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ANALYSIS OF WATER SCARCITY INDEX IN WET CLIMATE AREAS: A CASE STUDY IN SOUTH SINJAI DISTRICT

ANALISIS KEKRITISAN AIR PADA DAERAH BERIKLIM BASAH: STUDI KASUS DI KECAMATAN SINJAI SELATAN

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ABSTRACT

Water availability in humid regions is often considered abundant due to high rainfall. However, uneven water distribution can lead to water shortages, especially when meeting domestic and agricultural demands. This study aims to analyze the level of water scarcity in South Sinjai District. The data included rainfall, soil characteristics, population numbers, and domestic and agricultural water demands. Water availability and its scarcity were analyzed using the water balance and Water Scarcity Index (WSI) approach. The study showed that the four villages studied experienced water availability and demand variations. Aska and Talle villages have higher water availability than Palae and Bulukamase villages. However, the increased water demand due to intensive planting patterns and population growth has caused some villages to be near critical to very critical. If a two- to three-season planting pattern is applied without good water resource management, the WSI can exceed 100%, signaling a very critical condition. Therefore, more efficient water management strategies are needed, including optimizing irrigation infrastructure, using water storage technologies, and implementing climate-based adaptive policies to reduce pressure on water resources.

ABSTRAK

Ketersediaan air di wilayah beriklim basah sering dianggap melimpah karena curah hujan yang tinggi. Namun, distribusi air yang tidak merata dapat menyebabkan kekritisan air, terutama dalam memenuhi kebutuhan domestik dan pertanian. Penelitian ini bertujuan untuk menganalisis tingkat kekritisan air di Kecamatan Sinjai Selatan. Data yang digunakan meliputi curah hujan, karakteristik tanah, jumlah penduduk, serta kebutuhan air domestik dan pertanian. Ketersediaan air dianalisis menggunakan pendekatan Indeks Kekritisan Air (WSI). Hasil penelitian menunjukkan bahwa keempat desa yang diteliti mengalami variasi dalam ketersediian dan kebutuhan air. Desa Aska dan Talle memiliki ketersediaan air lebih tinggi dibandingkan Desa Palae dan Bulukamase. Namun, kebutuhan air yang meningkat akibat pola tanam intensif dan pertumbuhan populasi menyebabkan beberapa desa berada dalam kategori mendekakti kritis hingga sangat kritis. Jika pola tanaman dua hingga tiga musim diterapkan tanpa pengelolaan sumber daya air yang baik, nilai WSI dapat melebihi 100%, menandakan kondisi sangat kritis. Oleh karena itu, strategi pengelolaan air yang lebih efisien diperlukan, termasuk optimalisasi infrastruktur irigasi, pemanfaatan teknologi penyimpanan air, serta kebijakan adaptif berbasis iklim untuk mengurangi tekanan terhadap sumber daya air.

KATA KUNCI:
Indeks kekritisan air, ketersediaan air, kebutuhan air domestik, kebutuhan air pertanian, neraca air

1. INTRODUCTION

Humid regions are generally characterized by high annual rainfall and a relatively even distribution of rainfall throughout the year. Consequently, water resources in these regions are often perceived as abundant and virtually unlimited. However, the physical availability of water does not necessarily guarantee that human water demands can be adequately met. Inadequate water resources management, land-use change, and environmental degradation can lead to water scarcity affecting both domestic and agricultural sectors (Alcamo & Henrichs. 2002). Moreover, uneven spatial and temporal water distribution, increasing water demand driven by rapid population growth, and insufficient water infrastructure further exacerbate water scarcity (Gleick & Cooley, 2021; Primandani *et al*., 2022; Ariyanto *et al*., 2023). Van Vliet *et al.* (2021) estimated that approximately 40% of the global population experiences severe water scarcity at least once each year. Similar conditions have been reported in Kediri Regency, Indonesia, where high agricultural water demand has significantly reduced water availability during both the wet and dry seasons (Sekaranom *et al*., 2022).

