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Development of Computer Model for Specification of Irrigation Service: A Case Study of Irrigation System in Northern Vietnam

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ABSTRACT

Irrigation service defines the responsibilities and rights of irrigation system management agencies, water users, and other parties involved in the irrigation service contract. As a result, the irrigation service must be clearly specified and updated by crop seasons and by all partners. Given the inherent complexity of the service, this article presents and discusses the development and application of a computer model designed to support the specification of public service levels in rice-based irrigation systems. Applied to the Tu Mai irrigation system, the model has enabled all involved parties to define irrigation service levels through systematic analysis and a thorough consideration of constraints such as water resource characteristics, hydraulic structures, and the operational plans of the irrigation system. The research findings have also helped relevant agencies reach agreements on irrigation service levels for the particular irrigation season of spring 2023, which included one irrigation period for land preparation and five subsequent irrigation periods for rice crops corresponding with a specific schedule for operating the system (discharges and duration) that met the farmers' requests for their farming practices and reduced the loss due to rice crop yield decline at the irrigation system as a whole. Additionally, recommendations for improving irrigation services in the Tu Mai system have been made, including upgrading the head pumping station to accommodate lower water levels in the Cau River, aligning the irrigation schedules of the Water User Associations (WUAs) more flexibly, and strictly supervising water deliveries to ensure safety and fairness.

Keywords: Irrigation Service Level; Water Shortage; System Operation; Computer Model

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1. Introduction

The history of irrigation management worldwide has evolved through various stages, beginning with water supply-focused management, followed by water demand-driven schemes, and currently, the most widely adopted approach is service-oriented management [1]. In this new approach to irrigation management, a key process that needs to be addressed is the specification of service levels [2]. While in the irrigation and drainage sector, the level of service is defined as: "A set of operational standards established by the irrigation and drainage organization in consultation with irrigators, the government, and other affected parties to manage an irrigation and drainage system" [3].

Basically, the level of irrigation service is determined by the system's operation parameters such as rates, durations and frequency of water supply [3]. In Vietnam, irrigation water provision has been regulated as a public service. Accordingly, the government covers most of the operation and maintenance (O&M) costs of the irrigation system, from the headworks to the service delivery points. Additionally, the irrigation system management organization must also ensure other social benefits, support national development goals, and fulfill international commitments that Vietnam has participated in [4].

Global warming and climate change are impacting nearly all aspects of socio-economic development. As a result, Vietnam is ranked among the five countries most severely affected by these changes [5, 6]. In many river basins, annual water discharges fluctuate significantly, and water levels during the dry season are now consistently lower than the historical averages. Additionally, due to various factors, riverbeds have been declining, which further reduces the availability of water for irrigation [7]. Therefore, mitigating and adapting to climate change are critical tasks, not only for the government but also for irrigation service providers and water users.

With more than 7 million hectares of rice crops grown annually, the level of public irrigation services for rice production in Vietnam must be designed to maximize system-wide productivity, conserve water, and minimize greenhouse gas (GHG) emissions [8]. Recently, initial experiments and studies have begun to explore the operation of irrigation systems with these considerations in mind. Based on desk studies and field experiments, this article discusses the methods and findings related to specifying the public irrigation service level for rice-based irrigation systems in the northern region of Vietnam.

2. Materials and Methods

2.1. Literature Reviews

To reach an agreement on irrigation service, a compromise must be jointly negotiated between water users and irrigation system management organizations. For a given system, this compromise balances technical opportunities and constraints, the desires of farmers influenced by the agricultural system, and the operational costs incurred. Decision-making can be viewed as a process of comparing what is desirable with what is feasible, which then leads to what is affordable [9]. In Vietnam, since water supply for agricultural production is regulated as a public service with prices set and paid by the government, irrigation service levels must be determined by considering and harmonizing all factors, including the cropping systems, farmers' expectations, and the government's requirements for maintaining and developing other sectors [4].

2.1.1. Water Demands and Irrigation Regimes for Rice Crops

Water demand is a key factor that determines the level of irrigation services. Crop water requirements are influenced by several factors, including soil conditions, farming techniques, weather and climate characteristics, crop varieties, and the plant's biochemical processes. Numerous studies have been conducted on irrigation regimes and the water demands of rice crops, with their findings synthesized in various literature reviews.

In a study on irrigation regimes for rice crops in Southern China, Hamoud et al. [10] tested three alternative wetting and drying irrigation techniques including 30 mm-100% (100% saturation with 30 mm of flooding), 30 mm-90% (90% saturation with 30 mm of flooding), and 30 mm-70% (70% saturation with 30 mm of flooding). The experimental results showed that the 30 mm-90% irrigation regime was the most effective in terms of water savings and rice yield improvement. This result was consistent across different soil types, with the experimental soils having 40%, 50%, and 60% clay content, respectively. Through another study conducted in California (United States), Carrijo et al. [11] investigated the impact of variable soil drying episodes in alternate wetting and drying irrigation systems on rice crop yields. They concluded that rice yields were not reduced under alternate wetting and drying, a result attributed to the soil's matric potentials, which maintained soil moisture above –25 kPa at the 25–35 cm rooting depth.

Other experiments were conducted to determine the effect of rice crop varieties (Koshihikari for lowland and Dourado Precoce for upland varieties) on GHG emissions under two water management practices: alternate wetting and drying (AWD) and continuous flooding. The results revealed that on-farm water management significantly affected CH_4 and N_2O emissions, while no significant differences were observed between the rice varieties. Although alternate wetting and drying reduced CH_4 emissions, it increased N_2O emissions compared to continuous flooding, likely due to increased oxygen availability. With a 55.6% reduction in GHG emissions in lowland fields and a 59.6% reduction in upland fields under AWD compared to continuous flooding, Phungern et al. [12] suggest that AWD irrigation might be an effective water management strategy for mitigating GHG emissions from rice fields. These similar scientific evidences were also found in Bangladesh [13]. From a similar study in the central part of Vietnam, Tran et al. [14] found that seasonal cumulative CH_4 emissions were significantly reduced by 26% in fields under alternate wetting and drying compared to those under continuous flooding, while seasonal cumulative N_2O emissions showed no significant difference between the treatments.

