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Impact of irrigation modernization on rice productivity in Yogyakarta: An integrated evaluation

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Abstract

Indonesia continues to face persistent challenges in achieving sustainable rice productivity despite substantial investments in irrigation infrastructure. This study examines the influence of five pillars of irrigation modernization—water supply reliability, infrastructure improvement, management systems, institutional strengthening, and human resource development—on rice productivity in the Special Region of Yogyakarta. Utilizing a mixed-methods approach, the research integrates a readiness index evaluation, structural equation modeling, and SWOT analysis across ten irrigation areas involving 150 stakeholders. The findings reveal that while most regions exhibit an adequate level of readiness for modernization, significant disparities exist between centrally and regionally managed systems. Quantitative modeling confirms that water supply reliability, infrastructure, and management systems have a statistically significant impact on rice yields. In contrast, institutional and human resource variables, though positively associated, demonstrate weaker direct effects. Strategic analysis places all regions in an aggressive development quadrant, indicating favorable internal and external conditions for modernization. These results highlight the need for targeted investment strategies, particularly in human capital and institutional coordination. This study contributes to irrigation policy discourse by presenting a comprehensive, empirical model for assessing modernization impact and guiding implementation.

Keywords: Agricultural development, Irrigation modernization, Readiness index, Rice productivity, Structural equation modeling, SWOT analysis, Yogyakarta.

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1. Introduction

Indonesia, an agrarian country with a rapidly growing population, faces enduring challenges in achieving sustainable food security. The agriculture sector, particularly the rice farming sub-sector, remains a cornerstone of national food provision and economic sustenance. According to national statistical data, Indonesia had a population of 270.20 million in 2021, growing at an average rate of 1.25% annually between 2010 and 2020, which consequently exerts increasing pressure on national food production systems [1]. Despite its position as the fourth-largest global rice producer, the country paradoxically continues to import rice to meet domestic demand [2]. In 2022, rice production reached 34.40 million tons, yet Indonesia still imported 1.60 million tons [3]. The inconsistency between domestic production and consumption underscores systemic inefficiencies in agricultural infrastructure, most notably irrigation management, which is crucial for stable rice productivity [4].

Multiple studies have revealed the significant correlation between well-functioning irrigation systems and the achievement of agricultural sustainability. However, the nation's irrigation infrastructure is often compromised due to outdated facilities, poor water distribution networks, and inadequate maintenance strategies [5, 6]. In comparison with regional counterparts such as Vietnam, Indonesia's rice productivity is still lagging behind. For instance, in 2021, Indonesia's productivity was only 5.22 tons per hectare, whereas Vietnam achieved 6.25 tons per hectare [7]. This disparity is partially attributed to deficient irrigation management practices, such as sedimentation in reservoirs, canal degradation, and an overall mismatch between irrigation systems and the evolving climatic context [8]. These technical shortcomings are further exacerbated by institutional limitations, including underqualified human resources and fragmented policy implementation across national and regional jurisdictions [9].

The persistent performance gap in irrigation management presents a critical research problem. Existing irrigation systems, heavily dependent on outdated operational paradigms, have become increasingly ineffective in meeting the water demands of paddy farming. Furthermore, the lack of integration between irrigation infrastructure, water distribution protocols, and human resource development strategies weakens the systemic functionality needed for enhancing productivity [10]. In response to these challenges, stakeholders and policymakers have advocated for irrigation modernization—a participatory, efficient, and sustainable approach to water management in agriculture [11]. This model aims to resolve the inefficiencies inherent in traditional irrigation systems and strengthen institutional resilience by aligning operational protocols with modern agricultural demands.

The general framework of irrigation modernization includes the integration of five core components or "pillars": improvement of irrigation water supply reliability, repair and upgrade of irrigation infrastructure, enhancement of management systems, strengthening of irrigation institutions, and human resource capacity building [12]. These pillars collectively aim to form a holistic and dynamic system capable of adapting to both environmental and institutional challenges. Each pillar is associated with specific indicators and operational criteria to ensure consistent implementation and monitoring. The institutionalization of these pillars is also reinforced through regulatory frameworks such as Indonesia's Ministry of Public Works Regulation No. 30/PRT/2015, which underscores the significance of readiness assessment and structured implementation [13].

Several empirical studies have applied this five-pillar framework in various regional contexts to evaluate irrigation modernization readiness and its impact. For instance, Ristiyana, et al. [14] utilized the Analytical Hierarchy Process (AHP) and SWOT methods to design a roadmap for modernization in Batang Anai, West Sumatra [14]. Similarly, Sari, et al. [15] employed the Fuzzy Analytical Hierarchy Process (FAHP) and Simple Additive Weighting (SAW) techniques to assess implementation readiness in Mojokerto Regency [15]. These methodologies have allowed researchers to identify and prioritize infrastructural and institutional gaps, but have typically remained isolated to planning stages without robust linkage to outcome-based productivity measures. Other studies have emphasized prioritization steps in modernization efforts, such as those by Putri, et al. [16] in the Wadaslintang Irrigation Area, which stressed the operational importance of selected modernization steps in improving local irrigation governance [16].

