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The Influence of Subak Farmer Groups on Weir Intake Operations

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ABSTRACT

Subak is a traditional irrigation management system in Bali that integrates social, religious, and technical dimensions within agricultural practice through collective agreements among farmers. This study examines the influence of *Nabdab Yeh*, the water allocation mechanism employed by the Subak institution on the intake operation of Mambal Weir, which supplies irrigation water to 43 Subak units within the Tukad Ayung Irrigation Area. Quantification Analysis I was applied to assess the impact of four principal determinants, namely antecedent precipitation, ponding depth, water demand, and Paddy cultivation percentage. Each determinant was systematically categorized and converted into binary variables to formulate a predictive model. The resulting model yielded an R-total value of 0.78, indicating a strong correlation and high predictive accuracy. Partial correlation analysis revealed that antecedent precipitation (R-partial = 0.515) exerted the most dominant influence, followed by ponding depth (0.470), while water demand (0.249) and Paddy percentage (0.220) demonstrated comparatively lower significance. These findings affirm that climatic and hydrological conditions constitute the primary determinants governing intake operations, whereas agricultural cropping patterns function as an adaptive response to prevailing water availability. The developed model provides a scientific basis for adaptive irrigation management while sustaining the local ecological wisdom inherent to the Subak system.

Keywords: Irrigation Operation; Mambal Weir; *Nabdab Yeh*; Quantification Analysis I; Subak

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1. INTRODUCTION

Subak is a traditional irrigation management system in Bali that integrates social, religious, and technical aspects of agriculture. The system is based on the philosophy of Tri Hita Karana. This philosophy emphasizes harmony among three relationships: humanity and the Divine (*Parahyangan*), humanity and nature (*Palemahan*), and among community members (*Pawongan*). Subak functions as an autonomous organization for water distribution and resource management [1], [2]. The Subak system controls water distribution, cropping schedules, and the conduct of agricultural rituals through collective deliberation among farmers. Subak water management is adapted to Bali's steep, terraced landscapes, utilizing gravity-driven flow along natural contours to reduce runoff, retain water on slopes, and direct it toward lower areas. Under water-abundant conditions, Subak typically applies a paddy–paddy cropping pattern. During water scarcity, farmers shift to a paddy–maze pattern. This adjustment follows the *nyorog* system. The system distributes water sequentially from upstream to downstream units. It aims to ensure equitable water allocation. [3]–[6].

One area that actively maintains the Subak system is the Tukad Ayung Irrigation Area (I.A. Tukad Ayung). It is located within the Ayung River Basin (DAS Ayung). The area includes 43 Subak units across Denpasar City, Badung Regency, and Tabanan Regency. Subak communities in this region depend on water from Mambal Weir. They adjust crop selection and planting schedules based on water availability and seasonal conditions. Water distribution is coordinated through the Nabdab Yeh process. This process is a structured mechanism for water allocation. It considers crop type, antecedent precipitation, and previous stream discharge. Following the determined water allocation, the Subak requests the water demand to the weir operator for intake operation. Although the Nabdab Yeh process influences these operations, the contribution of each factor remains unclear. Existing irrigation controls often ignore the reality of increasing variability in discharge and rainfall [7]. Quantitative evidence is still limited [5], [6], [8].

This study investigates the relationship between these factors and intake operations. It applies Quantification Analysis I. This method quantifies the influence of categorical variables on numerical outcomes. [5], [9]. A predictive model of Mambal Weir intake operation was developed using 2021–2022 data. The model includes four factors: antecedent precipitation, ponding depth, water demand, and paddy cultivation percentage. To improve hydrological representation, this study uses satellite precipitation data. Remote sensing technology is increasingly being developed to support global precipitation monitoring, addressing challenges in estimating rainfall data for water resource management [10]. A key benefit of satellite-based precipitation estimates is their ability to capture a comprehensive view of precipitation systems, which is difficult to achieve with limited and unevenly distributed rain gauge networks. This capability significantly improves our understanding of natural rainfall patterns [11]. CHIRPS provides high spatial resolution and long-term coverage. The data show satisfactory accuracy for Denpasar and Badung areas. Therefore, they are suitable for this analysis. [12]–[14].

