U Karst
Volume 09 Number 01 Year 2025

ISSN (*Online*) 2581-0855
ISSN (*Print*) 2579-4620

Available Online at
https://ojs.unik-kediri.ac.id/index.php/ukarst/index

https://dx.doi.org/10.30737/ukarst.v9i1.6628

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Optimization System Irrigation Using Linear Programs in the D.I. Delta Brantas Region Sidoarjo (Case Study: Dungus Intake)

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A R T I C L E I N F O

Article History :
Article entry : 21 – 02 – 2025
Article revised : 19 – 03 – 2025
Article received : 24 – 04 – 2025

Keywords **:**
Cropping Patterns, Irrigation Optimization, Linear Programming, Water Efficiency.

IEEE Style in citing this article:
K. Nisa and D. A. D. Nusantara, "Optimization System Irigation Using Linear Programs in the D. I. Delta Brantas Region in the Regency Sidoarjo (Case Study: Dungus Intake)," U Karst, vol 9, no. 1, pp 62 – 77, 2025, doi: 10.30737/ukarst.v9i1.6628

ABSTRACT

Global food security is facing challenges due to climate change and increasing water needs for agriculture. One area experiencing these problems is the Dungus intake irrigation area in Sidoarjo Regency, which faces water management due to land use changes and uncertainty of water availability. As a result, the efficiency of water distribution decreases, and agricultural productivity is disrupted, so efforts are needed to optimize the irrigation system. This study aims to optimize the irrigation system in the Dungus Intake Irrigation Area to increase the efficiency of water distribution. This effort is carried out by determining the optimal planting pattern and irrigation water allocation using the linear programming method. This method is applied by considering the mainstay discharge of the Dungus intake, crop irrigation needs, and economic benefits from various cropping pattern scenarios. The results show that the mainstay discharge ranges from 0,479–0,754 m³/sec with an allocation discharge of 2.604 m³/sec. The optimal alternative cropping pattern 3, with a land area of 1.890 ha, consisting of rice, corn, and shallots in three planting seasons, produces a maximum profit of Rp 242.087.200.000 per year. This study can develop an irrigation optimization model based on hydrology and economics that can improve the efficiency of water distribution. This irrigation optimization model provides a reference for irrigation managers and farmers in designing better water distribution strategies that can increase agricultural yields and economic profits through more appropriate water allocation and optimal land use.

1. Introduction

Water is a crucial resource for the agricultural sector, especially in ensuring sustainable food availability [1], [2]. The main problem is the imbalance between water availability and demand, which is often exacerbated by climate change, erratic rainfall patterns, and suboptimal water resource management. Several regions are experiencing significant impacts from this problem. One of them is Sidoarjo Regency, which faces significant challenges in terms of

ISSN (*Online*) 2581-0855
ISSN (*Print*) 2579-4620

changes in land use, shallowing of channels, and uncertainty of water resources during the planting season (BPS Sidoarjo Regency) [3], [4]. This imbalance between water availability and demand has a direct impact on agricultural productivity, with rice production in Sidoarjo decreasing from 202.501 tons in 2021 to 194.540 tons in 2022, before increasing slightly to 195.855 tons in 2023 (BPS Sidoarjo Regency) [5]. This decline in crop yields threatens local food security, triggers economic losses for farmers, and increases the potential for water use conflicts between farmers and other sectors [6]. Inefficiency in irrigation water distribution, water allocation that does not match land needs, and minimal infrastructure maintenance worsen this condition [7],[8]. As a result, farmers rely on more expensive alternative water sources, increasing agricultural production costs and reducing welfare [9]. More efficient and data-based water management strategies are needed to improve agricultural resilience in this region [10].