Despite these advancements, there remains a significant gap in studies that comprehensively evaluate the causal impact of each of the five pillars on rice productivity outcomes. While modernization roadmaps and readiness indices provide valuable planning tools, they fall short in demonstrating the measurable productivity effects of each pillar in real-world conditions. Moreover, current literature has yet to fully explore the synergistic effects of the five pillars when implemented concurrently, particularly within an empirical framework that integrates both quantitative and strategic analyses.

This study seeks to address this research gap by combining three analytical approaches: the Irrigation Modernization Readiness Index (IKMI), Structural Equation Modeling (SEM), and SWOT analysis. By applying this integrated methodology to the Special Region of Yogyakarta (DIY), the study investigates the direct and indirect impacts of each modernization pillar on rice productivity. The IKMI provides a diagnostic overview of modernization readiness across multiple irrigation areas. SEM is employed to statistically examine the strength and direction of relationships between modernization indicators and productivity outcomes. Finally, the SWOT analysis contextualizes these findings within strategic development frameworks for regional water governance.

The study's contributions are threefold. First, it establishes an empirical linkage between modernization pillars and productivity, offering practical insights for policymakers and regional planners. Second, it introduces a strategic framework for implementing aggressive modernization based on strengths and opportunities, as identified through the SWOT matrix. Third, the study contributes to methodological innovation by demonstrating the efficacy of integrating quantitative modeling (SEM), index-based diagnostics (IKMI), and qualitative strategic tools (SWOT) within a single analytical paradigm. These elements position the study as a novel and comprehensive evaluation of irrigation modernization as a means of enhancing rice productivity.

2. Literature Review

2.1. Concept of Irrigation Modernization

Irrigation modernization is increasingly recognized as a comprehensive reform strategy aimed at improving the effectiveness, efficiency, and sustainability of water management systems in agricultural sectors. The modernization process is not merely about infrastructural upgrades but also involves institutional strengthening and human resource development. According to the Directorate General of Water Resources [12] irrigation modernization encompasses five core pillars: (1) improving the reliability of irrigation water supply, (2) upgrading irrigation facilities and infrastructure, (3) enhancing irrigation management systems, (4) strengthening irrigation management institutions, and (5) empowering human resources. These five pillars form the structural backbone for any systematic irrigation reform process in Indonesia and are intended to support broader national goals such as food security, economic stability, and rural development.

The Indonesian government, through Ministry of Public Works Regulation No. 30/PRT/2015, has codified these pillars into official regulatory frameworks [13]. This regulation serves as the guiding document for planning, implementing, and evaluating irrigation modernization programs across various administrative levels. The implementation is generally assessed through the Irrigation Modernization Readiness Index (IKMI), which evaluates each pillar based on weighted indicators and stakeholder input.

2.2. Pillars of Irrigation Modernization

Each of the five pillars plays a distinct but interconnected role in the modernization framework:

- Water Supply Reliability: Ensures stable, adequate, and timely distribution of water to meet agricultural demand. It also emphasizes upstream and downstream water conservation and reduction of water losses [11].
- Infrastructure Upgrades: Focuses on the physical aspects such as primary and secondary canals, diversion structures, and transportation facilities, which collectively determine the efficiency of water delivery systems [6].
- Management Systems: Involves the adoption of Standard Operating Procedures (SOPs), automation tools,

and monitoring mechanisms for water use, crop planning, and irrigation scheduling [16].

- Institutional Strengthening: Targets the functional capacity of water user associations (P3A and GP3A), irrigation commissions, and local governance bodies responsible for water distribution and conflict resolution [9].
- Human Resource Empowerment: Addresses training, operational management, and performance accountability to ensure the availability of skilled personnel for planning and maintenance [3].

2.3. Readiness and Assessment Models

To implement these pillars effectively, several evaluative frameworks have been developed. The most widely adopted is the IKMI, which quantifies readiness by combining questionnaire data with expert scoring on specific criteria under each pillar [11]. The resulting scores categorize regions into four levels of readiness: inadequate, moderate, adequate, and excellent. This diagnostic tool allows policymakers to allocate resources efficiently and prioritize areas needing intervention.

Complementary methodologies have also been utilized. For instance, Ristiyana, et al. [14] applied the Analytical Hierarchy Process (AHP) and SWOT analysis in Batang Anai, West Sumatra, to develop short- and long-term modernization strategies based on stakeholder prioritization [14]. Similarly, Sari, et al. [15] employed the Fuzzy Analytical Hierarchy Process (FAHP) and Simple Additive Weighting (SAW) in Mojokerto to assess implementation readiness [15]. These multi-criteria decision-making tools offer valuable insights into stakeholder preferences, risk perceptions, and prioritization logic.

