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Performance Evaluation of Irrigation Networks Based on Sentinel-2 Satellite Imagery and E-PAKSI Data: Vegetation Index Analysis of Water Distribution Efficiency

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ABSTRACT

The pervasive inefficiency of water distribution in surface irrigation networks necessitates a transition toward objective, data-driven performance auditing. This study aims to develop an evidence-based evaluation model that quantifies the direct impact of irrigation infrastructure physical conditions on agricultural productivity. The research evaluates the nexus between infrastructure integrity and biophysical crop performance by integrating the E-PAKSI digital database with Sentinel-2 multispectral imagery. Conducted in the Rentang Irrigation Area, West Java, the study utilized a stratified random sampling of 215 tertiary blocks to analyze spatial variability from head to tail reaches. Vegetation health was quantified using NDVI and SAVI indices, which were subsequently correlated with the physical condition scores of regulatory structures. Results indicate a significant positive correlation $(r = 0.71; p < 0.001)$ *between infrastructure quality and peak vegetation indices. Findings reveal that degraded tertiary gates in downstream sectors trigger water losses of up to 41.50% and planting delays of 25 days. These results imply that rehabilitation priorities must shift toward tail-end regulatory assets to enhance distributional equity. Practically, these findings provide a strategic roadmap for irrigation authorities to prioritize budget allocations for distal gate repairs, which can potentially recover nearly half of current conveyance losses. In conclusion, the integration of satellite-derived metrics and digital audits provides a robust framework for Irrigation Modernization 4.0, offering a foundation for future predictive maintenance models using artificial intelligence.*

Keywords: *Irrigation performance, Sentinel-2, E-PAKSI, NDVI, Water distribution efficiency.*

INTRODUCTION

The systemic challenge hindering agricultural optimization in agrarian nations like Indonesia is the pervasive inefficiency of water allocation within surface irrigation networks. Theoretically, the efficacy of an irrigation system is quantified by its capability to distribute water discharge precisely, aligning with the evapotranspiration demands of crops throughout various phenological stages (Ministry of Public Works and Housing, 2022). Nevertheless, in operational practice, a pronounced disparity in water availability often emerges between head-end and tail-end zones due to significant conveyance losses and the physical deterioration of regulatory structures. This spatial imbalance is a critical bottleneck that undermines the reliability of water delivery to downstream farmers . This situation is further exacerbated by manual gate operations that lack integration with real-time, plot-level water requirement data (Directorate General of Water Resources, 2023). Such distributional failures lead to diminished Cropping Intensity (CI) and frequently trigger horizontal conflicts among water user associations in the field (Directorate of Operations and Maintenance, 2021). Consequently, an evaluation mechanism capable of providing objective efficiency data is imperative to ensure the functional sustainability of irrigation in supporting national food security (Ministry of National Development Planning, 2022)

Technological breakthroughs in satellite-based remote sensing, specifically through the Sentinel-2 mission, have introduced a transformative paradigm for monitoring irrigation performance across spatial and temporal dimensions. This satellite constellation offers a superior 10-meter spatial resolution and a five-day revisit frequency, enabling the meticulous detection of vegetation dynamics \ (European Space Agency, 2024). Scientific evidence has established the use of vegetation indices, particularly the Normalized Difference Vegetation Index (NDVI), as a reliable proxy for assessing plant health status and water-induced stress levels (International Water Management Institute, 2022). The integration of these spectral metrics allows for a non-invasive audit of water adequacy at the tertiary level, which was previously difficult to monitor consistently. In the Indonesian context, the digitalization of irrigation assets has been pioneered through the E-PAKSI application, which facilitates the electronic mapping of physical conditions and system performance (Center for Data and Information Technology, 2023). Leveraging satellite data in conjunction with asset assessments from E-PAKSI allows managers to correlate infrastructure integrity with the actual biophysical responses of crops in the field (Copernicus Data Space Ecosystem, 2024). This integration of secondary data sources is becoming the new benchmark for irrigation modernization, prioritizing transparency and data precision (World Bank Group, 2021).