Global challenges to food security are increasingly complex due to climate change and population growth, so a more adaptive water resource management system is needed [11]. The Sustainable Development Goals (SDGs) also emphasize the importance of efficient water use to support sustainable food production [12]. One approach that has proven effective in increasing the efficiency of irrigation systems is linear programming-based optimization [13]. This approach allows the determination of optimal water distribution by considering variables such as water availability, crop needs, and irrigation channel capacity to minimize waste and increase agricultural yields more evenly [14].

Previous irrigation optimization research has been conducted using various approaches. A study in Cidurian Tangerang Regency used linear programming for irrigation optimization but did not comprehensively consider hydrological conditions and agricultural land distribution [15]. Another study in Kedungrejo irrigation, Madiun, optimized planting patterns for efficient water use, but it has not considered variations in river discharge and geographical factors that affect water distribution [16]. Another study showed that hydrological models can improve water optimization by considering evapotranspiration and plant needs, but it has not included daily discharge variation factors [17]. On the other hand, remote sensing-based research has been used to monitor water availability, but has not integrated socio-economic factors in irrigation optimization [18]. In addition, a water distribution model has been developed based on geographical characteristics, but the technical application of linear program optimization has not been widely studied [19]. From these various studies, there is a need to develop a more comprehensive irrigation optimization model that considers not only technical and hydrological aspects but also spatial and socio-economic factors of farmers.

https://dx.doi.org/10.30737/ukarst.v9i1.6628

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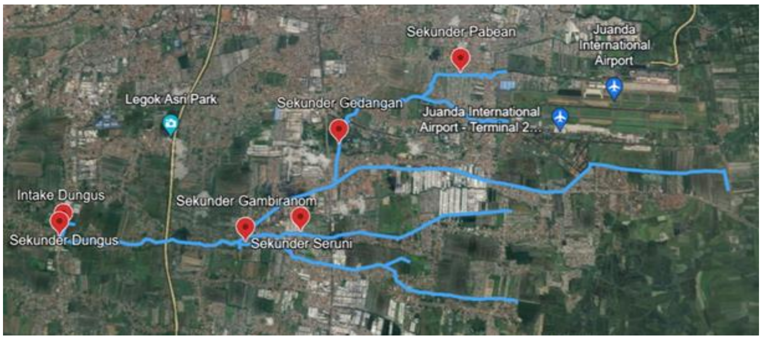
Volume 09 Number 01 Year 2025
ISSN (*Online*) 2581-0855
ISSN (*Print*) 2579-4620

The Dungus Intake Irrigation Area was chosen as a case study because it has unique hydrological characteristics, including significant variations in water discharge and diverse distribution of agricultural land. However, research examining the optimization of irrigation systems in this area by considering these characteristics is still very limited. The Dungus Intake requires a more specific optimization approach to adjust water distribution to sustainable cropping patterns. This study aims to develop an irrigation system optimization model based on linear programming that considers hydrological aspects and spatial and socio-economic factors of farmers in the Dungus Intake area. This model is expected to improve the efficiency of water distribution, maximize agricultural yields, and support the sustainability of cropping patterns.

2. Research Methods

This research was conducted in the Delta Brantas Irrigation Area (Dungus intake), Sidoarjo Regency, which has a standard rice field area of around ±1890 Ha based on data from BBWS Brantas. The irrigation system in this area consists of five secondary channels, Dungus, Gambiranom, Seruni, Gedangan, and Pabean, with an existing planting pattern of two dominant rice plantings without using wells. The research began with collecting primary and secondary data on the characteristics of the irrigation system, land area, and agricultural conditions. The mainstay discharge data and crop water requirements were analyzed to compile several cropping pattern scenarios. Furthermore, cropping pattern optimization was carried out using quantitative descriptive methods and linear programming approaches to determine the most efficient and profitable water allocation and crop combinations. The results of this optimization are the basis for recommending sustainable irrigation management strategies and cropping patterns in the research area.



Source: Planning Personal, Google Earth (2024).

Figure 1. Dungus Intake Research Location in D.I. Delta Brantas.