2.4. Impact-Oriented Studies on Modernization

Despite the growing application of readiness indices and planning frameworks, empirical studies that directly measure the impact of modernization on agricultural productivity remain scarce. Most existing research is confined to the design and prioritization stages of irrigation modernization without extending into outcome evaluation.

Putri, et al. [16] in their study of the Wadaslintang Irrigation Area, prioritized 18 modernization steps across all five pillars but did not assess their collective impact on rice yields [16]. Another study by Pradipta, et al. [17] analyzed readiness in the Kedung Putri Irrigation Area using K-Medoids Clustering, focusing primarily on classification rather than causality [17]. These studies highlight the operational complexity of implementing modernization policies but often fall short in linking modernization efforts with agricultural outputs.

2.5. Strategic Integration through SWOT Analysis

Strategic planning tools such as SWOT analysis are crucial for translating diagnostic results into actionable policies. SWOT frameworks assess internal and external factors—namely strengths, weaknesses, opportunities, and threats—to guide strategy formulation. According to Sinambela [18] SWOT analysis allows stakeholders to identify leverage points for development while mitigating risks [18].

Riyanto emphasized the importance of integrating SWOT matrices with quantitative indicators to generate actionable strategies based on the balance of internal capacities and external conditions [19]. In irrigation modernization, this approach can guide local governments in deciding whether to pursue aggressive expansion, gradual improvement, risk minimization, or retrenchment.

2.6. Structural Equation Modeling in Agricultural Research

A notable methodological advancement in this field is the application of Structural Equation Modeling (SEM). SEM allows researchers to test complex causal relationships between latent constructs, such as modernization pillars and rice productivity. The technique is particularly useful when dealing with interdependent variables and multicollinearity, making it well-suited for multifactorial policy evaluations [20].

Ghozali and Latan [21] demonstrated the effectiveness of SEM using SmartPLS software to measure causal paths in models with latent variables [21]. The technique incorporates factor loadings, average variance extracted (AVE), composite reliability, and path coefficients to validate model robustness. In the context of irrigation modernization, SEM offers a powerful framework for simultaneously assessing the influence of all five pillars on productivity outcomes.

2.7. Identified Research Gaps

While the existing literature provides a solid foundation for understanding the components and planning processes of irrigation modernization, several gaps persist. First, the absence of integrated models that combine readiness assessments (e.g., IKMI), outcome evaluations (e.g., SEM), and strategic planning tools (e.g., SWOT) limits the practical utility of current research. Second, studies often fail to examine the interaction effects among the five pillars, assuming them to be independent rather than mutually reinforcing. Third, regional heterogeneity is frequently underexplored, despite clear differences in irrigation infrastructure quality and governance capacity across provinces.

This study seeks to address these gaps by implementing an integrated methodological framework that combines IKMI diagnostics, SEM impact analysis, and SWOT-based strategic planning. By applying this model to the Special Region of Yogyakarta, the research aims to offer actionable insights into both the planning and implementation phases of irrigation modernization, thus bridging the divide between theoretical models and field-level realities.

3. Method

This study employs a mixed-method approach, combining quantitative and qualitative research methods. The survey method is utilized to collect data in the form of opinions or perspectives from respondents who directly interact with the research object. This method aims to gather general information about the research object through a sample, which is then systematically interpreted and analyzed. The sampling technique used to select respondents is purposive sampling, a method based on specific criteria [22]. The criteria include respondents involved in implementing irrigation modernization, officials whose primary duties and functions are related to irrigation modernization, and operational and maintenance personnel. The criteria and sub-criteria for this research were derived from the identification and elaboration of the Five Pillars of Irrigation Modernization as outlined in the General Guidelines for Irrigation Modernization from the Ministry of Public Works and Public Housing [16].

Questionnaires and interviews were conducted with representatives from the Serayu Opak River Basin Organization (BBWS-SO), the Department of Public Works, Housing, and Energy Mineral Resources (DPUPESDM) of DIY, the Department of Public Works, Housing, and Settlement Areas (DPUPKP), operational and maintenance personnel (OP), field extension workers (PPL), the Association of Farmers' Water User Groups (GP3A), and Water User Farmers' Groups (P3A). The study was conducted in three districts in the Special Region of Yogyakarta (DIY): Sleman, Kulon Progo, and Bantul. In each district, samples were taken from three irrigation areas under the authority of the central, provincial, and district governments, with 15 respondents per irrigation area. The irrigation areas in Bantul District are not under central government authority; only provincial and district authorities manage them. Therefore, four irrigation areas in Bantul were sampled, comprising two under provincial and two under district authority.

This study used primary data from Likert-scale questionnaires to determine the weighted scores for each sub-criterion. The scoring used a scale from 1 to 5, where 1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, and 5 = strongly agree. The data and number of respondents are presented in Table 1:

Table 1.
Mapping of Respondents.

