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Rice Irrigation Deficits under Monsoon-Dominated Hydrology: A Water Balance Study of the Bila Catchment, Indonesia

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Abstract: Food security in monsoon-dominated regions is threatened by mismatches between water availability and rice irrigation demand. Most water balance studies focus on annual availability, often masking critical intra-seasonal deficits. This study aims to analyze the intra-seasonal alignment and misalignment between water supply and rice irrigation demand in the Bila Watershed, Indonesia, a key rice-producing catchment. The novelty lies in the integration of the Soil and Water Assessment Tool (SWAT) hydrological model with the Food and Agriculture Organization's (FAO) CROPWAT model to provide a quantitative reliability assessment using the Irrigation Reliability Index (IRI) and Irrigation Deficit Severity Index (IDSI), which are metrics that are rarely applied in this region. The calibrated and validated SWAT model showed very good performance (NSE 0.77 calibration, 0.76 validation). The model revealed that the basin's hydrology is dominated by subsurface flow (81.7% of total water yield), providing a stable but slow release. Conversely, rice irrigation demand is concentrated during land preparation and vegetative growth (>80% of total demand). Despite a large annual water surplus, we identified a significant temporal mismatch (IRI 0.75; IDSI 106.12 mm) concentrated in April, October, and November. This finding highlights that the primary water management challenge is not overall water scarcity, but rather a critical temporal mismatch between slow-releasing hydrological supply and concentrated agronomic peak demand.

Keywords: food security; hydrological modeling; rice fields; sustainable irrigation; water balance.

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季风主导水文条件下水稻灌溉缺口研究：印尼比拉流域水文平衡分析

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摘要：
季风主导区域的粮食安全正面临水资源供给与水稻灌溉需求时间错配的威胁。多数水文平衡研究聚焦于年度水资源供给，往往掩盖了关键的季内缺口。本研究旨在分析印尼比拉流域——这一重要稻米产区——水资源供给与水稻灌溉需求在季内的匹配与错配情况。研究创新点在于将土壤与水评估工具（SWAT）水文模型与联合国粮农组织（FAO）的 CROPWAT 模型相结合，并采用灌溉可靠性指数（IRI）和灌溉缺水严重度指数（IDSI）开展定量可靠性评估——这些指标在本区域中极少应用。经校准与验证的 SWAT 模型表现优异（校准期 NSE 为 0.77，验证期为 0.76）。模型结果显示，流域水文特征以壤中流为主导（占总水量的 81.7%），形成稳定但释放缓慢的水源供给。相反，水稻灌溉需求主要集中于整地和营养生长期（占总需求的 80% 以上）。尽管全流域年水量呈显著盈余，但我们识别出明显的时间错配（IRI = 0.75；IDSI = 106.12 毫米），主要集中在 4 月、10 月和 11 月。研究表明，水资源管理的核心挑战并非整体水量不足，而是缓慢释放的水文供给与集中出现的农业高峰需水之间存在关键的时间错配。

关键词： 粮食安全；水文模型；稻田；可持续灌溉；水平衡。

1. Introduction

Rice (*Oryza sativa L.*) is a global staple, providing over 60% of the caloric intake for more than half of the world's population [1]. The production of this crop is contingent on the availability of water resources, and its demand for fresh water is two to three times greater than that of other cereal crops [2]. As global food demand increases, so does the competition for limited water resources, making water scarcity a critical challenge for agricultural sustainability, especially in tropical monsoon regions [3], [4].

Indonesia, a tropical monsoon region, relies on rice as its predominant staple food, which is consumed by nearly 90% of the population [5]. The South Sulawesi Province, in particular, is a major rice producer, with nearly 50% of its production depending on irrigated land [6]. However, agricultural activities in the Bila River Basin, a primary rice-producing region in the province, are increasingly vulnerable to seasonal hydrological fluctuations and uneven water distribution [7]. These issues have led to a significant decline in crop yields and a reduction in provincial rice production of 861,979.22 tons between 2018 and 2021 [8]. This decline underscores the pressing need for adaptive water management strategies to mitigate the impact of monsoon climate on the hydrological regime of the basin [9]. Given its critical role in national rice production and its documented hydrological vulnerability, the Bila Watershed was selected as an ideal and urgent case study to analyze this supply-demand gap.

Water balance assessments are imperative for diagnosing water availability, identifying periods of surplus or deficit, and formulating adaptive management strategies for water resource management [10], [11]. Hydrological modeling, particularly with the Soil and Water Assessment Tool (SWAT), provides a robust framework for simulating rainfall-runoff, water yield, and other key hydrological processes at the watershed scale [12], [13]. This tool has been used globally to facilitate comprehensive hydrological assessment [14]. The performance of this tool has been calibrated and validated in various agricultural watersheds, supported by a substantial user community and ease of implementation [15], [16]. Concurrently, the Food and Agriculture Organization's CROPWAT model is widely used to estimate crop water requirements and irrigation needs [17], [18]. The integration of SWAT and CROPWAT presents a robust methodology for correlating watershed hydrology with the irrigation demands of specific crops, thereby optimizing water allocation and enhancing irrigation reliability [19].