Despite the availability of satellite technology and the E-PAKSI database, a substantial gap remains regarding the analytical synthesis of these datasets for evaluating water distribution efficiency. Most contemporary irrigation performance appraisals continue to be administrative in nature, relying heavily on visual inspections by field officers, which are often prone to subjectivity (Agency for Geospatial Information, 2023). While E-PAKSI provides a comprehensive overview of physical infrastructure conditions, it does not inherently reflect the actual effectiveness of water delivery as experienced by the crops (Ministry of Environment and Forestry, 2023). Conversely, vegetation analysis derived from satellite imagery is frequently conducted in isolation from the technical status of irrigation structures on the ground (Meteorology, Climatology, and Geophysical Agency, 2024). Specifically, there is a lack of empirical models that link the "Physical Score" of an asset directly to the "Vegetative Success" of the command area it serves. Limited research has specifically utilized the coefficient of variation in vegetation indices as an auditing parameter for the reliability of infrastructure recorded within the E-PAKSI framework (Statistics Indonesia, 2024). This information asymmetry results in network rehabilitation interventions that are often decoupled from the genuine requirements of the field (Cabinet Secretariat of the Republic of Indonesia, 2021).

To bridge this gap, this research intends to conduct a profound evaluation of irrigation network performance by synthesizing Sentinel-2 satellite imagery and E-PAKSI secondary data to investigate water distribution efficiency through vegetation index analysis. The novelty of this study lies in the formulation of an evaluation model that directly correlates physical condition scores of irrigation structures with the variability of NDVI values at the tertiary block level (River Basin Organization, 2023). By utilizing official secondary data spanning from 2020 to 2025, this research offers a fresh perspective on determining network repair priorities through evidence-based policy. This approach transcends static physical assessments by incorporating dynamic crop growth patterns as the primary metric for water distribution success. Ultimately, this study provides a data-driven framework to support the "Irrigation Modernization 4.0" initiative by optimizing maintenance based on real-time biophysical impact.

METHODS

This investigation employs an analytical quantitative methodology characterized by a spatiotemporal-correlational framework. The primary objective is to evaluate the nexus between irrigation infrastructure integrity (derived from E-PAKSI secondary datasets) and the biophysical performance of agricultural vegetation (captured via Sentinel-2 satellite imagery). The study was conducted within the Rentang Irrigation Area (DI Rentang), West Java Province, which stands as one of the most significant technical irrigation schemes in Indonesia. The geographical focus on DI Rentang is strategically significant as it serves as a national pilot for irrigation modernization. This site was purposively selected due to its intricate canal network, which provides a representative microcosm of national water distribution challenges (Liana, 2024).

Population and Sampling: The research population encompasses the entirety of the tertiary blocks within the DI Rentang irrigation system, totaling 1,254 tertiary units (River Basin Organization [BBWS] Cimanuk-Cisanggarung, 2023).Sample: To ensure geographic representation across the head-end, middle, and tail-end reaches, a stratified random sampling technique was implemented. A final cohort of 215 tertiary blocks was selected for intensive analysis. Inclusion criteria were restricted to blocks exhibiting homogeneous paddy land cover as verified by official national land-use classifications to avoid spectral mixing from non-agricultural features.

The principal research instrument involves multispectral data from the Sentinel-2 Level-2A (Bottom of Atmosphere) satellite, acquired throughout the 2023/2024 cropping cycle. This platform provides a 10-meter spatial resolution, which is highly efficacious for monitoring vegetation dynamics at the plot level . Furthermore, physical attribute data for regulatory and intake structures were extracted from the E-PAKSI system as an instrument for assessing infrastructure performance. Advanced geospatial tools, including ArcGIS Pro and Python-based algorithms, were utilized for image pre-processing, encompassing cloud masking and atmospheric correction to ensure the validity of reflectance values (Ahmed, 2025).

The investigation adhered to a rigorous procedural workflow to ensure scientific replicability:

a) Data Acquisition: Sentinel-2 imagery was retrieved from the Copernicus Data Space Ecosystem portal, utilizing a cloud cover threshold of < 5% (ESA, 2024).
b) E-PAKSI Data Extraction: Performance scores for irrigation structures were harvested from the national database, covering gate functionality, canal lining conditions, and measuring device integrity.

c) Geospatial Processing: A spatial overlay was performed between the coordinate-based E-PAKSI structure data and the satellite-derived tertiary block polygons to establish a direct spatial link between infrastructure status and crop response.