In a 3-year field experiment on rice irrigation in the Tu Mai irrigation scheme, located in the northern region of Vietnam, Tuan, Dat and Dung [15] found that the seasonal water demand (evapotranspiration) for spring rice crops ranged from 475.4 to 516.6 mm per season (4,754 to 5,166 m³ ha^{-1} per season), and for summer rice crops, it ranged from 441.0 to 495.5 mm per season (4,410.0 to 4,955.0 m³ ha^{-1} per season). The rice crop coefficients (Kc) for the four growth stages—initial, crop development, mid-season, and end-season—were estimated as 1.02, 1.37, 1.39, and 1.26 for spring rice crops, and 1.10, 1.54, 1.73, and 1.21 for summer rice crops. Based on the environmental and field conditions in the northern region, the authors suggested that the most appropriate irrigation regime for achieving optimal rice crop yield while reducing greenhouse gas (CH_4) emissions is 60 mm-55% (55% saturation with 60 mm of flooding). These findings indicate that alternate wetting and drying (AWD) is the most suitable irrigation regime for rice crops in the research area, as it enhances productivity, conserves water, and reduces GHG emissions. This is illustrated in **Figure 1** below.

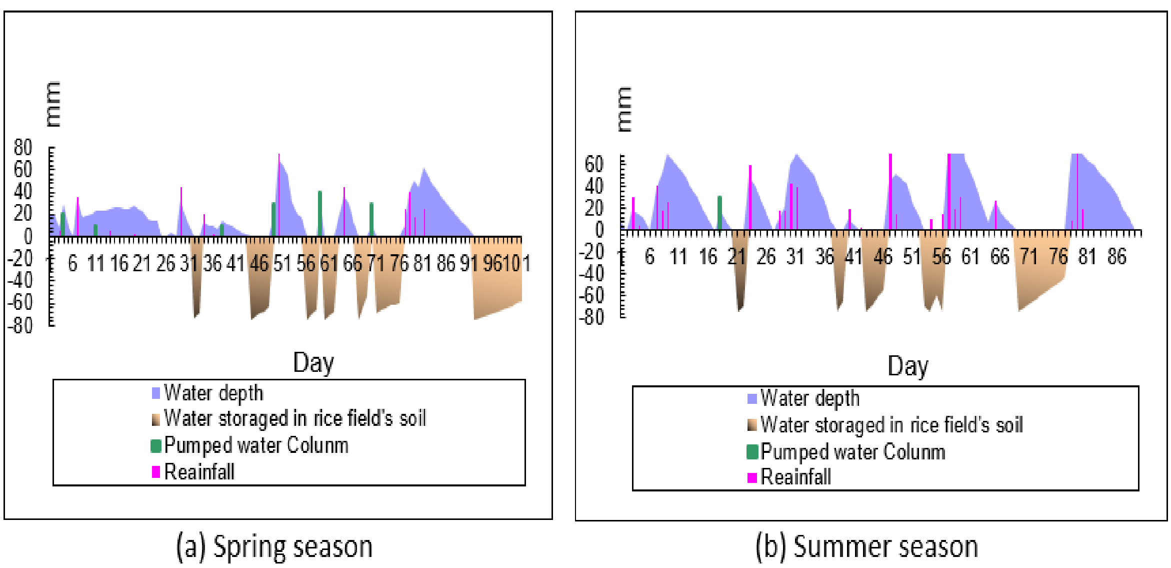


Figure 1. An appropriate water regime on rice fields.

Note: Original figure from Tuan, Dat and Dung [15].

2.1.2. Water Sensitivity of Rice Crops

In situations of water shortage, the level of irrigation service is inevitably affected. Scientifically, the impact of water stress on crop yields under specific conditions (such as variety, climate, and environment) can be predicted using various methods. While some researchers advocate for the use of multiplicative models [16], Kassam and Smith [17] have suggested the use of additive models. In evaluating the accuracy and reliability of these two types of models for predicting crop yield reductions due to water stress, Thinh [18] found that multiplicative models provided higher accuracy than additive models. One of the widely used multiplicative models today is based on Jensen's approach [19]. Jensen's model is expressed in the following form:

$$\frac{Y_a}{Y_{max}} = \prod_{i=1}^{ns} \left(\frac{ET_a}{ET_{max}} \right)_i^{\lambda_i} \tag{1}$$

In which, λ_i: water sensitivity index of crop at the ith growth stage; Y_a: crop's actual yield (kg ha^{-1}); Y_{max}: crop's maximum yield under water stress situation (kg ha^{-1}); ET_a: actual evapotranspiration in growth stage number i (mm); ET_{max}: amount of water evapotranspiration corresponding to Y_{max} in growth stage number i (mm); ns: number of crop growth stages. Based on data collected from the field experiment on irrigation for rice crops in the Tu Mai irrigation system, the Jensen model has been calibrated. The four water sensitivity indexes achieved are λ = [0.055÷0.111, 0.172÷0.303, 0.212÷0.425, 0.079÷0.111] corresponding to spring rice crop and λ = [0.188÷0.266, 0.255÷0.337, 0.516÷0.524, 0.078÷0.084] corresponding to summer rice crop [20].

2.1.3. Water Balance on the Rice Crop Field Surface

Field water regimes precisely define the level of irrigation services received by water users. To assess the water regime on a rice field during a specific interval (e.g., 1 day), the water balance equation can be expressed as follows [21, 22]:

$$Irr = ET_a + W_s + W_p \pm \Delta a – W_c – Rf_e – Q_{in-out} \tag{2}$$

In which,

Irr: amount of irrigation water (mm day^{-1}). It needs to be provided by the irrigation system management organization.

Rf_e: effective rainfall (mm day^{-1}). The maximum value of Rf_e is equal to the height of rice crop field banks. It is determined along with consideration of other incoming and outgoing water components in Equation (2). In the Northern Delta, the largest Rf_e is around 60 mm [23].

Q_{in-out}: equivalent incoming and outgoing flow (mm day^{-1}).

ET_a: actual amount of water evaporation on the field surface (mm day^{-1}). If there is enough water for irrigation, $ET_a = ET_c = ET_o.K_c$; ET_c: crop evapotranspiration under standard conditions; ET_o: reference evapotranspiration (mm day^{-1}); K_c: crop coefficient. In this study, ET_o is determined by the Penman-Monteith equation [21]. K_c is derived from the field experiment. In Tu Mai irrigation system's commanded area, K_c for 4 stages of rice crop growth is calculated and discussed previously [15].

