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## RESEARCH ARTICLE

# WATER BALANCE ASSESSMENT OF A WATER-STRESSED TRADITIONAL IRRIGATION SYSTEM IN BALI USING F.J. MOCK RAINFALL–RUNOFF MODELLING: A CASE STUDY OF SUBAK BALANGAN

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## ABSTRACT

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Quantitative water balance assessments of traditional irrigation systems remain scarce, particularly for systems experiencing chronic water deficits driven by institutional rather than climatic factors. This study applied the F.J. Mock rainfall–runoff model to Subak Balangan, which has experienced a 20-year-long continuous water shortage due to an inter-district allocation dispute. Using 10-year climate data (2015–2024) and independent field validation measurements (March–July 2025, 10 half-monthly periods), the model achieved moderate-to-good performance (NSE = 0.521,  $R^2 = 0.833$ , RMSE = 0.01 m<sup>3</sup>/s). Water availability at 80% reliability ranged from 0.001 to 0.012 m<sup>3</sup>/s across 24 half-monthly periods. A comparative water balance analysis of two crop rotations revealed that the existing flower–cassava rotation experienced deficits in 75% of periods (maximum 0.017 m<sup>3</sup>/s), while a hypothetical paddy–paddy–maize rotation would produce deficits in 91.7% of periods, with 2.96-fold higher peak demand (maximum 0.074 m<sup>3</sup>/s). These results quantify the magnitude of water stress under existing institutional constraints and demonstrate the limitations of paddy-based crop intensification as a water management strategy in this specific context. Beyond empirical findings, the study advances two theoretical contributions: Institutional Hydro-Decoupling (IHD), extending Ostrom's common-pool resource theory to conceptualise conditions where governance failure structurally severs the link between catchment hydrology and effective irrigation supply; and Hydro-Adaptive Cropping Moderation (HACM), extending autonomous adaptation theory to identify farmer-led rotation adjustment as an endogenous demand-side mechanism that partially compensates for institutionally-suppressed water availability. The findings provide a baseline water balance reference for ongoing allocation dispute resolution and highlight the need for multi-Subak comparative studies to establish broader patterns.

### KEYWORDS

Water balance analysis, Institutional water scarcity, Crop water deficit and rotation systems

## 1. INTRODUCTION

Irrigation is essential to agricultural sustainability and food security, and it plays a major role in economic development. Not only does it increase land productivity, but it also influences agroecosystem functions such as local climate regulation and biodiversity conservation (Robinson, 2024). Traditional irrigation systems, developed over centuries, encapsulate sophisticated water management knowledge. However, these systems now face mounting pressures from climate variability, population growth, and institutional failures (Araujo et al., 2021; Stavi et al., 2021). While modern hydrological modelling has improved water resource assessment in conventional schemes (Chandrasasi et al., 2020; Oktarini & Marselina, 2024), a critical methodological gap persists in applying these techniques to culturally-embedded agricultural systems operating under indigenous governance principles. This gap becomes particularly acute where traditional systems support significant populations but face chronic water deficits from allocation disputes and environmental change (Hashemi et al., 2024; Mgendi, 2024).

The Subak system in Bali exemplifies this methodological gap. Recognized as a UNESCO World Heritage site, Subak integrates cultural principles with hydraulic engineering to manage water distribution across terraced landscapes (Ardana et al., 2024). Nevertheless, the system is increasingly challenged by water allocation conflicts, land conversion, and climate variability. Despite its significance, technical water balance analyses are notably less prevalent than socio-anthropological studies (Eryani & Jayantari, 2024).

Rigorous quantitative assessment is necessary to address water management challenges in traditional systems such as Subak. Rainfall–runoff modelling is particularly relevant in this context. Among hydrological methods, the F.J. Mock approach stands out as suitable for data-limited tropical contexts such as Indonesian watersheds, integrating rainfall, evapotranspiration, infiltration, and soil moisture dynamics (Chandrasasi et al., 2020). Its effectiveness in estimating water flows under monsoonal climates makes it valuable for irrigation systems facing water stress. However, it remains confined to standard engineering

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schemes, with integration into indigenous water governance yet to be explored.

Previous applications of the F.J. Mock rainfall-runoff method in Indonesian contexts have demonstrated effectiveness for water availability estimation in conventional irrigation schemes. Batas et al. (2023) successfully applied the method to assess agricultural water reliability in Jetis Irrigation Area, while Purnaditya & Asyiah (2020) calculated 25-year water sufficiency in Cijung Watershed. Soerya et al. (2023) identified seasonal surplus-deficit patterns in the Leuwi Padjadjaran II catchment. However, these studies only addressed engineered systems with established allocation and procedures. None examined cases in which governance failures, rather than hydroclimatic factors, create chronic deficits, or in which traditional cultural practices dictate planting and water distribution.

This study addresses this gap by applying the F.J. Mock rainfall-runoff model to Subak Balangan in Badung Regency, Bali, a traditional irrigation unit that has experienced a well-documented 20-year continuous water shortage resulting from an upstream-downstream inter-district allocation dispute (Eryani & Jayantari, 2024). Subak Balangan provides a particularly instructive case for three reasons: the deficit is institutionally rather than climatically driven, allowing examination of water balance dynamics under allocation failure; the system continues to operate under traditional Subak governance despite severe water stress, demonstrating farmer adaptation; and complete climate records (2015–2024) combined with field-measured discharge data (2025) enable model calibration and independent validation.

The objectives of this study are as follows: (1) to estimate water availability at 80% reliability using the F.J. Mock model calibrated against field-measured discharge; (2) to calculate irrigation water requirements for both the existing flower-cassava rotation and a hypothetical paddy-paddy-maize alternative, reflecting local cultivation practices; (3) to quantify the temporal distribution and magnitude of water deficits throughout the annual cycle for both cropping patterns; and (4) to assess the sensitivity of water balance outcomes to key model parameters and input data limitations. By establishing a quantitative baseline water balance for a water-stressed Subak, this study provides empirical evidence to inform the ongoing allocation dispute-resolution process and serves as a documented case for comparison with future assessments of other Subak systems facing similar challenges.

Beyond these applied objectives, this study advances two interrelated theoretical propositions grounded in established frameworks. In conventional rainfall-runoff modelling, the 80% reliable flow ( $Q_{80}$ ) is treated as an inherently hydro-climatic quantity, implicitly equating modelled catchment runoff with water available at the irrigation intake. This study challenges that assumption: when an inter-district allocation dispute structurally caps flow reaching a Subak unit for two decades, the deterministic link between catchment hydrology and effective irrigation supply is systematically broken. This phenomenon is conceptualised as Institutional Hydro-Decoupling (IHD), a condition creating structural divergence between hydrological supply capacity and institutionally-permitted flow. Theoretically, IHD is rooted in Ostrom's (1990) common-pool resource (CPR) theory, which established that governance architecture fundamentally mediates biophysical resource outcomes, and extends it by addressing a failure condition Ostrom's framework does not explicitly treat: governance breakdown at a larger administrative scale imposing a structural supply ceiling on a lower-scale, internally well-governed CPR institution. This multi-scale failure exemplifies what Meinzen-Dick (2007) characterised as institutional mismatch in water governance, but IHD advances beyond diagnosis by quantifying the hydrological consequences through the distinction between  $Q_{80}(\text{hydro})$ , representing catchment supply capacity, and  $Q_{80}(\text{eff})$ , the institutionally-bounded flow at the intake. Complementarily, the data support a second proposition extending Smit and Wandel's (2006) concept of autonomous adaptation into irrigation hydrology. The flower-cassava rotation in Subak Balangan constitutes a hydro-adaptive cropping moderation (HACM) strategy: an endogenous demand-side mechanism whereby substitution of high-water-demand paddy with low-demand alternatives partially compensates for institutionally-suppressed supply. Lansing (2006) demonstrated that Balinese Subak systems exhibit self-organising properties enabling emergent coordination without centralised planning; HACM extends this by identifying cropping pattern adjustment as a specific hydrological moderation variable operating under institutional water stress. Both frameworks are developed empirically from the Subak Balangan case and elaborated theoretically in the Discussion.

## 2. MATERIALS AND METHODS

This study employed a quantitative descriptive approach combining

hydrological modelling with irrigation demand analysis to assess water balance conditions in Subak Balangan. The analytical framework comprised four integrated components: (1) water availability estimation through rainfall-runoff transformation, (2) irrigation requirement calculation for two cropping patterns, (3) comparative water balance analysis, and (4) sensitivity analysis to evaluate the robustness of results under parameter and input data uncertainty. The study period encompassed 2015–2024 for model development and 2025 (March–July) for independent validation.

### 2.1 Research Location

This study was conducted in Subak Balangan, Kuwum Village, Mengwi Subdistrict, Badung Regency, Bali Province. As shown in Figure 1, the area served as part of the Pama Palian Irrigation District (DI), with an elevation ranging from 315 to 335 meters above sea level (masl) and covering approximately 40 hectares (Directorate General of Water Resources, 2015). During the rainy season, the entire area is actively used as agricultural land. The site was selected based on four criteria: (1) documented 20-year continuous water deficit representing Bali's most severe case; (2) clear causative factors (inter-district allocation dispute); (3) continued agricultural production demonstrating farmer resilience; and (4) availability of complete climate records (2015–2024) enabling robust modelling calibration.