This study aims to identify the most influential factors in irrigation decision-making within Subak. The findings are expected to support more adaptive and efficient water management. They also aim to preserve the ecological wisdom embedded in the Subak system.

2. RESEARCH METHOD

2.1 Study Area

Mambal Weir is situated at the downstream end of the midstream reach of Tukad Ayung River, located in the southern portion of the Ayung River Basin, which spans an area of approximately 306 km² (Figure 1). The weir contains the flow of Tukad Ayung which is a perennial river with a total length of approximately 72 km, resulting in a relatively stable discharge availability at the intake structure. Intake operations are governed by consensual agreements among Subak farmers under the supervision of government-appointed irrigation officers. This governance arrangement shows that the continuity of the Subak system is highly dependent on the sustained availability of river discharge [15].

Figure 1. Location of Mambal Weir within the Ayung River Basin

A total of 43 Subak units, covering a combined irrigated area of 5,963 hectares, rely on water supplied by Mambal Weir. These Subak communities implement a rotational water allocation scheme (*nyorog*) with four distinct cropping patterns comprising Paddy and secondary crops. Following the classification proposed by Ankum (1995), this arrangement is characterized as a semi-demand system rather than a fully on-demand one [16]. The allocation of water by intake operators, conditioned upon reservoir availability, reflects the semi-demand operational procedure adopted jointly by Subak communities and Mambal Weir's management
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personnel. This practice follows the dynamic-program model for the Mambal Irrigation Area, in which the available discharge at the Mambal intake is treated as the state variable, while the amount of water allocated to each irrigation structure (BB, BBS, BS) serves as the decision variable. Water distribution to Subak-based units applies Subak-derived water-sharing rules, rooted in the Tri Hita Karana philosophy and implemented through coordinated decisions between Subak-based institutions and weir-level operators, thus embedding both technical responsiveness to discharge conditions and socio-cultural norms in the semi-demand-like operation of the system [17]. This also highlights the importance of synergy between top-down water management (government/operators) and bottom-up approaches (Subak) to ensure water supply sustainability [18].

2.2 Research Data

Intake discharge data and cropping pattern records were obtained from the Bali Provincial Office of Public Works, Spatial Planning, Housing, and Settlement Areas (PUPRKIM). Precipitation data were derived from CHIRPS satellite rainfall products. These datasets were compiled into semi-monthly time series from January 2021 to July 2022, resulting in 38 observations. Although the temporal coverage is relatively limited, the semi-monthly resolution allows the dataset to capture short-term variability in water allocation and cropping dynamics. This resolution is particularly relevant for representing operational decision-making processes within the Subak system, which are inherently periodic and responsive to changing hydrological conditions.

The Subak institution classifies growing seasons into three categories: *kertamasa*, referring to the period of water abundance typically coinciding with the wet season, during which Paddy cultivation is practiced; *gadon*, denoting a period of reduced water availability generally occurring during the dry season, when farmers transition to secondary crops and supplement water requirements from the weir; and *nengin*, indicating a period during which no crops are cultivated [5], [19], [20].

A notable shift in cropping patterns was observed in 2022, characterized by a transition from a Paddy – Paddy – Secondary Crops Cropping Pattern to a Paddy – Paddy – Paddy Cropping Pattern for certain Subak subgroups (*tempekan*). This transition resulted in an elevated monthly Paddy cultivation percentage, particularly during the dry season (gadon) spanning March through July, as presented in Table 1.

