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Development of a Mathematical Model for the Optimization of Natural Resources in Villages

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ABSTRACT

This study integrates Linear Programming (LP) and Geographic Information System (GIS) to optimize land and water resource utilization in Indonesian rural areas. The proposed multi-period LP model aims to maximize farmers' net profit under land, water, and labor constraints, where decision variables represent the land area (in tumbak) allocated to each crop per period. Conducted in three agricultural villages of Garut Regency with 60 farmer respondents selected through stratified sampling, the model was solved using Excel Solver and spatially visualized through GIS. Results show an optimal cultivated area of 453.202 tumbak, utilizing 16,412.49 m³ of water and 5,319.098 man-days of labor, producing Rp 2,078,047,500 in gross revenue and Rp 26,493,556 in net profit. Land-use efficiency improved by 64.8% from baseline conditions, with land as the main binding constraint. The model offers a practical decision-support tool for policymakers to plan crop rotation, irrigation scheduling, and sustainable land-use strategies.

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1. INTRODUCTION

Management of natural resources (NR) has long been a strategic global issue and a central topic in sustainable development. Since the publication of Our Common Future by the World Commission on Environment and Development (WCED, 1987), the concept of sustainability has emphasized using resources to meet present needs without compromising the ability of future generations to meet theirs [1][2]. However, the 2022 United Nations report indicates that nearly one-quarter of global ecosystems have been degraded due to unsustainable practices [3][4].

Indonesia, as an agrarian-based economy, faces similar but more complex challenges. More than 40% of the national workforce depends on natural resource–based sectors such as agriculture, fisheries, and forestry (BPS, 2022). Villages are therefore crucial socio-economic units where communities directly interact with land and water systems [5]. Yet, rural areas still struggle with basic irrigation systems, limited adoption of technology, and market-driven planting decisions, leading to inefficiencies in land productivity and water distribution [6].

These issues are evident in several agricultural villages in Garut Regency, West Java—particularly Sukamukti, Margahayu, and Margacinta. Although these areas possess fertile paddy fields, their agricultural activities remain constrained by manual irrigation, unequal water distribution, and fluctuating commodity prices that dictate cropping patterns more than productivity or sustainability [7]. Consequently, resource conflicts and underutilized land persist, illustrating the real challenges faced by Indonesian agrarian villages.

Previous studies have examined rural NR management from social, economic, or environmental perspectives. For example, explored water governance institutions [8], analyzed price volatility [9], and discussed the impact of fertilizers on land sustainability [10]. However, most of these studies remain descriptive and sectoral, focusing on isolated issues rather than integrated systems involving land, water, labor, and prices. In such complex systems, mathematical modeling—particularly Linear Programming (LP)—offers a structured way to identify optimal resource allocations [11][12].

LP is effective for simplifying multi-variable agricultural systems and maximizing specific objectives such as profit or food security. Yet, its outputs are typically presented as numerical tables that are difficult for policymakers and local stakeholders to interpret. Recent studies combining LP and Geographic Information Systems (GIS) have tried to overcome this limitation by visualizing optimization outcomes spatially [13][14][15]. However, most LP–GIS integrations remain focused on macro-scale or regional analyses, often overlooking the micro-scale realities of individual villages. This creates a crucial gap in the literature: there is still limited understanding of how LP–GIS models can be applied effectively for village-level planning, where decisions are made directly by smallholder farmers and local governments.

In addition to addressing this limitation, the present study extends the conventional LP–GIS framework by incorporating sensitivity analysis. Sensitivity analysis is crucial for testing the robustness of optimal solutions against changes in key variables such as selling prices, water availability, and labor [16]. In practice, such fluctuations are common in agrarian villages [17]. Without sensitivity analysis, model outputs risk becoming fragile under minor changes. By applying this method, the study provides a more realistic and resilient picture of NR management strategies.

Addressing this gap, the present study develops an integrated multi-period LP–GIS model specifically designed for micro-scale optimization at the village level. The model aims to optimize land and water resource allocation while incorporating the rotation of two key crops—rice and tobacco—across four planting periods. To ensure robustness, the model also applies sensitivity analysis to evaluate the stability of optimal solutions under varying conditions such as price and labor availability.

The novelty of this research lies in its methodological and contextual contributions. Methodologically, it integrates LP, GIS, and sensitivity analysis in a single framework. Contextually, it applies these tools at the village-scale, bridging the methodological precision of quantitative modeling with the spatial realities of rural Indonesia. This approach not only enhances the theoretical literature on data-driven resource optimization but also provides practical tools for village governments to design more efficient and sustainable agricultural policies.

Based on this rationale, the objective of this research is to develop a mathematical optimization model for sustainable natural resource (NR) management in agrarian villages, integrating multiperiod Linear Programming (LP) with GIS-based spatial data to generate optimization maps of land and water use. Previous studies have partially addressed LP–GIS integration, yet each presents certain methodological or contextual limitations, as summarized in Table 1 below.