No.	District (DI)	Irrigation Area	Institutions	Number of Respondents	Total Respondents
1	Sleman	Kalibawang	BBWSBBWS	2	
		Sapon	DPUPESDM	2	
		Kejuron Kayangan	DPUPKP	2	
			O&P	9	45
			PPL	6	
			P3A	21	
			GP3A	3	
2	Kulon Progo	Karang Talun	BBWS	2	
		Madean	DPUPESDM	2	
		Pule Donokerto	DPUPKP	2	
			O&P	9	45
			PPL	6	
			P3A	21	
			GP3A	3	
3	Bantul	Canden	BBWS	0	
		Pijenan	DPUPESDM	4	
		Dokaran	DPUPKP	4	
		Madean	O&P	8	60
			PPL	8	
			P3A	32	
			GP3A	4	
	Total				150

The determination of the Irrigation Modernization Readiness Index (IKMI) is based on the five pillars of irrigation, including water availability, infrastructure (irrigation facilities and infrastructure), management systems, management institutions, and human resources. These five pillars of irrigation modernization were assessed by stakeholders from each pillar using a Likert scale, and each pillar's weight was determined according to established procedures [15, 17]. The questionnaire content was derived from the criteria and sub-criteria outlined in the Five Pillars of Irrigation Modernization, as shown in Table 2.

Table 2.
Criteria and Sub-Criteria in IKMI.

No.	Criteria (5 Pillars)	Code	Sub Criteria (Indicators)
1.	Increasing the Reliability and Supply of Irrigation Water (RS)	RS_1	Reliability of irrigation water
		RS_2	Water supply distribution
		RS_3	Loss of irrigation water
		RS_4	Water source conservation
		RS_5	Water stability upstream and downstream
2.	Repair of Irrigation Facilities and Infrastructure (FI)	FI_1	Main building
		FI_2	Divider buildings
		FI_3	Carrier buildings
		FI_4	O&M Irrigation facilities
		FI_5	Means of transportation
3.	Improving the Irrigation Management System (MS)	MS_1	Planting patterns
		MS_2	Irrigation SOPs
		MS_3	Irrigation controllers
		MS_4	Irrigation water productivity
		MS_5	Irrigation management monitoring
4.	Strengthening Irrigation Management Institutions (MI)	MI_1	Strengthening farmers (P3A)
		MI_2	Irrigation management units
		MI_3	Irrigation Commission
		MI_4	Irrigation task force
		MI_5	Irrigation management department
5.	Human Resources Empowerment (HR)	HR_1	HR Management
		HR_2	HR Operations
		HR_3	HR Training
		HR_4	HR performance responsibilities
		HR_5	Quality of HR

Structural Equation Modeling (SEM) is a multivariate analysis method that can be used to simultaneously depict the linear relationships between observed variables (indicators) and variables that cannot be directly measured (latent variables) [23]. The initial phase of SEM using the WarpPLS approach involves designing an inner and outer model. The inner model demonstrates the relationship between variables within the model, while the outer model identifies whether the indicators forming the variables are reflective or formative. Thus, latent variables and their indicators must first be identified. Wold first developed SEM with Partial Least Squares (PLS) as a general method for estimating path models that use latent constructs with multiple indicators [24]. Data processing in SEM is assisted by using SmartPLS software, with significance tests based on the Original Sample (O), T-statistic > 1.96, and PValue < 0.05. The O value indicates whether the effect is positive or negative, depending on the sign (positive or negative). T-statistic > 1.96 and PValue < 0.05 indicate a statistically significant effect. Significance testing serves to identify the influence of the five pillars of irrigation modernization on rice productivity. The model of variable and indicator relationships in SEM is illustrated in Figure 1:

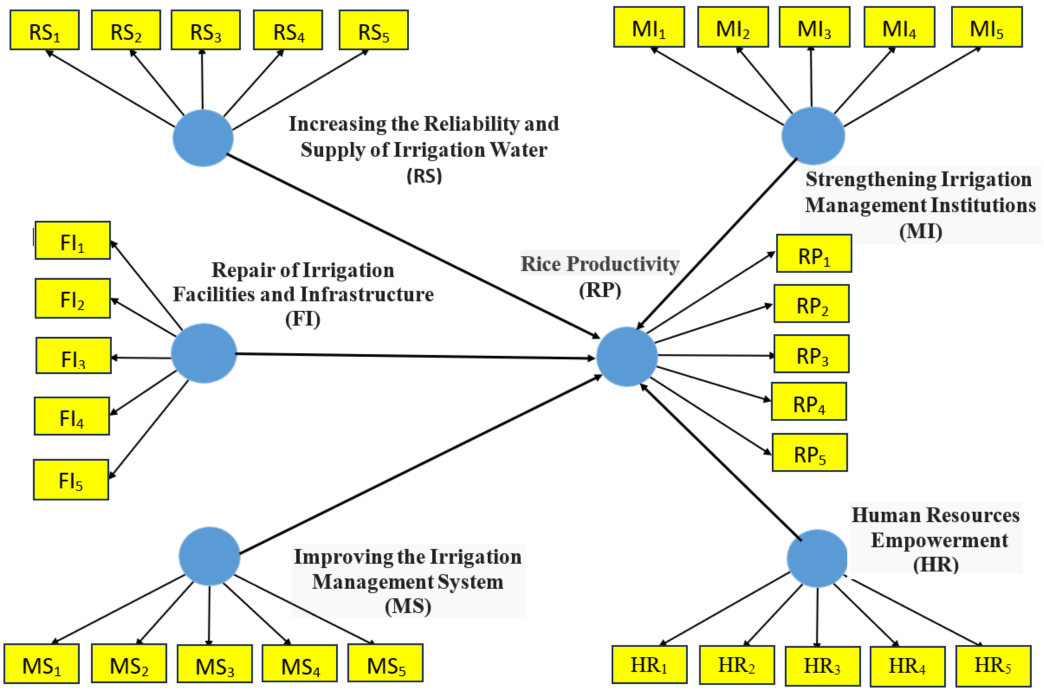

Figure 1.
SEM Variable and Indicator Relationship Model.

SWOT Analysis (Strengths, Weaknesses, Opportunities, Threats) systematically identifies various factors to formulate corporate strategies. This analysis is based on the interaction between internal factors—strengths and weaknesses—and external factors—opportunities and threats. SWOT analysis compares external factors (opportunities and threats) with internal factors (strengths and weaknesses). SWOT is used to assess the strengths and weaknesses of internal resources and the external opportunities and challenges [25]. SWOT analysis is a tool for systematically identifying various factors to formulate strategies based on the logic that maximizes potential and opportunities while minimizing weaknesses and threats, ultimately producing outcomes or actions to achieve goals. The calculation involves determining the weights, ratings, and scores for the IFAS and EFAS matrices.

4. Results

4.1. Irrigation Modernization Readiness Index (IKMI) Analysis

The analysis was conducted based on the criteria and sub-criteria of irrigation modernization, resulting in the weight of importance. The analysis of the five pillars produced the levels, ratings, and IKMI of each irrigation area (DI), which were compared to the IKMI reference values. The IKMI evaluation uses the five pillars of irrigation modernization: water availability, irrigation infrastructure, management institutions, management systems, and human resources. Based on the IKMI evaluation for the three irrigation areas, the results are shown in Figures 2, 3, and 4:

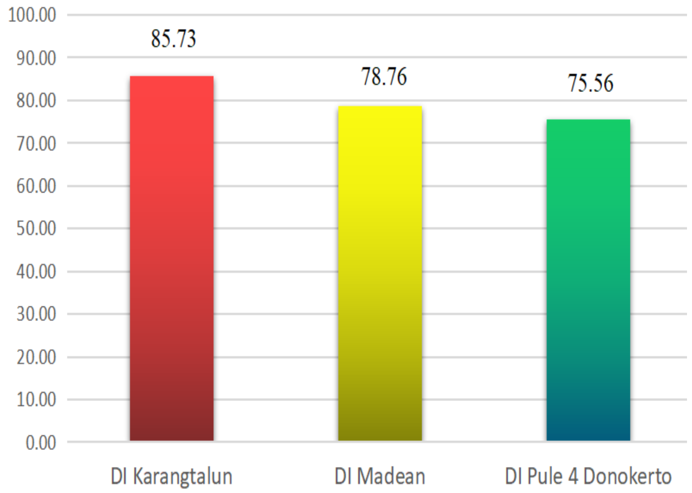

Figure 2.
IKMI Value of the Irrigation Area in Sleman Regency.

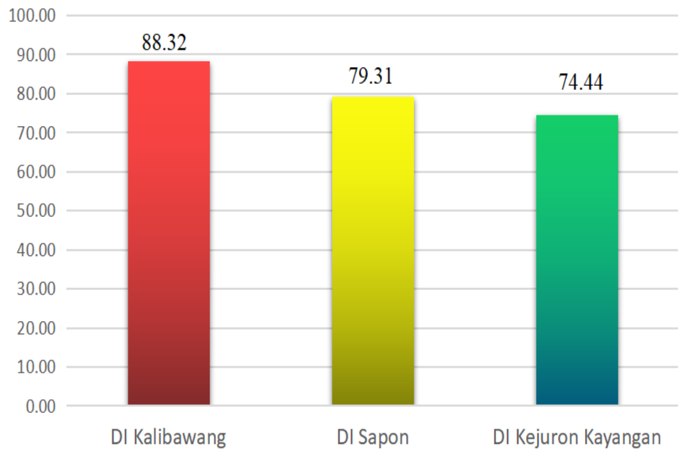

Figure 3.
IKMI Value of the Irrigation Area in Kulon Progo Regency.