ISSN (*Online*) 2581-0855
ISSN (*Print*) 2579-4620

2.1 Data collection

Data collection from related agencies is important to ensure relevance and suitability to field conditions. The data collected includes irrigation network schemes from BBWS Brantas, rainfall data with a span of the last 10 years (2014-2023) and allocation discharge from the PUBMSDA Service of Sidoarjo Regency, as well as RTTG data for the last 1 year to determine cropping patterns. In addition, agricultural business analysis data for the last 1 year from PANPERTA Sidoarjo Regency is used to increase profits, while climatology data for the last 1 year from BMKG helps understand environmental factors. All of these data support the analysis and conclusions of the study.

2.2 Hydrological, Water Needs, and Water Balance Analysis

Hydrological analysis provides estimates of water availability and future water needs. It is carried out through several stages, including calculating average rainfall using the Thiessen Polygon method [20], performing climatological calculations using the Penman method [21], calculating available discharge using the FJ Mock method [22], and determining mainstay discharge using the Weibull method [23]. Irrigation water requirement is the amount needed to replace water lost through evaporation [24], which includes the calculation of effective rainfall, land preparation calculations using the Van de Goor and Zijlsha methods [25], and calculating and planning alternative planting patterns. Water balance is a calculation that records the amount of water coming in and going out in an area during a specific period, making it possible to identify whether there is an excess or shortage of water [26]. A positive water balance indicates sufficient supply, while a negative value indicates a deficit affecting plant growth.

2.3 Alternative Planting Patterns

Alternative cropping pattern planning aims to achieve optimal conditions. The cropping pattern will be divided into several alternatives with different planting periods. Each alternative will also be divided into several categories to reduce the maximum water requirements. The existing planting pattern is only carried out 2 times during the planting season. In the first planting period, all land was used to plant rice with 100% intensity. Likewise, in the second planting period, the land was again planted with rice in full without any diversification of plant types. The recapitulation results of alternative planting patterns 1 to 3 are shown in **Table 1**.

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Table 1. Recapitulation of Alternative Planting Patterns 1 - 3

Planting Pattern	Planting Season I	Planting Season II	Planting Season III
Alternative 1	Rice (80%) – Onion red (20%)	Rice (100%)	Rice (79%) – Corn (21%)
Alternative 2	Rice (86%) – Corn (14%)	Rice (100%)	Rice (83%) – Onion red (17%)
Alternative 3	Rice (79%) – Corn (21%)	Rice (82%) – Onion red (18%)	Rice (83%) – Onion red (17%)

Source: Author's Research Results (2025).

Determining three alternative cropping patterns is based on water availability, irrigation efficiency, and optimization of agricultural output. Alternative 1 emphasizes the dominance of rice with a little diversification of shallots and corn. Alternative 2 increases the portion of rice with a combination of corn and shallots for water efficiency. Alternative 3 balances water use with rice-corn and rice-shallot patterns. This selection considers the sustainability of irrigation and land productivity.

2.4 Linear Program Optimization

Linear programming is a mathematical model used to allocate resources. Optimization is done using the Simplex method implemented in QM for Windows software [27]. Formulating an optimization model with linear programming involves three main factors: decision variables, objective function, and constraint function [28]. The decision variable used is the land area for each alternative planting pattern. This study's objective function (Z) is to maximize profits (P) obtained from all cropping patterns and is calculated using **Equation 1**. The constraint function considers land area constraints and water availability constraints. Each cropping pattern (Xi) must be within the limits of the available land area (Xt) described in **Equation 2**. The constraint of water availability (Qij) requires that the water requirement (q) for cropping pattern i in month j does not exceed the available discharge (Qj) described in **Equation 3**.