Table 1. Comparison of Recent LP–GIS Models and Identified Gaps

Author(s)	Method/Approach	Context	Key Contributions	Limitations / Research Gap
Aggarwal et al. (2022)	Integrated stochastic optimization with GIS-based crop rotation planning	Global (Asia)	Promoted sustainable crop rotation using geoinformatics	Limited focus on multiperiod optimization and village-scale application
Hasti et al. (2023)	LP combined with game theory and GIS visualization	Land allocation in Iran	Linked optimization with stakeholder negotiation and spatial mapping	No integration of temporal (multiperiod) resource dynamics
Li et al. (2024)	Simulation–optimization coupling GIS and crop growth models	Climate adaptation and land use change (China)	Combined spatial simulation with optimization for carbon and yield benefits	Focused on macro-scale; lacks policy-level integration for rural planning

This Study	Multiperiod LP integrated with GIS and sensitivity analysis	Agrarian villages in Indonesia	Produces spatiotemporal optimization maps of land and water use; supports local policymaking	Addresses prior gaps in spatial-temporal modeling and rural applicability

Building upon these findings, this study seeks to overcome the identified limitations by applying an integrated multiperiod LP–GIS model within the context of Indonesian rural agriculture. The research also aims to deliver quantitative and spatial recommendations for village governments and farmer groups to design strategies that enhance food security, improve economic efficiency, and ensure long-term ecological sustainability.

Accordingly, this study seeks to answer: How can LP–GIS integration optimize land and water use in Indonesian agrarian villages while improving both economic efficiency and sustainability?

2. RESEARCH METHOD

The research method is designed to describe the steps undertaken in developing the model, including research design, data collection, and analytical procedures.

2.1 Research Design

This study employed a quantitative approach with an experimental simulation design based on mathematical modeling. The primary method used was multiperiod Linear Programming (LP) combined with Geographic Information Systems (GIS). This approach was chosen because it is capable of formulating optimal strategies for managing diverse and complex village resources, while also allowing numerical outputs to be visualized spatially, making them more communicative for policymakers.

2.2 Research Location

The study was conducted in three agrarian villages in Leuwigoong and Banyuresmi subdistricts, Garut Regency, namely Margahayu, Margacinta, and Sukamukti Villages, which share similar characteristics. These three villages were purposively selected based on several considerations. First, almost all agricultural land in the villages relies on the same water source, namely a small river with a manual distribution system. Second, the irrigation system is still based on a manual open–close method rather than a technical irrigation network. Third, the land characteristics and dominant crop types are relatively uniform, with rice as the staple crop and tobacco as a high-value commodity. Selecting locations with comparable characteristics was expected to strengthen the external validity of the study, as the optimization results would be more representative of agrarian villages with similar conditions in other regions.

2.3 Sampling Technique

From the three villages, a total of 60 farmer respondents were selected from the three villages, with 20 farmers representing each location. The sample size was determined based on both practical and statistical considerations. From a representativeness standpoint, each village exhibits relatively homogeneous characteristics in irrigation access, soil type, and cropping systems, making 20 respondents per village sufficient to capture variations in land ownership and farming practices. Statistically, a power analysis was conducted using a conventional significance level of $\alpha = 0.05$ and a desired power of 0.80. For detecting a medium effect size (Cohen's $d = 0.5$) in paired comparisons—such as changes between planting periods—the required minimum sample size would be approximately 34 respondents. Since this study involves repeated observations across four planting periods, the statistical power increases further, indicating that 60 respondents exceed the minimum threshold needed to obtain valid and reliable results. In addition, stratified sampling based on landholding size (small, medium, and large) ensured balanced representation while maintaining research efficiency. Therefore, although smaller than macro-scale surveys, this sample size is adequate to detect meaningful variations and draw statistically sound conclusions for the village-level context [18].

2.4 Types and Sources of Data

This study employed a combination of primary and secondary data. Primary data were collected through structured questionnaire interviews with sampled farmers. The questionnaire was designed to obtain information on cropping patterns across four periods (T1–T4), land productivity by commodity, water and labor requirements, production costs, and commodity selling prices for each period. Meanwhile, secondary data were obtained from the Central Bureau of Statistics (BPS), the Garut Regency Agriculture Office, and village administrative documents. These included data on village land area, labor force, and agricultural production records. The combination of primary and secondary data ensured that the model was both empirically grounded and aligned with the factual conditions in the field.

2.5 Research Variables, Objective Function, and Constraints

The model in this study was developed using parameters and decision variables related to land, water, and labor resources. The parameters include the average land size of farmers (L_i), measured in tumbak, where 1 tumbak is approximately equal to 14 square meters, selling price per kilogram ($p_{k,t}$), productivity ($y_{k,t}$), production cost per tumbak ($c_{k,t}$), water requirement per tumbak ($W_{k,t}$), labor requirement per tumbak ($l_{k,t}$), total available labor per period (Lb_t), and total available water per period (W_t). The model is constructed as an aggregate representation of three villages, thereby reflecting multiperiod conditions under shared resource constraints.