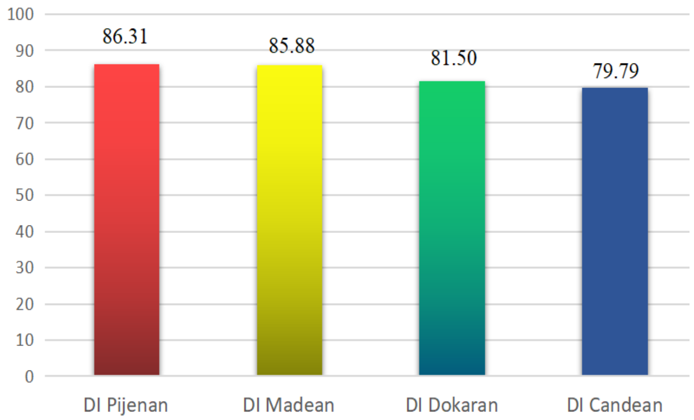

Figure 4.
IKMI Value of the Irrigation Area in Bantul Regency.

Based on Figures 2, 3, and 4, the Irrigation Areas in DIY achieved IKMI scores above 80 and were rated as "adequate" in six Irrigation Areas, or 60%. IKMI scores between 50 and 80, rated as "sufficient," were found in four Irrigation Areas or 40%. The percentage of "adequate" ratings by management authority was 100% under central authority, 50% under provincial authority, and 25% under district authority. Irrigation Areas with an "adequate" rating can implement irrigation modernization, while those rated as "sufficient" require improvements and refinements in the Five Pillars of Irrigation Modernization.

4.2. SEM (Structural Equation Modeling) Analysis

The SEM analysis uses parameter estimation from the PLS process, including Loading Factor, AVE value of latent variables, Cronbach Alpha, and Composite Reliability. Hypothesis testing used a t-statistic > 1.96 or p-value < 0.05 and the R^2 value. The Loading Factor for indicators must exceed 0.7. The influence of the Five Pillars on rice productivity in DIY is presented in Tables 3, 4, and 5.

Table 3.
Path Coefficient Values in the Sleman Regency Irrigation Area

Construk	Original Sample (O)	Sample Mean (M)	Standard Deviation (STDEV)	T Statistics (|O/STDEV|)	P Values
Pillar 1 -> Rice Productivity	0.336	0.419	0.246	2.621	0.016
Pillar 2 -> Rice Productivity	0.327	0.415	0.242	2.497	0.019
Pillar 3 -> Rice Productivity	0.371	0.409	0.165	2.253	0.025
Pillar 4 -> Rice Productivity	0.206	0.372	0.216	1.490	0.065
Pillar 5 -> Rice Productivity	0.253	0.298	0.135	1.876	0.061

Table 4.
Path Coefficient Values in the Kulon Progo Regency Irrigation Area

Construk	Original Sample (O)	Sample Mean (M)	Standard Deviation (STDEV)	T Statistics (|O/STDEV|)	P Values
Pillar 1 -> Rice Productivity	0.471	0.436	0.260	2.132	0.025
Pillar 2 -> Rice Productivity	0.370	0.490	0.206	2.301	0.022
Pillar 3 -> Rice Productivity	0.483	0.444	0.224	2.151	0.032
Pillar 4 -> Rice Productivity	0.399	0.343	0.245	1.662	0.104
Pillar 5 -> Rice Productivity	0.372	0.359	0.243	2.118	0.024

Table 5.
Path Coefficient Values in the Bantul Regency Irrigation Area

Construk	Original Sample (O)	Sample Mean (M)	Standard Deviation (STDEV)	T Statistics (|O/STDEV|)	P Values
Pillar 1 -> Rice Productivity	0.423	0.426	0.095	4.450	0.000
Pillar 2 -> Rice Productivity	0.282	0.098	0.093	2.886	0.018
Pillar 3 -> Rice Productivity	0.208	0.091	0.102	2.059	0.045
Pillar 4 -> Rice Productivity	0.436	0.403	0.130	3.340	0.000
Pillar 5 -> Rice Productivity	0.134	0.057	0.134	1.257	0.079

Based on Tables 3, 4, and 5, Pillar 1 (Improving the Reliability of Irrigation Water Supply), Pillar 2 (Improvement of Irrigation Facilities and Infrastructure), and Pillar 3 (Refinement of Irrigation Management Systems) have a "positive" and "significant" impact on rice productivity. In some Irrigation Areas, Pillar 4 (Strengthening Irrigation Management Institutions) and Pillar 5 (Empowerment of Human Resources) have a "positive" but not significant impact on rice productivity.