$$Z = P_1.X_1 + P_2.X_2 + P_3.X_3 \quad (1)$$

$$X_1 + X_2 + X_3 \leq X_t \quad (2)$$

$$(q_{ij} + X_1) + .. + (q_{ij} + X_n) \leq Q_j \quad (3)$$

3. Results and Discussion

3.1 Hydrological Analysis

To support the optimization of water distribution, this study analyzes hydrology by calculating the Thiessen Polygon weighting coefficient factor by dividing the watershed area

https://dx.doi.org/10.30737/ukarst.v9i1.6628

ISSN (*Online*) 2581-0855
ISSN (*Print*) 2579-4620

of the rainfall station by the total watershed area of 6 rainfall stations. **Table 2** shows the results of recapitulating the weighting coefficients of the other five rainfall stations.

Table 2. Weighting Factor Calculations

No	Area of River Basin Area (DAS Km^2)		Weight
1	Kemlaten station	1,487	0,065
2	Ponokawan station	6,121	0,269
3	Bakalan station	4,166	0,183
4	Krian Station	1,730	0,076
5	Ketawang station	4,617	0,202
6	Luwung station	4,630	0,203
Total		22,754	1

Source: Author's Research Results (2025).

The analysis results in **Table 2** show that Ponokawan Station has the largest weight of 0,269, while Kemlaten Station has the smallest weight of 0,065. This difference reflects the variation in rainfall distribution in the study area, which is influenced by climatology, topography, and wind weight patterns. These variations directly impact the availability of irrigation water, especially in the dry season when rainfall is a crucial factor. The Thiessen Polygon method used in this study is considered more accurate in representing rainfall distribution than the arithmetic mean method, especially in areas with high level of spatial variation [29]. However, this study has limitations, including rainfall variability that affects global climate phenomena such as El Niño and La Niña, as well as the potential bias due to uneven spatial distribution of rainfall stations. This is because the Thiessen Polygon method assumes that rainfall is uniformly distributed within each polygon area, which may not accurately capture localized extreme events or microclimate variations.

3.2 Water Availability

Analysis of water availability using the FJ Mock method shows that the mainstay discharge varies between 0,48–0,75 m³/s, with a peak in March (0,75 m³/s) and the lowest in Period III (0,48 m³/s). The increase in discharge during the rainy season is caused by high rainfall, while the stability of discharge during the dry season (0,48–0,53 m³/s) indicates the possibility of flow regulation or alternative water sources. Previous research in the Amprong Sub-DAS showed that the FJ Mock method is more accurate in estimating discharge with an NSE of 0,995 and a correlation coefficient of 0,998 [31]. These results support the use of the same method in areas with similar hydrological characteristics, although its limitations include

https://dx.doi.org/10.30737/ukarst.v9i1.6628

ISSN (*Online*) 2581-0855
ISSN (*Print*) 2579-4620

not considering changes in land use and climate variability that can cause discharge fluctuations. In addition to hydrological factors, water availability is also influenced by local irrigation policies, such as a water distribution system based on a rotation schedule, which can cause inequality in distribution between lands. Farmers' preferences in cropping patterns also affect water demand, especially during the dry season when water demand increases due to the dominance of rice plants.

Mainstay discharge is an important factor in irrigation planning to ensure adequate water availability for agriculture [32]. Analysis of the 80% mainstay discharge volume showed a variation between 266.000–290.000 m³, with a peak in March Period I (290.000 m³) and the lowest point in Period III (266.000 m³). The increase in volume during the rainy season was due to high rainfall, while the stability of the volume during the dry season (270.000 m³) indicated fairly effective irrigation management. Previous research shows that reliable discharge is 80% effective in estimating water supply compared to the annual average value [33]. This approach helps anticipate the risk of water shortages in the dry season, so water resource management strategies can be more efficient and adaptive to hydrological variability. However, this study has limitations in considering local irrigation policies and climate variability that can affect water availability. This is due to the dynamic nature of regional water regulations and the unpredictable patterns of rainfall influenced by climate change, which were not fully incorporated into the analysis.

