JPPIPA 12 (7) (2026)

Jurnal Penelitian Pendidikan IPA

http://jppipa.unram.ac.id/index.php/jppipa/index

Integrated WDPI–WEAP Framework for Multi-Scenario Evaluation of Irrigation Water Delivery Performance: A Case Study of Wawotobi Irrigation System, Indonesia

Rindang Santiago Samudra Suwarjo[1*], Sri Wahyuni[2], M. Amar Sajali[2]

[1] Master's Program Student in Water Resources Engineering, Universitas Brawijaya, Malang, Indonesia.
[2] Department of Water Resources Engineering, Universitas Brawijaya, Malang, Indonesia.

Received: May 21, 2026
Revised: June 21, 2026
Accepted: July 25, 2026
Published: July 31, 2026

Corresponding Author:
Rindang Santiago Samudra Suwarjo
rindangsss31@gmail.com

DOI: 10.29303/jppipa.v12i7.15366

Abstract: The operational performance of aging irrigation infrastructure in tropical developing countries remains poorly understood at the zone level, since aggregate evaluation conceals inter-zonal disparities. This study evaluated the Wawotobi Irrigation System, a 42-year-old scheme served by Wawotobi Weir, encompassing 11,595 ha across five zones in Southeast Sulawesi, Indonesia, using an integrated Water Delivery Performance Index (WDPI) and Water Evaluation and Planning (WEAP) framework under normal-year (Q50) and dry-year (Q80) conditions. Zone-disaggregated evaluation revealed a composite WDPI of 0.39 (poor), with adequacy ranging from 0.31 to 0.79 and reliability as low as 0.00 in two zones. Sensitivity analysis identified intake withdrawal capacity as the dominant constraint on reliability (sensitivity index = 2.81), whereas transmission loss coefficients showed uniformly low sensitivity. Multi-scenario simulation showed that Intake Optimization achieved the highest performance (WDPI of 0.76 under Q50 and 0.56 under Q80), while Downstream Priority reallocation proved counterproductive, reducing equity from 0.58 to 0.10 under Q50 by withholding supply from lower-priority zones. A strong adequacy-reliability correlation (r = 0.91 under Q50) explains why intake-focused interventions outperform distributional adjustments alone, identifying intake capacity enhancement as the most effective strategy for improving irrigation performance in aging tropical systems.

Keywords: Adequacy; Equity; Reliability; Sensitivity analysis; Water delivery performance index

Introduction

Food security remains one of the most significant challenges of the twenty-first century, particularly in densely populated agrarian countries where agricultural production depends heavily on reliable irrigation water supply. Indonesia, with a population of more than 270 million people, faces increasing pressure to expand agricultural production to meet growing domestic food demand (Yuliani & Asrofani, 2024), with more than 74% of national freshwater use allocated to agriculture (Tirtalistyani et al., 2022). This dependence is increasingly threatened by deteriorating irrigation infrastructure, approximately 46% of which is categorized as moderately to heavily damaged (Tirtalistyani et al., 2022), compounded by shortcomings in water governance and operational management (Grafton et al., 2024). In tropical irrigation systems with high seasonal variability, these shortcomings manifest as recurring distribution failures that rehabilitation alone cannot resolve, particularly where equitable and reliable delivery across spatially distributed service zones remains structurally constrained (Chala & Akamo, 2024; Hassan et al., 2023) amid limited operational

How to Cite:
Suwarjo, R. S. S., Wahyuni, S., & Sajali, M. A. (2026). Integrated WDPI–WEAP Framework for Multi-Scenario Evaluation of Irrigation Water Delivery Performance: A Case Study of Wawotobi Irrigation System, Indonesia. *Jurnal Penelitian Pendidikan IPA*, *12*(7), 216–225. https://doi.org/10.29303/jppipa.v12i7.15366

adaptability to hydrological variability (Sikka et al., 2022).

The Wawotobi Irrigation System in Konawe Regency, Southeast Sulawesi, reflects these conditions. It serves a functional irrigation area of 11,595 ha, sourced from the Konaweha River through Wawotobi Weir and distributed across five observation zones: Wawotobi, Wonggeduku, Pondidaha, Ameroro, and Unaaha. The Ameroro zone here denotes an administrative service block supplied through the right intake of Wawotobi Weir, distinct from the separately managed D.I. Ameroro scheme served by the newly commissioned Ameroro Dam. Constructed in 1982, Wawotobi Weir has operated for more than 42 years and is approaching the end of its design service life; operational records from 24 semi-monthly periods show that 11 experienced distribution deficits stemming from conveyance losses, a static operational approach poorly responsive to hydrological variability, and the absence of zone-based performance evaluation limiting interventions to system-wide symptoms rather than zone-specific causes.