4.3. SWOT Analysis

The SWOT analysis was conducted to determine the SWOT quadrant. Each factor's weight was calculated, followed by rating and score or value calculations. Finally, the quadrant was determined using the difference in the IFAS matrix (Strength-Weakness) and the difference in the EFAS matrix (Opportunities-Threats), as shown in Figures 5, 6, and 7:

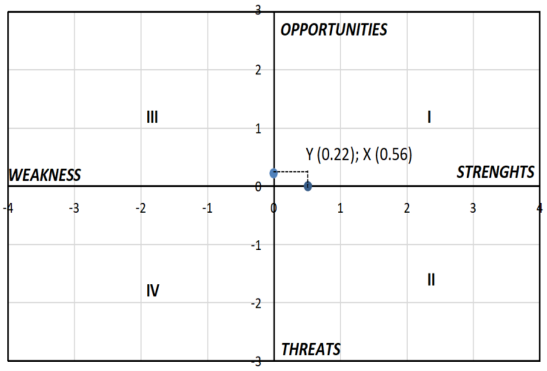

Figure 5.
Five Pillar SWOT Diagram in Sleman Regency.

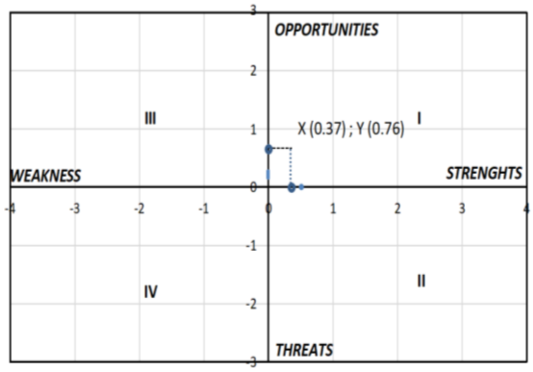

Figure 6.
Five Pillar SWOT Diagram in Kulon Progo Regency.

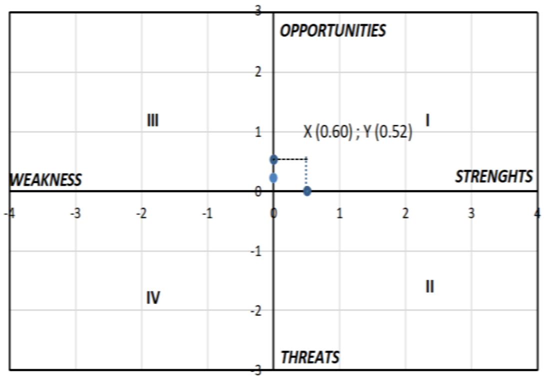

Figure 7.
Five Pillar SWOT Diagram in Bantul Regency.

Based on Figures 5, 6, and 7 the SWOT reference points in the three districts of the DIY Province show that the Five Pillars of Irrigation Modernization are positioned in Quadrant I. This position indicates that the Five Pillars of Irrigation Modernization strategy falls under an aggressive strategy, the most favorable situation as it lies between strengths and opportunities. The strategy for implementing the Five Pillars of Modernization focuses on leveraging existing strengths to maximize opportunities. These strengths include sufficient water resources, well-maintained irrigation channels for water distribution, and a management system aligned with standard operating procedures. The opportunities lie in the synergy between the Five Pillars of Irrigation Modernization in DIY, leading to increased rice productivity.

5. Discussion

5.1. Interpretation of the Readiness Index (IKMI) Findings

The IKMI results indicate that the majority of irrigation areas in the Special Region of Yogyakarta are categorized as "adequate" in terms of modernization readiness. This suggests that the foundational components of irrigation modernization—especially water supply and infrastructure—have been relatively well established. The presence of functioning canal networks and reliable water flow in several areas reflects the outcomes of long-term investment and routine maintenance, particularly in centrally managed irrigation systems. However, the areas categorized as “moderate” still face systemic deficiencies, particularly in the domains of institutional performance and human resource development. These findings resonate with prior studies highlighting that technical readiness often precedes institutional maturity in the modernization process [3].

The discrepancy in performance between central and district-managed irrigation systems underscores the role of governance and funding structures. Centrally managed systems tend to benefit from higher operational budgets, professional oversight, and access to advanced technologies. Meanwhile, district-managed systems are often constrained by limited technical expertise and fragmented coordination among agencies, a pattern previously observed by Angguniko and Hidayah [9].

5.2. Significance of Pillars in Driving Productivity (SEM Analysis)

The SEM analysis confirms the hypothesis that the five pillars of irrigation modernization have varying degrees of influence on rice productivity. Pillars 1 (Water Supply Reliability), 2 (Infrastructure), and 3 (Management Systems) emerged as statistically significant predictors, supporting the assertion that physical and operational components are crucial determinants of agricultural performance.