Subak Balangan is situated in the Tabanan-Denpasar Groundwater Basin (Mudiana & Setiadi, 2008). Due to geological characteristics, the area is classified in the Buyan-Bratan Group and Batur Volcanics formations, primarily consisting of tuff and lahar from the Holocene epoch (Purbo-Hadiwidjojo et al., 1998). The geological makeup comprises recent volcanic materials, including volcanic breccia, sandy tuff, and lahar deposits, predominantly consisting of unconsolidated materials ranging from sand to boulder size, with localized lava flows. Subak Balangan has moderate to high permeability, particularly pronounced in lahar deposits and vesicular lavas (Sudadi et al., 1986).

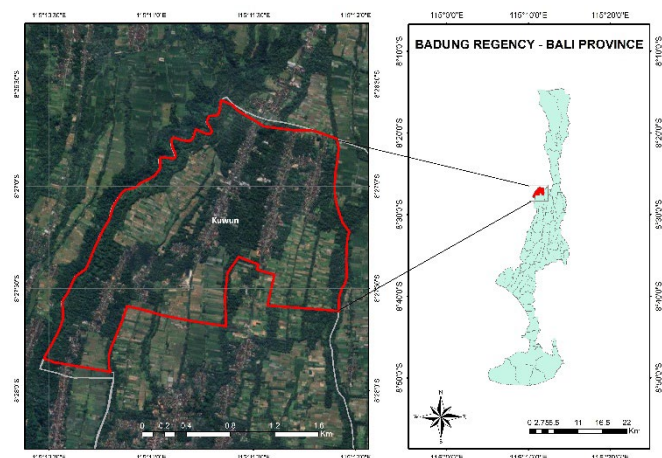


Figure 1: Map of study area

### 2.2 Data Collection

Primary data comprised field observations of existing irrigation network conditions and crop patterns, supplemented by direct weekly flow-rate measurements conducted from March I to July II 2025 (10 half-monthly periods). Flow measurements were obtained using the velocity-area method at the main intake point of Subak Balangan during each half-monthly period, providing independent validation data not used in model calibration. Secondary data included: (a) daily rainfall records from Penatahan Rainfall Station for 2015–2025, obtained from the Bali Penida River Basin Office (BWS); (b) climate variables (air humidity, air temperature, wind speed, and sunshine duration) from the Sanglah Geophysical Station for 2010–2024, obtained from Indonesia's Meteorology, Climatology, and Geophysics Agency (BMKG Region III); and (c) spatial data including administrative boundaries, river basin maps, and irrigation area schemes from national databases and the Ministry of Public Works.

A single rainfall station (Penatahan) provides the precipitation input for this analysis. Although this station is the closest and most representative for the Subak Balangan catchment, reliance on a single-point measurement introduces spatial rainfall uncertainty that the model does not address. The implications of this limitation are further examined in the sensitivity analysis and discussed in the limitations section.

### 2.3 Data Analysis

Data analysis in this study was conducted through several systematic, interrelated stages to develop a comprehensive understanding of irrigation water availability and demand in the Subak Balangan area.

#### 2.3.1 Study Area Delineation

The Subak Balangan area was delineated using a Geographic Information System (GIS)-based application. This process aimed to accurately map the boundaries of the study area, which served as the basis for the spatial analysis of hydrological data and crop patterns. Additionally, GIS enables the integration of thematic data needed for this study, including topographic maps, irrigation channel networks, and land-use data (Gandharum et al., 2025).

#### 2.3.2 Hydrological Modelling Framework

Rainfall-runoff transformation is a fundamental component of hydrological analysis for quantifying available water flow in a given area. Among the available methods, the F.J. Mock approach is widely used due to its systematic integration of key hydrological factors, including rainfall, evapotranspiration, infiltration, and soil moisture conditions. In this study, water availability was estimated using the F.J. Mock rainfall-runoff transformation, which has demonstrated effectiveness in data-limited tropical watersheds (Chandrasasi et al., 2020).

Evapotranspiration is the combined process of water evaporation from the soil surface and transpiration from plant leaves into the atmosphere (Hamimed et al., 2017, 2025; Pandey et al., 2021). As an important part of the hydrological cycle, it is used in calculating crop water requirements and resource management (Ahmadi et al., 2023; Babaeian et al., 2022). In calculating water requirement, the concept of potential evapotranspiration ( $ET_0$ ) is used, representing the maximum evapotranspiration rate at the reference surface with sufficient water availability (Sharafi et al., 2023; Srdić et al., 2023). This study uses the Modified Penman method (Equation 1) to estimate potential evapotranspiration by considering air temperature, humidity, wind speed, and solar radiation duration (Azizi & Sutopo, 2022; Kusumastuti et al., 2021).

$$ET_0 = c (W \times R_n + (1-W) \times f(u) \times (ea-ed)) \quad (1)$$

Information:

$ET_0$	=	Potential evapotranspiration (mm/day)
$c$	=	Adjustment factor for daytime and nighttime weather conditions, derived as a function of mean air temperature ( $T$ , °C) and the ratio of daytime to nighttime wind speeds; values are obtained from standard Modified Penman tables or regression equations calibrated for tropical climates
$W$	=	Temperature-dependent weighting factor for the relative influence of net radiation versus aerodynamic terms in $ET_0$ ; determined from air temperature using psychrometric tables ( $W$ increases with temperature, ranging from approximately 0.55 at 20°C to 0.75 at 35°C under tropical conditions)
$f(u)$	=	Wind speed function (m/s), calculated as $f(u) = 0.27 \times (1 + u/100)$ , where $u$ is the mean daily wind speed measured at 2 m height (km/day); this term quantifies the aerodynamic capacity of the air mass to transport water vapour away from the evaporating surface
$R_n$	=	Net radiation expressed in equivalent evaporation depth (mm/day), calculated as $R_n = R_s(1-\alpha) - R_{nl}$ , where $R_s$ is incoming shortwave solar radiation derived from sunshine duration data ( $n/N$ ratio), $\alpha = 0.25$ is the reflection coefficient for grass reference surface, and $R_{nl}$ is net outgoing longwave radiation determined from air temperature and relative humidity
$ea$	=	Saturated vapour pressure at mean air temperature (mbar), computed from the Magnus formula: $ea = 6.107 \times 10^{(7.5T/(237.3+T))}$ , where $T$ is mean daily air temperature (°C)
$ed$	=	Actual vapour pressure (mbar), derived as $ed = (RH/100) \times ea$ , where $RH$ is the mean daily relative humidity (%) measured at the climate station; the vapour pressure deficit ( $ea-ed$ ) drives the aerodynamic component of $ET_0$

The estimation process of rainfall-runoff transformation with the F.J. Mock method includes several main steps, namely determining actual evapotranspiration ( $ET_a$ ), the amount of rainfall on the soil surface, soil

moisture content (SMC), infiltration ( $i$ ), ranging from 0 to 1, and the excess water in the soil (water surplus). Furthermore, other parameters include determining soil water content ( $V_n$ ), change in the soil water content ( $\Delta V_n$ ), base flow (BF), direct runoff (DRO), and the total available runoff discharge.

For accurate results, model calibration is required by optimizing parameter values to produce discharge estimates that are closest to actual flow data. This calibration process uses several testing methods, including NSE, Correlation Coefficient ( $r$ ), Determination Coefficient ( $R^2$ ), and Root Mean Square Error (RMSE) (Chandrasasi et al., 2020). The values of each test are determined based on the following Equations 2 through 5.

$$NSE = 1 - \left( \frac{\sum_{i=1}^N (X_i - Y_i)^2}{\sum_{i=1}^N (X_i - \bar{X})^2} \right) \quad (2)$$

$$r = \frac{\sum_{i=1}^N (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{N \sum_{i=1}^N (X_i - \bar{X})^2} \sqrt{N \sum_{i=1}^N (Y_i - \bar{Y})^2}} \quad (3)$$

$$R^2 = r^2 \quad (4)$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^N (X_i - Y_i)^2} \quad (5)$$

Information:

NSE	=	Nash-Sutcliffe coefficient (%)
$r$	=	Correlation coefficient
$R^2$	=	Coefficient of determination
RMSE	=	Root Mean Square Error
$X_i$	=	Observed discharge ( $m^3/s$ )
$Y_i$	=	Calculated discharge ( $m^3/s$ )
$\bar{X}$	=	Mean observed discharge ( $m^3/s$ )
$N$	=	Number of data

Reliable flow (80% probability) was calculated using the Basic Year method, sorting annual half-monthly discharges and extracting values with Equation 6. This approach provides conservative water availability estimates appropriate for irrigation planning (Dharmawati et al., 2025).

$$P = \frac{m}{n+1} \quad (6)$$

Information:

$P$	=	Probability (%)
$m$	=	Rank order ranking and $n$ is the number of data
$n$	=	Number of data

#### 2.3.3 Irrigation Demand Analysis

Crop water requirements followed Indonesian KP-01 standards (Permadi & Parjono, 2020), analyzing two patterns: (1) existing flower-cassava rotation (November I initiation); and (2) alternative paddy-paddy-maize intensification (November II initiation). Complete parameter definitions and derivation procedures for all demand components, crop coefficient ( $K_c$ ), net field requirement (NFR), and withdrawal requirement (DR), are provided in the expanded description below.

