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Water Balance Analysis for Food Estate Program in Gunung Mas Regency, Central Kalimantan, Indonesia

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The implementation of food estate programs aimed at national food security requires comprehensive environmental considerations, particularly regarding soil conditions and water availability. This study employs the Thornthwaite-Mather method to model the water balance based on precipitation, air temperature, and soil characteristics. Analysis of climatological data from 2004 to 2023 reveals that Gunung Mas Regency, Central Kalimantan, maintains abundant groundwater availability throughout the year, with monthly percentages consistently reaching 100%. Average monthly temperatures range from 25.5°C to 26°C, while monthly rainfall varies significantly between 147 and 556 mm. According to the Oldeman classification, the region falls into category B2, characterized by nine wet months and fewer than three dry months. Land suitability evaluations indicate that the region is highly compatible with wetland-based cultivation, with optimal planting periods from November to January. Corn is suitable for cultivation between April and May. Conversely, the results suggest that cassava is less suitable for large-scale development in this region. This incompatibility stems from the persistent water surplus and high rainfall, which conflict with cassava's biological requirement for well-drained, drier upland conditions.

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1. INTRODUCTION

Indonesia is an archipelagic nation possessing approximately 188.2 million hectares of dry land and swamps [1]. Indonesia holds the largest swamp area in Southeast Asia, covering 33 million hectares [2]. Approximately 13.4–14.9 million hectares of these wetlands consist of peatlands, with 4.54 million hectares distributed across Kalimantan Island [3]. These peatlands serve as vital global climate regulators due to their immense capacity for carbon sequestration and storage [4]. The hydrological stability of these ecosystems is essential for maintaining regional water cycles and preventing land degradation [5].

In response to the economic downturn triggered by the COVID-19 pandemic in 2020, the Indonesian government initiated several National Economic Recovery (PEN) programs. A key strategy involved the development of "food estates" to bolster long-term economic and food resilience [6]. A food estate is defined as large-scale food crop cultivation (>25 ha) utilizing an industrial system integrated with modern technology, capital, and sustainable management [7]. This program aims to establish rural-based agribusinesses by empowering local communities as the foundation for regional growth. The central government has designated forest areas for this program, specifically in Central Kalimantan Province [8]. Development here focuses on rice commodities managed by the Ministry of Agriculture and cassava commodities overseen by the Ministry of Defense [9], [10]. However, the implementation has faced several hydrological challenges, including an expansion of flood-prone areas [11]. Such flooding often results from land-use changes that alter the natural catchment characteristics [12].

In the context of flooding and agricultural productivity, water availability is a critical factor. Within the hydrological cycle, the water volume in a specific location is determined by the balance of inflows and outflows over time, a concept known as the water balance. According to Sosrodarsono and Takeda [13], water balance represents the fundamental relationship between inflow and outflow, which is an absolute necessity for plant physiological processes. This balance is influenced by precipitation, evapotranspiration, and soil physical characteristics, which collectively indicate periods of water surplus or deficit [14], [15]. A significant imbalance can lead to severe agricultural disruptions, such as seasonal shifts that cause delayed planting, altered harvesting patterns, and potential crop failure [16].

To assess the hydrological state of a region, precise water balance calculations are required. The Thornthwaite-Mather (TM) method is widely recognized by experts for this purpose. This method is preferred because it requires relatively minimal data inputs while maintaining high predictive accuracy [14], [17], [18]. Previous studies by Pramono and Adi [19], demonstrated that TM-based predictions align closely with empirical field measurements. Similarly, research in India confirmed that the TM method effectively predicts potential evapotranspiration (PET) across diverse observation stations [18]. Consequently, this method remains a robust tool for regional hydrological assessment in data-scarce environments [20]. This study analyzes the water balance conditions in Gunung Mas Regency to evaluate its suitability for the food estate program from a hydrological perspective. Specifically, the research examines groundwater availability and potential evapotranspiration values to determine the viability of various agricultural commodities.