The objective function is mathematically expressed as:

$$Max\ Z = \sum_{t}^{4}\sum_{k} x_{i,t,k}.(p_{k,t}.y_{k,t} - c_{k,t}) \tag{1}$$

where:
Z = total net profit of farmers (Rp),
$x_{i,k,t}$ = land area (tumbak) allocated to crop k by farmer i in period t,
$p_{k,t}$ = selling price per kilogram of crop k in period t (Rp/kg),
$y_{k,t}$ = productivity of crop k in period t (kg/tumbak),
$c_{k,t}$ = production cost per tumbak of crop k in period t (Rp/tumbak),
k = planting period (T1–T4),
t = type of crop (rice or tobacco).

The model is subject to several real constraints reflecting the conditions of agrarian villages:
Land capacity constraint, ensuring that total cultivated land does not exceed the available land

$$\left(\sum_{k}\sum_{t} x_{i,t,k} \leq \sum_{i} L_i\right) \tag{2}$$

Crop rotation constraint, maintaining a rice–tobacco alternation pattern

$$(x_{T1,P} = x_{T2,T} = x_{T3,P} = x_{T4,T}) \tag{3}$$

Water availability constraint, ensuring that total water used does not exceed the available amount in each period

$$\left(\sum_{k} x_{i,t,k} \cdot w_{k,t} \leq W_t\right) \tag{4}$$

Labor availability constraint, ensuring that total labor requirements do not exceed available labor per period.

$$\left(\sum_{k} x_{i,t,k} \cdot l_{k,t} \leq Lb_t\right) \tag{5}$$

Non-negativity condition. ($x_{i,t,k} \geq 0$). (6)

These constraints collectively ensure that the optimal solution remains realistic, adhering to the actual physical, temporal, and socio-economic limitations faced by rural farmers [19][20][21].

2.6 Sensitivity Analysis

Sensitivity analysis is employed to evaluate the robustness of the optimal solution generated by the model. In this study, three main indicators are analyzed. First, the reduced cost is used to assess the contribution of each decision variable to the optimal solution. Second, the shadow price serves to measure the marginal value of each resource utilized in the model. Third, the allowable increase/decrease is applied to determine the range of parameter changes that still allow the optimal solution to remain valid.

2.7 Integration with GIS

The multi-period LP optimization results were integrated with a Geographic Information System (GIS) using QGIS 3.40 to transform numerical outcomes into spatial representations. Spatial boundary data were prepared using village administrative shapefiles (.shp) from the Garut Regency Spatial Planning Office, while the LP outputs—such as optimal land allocation ($x_{i,t,k}$), water use, labor, and income—were exported in CSV format. These datasets were linked through a unique village identification code using the Join Attributes by Field Value function in QGIS.

Thematic maps were generated by applying categorized symbology to differentiate crop types (rice and tobacco) and graduated symbology to visualize water, labor, and income intensity. This process enabled direct spatial interpretation of the optimization results. Visualization was presented mainly through an aggregate map summarizing land and water use across all periods, providing a concise and communicative tool for policymakers. Although period-specific maps (T1–T4) were also produced for validation, they revealed minimal variation and thus were excluded from the main presentation for clarity and efficiency [22]. Through this integration, GIS effectively converts LP results into spatial decision-support tools for land use, irrigation, and labor management at the village level.

2.8 Model Validation

Model validation is carried out through two complementary approaches. First, empirical validation is conducted by comparing the model's optimization results with the historical production data of the village, thereby testing the extent to which the model can quantitatively represent real-world conditions. Second, participatory validation is undertaken through in-depth discussions with farmer groups and village officials to confirm the consistency of the model's results with the practical experiences of local stakeholders.

The combination of these two approaches not only ensures that the model is mathematically valid but also guarantees its practical relevance to the actual conditions of agrarian villages. Thus, the research findings are not only strong from a methodological standpoint but also possess important social legitimacy to support their application in village-level decision-making.