Calculations integrated crop coefficients ( $K_c$ , dimensionless, representing the ratio of actual crop evapotranspiration to reference  $ET_0$ ) for each growth stage, potential evapotranspiration ( $ET_0$ ), percolation rates (2–4 mm/day for the medium-textured soils characteristic of the study area), and effective rainfall contributions ( $Re = 70\%$  of total rainfall for paddy,  $Re = 50\%$  for maize crops, following KP-01 guidelines). Net Field Requirement (NFR, mm/day, the crop water demand at the field level before accounting for conveyance losses) incorporated land preparation demands ( $IR$ , mm/day, for paddy only), consumptive crop use ( $ET_c = K_c \times ET_0$ ), percolation losses ( $P$ , mm/day), and water layer replacement (WLR, mm/day). Withdrawal Requirement (DR, mm/day, the gross water requirement at the intake structure) adjusted NFR for irrigation conveyance efficiency: 90% for primary-secondary channels and 50% for tertiary distribution, reflecting typical Subak infrastructure conditions as documented in field surveys. The relationship is expressed as  $DR = NFR / (e_{primary} \times e_{tertiary})$ , where the combined system efficiency is  $0.90 \times 0.50 = 0.45$ . DR values were then converted from mm/day to  $m^3/s$  using the Subak Balangan command area of 40 ha.

#### 2.3.4 Sensitivity Analysis and Uncertainty Assessment

Given the moderate model performance ( $NSE = 0.521$ ) and the constraints of a 10-year climatic record with a single rainfall station, a structured sensitivity analysis was conducted to evaluate the robustness of the water balance conclusions. Three sources of uncertainty were examined:

First, parameter sensitivity was assessed by systematically varying the F.J. Mock infiltration coefficient ( $\pm 20\%$  of calibrated value) and the soil

moisture storage capacity ( $\pm 15\%$ ), as these are the two parameters to which Mock model outputs are most sensitive in tropical volcanic catchments. For each parameter combination, the full water balance was recalculated to determine the range of  $Q_{80}$  estimates and consequent deficit magnitudes.

Second, the effect of record length on reliable flow estimation was evaluated using a leave-one-out jackknife resampling approach. The jackknife is a particular resampling method that aims primarily at the calculation of the bias and the variance of estimates, without making very restrictive distributional assumptions (Friedl & Stampfer, 2002).  $Q_{80}$  values were recalculated from nine of the ten available years (systematically excluding each year in turn), producing a distribution of reliable flow estimates that reflects the sampling variability inherent in the limited record. The coefficient of variation (CV) of the jackknife  $Q_{80}$  estimates provides a measure of the stability of the reliable flow calculation.

Third, the implications of single-station rainfall input were qualitatively assessed by comparing Penatahan station rainfall characteristics (annual totals, monthly distribution, number of rain days) with those of the nearest alternative stations to evaluate spatial representativeness. A quantitative rainfall perturbation analysis ( $\pm 10\%$  of monthly totals) was also performed to assess the sensitivity of water availability estimates to potential spatial rainfall gradients not captured by the single-station input.

### 2.3.5 Water Balance Integration

Water balance analysis is critical for identifying the equilibrium between water availability and crop demand, thereby supporting effective distribution and sustainable resource management (Liu et al., 2020). In this study, water balance was assessed by comparing available discharge at 80% exceedance probability ( $Q_{80}$ , the discharge value exceeded in 8 out of 10 years and used as a conservative design flow for irrigation planning) with net irrigation demand at the withdrawal point (DR, the gross water requirement at the intake after accounting for conveyance efficiency losses) across 24 half-monthly periods per year. Net field requirements (NFR), representing actual crop water demand at the field level before accounting for irrigation efficiency, were calculated and then converted to DR using the specified efficiency factors. Surplus conditions ( $Q_{80} \geq DR$ ) indicated adequate supply, while deficit conditions ( $Q_{80} < DR$ ) quantified shortages requiring supplementary sources or adaptive management. Temporal deficit patterns were analyzed to identify critical intervention periods. The conceptual framework linking all water balance components, from rainfall input through the F.J. Mock runoff transformation, reliable flow estimation, irrigation demand calculation, and water balance integration, is illustrated schematically in Figure 7.

## 3. RESULTS

### 3.1 Potential Evapotranspiration

Potential evapotranspiration ( $ET_0$ ) calculated using the Modified Penman method based on 15 years of climate data (2010–2024) from the Sanglah Geophysical Station exhibited clear seasonal patterns consistent with Bali’s tropical monsoon climate (Figure 2). Monthly average  $ET_0$  ranged from a minimum of 4.742 mm/day in June to a maximum of 7.614 mm/day in October, with an annual average of 6.07 mm/day. The seasonal pattern showed a decreasing trend from March through July (corresponding to reduced solar radiation during the transition to the dry season), followed by increasing values through October as solar radiation intensifies, with a slight reduction at year-end coinciding with the onset of the wet season. This temporal  $ET_0$  pattern is directly relevant to the water balance because the period of highest crop water demand (driven by high  $ET_0$ ) coincides with declining rainfall availability, amplifying deficit conditions during May–July.

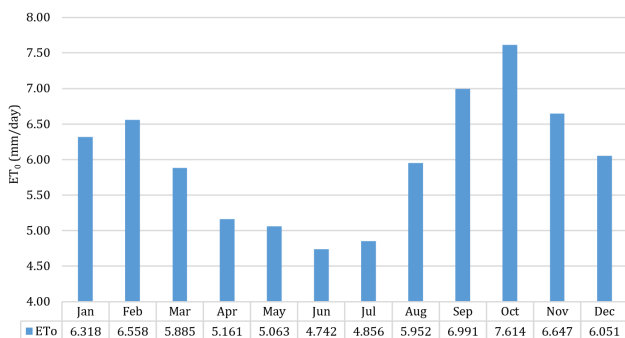


Figure 2: Potential  $ET_0$  values in Subak Balangan

### 3.2 Water Availability and Model Calibration

Half-monthly discharge values estimated using the F.J. Mock model for the period 2015–2024 are presented in Figure 3. The discharge data exhibited pronounced seasonal variability, with peak values typically occurring during January–March (wet season) and minimum values during August–October (late dry season). Inter-annual variability was also substantial, reflecting the influence of large-scale climate modes on monsoonal rainfall patterns in Bali.

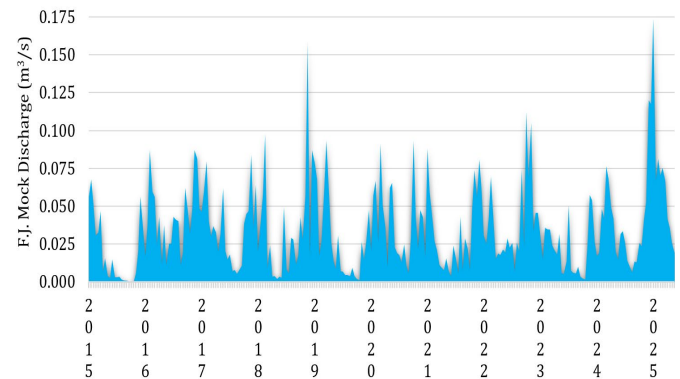


Figure 3: Graph of the F.J. Mock discharge fluctuations in Subak Balangan

Model performance was evaluated by comparing estimated discharge against independent field measurements obtained during March I to July II 2025 (Figure 4). The calibration statistics are summarised in Table 1. The NSE value of 0.521 falls in the “satisfactory” range according to widely used performance criteria (Moriassi et al., 2007), indicating that the model explains approximately 52% of the observed discharge variance. While this performance level is adequate for water availability estimation at the planning level, it warrants careful interpretation. The moderate NSE reflects several factors: the inherent difficulty of modelling small catchment discharge from a single rainfall station, the complex groundwater–surface water interactions in the volcanic geological substrate, and the short validation period (10 half-monthly values). The high  $R^2$  (0.833) and correlation coefficient ( $r = 0.913$ ) indicate that the model captures the temporal pattern and relative magnitude of discharge variability well, even though the absolute values show moderate scatter. The low RMSE (0.01  $m^3/s$ ) reflects the small absolute discharge magnitudes involved and should not be interpreted as indicating high precision in relative terms.