2. RESEARCH METHOD

2.1. Study Area and Data Sources

The research was conducted in Gunung Mas Regency, Central Kalimantan Province. Geographically, the area is located between 0°18’00’’ – 01°40’30” S and 113°01’00″ – 114°01’00’’ E. The region is traversed by three major river branches, the Miri, Rungan, and Manuhing, all of which flow into the Kahayan River, with an estimated total surface flow of 90 billion m3/year [21].

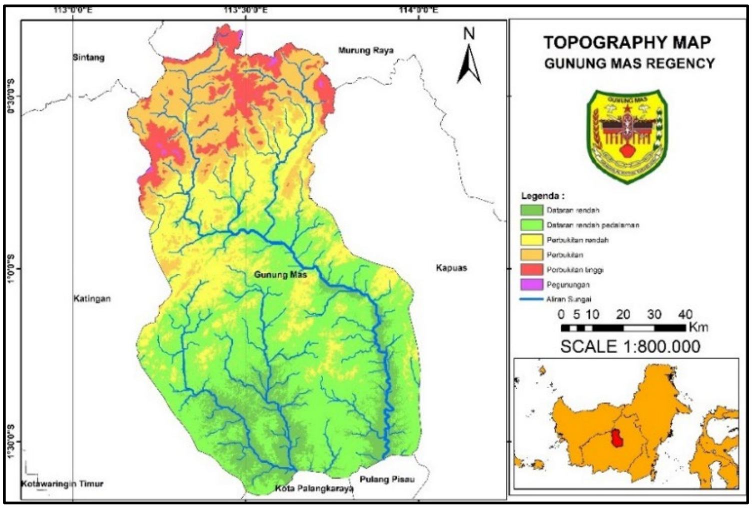

Fig. 1 Research the map area

This study utilized the following datasets:

a. Precipitation Data: Monthly reanalysis data (2004–2023) obtained from the Center for Hydrometeorology and Remote Sensing (CHRS) in TIFF format, with a spatial resolution of 0.04° x 0.04° (~4 km).
b. Air Temperature Data: Monthly reanalysis data (2004–2023) from Copernicus (ERA5-Land) in NetCDF format, with a spatial resolution of 0.1° x 0.1° (~11 km). The use of reanalysis data is justified in regions with limited ground-based observation stations [22].
c. Soil Properties: Field Capacity (FC) and Permanent Wilting Point (PWP) values were sourced from secondary data provided by the Water Resource Utilization Implementation [23]. For Gunung Mas, the FC is estimated at 74.2 and PWP at 20.4.
d. Crop Coefficients (Kc): The studied commodities (rice, corn, and cassava) were assigned Kc values of 1.13, 0.79, and 0.5, respectively [24], [25], [26].

2.2. Data Processing and Water Balance Modelling

The groundwater balance was modelled using the Thornthwaite-Mather method (1957) [27]. Air temperature data were used to calculate the Heat Index (I) and Potential Evapotranspiration (PET). The procedure involved the following stages:

a. Calculating Potential Evapotranspiration
   a) For average temperatures < 26.5 °C

$$ETP = 1{,}6\left(\frac{T}{I}\right)a \quad (1)$$

   b) For average temperatures ≥ 26.5 °C

$$ETP = -4{,}33 \times 10^{-2}\, T^2 + 3{,}2244\, T - 41{,}545 \quad (2)$$

   Notes:

$$a = 6{,}75 \times 10^{-7}\, I^3 - 7{,}71 \times 10^{-5}\, I^2 + 1{,}792 \times 10^{-2}\, I + 0{,}49239 \quad (3)$$

$$I\ (yearly\ heat\ index) = \sum_{i=1}^{12}\left(\frac{T_i}{5}\right)^{1{,}5114} \quad (4)$$

b. PET Correction
   The initial PET was adjusted based on the latitude and the number of days in each month to account for variations in day length [28].

$$ETP_{correction}(mm) = ETP\left(\frac{\theta}{30}\right)\left(\frac{h}{12}\right) \times 10 \quad (5)$$

c. Precipitation and PET Difference:
   The difference between precipitation (P) and PET (P - PET) was calculated to identify periods of moisture surplus or deficit.