Notwithstanding the considerable progress achieved in the field of hydrological and irrigation modeling, the preponderance of prior studies in Southeast Asia has been centered on annual or aggregate water balance, thereby disregarding the pivotal intra-seasonal misalignment between water supply and demand. Although SWAT has been applied to quantify water yield components and CROPWAT has been used to estimate crop water requirements [20], there is a paucity of explicit coupling of these models to evaluate irrigation reliability under monsoon-driven variability in the region. Moreover, operational frameworks incorporating quantitative reliability indices, such as the Irrigation Reliability Index (IRI) and Irrigation Deficit Severity Index (IDSI), are virtually non-existent in Indonesia, despite the nation's heavy reliance on irrigated rice cultivation for food security.

To address these gaps, this study integrated SWAT-based hydrological simulations with CROPWAT-derived irrigation demand analyses. This integration was undertaken to quantify the intra-seasonal alignment and misalignment between the water yield and rice irrigation requirements in the Bila River Basin. The overarching objective was to identify critical surplus and deficit periods, assess irrigation reliability through IRI and IDSI, and generate actionable insights for adaptive water management. This study established an operational framework that links hydrological supply dynamics with crop-specific irrigation demand. This framework provides evidence-based implications for enhancing water-use efficiency, mitigating irrigation risk under monsoon variability, and strengthening regional food security.

2. Materials and Methods

2.1 Study Area

This study was conducted in the Bila River Basin, South Sulawesi, Indonesia (3° 33′ 20″–3° 53′ 20″ S, 119° 55′ 0″–120° 10′ 0″ E), covering an area of 41,919.39 ha (Figure 1). The Bila River Basin was selected because of its role as a representative monsoon-dominated rice irrigation system in Eastern Indonesia, where more than 50% of the regional rice production relies on small-scale surface and groundwater irrigation [5]. Its hydrological sensitivity to rainfall seasonality and dependence on shallow aquifers make it an ideal testbed for evaluating temporal irrigation reliability. The basin experiences a tropical monsoon climate with an average annual rainfall of 2,555 mm and an average temperature ranging from 21.5°C to 27.6°C. The land use was dominated by forest shrublands, dryland agriculture, and wetlands (rice fields), with a small proportion of residential areas and water bodies. Hydrological dynamics are significantly influenced by pronounced seasonal fluctuations in monsoon precipitation, with the wet season typically spanning October to March and the dry season from April to September [21].

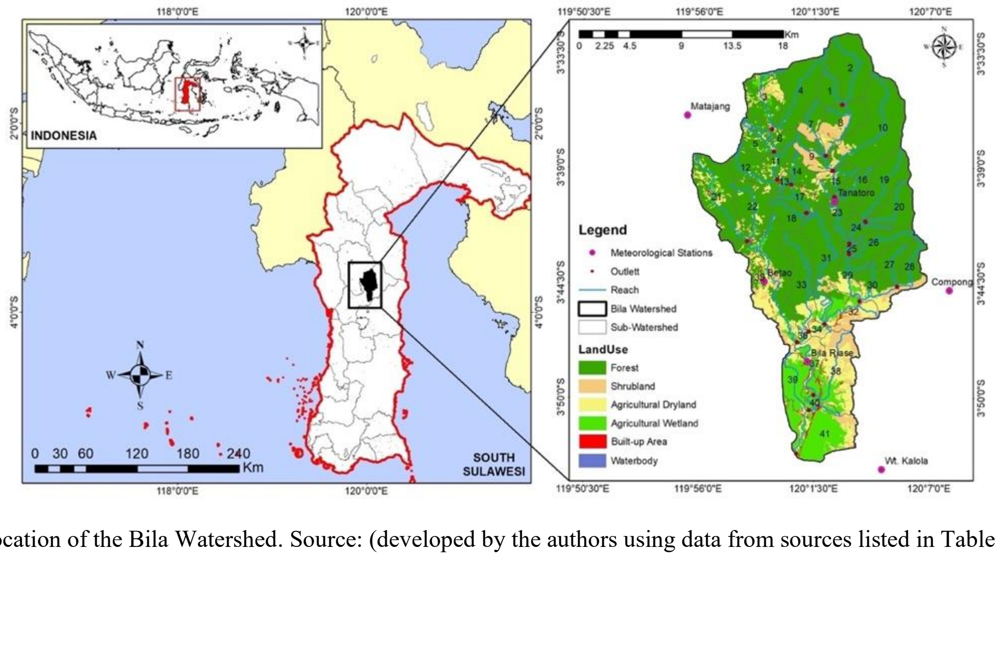

Fig. 1 Location of the Bila Watershed. Source: (developed by the authors using data from sources listed in Table 1, 2025)