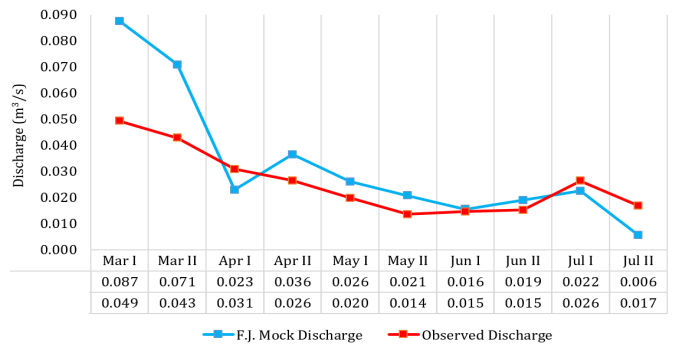


Figure 4: Comparison of the F.J. Mock discharge with observed discharge

Testing Method	Results	Description
Nash-Sutcliffe Efficiency (NSE)	0.521	Satisfactory
Correlation Coefficient ( $r$ )	0.913	Very high
Coefficient of Determination ( $R^2$ )	0.833	Very high
Root Mean Square Error (RMSE)	0.01	-

Water availability at 80% exceedance probability, hereinafter the 80% reliable flow ( $Q_{80}$ , defined as the discharge value equalled or exceeded in 80% of years, i.e., in 8 out of the 10 recorded years, providing a conservative water availability estimate appropriate for irrigation planning), derived from the ranked 10-year discharge record, ranged from 0.001  $m^3/s$  during the driest periods (August–October) to 0.012  $m^3/s$  during peak rainfall months (March I). The temporal distribution showed pronounced seasonal variation consistent with the monsoonal climate regime. These extremely low  $Q_{80}$  values, even during peak rainfall months,

reflect the combined effects of the small catchment area (40 ha) and the upstream allocation constraints that reduce available flow to Subak

Balangan regardless of climatic conditions.

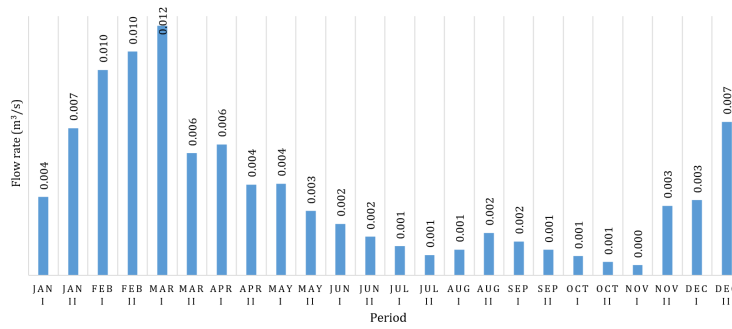


Figure 5: Water availability graph for Subak Balangan

3.3 Irrigation Water Requirement

Irrigation water requirement was calculated based on the two crop patterns used in this study. The first was the existing flower-cassava, which started in November I, with water requirement presented in Table 2. The second was paddy-paddy-maize starting in November II. For the existing flower-cassava cropping pattern (Table 2), half-monthly irrigation water requirements ranged from 0.000 to 0.025 m³/s, with most periods exhibiting relatively low values. The temporal pattern demonstrated peak requirements during May II (0.025 m³/s), corresponding to the flowering phase when crop water demand reaches its maximum. Minimum requirements occurred during land preparation

and crop establishment phases.

For the alternative paddy-paddy-maize cropping pattern, half-monthly irrigation water requirements exhibited substantially higher values, ranging from 0.000 to 0.074 m³/s. This marked increase reflects the higher water demands characteristic of paddy cultivation, particularly during land preparation and the vegetative growth phase. Peak requirements occurred during June II (0.074 m³/s), coinciding with the second paddy crop's maximum water demand period. The paddy-paddy-maize pattern demonstrated 2.96 times higher peak water demand compared to the flower-cassava pattern.

Table 2: Irrigation water requirement for flower-cassava

Periode	Nov		Dec		Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov
	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	
	FLOWER												CASSAVA												
P	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
ETc	1.17	2.94	5.25	6.77	6.85	6.34	5.31	3.45	2.74	2.30	3.16	3.73	4.05	3.79	3.79	3.88	3.88	4.51	4.02	3.85	2.97	1.84	0.76	0.00	
WLR	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
IR	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Re	2.45	3.08	3.24	1.95	2.98	4.11	2.60	3.06	2.60	1.36	0.75	0.94	0.30	0.46	0.90	0.55	0.17	0.33	0.21	0.77	0.52	0.00	0.00	2.35	
NFR	0.00	0.00	2.01	4.82	3.87	2.22	2.71	0.40	0.14	0.94	2.41	2.80	3.75	3.33	2.90	3.33	3.71	4.19	3.80	3.08	2.45	1.84	0.76	0.00	
DR	0.00	0.00	0.25	0.62	0.49	0.28	0.34	0.05	0.01	0.18	0.12	0.31	0.36	0.48	0.42	0.37	0.42	0.47	0.53	0.48	0.39	0.31	0.23	0.09	0.00
Q	0.00	0.00	0.01	0.02	0.02	0.01	0.01	0.00	0.00	0.00	0.01	0.01	0.01	0.02	0.01	0.01	0.02	0.02	0.02	0.01	0.01	0.01	0.00	0.00	0.00

3.4 Water Balance Analysis

The comparative water balance results are presented in Figure 6. For the existing flower-cassava rotation, deficits occurred in 18 of 24 half-monthly periods (75%), with a maximum shortage of 0.017 m³/s during May II. Surplus conditions were limited to six periods concentrated in the peak and late wet season: March I-II, April I, November I-II, and December I. For the hypothetical paddy-paddy-maize pattern, deficit frequency increased to 22 of 24 periods (91.7%), with a maximum deficit of 0.074

m³/s during June II, representing a 4.35-fold increase in peak shortage relative to the flower-cassava pattern. Surplus conditions contracted to only 2 periods (March II and November I). The temporal distribution of deficits followed a predictable pattern for both cropping systems: the most severe shortages consistently occurred from May II through September I, when declining rainfall-derived availability intersects with sustained or increasing crop water demand. This systematic seasonal concentration of deficits is a robust finding that persists across the sensitivity analysis variants.

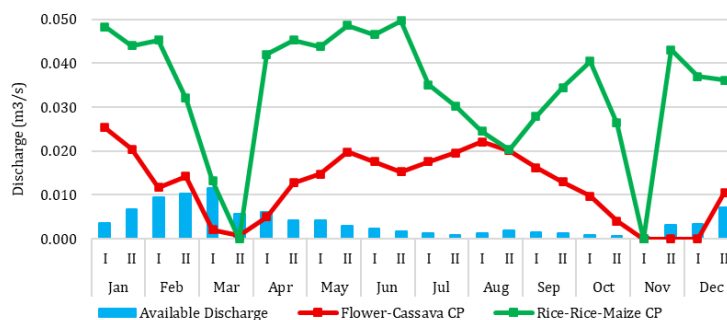


Figure 6: Water balance graph in Subak Balangan

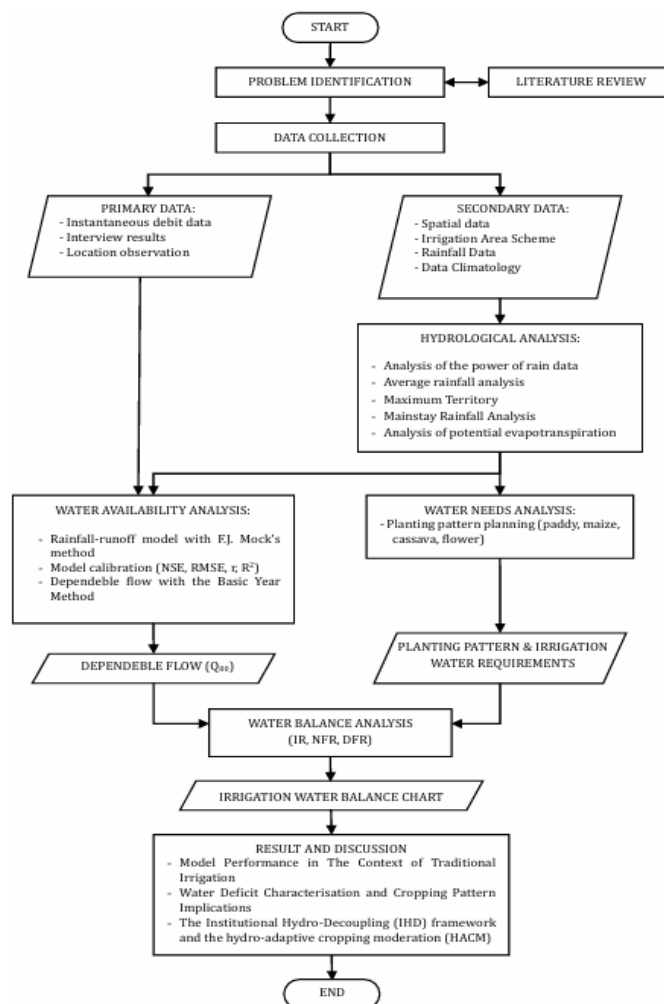


Figure 7: Schematic diagram of the water balance analytical framework applied in Subak Balangan

### 3.5 Sensitivity Analysis Results

Parameter sensitivity analysis revealed that F.J. Mock model outputs were moderately sensitive to both infiltration coefficient and soil moisture storage capacity variations. A  $\pm 20\%$  change in the infiltration coefficient produced  $Q_{80}$  variations of approximately  $\pm 15\text{--}18\%$  during wet-season periods and  $\pm 8\text{--}12\%$  during dry-season periods, reflecting the reduced influence of infiltration partitioning when total rainfall is low. Soil moisture storage capacity variations ( $\pm 15\%$ ) yielded smaller effects on  $Q_{80}$ , in the range of  $\pm 5\text{--}10\%$ , primarily affecting the timing of baseflow recession rather than peak discharge estimates. Critically, none of the parameter combinations tested altered the fundamental water balance conclusion: deficits persisted in at least 67% of periods for the flower-cassava pattern and 83% for the paddy-paddy-maize pattern, even under the most favourable parameter assumptions.