d. Accumulated Potential Water Loss (APWL):
   a) If CH ≥ETP, then APWL = 0
   b) If CH < ETP, then APWL = ∑ (P-PET)

e. Groundwater Content (KAT):
   KAT is the maximum capacity of water that the soil can store. It is influenced by space capacity (the amount of water that stays in the soil after the water flows due to the earth's gravity and the dew point, when plants cannot extract water from the soil), empirically formulated by Mashudi [29].
   a) If APWL ≠ 0:

$$KAT = TLP \times \left[\left(1{,}00041 - \frac{1{,}07381}{AT}\right)\right]^{|APWL|} \times AT \quad (6)$$

   b) If APWL = 0

$$KAT_i = KAT_{i-1} + CH - ETP \quad (7)$$

   c) If KAT gas reached KL, then:

$$KAT = KL \quad (8)$$

f. Calculate dKAT with the formula:

$$dKAT = KAT_{i-1} - KAT_i \quad (9)$$

g. Calculate actual evapotranspiration (AET), with the formula:
   a) If P > ETP, then AET = ETP
   b) If P ≤ ETP, then AET = CH + |dKAT|

h. Calculate water balance surplus or deficits, with the formula:

$$surplus = CH - ETP + dKAT \quad (10)$$

$$deficit = ETP - AET \quad (11)$$

i. Calculate Groundwater Availability (ATS), with the formula:

$$ATS = \frac{KAT - TLP}{KL - TLP} \times 100\% \quad (12)$$

   ATS values are categorized into five (5) parts:
   a) Critically Low, if ATS < 10%
   b) Low, if 10% < ATS < 40%
   c) Moderate, if 40% < ATS < 60%
   d) Sufficient, if 60% < ATS < 90%
   e) Abundant, if ATS > 90%

2.3. Land Appropriation for Rice, Corn, and Cassava Commodities

The assessment of land appropriation for the Food Estate program requires a detailed understanding of the agro-climate requirements for rice, corn, and cassava. Rice remains the most strategic food commodity in Indonesia, serving as the primary staple for the majority of the population. This crop exhibits broad adaptability across altitudes ranging from 0 to 1,500 meters above sea level (masl). Most rice varieties thrive in high-humidity environments with consistent monthly precipitation exceeding 200 mm, ideally distributed over at least a four-month growing season. Furthermore, rice development requires ambient temperatures between 19°C and 27°C, with an optimal physiological threshold at 23°C [15]. Conversely, corn serves as a vital complementary carbohydrate source with a typical cultivation cycle of 80 to 150 days. Unlike rice, corn is better suited for drier environments and is susceptible to physiological stress under high-humidity conditions. The ideal precipitation for corn ranges from 85 to 200 mm per month with uniform distribution; moisture is particularly critical during the germination and flowering phases, which typically occur at the end of the rainy season, to ensure maximum solar radiation for fruit formation at an ideal temperature of 25°C [30].

Climate significantly dictates both the quantity and starch quality of cassava growth. During the initial 0 to 90 days, the ideal precipitation for this crop is 150–200 mm/month, which increases to 250–300 mm/month during the active growth phase (90 to 280 days), before tapering off to 100–150 mm/month as it approaches harvest [31]. In addition to requiring a minimum temperature of 10°C and optimal relative humidity of 60–65%, cassava is highly dependent on friable, non-clayey soil characteristics to support tuber expansion. Such soils must be rich in organic matter with an ideal pH of approximately 5.8, and the crop is best suited for altitudes between 10 and 500 masl [32]. Effective soil drainage is a critical limiting factor, as cassava is highly sensitive to waterlogged or anaerobic soil conditions. To determine the compatibility of the land with these commodities, this study employs the Oldeman and Frere climate classification [33], which is specifically designed for rain-fed agriculture. This system categorizes climates based on the frequency of consecutive Wet Months (WM), defined by rainfall > 200 mm, and Dry Months (DM), defined by rainfall < 100 mm. This methodology provides a robust framework for determining potential cropping intensity based on natural water availability in tropical regions [34].

