Water productivity analysis in irrigated central rice production area of SolokRegency, Indonesia

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Abstract. To feed the increasing world population, the demand for food and consequently irrigation water is predicted to increase in the future. However, the amount of water available for agriculture is increasingly becoming uncertain in the face of global climate change. Therefore, improvement in water productivity is necessary for sustainable production of crops such as rice. Water productivity varies across regions and across fields within a region, and is dependent on several factors such as crop patterns, climate patterns, irrigation technology and field water management, land and infrastructure, and other inputs, including labor, fertilizer, and machinery. The objective of this study was to estimate water supply and demand in Sumani watershed, a primary rice-producing region, to analyze water productivity for sustainable rice production. Approximately 30% of the area in Sumani paddy fields, which depend on the availability of water resources. In this area. Approximately 67% of the rice fields are cultivated three times a year. In general, the planting schedule of rice is divided into three periods: main planting season (wet season), Gadu planting season (planting in the end of wet season and harvesting in the dry season), and dry planting season. Although the planting schedules are not uniform, we assumed these as uniform, to simplify the analysis, by using majority cropping schedule in the study site. To ensure water availability in the dry season, four types of irrigation systems were used: technical irrigation (TI), semi-technical irrigation (STI), simple irrigation (SI), and non-government irrigation (NGI). The results showed that depending on the planting season and irrigation system, water productivity varied from 0.33 kg/m³ in the Gadu season in areas irrigated by the SI and NGI systems to 0.73 kg/m³ in the wet season in area irrigated by the TI system. The average water productivity in the study area was 0.53 kg/m³. Water productivity in this study area was lower than the average water productivity in other rice production areas in Java and Bali.

1. Introduction
Agriculture sector, which consumes approximately 70% of the freshwater resources, is expected to increase by 10% in 2050 [1]. Increase in the demand for water resources increases the pressure on water supply. Thus, water availability is the bottleneck of a sustainable and healthy national economy [2]. Given the global climate change, water available for agriculture is expected to decline in the future [3].
Irrigation systems have been under pressure to produce more with lower water supply. The demand for irrigation water is driven mainly by farmers’ perceptions, climatic conditions, production factors, and the market value of crop yield [4]. Moreover, the impact of reallocating water to other sectors such as urban areas, industry, and industry is severe on the local irrigation system [5]. Even in the absence of significant population pressure, the demand for freshwater in low and middle-income countries is likely to increase with economic development and related processes, such as industrialization, energy production, health and sanitation developments, and changing food habits [6].

To address the challenges facing irrigated agriculture in this century, it is important to improve equity, reduce environmental damage, increase ecosystem service, and enhance water and land productivity in existing and new irrigated systems [7]. There are compelling reasons to continue investing in irrigation: to preserve the existing stock of irrigation infrastructure and the value of that investment; to increase the livelihoods of the poor population in rural areas and moving them out of poverty; to adapt to and satisfy the changing food preferences of increasingly wealthy urban and rural populations; to productively, safely, and cheaply reuse the increasing volume of urban wastewater that will be generated in the future; and to adapt to the impact of climate change [8].

To meet the increasing demand for food, it is necessary for irrigated areas to produce more crops with the currently available water resources [8]. Water use efficiency as well as water productivity are important indicators of water use in a green economy [9]. Improving water productivity is necessary to improve water management for sustainable agriculture, food security, and healthy ecosystem [10]. Water productivity varies among regions and fields depending on several factors, such as crop patterns, climate patterns (if rainfall fits crop growth), irrigation technology and field water management, land and infrastructure, and inputs, including labor, fertilizer, and machinery [11]. The objective of this study was to estimate water supply and demand to analyze water productivity, based on the current condition of agricultural system, for sustainable rice production. This would be used as a basis for decision making in future investments.

2. Methodology

2.1. Study area
Sumani watershed (figure 1) is a primary rice cultivation area. The total area of Sumani watershed is approximately 57.085 km². The major land use in the watershed is dryland, which occupies approximately 32.66% of the total area. The second largest land use is wetland (paddy field), which accounts for approximately 29.9% of the total area. The highland forest as the water catchment area is by approximately 17.84% of the total area. The other land uses account for less than 10% of the total watershed area, and include settlement, lake, reservoir, brush/shrub, mix farm, and plantation.