Table 1. Monthly Paddy cultivation Percentage in I.A. Tukad Ayung

Year	**Monthly Paddy cultivation Percentage**											
	Jan	Feb	Mar	Apr	Mei	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2021	100%	100%	90%	89%	89%	89%	99%	100%	100%	100%	100%	100%
2022	100%	100%	94%	93%	93%	93%	99%	100%	100%	100%	100%	100%

Shifts in cropping patterns directly influence intake discharge, particularly when crops exhibiting higher water requirements, such as Paddy, which necessitate continuous ponding conditions replace less water-intensive alternatives. An increase in Paddy cultivation percentage during the dry season reflects sufficient water discharge from the weir in the preceding period, which motivates farmers to opt for Paddy cultivation. This observation corroborates the well-documented sensitivity of Subak activity to precipitation cycles [5], [21], while simultaneously signaling an anticipated increase in the discharge volume operated at the intake structure. Among the factors demonstrably influencing irrigation management performance are crop type composition and antecedent precipitation [22]. Within the *Nabdab Yeh* process, these factors collectively drive escalating water demand at the intake. Precipitation data were processed as daily records aggregated into semi-monthly totals, with data retrieval facilitated through Google Earth Engine (GEE) using the Irrigation Area boundary as the spatial input. In addition to precipitation, ponding depth on agricultural fields was incorporated as a critical consideration, particularly for parcels under Paddy cultivation.

2.3 Analytical Method

Quantification Analysis I has been demonstrated to be capable of modeling the influence of factors embedded in the *Nabdab Yeh* process and broader Subak activities on weir operational decision-making [3]. This method was therefore applied to analyze intake operation patterns at the weir. All data were categorized into discrete items and subsequently converted into binary variables: 1 denoting 'YES' and 0 denoting 'NO', based on qualitative assessments derived from field observation and recorded measurements. Binary values were employed to compute item-specific weights, thereby constructing a unique predictive model for each observation. Model fit was evaluated through calibration to assess item influence under initial conditions, while predictive accuracy was verified using data from an independent validation year [5], [9], [23].

Item-category pairs were formulated based on factors identified as relevant to intake operations, yielding: Antecedent Precipitation (Item 1), Ponding Depth (Item 2), Water Demand (Item 3), and Paddy Percentage (Item 4). Category thresholds are detailed in Table 2. The category thresholds were not arbitrarily defined but were derived from the statistical distribution of the observed data and informed by field-based irrigation practices within the Subak system. Specifically, threshold values were determined using data clustering tendencies and natural breakpoints observed in the semi-monthly dataset. This approach ensures that each category reflects meaningful distinctions in hydrological and operational conditions rather than uniform or subjective intervals.

For antecedent precipitation, the thresholds (5.79 mm/day and 16.65 mm/day) represent transition points between low, moderate, and high rainfall conditions based on observed variability in the dataset. Similar principles were applied to ponding depth, water demand, and paddy percentage, where category limits correspond to operationally relevant ranges identified from field observations and existing irrigation practices. This categorization approach enhances the interpretability of the model and ensures consistency with real-world decision-making processes within the Subak system. Based on these categories, binary response sets were generated for further analytical processing.

Table 2. Item-Category Identification

Item	Category	Parameter	Description
Yesterday's precipitation (item 1)	X1	Low (X11)	Pt-1 < 5,79 mm/day
		Moderate (X12)	5,79 mm/day < Pt-1 ≤ 16,65 mm/day
		Heavy (X13)	Pt-1 ≥ 16,65 mm/day
Ponding depth (item 2)	X2	Shallow (X21)	ht-1 < 86,6 mm
		Moderate (X22)	86,6 mm < ht-1 ≤ 249,9 mm
		Deep (X23)	Pt-1 ≥ 249,9 mm
Water demand (item 3)	X3	Low (X31)	Qt-1 < 2,76 m^3/s
		Moderate (X32)	2,76 m^3/s < Qt-1 ≤ 3,21 m^3/s
		High (X33)	Qt-1 ≥ 3,21 m^3/s
Paddy percentage (item 4)	X4	Low (X41)	Paddy < 90%
		Moderate (X42)	90% < Paddy ≤ 97%
		High (X43)	Paddy ≥ 97%