Table 1. Oldeman climate classification

Main Type	WM Total
A	> 9
B	7 – 9
C	5 – 6
D	3 – 4
E	< 3

Sub-Division	DM Total
1	< 2
2	2 – 3
3	4 – 6
4	> 6

3. RESULT AND DISCUSSION

The comprehensive evaluation of the hydrological cycle in Gunung Mas Regency provides a fundamental baseline for assessing agricultural potential. As the water balance analysis consistently indicates a significant moisture surplus and high groundwater availability throughout the year, it is imperative to examine how these specific hydrological conditions align with the biological requirements of various food crops. Consequently, the following section evaluates the suitability of rice, corn, and cassava commodities within the context of the region's persistent water-rich environment and its implications for the proposed food estate development.

3.1. Water Balance Analysis

On the processing of precipitation data (CH) for 20 years (2004-2023), the average total CH of Gunung Mas Regency ranges from 147 to 556 mm/month. Global, regional, and local factors influence the magnitude of precipitation intensity at the research site. One is the valley/Gunungain wind because Gunung Mas Regency has a complex natural landscape from low to high plains. In addition, the research is located at the height of the river, resulting in the blockage of the movement of clouds by the mountains, which resulted in the accumulation of rain clouds due to wind movement. If this happens continuously, it will result in a high intensity of precipitation falling at the site of the study.

According to the Oldeman classification applied to the study site, there are nine wet months (BB) with CH ≥ 200mm, in January-May and September-December, accompanied by three wet months with 100 mm <

CH < 200 mm occurring in June-August. Evapotranspiration at the study site ranged from 112.1 mm to 128.5 mm, with the lowest total occurring in February and the highest in May. Precipitation and evaporation conditions in Gunung Mas Regency can be observed in the following table.

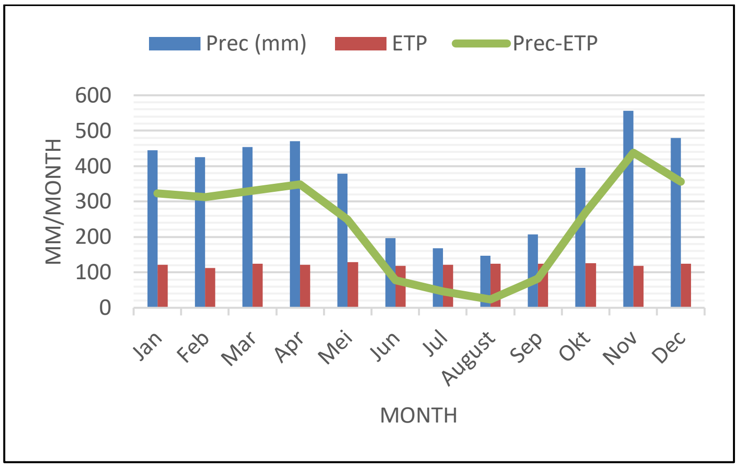

Fig. 2 Monthly ratio of precipitation, land evapotranspiration, and precipitation and land evaporation of Gunung Mas Regency in 2004-2023

The difference between soil evapotranspiration and precipitation was highest in November at 437.8 mm and lowest in August at 23.5 mm. In Table 2, there was no difference between the negative values of precipitation and evaporation of soil (in all CH> ETP months) during 2004-2023. The potential water loss for evaporation (APWL) in Gunung Mas Regency is relatively small and does not even occur. The amount of groundwater (AT) at the research site was obtained from the difference between the field's capacity and the plant's permanent dew point, which is 53.8 mm for Gunung Mas Regency.