2.2 Material

An array of spatial, climatic, hydrological, and agronomic datasets was used to support hydrological simulations with the SWAT model and crop water requirement estimations using CROPWAT (Table 1). Spatial datasets, including Forest and Buildings, removed Copernicus DEM (FABDEM) [22], and Sentinel-2A imagery, were primarily used for the model setup and HRU definition. Specifically, the Land Use/Land Cover (LULC) map was derived from the Sentinel-2A imagery (2024) using a supervised Maximum Likelihood classification in QGIS. Climatic and hydrological datasets from the Pompengan-Jeneberang River Basin Agency (BBWS) and NASA POWER, along with streamflow data from the Jeneberang-Walanae River Basin Management Agency (BPDAS), are essential for model calibration, validation, and simulation. For the CROPWAT analysis, key agronomic parameters, including the planting calendar (October and April) and stage-specific crop coefficients (Kc) for the Inpari 32 variety, were determined and validated using FAO-56 guidelines, local agronomic studies, and data from the Jeneberang-Walanae River Basin Management Agency (BPDAS). Rainfall inputs from the six gauges were completed using the Thiessen polygon method and climate variables were bias-corrected against local observations.

Tab. 1 Summary of datasets used in this study

Data Type	Source	Resolution / Scale	Period	Purpose
Digital Elevation Model (DEM)	Forest And Buildings removed Copernicus DEM (FABDEM) v1-2 [22]	30 m	–	Watershed delineation, slope classification
Land Use/Land Cover (LULC)	Sentinel-2A imagery (European Space Agency/ESA) [23]	10 m	2024	HRU definition, land cover classification
Soil Data	Indonesia Geospatial Information Agency (BIG) [24]	1:50,000	–	Soil parameters for SWAT & CROPWAT
Precipitation Data	Pompengan-Jeneberang River Basin Agency (BBWS), Ministry of Public Works and Housing (PUPR) Indonesia	Daily	2010–2023	SWAT hydrological simulation, CROPWAT ETo estimation
Climate Data	National Aeronautics and Space Administration (NASA) Langley Research Center's Prediction Of Worldwide Energy Resources (POWER) [25]	Daily	2010–2023	SWAT hydrological simulation, CROPWAT ETo estimation
Hydrological Data	Jeneberang-Walanae River Basin Management Agency (BPDAS), Ministry of Public Works and Housing (PUPR) Indonesia.	Daily	2010–2023	SWAT calibration & validation (streamflow)
Crop Parameters	FAO-56 guidelines, local agronomic studies	–	–	CROPWAT crop water requirement calculation (Kc, stage duration, rooting depth)

Source: (developed by the authors, 2025)

2.3 Methods

A five-stage procedure was employed to simulate hydrological processes using SWAT Rev. 2012 via the QSWAT interface. The procedure involved watershed delineation, hydrological response unit (HRU) analysis, input data preparation, model execution, and calibration and validation. This framework has gained significant traction in basin-scale hydrology because of its ability to integrate spatial heterogeneity, climate, and land-use dynamics within a unified modeling environment [13], [26]. Following the approach of [27], zero thresholds (0% land use, 0% soil, and 0% slope) were implemented to preserve the complete spatial heterogeneity of the landscape, which is crucial for representing the fine-grained mosaic of smallholder rice paddies and fragmented agroforestry plots in the Bila watershed. This resulted in the subdivision of the basin into 41 subbasins and 1,111 HRUs. At the HRU scale, SWAT governs the daily soil–water balance (eq. 1.) [28]:

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - ET - W_{seep} - Q_{gw}) \quad (1)$$

where: SW_t is final soil water storage (mm); SW_0 is initial storage (mm), R_{day} is precipitation (mm d^{-1}); Q_{surf} is surface runoff (mm d^{-1}); ET is actual evapotranspiration (mm d^{-1}); W_{seep} is percolation (mm d^{-1}); Q_{gw} is return flow from shallow aquifer (mm d^{-1}). The model application focused on four key outputs: surface runoff (Q_{surf}), lateral flow (Q_{lat}), groundwater flow (Q_{gw}), and water yield

(W_{yld}). The collective contributions of these components were computed at the HRU level and subsequently routed through the sub-basins and river channels to generate the total simulated streamflow at the watershed outlet (Q_{sim}). The total water yield is defined by the following (eq. 2.) [29]:

$$W_{yld} = Q_{surf} + Q_{lat} + Q_{gw} - T_{loss} \tag{2}$$

where: T_{loss} is transmission losses (mm d^{-1}). This formulation provides a physically consistent representation of the effective hydrological pathways sustaining streamflow, thereby serving as a robust proxy for evaluating irrigation water supply in monsoon-regulated tropical catchments [30].