Therefore, assessing water scarcity has become increasingly important, even in regions that receive abundant rainfall (Santikayasa & Okhy Wiranta, 2022). Such assessments provide essential information for developing sustainable water resources management strategies (Leijnse *et al*., 2024). Water scarcity can be evaluated using a water balance approach, which quantifies the relationship between water availability and water demand (Nkiaka, 2022; Santikayasa & Okhy Wiranta, 2022). Water balance analysis is fundamental for understanding the dynamics of water availability and its capacity to satisfy agricultural and domestic water demands (Massari *et al*., 2020; Kurniasari *et al*., 2021). Consequently, comprehensive investigations of water balance, evapotranspiration, water demand, and water availability are essential for ensuring the sustainable management of water resources.

The water balance represents a fundamental hydrological framework for evaluating the equilibrium among rainfall, surface runoff, evapotranspiration, and changes in water storage. This approach provides an effective basis for assessing whether available water resources are sufficient to meet agricultural and domestic water demands (Moazami *et al*., 2016). In agricultural systems, water availability depends not only on rainfall amount but also on the soil's water-holding capacity and the temporal distribution of rainfall throughout the year (Valdés-Pineda *et al*., 2016). Consequently, water availability exhibits pronounced seasonal variability, with water surplus commonly occurring during the rainy season and deficits during the dry season (Masduqi, 2020; Sekaranom *et al*., 2022) .

In addition to agricultural water requirements, domestic water demand represents another critical component of sustainable water resource management. Rapid population growth in many humid regions has intensified pressure on available freshwater resources. Domestic water is required not only for drinking, cooking, bathing, and laundry but also for sanitation and other household activities. Shiklomanov (2000) demonstrated that population growth and urbanization substantially increase domestic water consumption, although water use efficiency in this sector generally remains lower than in other sectors. Furthermore, Hoekstra *et al*. (2011) introduced the concept of the water footprint as an indicator for quantifying the environmental impacts of domestic and industrial water consumption. Accordingly, evaluating the extent to which domestic water demand can be satisfied is essential for identifying potential water criticality and supporting sustainable water resources planning.

This study aims to evaluate the water status of a humid tropical region, represented by South Sinjai District, Indonesia, using the Water Scarcity Index (WSI). The WSI is an indicator that assesses the level of pressure on water resources by comparing water availability with water demand (including water requirements for agriculture) within a given region. The findings are expected to provide a scientific basis for developing sustainable and adaptive water resource management strategies capable of addressing future environmental and socio-economic challenges (Salehi, 2022).

2. MATERIALS AND METHODS

2.1 Research Location

This research was conducted in South Sinjai District, Sinjai Regency, Indonesia, especially in Aska Village, Palae Village, Talle Village, and Bulukamase Village (Figure 1). Geographically, South Sinjai Regency is located at 5°2'56" to 5°21'16" S and 119°56'30" to 120°25'33" E. The study area is situated at an elevation of 100-500 m above sea level and is characterized by a tropical climate with a mean annual rainfall of 2,696.4 mm and an average temperature of 25°C. The soil type is Inceptisol, with texture ranging from silt loam to clay. Soil bulk density ranges from 1.25 to 1.45 g cm^{-3}, while soil organic carbon content is relatively low, varying between 1.3% and 1.5%.

2.2 Data collection methods

2.2.1 Rainfall

The daily rainfall and temperature data used are data for 30 years (1993 – 2023). The daily rainfall data is sourced from CHRIPS, while the daily temperature of South Sinjai District is sourced from NASA (Power CERES/MERRA 2 which is downloaded through the NASA POWER website using the geographical coordinates of South Sinjai District, which are 5.3240°S and 120.4815° E.

2.2.2 Soil characteristics

Soil physical and chemical properties, including soil texture, bulk density, and soil organic carbon (SOC) content, were determined through laboratory analyses of both undisturbed and disturbed soil samples. The samples were collected from paddy fields in Aska, Bulu Kamase, Palae, and Talle villages. Five sampling sites were selected within each village, resulting in a total of 20 soil sampling locations across the study area.