![Figure 1. Sumani watershed.](image-url)
Assurance of irrigation water is required for sustainable rice production. In this study site, the irrigated area was divided into four groups based on the type of irrigation used: technical irrigation (TI), semi-technical irrigation (STI), simple irrigation (SI), and non-government irrigation (NGI). TI has high irrigation efficiency because the irrigation channel and drainage are separate. Moreover, it is equipped with devices that measure the water flow at each water diversion. STI system is also equipped with water flow-measuring devices, however only at intake; therefore, the irrigation efficiency is moderate. SI is neither measured nor regulated. Finally, NGI is a simple irrigation system constructed by farmers.

In this study area, cropping intensity varies from once a year to three times a year. This cropping index affects the water requirement of crop for growth. Approximately 67% of the rice fields are cultivated three times a year. Usually, farmers cultivate rice based on water availability. In general, rice-planting schedule is divided into three periods: main planting season (wet season), “Gadu” planting season (planting at the end of wet season and harvesting in the dry season), and dry planting season. The main planting season starts in November–March, and harvesting season starts in February–June. “Gadu” planting season starts in April–July, and the harvesting season starts in July–October. Dry season planting starts in August–October, and harvesting season starts in November–January. In the study area, planting schedules are not uniform. However, to simplify the analysis, we assumed a uniform cropping schedule is uniform based on the majority cropping schedule. The main planting, Gadu planting, and dry planting were started in December, April, and July, respectively, and planting period of each season was 110 days.

2.2. Water balance of F.J. Mock tank model
The total water available in the basin in a given time period can be expressed by Equation 1 and 2[12]:

\[ P = AET + \Delta S + TRo \]  
\[ TRo = BF + DRO \]  

where, \( P \) is rainfall (mm/year); \( AET \) is actual evapotranspiration (mm/year); \( \Delta S \) is groundwater storage change (mm/year); \( TRo \) is total run off (mm/year); \( BF \) is base flow (mm/year), and \( DRO \) is direct run off (mm/year). Model calibration was conducted using optimization function of Excel by determining the values of several parameters with range value for Indonesia region (table 1) [13][14][15].

| Variables                              | Minimum | Maximum |
|----------------------------------------|---------|---------|
| Initial Soil Moisture Capacity Moisture (ISM) | 10      | 100     |
| Soil (SMC)                             | 300     | 500     |
| Infiltration Coefficient in the wet season (Ciw) | 0.5     | 1       |
| Infiltration Coefficient in the dry season (Cid) | 0.5     | 1       |
| Groundwater Recession Constant (K)     | 0.5     | 0.99    |
| Initial Ground Water Storage (IGWS)    | 1,000   | 3,000   |

2.3. Water productivity
Water productivity is generally defined as crop yield per cubic meter of water consumption [11]. Water consumption is divided into two types: beneficial water consumption, which is equal to net irrigation water requirement, and non-beneficial water consumption, which is defined as water loss during irrigation distribution affected by irrigation efficiency. Water productivity is calculated by equation 3 [11]:

...
\[ WP = \frac{P}{WC} \]  

(3)

where, WP is water productivity (kg/m\(^3\)); P is crop production (kg); WC is water consumption (m\(^3\)). Water productivity in the irrigated area or irrigation water productivity is defined as the production relative to the amount of irrigation water[16]. Hence, water consumption in this study is equal to irrigation water requirement. Irrigation water requirement is calculated using Equation 4 and 5[17]:

\[ IN_{net} = ET_{crop} + SAT + PERC + WL - Pe \]  

(4)

\[ IN_{gross} = \frac{IN_{net}}{e} \]  

(5)

where, \( IN_{net} \) is net irrigation water requirement (mm/year); \( ET_{crop} \) is crop water requirement (mm/year); \( SAT \) is water needed to saturate the soil for land preparation by puddling (mm/year); \( PERC \) is percolation (mm/year); \( WL \) is water layer (pounding water depth on plant height) (mm/year); \( Pe \) is effective rainfall (mm/year); \( IN_{gross} \) is gross irrigation water requirement (mm/year); and \( e \) is irrigation efficiency.

2.4. Data collection

Data for 10 years (2004–2014) were collected from the government institutions of Indonesia. Daily rainfall and discharge data were collected from rainfall station and gage station of the Indonesian Ministry of Public Work located near the outlet of the watershed. Climatological data were collected from the climatology station of Indonesian Ministry of Agriculture located downstream of the Sumani watershed. In addition, agricultural data such as rice production, irrigated area, cropping intensity, and yield were collected from the Indonesian Central Bureau of Statistics.