3.3 Water Needs

The results of the analysis of water requirements for land preparation varied between 1,58–1,90 l/s/ha throughout the year, with a peak in November period III (1,90 l/s/ha) and the lowest in January period I (1,68 l/s/ha). The increase in water requirements from August to November reflects the intensification of land cultivation before the primary planting season, influenced by water loss due to evaporation and irrigation efficiency. To overcome the challenges in meeting the increasing water needs, it is necessary to implement more efficient water management strategies, one of which is using a water balance model. Previous studies have found that the water balance model can save irrigation water by 27–42% compared to conventional methods [34]. However, uneven water distribution in the irrigation network can cause an imbalance in supply between upstream and downstream, so a management system based on sensor technology or water gate automation is needed so that water supply is more effective and in accordance with land needs. **Table 3** shows the results of calculating plant water availability and water requirements that support irrigation planning.

https://dx.doi.org/10.30737/ukarst.v9i1.6628

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Table 1 Recapitulation Calculation Water Availability and Water Needs

Parameter	Jan			Feb			Mar			Apr		
	I	II	III	I	II	III	I	II	III	I	II	III
Average Rainfall (mm)	13	50	51	53	44	56	38	34	41	39	43	50
Evapotraspiration (mm/day)	4,55	4,11	3,70	3,84	3,99	4,71	3,33	4,06	3,52	3,36	3,85	3,25
Mainstream Discharge (m^3/s)	0,53	0,53	0,48	0,55	0,56	0,66	0,75	0,62	0,57	0,62	0,53	0,55
Vol. Water Availability (m^3)	270	270	266	272	273	281	290	278	273	278	270	272
Land Preparation (l/dt/ha)	1,68	1,64	1,61	1,62	1,63	1,69	1,58	1,64	1,60	1,58	1,62	1,58
Water Requirements (l/dt/ha)	1,49	1,19	0,98	0,76	0,20	0,17	0,06	0,91	0,82	1,10	1,30	1,10
Parameter	May			June			Jul			Aug		
	I	II	III	I	II	III	I	II	III	I	II	III
Average Rainfall (mm)	14	2	0	1	0	2	16	0	0	1	13	1
Evapotraspiration (mm/day)	3,58	3,73	4,17	4,00	3,85	3,95	3,89	4,31	4,25	4,78	4,77	4,70
Mainstream Discharge (m^3/s)	0,53	0,53	0,48	0,53	0,53	0,53	0,53	0,53	0,48	0,53	0,53	0,48
Vol. Water Availability (m^3)	270	270	266	270	270	270	270	270	266	270	270	266
Land Preparation (l/dt/ha)	1,60	1,61	1,65	1,63	1,62	1,63	1,62	1,66	1,65	1,70	1,69	1,69
Water Requirements (l/dt/ha)	1,43	1,50	1,36	1,21	0,67	0,52	0,40	0,53	0,54	0,54	0,50	0,54
Parameter	Sep			Oct			Nov			Dec		
	I	II	III	I	II	III	I	II	III	I	II	III
Average Rainfall (mm)	8	34	52	52	31	40	0	4	9	31	26	40
Evapotraspiration (mm/day)	4,80	4,92	4,82	6,35	6,48	6,65	7,12	7,07	7,26	6,43	6,88	6,39
Mainstream Discharge (m^3/s)	0,53	0,53	0,53	0,53	0,53	0,48	0,53	0,53	0,53	0,53	0,53	0,48
Vol. Water Availability (m^3)	270	270	270	270	270	266	270	270	270	270	270	266
Land Preparation (l/dt/ha)	1,70	1,71	1,70	1,83	1,84	1,85	1,89	1,89	1,90	1,83	1,87	1,83
Water Requirements (l/dt/ha)	0,54	0,54	0,49	0,48	0,43	0,26	0,52	1,88	1,82	1,69	1,86	1,68

Source: Author's Research Results (2025).