The jackknife resampling analysis of  $Q_{80}$  stability showed that the coefficient of variation across the 10 leave-one-out estimates averaged 12–18% for wet-season periods and 20–28% for dry-season periods. This indicates that reliable flow estimates during the dry season, the periods most critical for deficit assessment, carry greater sampling uncertainty due to higher inter-annual variability in low-flow conditions. However, even at the upper bound of jackknife  $Q_{80}$  estimates, the deficit structure remained qualitatively unchanged: both cropping patterns exhibited persistent deficits throughout the May–September period.

Rainfall perturbation analysis ( $\pm 10\%$  of monthly totals) produced  $Q_{80}$  changes proportionally larger than the input perturbation during wet-season months (amplification factor of approximately 1.3–1.5) and proportionally smaller during dry-season months (amplification factor of 0.6–0.8), consistent with the non-linear soil moisture response embedded in the F.J. Mock formulation. Under the +10% rainfall scenario, deficit frequency for the flower-cassava pattern decreased from 75% to approximately 63% of periods, while the paddy pattern deficit frequency decreased only marginally from 91.7% to 87.5%. This asymmetric response confirms that the paddy-based pattern's water demand substantially exceeds available supply, regardless of reasonable rainfall uncertainty, while the flower-cassava pattern's deficit frequency is somewhat sensitive to rainfall input accuracy.

## 4. DISCUSSIONS

This section interprets the quantitative findings presented in the Results section, situates them within the broader literature on irrigation water management and traditional agricultural systems, and explores their implications for policy and practice in Subak Balangan and similar water-stressed systems.

### 4.1 Model Performance in The Context of Traditional Irrigation

The moderate model performance (NSE = 0.521) achieved in this study warrants contextual interpretation rather than uncritical acceptance. According to the widely referenced criteria for watershed-scale hydrological models (Moriarty et al., 2007), NSE values between 0.50 and 0.65 are classified as “satisfactory,” which places this model at the lower end of the acceptable range. Several factors likely contribute to this moderate performance that are specific to the study context rather than indicative of fundamental model inadequacy.

The reliance on a single rainfall station (Penatahan) to represent precipitation input for the catchment introduces spatial rainfall uncertainty that the F.J. Mock model, as a lumped conceptual model, cannot resolve. This limitation warrants explicit treatment in relation to the model's moderate NSE, as the Subak Balangan catchment lies within a topographically complex volcanic landscape where rainfall spatial variability is driven by two distinct mechanisms. First, the monsoon-driven large-scale stratiform rainfall that dominates the November–March wet season is relatively spatially uniform at the scales of this study (~40 ha catchment) and is likely well represented by a single nearby station. Second, the convective thunderstorm events that characterise the April–October transitional and dry season periods exhibit pronounced spatial heterogeneity: cell sizes of 5–15 km are common in tropical volcanic settings, meaning that intense short-duration events may occur directly over the catchment but be absent or substantially attenuated at Penatahan station, or vice versa. This convective rainfall uncertainty is most consequential precisely during the May–September period identified as the critical deficit season: if the model systematically underestimates convective inputs during this period, deficit magnitudes may be overestimated; conversely, if convective events measured at Penatahan do

not consistently reach the Balangan catchment, the model may overestimate dry-season water availability. The rainfall perturbation sensitivity analysis ( $\pm 10\%$  monthly totals) provides a partial assessment of this uncertainty, but it cannot capture the episodic nature of individual convective events. Future installation of an on-catchment rain gauge would substantially reduce this source of uncertainty and improve model reliability for operational irrigation management. The volcanic geological substrate of the study area, characterised by highly permeable lahar deposits, further complicates the rainfall–runoff relationship through rapid infiltration and complex subsurface flow paths that a lumped model simplifies considerably. Additionally, the validation period (March–July 2025, 10 half-monthly measurements) is short, covering only the wet-to-dry season transition, which limits evaluation of model performance during the critical dry season and peak wet season periods.

Despite these limitations, the model captures the temporal structure of discharge variability well ( $R^2 = 0.833$ ,  $r = 0.913$ ), suggesting that it adequately represents the dominant hydrological processes governing water availability in the catchment. For this study, comparative water balance assessment between cropping patterns, rather than precise discharge prediction, the model performance is sufficient to support the qualitative and semi-quantitative conclusions drawn. The sensitivity analysis further demonstrates that the principal findings regarding deficit frequency and seasonal concentration are robust to the range of uncertainty associated with model parameter and input data limitations.

#### 4.2 Water Deficit Characterisation and Cropping Pattern Implications

The water balance results reveal severe and chronic water deficits in Subak Balangan under both cropping patterns examined. The existing flower–cassava rotation, which represents the farmers' adaptive response to prolonged water scarcity, still experiences deficits in 75% of half-monthly periods. This finding quantifies what has been documented qualitatively by Eryani & Jayantari (2024) (Eryani & Jayantari, 2024): the allocation dispute has reduced water availability to levels insufficient for sustained agriculture, regardless of crop choice. The deficit severity in Subak Balangan substantially exceeds conditions reported in other F.J. Mock studies of Indonesian irrigation areas. Batas et al. (2023) found adequate water availability in the Jetis Irrigation Area, and Purnaditya & Asyiah (2020) documented 25-year sufficiency in the Cijung Watershed. This contrast is attributable to the institutional origin of Subak Balangan's water shortage: the system's deficit arises from allocation constraints rather than inherent hydro-climatic insufficiency, a distinction that is important for identifying appropriate interventions.

The comparative analysis of the paddy–paddy–maize pattern provides a quantitative context for evaluating crop intensification proposals in this specific setting. The 2.96-fold increase in peak water demand and the expansion of deficit frequency from 75% to 91.7% demonstrate that, under current allocation constraints, a shift to paddy-based production would substantially worsen water stress in Subak Balangan. This finding is consistent with the broader principle established by Kusumastuti et al. (2021) that paddy cultivation imposes fundamentally higher water demands than dryland alternatives in Indonesian irrigation contexts. However, it is important to emphasise that this conclusion is specific to the current allocation conditions in Subak Balangan. If the upstream–downstream allocation dispute were resolved, thereby increasing available supply, the feasibility of paddy cultivation would need to be reassessed in light of the modified water availability.

The seasonal concentration of deficits during May–September is a robust finding confirmed across all sensitivity analysis variants. This temporal pattern has substantive implications for adaptive management planning under the Subak governance framework, and these implications extend beyond purely engineering interventions to encompass institutional, agronomic, and policy dimensions.

From an institutional water management perspective, the most fundamental adaptive strategy for Subak Balangan remains the resolution of the upstream–downstream inter-district allocation dispute. The water balance data quantified in this study provide concrete evidence for this negotiation: even under the existing low-demand flower–cassava rotation, Subak Balangan requires a minimum supply of approximately  $0.013 \text{ m}^3/\text{s}$  (equivalent to the  $Q_{80}$  value of March I) to achieve year-round adequacy. Under the paddy–paddy–maize alternative, peak demand reaches  $0.074 \text{ m}^3/\text{s}$  in June II, a flow rate that the catchment can only sustain during the peak wet season. These figures provide the water allocation authorities with a quantitative reference for setting minimum environmental flow releases from upstream districts to Subak Balangan.

In the interim, before dispute resolution, supplementary water sources targeted at the May–September critical deficit period represent the most

cost-effective engineering adaptation. Groundwater development via shallow dug wells is feasible given the moderate-to-high permeability of the lahar deposits underlying Subak Balangan, though extraction volumes must be managed to avoid depleting the aquifer system that also supports domestic water supply in the Kuwum Village area. Small-scale rainwater harvesting structures (small farm ponds with capacities of  $500\text{--}2,000 \text{ m}^3$ ) could buffer the May II–June I period when deficit peaks for the flower–cassava pattern. These interventions are technically compatible with the Subak governance model, as small-scale water storage structures have historical precedents in Bali's traditional irrigation landscape and can be managed collectively under Subak regulations (*awig-awig*) without disrupting the communal water distribution principles central to Tri Hita Karana.

The high deficit frequency under the hypothetical paddy–paddy–maize rotation (91.7% of periods, maximum deficit  $0.074 \text{ m}^3/\text{s}$ ) carries explicit policy and crop planning implications that warrant direct discussion. Paddy cultivation has deep cultural significance in Bali as the foundation of Subak ceremonies and the Tri Hita Karana cosmological framework; any policy recommendation to forgo paddy must therefore balance agronomic and hydrological realities against cultural sustainability imperatives. This study's findings suggest that, under current water allocation conditions, blanket paddy intensification policies, applied uniformly to water-stressed Subak units such as Subak Balangan, are counterproductive: they would worsen food security outcomes by causing near-total crop failure due to water deficit rather than improving staple grain production. The practical implication for agricultural extension services and Badung Regency agricultural planners is that crop subsidies, planting incentive programmes, and irrigation infrastructure investments directed at paddy intensification in chronically water-limited Subak systems should be conditional on verified resolution of upstream allocation constraints. Until that condition is met, policy support should prioritise drought-tolerant, lower-demand alternatives in the existing flower–cassava tradition, combined with market development for non-paddy Subak products (ceremonial flowers, tubers, and horticultural crops) that generate adequate farmer income without exacerbating water stress. This conditional crop-diversification framing aligns with the broader food systems resilience literature, which recognises that productive agricultural systems under water scarcity require alignment between policy incentives, institutional water governance, and biophysical constraints.