2.4 Predictive Model

The 'yes' and 'no' responses were converted into binary values (1 for 'yes' and 0 for 'no') and arranged as dummy variables (Xijk) in a matrix of size m × N. Based on the Quantification Analysis I equation proposed by Dr. Hayashi [9], the predicted discharge (yk) is computed using Equation (1):

$$y_k = \bar{Y} + \sum_{i=1}^{m}\sum_{j=1}^{n_i}\left(a^{ij} - \sum_{k=1}^{n_i} a^{ik}\bar{X}_{ik}\right)X_{ijk} \quad (1)$$

y_k = predicted discharge for sample k
$\bar{Y}$ = mean of observed discharge
$a^{ij} - \sum_{k=1}^{n_i} a^{ik}\bar{X}_{ik}$ = weighting coefficient for each category
X_{ijk} = binary category variable for each item

The total correlation coefficient (R-total) is derived via Equation 2. An R-total value ≥ 0.5 indicates a sufficiently strong association between variables, such that the model may be considered to exhibit satisfactory accuracy with acceptably low prediction error [24]. This correlation metric is essential for ensuring that the model remains responsive to system dynamics driven by both natural processes and anthropogenic activities [25]. The correlation between the model output and intake operations is determined by the relationship between observed and predicted discharge values.

$$\boldsymbol{R}_{y,1,2,3,\ldots} = \sqrt{\frac{\sum_{k-1}^{N}(y_k-\bar{Y})^2}{\sum_{k-1}^{N}(Y_k-\bar{Y})^2}} \quad (2)$$

Upon achieving a satisfactory R-total value, the categorical items constituting the model are considered well-specified, and the individual influence of each item is subsequently quantified. The degree of influence of each factor is determined by the magnitude of its partial correlation coefficient (R-partial), as presented in Table 3. Calculation of R-partial follows Equation 3:

$$\boldsymbol{\rho}(\boldsymbol{y},\boldsymbol{i}) = \frac{-r^{iy}}{\sqrt{r^{ii}}\sqrt{r^{yy}}} \quad (3)$$

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Table 3. Partial Correlation Coefficient (R-partial) Influence Categories

R-partial	Category
$0 < \rho \leq 0,1$	None
$0,1 < \rho \leq 0,3$	Low
$0,3 < \rho \leq 0,5$	Moderate
$0,5 < \rho \leq 1$	High