The crop water requirements show variations throughout the year, with a peak in November period II (1,88 l/sec/ha) and the lowest in March period I (0,06 l/sec/ha). Water requirements increase at the beginning and end of the year along with the primary planting season, while the decrease in the middle of the year is likely influenced by effective rainfall. Research conducted in the Cikunten II Irrigation Area showed a significant difference in the estimation of water requirements compared to the Cropwat method, reaching 277,42% [35]. This difference emphasizes the importance of a calculation method appropriate to local conditions. However, limitations in considering climate variability and irrigation system efficiency can affect the estimate's accuracy. Previous studies have shown that this method is effective in irrigation planning because it comprehensively considers hydrological and agronomic variables [36]. With this approach, water availability can be managed more

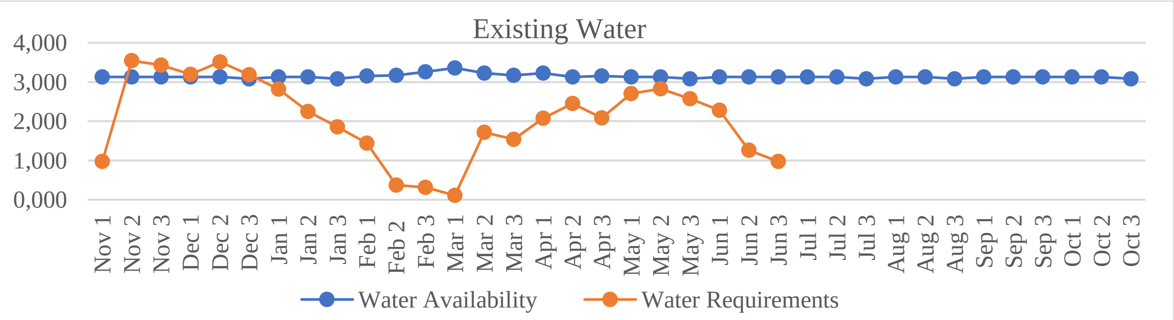
ISSN (*Online*) 2581-0855
ISSN (*Print*) 2579-4620

optimally to ensure sufficient supply during the crop growth period and minimize water loss due to percolation and evaporation.

Whereas evapotranspiration (ET) varies throughout the year, with the lowest value in April (3,25 mm/day) and the highest in November (7,26 mm/day), influenced by rainfall, air temperature, and solar radiation. During the rainy season (January–April), ET is lower due to high rainfall, while in the dry season (May–September), temperature and radiation increase. The peak of ET in October–November indicates the high need for irrigation water, so efficient water management is needed. Previous studies have found that the Modified Penman method is more accurate than Thornthwaite in modeling discharge in tropical climates [30]. However, this study has not considered changes in land cover and microclimate variations that can affect water balance.

3.4 Water Balance

Water balance calculations are carried out to optimize the irrigation system by comparing three alternative and existing planting patterns. Comparison of water balance in **Figures 2, 3, 4, and 5** shows that the existing cropping pattern has quite large fluctuations in water availability, with several months experiencing deficits. Alternative 1 is slightly better because water needs are more evenly distributed and tend to be lower. Alternative 2 is more optimal in adjusting needs to water availability, so its fluctuations are more stable. Meanwhile, Alternative 3 was chosen as the best cropping pattern because it shows an optimal balance between water needs and availability, with minimal water deficit, thus increasing irrigation water use efficiency. Theoretically, a combination of crops with different water needs, such as rice requiring a lot of water and shallots more tolerant of dry conditions, can increase irrigation efficiency. These results align with previous studies, which show that diversification of rice crops to corn can increase agricultural productivity and farmer income [37]. **Figures 2, 3, 4, and 5** show the results of the water balance comparison for the existing cropping pattern and three alternative planting patterns.