W_s: the amount of water that needs to saturate the arable soil layer (mm day^{-1}). With the clay loam soil in the rice field in Tu Mai irrigation system, Dat [24] recommended that its infiltration rates get the values of $K_t = 216.86.T^{-1,1306}$ and $K_t = 126.83.T^{-0,8045}$ in the periods of land preparation and rice crop's growth stages (T is time for saturating the arable soil layer – day).

W_p: seepage percolation rate (mm day^{-1}). Dat [25] found that the seepage percolation rate of clay loam soil in the rice field in Tu Mai irrigation system would be calculated by the empirical equation $W_s = 0.4330 \ln(a+3.45) – 0.536$. Where, a is the current daily water depth on the rice field surface (mm).

W_c: capillary water (mm day^{-1}). It should be calculated by the empirical equation. For the rice field's clay loam soil in Tu Mai irrigation system, the empirical equation is $W_c = –1.552 \ln(d) + 6.760$, where d is the current daily water storage in the rooting soil layer (mm) [24].

Δa: equivalent amount of water stored (or removed) on the rice crop field surface (or in the arable soil layer) (mm).

2.2. Research Methods and Materials

2.2.1. Selection of Research Site

In order to inherit the research results on the permeability characteristics of cultivated land and irrigation regimes for rice crops in the same location conducted by Tuan, Dat and Dung [15], Dat [24] and Dat [25], this research was carried out on the Tu Mai irrigation system, which is managed by Nam Song Thuong Limited Company for Irrigation Management (IMC), in Bac Giang province, Northern region of Vietnam (**Figure 2**).

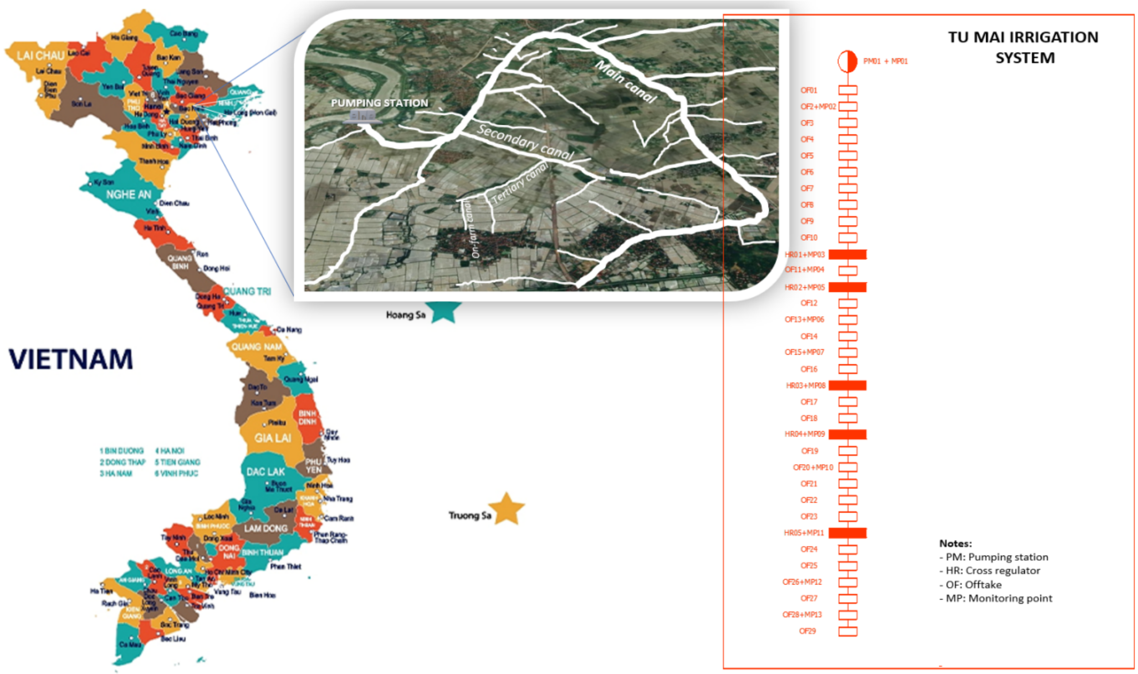


Figure 2. Tu Mai irrigation system.

The Tu Mai irrigation system is located in the south of Bac Giang city, functioning in irrigation and drainage serving 1,694.4 hectares of agricultural land. The system's headwork is named after Tu Mai pumping station and it is far from Pha Lai hydrological station with about 7.5 km in upstream side.

2.2.2. Climate and Hydrology

Recorded data from Bac Giang meteorological stations and Phai Lai hydrological stations (close to Tu Mai irrigation system) are used for the research. The data recorded from 2005 to 2009 is used to validate the irrigation system operation model and other data recorded from 2018 to 2022 is for simulation of the system's operational scenarios in the 2023 spring crop season. The meteorological data from the Bac Giang meteorological station shows that temperature fluctuates widely among the seasons in a year. In the winter season, the average temperature is about 17 °C. Meanwhile, the average temperature approximately reaches 30 °C in the summer season. The average monthly relative humidity in the study area ranges from 75% to 85%. The highest humidity usually occurs in the spring season (monthly relative humidity often reaches 85% to 100%). In contrast, the air in these areas is relatively dry in winter season. The average monthly time of sunshine also fluctuates significantly in seasons of a year. During the hot season, the average sunshine hours are relatively stable from year to year (rangeing from 150 to 170 hours per month). In February and March, because the weather is often cloudy, wet, and drizzly, the sunshine hours are often the lowest. It is also different compared to relative humidity; the monthly average wind speed does not fluctuate much in seasons of the year. The average annual evaporation in the study area ranges from 815.43 mm per year to 924.65 mm per year. Large amounts of water evaporation occur in the months from April to June or from October to December annually.

The average total rainfall over years in the study area ranges from 1,474.38 mm per year to 1,846.32 mm per year. The region's rainfall distribution is clearly distinctive in seasons. During the spring rice crop season, monthly rainfall is usually very low (around 70 mm per month). While in the summer rice crop season, the monthly rainfall is much higher (around 350 mm per month). Comparing the distributions between monthly rainfall and evaporation shows that irrigation water stress is more likely to occur in particular periods in the spring crop season.