3. Results and discussion

3.1. Available water supply in Sumani watershed

The values of various parameters in the F.J. Mock tank model for Sumani watershed were 68 mm, 311 mm, 0.65, 1, 0.93, and 1000 mm for ISM, SMC, Ciw, Cid, K, and IGWS, respectively. Monthly calibration of F.J. Mock tank model showed high accuracy with a Nash Sutcliffe Efficiency of 0.99, correlation coefficient of 0.93, and mean square error of 0.9.

The simulation results showed that average available water supply in the Sumani watershed was approximately 40% of the average annual rainfall or approximately 768 mm (table 2). Water available in the watershed was higher than average annual water yield, which was approximately 35% of the average annual rainfall or 669 mm. This indicates a reduction in the groundwater storage, with an annual average of 99 mm.

| Actual Evapotranspiration (mm) | Ground Water Storage Change (mm) | Direct Runoff (mm) | Base Flow (mm) | Rainfall (mm) |
|-------------------------------|---------------------------------|--------------------|----------------|--------------|
| 1,250                         | -99                             | 116                | 652            | 1,919        |
| 65%                           | -5%                             | 6%                 | 34%            | 100%         |

Water yield was approximately 99 mm in the dry season from May to September, and 571 mm in the wet season from October to April. This affected the water availability in dry and wet seasons; the available water was 250 and 519 mm in the dry and wet season, respectively (figure 2). The groundwater level decreased by approximately 151 mm in the dry season. Hence, it is importance for this area to have adequate infrastructure, such as reservoirs, to conserve water in the wet season, so that it is available to all users in the dry season. For rice cultivation, a proper irrigation system is also crucial for ensuring water availability in the dry season and for maintaining high water productivity.
3.2. Irrigation water requirement

Based on the cropping schedule, rice cultivation in the dry season required approximately 40% more irrigation water than that in the main planting season (Figure 3). However, the Gadu season required approximately only 5% more water than the main planting season. Thus, the net irrigation water requirement of the main planting season was approximately 451.2 mm, while that of the Gadu planting season was approximately 474.4 mm. The net irrigation water requirement was the highest in the dry planting season (approximately 629.1 mm) because of low effective rainfall.

During the 10-year time period (2004–2014), the net annual irrigation requirement increased because of reduction in the effective rainfall (Figure 4). The irrigation water requirement increased from 1,530 mm in 2004 to 1,930 mm in 2014, while the effective rainfall decreased from 1,432 mm to 988 mm. This indicates that the study site should consider changing the production pattern; for example, planting a crop that is tolerant to the dry season, such as a cash crop, or adjusting the cropping schedule with rotation irrigation water used system.
Considering the irrigated area in the watershed, total net irrigation water requirement was approximately 196,941,863 m³/year or 1,748 mm/ha/year. The highest net irrigation water requirement was approximately 29,775,183 m³ in July. This is because July marks the beginning of the dry season planting; during this time the total water requirement consists of water required for land preparation and water layer maintenance. The lowest irrigation demand was approximately 6,730,658 m³ in January, which coincides with the maturity stage in the main planting season. The gross irrigation water requirement, taking into account the irrigation efficiency in the study area, was approximately 382,299,333 m³/year. This amount is almost twice the amount of net irrigation water requirement. Gross irrigation requirement was the highest in March because the planting area was irrigated by simple irrigation and non-government irrigation systems, which have low irrigation efficiency. The monthly average of total irrigation water requirement is shown in figure 5.

The annual irrigation requirement ranged from 355,023,742 m³ to 436,481,527 m³ during 2004–2014. Increase in the irrigation requirement was followed by a decline in the arable area. Thus, the
irrigated area decreases from 13,936 ha in 2004 to 13,486 ha in 2014. Since the gross irrigation water requirement was almost twice the net irrigation requirement, increasing irrigation efficiency in this area could be the solution in the reduction of irrigated area in 2014. The tendency of irrigation water requirement and irrigated area is shown in figure 6.