2.9 Research Flow

The research flow consists of five main stages presented as follows:

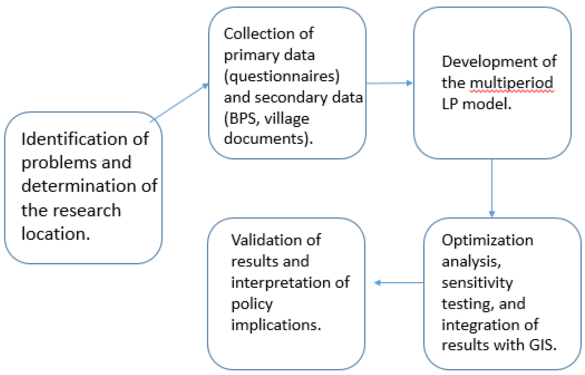

Figure 1. Research Flow

In Figure 1, the research flow begins with the identification of problems and the determination of the research location, followed by the collection of primary data through questionnaires and secondary data from BPS and village documents. The collected data are then used to develop a multiperiod Linear Programming (LP) model. The LP model was formulated and solved using Microsoft Excel Solver, which was utilized to perform the optimization and sensitivity analysis. This software was selected due to its computational accuracy, accessibility, and suitability for small- to medium-scale optimization problems in applied agricultural studies. This model is analyzed through optimization, sensitivity testing, and integrated with Geographic Information Systems (GIS) to spatially map the results. The final stage involves validating the results—both empirically and participatorily—as well as interpreting policy implications to ensure that the model is mathematically valid while also relevant to real-world conditions in the field.

3. RESULT AND ANALYSIS

3.1 Results of Multiperiod LP Analysis

Table 3. Multiperiod Linear Programming Analysis

Period	Total Decision (Tumbak)	Total Water (m^3)	Total Labor (HOK)	Gross Revenue (Rp)	Total Cost (Rp)	Net Profit (Rp)
T1	127.772	3,849.21	509.176	288,095,000	103,984,000	4,289,620
T2	146.072	4,774.90	3,135.770	902,350,000	420,170,000	14,547,000
T3	89.256	3,746.03	172.352	292,862,500	101,186,800	3,293,056
T4	90.102	4,042.35	1,502.800	594,740,000	431,224,000	4,363,880
Total	453.202	16,412.49	5,319.098	2,078,047,500	1,056,564,800	26,493,556

Table 3 presents the optimization results of the rice–tobacco crop rotation over four periods, covering decision areas, water and labor use, gross revenue, total costs, and net profit. This descriptive analysis provides insights into resource efficiency, profitability, and the strategic implications of the applied rotation pattern.

The optimization results also revealed a significant improvement in land-use efficiency compared to the baseline condition. The efficiency was calculated by comparing the total optimized cultivated area to the total available land in the study area. Based on the model results, the optimized cultivated land reached 35,840.44 tumbak, while the total available land was 21,744 tumbak, producing an efficiency ratio of 164.8%. This indicates an increase of approximately 64.8% compared to the baseline (100%). The result demonstrates that the optimization model successfully reallocated underutilized land parcels into more productive crop combinations, enabling farmers to achieve higher output and profitability using the same land resources

The implemented crop rotation follows the rice–tobacco–rice–tobacco pattern across four consecutive periods, providing a balanced approach between food security objectives and economic profitability. Rice, cultivated in periods T1 and T3, serves as a strategic commodity to fulfill local food needs, while tobacco, cultivated in T2 and T4, acts as a high-value crop that significantly enhances farmers' income. Cross-period comparison reveals substantial variations in economic performance. Period T2 emerges as the most profitable, with decision-based profit reaching Rp 14,547,000—far exceeding other periods. This outcome is primarily attributed to the combination of optimal land area (146.072 tumbak), high labor intensity (3,135.770 workdays), and efficient water use (4,774.90 m^3). Conversely, period T3 records the lowest profit (Rp 3,293,056), corresponding to smaller land allocation (89.256 tumbak) and relatively low labor input (172.352 workdays). These findings suggest that financial success within the rotation system is strongly influenced by both the crop type and the level of resource management intensity.

The rice–tobacco sequence also highlights a fundamental trade-off between food and economic objectives. While rice contributes to food security, it offers relatively lower profit margins compared to tobacco. In contrast, tobacco provides higher economic returns but demands greater labor and water input. This trade-off underlines the necessity of a balanced management strategy that simultaneously safeguards food availability and maximizes economic gain. Hence, land allocation decisions should consider both profitability and food security priorities. Furthermore, the rice–tobacco rotation carries significant implications for production diversification and the mitigation of monoculture risks. By alternating crops across periods, the system not only optimizes land and water resource utilization but also reduces pest and disease incidence that commonly increases under continuous monocropping [23] This strategy ultimately supports sustainable agriculture by ensuring a synergistic combination of economic benefits, environmental protection, and income stability for farmers [24].

3.2 Sensitivity Analysis

Table 4. Sensitivity Analysis

Variable (Period)	Final Value	Obj. Coefficient	Reduced Cost	Allowable Increase	Allowable Decrease	Status
Rice – T1	127.772	19,312.5	0	∞	19,312.5	Active
Tobacco – T2	146.072	109,125	0	∞	109,125	Active
Rice – T3	89.256	3,125	0	∞	3,125	Active
Tobacco – T4	90.102	134,25	0	∞	134,25	Active
Alternative variables (others)	0	Negative Value	<0	very small value	∞	Not selected

In Table 4, sensitivity analysis results show clear fluctuations in profitability across the four planting periods. During T1 (rice), the objective coefficient reached Rp 19,312.5 per tumbak, indicating modest returns due to moderate productivity and high-water use. Profit then increased sharply in T2 (tobacco) to Rp 109,125 per tumbak, reflecting higher selling prices and more efficient land utilization.