The hydrological regime on the Thai Binh river system is also divided into two seasons: dry season and flood season. Analyzed monitoring data from Phai Lai hydrological station shows that the amount of water in the dry season on the Thai Binh river system only accounts for 20% to 25% of the total annual flow. The water level of Cau River in the dry season (from 2018 to 2022) is lower than the average long-term water level in the same period and lower than the design water level upstream of the irrigation system's headwork. In particular, the lowest water level in 2022 on Cau River at Pha Lai is only +0.07 compared to sea level. Besides, under the influence of tides, saltwater intrusion is strongly moving inland. This has led to drought and lack of irrigation water occurring in many places and on a large scale. That is the reason why this study focuses on consideration of the irrigation service in the spring crop season (during the dry season) on the Tu Mai system as presented below.

2.2.3. Tu Mai Irrigation System

The Tu Mai irrigation system was built and started operation in 1963; it has been managed by the Nam Song Thuong Irrigation Management Company Ltd. (IMC). The system's headwork is a multifunctional pumping station (irrigation and drainage), including 6 units. The designed pump discharge of each pump unit is 2,970 $m^3\ h^{-1}$ (**Table 1**).

Tested results show that the actual discharge of each pump unit is currently low compared to manufacturing parameters (**Table 1**). The lowest and highest designed water levels at the suction tank of Tu Mai pumping station are +0.4 and +4.2, respectively (**Table 2**). Comparing with the water level fluctuation on Cau River in recent years (**Figure 3a**), it can be seen that water resources cannot maintain the water requirement in particular periods for the operation of Tu Mai pumping station (**Figure 3b**).

Table 1. Design and actual capacity of Tu Mai pumping station.

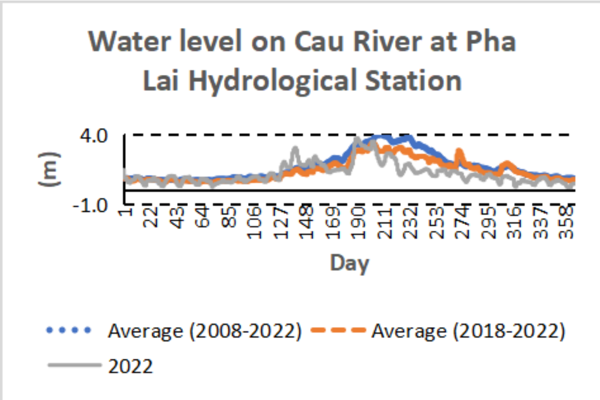
Pump Units	Q_{design} ($m^3\ h^{-1}$)	Q_{actual} ($m^3\ h^{-1}$)
1	2,970	2,375
2	2,970	2,238
3	2,970	2,784
4	2,970	2,656
5	2,970	2,864
6	2,970	2,782

Source: Nam Song Thuong IMC, 2022.

Table 2. Current status of main irrigation canal.

№	Cross Section	Location (m)	Main Irrigation Canal's Parameters				
			Bed Slop	Bottom Width (m)	Side Slop	Roughness Coefficient	Designed Water Depth (m)
1	Tu Mai pumping station's DS	0	0.00015	2.80	0.00	0.02	2.02
2	D8	3,500	0.00015	2.80	0.00	0.02	2.02
3	D9	3,600	0.00015	2.80	1.00	0.02	2.02
4	D10	3,700	0.00015	2.80	1.00	0.02	2.02
5	Cross regulator N°1's US	4,000	0.00015	2.50	1.00	0.02	2.02
6	D11	4,338	0.00015	2.50	1.00	0.02	2.02
7	Cross regulator N°2's US	4,400	0.00015	2.40	1.00	0.02	2.02
8	D16	5,628	0.00015	2.40	1.00	0.02	2.02
9	Cross regulator N°3's US	5,700	0.00015	2.00	1.00	0.02	2.02
10	D21	7,782	0.00015	2.00	1.00	0.02	2.02
11	Cross regulator No5's US	8,000	0.00015	1.80	1.00	0.02	1.50
12	US of Dong Viet pumping station	9,161	0.00015	1.80	1.00	0.02	1.50

Source: Nam Song Thuong IMC (2022).



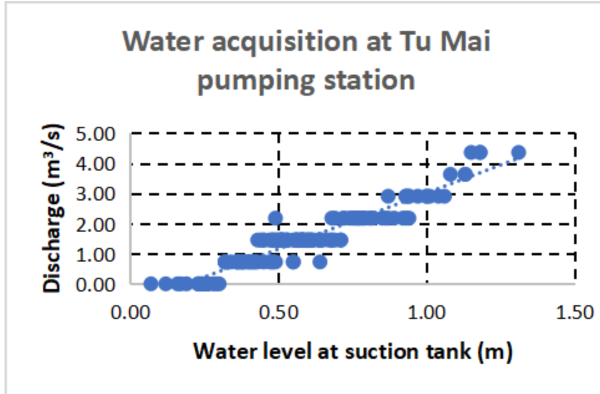


Figure 3. Water resource conditions at Tu Mai irrigation system.

Main irrigation canal: the length of the main irrigation canal has a total length of 9,161 km and has been completely lined. The first block on the upper system is 3,500 km long with a rectangular cross-section. Another block at the tail end of the system is 5,661 km long, and it has been lined with a trapezoidal cross-section.

Hydraulic works on the main irrigation canal: the Tu Mai irrigation system has 5 cross-regulators and 29 offtakes (water delivery structures). According to the assessment results of the Nam Song Thuong IMC, the current status of the hydraulic works on the main irrigation canal is synthesized in **Table 3**.

Table 3. Current status of water delivery structures on Tu Mai irrigation canal.