The identification of this temporal deficit concentration represents the most actionable finding for Subak Balangan's water management planning and provides a quantitative foundation for the multi-stakeholder negotiation process involving Badung and Tabanan Regency water authorities, the Bali River Basin Organisation (BWS Bali-Penida), and the Subak Balangan *pekaseh* (traditional irrigation manager).

#### 4.3 Contextualisation Within Traditional Irrigation Research: Theoretical Contributions

This study contributes to the limited body of quantitative hydrological assessments of traditionally managed irrigation systems, but its significance extends beyond methodological application to advance two interrelated theoretical propositions that challenge foundational assumptions in irrigation hydrology. The first is the Institutional Hydro-Decoupling (IHD) framework; the second is the concept of hydro-adaptive cropping moderation (HACM). Together, they constitute a theoretical synthesis of hydrological science and institutional water governance theory that has not previously been articulated in the irrigation modelling literature.

The IHD framework addresses a critical but unexamined gap in the interpretation of rainfall–runoff model outputs. Standard applications of the F.J. Mock method and, more broadly, any lumped hydrological model used for irrigation planning implicitly assume that the modelled runoff reaching a gauge point or intake location is functionally equivalent to the water available for agricultural use. This assumption is valid in systems where institutional governance is aligned with hydrological processes: when water allocation rules, infrastructure operation, and upstream demand are calibrated to allow downstream users to access what the catchment produces. However, this assumption fails categorically in the presence of upstream institutional constraints that operate independently of, and in systematic opposition to, catchment hydrology. In the Subak Balangan case, the inter-district allocation dispute has maintained available flow to the system at a fraction of the catchment potential for two decades. The F.J. Mock model, applied to the Subak Balangan catchment, estimates what the hydrology can produce, but the effective water available for irrigation is not the hydrological  $Q_{80}$ ; it is the institutionally-bounded  $Q_{80}$ , systematically suppressed by the governance constraint. The gap between these two quantities constitutes the Institutional Water

Stress Deficit (IWSD): a deficit that no hydrological intervention (additional rainfall, improved catchment management) can close, because its root cause is not in the hydrological system but in the institutional one. This conceptual distinction, between hydro-climatic water stress and institutional water stress, is the central theoretical refinement this study contributes. It refines the reliable flow concept ( $Q_{80}$ ) by contextualising it as a two-component variable:  $Q_{80}(\text{hydro})$ , representing the hydrological system's supply capacity, and  $Q_{80}(\text{eff})$ , representing the effective flow after institutional constraints are applied. Crucially, for IHD-affected systems, modelled  $Q_{80}(\text{hydro})$  systematically overestimates  $Q_{80}(\text{eff})$ , and calibrating a rainfall-runoff model against field-measured discharge at the intake simultaneously estimates  $Q_{80}(\text{eff})$  and encodes the institutional constraint within the model parameters. This methodological insight has significant implications for model transferability to other constrained systems.

The IHD framework aligns with and extends Ostrom's common-pool resource (CPR) theory (Ostrom, 1990), which establishes that the governance architecture of a resource system can create outcomes fundamentally different from those predicted by biophysical models alone. Ostrom's framework, however, was developed primarily to explain how robust governance prevents resource degradation; it describes functional CPR systems. The IHD concept addresses a failure condition absent from Ostrom's taxonomy: when governance failure at a larger administrative scale (inter-district allocation dispute) imposes a structural ceiling on the resource supply available to a lower-scale, internally well-governed CPR institution (the Subak). This cross-scale governance failure condition extends the institutional mismatch diagnosis articulated by Meinzen-Dick (2007), who argued that no single institutional arrangement constitutes a panacea for water management and that performance depends critically on the fit between governance structure and contextual conditions. The IHD framework operationalises this insight in quantitative hydrological terms: the mismatch between inter-district allocation governance and Subak-level resource requirements is not merely an institutional diagnosis but a measurable hydrological variable expressed as the gap between  $Q_{80}(\text{hydro})$  and  $Q_{80}(\text{eff})$ . This multi-scale institutional failure generates a paradox that the CPR literature has not previously quantified: a locally well-governed Subak, with intact awig-awig, active pekaseh leadership, and functional water distribution, fails to achieve agricultural sustainability not because of internal governance deficiency but because of external institutional disruption. Hydrological modelling, as demonstrated here, provides the quantitative evidence needed to distinguish these failure modes: the model output (moderate NSE, high  $R^2$ , low RMSE) confirms that the catchment hydrology is functional and that Subak's internal water distribution is operating normally. The deficit is therefore entirely attributable to the institutional constraint, and this attribution has profound implications for both theory and policy.

The second theoretical contribution, hydro-adaptive cropping moderation (HACM), builds upon the IHD framework to explain an observable but theoretically unaccounted phenomenon in the Subak Balangan data: the persistence of agricultural production despite a 20-year severe water deficit. Conventional agricultural vulnerability frameworks predict that chronic water deficits at the severity documented here (75% deficit frequency) should cause system abandonment or collapse. This prediction follows from linear vulnerability models in which exposure severity determines system outcome without accounting for endogenous adaptive responses (Smit & Wandel, 2006). Yet Subak Balangan continues to function. The HACM concept proposes that this persistence is explained not merely by farmer resilience or cultural commitment, explanations typically offered in the socio-anthropological literature, but by a rational, endogenous demand-side moderation mechanism consistent with what Smit and Wandel (2006) term autonomous adaptation: adjustments undertaken by affected communities without external policy direction, driven by experienced conditions rather than projected scenarios. Moreover, Lansing (2006) demonstrated that Balinese Subak networks function as self-organising systems in which farmer collectives achieve emergent solutions to water allocation problems through iterative local decision-making; the HACM mechanism represents a specific manifestation of this self-organising capacity applied to demand-side management under institutional water stress. The adoption of cropping patterns whose water demands are calibrated, likely through iterative learning over multiple growing seasons, to fall within the feasible range of the institutionally-bounded  $Q_{80}(\text{eff})$  constitutes an endogenous adaptation pathway that standard vulnerability frameworks, which assume passive exposure, do not predict. The flower-cassava rotation, with its peak demand of  $0.025 \text{ m}^3/\text{s}$  (compared to  $Q_{80}$  peak of  $0.012 \text{ m}^3/\text{s}$ ), represents an imperfect but directionally rational HACM response: it reduces deficit frequency from the 91.7% that would characterise paddy cultivation to 75%, and reduces maximum deficit magnitude from 0.074

to  $0.017 \text{ m}^3/\text{s}$ . The theoretical significance of HACM lies in its framing of cropping pattern choice not as a static agronomic decision but as a dynamic hydrological moderation variable that partially compensates for supply-side institutional failure. This reframing has important implications for how irrigation vulnerability is conceptualised and measured: a system with high deficit frequency but a HACM-adapted cropping pattern is fundamentally more resilient than a system with the same deficit frequency under a demand-maximising cropping pattern, because the HACM strategy preserves a non-zero probability of agricultural production in each period. Measuring resilience by deficit frequency alone, as is standard in water balance studies, conflates the hydrological severity of water stress with the agricultural severity of its consequences, a conflation that HACM theory resolves by introducing cropping pattern adaptation as a moderating construct between supply deficit and agricultural outcome.

Taken together, IHD and HACM constitute a theoretical synthesis that bridges three traditionally separate bodies of literature: hydrological modelling (where the contribution lies in reframing reliable flow estimation), institutional water governance (where the contribution lies in quantifying the downstream biophysical consequences of inter-scale governance failure), and agricultural adaptation (where the contribution lies in identifying cropping pattern choice as a demand-side moderation mechanism rather than merely a cultural or economic variable). This synthesis is empirically grounded in the Subak Balangan data but points to a generalizable research programme: testing whether IHD and HACM are observable in other traditionally-governed irrigation systems experiencing allocation-driven water stress, including comparable systems in South and Southeast Asia, sub-Saharan Africa, and the Andean highlands where indigenous irrigation governance operates within contested inter-institutional allocation environments. It would be premature to assert universality from a single case; however, the logical structure of IHD, which models runoff overestimates effective supply when institutional constraints operate upstream, is not specific to Subak Balangan but is a general property of any system where the governance architecture decouples hydrological production from water delivery. The Subak Balangan case provides the first quantified demonstration of this mechanism and the analytical template for future comparative testing.

#### 4.4 Limitations and Sources of Uncertainty

Several limitations constrain the scope and certainty of this study's findings, and these should be weighed against the strength of the conclusions drawn. The most fundamental limitation is the reliance on a single Subak system, which precludes generalisation to other traditional irrigation systems without comparative evidence. While Subak Balangan's extreme water stress makes it an informative case for quantifying deficit dynamics, it is not representative of the broader Subak landscape in Bali, where water availability and institutional conditions vary substantially.