Performance evaluation based on adequacy, equity, and reliability indicators, established through the Water Delivery Performance Index (WDPI) of Molden & Gates (1990) and extended by Dziedzic & Karney (2016), provides a structured basis for such evaluation. Prior WDPI studies, however, have generally evaluated performance at the aggregate system level, a practice that, as this study demonstrates, conceals inter-zonal disparities and renders the equity dimension mathematically uncomputable, since equity requires variability between zones within the same period (Chala & Akamo, 2024; Gebeyhu et al., 2024). This tendency is also evident in Indonesian irrigation studies, where indices such as the national Irrigation System Performance Index (IKSI) are typically applied at the system-wide scale without disaggregating performance across service zones (Pratama et al., 2022), while WEAP-based studies have mainly addressed water balance and unmet demand without translating zone-level outputs into structured performance indicators (Ahmed et al., 2026; Dhaqane et al., 2025). No established framework therefore combines zone-level diagnostic evaluation with scenario-based simulation, a gap particularly consequential for aging tropical infrastructure, where rehabilitation is costly and operational adjustment is often the only feasible intervention.

This study addresses this gap by integrating WDPI and WEAP to evaluate the operational performance of the Wawotobi Irrigation System, evaluating existing performance across the adequacy, equity, and reliability dimensions at the zone level, simulating performance under normal-year (Q50) and dry-year (Q80) conditions, and comparing outcomes across scenarios to identify the interrelationships among the three dimensions, extending the scenario-based operational evaluation approach recently applied to reservoir-fed irrigation systems in Indonesia (Lufira et al., 2025) into a zone-disaggregated diagnostic framework. Its novelty lies in establishing zone-based service boundaries as a prerequisite for valid equity computation, integrating zone-disaggregated WDPI directly into WEAP's scenario output as a diagnostic-to-prescriptive framework, and applying it to an aging tropical system under two contrasting hydrological conditions, a combination largely absent from existing literature. Relying only on routinely collected operational data rather than specialized instrumentation, the approach is directly replicable across similarly aging, data-limited irrigation systems, offering agencies methodological grounds to adopt zone-based monitoring in place of aggregate indices that may mask the inequities most consequential for downstream farmers.

Method

The Wawotobi Irrigation System is located in Konawe Regency, Southeast Sulawesi Province, Indonesia. Wawotobi Weir, the primary control structure of the system, is situated at coordinates 4°10'30" S and 122°30'30" E at an elevation of approximately 30 m above sea level, with water sourced primarily from the Konaweha River. The irrigation service area spans 11 administrative districts, with a distribution network comprising two main intake structures serving 24 distribution zones through three primary canals and 18 secondary canals, with a total canal length of 139 km and flow regulation controlled through 107 offtake structures. The system's original design area of 18,550 ha has been reduced to a potential area of 16,010 ha due to land use conversion, with an active functional area of 11,595 ha, representing 72.4% of the potential area, distributed across five observation zones served through two intakes: the right intake serving Ameroro, and the left intake serving Unaaha, Wawotobi, Wonggeduku, and Pondidaha. The geographical location of the study area is presented in Figure 1. The functional area of each zone is summarized in Table 1.

Table 1. Functional area of each observation zone

Zone	Functional Area (ha)
Ameroro	925.43
Unaaha	2,482.58
Wawotobi	1,579.01
Wonggeduku	2,620.26
Pondidaha	3,987.72
Total	11,595.00