Nº	Offtake Name	Commanded Area (ha)	Distance from Headwork (m)	Description	
				Q_{design} ($m^3\ s^{-1}$)	Size and Downstream Canal Status
1	D2a	35	300	0.31	Ø30 cm, very good conditions and earth canal
2	D2	260	1,100	0.50	Ø40 cm, good conditions and earth canal
3	D3	25	1,150	0.31	Ø30 cm, good conditions and earth canal
4	D4	30	1,700	0.30	Ø30 cm, moderate conditions and earth canal
5	D5	30	2,500	0.30	Ø30 cm, very good conditions and earth canal
6	D6	30	2,500	0.31	Ø30 cm, good conditions and earth canal
7	D7	110	3,200	0.47	Ø40 cm, moderate conditions and earth canal
8	D8	25	3,500	0.30	Ø30 cm, poor conditions and earth canal
9	D9	40	3,600	0.37	Ø30 cm, good conditions and earth canal
10	D10	20	3,700	0.19	Ø25 cm, good conditions and earth canal
11	D11	200	4,338	0.50	Ø40 cm, good conditions and earth canal
12	D12	15	4,551	0.18	Ø25 cm, good conditions and earth canal
13	D13	25	4,810	0.30	Ø30 cm, good conditions and earth canal
14	D14	25	5,200	0.30	Ø30 cm, good conditions and earth canal
15	D15	40	5,628	0.36	Ø30 cm, good conditions and earth canal
16	D16	15	5,628	0.18	Ø25 cm, good conditions and earth canal
17	D17a	20	5,917	0.19	Ø25 cm, very good conditions and lined canal
18	D17	12	6,176	0.19	Ø25 cm, poor conditions and earth canal
19	D18	50	6,468	0.31	Ø30 cm, good conditions and earth canal
20	D19	50	7,614	0.31	Ø30 cm, good conditions and earth canal
21	D20a	25	7,489	0.30	Ø30 cm, good conditions and earth canal
22	D20	25	7,727	0.30	Ø30 cm, poor conditions and earth canal
23	D21	10	7,782	0.18	Ø25 cm, moderate conditions and earth canal
24	D22a	25	8,284	0.31	Ø30 cm, very good conditions and lined canal
25	D22	45	8,290	0.30	Ø30 cm, poor conditions and earth canal
26	D24	40	8,782	0.30	Ø30 cm, moderate conditions and earth canal
27	D26	15	9,046	0.18	Ø25 cm, moderate conditions and earth canal
28	D23	300	9,161	0.75	Ø50 cm, good conditions and earth canal
29	TB D.Viet	150	9,161	0.47	40 × 120 cm, moderate conditions and famer-owned small pumping station at downstream

Source: Nam Song Thuong IMC (2022).

The system's irrigating function: mainly supplying water for rice crop cultivation in spring and summer seasons.

2.2.4. Rice Production in Spring Season 2023

Data on rice production are collected from Water User Associations (WUAs), which utilize water from the Tu Mai irrigation system, prior to signing a contract for irrigation service provision. The total rice-growing area within the irrigation system is 1,694.4 hectares. The primary rice variety cultivated is Khang Dan. Farmers use four planting methods and stages: Early Conventional Intensive Rice (early CIR), Late Conventional Intensive Rice (late CIR), Early System of Rice Intensification (early SRI), and Late System of Rice Intensification (late SRI). The soil preparation techniques employed include drying and mechanical tillage. The growth period for CIR is 112 days, while for SRI it is 97 days[15]. The recommended water management for the rice crop is alternative wetting and drying irrigation.

2.2.5. Modeling Irrigation System Operations

The irrigation system operation model (ISOM) was recently developed using Visual Studio and App Script. Its functions are to explain how different irrigation service delivery options are likely to be established and implemented. The fundamental principle of the model is to integrate and link several modules, including: i) calculation of the water demands for crops; ii) determination of water loss components on the field surface; iii) determination of the inflow water on the field surface; iv) calculation of water balance at the field surface and irrigation requirements at water delivery structures; v) determination of conveying water loss on the canal system; vi) calculation and simulation of water flow on the canal system (based on hydraulic laws or artificial neural networks); vii) determination of operating parameters for hydraulic works (headwork, cross-regulators, water delivery structures etc.).

The ISOM simulates the irrigation system through a computational network. The actual hydraulic works on the system are encoded into nodes with order increasing from the head to the tail end of the system (from 1 to N, where N is the total number of hydraulic works on the system and also the number of simulated nodes). The irrigation system is simulated in detail through i) number of canal branches; ii) number of nodes; iii) structural code (code of culvert under the dyke - SL; pumping station - PM; cross-regulators - HR; measuring stations - MP; water delivery structures - OFF; canal connecting points - COO; external water inflows - RO; return flows - RF). The irrigation requirement of each canal branch is determined through the accumulation of the water requirement of each base node (directly connected to the field surface) and the conveyance water loss of the corresponding canal section, from the end to the head of the canal branch. The ISOM calculates water discharges along the canal system following the step-by-step process, from the base node or last branch to the initial node and the headworks.

The objective function for maximizing the irrigation system's common benefits (maximizing rice productivity from the irrigation system) is described as:

$$MaxP = Max \sum_{j=1}^{NC} \sum_{k=1}^{NO} A_{jk}.(\theta_j.Y_{j,k}) \quad (3)$$

In which, j and k: indices; NC: number of crop types or crop planting stages; NO: the number of fields corresponding to different options of water stress level. In this study, each field is considered as the served area of a base node; P: irrigation system's total crop productivity (tons); $A_{j,k}$: area of the jth crop corresponding to the field number kth (ha); θ_j: yield conversion coefficient between crops planted on the irrigation system; $Y_{j,k}$: yield of crop jth in the kth field (tons ha^{-1}). $Y_{j,k}$ is determined through the crop yield prediction model. From (1), Jensen's Equation (4) for the crop's growth stages) is rewritten in the form corresponding to the ISOM's calculating interval (1 day):

$$\frac{Y_a}{Y_{max}} = \prod_{ii=1}^{tst_{(1)}} \left(\frac{ET_{a(1)}}{ET_{(1)max}}\right)^{\lambda_1/tst_{(1)}} * \ldots * \prod_{ii=1}^{tst_{(4)}} \left(\frac{ET_{a(4)}}{ET_{(4)max}}\right)^{\lambda_4/tst_{(4)}} \quad (4)$$

In which: ii: time index (days) when divided from the particular growing period (st) of the plant number ith; tst: growth time of stage number i; other symbols are described like Equation (1).

This study considers a number of constraints that need to be satisfied including:

- Constraints on rice crop field's water depth:

In fact, irrigation for rice crops is always practiced by applying the flooding irrigation method. It means that the irrigation flow on the field surface must be large enough to spread from plot to plot. At least, the water depth on the rice crop field needs to be greater than the average field surface roughness (a_{min}). In addition, the water depth for each field plot should not exceed the field bank's height or the maximum water depth to maintain the highest rice crop yield and to reduce GHG emissions (a_{max}). Thus, the constraint on rice crop field's water depth is as Equation (5) below.

$$a_{min} \leq a \leq a_{max} \quad (5)$$

With rice crop fields in the Northern region of Vietnam, a_{min} = 0 and a_{max} = 60 mm[15].