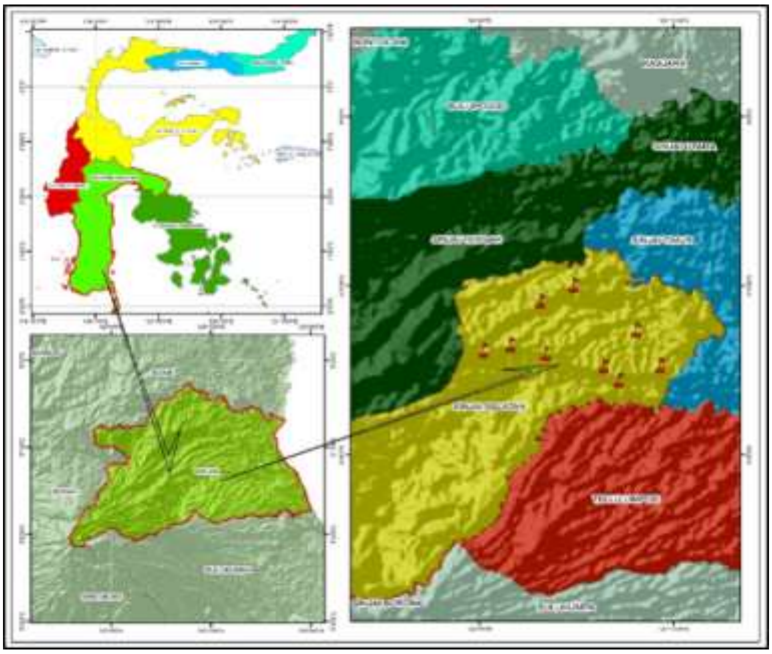

Figure 1. Administrative map of the water criticality level research site in South Sinjai District.

2.2.4 Population and its water consumption

Population data, including the total number of inhabitants in each village, were obtained from the 2024 database of Statistics Indonesia (BPS). Information on domestic water use was collected through structured household interviews conducted across the study area. The survey quantified water consumption for bathing, laundry, sanitation, cooking, household cleaning, and other domestic activities. These data were used to estimate the annual domestic water demand for each of the four study areas.

2.3 Data Analysis

2.3.1 Water Availability

Water availability was estimated using a water balance model (Equation 1) based on the approach proposed by (Thornthwaite and Mather, 1957). The model incorporated monthly rainfall, soil characteristics, and potential evapotranspiration as the primary input variables. The water balance analysis generated estimates of water surplus (S) and water deficit (D), which were subsequently used to evaluate the temporal dynamics of water availability within the study area.

$$P = ETp + ds \quad (1)$$

Note: P = monthly rainfall (mm), Etp = potential evapotranspiration (mm), and ds = change in water reserves in the soil (mm).

2.3.2 Domestic Water Demand

Domestic water demand was estimated based on the total population and the average per capita daily water consumption. Information on individual water use was obtained through household interviews conducted in each study area. The annual domestic water demand for each study area was calculated using Equation 2.

$$Q(dd) = Pw\ x\ Wd\ x\ T \quad (2)$$

Note: $Q_{(dd)}$ = domestic water demand (m^3 $year^{-1}$), Pw = population of each village, Wd = water needs per person (m^3 day^{-1}), and T = amount of time (365 days).

2.3.3 Water requirement for Agriculture

Agricultural water requirements for paddy fields was determined based on the cultivated area, crop water requirements, crop growth duration, and cropping pattern. According to Heryani *et al.* (2017), the average water requirement for optimum rice production ranges from 180 to 300 mm $month^{-1}$, whereas secondary food crops require approximately 100 – 200 mm $month^{-1}$. The rice growing period was assumed to be 120 days per cropping season. Agricultural water demand was calculated using the formulation proposed by Santikayasa & Okhy Wiranta (2022) (Equation 3), considering three representative cropping patterns: rice-fallow-fallow (one cropping season per year), rice-rice-fallow (two cropping seasons per year), and rice-rice-secondary crops (three cropping seasons per year).

$$Q(ptn) = Ai\ x\ qo\ x\ t\ x\ s \quad (3)$$

Note: Q(ptn) = water requirement (m^3 $year^{-1}$), A = rice field area (m^2), qo = standard plant water needs (mm day^{-1}), t= plant age (days), and s = planting pattern system.