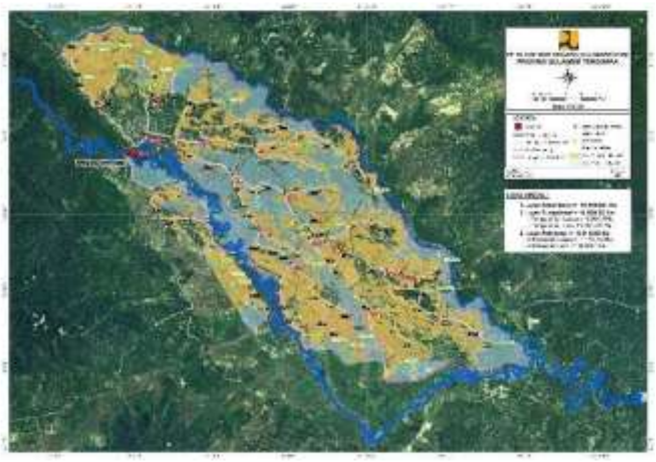

Figure 1. Study area

Data Collection

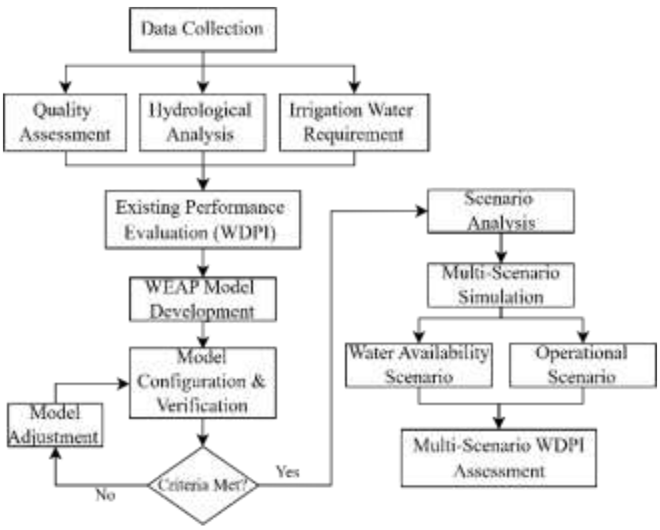

Figure 2. WDPI-WEAP multi-scenario evaluation framework

This study utilized secondary data obtained from relevant institutional sources, selected based on the requirements of WDPI computation and WEAP model development, following the overall methodological framework summarized in Figure 2. Streamflow records for the 2015 to 2024 period were provided by the Regional River Basin Organization (BWS Sulawesi IV Kendari), serving as the primary input for reliable discharge analysis and WEAP supply configuration. Actual distribution volumes per observation zone and weir operational reports covering the same period were supplied by the Regional Water Resources Management Unit (UPT PSDA Konawe), forming the basis for model calibration, validation, and performance index computation. Rainfall and climatological parameters, including monthly precipitation, temperature, relative humidity, sunshine duration, and wind speed, were sourced from the Konaweha rainfall station network comprising three stations (Lambuya, Abuki, and Mowewe) and the Kendari Meteorological Agency (BMKG). Irrigation network specifications, cropping pattern schedules, and crop coefficients were obtained from UPT PSDA Konawe and the Konawe District Agriculture Office, following the Indonesian Irrigation Planning Standards (KP-01; Kementerian Pekerjaan Umum, 2013). All data collection procedures were consistent with the data requirements prescribed for irrigation performance evaluation and hydrological modeling in data-limited developing country contexts (Moriasi et al., 2007; Ahmed et al., 2026).

Data Quality Assessment

Prior to analysis, streamflow and rainfall data were subjected to systematic quality assessment to ensure statistical validity. Rainfall consistency was evaluated using the Double Mass Curve method, comparing cumulative records from each station against the cumulative average of neighboring reference stations, with inconsistent records corrected through station-specific correction factors. Stationarity and independence were subsequently verified through the Fisher F-test, the Student t-test, and the Spearman rank correlation coefficient (persistence and trend absence tests), all applied at a 5% significance level. For streamflow data, homogeneity was assessed using four complementary tests implemented within the XLSTAT platform (Pettitt, SNHT, Buishand, and von Neumann), while trend analysis was performed using the Mann-Kendall test. Only data series satisfying all quality criteria were retained for subsequent hydrological analysis.

Hydrological Analysis

Areal rainfall was computed using the Thiessen polygon method, with station influence areas determined through spatial analysis in ArcGIS. Reference evapotranspiration (ETo) was calculated using the modified Penman method applied to climatological data averaged over the 2015 to 2024 period. Reliable discharge analysis was performed using the Weibull probability method applied to the 10-year streamflow dataset, from which two hydrological conditions were established as water availability scenarios for simulation: the normal-year condition, represented by the 50th percentile discharge (Q50), and the dry-year condition, represented by the 80th percentile discharge (Q80), corresponding respectively to typical and water-limited supply situations, consistent with recent scenario-based water allocation assessments under climate variability in comparable developing-country contexts (Mwelwa et al., 2024).

Irrigation Water Requirement

Irrigation water requirements were computed for each of the five observation zones based on their respective functional areas and cropping schedules, providing zone-disaggregated demand inputs for both WDPI computation and WEAP model configuration. Three cropping seasons were considered: Cropping Season I (CS-I, paddy), Cropping Season II (CS-II, paddy), and Cropping Season III (CS-III, maize), following the actual cropping calendar obtained from the Konawe District Agriculture Office. Crop coefficients (Kc) followed the KP-01 standard, with paddy coefficients of 1.10, 1.10, 1.05, 0.95, and 0.00 for successive growth stages, and maize coefficients applied accordingly. Percolation was set at 3 mm/day for medium clay soil conditions, and water layer replacement was applied at 3.3 mm/day. Land preparation requirements were computed using the van de Goor and Zijlstra method (30-day preparation period, 250 mm soil water storage). Effective rainfall was derived from the 80th percentile reliable rainfall (R80) with a utilization coefficient of 0.7 for paddy fields, and total irrigation efficiency was set at 65%, consistent with the existing infrastructure condition of the 42-year-old system. The resulting differentiation of irrigation demand across zones, reflecting variation in functional area and cropping schedule, constitutes the demand basis for equity computation in the WDPI framework.

Existing Performance Evaluation (WDPI)

Performance evaluation was conducted in two sequential stages to capture both system-level and zone-level distributional characteristics. At the aggregate level, adequacy can be quantified directly; however, the equity dimension requires zone-disaggregated data to be computed validly, as it measures inter-zonal distributional variability within each observation period. In the second stage, performance was evaluated independently for each of the five observation zones using zone-level actual distribution data and zone-specific irrigation water requirements.