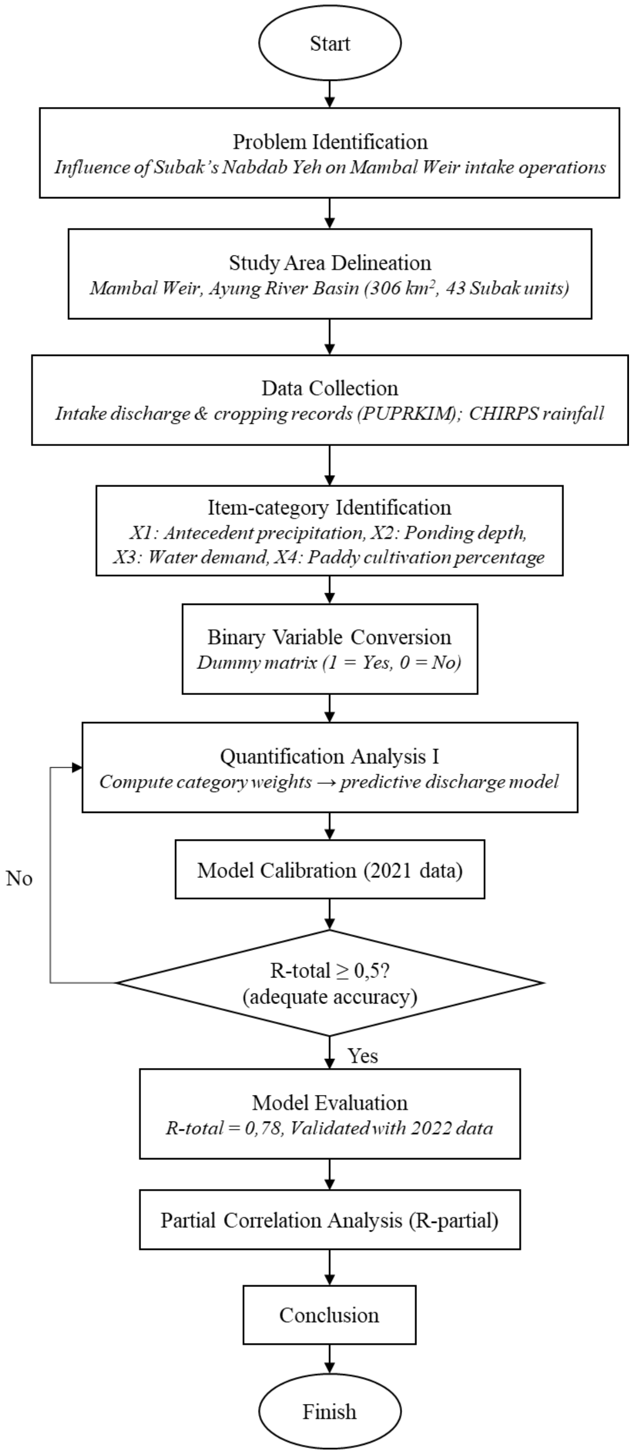

Figure 2. Flowchart

3. RESULTS AND DISCUSSION

The distribution of categorical conditions for the factors influencing irrigation operations, namely antecedent precipitation, ponding depth, water demand, and Paddy cultivation percentage is illustrated in Figure 3. In general, moderate and high categories predominate across all items, indicating a stable irrigation regime characterized by consistently elevated water availability. The proportion of high-category Paddy cultivation percentage reaches approximately 70%, reflecting the dominance of Paddy fields requiring substantial water inputs. Water demand is likewise concentrated in moderate and high categories, consistent with the elevated water requirements associated with the prevailing Paddy cultivation intensity. Ponding depth predominantly falls within the moderate category, suggesting relatively well-regulated field water management. Meanwhile, antecedent precipitation is predominantly classified as moderate, indicative of climatic conditions conducive to irrigation without extreme hydrological fluctuations, thereby sustaining sufficient discharge from the weir.

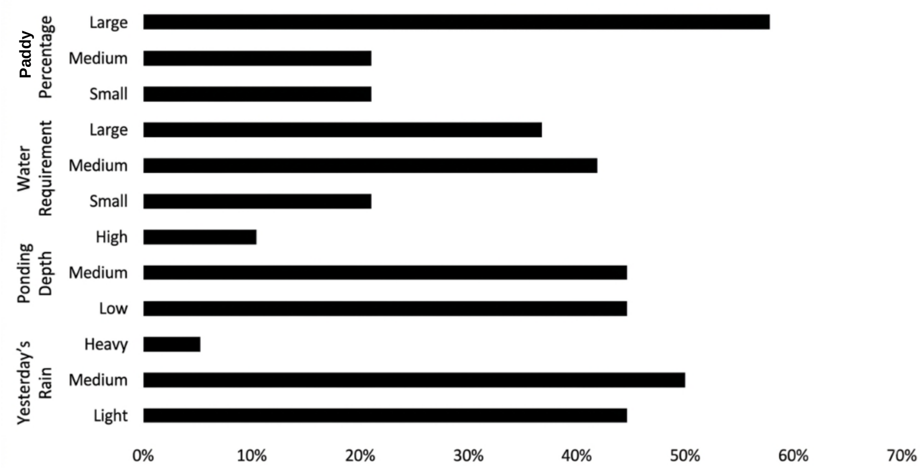

Figure 3. Item-Category Classification Results

The categorical data were subsequently analyzed using Equation 1, yielding the following predictive model expressed as Equation 4:

$$yk = 9.121661218 + -0.95X11 + 0.8250X12 + 0.2003X13 + -0.6216X21 + 0.5910X22 + 0.1300X23 + 0.5883X31 + -0.4060X32 + 0.1279X33 + 0.1640X41 + -0.3686X42 + 0.0744X43 \quad (4)$$

To assess the reliability of the model, predicted intake discharge values were compared with observed data during the calibration process. The comparison indicates that the model is able to capture the general trend of intake variation, particularly under typical operational conditions. Minor deviations are observed under extreme conditions, which is expected given the limited temporal coverage of the dataset. Overall, the model demonstrates acceptable performance in representing intake operation behavior within the Subak system.