Table 1. Water scarcity class (Santikayasa & Okhy Wiranta, 2022).

Water Scarcity index (%)	Water Scarcity class
< 50	Not yet critical
50 – 75	Near critical
75 – 100	Critical
>100	Very critical

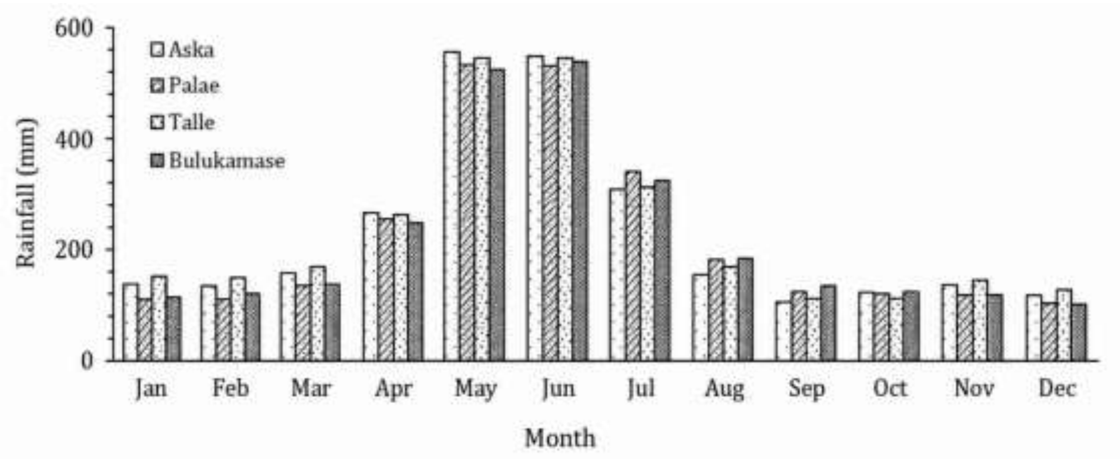

Figure 2. The average amount of rainfall in Aska Village, Palae Village, Talle Village, and Bulukamase Village, South Sinjai District for 30 years (1993 – 2023).

2.3.4 Water Scarcity Index

The Water Scarcity Index (WSI) was used to assess the level of water scarcity following the approaches proposed by (Widayani, 2011; Zeng, Liu, & Savenije, 2013). The WSI represents the ratio between total water demand and available water resources (Equation 4), thereby indicating the degree of pressure exerted on regional water resources. Water scarcity levels were classified according to the criteria established by the Directorate of Irrigation Program Development, as presented in Table 1 (Santikayasa & Okhy Wiranta, 2022).

$$WSI\ (\%) = \frac{Wn}{Ws}\ x\ 100 \qquad (4)$$

Note: WSI = water scarcity index (%), Wn = total water demand (m^3 $year^{-1}$) (including domestic water demand and agricultural water requirements), and Ws = total water availability (m^3 $year^{-1}$).

3. RESULTS AND DISCUSSION

3.1 Climate

The long-term rainfall pattern (30-year average) showed that the lowest monthly rainfall occurred in December across all four study villages. The average rainfall in December was 155 mm $month^{-1}$ in Aska Village, 101 mm $month^{-1}$ in Palae Village, 125 mm $month^{-1}$ in Talle Village, and 99 mm $month^{-1}$ in Bulukamase Village. In contrast, the highest monthly rainfall was generally recorded in May, with average rainfall reaching 554 mm $month^{-1}$, 534 mm $month^{-1}$, and 546 mm $month^{-1}$ in Aska, Palae, and Talle villages, respectively. Bulukamase Village exhibited a slightly different rainfall pattern, with peak rainfall occurring in June at an average of 539 mm $month^{-1}$ (Figure 2).

According to the Schmidt-Ferguson climate classification, all four villages are classified as very wet climatic zones, with a mean annual air temperature ranging from 24 to 27°C (Figure 3). These climatic conditions indicate a humid tropical environment characterized by abundant rainfall throughout most of the year.

Figure 3. The average temperature of South Sinjai District for 30 years (1993 – 2023).