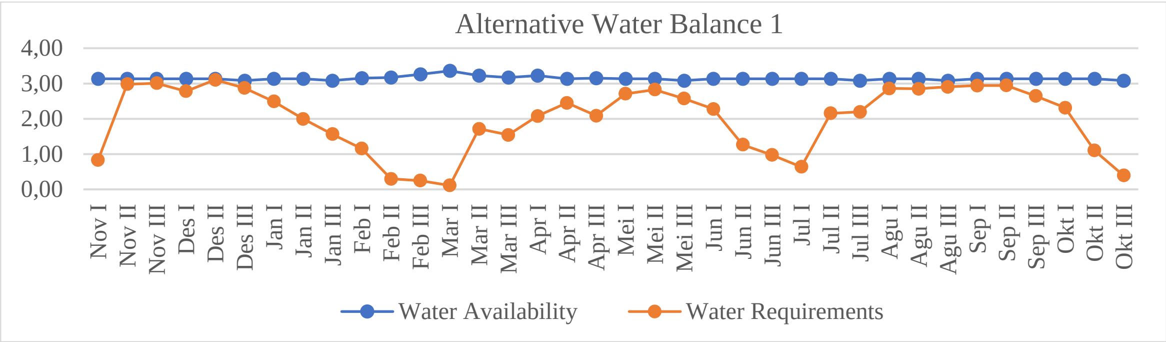


Source: Author's Research Results (2025).

Figure 2. Water Balance of Existing Cropping Patterns

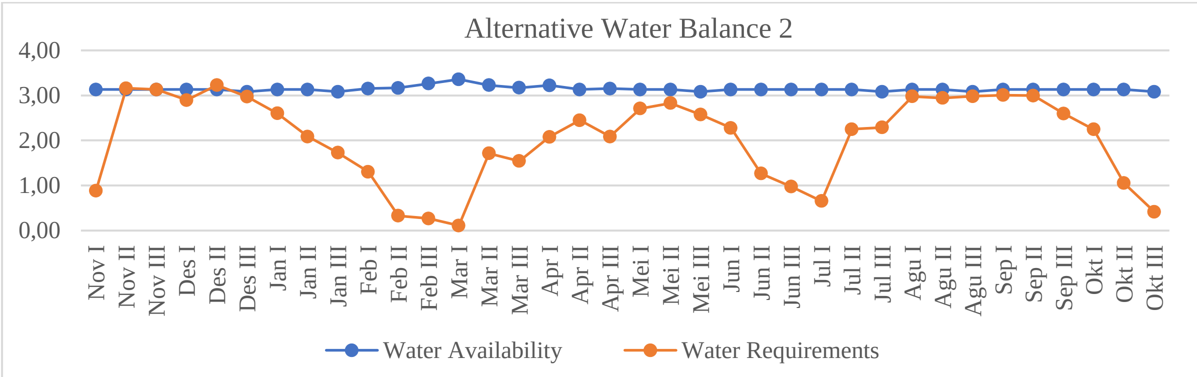
https://dx.doi.org/10.30737/ukarst.v9i1.6628

ISSN (*Online*) 2581-0855
ISSN (*Print*) 2579-4620



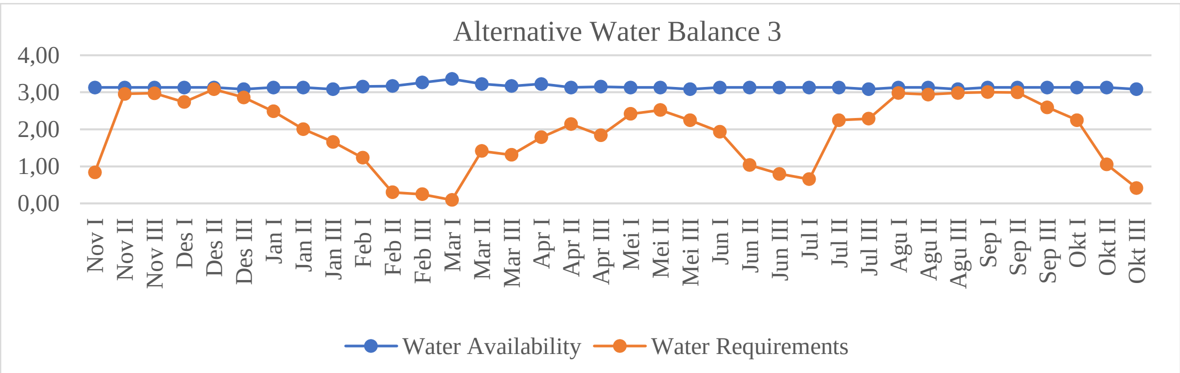
Source: Author's Research Results (2025)