The simulation period spanned from 2010 to 2023 and was divided into a two-year warm-up period (2010–2011) to stabilize the model outputs, followed by calibration (2011–2018) and validation (2019–2023). The SWAT model was run at a daily time step, and calibration and validation were conducted against the monthly aggregated streamflow to reduce noise from daily rainfall variability [15], [31]. The calibration and validation processes were executed using the SWAT-CUP model, employing the SUFI-2 (Sequential Uncertainty Fitting 2) algorithm. The performance of the model was evaluated by comparing the simulated streamflow (Q_{sim}) with the observed streamflow data (Q_{obs}). The primary metrics used for this evaluation were Nash–Sutcliffe Efficiency (NSE), coefficient of determination (R^2), and Percent Bias (P_{bias}) [32]. A comprehensive performance evaluation metric based on the recommended statistical thresholds for SWAT model simulations was used, as detailed in Table 2.

Tab. 2 SWAT model performance rating for streamflow

Performance rating	NSE	R^2	P_{bias} (%)
Very good	0.75 < NSE ≤ 1.00	0.75 < R^2 ≤ 1.00	P_{bias} < ±10
Good	0.65 < NSE ≤ 0.75	0.65 < R^2 ≤ 0.75	±10 < P_{bias} ≤ ±15
Satisfactory	0.50 < NSE ≤ 0.65	0.50 < R^2 ≤ 0.65	±15 < P_{bias} ≤ ±25
Unsatisfactory	NSE ≤ 0.50	R^2 ≤ 0.50	P_{bias} > ±25

Source: (adapted from [15] [32])

The calibration process focused on a set of hydrologically sensitive parameters that govern runoff, base flow, soil water dynamics, and evapotranspiration, which is consistent with the findings from other monsoon-regulated basins. For a comprehensive overview, refer to Table 3.

Tab. 3 Key SWAT parameters used in calibration

Parameter (code)	Description	Transformation	Unit	Calibrated Value	Range (Min–Max)
CN2.mgt	SCS curve number for moisture condition II	r__ (relative)	–	–0.24	–0.30 to 0.30
ALPHA_BF.gw	Baseflow recession constant	v__ (replace)	day^{-1}	0.53	0.00 to 1.00
GW_DELAY.gw	Groundwater delay time	v__ (replace)	days	38.33	0 to 500
GWQMN.gw	Threshold water depth in shallow aquifer for return flow	v__ (replace)	mm	0.50	0 to 500
SOL_AWC().sol	Available water capacity of the soil layer	v__ (replace)	mm mm^{-1}	0.70	–1 to 2
CH_N2.rte	Manning's roughness coefficient for main channel	v__ (replace)	–	0.77	0.01 to 1.00
CH_K2.rte	Effective hydraulic conductivity in main channel	v__ (replace)	mm h^{-1}	450.00	0 to 1,000
ESCO.hru	Soil evaporation compensation factor	v__ (replace)	–	0.51	0.01 to 1.00
EPCO.hru	Plant uptake compensation factor	v__ (replace)	–	0.70	0.01 to 1.00
RCHRG_DP.gw	Deep aquifer percolation fraction	v__ (replace)	–	0.10	0.00 to 1.00
OV_N.hru	Manning's roughness coefficient for overland flow	v__ (replace)	–	1.01	0.01 to 30.00
SURLAG.bsn	Surface runoff lag coefficient	v__ (replace)	days	15.22	0.05 to 24.00
REVAPMN.gw	Threshold depth of water in shallow aquifer for revap	r__ (relative)	mm	575.00	0 to 750

Source: (developed by the authors based on literature [28] [30] [31] [32])

Relative transformations were applied to the dimensionless indices, whereas absolute replacements were reserved for the physically based parameters. This approach ensures transparency, prevents overfitting, and maintains physical consistency within the SWAT-CUP guidelines [36]. All parameter ranges were bounded by the recommended thresholds and previous literature, ensuring the reproducibility and robustness of the calibration procedure.