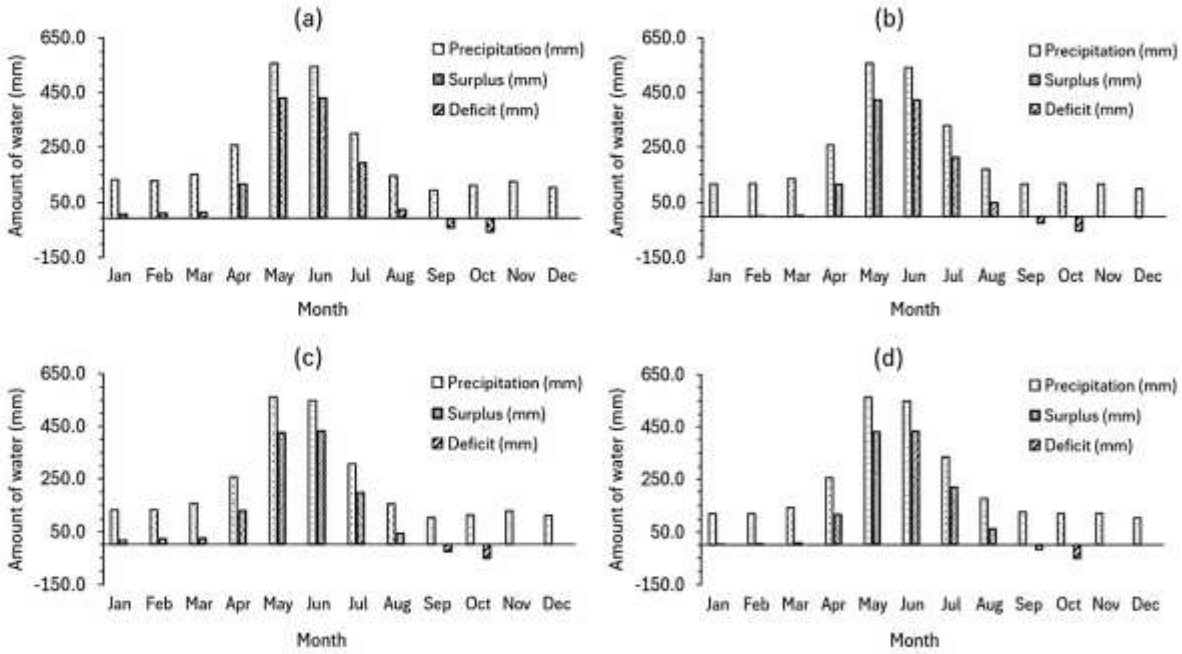

Figure 4. Distribution of surplus and water deficit for one year in South Sinjai District, especially in (a) Aska Village, (b) Talle Village, (c) Palae Village, and (d) Bulukamase Village.

3.2 Water balance

Water balance with a meteorological approach is needed to evaluate the availability of rainwater in an area, especially to determine when surpluses and deficits occur. Figure 4 presents the distribution of water surplus and deficit for one year in South Sinjai District, focusing on four villages, namely Aska Village, Talle Village, Palae Village, and Bulukamase Village. In general, the four villages experienced a water deficit from September to October. October showed the highest deficit rate of around 46.5 to 57.6 mm month^{-1}.

Seasonally, high rainfall occurs from January to August, providing favorable conditions for agricultural activities throughout the early and middle parts of the year. The highest rainfall is recorded between April and June, resulting in the maximum annual water surplus. This surplus indicates that water availability exceeds water demand during these months, creating opportunities to capture and store excess water for subsequent use during the dry season, particularly in September and October, when water deficits occur. These findings underscore the importance of implementing effective water resource management strategies to maintain agricultural productivity throughout the year.

One practical approach is to utilize surplus water storage technologies, such as reservoirs, farm ponds, and infiltration wells (Masduqi, 2020). Additional strategies include improving irrigation efficiency and promoting water-saving agricultural practices, such as the System of Rice Intensification (SRI). Previous studies have demonstrated that SRI can reduce irrigation water consumption by up to 35% while increasing rice productivity by approximately 29.8% (Budianto *et al*., 2020). Furthermore, integrating historical rainfall records with climate prediction models and implementing soil management practices that enhance soil water-holding capacity can support more adaptive water resource planning, thereby strengthening the sustainability of agricultural production in humid regions (Valdés-Pineda *et al*., 2016).