However, profitability declined significantly in T3 (rice) to Rp 3,125 per tumbak, suggesting reduced yields following soil nutrient depletion in the rotation cycle. It then rebounded strongly in T4 (tobacco) to Rp 134,250 per tumbak, marking the highest level of economic efficiency throughout the planning horizon. Overall, the alternating pattern—moderate (T1), high (T2), low (T3), and very high (T4)—demonstrates that rice–tobacco rotation optimizes both land productivity and farmer income over multiple periods.

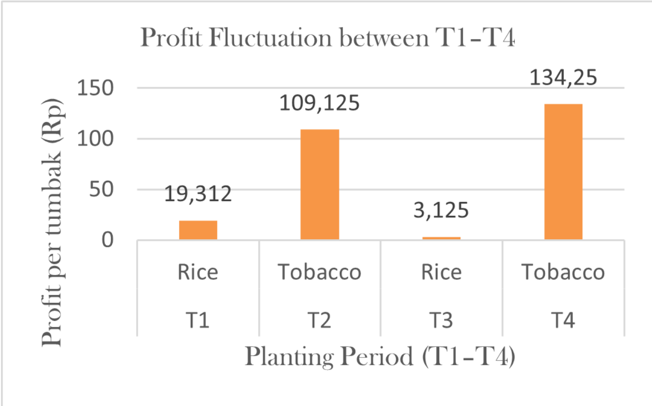

Figure 2. Profit Fluctuation between T1–T4

The bar chart in Figure X clearly visualizes how net profit fluctuates across the four planting periods, showing a sharp contrast between rice and tobacco cycles. The pattern demonstrates that tobacco seasons (T2 and T4) provide substantially higher returns compared to rice seasons (T1 and T3), confirming the economic advantage of alternating crop rotations. Furthermore, the optimized allocation achieved a 64.8% improvement in land-use efficiency compared to the baseline condition, indicating that the model not only enhances profitability but also maximizes the productive utilization of available land. This fluctuation analysis provides a foundation for understanding how each crop contributes to the objective function, which will be further examined in the following section on Reduced Cost Analysis

The analysis of each variable's contribution in the optimization model highlights the importance of different commodities in the rice–tobacco rotation scheme. In the first period, rice (T1) covering 127.772 tumbak contributed a profit of Rp19,312.5 per tumbak, indicating that each additional unit of rice land in this period would significantly increase income. In the second period, tobacco (T2) with 146.072 tumbak provided a much higher contribution, amounting to Rp109,125 per tumbak, reinforcing tobacco's role as the primary driver of farmers' income. The third period again involved rice (T3) with 89.256 tumbak, which, although its contribution was relatively small at Rp3,125 per tumbak, remained necessary to maintain the continuity of the rotation system. In the fourth period, tobacco (T4) with 90.102 tumbak provided the highest contribution among all variables, reaching Rp134,250 per tumbak, making it the most profitable commodity in the entire rotation scheme. Meanwhile, all alternative variables showed negative reduced costs, indicating that forcing them into the optimal solution would reduce total profit. This reinforces that the rice–tobacco combination across four periods is the most optimal strategy given the resource constraints.

Allowable Increase & Decrease Analysis

The sensitivity analysis reveals that the Allowable Increase values for all active variables are extremely large, namely ∞, suggesting that increases in selling prices or productivity would not alter the structure of the optimal solution. In other words, even if tobacco prices were to double, the rice–tobacco rotation pattern would remain unchanged, underscoring the robustness of the solution against profit increases. Conversely, the Allowable Decrease values for each variable are limited: Rp19,312.5 for Rice T1, Rp109,125 for Tobacco T2, Rp3,125 for Rice T3, and Rp134,250 for Tobacco T4. This means that if selling prices or productivity fall below these thresholds, the associated variables risk being excluded from the optimal solution. Thus, stabilizing prices and controlling input costs become crucial. For instance, if fertilizer costs rise significantly, reducing the profit margin of Tobacco T2 below Rp109,125 per tumbak, then this commodity would no longer be selected as an active variable. Similarly, a decline in rice prices below Rp3,125 per tumbak would eliminate the role of Rice T3 in the rotation scheme, highlighting the importance of price and input management to sustain the optimal planting strategy.