The Water Delivery Performance Index (WDPI), originally developed by Molden & Gates (1990) and extended by Dziedzic & Karney (2016), was applied to quantify three independent performance dimensions. The adequacy index (A) measures the ratio of actual water delivery to irrigation water requirement for each zone across all observation periods, computed as the mean of period-level adequacy ratios capped at unity:

$$A_{i,t} = \min\left\{\frac{Q_{del,i,t}}{Q_{dem,i,t}}, 1\right\} \quad (1)$$

The aggregate adequacy index is:

$$\overline{A} = \frac{1}{T}\sum_{t=1}^{T}\frac{1}{N}\sum_{i=1}^{N}A_{i,t} \quad (2)$$

The equity index (E) quantifies distributional uniformity among zones within each period through the coefficient of variation of zone-level adequacy ratios:

$$E_t = \max(0, 1 - CV_t) \quad (3)$$

$$CV_t = \frac{\sigma(A_{i,t})}{\mu(A_{i,t})} \quad (4)$$

The aggregate equity index is:

$$\overline{E} = \frac{1}{T}\sum_{t=1}^{T}E_t \quad (5)$$

The reliability index (R) measures the proportion of observation periods in which water supply meets or exceeds the minimum crop water requirement for each zone:

$$R_i = \frac{1}{T}\sum_{t=1}^{T}r_{i,t} \quad (6)$$

where $r_{i,t} = 1$ if $Q_{del,i,t} \geq Q_{dem,i,t}$, and $r_{i,t} = 0$ otherwise. The aggregate reliability index is:

$$\overline{R} = \frac{1}{N}\sum_{i=1}^{N}R_i \quad (7)$$

The composite WDPI is the arithmetic mean of the three dimensions:

$$WDPI = \frac{\overline{A} + \overline{E} + \overline{R}}{3} \quad (8)$$

Performance was classified as very good (WDPI ≥ 0.80), good (0.65 ≤ WDPI < 0.80), moderate (0.50 ≤ WDPI < 0.65), and poor (WDPI < 0.50), consistent with the classification framework applied in recent irrigation performance studies (Chala & Akamo, 2024; Bosco, 2024).

WEAP Model Development, Configuration, Calibration, and Validation

The WEAP model was developed to represent the water allocation dynamics of the Wawotobi Irrigation System, configured with Wawotobi Weir on the Konaweha River as the primary supply node with two intake structures, five demand sites corresponding to the observation zones, and the distribution network schematic connecting intakes to demand sites through primary and secondary canals. Reliable discharge series under Q50 and Q80 conditions served as supply time series inputs, while zone-level irrigation water requirements served as demand inputs. The model employed a priority-based allocation mechanism, with all zones initially assigned equal allocation priority under the baseline configuration.

Model configuration was verified through iterative calibration using actual distribution data for the 2015 to 2020 period, adjusting the transmission loss coefficient (Loss From System) along the distribution network until simulated distribution volumes converged with observed operational records across all five zones. Model performance was evaluated using three statistical criteria recommended by Moriasi et al. (2007): Nash-Sutcliffe Efficiency (NSE, satisfactory at NSE ≥ 0.50)

$$NSE = 1 - \frac{\sum_{t=1}^{T}\left(Q_{obs,t} - Q_{sim,t}\right)^2}{\sum_{t=1}^{T}\left(Q_{obs,t} - \bar{Q}_{obs}\right)^2} \quad (9)$$

Percent Bias (PBIAS, satisfactory within ±25%),

$$PBIAS = \frac{\sum_{t=1}^{T}\left(Q_{obs,t} - \bar{Q}_{obs}\right)}{\sum_{t=1}^{T} Q_{obs,t}} \quad (10)$$

and coefficient of determination (R^2, satisfactory at $R^2 \geq 0.60$),

$$R^2 = \frac{\left[\sum_{t=1}^{T}\left(Q_{obs,t} - \bar{Q}_{obs}\right)\left(Q_{sim,t} - \bar{Q}_{sim}\right)\right]^2}{\sum_{t=1}^{T}\left(Q_{obs,t} - \bar{Q}_{obs}\right)^2 \sum_{t=1}^{T}\left(Q_{sim,t} - \bar{Q}_{sim}\right)^2} \quad (11)$$

Model verification satisfying all three criteria completed the calibration loop; where criteria were not met, the loss coefficient was further adjusted before re-evaluation. Model validation was subsequently conducted using independent data from the 2021 to 2024 period, applying the calibrated parameters without further adjustment and evaluating performance against the same statistical criteria to confirm predictive transferability.