Effective adaptation also requires strong collaboration between local governments and farming communities to develop climate-responsive policies capable of addressing changes in rainfall patterns that may affect future water availability (Mukhlis & Perdana, 2022; Rejekiningrum *et al*., 2022). Such collaborative efforts should include investments in water management infrastructure and capacity building programs that enhance farmers' ability to adapt to changing climatic conditions (Talbi *et al*., 2024). Collectively, these measures can improve the long-term sustainability and resilience of water resource management in the four study villages under climate conditions.

3.3 Water Availability

Water availability for agricultural and domestic purposes varied considerably among the four study villages (Table 2). Talle Village recorded the highest annual water availability at 6,783,176.70 m^3, followed by Aska Village with 5,551,308.92 m^3. In contrast, Buliukamase Village had an annual water availability of 3,521,140.54 m^3, whereas Palae Village exhibited the lowest availability, amounting to 2,279,492.41 m^3. These differences indicate substantial spatial variability in water resources, which may influence local water allocation and management practices.

The observed variation in water availability is primarily associated with differences in rainfall distribution among the villages. Aska and Talle villages received relatively greater water inputs than Palae and Bulukamase villages, reflecting differences in both the temporal distribution and variability of rainfall. In general, regional water availability is largely determined by two key factors: annual rainfall and the water storage capacity of the local hydrological system. Uneven rainfall distribution can lead to considerable fluctuations in water availability, particularly in areas that rely heavily on natural water supplies (Sutapa *et al*., 2022). Moreover, intensive domestic and agricultural water use may further exacerbate the imbalance between water supply and demand.

Table 2. The amount of water availability for agricultural and domestic purposes in Aska Village, Palae Village, Talle Village, and Bulukamase Village, South Sinjai District.

Village	Water availability (m^3 $year^{-1}$)
Aska	5,551,308.92
Sludge	2,279,492.41
Waist	6,783,176.70
Bulukamase	3,521,140.54

Table 3. Domestic water demand in South Sinjai District.

Village	Total Population	Water demand (m^3 $year^{-1}$)
Aska	4,156	265,464.50
Palae	3,558	212,981.88
Lamb	5,532	302,877.00
Bulukamase	3,764	226,686.90

Table 4. Simulation of water requirements for agriculture in 1 planting season with a rice-bero-bero planting pattern, 2 planting seasons with a rice-padi-bero planting pattern, and 3 planting seasons with a rice-padi-secondary crops planting pattern in South Sinjai District.

Village	Rice field area (ha)	Water requirements for agriculture ((m^3 year^{-1}))		
		1 growing season	2 growing seasons	3 growing seasons
Ash	439	3,160,800.00	6,321,600.00	8,077,600.00
Palae	185	1,332,000.00	2,664,000.00	3,404,000.00
Lamb	519	3,736,800.00	7,473,600.00	9,549,600.00
Bulukamase	291	2,095,200.00	4,190,400.00	5,354,400.00

Table 5. The level of water scarcity in Aska, Palae, Talle, and Bulukamase Villages, South Sinjai District.

Village	Rice field area (ha)	Total Population (Soul)	Water scarcity rate (%)		
			1 growing season	2 growing seasons	3 growing seasons
Ash	439	4,156	61.7	118.7	150.3
Palae	185	3,558	67.8	126.2	158.8
Lamb	519	5,532	59.6	114.6	145.3
Bulukamase	291	3,764	65.9	125.4	158.5

Table 6. Water scarcity index in Aska Village, Palae Village, Talle Village, and Bulukamase Village, South Sinjai District.