The CROPWAT 8.0 model was used to quantify the irrigation requirements for the rice cultivation. Reference evapotranspiration (ET_0) was calculated using the FAO Penman–Monteith equation, and crop evapotranspiration (ET_c) was derived by multiplying ET_0 with stage-specific crop coefficients (K_c) for rice. Effective rainfall (P_{eff}) was estimated using the USDA–SCS method [37]. This procedure ensures that irrigation demand is quantified in a manner consistent with internationally recognized FAO guidelines and is widely adopted in irrigation planning studies [38]. The net irrigation requirement (NIR) was defined as the difference between ETc and Peff (eq. 3.), and the gross irrigation requirement (GIR) was adjusted for conveyance (η_{conv}) and field application efficiency (η_{field}). The formula for calculating GIR from NIR is as follows [39], [40]:

$$NIR = \max(0, ET_c - P_{eff}) \tag{3}$$

$$GIR = \frac{NIR}{\eta_{conv} \cdot \eta_{field}} \tag{4}$$

Following the approach of [41], [42], the monthly gross irrigation requirement (GIR_m) was compared with the SWAT-simulated water yields ($Q_{k,m}$) for both aggregate (W_{yld}) and individual hydrological components $k \in \{Q_{surf}, Q_{lat}, Q_{gw}\}$. The balance between supply and demand was quantified, with negative values indicating an irrigation deficit ($Balance_{k,m} < 0$) (eq. 5.). To provide a robust quantitative foundation for evaluating irrigation shortfalls, two indicators from the reliability–vulnerability framework [43] were analyzed: the the Irrigation Reliability Index (IRI_k), which measures the proportion of months when the water supply met or exceeded irrigation demand (where, I (condition) = 1 if condition true, 0 otherwise) (eq. 6.), and the Irrigation Deficit Severity Index ($IDSI_k$), which captures the cumulative magnitude of irrigation deficits across the cropping cycle (eq. 7.). Together, these indices measure both the frequency IRI and IDSI of irrigation shortfalls, offering critical insights into the reliability of water resources for sustaining rice irrigation under monsoon-driven hydrological fluctuations. The equations are as follows:

$$Balance_{k,m} = Q_{k,m} - GIR_m \tag{5}$$

$$IRI_k = \frac{1}{N} \sum_{m=1}^{N} I \left(Q_{k,m} \geq GIR_m\right) \tag{6}$$

$$IDSI_k = \sum_{m=1}^{N} max \left(0, GIR_m - Q_{k,m}\right) \tag{7}$$

3. Results

3.1 SWAT Model Performance Evaluation

The hydrological model's performance during both the calibration (2011–2018) and validation (2019–2023) periods demonstrated a robust agreement between the observed and simulated streamflows (Fig. 2). The NSE values of 0.77 (calibration) and 0.76 (validation) indicated very good model performance, successfully exceeding the recommended threshold of 0.75. This strong agreement was further supported by high R^2 values (0.80 and 0.77), which reflect a strong correlation between the simulated and observed data (see Table 2). The model demonstrated minimal overall bias, as evidenced by the low P_{bias} values of -2.12% and -0.89%. The model overestimation is shown by negative P_{bias} values, but the performance rating is still very good compared to the total flow volume [44]. Hydrograph comparisons further confirmed that the model effectively captured monsoon-driven streamflow seasonality, with a good representation of both wet-season peak flows and dry season baseflows. Although some discrepancies occur during extreme rainfall events, this limitation is common in tropical catchments characterized by high rainfall variability and short concentration times [45].

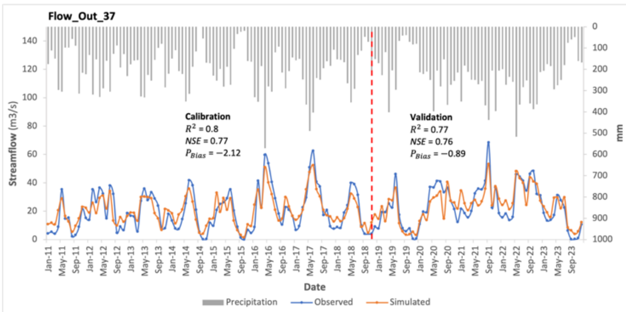

Fig. 2 Comparison of observed and simulated streamflow during calibration and validation periods. Source: (developed by the authors, 2025)

3.2 Hydrological Implications in the Bila Watershed

The simulated annual water balance revealed that the total precipitation in the Bila watershed averaged 2,555 mm yr^{-1}, of which 1,880.91 mm yr^{-1} (73.6%) contributed to the total water yield, whereas 637.2 mm yr^{-1} (24.9%) was lost through actual evapotranspiration. The ratio of actual to potential evapotranspiration (ΔET/PET) was 0.70, suggesting that despite high rainfall, evaporative demand was not fully met.

Decomposition of the W_{yld} components revealed that subsurface flows dominated the hydrological regime. Lateral flow (976.55 mm yr^{-1}; 51.9% of W_{yld}) and groundwater flow (587.04 mm yr^{-1}; 29.8%) together accounted for 81.7% of streamflow generation, compared with surface runoff (317.65 mm yr^{-1}; 16.9% of W_{yld}). Aquifer recharge processes were also clearly represented, with soil percolation (607.29 mm yr^{-1}) closely matching the groundwater recharge (605.81 mm yr^{-1}). Shallow aquifer contributions (557.08 mm yr^{-1}) dwarfed the deep aquifer outflow (29.96 mm yr^{-1}). The structural integrity of the model was confirmed by a highly accurate water mass balance with a negligible annual residual of only 1.44% (36.89 mm).