Shadow Price Analysis

The shadow price analysis provides additional critical insights into the binding constraints of the agricultural system [25]. Land constraints show a positive shadow price, for example Rp250,000, meaning that each additional tumbak of land would increase net profit by Rp250,000. This confirms that land is the primary binding constraint in determining cropping patterns in the village. In contrast, water and labor constraints show shadow prices of zero, indicating that they are non-binding constraints. In other words, increasing water supply or labor availability would not enhance profits, as both resources are already sufficiently available under the optimal solution. This analysis underscores that land management is the key to improving efficiency and profitability in agriculture, while water and labor are not currently limiting factors.

Implications

Land is the most critical asset in the village agricultural system, as any expansion or consolidation of land directly impacts profit growth [26]. Therefore, efforts such as land redistribution programs, cultivation of idle land, or intensification of existing land productivity should be prioritized in agricultural policy formulation. Meanwhile, although water and labor are operationally important, they are relatively less urgent as primary levers of profit under the current conditions. Accordingly, policy interventions should focus on improving land quality and diversifying commodities, rather than merely increasing labor supply or water availability. Such an approach will ensure profit optimization while maintaining the sustainability of the village agricultural system.

Table 5. Main Constraint Analysis

Constraint	Final RHS	Shadow Price	Allowable Increase	Allowable Decrease	Status
Water – T1	3,849	0	∞	58.81	Non-binding
Labor – T1	509.18	0	∞	49.84	Non-binding
Water – T2	4,775	0	∞	702.83	Non-binding
Labor – T2	3,136	0	∞	600	Non-binding
Water – T3	3,746	0	∞	58.81	Non-binding
Labor – T3	172.35	0	∞	65.56	Non-binding
Water – T4	4,042	0	∞	702.83	Non-binding
Labor – T4	1,503	0	∞	600	Non-binding
Total Land	Within capacity	>0 (positive)	Limited	Limited	Binding

From table 5 the perspective of constraints, the sensitivity analysis results indicate that almost all labor and water constraints in each period are non-binding, as reflected by a Shadow Price value of zero. This suggests that the availability of labor and water remains relatively flexible and does not serve as a primary limiting factor within the system. In contrast, the total land constraint emerges as the only truly binding constraint, with a positive Shadow Price. This condition implies that every additional hectare of land would directly increase total profit in accordance with the value of the shadow price. This finding is highly relevant for policy, as it highlights land scarcity as a key factor in village resource management.

Overall, the sensitivity analysis confirms that the developed model not only produces an optimal solution but also provides insights into the stability of decisions and the critical factors influencing them. For village governments and farmer groups, this information can serve as a foundation for designing sustainable resource utilization strategies. In particular, policy efforts should focus on improving land-use efficiency, while labor and water aspects can still be tolerated without reducing the optimality of the results.

3.3 GIS Integration

The results of the multi-period Linear Programming (LP) optimization provide a quantitative overview of land allocation, water requirements, labor, income, costs, and profit decisions. However, numerical data presented in tables is often difficult to intuitively interpret for non-technical readers or policymakers at the village level. Therefore, this study integrates LP results with Geographic Information Systems (GIS) to produce thematic maps. This visualization serves a dual role: first, as a spatial validation tool for the mathematical optimization results, and second, as a practical instrument to support area-based planning and decision-making.

Compared to tabular data, GIS-based maps offer greater clarity and accessibility for policymakers by visually translating numerical outputs into spatial patterns. Thematic maps enable stakeholders to easily identify which areas have the highest profitability, the most intensive water use, or labor concentration—information that would be less evident in tables alone. Consequently, GIS visualization enhances the communicative value of the optimization results, allowing village governments to make more informed, location-specific policy decisions.

In this study, the GIS integration results are presented primarily in the form of an aggregate map, which summarizes the overall spatial distribution of land and water use across all periods. However, for the sake of completeness and transparency, additional period-specific maps (T1–T4) are also provided in the Appendix. These supplementary maps depict temporal variations in land allocation and resource intensity, offering deeper insights into inter-period dynamics even though their spatial differences are relatively minor. The combination of both aggregate and period-specific maps ensures a more comprehensive visualization of resource optimization outcomes for policymakers and researchers alike.

Figure 3. Village Administrative Map

Figure 3 the village administrative map is used as the foundational framework for mapping the optimization results. The village boundaries ensure that every allocation of land, water use, labor, and income distribution remain contextual to the local spatial arrangement. Based on this framework, the model results do not remain as abstract figures but are instead grounded in real geographic spaces that can be recognized by policymakers and the community