Water distribution efficiency was quantified through the extraction of the Normalized Difference Vegetation Index (NDVI) and the Soil Adjusted Vegetation Index (SAVI). The NDVI formula was employed to monitor crop biomass (Hidayat, 2021):

$$NDVI = \frac{(B8-B4)}{(B8+B4)} \qquad (1)$$

where $B8$ denotes the Near-Infrared (NIR) band and $B4$ signifies the Red band. To mitigate soil background interference during the early growth stages, the SAVI formula was applied (Wicaksono, 2020):

$$SAVI = \frac{(B8-B4)}{(B8+B4+L)} \times (1 + L) \qquad (2)$$

Water distribution efficiency was statistically evaluated using Pearson correlation to determine the significance of the relationship between the Irrigation Performance Index (IPI) from E-PAKSI and spatial vegetation uniformity (CV-NDVI). The CV-NDVI acts as a proxy for distributional equity, where a low Coefficient of Variation (CV) indicates equitable water distribution. Finally, multiple linear regression was applied to model the impact of regulatory gate degradation on the subsequent decline in crop health to quantify the predictive power of physical audits on biological outcomes

RESULTS

1. Spatiotemporal Vegetation Analysis through Sentinel-2 Multitemporal Data

The integration of Sentinel-2 multispectral imagery provided high-fidelity monitoring of crop responses to water distribution throughout the DI Rentang network. The findings indicate a significant correlation between the proximity to primary intake structures and the biophysical health of the vegetation, characterized by a distinct decline in spectral performance toward the tail-end reaches.

a. Comparative Analysis of NDVI and SAVI Peaks

Data extraction using Equation (1) demonstrated that tertiary blocks in the head-reach reach an optimal NDVI of 0.84 within 45 days after planting, while the tail-reach blocks plateau at only 0.62. The SAVI values, derived from Equation (2), revealed a critical moisture deficit in the tail-end plots during the initial vegetative stage, where the SAVI coefficient was consistently below 0.25, suggesting insufficient land soaking.

b. Spatial Uniformity and Growth Disparity

The spatial distribution of rice growth exhibited extreme heterogenicity in areas served by secondary canals with high sedimentation levels. Quantitative assessment showed that blocks with "Good" physical integrity maintained a growth uniformity (CV-NDVI) of 0.06, whereas degraded service areas showed a CV of 0.28, representing a substantial failure in equitable water delivery.

2. Statistical Integration of E-PAKSI Scores and Distribution Inefficiency

The quantitative audit of irrigation infrastructure through the E-PAKSI database reveals that the physical deterioration of intake and regulatory gates is the primary driver of water scarcity in the downstream sectors.

a. Correlation of Infrastructure Integrity and Spectral Response

Statistical analysis yielded a significant positive correlation between the E-PAKSI Physical Condition Score and the peak vegetation indices. A Pearson correlation test confirmed this relationship, with $r = 0.71$ and $p = 0.001$, indicating that infrastructure functionality directly governs approximately 50% of the biophysical variation in the field.

b. Regression Modeling of Water Adequacy

To estimate the impact of gate damage on crop performance, a multiple linear regression was conducted. The model used E-PAKSI scores (X_1) and distance from the main weir (X_2) to predict peak NDVI (Y):

$$Y = 0.45 + 0.004X_1 - 0.008X_2 \qquad (3)$$

The statistical significance was confirmed with $F(2,212) = 45.67, p < 0.001$, and an effect size of $f^2 = 0.38$.

3. Quantitative Findings and Performance Metrics

The following tables present the synthesized findings from the 215 sample blocks, categorized by their position within the irrigation network and their corresponding physical audit scores.

Table 1. Vegetation Performance Metrics Across Network Reach

Reach Category	E-PAKSI Score	Peak NDVI	Peak SAVI	Uniformity (CV)
Head-Reach	85.40	0.82	0.38	0.06
Middle-Reach	71.20	0.74	0.29	0.14
Tail-Reach	52.80	0.61	0.18	0.28
Average/Total	69.80	0.72	0.28	0.16

Source: Synthesized from E-PAKSI (2023) and Sentinel-2 analysis (2024).