The obtained R-total value of 0.78 indicates that the model is suitable for predicting intake operations by substituting binary values from each item-category combination. This result further substantiates that the item-categories representing the factors embedded in the *Nabdab Yeh* process of Subak communities within I.A. Tukad Ayung exhibit statistically meaningful correlation with the intake operations of Mambal Weir. Accordingly, partial correlation analysis was conducted to determine the relative influence level of each item-category, with results presented in Table 4.

Table 4. Relative Influence Level of Each Factor (R-partial)

Item (Influencing Factor)	R-partial value	Influence Level
Yesterday's precipitation (X1)	0,515	High
Ponding Depth (X2)	0,470	Moderate
Water Demand (X3)	0,249	Low
Paddy Percentage (X4)	0,220	Low

Potential interrelationships among explanatory variables were considered, particularly between antecedent precipitation and water demand. While these variables may be conceptually related, they represent different functional roles within the Subak system. Antecedent precipitation reflects natural hydrological input, whereas water demand represents a managerial response based on cropping requirements. In the context of Quantification Analysis I, variables are treated as categorical and transformed into binary representations, which reduces the effect of linear dependency. Therefore, all variables were retained to preserve the interpretability of the model.

The analytical results indicate that Antecedent Precipitation (X1) attains the highest R-partial value of 0.515, classified within the high influence category. This finding establishes that prior precipitation conditions constitute the dominant determinant in shaping irrigation intake operations. Ponding Depth (X2) yields an R-partial of 0.470, categorized as moderate influence, signifying that variability in field water depth contributes meaningfully to operational decisions, albeit to a lesser extent than precipitation. Water Demand (X3) and Paddy Cultivation Percentage (X4) register R-partial values of 0.249 and 0.220, respectively, both falling within the low influence category. These results indicate that while these factors contribute to irrigation operations, their relative significance is considerably lower compared to precipitation and ponding depth. Overall, antecedent precipitation emerges as the most determinative factor governing intake discharge variability within the study area.

4. CONCLUSION

The results of this study demonstrate that the factors incorporated within the *Nabdab Yeh* process exert a statistically significant influence on the intake operations of Mambal Weir. The predictive model developed through Quantification Analysis I yielded an R-total value of 0.78, indicating a high degree of predictive accuracy and a robust association between the identified factors and the operational discharge. Among the four factors examined, antecedent precipitation exerts the most dominant influence on intake discharge variability (R-partial = 0.515), followed by ponding depth (R-partial = 0.470). This dominance can be explained hydrologically, as precipitation directly governs runoff generation and river inflow within the Ayung watershed. Increased antecedent rainfall enhances soil moisture and reduces infiltration capacity, thereby increasing surface runoff and contributing to higher stream discharge at the weir. Consequently, intake operations are highly responsive to precipitation conditions, as they reflect the immediate availability of water resources. Ponding depth also demonstrates a substantial influence, reflecting field-level water storage conditions that regulate irrigation demand. Higher ponding depth indicates sufficient water availability within paddy fields, thereby reducing additional intake requirements, while lower ponding depth signals the need for increased water diversion.

In contrast, water demand (R-partial = 0.249) and paddy cultivation percentage (R-partial = 0.220) exhibit comparatively lower influence. These variables represent adaptive management responses rather than primary hydrological drivers. Water demand is influenced by cropping decisions and irrigation scheduling, while paddy cultivation percentage reflects the extent of water-intensive land use. Both factors respond to existing hydrological conditions, particularly precipitation, rather than directly controlling water availability. These findings highlight that hydroclimatic drivers, especially precipitation, play a fundamental role in shaping intake operations, while management-related factors function as secondary adjustments within the Subak irrigation system.

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