The spatial analysis of hydrological outputs (Figures 3a–d) revealed pronounced heterogeneity across the sub-watersheds. Surface runoff displayed the highest average values (16–136 mm yr^{-1}) in the downstream zone (Figure 3a). In contrast, the lateral flow reached maximum values in the upstream headwaters (99–139 mm yr^{-1}; Figure 3b). The midstream watershed functioned as the primary recharge zone, with an average groundwater flow contribution of 52–85 mm yr^{-1} (Figure 3c). Finally, the total water yield exhibited the highest average values (162–185 mm yr^{-1}) in the upstream and midstream zones (Figure 3d).

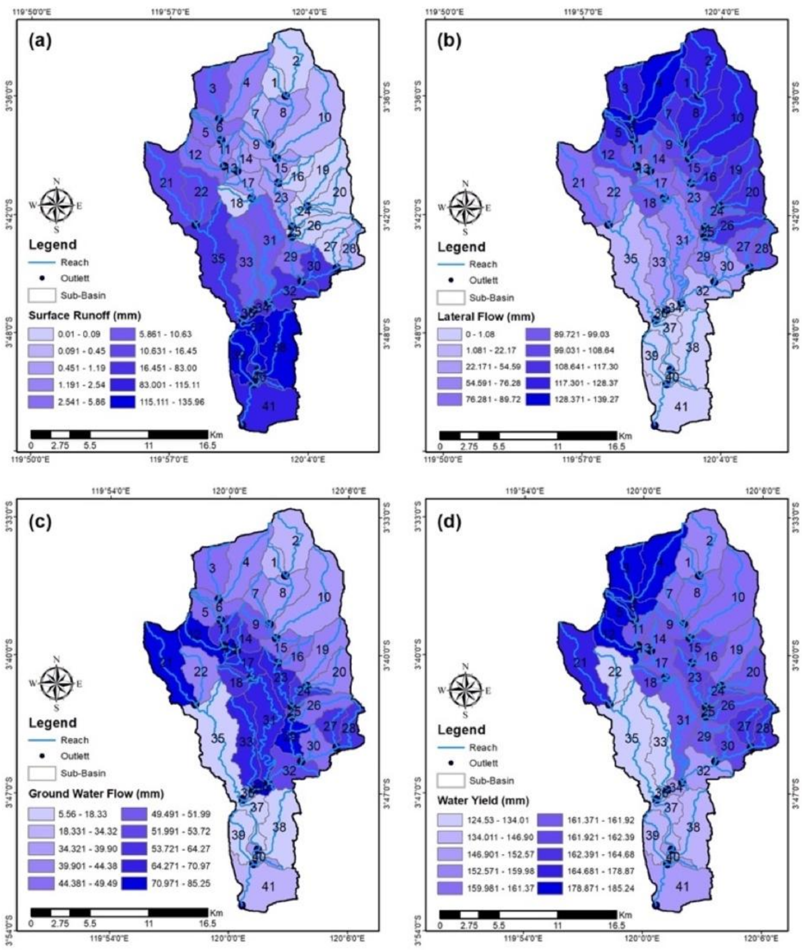

Fig. 3 Distribution of the annual water balance components in the Bila River Basin: (a) surface runoff, (b) lateral flow, (c) groundwater flow, and (d) water yield. Source: (developed by the authors, 2025)

3.3 Irrigation Requirements for Rice Cultivation

The seasonal NIR was estimated for the rainy season (October–March) and dry season (April–September) in accordance with the monsoon climate pattern and local farmers' planting calendar. The GIR was calculated by dividing the NIR by the combined efficiencies (η = 0.60), following FAO guidelines and empirical measurements in tropical Asia [5], [40]. Stage-specific Kc values for Inpari 32 ranged from 0.90–1.10 in early stages, 1.10–1.30 during vegetative and reproductive stages, and 1.00–1.20 at maturity [46].

The seasonal net irrigation requirement (NIR) was estimated for the rainy season (October–March) and dry season (April–September) in accordance with the monsoon climate pattern and local farmers' planting calendar. The gross irrigation requirement (GIR) was calculated by dividing the NIR by the combined efficiencies (η = 0.60). Stage-specific Kc values for Inpari 32 ranged from 0.90–1.10 in early stages, 1.10–1.30

during vegetative and reproductive stages, and 1.00–1.20 at maturity.