Village	Rice field area (ha)	Total Population (Soul)	Water scarcity index		
			1 growing season	2 growing seasons	3 growing seasons
Ash	439	4,156	Close to Critical	Very critical	Very critical
Palae	185	3,558	Close to Critical	Very critical	Very critical
Waist	519	5,532	Close to Critical	Very critical	Very critical
Bulukamase	291	3,764	Close to Critical	Very critical	Very critical

3.4 Water Demand

3.4.1 Domestic water demand

Domestic water demand in South Sinjai District varied substantially among the study villages (Table 3). Talle Village, with a population of 5,532 inhabitants, recorded the highest annual domestic water demand, reaching 302,877 m^3 year^{-1}. This finding indicates a greater requirement for reliable drinking water infrastructure to ensure adequate access to safe and clean water for the local population (Salehi, 2022). Conversely, Palae Village had the smallest population (3,558 inhabitants) and consequently the lowest annual domestic water demand, estimated at 212,981.88 m^3 year^{-1}. Overall, domestic water demand exhibited a positive relationship with population size, indicating that villages with larger populations generally require greater volumes of water. Nevertheless, population size alone does not fully explain differences in water demand, as consumption patterns, socioeconomic characteristics, and local water availability may also influence household water use.

3.4.2 Agricultural water requirements

Table 4 presents the simulated agricultural water requirements under three cropping scenarios in South Sinjai District. The first scenario represents a single annual rice-growing season (rice-fallow-fallow), the second represents two annual rice-growing seasons (rice-rice-fallow), and the third represents three annual cropping seasons (rice-rice-secondary crops). These simulations were designed to evaluate how different cropping patterns influence agricultural water demand under the prevailing climatic, soil, and crop conditions. Agricultural water requirements differed considerably among villages according to cultivated land area and cropping intensity. Talle Village, which has the largest paddy field area (519 ha), required approximately 3,736,800 m^3 of water for a single rice-growing season. Water demand increased to 7,473,600 m^3 under the two-season scenario and reached 9,549,600 m^3 under the three-season scenario. This substantial increase highlights the need for irrigation infrastructure capable of supporting land. Adequate irrigation capacity will be essential for sustaining agricultural productivity and strengthening regional food security.

Agricultural water requirements are strongly influenced by cropping patterns because different crops exhibit distinct evapotranspiration rates and water requirements throughout their growth stages (Laban *et al*. 2015; Wanniarachchi & Sarukkalige, 2022). In addition, cultivation practices and soil management influence irrigation requirements by affecting soil moisture retention and water use efficiency. Therefore, the simulation results provide valuable insight into future agricultural water requirements and offer a scientific basis for improving sustainable water resource planning and supporting long-term food security in South Sinjai District.

3.5 Water Scarcity

The Water Scarcity Index in South Sinjai District exhibited substantial spatial variation among the study villages, ranging from 59.6% to 158.8% (Table 5), corresponding to close to critical and very critical water scarcity categories (Table 6). These findings indicate that water resources in the study are under considerable pressure due to the combined demands of agricultural production and domestic water consumption. Water scarcity becomes particularly severe when rice fields are cultivated under two or three cropping seasons per year, resulting in a very critical water scarcity status. Without effective water resource management and adequate irrigation infrastructure, the implementation of intensive cropping systems is likely to exacerbate water scarcity by further increasing water demand beyond the available supply. Moreover, continued reliance on limited water resources may threaten the long-term sustainability of irrigation systems and reduce the availability of fresh water for domestic use.

4. CONCLUSION

Although South Sinjai District is characterized by a humid tropical climate with abundant annual rainfall, water availability does not consistently satisfy water demands due to domestic water demand and agriculture water requirements because of the pronounced seasonal variability in rainfall distribution. The Water Scarcity Index analysis revealed that several villages in South Sinjai Distric experienced water scarcity conditions ranging from close to critical to very critical, particularly under cropping systems with two to three planting seasons per year, indicating that increasing cropping intensity substantially intensifies pressure on local water resources. These findings highlight the importance of implementing integrated water resource management strategies to improve water-use efficiency and ensure reliable water availability throughout the year. Such strategies should prioritize the optimization of water storage infrastructure, including reservoirs, farm ponds, and infiltration wells, together with the adoption of efficient irrigation technologies. Furthermore, strengthening collaborations among local government, water management agencies, and farming communities is essential for developing climate-adaptive policies that enhance resilience to changing rainfall patterns and promote the long-term sustainability of water resources and agricultural production.

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