitable (S2, S3)	Pesisir Selatan	Available	P1	57,892.3
	Suitable (S2, S3)	Sawahlunto	Available	P1	324.7
	Suitable (S2, S3)	Sijunjung	Available	P1	17,575.8
	Suitable (S2, S3)	Solok	Available	P1	9,015.1
	Suitable (S2, S3)	Solok Selatan	Available	P1	38,946.0
	Suitable (S2, S3)	Tanah Datar	Available	P1	8,821.9
Natural Reserve	–	–	Not Available	TP	20,299.1
Protection Forest	–	–	Not Available	TP	213,561.5
Primary Forest	–	–	Not Available	TP	13,579.4
Permanent Production Forest	–	–	Not Available	TP	117,425.1
Convertible Production Forest (HPK)	Suitable (S2, S3)	Agam	Not Available	P2	3,931.0
	Suitable (S2, S3)	Dharmasraya	Not Available	P2	14,951.0
	Suitable (S2, S3)	Lima puluh Kota	Not Available	P2	473.8
	Suitable (S2, S3)	Pasaman	Not Available	P2	28.9
	Suitable (S2, S3)	Pasaman Barat	Not Available	P2	1,532.1
	Suitable (S2, S3)	Pesisir Selatan	Not Available	P2	9,880.2
	Suitable (S2, S3)	Sawahlunto	Not Available	P2	125.6
	Suitable (S2, S3)	Sijunjung	Not Available	P2	6,478.4
	Suitable (S2, S3)	Solok	Not Available	P2	1,438.8
	Suitable (S2, S3)	Solok Selatan	Not Available	P2	7,078.2
	Suitable (S2, S3)	Tanah Datar	Not Available	P2	11.6
Limited Production Forest	–	–	Not Available	TP	195,360.8
Nature Conservation Area	–	–	Not Available	TP	1,343,683.9
Exsisting Paddy Fields	–	–	Available	P1	198,260.0
River/Lake	–	–	Not Available	TP	47,574.3
National Park	–	–	Not Available	TP	13,735.5
Sub Total P1					689,415.1
Sub total P1 without existing paddy fields					491,155.2
Sub Total P2					45,929.5
Total P1 and P2					537,084.6

fields, which inherently involves altering existing land uses. In this context, converting land for paddy cultivation may lead to negative environmental impacts, such as reduced water availability in river systems (Brown et al., 2007), increased methane (CH4) emissions (Yagi et al., 1996; Soebandiono et al., 2021), and a contribution to climate change. Consequently, the implementation of land improvement strategies must be carefully tailored to the land's limiting factors (Table 5). Additionally, certain alternatives can help maintain land sustainability, including the modernisation of irrigation systems to improve water-use efficiency (Tirtalistyani et al., 2022), the adoption of technologies such as alternate wetting and drying to reduce CH4 emissions and boost crop yields (Ishfaq et al., 2020), the optimisation of fertilisation and cropping systems (Jiang et al., 2023), and the use of biochar for soil amelioration (Canatoy et al., 2023).

4. Conclusions

This study assessed land suitability and priority for irrigated paddy fields in West Sumatra using the climate, physical, and legal status of the land. Our results indicate that 23% (827,065.5 ha) of the region is suitable for paddy the cultivation of irrigated paddy fields, consisting of 671,636.4 ha in class S2 and 155,429.1 ha in class S3. The main limiting factors for land suitability include slope and rooting media (drainage, coarse texture, shallow soil depth). The potential expansion area is 537,085 ha, with 491,155.2 ha in Non-Forest Areas (APL) as Primary Priority (P1) and 45,929.5 ha in Convertible Production Forests (HPK) as Secondary Priority (P2). Expanding paddy fields in these areas must prevent land degradation and align with spatial planning regulations. This study also indicates that the GIS-based multi-criteria approach, incorporating legacy soil data, is effective for land suitability and land priority analysis, narrowing expansion to just 15% of the total area. Ultimately, the strength and accuracy of the analysis rely on the quality of the input data.

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Conflict of interest

The authors declare no conflict of interest. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. This research did not involve human or animal subjects.

Author Contributions

Zuldadan Naspendra – Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Nurul Hijri** – Data curation, Investigation, Methodology, Visualization, Writing – review & editing. **Mimien Harianti** – Investigation, Supervision, Validation. **Adrinal** – Conceptualization, Supervision, Validation, Writing – review & editing. **Nofrita Sandi** – Data curation, Investigation, Visualization, **Junaidi** – Investigation, Supervision, Validation.

All authors read and approved the final manuscript.

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