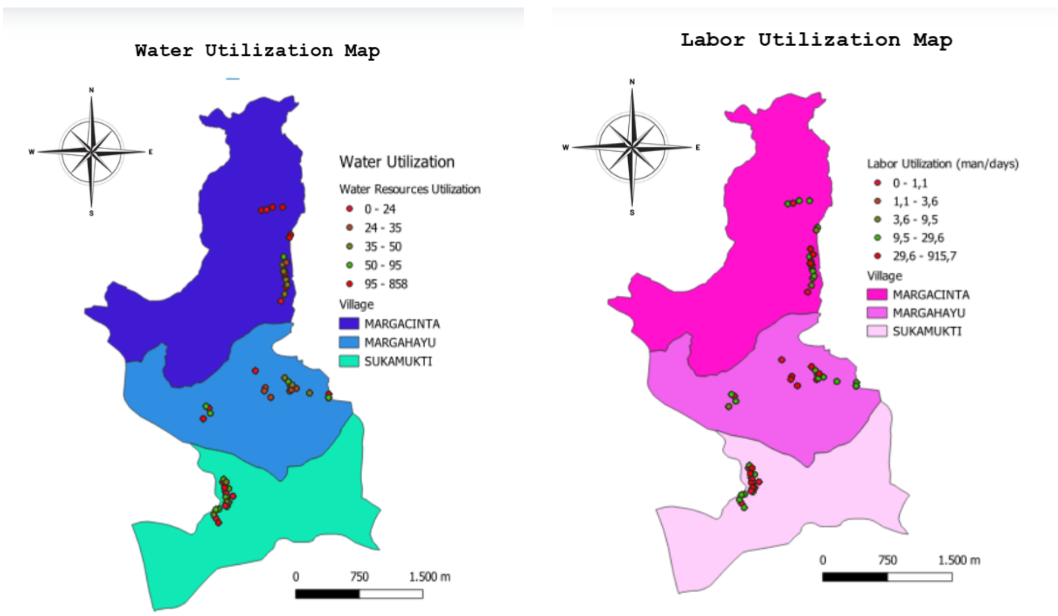

Figure 4. Water and Labor Resources Utilization Map

In Figure 4 the pattern of water and labor requirements closely aligns with land allocation and the rice–tobacco rotation. Rice requires less water, namely 3,849.21 m³ in T1 and 3,746.03 m³ in T3, while tobacco demands higher volumes, 4,774.90 m³ in T2 and 4,042.35 m³ in T4, resulting in a total water requirement of 16,412.49 m³. Although sensitivity analysis indicates that water is not a binding constraint, the water utilization map remains important for irrigation infrastructure planning and conservation efforts.

Labor requirements exhibit sharper contrasts: rice is relatively labor-efficient (509.176 man-days in T1 and 172.352 man-days in T3), while tobacco is highly labor-intensive (3,135.770 man-days in T2 and 1,502.800 man-days in T4), with a total of 5,319.098 man-days. The spatial distribution highlights labor concentration during tobacco cultivation, signaling the need for social planning to anticipate surges in labor demand while simultaneously leveraging local demographic potential.

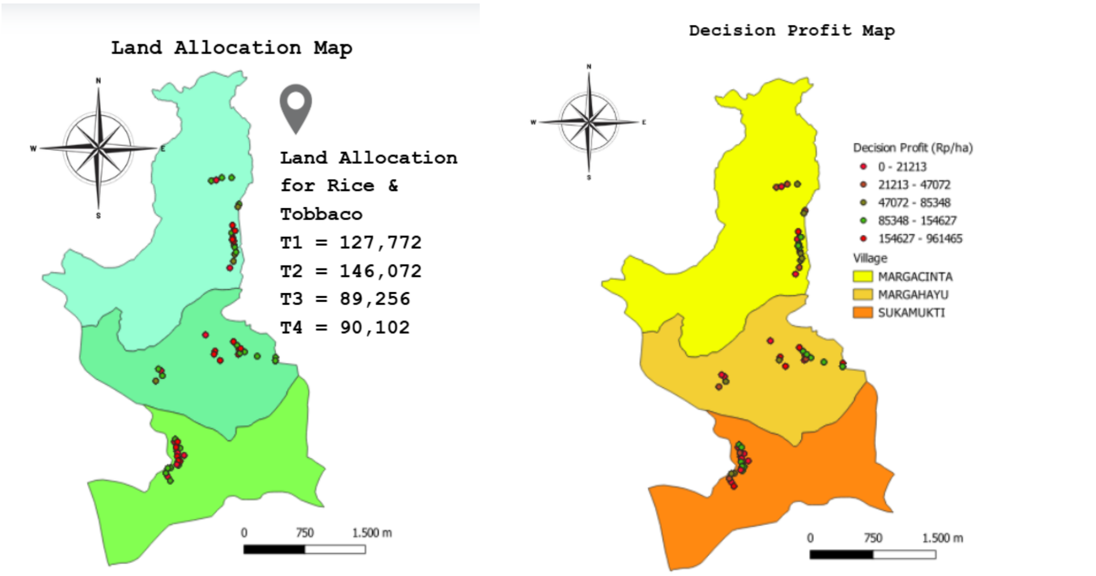

Figure 5. Land Allocation & Decision Profit Map

Map in figure 5. Multiperiod LP results illustrate a consistent and structured rice–tobacco rotation pattern. In T1, rice occupies 127.772 tumbak, which is then replaced by tobacco covering 146.072 tumbak in T2. In T3, rice is cultivated again with 89.256 tumbak, and in T4 tobacco takes over with 90.102 tumbak, bringing the total utilized land to 453.202 tumbak. The visualization of land distribution through the map confirms that this rotation is not only mathematically optimal but also establishes an orderly spatial pattern, supporting agricultural sustainability through commodity diversification and reducing the risk of degradation caused by monoculture.