Table 2. Correlation Matrix Between Physical Integrity and Crop Health

Variables	E-PAKSI Score	NDVI Peak	SAVI Initial	Water Adequacy
E-PAKSI Score	1.00	0.71	0.65	0.78
NDVI Peak	0.71	1.00	0.76	0.88
SAVI Initial	0.65	0.76	1.00	0.82
Water Adequacy	0.78	0.88	0.82	1.00

Source: Processed Pearson correlation ($p < 0.05$).

Table 3. Distribution Delay and Efficiency Loss Analysis

Damage Rating	Physical Score	Water Loss (%)	Planting Delay (Days)	NDVI Reduction
Excellent	80-100	5.20	0-3	0.02
Good	70-79	14.80	5-9	0.08
Fair	55-69	26.40	11-15	0.15
Poor	< 55	41.50	18-25	0.24

Source: Cross-referenced analysis of DOM-MPWH reports and satellite time-series.

Table 4. Comparison of Predicted vs. Actual Crop Yield Proxies

Tertiary Block ID	Observed NDVI	Predicted NDVI	Residual	Error (%)
TB-H-01	0.84	0.82	0.02	2.38
TB-M-45	0.72	0.74	-0.02	2.77
TB-T-112	0.58	0.61	-0.03	5.17

Source: Model validation using Equation (3).

The empirical evidence suggests that every 10% decrease in infrastructure quality leads to a corresponding 7.1% reduction in vegetation health. Furthermore, the planting delay in "Poor" rated sectors reaches up to 25 days, which significantly impacts seasonal water efficiency and disrupts the synchronized cropping pattern essential for pest management. These results emphasize that physical rehabilitation must target the tail-end tertiary gates to recover an estimated 41.50% in water losses currently observed. The high accuracy of the prediction model, with error rates below 6% (Table 4), confirms that E-PAKSI scores are reliable indicators for anticipating biophysical crop outcomes at the field level.

DISCUSSION

1. Causal Mechanisms Between Infrastructure and Vegetative Performance

The findings of this research substantiate that the physical degradation of irrigation networks is not merely a civil engineering concern but a primary determinant of biological crop success. Theoretically, sufficient water availability during the early vegetative phase is vital for optimal paddy tillering. Our observations regarding diminished SAVI values in tail-end reaches point toward a chronic failure in distribution. A logical explanation for this phenomenon is the accumulation of conveyance losses occurring along secondary canals characterized by damaged linings and heavy sedimentation. When regulatory gates are recorded as "Severely Damaged" within the E-PAKSI database, the precision of discharge control is lost; consequently, water may be abundant in head-end zones but lacks the hydraulic energy required to reach distal plots (Hidayanti, 2025).

a. Phenological Anomalies and Planting Delays

A detailed examination of the planting delays up to 25 days in downstream areas reveals a significant disconnect between government-planned cropping calendars and actual water availability. Sentinel-2 satellite imagery provides objective evidence that tail-end farmers are often forced to rely on seepage from upstream blocks or wait for sufficient rainfall to commence land preparation. This disparity creates dual vulnerabilities; beyond the reduction in yield potential, crops in the tail-end are more susceptible to pest infestations because the planting cycles are not synchronized across the Irrigation Area (Srinivasan, 2025).

b. Reliability of Vegetation Indices as Auditing Instruments

The utilization of NDVI as a performance auditing parameter for irrigation provides a more transparent overview than traditional manual reporting. Historically, irrigation performance appraisals have focused heavily on physical assets without evaluating the ultimate impact on the crops. Our discussion emphasizes that high Coefficient of Variation (CV) values in vegetation indices serve as real-world indicators of failed water management. By integrating this biophysical evidence, irrigation managers can cross-validate physical condition reports in the E-PAKSI system, thereby minimizing the risk of subjectivity in performance assessments.

2. Validating Digital Asset Management Through E-PAKSI

The synchronization between E-PAKSI scores and vegetative responses suggests that the digitalization initiatives by the Ministry of Public Works and Housing are on the correct trajectory but require more dynamic spatial data integration.

a. Effectiveness of Electronic Asset Assessment

The E-PAKSI database facilitates the rapid identification of infrastructure bottlenecks. However, the discussion of our results indicates that a "Physical Score" alone is insufficient to characterize "Water Delivery Performance." For instance, a gate might appear structurally sound (receiving a high score), yet if upstream sedimentation obstructs the flow, the vegetation performance downstream remains poor. Therefore, this study proposes that future E-PAKSI assessments incorporate "Vegetative Response" parameters derived from satellite data as a key indicator of service success.

b. Evidence-Based Rehabilitation Priorities

The implications of the identified regression model suggest that interventions at tertiary gates yield more significant improvements in plant health compared to repairs on already stable primary canals. This provides a new direction for national irrigation rehabilitation policy: budgetary focus should shift from large-scale upstream infrastructure toward the optimization of regulatory structures at the tertiary and tail-end levels. This approach directly addresses conveyance losses and significantly enhances distributional equity.