The analysis of irrigation water requirements showed gross irrigation requirements (GIR) of 379.9 mm and 385.5 mm during the wet and dry seasons, respectively (Figure 4). The Land Preparation and Vegetative Growth stages comprised over 80% of the seasonal irrigation demand. The maximum irrigation demand during Land Preparation reached 162.5 mm in the wet season and 260.0 mm in the dry season, whereas irrigation during vegetative growth was 166.7 mm and 90.0 mm, respectively.

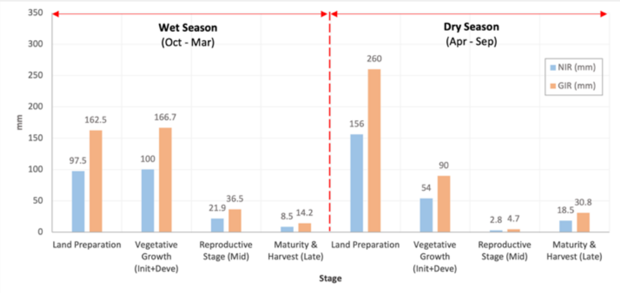

Fig. 4 Net and Gross Irrigation Requirements per Stage and Season. Source: (developed by the authors, 2025)

3.4 Supply–Demand Coupling and Reliability Assessment

The integration of SWAT water yield with CROPWAT gross irrigation requirements revealed temporal discrepancies between water availability and demand, despite an annual surplus (Figure 5). Irrigation demand peaked in April (260.0 mm), October (162.5 mm), and November (145.83 mm). Although the annual water production (1,880.91 mm) was nearly 2.5 times the annual irrigation requirement (765.33 mm), three critical months experienced deficits.

The Irrigation Deficit Severity Index (IDSI) reached 106.12 mm, concentrated in April (48.18 mm), October (48.57 mm), and November (9.37 mm). This value is equivalent to approximately 13.9% of the total annual irrigation requirements. The Irrigation Reliability Index (IRI) was 0.75, indicating that irrigation demand was met in 9 of the 12 months.

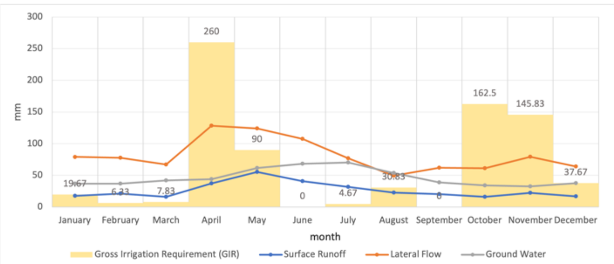

Fig.5 Monthly Water Supply (SWAT components) vs. Gross Irrigation Demand (CROPWAT). Source: (developed by the authors, 2025)

4. Discussion

The findings of this study suggest that the primary challenge confronting water management in the Bila watershed is not the total annual scarcity of water but rather the temporal discrepancy between the supply and demand for irrigation. Despite the fact that annual water availability is nearly 2.5 times the irrigation demand, deficits are concentrated in April, October, and November, coinciding with the critical phases of land preparation and vegetative growth in the Bila River Basin. These findings reinforce the irrigation reliability framework proposed by [10], which posits that the assessment of system performance should be based on the frequency and severity of deficits, as opposed to merely the annual balance.

In addition, the excellent performance of the SWAT model in calibration and validation (NSE > 0.75, R^2 > 0.77, and Pbias < ±5%) provides confidence that the dominant hydrological processes in the watershed were well captured. These metrics are consistent with the performance benchmarks and are comparable to those of other tropical catchment studies [15]. This strengthens the robustness of the subsequent analysis of water supply–demand interactions.

The preponderance of subsurface flow (lateral 51.9% and groundwater 29.8%) signifies that the Bila watershed hydrological system is governed by infiltration and shallow aquifer storage. These results are consistent with the findings of studies by [47], [48], which demonstrated that shallow aquifers play a significant role in supporting baseflow in tropical monsoon watersheds. However, the stable yet gradual rate of groundwater discharge is incapable of compensating for the substantial surge in irrigation demand over a brief period, as evidenced by the findings of the study conducted by [49] in South Asia.

The spatial heterogeneity observed in the Bila watershed highlights the importance of differentiated management strategies. Runoff was highest in the downstream areas with intensive agriculture and settlements, whereas lateral flow peaked in the upstream headwaters with steep slopes and permeable soils, and groundwater flow was strongest in the midstream recharge zones. Similar spatial patterns have been reported by [50], indicating that catchment function is highly dependent on land use and the geomorphology of the area. Therefore, water management in the Bila River must prioritize upstream conservation to sustain infiltration, midstream recharge protection to maintain baseflow, and downstream efficiency improvements to mitigate excessive runoff.