This is due to more considerable precipitation when compared with the evapotranspiration of the soil, which occurred, so that the potential loss of water does not occur. This is in direct comparison with the value of dKAT, which is zero because KAT is the same each month. Since the amount of precipitation at the study site is greater than the potential evaporation at each month, then the actual value of evaporation is equal, so that ETP=ETA. This will be observed from the availability of groundwater (ATS), which reaches 100% each month, which indicates that water is sufficient to meet the land needs in Gunung Mas Regency each year.

Table 2. Oldeman climate classification

Month	P	ETP	P-ETP	APWL	KAT	dKAT	AET	Deficit	Surplus	ATS
Jan	445	122,1	323,2	0	74,2	0	122,1	0	323,2	100%
Feb	425	112,1	312,8	0	74,2	0	112,1	0	312,8	100%
Mar	454	123,9	329,9	0	74,2	0	123,9	0	329,9	100%
Apr	470	121,4	348,8	0	74,2	0	121,4	0	348,8	100%
Mei	378	128,5	249,6	0	74,2	0	128,5	0	249,6	100%
Jun	197	119	78,3	0	74,2	0	119	0	78,3	100%
Jul	168	121,3	46,5	0	74,2	0	121,3	0	46,5	100%
Agu	147	123,8	23,5	0	74,2	0	123,8	0	23,5	100%
Sep	207	125	81,6	0	74,2	0	125	0	81,6	100%
Okt	395	126,6	268,6	0	74,2	0	126,6	0	268,6	100%
Nov	556	118,3	437,8	0	74,2	0	118,3	0	437,8	100%
Dec	480	123,9	356,4	0	74,2	0	123,9	0	356,4	100%

3.2. Land Adequacy Analysis of Rice, Corn, and Cassava Commodities

Analysis of climatological data from 2004 to 2023 indicates that Gunung Mas Regency has a stable monthly air temperature range of 25.5°C to 26°C. The minimum thermal values were recorded in July, while the maximum peak occurred in September. Concurrently, the average monthly precipitation in the region varies significantly from 147 mm to 556 mm. According to the Oldeman climate classification, Gunung Mas Regency is categorized as Type B2 (based on 9 consecutive wet months). Within this agro-climatic framework, rice demonstrates high land suitability due to its tolerance for high moisture levels. Conversely, corn and cassava exhibit lower suitability levels. This is primarily due to persistent high-intensity rainfall throughout the year, which induces excessive soil moisture, a condition known to inhibit the physiological development of corn and the tuber formation of cassava, both of which require well-drained soil.

Table 3. Evapotranspiration values of soil and plants of rice, cassava, and corn

Month	Land ET_P	Rice ET_C	Cassava ET_C	Corn ET_C
January	122,1	138	61,1	96,5
February	112,1	126,6	56	88,5
March	123,9	140	62	97,9
April	121,4	137,2	60,7	95,9
May	128,5	145,2	64,3	101,5
June	119	134,4	59,5	94
July	121,3	137	60,6	95,8
August	123,8	139,9	61,9	97,8
September	125	141,3	62,5	98,8
Oktober	126,6	143	63,3	100
November	118,3	133,7	59,2	93,5
December	123,9	140	62	97,9

The calculation of crop-specific evapotranspiration (ETc) was performed by integrating potential evapotranspiration (ETp) with crop coefficients (ETc) derived from established literature [24], [26], [35]. As shown in Table 3, the ETc values for all three commodities reached their maximum in May, coinciding with the peak land ETp of 128.5 mm. During this peak period, the ETc for rice, cassava, and corn were 145.2 mm, 64.3 mm, and 101.5 mm, respectively. In contrast, the minimum ETc values occurred in February, corresponding to a land ETp of 112.1 mm, with ETc values of 126.6 mm for rice, 56 mm for cassava, and 88.5 mm for corn. These fluctuations underscore the significant influence of local meteorological parameters on the atmospheric water demand of each commodity.