• Constraints on water resources

It must be ensured that the total amount of required water for irrigation at the headwork is less than the potential pumped water at the same time. The equation to determine the potential pumped water is as follows:

$$Whw_{max} = 86.400 \text{ x IrrTime x } Qhw_{max} \quad (6)$$

In which, IrrTime: Total working time of the headwork (days); Qhw_{max}: Average daily water discharges of the headworks ($m^3\ s^{-1}$). With the pumping station headwork, Qhw_{max} depends on the average actual discharge of the pump units and water level on the river.

• Constraints on serving area of the irrigation system

The total crop area for each irrigation period must be less than the largest area in charge of the irrigation system. This constraint can be expressed as:

$$\sum_{j=1}^{No\ Of\ Fields} A_j \leq A_{sys} \quad (7)$$

In which, A_j: area of irrigating field number jth, corresponding to a particular node in the computational network; A_{sys}: largest area in charge of the irrigation system (ha); NoOfFields: total number of fields in the irrigation system; other symbols are the same as the statement in the objective function.

As illustrated in **Figures 2** and **4**, the ISOM was applied to determine the appropriate level of irrigation service for the spring rice crop season of 2023 (including rate, duration, and frequency), based on the water demand and pumping capacity of the study sites. The goal was to optimize overall rice crop productivity while minimizing GHG emissions. Factors considered and adjusted simultaneously included changes in crop patterns, rescheduling of land preparation, and resizing of the rice crop area to ensure adequate irrigation service. These adjustments were negotiated by the IMC, WUAs, and relevant local government agencies.

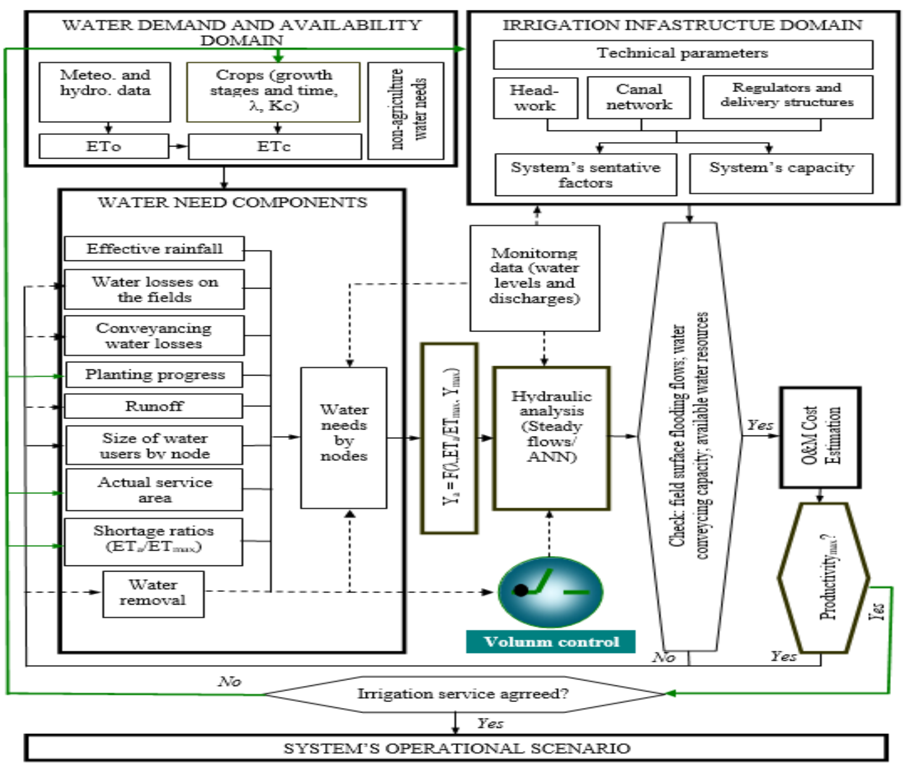


Figure 4. Irrigation system simulation flowchart.

3. Results and Discussion

3.1. Public Irrigation Services in Vietnam

As mentioned above, large and medium irrigation systems in Vietnam are currently managed by organizations such as IMCs, government administrative bodies (referred to as government agencies), and WUAs. The government establishes criteria for defining irrigation service delivery points and for transferring on-farm irrigation works to WUAs. Government agencies are responsible for managing (operating and maintaining) the infrastructure from the headworks to the water delivery structures, while WUAs manage on-farm works. Government agencies provide irrigation services for agricultural production, aquaculture, and salt production, which are considered public irrigation services. The government subsidizes the costs of these public irrigation services on behalf of farmers, allowing government agencies to cover their operation and maintenance (O&M) costs.

Current public irrigation service prices have been regulated by the Vietnamese government since 2018, based on actual operation and maintenance (O&M) costs from previous years. For pumped irrigation in the Northern Delta, such as the Tu Mai irrigation system, the maximum price currently applied for rice-based irrigation services is 1,646,000 VND ha^{-1} per season (68.58 USD ha^{-1} per season). The main cost components that make up the public irrigation service price include: i) labor costs (including salaries and insurance); ii) costs of raw materials and fuel for the operation and maintenance of machinery and equipment; iii) fuel costs for pumping water; iv) protection and safety costs for staff; v) protection costs for machinery; vi) maintenance costs; vii) agency management costs; and viii) the firm's expected profits (not exceeding 5%).

3.2. Analyzing the Tu Mai Irrigation System's Operating Scenarios

3.2.1. Validation of ISOM Model

In addition to the sensitivity indexes of rice crops (λ) due to water shortage founded from field experimental research as presented previously [20]. The ISOM model was validated based on hydrometeorological data, from 2005 to 2009; flows observed on the Tu Mai irrigation system and data regarding to irrigated area, rice crop types and their yields corresponding to the spring and summer rice crops of 2009. The validation results of the ISOP are as follows:

- ET_o prediction

Using the meteorological and hydrological data described above, the ISOM and CROPWAT models were applied to calculate the standard evapotranspiration (ETo) for each year from 2005 to 2009. The difference in the annual ETo results between the two models ranged from 1.01% to 4.47%. This indicates that changes in climate parameters impact model accuracy, but the variations remain within an acceptable range of less than 5%, with an average error of 2.26%.