Scenario Analysis and Multi-Scenario WDPI Assessment

Following model validation, sensitivity analysis was conducted to identify the operational parameters most influential on distribution performance. Two continuous parameters, the transmission loss coefficient (Loss From System) and the intake capacity parameter (Maximum Diversion), were each varied by ± 20% from their calibrated baseline under Q50 conditions while holding other parameters constant. Priority allocation parameters were excluded, as their ordinal nature precludes meaningful percentage-based variation within the WEAP allocation framework. The sensitivity index (Si) was computed using an elasticity-based method:

$$S_i = \frac{(Y - Y_0)/Y_0}{\left(x_i - x_{i,0}\right)/x_{i,0}} \quad (12)$$

Where Y is the WDPI output after parameter variation, Y_0 is the baseline WDPI output, $xi$is the varied parameter value, and $x_{i,0}$ is the baseline value. Sensitivity was classified as high (S_i > 1.0), moderate (0.5 < S_i ≤ 1.0), low (0.2 < S_i ≤ 0.5), or negligible (S_i ≤ 0.2).

Multi-scenario simulation combined two water availability scenarios (Q50, Q80) with five operational scenarios, yielding 10 combinations. The Existing scenario replicated current operations with equal allocation priority across zones, serving as the baseline. The Downstream Priority scenario compensated for structural deficits in the most downstream zones: for the right intake serving Ameroro, priority remained at 1; for the left intake, priority 1 was assigned to Wonggeduku and Pondidaha as the most downstream zones, while Wawotobi and Unaaha, closer to the intake head, received priority 2 and 3 respectively, restricting upstream withdrawal in favor of tail-end delivery. The Network Efficiency scenario simulated rehabilitation by reducing zone-specific losses toward the KP-01 technical standard, from existing calibrated levels (8%) for Ameroro, 10% for Unaaha, 10% for Wawotobi, 12% for Wonggeduku, and 12% for Pondidaha) to a uniform 5%, representing a well-maintained but physically realistic network rather than a zero-loss condition. The Intake Optimization scenario maximized withdrawal by setting each zone's supply to its historically recorded maximum discharge per period. The Combined scenario simultaneously applied all three preceding adjustments. WDPI computation followed the procedure in the preceding section, generating a performance matrix of adequacy, equity, reliability, and composite WDPI for all 10 combinations, compared across scenarios and hydrological conditions to evaluate relative effectiveness.

Result and Discussion

Model Calibration and Validation Performance

Model calibration using 2015–2020 data showed satisfactory performance at both intakes (NSE, PBIAS, R^2 of 0.65, 21.03%, 0.74 for the right intake; 0.60, 20.46%, 0.70 for the left), meeting the criteria of Moriasi et al. (2007). Validation with independent 2021–2024 data confirmed predictive capability (0.54, 24.34%, 0.65 for the right intake; 0.50, 24.10%, 0.60 for the left), also satisfying the recommended thresholds; the slightly lower validation values are expected when applying the model to an independent dataset and do not affect its suitability for scenario simulation. Zone-level evaluation of existing operational performance revealed substantial disparities among the five service zones, summarized in Table 2.

The adequacy dimension shows Pondidaha achieving the highest zone-level value (0.79), while Ameroro records the lowest (0.31), a disparity of nearly 0.5 that would be entirely invisible under aggregate-level evaluation. This finding directly supports the methodological argument advanced in the introduction: aggregate evaluation systematically overestimates system performance by masking zone-specific deficiencies. The reliability dimension yields the most critical result, with Wawotobi and Ameroro recording values of 0.00, indicating that supply never met crop water requirements across the full observation period in these two zones, while even the best-performing zone, Pondidaha, only reaches 0.21. The equity index of 0.58 reflects moderate inter-zonal variability, a level that, notably, is not the weakest of the three dimensions, indicating that the system's principal constraint lies less in unequal distribution per se than in its general inability to reliably meet demand across zones. The composite WDPI of 0.39 places the existing operational condition in the poor category, confirming that the Wawotobi Irrigation System, after 42 years of operation, has not delivered water adequately, equitably, or reliably under current management practices. This poor classification stands in notable contrast to the conventional Irrigation System Performance Index (IKSI) score of 58.85%, categorized as moderate under national infrastructure assessment criteria; the discrepancy arises because IKSI evaluates physical infrastructure condition and productivity at the system-wide scale, whereas WDPI captures the zone-level and period-level distributional failures that aggregate infrastructure scoring cannot resolve, underscoring the diagnostic value of zone-disaggregated evaluation over conventional infrastructure-based assessment alone.

Table 2. Zone-level WDPI of the Wawotobi irrigation system under existing operational conditions

Dimension	Wawotobi	Wonggeduku	Pondidaha	Unaaha	Ameroro	Composite	Category
Adequacy	0.34	0.55	0.79	0.54	0.31	0.51	Moderate
Equity		computed across zones per period				0.58	Moderate
Reliability	0.00	0.04	0.21	0.08	0.00	0.07	Poor
Composite WDPI						0.39	Poor

Sensitivity Analysis of WEAP Model Parameters

Sensitivity analysis results, summarized in Table 3, reveal markedly contrasting parameter influence across the four WDPI dimensions. The Loss From System parameter exhibits uniformly low sensitivity across all dimensions, indicating that variation in network transmission losses within ± 20% produces negligible change in system-level performance. In contrast, Maximum Diversion demonstrates substantially higher influence, particularly on reliability, where a mean Si of 2.81 exceeds the high-sensitivity threshold (Si > 1.0) by a wide margin. This indicates that intake withdrawal capacity, not conveyance efficiency, is the dominant operational constraint on the temporal consistency of water supply. The moderate sensitivity of Maximum Diversion to adequacy (Si = 0.76) further suggests that intake capacity improvements would yield measurable gains in supply sufficiency, whereas its low sensitivity to equity (Si = 0.06) indicates that the proportional allocation mechanism distributes any intake-level change relatively uniformly across zones, leaving inter-zonal distributional uniformity largely unaffected by intake-level intervention alone.