The concentrated irrigation requirements for rice, which exceed 80% during the Land Preparation and Vegetative Growth stages, align with the reports by [38], [51], which indicate that the land preparation and vegetative phases are periods of highest water consumption. This reinforces the recommendation that water management strategies should focus on providing a reliable supply of water during the early stages of plant growth.

The broader implications of these findings emphasize the urgent need for an efficiency-based irrigation management approach in tropical monsoon regions. Adjustments to planting calendars, use of ET-based irrigation scheduling [52], application of laser land levelling [53], and implementation of Alternate Wetting and Drying (AWD) [54] can help spread peak loads and increase water productivity. On the supply side, converting surface runoff into more stable reserves through retention ponds and nature-based solutions [55], as well as utilizing shallow wells [56], can be practical strategies relevant to the context of the Bila watershed.

A limitation of this study is that the model calibration was based solely on river discharge. As emphasized by [57], multi-objective calibration involving evapotranspiration, soil moisture, and groundwater data can strengthen model validity. In addition, the socio-economic aspects of farmers and water distribution institutions were not modelled, even though these factors influence the implementation of irrigation strategies in the field.

Future research should integrate groundwater monitoring, satellite-based evapotranspiration estimates [27], climate change, and socio-hydrological adaptation scenarios [58]. Thus, the results of this study can be used to support national food security policies amid increasingly high monsoon climate variability.

5. Conclusions

5.1 Research Summary

This study established a robust, coupled hydro–agronomic framework for the Bila River Basin by integrating SWAT with CROPWAT to diagnose spatiotemporal water balance and irrigation reliability. Model skill was high (NSE 0.77/0.76; R^2 0.80/0.77; Pbias −2.12%/−0.89% for calibration/validation), indicating good model performance. The basin hydrology is unequivocally subsurface-dominated: lateral flow contributes 51.9% and groundwater 29.8% of the total water yield, which averages 1,882 mm yr^{-1}, while surface runoff accounts for only 16.9%. Despite this apparent annual surplus, our analysis reveals a critical intra-seasonal mismatch between supply and irrigation demand. Peak water needs during land preparation and vegetative growth generated persistent shortfalls in April, October, and November, yielding an IDSI of 106.12 mm (13.9% of annual irrigation requirement) and an IRI of 0.75 (demand unmet in three of twelve months) concentrated in April, October, and November. Groundwater provides the most stable contribution but cannot offset short, intense demand spikes, whereas surface runoff is too volatile to be reliable. The theoretical and practical novelty of this research lies in explicitly coupling hydrological outputs with crop-demand indices to pinpoint deficit windows and motivate targeted interventions, especially food security. These insights are actionable for scientists advancing coupled models, water managers optimizing intra-seasonal allocations, and policymakers shaping food security strategies in monsoon regions.

The primary academic contribution of this study lies in its departure from the conventional annual water balance assessments. While the existing literature often identifies annual surpluses, our study diagnoses a critical, previously unquantified vulnerability. This theoretical innovation demonstrates that hydrologically stable, subsurface-dominated watersheds can still face severe irrigation deficits when their slow-release nature fails to meet intense, short-duration agronomic demands. By operationalizing reliability and deficit indices, metrics rarely applied in this region, this study provides a novel, replicable framework that shifts the management paradigm from managing annual supply to addressing specific intra-seasonal temporal mismatches.

5.2 Future Research

Future work should focus on multi-objective calibration and validation that jointly assimilates streamflow with independent observations of evapotranspiration, soil moisture, and groundwater storage to reduce structural and parameter uncertainties. Integrating satellite-based ET products, groundwater monitoring networks, and socio-hydrological data on farmer behavior and allocation rules will enable a more realistic representation of demand and operations. Reliability should be stress-tested under climate-change scenarios and adaptive operating policies, with decision-support tools that operationalize monthly reliability/deficit metrics for canal scheduling and conjunctive-use planning at the scheme and basin scales.

5.3 Research Limitations

The present calibration relied solely on river discharge, without independent validation of ET partitioning, soil moisture dynamics, or groundwater storage; this constraint may under-characterize process uncertainty and bias some pathway attributions. In addition, the operational and socio-economic determinants of irrigation (delivery rules, maintenance, and on-farm practices) were not explicitly modeled, which can limit direct policy translation without complementary field data and institutional diagnostics.

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Author Contributions

Conceptualization - A.M. ; methodology - A.M. and R.A. ; software - R.A. ; validation - H.Z. and M.A. ; formal analysis - R.A. and M.A. ; investigation - A.M. and H.Z. ; data curation - R.A. ; visualization - R.A. ; writing—original draft preparation, all authors contributed equally; writing—review and editing - A.M. and R.A. ; supervision - H.Z. and M.A. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest Declaration

The authors declare that they have no connections or participation with any organization or entity that has financial stakes in the topics or materials covered in this manuscript.

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