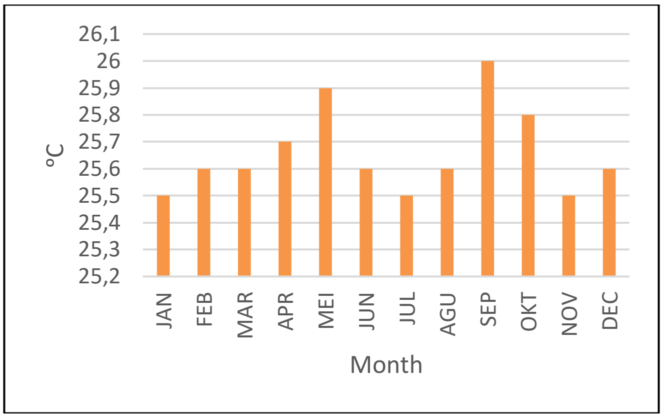

Fig. 3 Average monthly air temperature from 2004 to 2023

Figure 4 illustrates the monthly water surplus for each studied commodity alongside the general land water surplus. The analysis reveals that the surplus values for all crops follow a consistent seasonal pattern that aligns with the regional hydrological cycle. The maximum surplus for all commodities was observed in November, while the minimum occurred in August, coinciding with the peak and trough of the annual precipitation cycle. The higher surplus values for corn and cassava relative to their biological requirements are due to their lower water consumption (ETc) compared to wetland rice.

Regarding agricultural productivity, the persistent precipitation patterns in Gunung Mas Regency are highly suitable for wetland rice cultivation, as the continuous water availability ensures optimal irrigation throughout the growing season. However, for corn and cassava, the water availability is significantly over-abundant due to the region's high rainfall. This excessive moisture can lead to suboptimal growth conditions; for instance, over-saturated soils often result in root rot, reduced starch quality in tubers, and a higher prevalence of water-borne plant diseases. Consequently, while the region possesses a robust hydrological surplus, the cultivation of upland crops like corn and cassava requires strategic drainage management to mitigate the risks associated with excessive soil moisture.

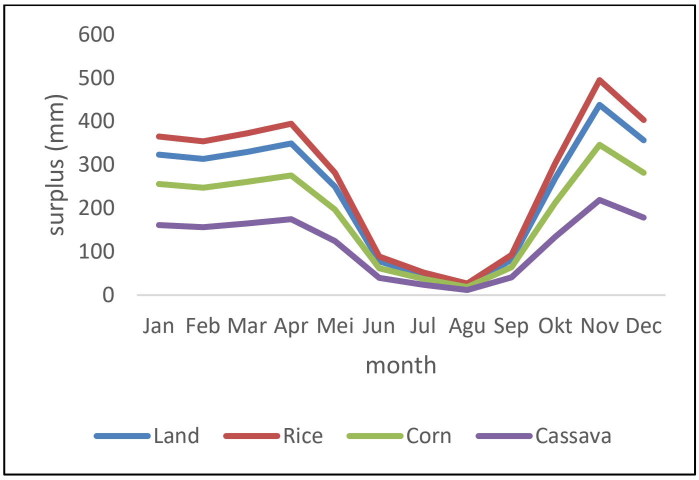

Fig. 4 Average monthly groundwater availability 2004-2023

4. CONCLUSION

Based on the hydrological analysis and water balance modeling, Gunung Mas Regency exhibits an abundant and persistent groundwater surplus, with availability consistently reaching 100% throughout the year. Remote sensing data indicate that monthly precipitation ranges from 147 mm to 556 mm, complemented by stable average temperatures between 25.5°C and 26°C. The region's complex topography further intensifies these hydrological characteristics, creating an environment that is highly conducive to wetland-based agriculture. Specifically, the hydrological profile of the study area is ideally suited for rice cultivation across all seasons, with the optimal planting window occurring from November to January.

In contrast, the persistent water surplus presents a significant limiting factor for upland crops such as corn and cassava. Corn cultivation is only deemed suitable during the transition at the end of the peak wet season (April–May), allowing the harvest to coincide with the relatively lower rainfall period from June to August. Cassava, however, is categorized as less suitable for large-scale development in this region due to its physiological intolerance to the high precipitation and saturated soil conditions identified in the water balance profile.

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