The 10-year hydrological record (2015–2024) used for model development and reliable flow estimation is relatively short for robust frequency analysis. The jackknife resampling analysis revealed that dry-season  $Q_{80}$  estimates carry coefficients of variation of 20–28%, indicating non-trivial sampling uncertainty. A longer record would reduce this uncertainty and improve the stability of reliable flow estimates. Furthermore, the 10-year period may not adequately capture the full range of climatic variability affecting the study area, including the influence of El Niño–Southern Oscillation (ENSO) cycles that significantly affect Indonesian rainfall patterns over multi-decadal timescales.

The use of a single rainfall station introduces spatial precipitation uncertainty that is not quantified by the model calibration statistics. In the absence of additional rain gauges within or near the catchment, the magnitude of this uncertainty remains unknown, though the rainfall perturbation analysis ( $\pm 10\%$ ) provides some indication of the sensitivity of results to potential input errors. The short validation period (March–July 2025, covering only the wet-to-dry transition) means that model performance during the dry season and peak wet season, when the most critical water balance decisions are made, has not been independently verified.

The NSE value of 0.521, while classified as satisfactory, indicates that approximately 48% of observed discharge variance is unexplained by the model. This residual variance may arise from spatial rainfall heterogeneity, sub-daily flow dynamics not captured by half-monthly time steps, or complex groundwater interactions in the volcanic substrate. The conclusions drawn from this study are therefore semi-quantitative: the direction and approximate magnitude of water deficits are well established, but precise deficit volumes should be treated as order-of-magnitude estimates rather than exact values.

Finally, the irrigation demand calculations assume standard crop

coefficients and efficiency values from Indonesian planning guidelines, which may not precisely match actual conditions in Subak Balangan, where farmer practices have adapted to chronic water scarcity. Actual water use efficiency may be higher than assumed due to farmers' adaptive strategies, which would reduce realised deficits somewhat. Conversely, infrastructure deterioration could reduce conveyance efficiency below assumed values. Field measurement of actual crop water use and conveyance losses would strengthen future analyses.

#### 4.5 Implications for Future Research

The findings and limitations of this study point to several priorities for future research. Most importantly, comparative water balance assessments across multiple Subak systems spanning different deficit severities, catchment characteristics, and institutional conditions are needed to establish whether the patterns observed in Subak Balangan, particularly the seasonal deficit concentration and the sensitivity to cropping pattern choice, are generalisable or case-specific. Such comparative work would also allow identification of threshold conditions under which paddy cultivation becomes hydrologically feasible, addressing the crop choice question with broader empirical support. Additionally, scenario analysis incorporating the potential resolution of the allocation dispute (i.e., increased water supply to Subak Balangan) would provide a more complete basis for agricultural planning by quantifying the supply increase needed to support different cropping alternatives. Integration of climate change projections with the water balance framework would extend the analysis beyond current conditions to assess long-term sustainability. Finally, farmer-level studies examining actual water use practices, adaptation strategies, and preferences would complement this supply-side hydrological assessment with demand-side behavioural evidence.

## 5. CONCLUSION

This study applied the F.J. Mock rainfall-runoff model to quantify water balance conditions in Subak Balangan, a traditionally managed irrigation system in Bali experiencing a 20-year chronic water deficit caused by an inter-district allocation dispute. The model achieved moderate-to-good calibration performance ( $NSE = 0.521$ ,  $R^2 = 0.833$ ) against independent field measurements, and a structured sensitivity analysis confirmed the robustness of the principal findings.

Three key findings emerge from this case study. First, water availability at 80% reliability ( $0.001\text{--}0.012\text{ m}^3/\text{s}$ ) is insufficient to meet irrigation demands under either of the two cropping patterns examined, confirming the severity of institutional water stress quantitatively. Second, the existing flower-cassava rotation, while still experiencing deficits in 75% of periods, represents a substantially less water-demanding alternative than paddy-based intensification, which would produce deficits in 91.7% of periods with 2.96-fold higher peak demand. Third, water deficits are seasonally concentrated during May-September, suggesting that targeted seasonal interventions could address the majority of annual water stress.

These findings provide a quantitative baseline for the ongoing allocation dispute resolution process affecting Subak Balangan and demonstrate the feasibility of applying standard hydrological modelling approaches to traditionally managed irrigation systems. However, the conclusions are specific to the study site and current allocation conditions, and should not be extrapolated to other Subak systems or to broader policy contexts without comparative evidence. The analytical framework developed here is replicable and can serve as a template for the multi-Subak comparative studies needed to establish general patterns in water-stressed traditional irrigation systems.

This research demonstrates successful integration of F.J. Mock hydrological modelling with traditional Subak irrigation governance, addressing a critical methodological gap in water resource assessment for cultural heritage agricultural systems. The calibrated model ( $NSE=0.521$ ,  $R^2=0.833$ ) quantified severe water deficits in Subak Balangan: existing flower-cassava cultivation experiences shortages in 75% of periods (maximum  $0.017\text{ m}^3/\text{s}$ ), while paddy-based intensification exacerbates stress to 91.7% of periods (maximum  $0.074\text{ m}^3/\text{s}$ ). Paddy cultivation increases peak water demand 2.96-fold while reducing surplus periods from 25% to 8.3%, providing empirical evidence that staple crop intensification paradoxically threatens food security under current water-limited conditions.

From a theoretical perspective, this study advances two interconnected conceptual contributions that extend beyond the empirical case of Subak Balangan and challenge foundational assumptions in irrigation hydrology and water governance science. The first, the Institutional Hydro-Decoupling (IHD) framework, proposes that in traditionally governed irrigation systems subjected to inter-institutional allocation disputes, the

80% reliable flow ( $Q_{80}$ ) estimated through rainfall-runoff modelling must be understood as a two-component variable: the hydrological  $Q_{80}(\text{hydro})$ , representing catchment supply capacity, and the effective  $Q_{80}(\text{eff})$ , representing the institutionally-bounded flow actually available at the intake. In IHD conditions, the deterministic link between catchment hydrology and irrigation water supply is structurally severed by governance failure, rendering standard model-to-intake interpretations systematically misleading. This refinement of the reliable flow concept has direct implications for how hydrological models should be calibrated, interpreted, and applied in institutional governance contexts globally. The second contribution, hydro-adaptive cropping moderation (HACM), proposes that farmer-led substitution of high-demand staple crops with low-demand alternatives in IHD-affected systems constitutes a rational endogenous moderation mechanism that partially compensates for institutionally-suppressed supply, reframing cropping pattern adaptation as a hydrological moderation variable rather than merely a cultural or economic choice. The persistence of agricultural activity in Subak Balangan despite chronic severe deficit conditions is theoretically explained by the HACM mechanism: the flower-cassava rotation reduces demand sufficiently to remain within the feasible range of  $Q_{80}(\text{eff})$ , whereas paddy cultivation would eliminate this feasibility. These two propositions, grounded empirically in the Subak Balangan case, constitute the first quantified demonstration of IHD and HACM and provide the conceptual architecture for a broader comparative research programme testing their generalizability across indigenous irrigation systems operating within contested inter-institutional allocation environments.

Practical implications for Subak Balangan and similar water-stressed traditional systems include: (1) urgent resolution of inter-district allocation disputes as prerequisite for agricultural sustainability; (2) implementation of supplementary water sources (groundwater development, rainwater harvesting) strategically deployed during critical May-July deficit periods; (3) high-efficiency irrigation technologies adapted to traditional infrastructure; and (4) strategic crop scheduling aligned with seasonal water availability rather than cultural calendars alone. The urgency of integrated interventions cannot be overstated: continued inaction threatens not only food security but also the viability of UNESCO-recognized cultural heritage embodying sophisticated indigenous water management knowledge developed over millennia.

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## REFERENCES

- Ahmadi, A., Daccache, A., Sadegh, M., & Snyder, R. L. (2023). Statistical and deep learning models for reference evapotranspiration time series forecasting: A comparison of accuracy, complexity, and data efficiency. *Computers and Electronics in Agriculture*, 215, 108424. <https://doi.org/10.1016/j.COMPAG.2023.108424>
- Araujo, H. F. P. De, Machado, C. C. C., Pareyn, F. G. C., Nascimento, N. F. F. Do, Araújo, L. N. D. A., Borges, L. A. P. De, Santos, B. A., Beirigo, R. M., Vasconcellos, A., Dias, B. D. O., Alvarado, F., & Silva, J. M. C. Da. (2021). A sustainable agricultural landscape model for tropical drylands. *Land Use Policy*, 100. <https://doi.org/10.1016/j.landusepol.2020.104913>
- Ardana, P. D. H., Suparwata, D. O., Sudrajat, A., Chatun, S., & Harsono, I. (2024). The role of Bali's traditional subak farming system in the preservation of natural and cultural resources. *West Science Nature and Technology*, 2(01), 31-38. <https://doi.org/10.58812/wsnst.v2i04.754>
- Azizi, M. A., & Sutopo, Y. (2022). Water needs using paddy-paddy-maize plants in irrigation area (DI) Sidopangus Regency, Semarang, Indonesia. *Proceedings of the 6th International Conference on Science, Education and Technology (ISET 2020)*, 574. <https://doi.org/10.2991/assehr.k.211125.137>
- Babaeian, E., Paheding, S., Siddique, N., Devabhaktuni, V. K., & Tuller, M.