Table 3. Mean sensitivity index (Si) of WEAP model parameters across WDPI dimensions

Parameter	Adequacy ($\bar{A}$)	Equity ($\bar{E}$)	Reliability ($\bar{R}$)	Composite WDPI
Loss From System	0.10 (Negligible)	0.00 (Negligible)	0.31 (Negligible)	0.06 (Negligible)
Maximum Diversion	0.76 (Moderate)	0.06 (Negligible)	2.81 (High)	0.53 (Moderate)

Table 4. WDPI performance outcomes across operational scenarios under Q50 and Q80 conditions

Condition	Scenario	Adequacy	Equity	Reliabillity	Composite	Category
Q50	Existing	0.55	0.58	0.09	0.41	Poor
	Network Efficiency	0.58	0.53	0.15	0.42	Poor
	Downstream Priority	0.47	0.10	0.24	0.27	Poor
	Intake Optimization	0.86	0.75	0.66	0.76	Good
	Combined	0.78	0.57	0.61	0.66	Good
Q80	Existing	0.45	0.57	0.08	0.36	Poor
	Network Efficiency	0.50	0.54	0.13	0.39	Poor
	Downstream Priority	0.39	0.07	0.20	0.22	Poor
	Intake Optimization	0.67	0.64	0.38	0.56	Moderate
	Combined	0.65	0.48	0.47	0.53	Moderate

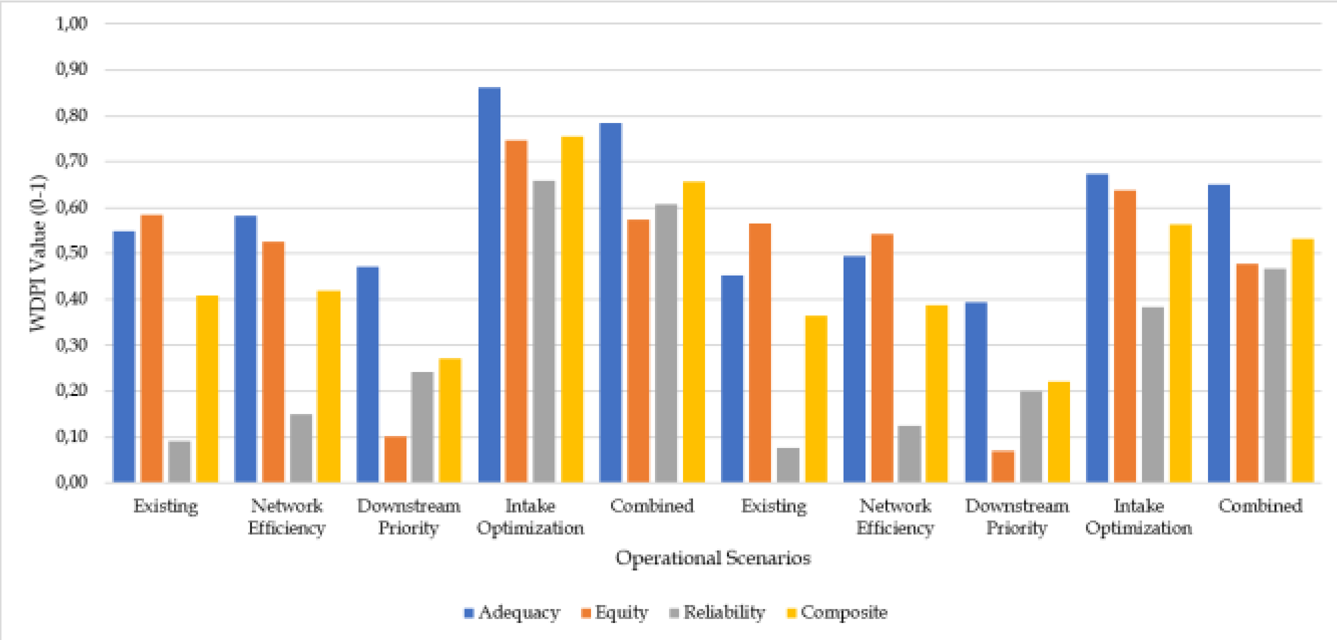

Figure 3. Comparison of WDPI dimensions under operational scenarios for Q50 (normal flow) and Q80 (dry flow) conditions