- Calculating irrigation water

Evaporation is converted into the required irrigation water for a specific period by applying the crop coefficient (Kc) and accounting for water loss due to seepage and leakage from the field banks. The irrigation water calculated by the ISOM model is then compared with the actual water supplied to the field plots to assess the model's reliability. Seven field plots, corresponding to seven Level II canals (D2, D11, D13, D15, D19, D23, D24), were selected for the irrigation period from August 30 to September 3, 2009. The difference between the calculated results and the actual field measurements ranged from –2.7% to +10.0%, with an average difference of 4.2%. This indicates that variations in rice plant density, physical characteristics, soil properties, and the data used for calculations do not significantly affect the model's reliability.

- Regarding the results of the flow simulation in the channel

Two water measurement points were established at the cross-sections of the main Tu Mai canal and the regulating sluice No. 5. To verify the model, the simulated water levels at the corresponding nodes were compared with actual water level data. With a time step of 3 hours, the comparison of calculated and measured results from August 19 to August 29, 2009, showed that the difference between the calculated and measured water levels fluctuated between –30 cm and +15 cm. However, the average water level difference over the entire irrigation period for the two cross-sections was only 6 cm at the downstream of the Tu Mai pumping station and 5 cm at the Cross Regulator No. 5. Therefore, the parameters of the system and the flow simulation method used in the model are suitable for operating under actual conditions.

3.2.2. Scenarios for Operating Tu Mai Irrigation System

In the Tu Mai irrigation system, to specify the levels of public irrigation service and to sign contracts, farmers (through WUAs) are requested to provide information about their rice crop planting schedules, expected irrigation periods and corresponding watering time. Based on this information, irrigation system operation scenarios and other management tasks of the government agencies and WUAs will be considered.

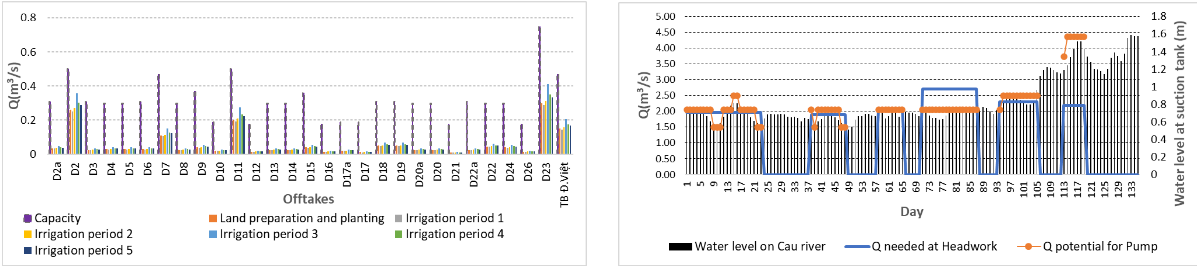
According to farmers' expectations for irrigation schedules, the proposed start date for irrigation was January 7, 2023. Rice field owners request irrigation water in six periods, using the alternative wetting and drying irrigation technique. Each irrigation period is designed to meet the crop's water demand (based on farmers' experience) and the requirements of their farming practices. This full consideration of farmers' requests in the modeling of the irrigation system operation is referred to as the base scenario (Scenario N°1).

Two other irrigation system operation scenarios are also considered, including: Scenario N°2, which involves a fixed 10-day alternative wetting and drying irrigation technique, excluding irrigation for land preparation; and Scenario N°3, which involves a flexible alternative wetting and drying irrigation technique.

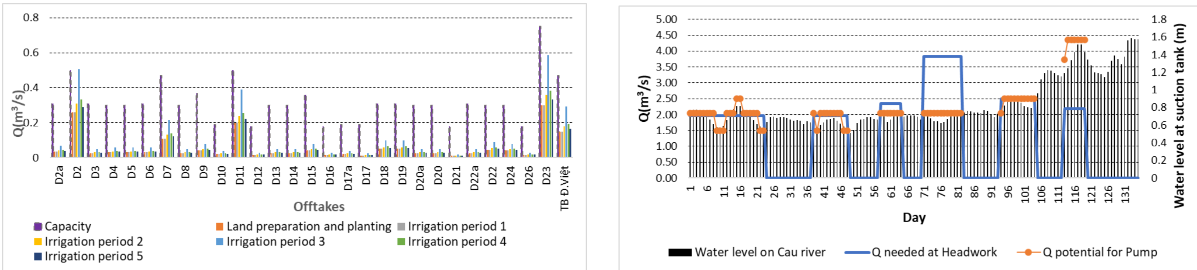
In the context of declining water level in Cau River, ISOM is applied to develop irrigation system operating scenarios with varying levels of water shortage, ranging from 0 to 70% with increments of 1% for each iteration. By adjusting irrigation schedule (dates and times), and water flow, while considering the satisfaction of the given constraints as described above, it is shown that none of the three scenarios can overcome the water shortage situation. Specifically, to achieve the highest total rice crop productivities across the irrigation system, all scenarios need irrigating the entire area (1,694.4 ha) with limited water supply. In Scenario N°1, the first irrigation period is needed for land preparation, followed by five irrigation periods for rice crop with a decrease in water supply: 3.70%, 12.59%, 46.54%, and 1.66% for the 1st, 2nd, 3rd, and 4th periods respectively, due to the reduced potential water for pumping (Qhw_{max}). Scenario N°2 also requires one initial period of irrigation for land preparation and five subsequent irrigation periods for rice crops, with a decrease of 26.17% and 55.45% in water supply for the 1st and 3rd periods and 12.39% for the 4th one. Similarly, Scenario N°3 requires a total of six irrigation periods, but only the 3rd period experiences a 24.27% reduction in water supply. With these irrigation scenarios for the Tu Mai irrigation system, the total rice crop productivity declines by 20.81%, 22.46%, and 8.58% in Scenarios N°1, N°2, and N°3 respectively, as estimated by ISOM.

The analytical results from the ISOM's outputs show that, for all operating scenarios of the Tu Mai irrigation system, there is no limitation in capacity (water discharge) found at the irrigation water delivery structures (offtakes at the top of the secondary canals), although some of them are not in optimal working condition (**Figure 5a**). This indicates that the WUAs do not need to upgrade their irrigation management systems, but only need to carry out routine maintenance activities in accordance with technical standards for irrigation work management. However, in Scenarios N°1 and N°2, the 3rd irrigation period reveals a significant constraint on the main canal, where the irrigation water discharge at the downstream cross-section of the Tu Mai pumping station exceeds the canal's design capacity. Specifically, the discharge reaches 3.84 $m^3\ s^{-1}$ and 4.60 $m^3\ s^{-1}$, compared to the canal's design capacity of 3.05 $m^3\ s^{-1}$. Despite this, the main irrigation canal was recently lined, so upgrading the canal may not be a reasonable solution due to its high cost, especially given the declining water levels in the Cau River.