This optimal land allocation is reflected in the economic outcomes of the cropping pattern. The LP results indicate that tobacco makes the most dominant economic contribution, with gross revenues of IDR 902.35 million in T2 and IDR 594.74 million in T4. In contrast, rice contributes IDR 288.09 million in T1 and IDR 292.86 million in T3. In total, the four planting periods generated IDR 2.078 billion in gross revenue, with a net profit of IDR 26.49 million after deducting production costs. The spatial distribution of income highlights the differences between rice and tobacco areas, confirming that while rice is essential for food security, the greatest economic value is derived from tobacco. This visualization also provides a foundation for village governments to design policies on profit distribution and income diversification strategies to ensure that economic benefits are more evenly shared across the region.

3.4 Relevance of LP and GIS Integration

The integration of multiperiod LP results with GIS provides two essential contributions. First, it reinforces model validity through complementary validation approaches. Numerical validation ensures that the optimization produces consistent and optimal quantitative outcomes for land, labor, and water use, while GIS validation verifies that these solutions are spatially coherent and practically feasible within the actual village landscape. Overlay analysis confirmed that the optimized allocations corresponded accurately with existing agricultural zones and irrigation boundaries, ensuring that the model is both mathematically sound and geographically reliable.

Second, LP–GIS integration enhances the model's practical relevance by addressing one of the key challenges in rural resource planning—conflicts in land and water allocation. Spatial visualization helps policymakers clearly identify overlapping land uses, water-scarce zones, and trade-offs between crops, supporting transparent and equitable decision-making. The generated maps can be used directly by village governments to design planting calendars, optimize irrigation, regulate labor distribution, and develop fair profit-sharing schemes.

This integrated approach aligns with recent studies that combined optimization models with geospatial analysis to improve agricultural decision support. Aggarwal et al. (2022) integrated geoinformatics with stochastic optimization for crop rotation planning, while Hasti et al. (2023) employed linear programming and GIS to resolve spatial allocation conflicts in land-use management. Similarly, Li et al. (2024) developed a spatial optimization framework to evaluate cropping structures under climate and land-use changes. Compared to these studies, the present model introduces a distinctive village-scale LP–GIS framework emphasizing community-based optimization and local adaptability. It bridges the gap between quantitative precision and spatial policy relevance, advancing both methodological innovation and sustainable agricultural planning in rural Indonesia [13][14][15].

4. CONCLUSION

This study successfully developed a multiperiod Linear Programming (LP) optimization model integrated with Geographic Information Systems (GIS) to optimize land and water utilization at the village-aggregate scale. The model incorporated sensitivity analysis to ensure that its solutions are both measurable and resilient to parameter variations. The optimization results revealed a rice–tobacco rotation pattern—rice cultivated in periods T1 and T3, and tobacco in T2 and T4—covering a total of 453,202 tumbak, which closely approached the maximum available land capacity. Resource analysis indicated total water use of 16,412.49 m^3 and total labor requirements of 5,319.098 workdays (HOK), with the highest demand during tobacco periods. Economically, the model achieved a gross income of Rp 2,078,047,500 and a net profit of Rp 26,493,556 across four periods.

Further analysis identified period T2 as the most profitable, while T3 recorded the lowest return. Sensitivity testing confirmed that the model remains robust under parameter increases but becomes sensitive to reductions in profit margins. Shadow price analysis indicated that land serves as the primary limiting resource, whereas water and labor constraints remain non-binding.

Based on these findings, several policy implications can be highlighted. Village governments should prioritize land optimization programs, particularly by revitalizing underutilized plots and improving access to cultivable land for smallholders. Water management strategies should emphasize irrigation efficiency and channel maintenance, while labor allocation can be optimized by aligning short-term employment schemes with high-demand seasons (T2 and T4). Finally, GIS-based decision maps can serve as practical tools for area-based planning, equitable profit distribution, and monitoring the sustainability of land and water use.

The novelty of this study lies in combining multiperiod LP, sensitivity analysis, and GIS within a village-scale framework—producing not only quantitative optimization results but also spatially informed tools for decision-making. This integration bridges the gap between mathematical modelling and practical agricultural planning, enhancing evidence-based policymaking in rural Indonesia. Future research may extend this model by incorporating dynamic socio-economic variables, climate variability, and crop diversification scenarios to further improve adaptive and sustainable resource management at the local level.

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