Multi-Scenario Performance Under Normal-Year and Dry-Year Conditions (Q50 and Q80)

Table 4 presents the WDPI performance outcomes across all five operational scenarios under both Q50 and Q80 hydrological conditions. Under Q50 conditions, the existing scenario yields a composite WDPI of 0.41 (poor). Intake Optimization achieves the largest improvement, raising composite WDPI to 0.76 (good), a result directly attributable to the parameter identified as most influential in the sensitivity analysis above. The Combined scenario, at 0.66, remains in the good category but performs below Intake Optimization alone, indicating that simultaneously applying priority reallocation together with intake and network interventions does not necessarily outperform a single, well-targeted intervention. Network Efficiency produces only a marginal gain, from 0.41 to 0.42, remaining in the poor category and confirming the low sensitivity of the loss coefficient identified earlier. Most notably, Downstream Priority produces a counterintuitive decline, from 0.41 to 0.27, driven by a sharp fall in equity from 0.58 to 0.10. Within the WEAP priority-based allocation mechanism, assigning higher precedence to specific zones systematically constrains supply to lower-priority zones, increasing inter-zonal variability rather than resolving it, demonstrating that priority reallocation without a corresponding increase in total supply merely redistributes scarcity rather than alleviating it.

Under Q80 conditions, overall performance declines relative to Q50 across all scenarios, though the relative ranking among scenarios remains consistent. The existing scenario declines from 0.41 to 0.36, reflecting reduced water availability under dry-year conditions, a pattern consistent with observed vulnerability of both indigenous and conventional irrigation systems to seasonal water scarcity in tropical dry-zone contexts (Wickramasinghe & Nakamura, 2024). Intake Optimization again produces the largest improvement, though it no longer reaches the good category, plateauing at 0.56 (moderate), demonstrating that reduced streamflow limits the extent to which intake capacity alone can compensate for supply constraints. The Combined scenario similarly declines to 0.53. Downstream Priority again performs worst at 0.22, with equity collapsing from 0.57 to 0.07, an even sharper decline than under Q50, confirming that priority-based reallocation is counterproductive regardless of hydrological condition, and becomes more severe precisely when total water availability is most constrained. The narrowing gap between Intake Optimization (0.56) and Combined (0.53) under Q80, compared with the wider gap observed under Q50 (0.76 versus 0.66), suggests that as water availability tightens, the marginal cost of including a counterproductive priority component in a combined intervention becomes proportionally smaller relative to the binding constraint of total supply itself.

Comparative Performance Across Operational Scenarios

The comparison in Table 4 shows that, across both hydrological conditions, Intake Optimization consistently delivers the most robust improvement, achieving good performance under Q50 (0.76) and moderate performance under Q80 (0.56), directly addressing the operational constraint identified through sensitivity analysis. The Combined scenario slightly underperforms Intake Optimization alone under both conditions (0.66 versus 0.76 under Q50; 0.53 versus 0.56 under Q80), indicating that the inclusion of priority reallocation within the Combined scenario introduces an equity penalty that partially offsets the gains achieved through intake and network intervention. Network Efficiency yields only marginal improvement under both conditions (0.42 and 0.39, respectively), remaining in the poor category throughout, consistent with the low sensitivity of the transmission loss parameter. Downstream Priority underperforms the existing condition under both hydrological conditions, confirming that priority-based reallocation, without a corresponding increase in total supply, is counterproductive irrespective of water availability. Taken together, these results indicate that operational intervention effectiveness in the Wawotobi system is hydrologically conditional in magnitude but consistent in direction: the same scenario ranking holds under both normal and dry-year conditions, allowing irrigation managers to adopt a single prioritization strategy, intake capacity enhancement first, network rehabilitation second, and cautious or avoided use of priority-based reallocation, without needing to reconfigure operational strategy season by season based on hydrological forecast alone.

Interrelationships Among WDPI Dimensions

Pearson correlation analysis among the three WDPI dimensions across all operational scenarios, summarized in Table 5, reveals consistently positive relationships under both hydrological conditions, though of varying strength. This analysis addresses the third objective of this study by examining whether improvements in one performance dimension are systematically associated with improvements or trade-offs in the others, providing insight into the underlying mechanism through which operational interventions translate into overall system performance, rather than treating each dimension as an independent outcome.