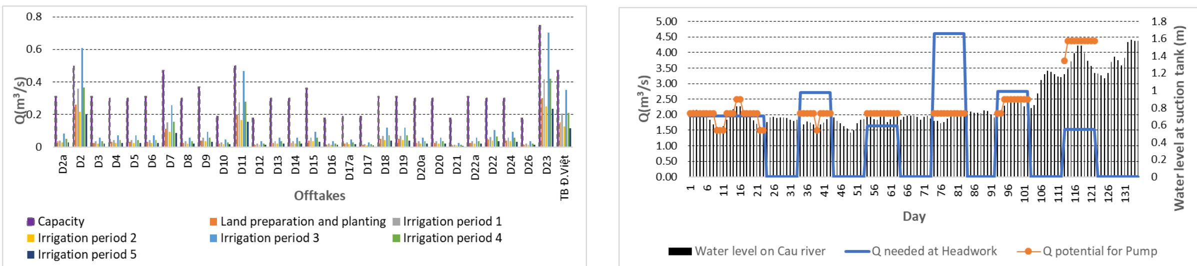
Therefore, it has been proved that the scenarios that facilitate farmers' field practices (Scenario N°1) or advantage IMC's O&M implementation (Scenario N°2) all arise problems due to the rice crop productivities of the entire Tu Mai irrigation system decreasing significantly and the irrigation water flow on the upper main canal exceeding its water conveying capacity.



Scenario N°1



Scenario N°2



Scenario N°3

(**a**) (**b**)

Figure 5. Operational parameters of Tu Mai irrigation system by three scenarios: (**a**) Capacity and needed discharges by irrigation periods and water service deliveries; (**b**) Water needs and acquisition at Tu Mai pumping station.

3.3. Specifying the Irrigation Service Level for the Spring Rice Crops 2023 in the Tu Mai System

Based on the above analysis, it is clear that Scenario N°3 of the operation is the most suitable and should be applied to the Tu Mai irrigation system for the spring crop season 2023 in the context of depletion of water resources in the Cau River. This operating scenario is largely in line with farmers' preferences regarding the number of irrigation periods. However, the date for starting the spring rice irrigation season in 2023 needs to be delayed to January 24th, instead of the initially proposed January 7th, as requested by the rice field owners. The number of irrigation days for each period differs from the farmers' expectations. Only the irrigation times for land preparation and the first and last irrigation periods for rice crops are fully aligned with the farmers' planned practices. The time of other irrigation periods needs to be extended to ensure adequate water supply, align with the rice crop's growth, and maintain the highest productivity for the entire irrigation system (see **Table 4**). The fourth irrigation period should be the longest, lasting from 12 to 17 days. It is an acceptable time per irrigation period for rice crop in Vietnam [26]. Despite this, the total amount of water provided by the Tu Mai irrigation system to the entire rice-growing area still only meets 75.73% of the total water demand.

With the 3rd operational scenario and the corresponding level of irrigation service, the estimated reduction in rice crop productivity is the lowest (8.85%), compared to 20.81% and 22.46% in the N°1 and N°2 scenarios, respectively. Based on the average rice price in Vietnam for 2023, the loss due to insufficient water in the Tu Mai irrigation system is estimated to be around US$ 218,632.

Table 4. Specification of irrigation service level for 2023 spring season in Tu Mai system by computer model.

Periods	Starting Date	Irrigating Time (Days)		Water Satisfied Ratio (%)	Discharge at the Headwork (m^3 s^{-1})	Irrigating Area (ha)	Rice Yield Loss (%)
		Expectation	Scenario N°3				
Land Pre.	24 Jan 23	23	23	100.0	1.965	1,694.4	0.00
1	2 Mar 23	11	11	100.0	1.899	1,694.4	0.00
2	22 Mar 23	7	8	100.0	2.052	1,694.4	0.00
3	4 Apr 23	12	17	75.7	2.707	1,694.4	8.85
4	27 Apr 23	11	12	100.0	2.292	1,694.4	0.00
5	16 May 23	7	7	100.0	2.183	1,694.4	0.00

With the level of irrigation service determined in **Table 4** (6 irrigation periods and 78 days of irrigation per season), and the total water used for the rice crops being 1,287,440 m^3, the total O&M cost of the Tu Mai irrigation system increases by 4.67% compared to the cost determined by the economic and technical norms issued by the local government. However, it remains lower than the amount estimated by the public irrigation service price prescribed by the central government. Nevertheless, the expected profit for the IMC will decrease to 0.33%, compared to the allowed value of 5.00%[27].

4. Conclusions and Recommendations

The service-oriented approach in irrigation management is becoming increasingly popular, not only in Vietnam but also in other countries and regions around the world. However, irrigation services encompass various attributes and are influenced by many complex factors, making it difficult for service providers, users, and relevant partners to be fully aware of or accurately describe them. This lack of clarity negatively impacts their collaboration in the conduction of O&M activities and the overall sustainability of the irrigation system.

ISOM has been developed to simulate and create scenarios for operating the irrigation system based on the natural characteristics, current status of hydraulic structures, crop production systems, and farmers' field practices. Specifically, the model allows irrigation management agencies to consider water resource depletion due to climate change and to apply it for developing the system's operational scenarios with limited water irrigation to reduce GHG emissions. Through a pilot application in the Tu Mai irrigation system, the model has helped irrigation management entities (IMCs, WUAs) and government agencies determine the appropriate irrigation service level through systematic analysis and a deeper understanding of the system's limitations, such as water resources, hydraulic structures, and irrigation operation plans.

The results of the study have helped the relevant parties reach an agreement on service levels and sign irrigation service contracts. At the same time, recommendations to improve irrigation services in the Tu Mai irrigation system should be considered by all parties, including: upgrading the main pumping station to enable water extraction at lower levels in the Cau River; flexibly aligning the WUAs' water usage schedules with farmers' farming practices; and strictly controlling the amount of water delivered from the main to the secondary canals to ensure fairness, as the designed discharge at the offtakes is much larger than the water requirements for rice crop growth.

Author Contributions

Conceptualization, methodology, formal analysis, and writing – original draft preparation, D.T.V.; writing – review and editing, visualization, and project administration, D.P.T. Both authors have read and approved the final version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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