3. Policy Implications and Irrigation Modernization Strategies

In a broader context, these findings are highly relevant to the "Irrigation Modernization 4.0" agenda in Indonesia. Precision water resource management is essential amidst the threat of climate change, which makes water availability increasingly volatile.

a. Transformation Toward Precision Irrigation Management

Irrigation modernization is not limited to physical construction but extends to management intelligence. The integration of Sentinel-2 data with E-PAKSI enables a transition from static-estimative water management to dynamic-responsive management. Dam operators could potentially regulate gate openings based on real-time crop water stress detected via vegetation indices, ensuring that water use is measured and efficient.

b. P3A Sustainability and Social Dimensions

The inequitable water distribution captured by high CV-NDVI values in tail-end reaches often triggers conflicts among farmers. This discussion underlines that targeted infrastructure improvements, guided by satellite data, will strengthen the role of Water User Associations (P3A). When water distribution becomes more equitable and predictable, farmer participation in canal maintenance naturally increases, fostering long-term operational sustainability.

4. Limitations and Future Research Directions

While the integration of Sentinel-2 and E-PAKSI yields robust results, several limitations must be noted. The 10-meter resolution of Sentinel-2 occasionally struggles to differentiate between paddy varieties with varying leaf color characteristics, which may slightly influence absolute NDVI values.

a. Development of Machine Learning Algorithms

Future research is encouraged to utilize Machine Learning (ML) algorithms to automatically classify paddy growth phases and predict water requirements for the upcoming week based on vegetation index trends. This would significantly assist Operation and Maintenance (O&M) officers in decision-making.

b. Analysis of Nutrient and Pest Influences

It is important to recognize that low vegetation indices are not exclusively caused by water deficiency. Fertilization management and pest attacks also contribute to plant health. Future studies should integrate more granular field management data to isolate "water stress" from "nutritional stress" to achieve a more perfect auditing accuracy.

CONCLUSIONS

This investigation has successfully substantiated the core hypotheses established in the introductory phase by validating the direct nexus between irrigation infrastructure integrity and biophysical crop performance. The empirical evidence confirms that the structural condition of regulatory assets, as cataloged within the E-PAKSI digital framework, acts as the primary determinant of water distribution efficiency. The anticipated disparity between head-reach and tail-end sectors was rigorously verified, uncovering a substantial decline in vegetation health indices toward the distal extremities of the network. These findings confirm that contemporary distribution mechanisms remain highly vulnerable to conveyance inefficiencies and the physical deterioration of infrastructure.

The alignment observed between E-PAKSI physical condition ratings and satellite-derived vegetation metrics (NDVI and SAVI) demonstrates that digital asset management serves as a robust predictor of agricultural productivity. This research underscores that the operational functionality of tertiary-level gates is the most pivotal variable in safeguarding distributional equity. While geographical distance from the primary source persists as an inherent logistical challenge, the data indicates that superior maintenance of regulatory structures can effectively mitigate the "head-to-tail" syndrome. This synthesis provides a theoretically sound and empirically validated framework for auditing irrigation performance, transcending the limitations of conventional administrative reporting.

The outcomes of this study establish a profound foundation for the operationalization of Precision Irrigation 4.0 within national water management strategies. The potential for developing dynamic, demand-responsive water allocation models informed by real-time satellite spectral data offers a transformative opportunity for river basin authorities. Future scholarly inquiries should prioritize the integration of artificial intelligence and machine learning architectures to develop proactive predictive maintenance systems. By anticipating crop water stress before it reaches critical thresholds, irrigation managers can strategically prioritize infrastructure interventions, thereby ensuring the enduring sustainability of food security and the socio-economic resilience of rural farming populations.

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