![Figure 6. Annual total irrigation water requirement](image)

3.3. Water productivity based on irrigation system and cropping schedule
Water productivity in the study area based on irrigation system and cropping schedule varied from 0.33 to 0.73 kg/m³. China and some Southeast Asian countries have higher water productivity of rice (0.4 to 0.6 kg/m³) than the average water productivity of developing countries (0.39 kg/m³) [11]. In the study area, area irrigated by the technical irrigation system showed the highest water productivity in the main season (0.73 kg/m³), as technical irrigation system in the main system has relatively high irrigation efficiency and effective rainfall. However, rice water productivity in the TI was lower than water productivity of other rice production countries such as in India, Philippine and Japan that reached 1.10 kg/m³ [11]. Compared to a more modern system, water productivity in technical irrigation is also lower than pipe irrigation which has a water productivity of 0.82 kg/m³ [18]. SI and NGI systems showed the lowest water productivity in the Gadu season (0.33 kg/m³). Low irrigation efficiency and effective rainfall were responsible for low water productivity in this study area. Hence, improvement in irrigation efficiency is required by at least 50% to increase water productivity. Table 3 shows water productivity based on the irrigation system and planting season.

| Irrigation System                  | Main Season | Gadu Season | Dry season |
|-----------------------------------|-------------|-------------|------------|
| Technical Irrigation              | 0.73        | 0.49        | 0.52       |
| Semi-Technical Irrigation         | 0.61        | 0.41        | 0.44       |
| Simple Irrigation                 | 0.49        | 0.33        | 0.35       |
| Non-Government Irrigation         | 0.49        | 0.33        | 0.35       |

3.4. Water productivity based on the agricultural systems
Water productivity varies from region to region and field to field depending on crop patterns, climate patterns (if rainfall fits crop growth), irrigation technology and field water management, land and infrastructure, and inputs, including labor, fertilizer, and machinery [11]. Central rice areas in Solok regency showed different levels of agricultural systems. Different types of irrigation systems and the arable area that occupied by irrigated area, and different agricultural inputs affect the level of water.
productivity. Based on the level of agricultural system, water productivity ranged from 0.15–0.59 kg/m³ (table 4). The highest water productivity was observed in Kubung sub-district (0.59 kg/m³). In this sub-district, approximately 83% of the irrigated area is occupied by technical and semi-technical irrigation systems, with irrigation efficiency greater than 50%. Land productivity in this area was relatively high (6.2 ton). By contrast, Danau Kembar sub-district showed low water productivity (approximately 0.15 kg/m³) because all of the arable area in this sub-district was occupied by non-government irrigation system. Additionally, land productivity in Danau Kembar sub-district was relatively low (3.5 ton). The average of water productivity in this study area is 0.53 kg/m³ which is much lower than the average of water productivity in Java (0.76 kg/m³) and Bali (1.1 kg/m³)[19].

| Sub Districts       | Total Water Consumption (m³) | Total Production (kg) | Water Productivity (kg/m³) |
|----------------------|------------------------------|-----------------------|---------------------------|
| Lembang Jaya         | 67,087,179.80                | 32,230,041.82         | 0.48                      |
| DanauKembar          | 1,605,225.51                 | 209380,9091           | 0.15                      |
| GunungTalang         | 105,708,237.43               | 55,175,421.82         | 0.53                      |
| Bukit Sundi          | 91,275,379.94                | 48,502,603.64         | 0.53                      |
| Kubung               | 80,181,886.09                | 47,359,512.73         | 0.59                      |
| X Koto Singkarak     | 53,824,104.07                | 29,102,806.36         | 0.55                      |
| Average              | 399,682,012.84               | 212,579,767.27        | 0.53                      |

3.5 Annual water productivity from 2004–2014
Annual water productivity during 2004-2014 ranged from 0.48 to 0.62 kg/m³ (figure 7). The fluctuation in annual water productivity is affected by the irrigated area and land productivity. The increase in water productivity mainly results from an increase in crop yield [11]. Water productivity increased from 0.48 kg/m³ in 2004 to 0.55 kg/m³ in 2006 because of the increase in land productivity, despite the decrease in irrigated area. In 2007, a reduction in irrigated area and land productivity resulted in a decrease in water productivity to 0.5 kg/m³. Water productivity tent increased from 2008 to 2010 due to the increase in land productivity. In 2008, water productivity decreased to 0.53 kg/m³, even though irrigated area was stagnant and land productivity increased. This was affected by the decline in effective rainfall. Effective rainfall also affected the increase in water productivity in 2012 to 0.62 kg/m³. However, water productivity decreased to 0.55 kg/m³ because of the decline in irrigated area.
4. Conclusions
Average water availability in Sumani watershed was approximately 40% of the average annual rainfall, and only 33% of the water was available in the dry season. Average water productivity in this central rice production was lower than the average water productivity in other rice production area in Java and Bali. Net irrigation requirement was half of the gross irrigation requirement. Thus, improvement in water productivity is required by improving irrigation efficiency by more than 50%. Improvement in simple irrigation and non-government irrigation systems would be substantial for improving water productivity in the central rice production area of the Solok Regency.

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