- (2022). Short- and mid-term forecasts of actual evapotranspiration with deep learning. *Journal of Hydrology*, 612, 128078. <https://doi.org/10.1016/j.jhydrol.2022.128078>
- Batas, E. S., Wijayanti, Y., & Kesuma, L. M. (2023). Assessing Agricultural Water Reliability in Jetis Irrigation Area Using the F.J. Mock Hydrological Model. 01023. [https://www.e3s-conferences.org/articles/e3sconf/abs/2023/63/e3sconf\\_icobar23\\_01023/e3sconf\\_icobar23\\_01023.html](https://www.e3s-conferences.org/articles/e3sconf/abs/2023/63/e3sconf_icobar23_01023/e3sconf_icobar23_01023.html)
- Chandrasasi, D., Limantara, L. M., & Juni, R. W. (2020). Analysis using the F. J. Mock Method for calculation of water balance in the Upper Konto Sub-Watershed. *IOP Conference Series: Earth and Environmental Science*, 437. <https://doi.org/10.1088/1755-1315/437/1/012019>
- Dharmawati, N. D., Suntoro, S., Komariah, K., & Hermantoro, H. (2025). Potential rainwater availability and crop water requirement of oil palm crops due to climate change. *IOP Conference Series: Earth and Environmental Science*, 1482(1). <https://doi.org/10.1088/1755-1315/1482/1/012006>
- Directorate General of Water Resources. (2015). Proposed Scheme for Channel Improvement in Pama Palean (Contract No. HK 02 03/BP/PPR/14). Ministry of Public Works.
- Eryani, I. G. A. P., & Jayantari, M. W. (2024). Water conflict analysis in the Balangan Irrigation Area: causes, impacts, and management strategies. *IOP Conf. Series: Earth and Environmental Science* 1311. <https://doi.org/10.1088/1755-1315/1311/1/012036>
- Friedl, H., & Stampfer, E. (2002). Jackknife resampling. In A. H. El-Shaarawi & W. W. Piegorsch (Eds.), *Encyclopedia of Environmetrics* (Vol. 2, pp. 1089–1098). John Wiley & Sons.
- Gandharum, L., Hartono, D. M., Sadmono, H., Sanjaya, H., Sumargana, L., Kusumawardhani, A. D., Alhasanah, F., Sencaki, D. B., & Setyaningrum, N. (2025). Advancing Land Use Modelling with Rice Cropping Intensity: A Geospatial Study on the Shrinking Paddy Fields in Indonesia. *Geographies*, 5(3), 1–27. <https://doi.org/10.3390/geographies5030031>
- Hamimed, A., Benslimane, M., Khaldi, A., Nehal, L., & Mansour, Z. (2025). Assessment of Actual Evapotranspiration and Water Stress from Landsat ETM Satellite Data Using the Priestley–Taylor Model in the Habra Plain, Algeria. 215–232. [https://openurl.ebsco.com/EPDB%3Agcd%3A7%3A24945399/deta ilv2?sid=ebsco%3Aplink%3Acrawler&id=ebsco%3Agcd%3A189111921&crl=f&link\\_origin=www.google.com](https://openurl.ebsco.com/EPDB%3Agcd%3A7%3A24945399/deta ilv2?sid=ebsco%3Aplink%3Acrawler&id=ebsco%3Agcd%3A189111921&crl=f&link_origin=www.google.com)
- Hamimed, A., Mansour, Z., Tewfik, Q. A., Mohamed, T., & Bakhtiar, D. (2017). Monitoring Daily Actual Evapotranspiration And Surface Water Status Over An Agricultural Area In Western Algeria Using Remote Sensing Data. 45–59. <https://asjp.cerist.dz/en/article/55446>
- Hashemi, S. Z., Darzi-Naftchali, A., Karandish, F., Ritzema, H., & Solaimani, K. (2024). Enhancing agricultural sustainability with water and crop management strategies in modern irrigation and drainage networks. *Agricultural Water Management*, 305. <https://doi.org/10.1016/j.agwat.2024.109110>
- Kusumastuti, D. I., Jokowinarno, D., Putri, R., & Khadijah, L. (2021). The needs and availability analysis of irrigation water of Way Wayah Irrigation Area. *IOP Conference Series: Earth and Environmental Science*, 739(1). <https://doi.org/10.1088/1755-1315/739/1/012028>
- Lansing, J. S. (2006). *Perfect Order: Recognizing Complexity in Bali*. Princeton University Press. <https://doi.org/10.1515/9781400845866>
- Liu, Z., Huang, Y., Liu, T., Li, J., Xing, W., Akmalov, S., Peng, J., Pan, X., Guo, C., & Duan, Y. (2020). Water balance analysis based on a quantitative evapotranspiration inversion in the Nukus irrigation area, Lower Amu River Basin. *Remote Sensing*, 12(14), 2297. <https://doi.org/10.3390/rs12142297>
- Meinzen-Dick, R. (2007). Beyond panaceas in water institutions. *Proceedings of the National Academy of Sciences*, 104(39), 15200–15205. <https://doi.org/10.1073/pnas.0702296104>
- Mgendi, G. (2024). Unlocking the potential of precision agriculture for sustainable farming. *Discover Agriculture*, 2(87). <https://doi.org/10.1007/s44279-024-00078-3>
- Moriasi, D. N., Arnold, J. G., Liew, M. W. Van, Bingner, R. L., Harmel, R. D., & Veith, T. L. (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE*, 50(3), 885–900. <https://doi.org/10.13031/2013.23153>
- Mudiana, W., & Setiadi, H. (2008). *Groundwater Basin Distribution Map of Bali Island*.
- Oktarini, A. A., & Marselina, M. (2024). Discharge Forecasting in Monsoonal Gung Watershed: A Comparative Analysis of F. J. Mock, Markov, and ARIMA Models. 02002. [https://www.e3s-conferences.org/articles/e3sconf/pdf/2024/87/e3sconf\\_icres2024\\_02002.pdf](https://www.e3s-conferences.org/articles/e3sconf/pdf/2024/87/e3sconf_icres2024_02002.pdf)
- Ostrom, E. (1990). *Governing the Commons: The Evolution of Institutions for Collective Action*. Cambridge University Press.
- Pandey, V., Srivastava, P. K., Das, P., & Behera, M. D. (2021). Irrigation water demand estimation in Bundelkhand region using the variable infiltration capacity model. *Agricultural Water Management: Theories and Practices*, 331–347. <https://doi.org/10.1016/B978-0-12-812362-1.00016-3>
- Permadi, M. G., & Parjono. (2020). The Efficiency of Rawa Mayo Irrigation Channels in Kurik Sub-District, Merauke. *Journal of Physics: Conference Series*, 1569. <https://doi.org/10.1088/1742-6596/1569/4/042102>
- Purbo-Hadiwidjojo, M. M., Samodra, H., & Amin, T. C. (1998). *Geological Map of Bali Sheet, Nusa Tenggara*.
- Purnaditya, N. P., & Asyah, S. (2020). Quantifying the Reliable Discharges as an Incipient Analysis of Agricultural Planning and Developing in Cijung Watershed. *IOP Conference Series: Earth and Environmental Science*, 715. <https://doi.org/10.1088/1755-1315/715/1/012004>
- Robinson, G. M. (2024). Global sustainable agriculture and land management systems. *Geography and Sustainability*, 5(4), 637–646. <https://doi.org/10.1016/j.geosus.2024.09.001>
- Sharafi, S., Ghaleni, M. M., & Scholz, M. (2023). Comparison of predictions of daily evapotranspiration based on climate variables using different data mining and empirical methods in various climates of Iran. *Heliyon*, 9(2), e13245. <https://doi.org/10.1016/j.heliyon.2023.e13245>
- Smit, B., & Wandel, J. (2006). Adaptation, adaptive capacity and vulnerability. *Global Environmental Change*, 16(3), 282–292. <https://doi.org/10.1016/j.gloenvcha.2006.03.008>
- Soerya, S. F., Asdak, C., Kendarto, D. R., Yan, T., & Riyadi, A. (2023). F.J Mock Method for Hydrological Moel in Water Reliability Study in Leuwi Padjadjaran II Reservoir. 44(5), 884–893. <https://jazindia.com/index.php/jaz/article/view/3292>
- Srdić, S., Srđević, Z., Stričević, R., Čereković, N., Benka, P., Rudan, N., Rajić, M., & Todorović, M. (2023). Assessment of Empirical Methods for Estimating Reference Evapotranspiration in Different Climatic Zones of Bosnia and Herzegovina. *Water*, 15(17). <https://doi.org/10.3390/w15173065>
- Stavi, I., Paschalidou, A., Kyriazopoulos, A. P., Halbac-Cotoara-Zamfir, R., Siad, S. M., Suska-Malawska, M., Savic, D., Pinho, J. R. De, Thalheimer, L., Williams, D. S., Hashimshony-Yaffe, N., Geest, K. Van Der, Cordovil, C. M. D. S., & Ficko, A. (2021). Multidimensional Food Security Nexus in Drylands under the Slow Onset Effects of Climate Change. *Land*, 10(12), 1–14. <https://doi.org/10.3390/land10121350>
- Sudadi, P., Setiadi, H., Denny, B. R., Arief, S., Ruchijat, S., & Hadi, S. (1986). *Hydrogeological Map of Bali Island Sheet*.