The positive effect of water supply reliability aligns with findings from Taufik and Ruzardi [8] who emphasized the role of water delivery efficiency in maintaining optimal crop growth cycles. Reliable water access ensures consistency in planting schedules and reduces the risk of crop failure due to water shortages or delays. Similarly, infrastructure upgrades contribute to minimizing conveyance losses and enabling targeted distribution, particularly when coupled with automation tools and real-time monitoring systems.

Management systems, including SOPs, planting calendars, and performance monitoring, act as mediating variables that translate infrastructure and water availability into actual productivity gains. These systems foster accountability, reduce inefficiencies, and enable adaptive management—a perspective echoed in Creaco, et al. [6] review of real-time water distribution technologies.

Conversely, Pillars 4 (Institutional Strengthening) and 5 (Human Resources) demonstrated positive but statistically insignificant relationships with productivity. This suggests that their contributions are more indirect or long-term. Institutional mechanisms and HR capacity are essential for sustaining modernization, but their effects may not be immediately reflected in yield data, particularly in the absence of measurable performance metrics or training evaluation systems. These findings are consistent with Ghozali and Latan [21] observation that structural reforms require lag time to manifest tangible impacts.

5.3. Strategic Implications from SWOT Analysis

The SWOT analysis places all studied irrigation areas in Quadrant I, indicating an aggressive strategic orientation. This implies that internal strengths—such as existing infrastructure and regulatory frameworks—can be leveraged to exploit external opportunities, including government incentives and technological advancements. The consistency of this strategic positioning across all regions suggests a favorable environment for scaling modernization programs.

However, weaknesses such as limited HR training and institutional fragmentation must be addressed to ensure sustainability. The continued reliance on central government support may hinder local innovation and reduce resilience to external shocks. These risks are particularly relevant in the face of increasing climate variability, which threatens water availability and infrastructure stability.

The strategic focus should therefore be twofold: first, consolidating gains in water supply and infrastructure through routine maintenance and technology integration; and second, investing in institutional capacity and human development to build adaptive governance systems. Riyanto [19] advocates for such dual strategies, combining short-term wins with long-term resilience planning.

5.4. Cross-District Comparisons and Equity Considerations

The comparative findings across Sleman, Kulon Progo, and Bantul demonstrate significant intra-regional disparities in modernization readiness and outcomes. Sleman, benefiting from central oversight, displayed higher performance across most indicators. In contrast, Bantul and Kulon Progo exhibited mixed results, largely due to their dependence on local administrative resources.

This divergence raises concerns about equity and the need for differentiated policy interventions. Uniform modernization programs may exacerbate regional imbalances if not calibrated to local needs and capacities. Equity-focused frameworks should prioritize underperforming districts by allocating targeted funding, technical assistance, and capacity-building programs. Such an approach aligns with principles of inclusive development and sustainable agricultural transformation.

A notable contribution of this study is its integrated use of IKMI, SEM, and SWOT tools. This triangulated methodology allows for a holistic evaluation of both readiness and impact, bridging the gap between planning and implementation. While previous studies have focused on either planning (e.g., AHP, FAHP) or outcomes (e.g., yield analysis), this research integrates both dimensions to offer a more comprehensive understanding of modernization dynamics.

Nonetheless, certain limitations must be acknowledged. The cross-sectional design restricts the ability to infer causality over time. Longitudinal studies would be beneficial for tracking the evolution of modernization impacts, especially concerning institutional and HR components. Additionally, while SEM provides robust statistical modeling, it does not capture contextual nuances such as political will, farmer motivation, or climate anomalies—all of which influence irrigation outcomes.

6. Conclusion

This study has demonstrated that irrigation modernization, structured around five key pillars—water supply reliability, infrastructure improvement, management systems, institutional strengthening, and human resource development—plays a crucial role in enhancing rice productivity. Quantitative analysis using Structural Equation Modeling confirmed that three of these pillars—water supply, infrastructure, and management systems—significantly influence productivity outcomes, while the remaining two provide foundational support that requires longer-term development. The Irrigation Modernization Readiness Index (IKMI) revealed that most irrigation areas in Yogyakarta fall within an "adequate" readiness category, though disparities remain between centrally and regionally managed systems. SWOT analysis further highlighted the strategic potential for aggressive improvement by leveraging internal strengths and policy-driven external opportunities.

These findings contribute to the broader body of knowledge by offering an integrated evaluation model that combines readiness diagnostics, causal impact assessment, and strategic planning. Unlike prior studies that often isolated planning or outcome dimensions, this research bridges both, offering practical tools for policymakers and irrigation managers.

The study underscores the need for equitable, region-specific strategies, particularly in underperforming districts. Future research should pursue longitudinal studies to assess the sustained impact of institutional and human resource reforms, as well as incorporate environmental variables like climate adaptation. Overall, the study affirms the critical role of coordinated, multi-dimensional modernization efforts in achieving sustainable agricultural development and national food security.

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