Figure 3. Water Balance of Alternative Cropping Pattern 1



Source: Author's Research Results (2025)

Figure 4. Water Balance of Alternative Cropping Pattern 2



Source: Author's Research Results (2025).

Figure 5. Water Balance of Alternative Cropping Pattern 3

3.5 Linear Program Optimization

Optimization of irrigation water management in the Dungus intake area was done using linear programming using QM for Windows 5, based on farmer income data from the Farming Business Analysis report of the Sidoarjo Regency Agriculture, Plantation, and Livestock Service. **Table 4** shows the optimization results for existing cropping patterns and alternative cropping patterns 1 to 3.

https://dx.doi.org/10.30737/ukarst.v9i1.6628

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Table 2. Summary of Optimization Results

Planting Pattern	Optimization Results
Existing	Rp 158.647.500.000
Alternative 1	Rp 237.680.600.000
Alternative 2	Rp 238.865.100.000
Alternative 3	Rp 242.087.200.000

Source: Author's Research Results (2025).

The optimization results show that alternative cropping patterns provide higher profits than existing cropping patterns. The income of the existing pattern was recorded at Rp 158,64 billion, while the three alternative cropping patterns generated higher income, with the highest value in alternative 3 of Rp 242,08 billion. Alternative 3 provides the highest income due to the optimal combination of plants and the efficiency of irrigation water use, making it a better strategy in water resource management.

However, negative impacts such as increased water demand and the risk of soil degradation need to be considered. Rainy and dry season factors also affect water availability and planting schedules, so further analysis is required. Previous research shows that crop diversification increases water use efficiency and farmer profits [38]. This aligns with the theory that the right combination of crops can maximize resource utilization and income.

4. Conclusion

This study shows that the mainstay discharge at the Dungus intake (Delta Brantas Inlet) ranges from 0,479 m^3/s to 0,754 m^3/s, with an allocated discharge of 2,604 m^3/s based on crop water needs, irrigation efficiency, and water availability in the dry season. Alternative cropping pattern 3 proved the most optimal, with a total land area of 1,890 ha, consisting of a combination of rice, corn, and shallots in three planting seasons. The advantage of this pattern lies in the balance between agricultural productivity and water availability, which ensures sufficient water supply throughout the season and generates a maximum profit of Rp 242.087.200.000 per year. These results confirm that the linear programming-based optimization approach improves water use efficiency and can integrate hydrological and economic factors simultaneously. This model provides new insights into irrigation planning by considering the dynamics of water availability and crop diversification to minimize the risk of water deficits. The results of this study can be a reference for irrigation managers in designing water distribution strategies that are more efficient and adaptive to changes in hydrological

ISSN (*Online*) 2581-0855
ISSN (*Print*) 2579-4620

conditions, while also helping farmers choose the most profitable and sustainable planting patterns.

5. Acknowledgement

The author sincerely thanks the Department of Civil Engineering, Faculty of Engineering, Universitas Negeri Surabaya, for their invaluable guidance and facilities throughout this research. The author would also like to thank the developers of QM for Windows 5 software, which supported the linear programming modeling and optimization process in this irrigation system study.

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