Table 5. Pearson correlation among WDPI dimensions under Q50 and Q80 conditions

Condition	Adequacy–Equity (A-E)	Adequacy–Reliability (A-R)	Equity–Reliability(E-R)
Q50	0.77	0.91	0.44
Q80	0.63	0.84	0.12

The adequacy-reliability relationship is the strongest under both conditions, indicating that improvements in supply sufficiency are closely associated with improvements in temporal consistency of delivery, a finding consistent with the sensitivity analysis result that intake capacity, the parameter most directly linked to adequacy, is also the dominant driver of reliability. This convergence between the correlation and sensitivity results provides internal methodological validation: two independent analytical procedures, one based on parameter perturbation and the other on cross-scenario association, arrive at the same operational conclusion, namely that adequacy and reliability are mechanistically linked through intake capacity rather than through independent pathways. The equity-reliability relationship is markedly weaker and declines further under Q80, from 0.44 to 0.12, indicating that under water-scarce conditions, more equitable distribution across zones does not translate into more reliable delivery to the same extent as under normal-year conditions. This weakening suggests that as total available supply diminishes, distributing it evenly across zones is no longer sufficient to raise reliability, since even a perfectly uniform but insufficient allocation still fails to meet zonal demand consistently across periods; in other words, equity and reliability become increasingly decoupled precisely when the system is under the greatest hydrological stress. Taken together, the dominance of the adequacy-reliability relationship across both hydrological conditions explains why Intake Optimization, the scenario most directly targeting adequacy, consistently produces the strongest overall performance gains observed in this study, reinforcing intake capacity as the single most consequential leverage point for improving the operational performance of the Wawotobi Irrigation System.

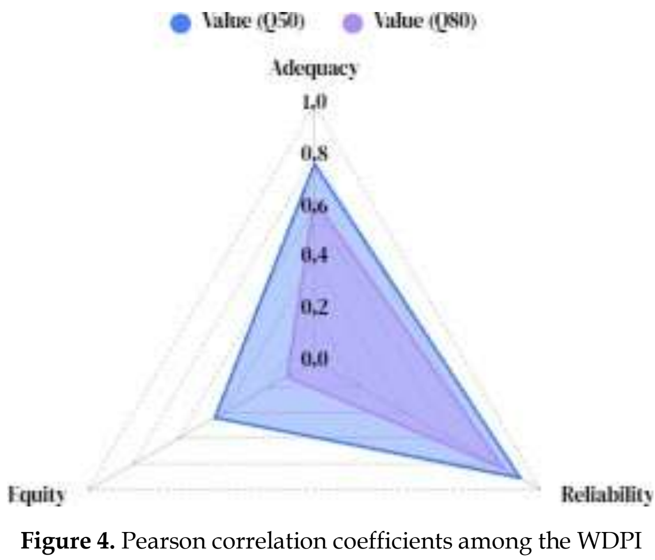

Figure 4. Pearson correlation coefficients among the WDPI dimensions for the Q50 and Q80 scenarios

Conclusion

This study developed and applied an integrated WDPI-WEAP framework to evaluate the operational performance of the Wawotobi Irrigation System, assessing existing conditions alongside eight alternative operational scenario combinations derived from cross-combining two hydrological conditions (Q50 and Q80) with four alternative management strategies. Zone-disaggregated evaluation of existing operational performance revealed a composite WDPI of 0.39, classified as poor, with pronounced inter-zonal disparities in adequacy ranging from 0.31 to 0.79 and reliability as low as 0.00 in two of the five service zones. This finding provides direct empirical evidence that aggregate-level evaluation conceals inter-zonal disparities that only become visible once distribution is disaggregated to the zone level, confirming the methodological premise underlying this study. Sensitivity analysis identified intake withdrawal capacity, represented by the Maximum Diversion parameter, as the dominant determinant of system performance, particularly for the reliability dimension, where the mean sensitivity index reached 2.81. Transmission loss coefficients, by contrast, exhibited uniformly low sensitivity across all four performance dimensions. Multi-scenario simulation confirmed this finding operationally: Intake Optimization consistently produced the strongest performance gains under both hydrological conditions, raising composite WDPI from 0.41 to 0.76 under normal-year conditions and from 0.36 to 0.56 under dry-year conditions, and consistently outperforming the Combined scenario under both conditions, while Downstream Priority proved counterproductive under both conditions due to the sharp equity decline induced by priority-based reallocation. Correlation analysis further showed that the adequacy-reliability relationship was consistently the strongest among the three performance dimensions, explaining why interventions targeting supply sufficiency, rather than distributional rules alone, yielded the most substantial improvements in overall system performance. Taken together, these findings indicate that operational adjustment of intake capacity, rather than physical network rehabilitation or priority-based redistribution, offers the most effective and immediately implementable pathway to improving irrigation performance in aging tropical infrastructure such as Wawotobi Weir. This study contributes a replicable, zone-based WDPI-WEAP diagnostic framework applicable to similarly aging, data-limited irrigation systems, relying only on routinely collected operational data rather than specialized field instrumentation. Future research should extend this framework by incorporating long-term climate variability as an additional hydrological scenario, validating simulated zone-level allocations against tertiary-level offtake data where such data become available, and exploring the integration of an explicit water-use efficiency dimension to capture actual on-field water utilization beyond distribution-level performance alone.

Acknowledgments
All author would like to thank to all parties who has supported this research.

Author Contributions
Conceptualization, methodology, formal analysis, investigation, writing—original draft, software, data curation, R.S.S.S.; writing—review and editing, supervision, visualization, S.W. and M.A.S. All authors have read and approved the published version.

Funding
This research received no external funding.

Conflicts of Interest
The authors declare no conflict of interest.

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