Online at: https://researchtrendsjournal.com **ISSN No:** 2584-282X
Indexed Journal **Peer Reviewed Journal**

INTERNATIONAL JOURNAL OF TRENDS IN EMERGING RESEARCH AND DEVELOPMENT

Volume 3; Issue 3; 2025; Page No. 17-29

Received: 14-02-2025
Accepted: 23-03-2025

Integrated Water Allocation Optimization in Pidekso Dam Reservoir for Raw Water, Irrigation, and Renewable Energy

[1]Kuntjoro, [2]Meika Victoria and [3]Dwi Indriyani

[1, 2]Department of Infrastructure Engineering, Vocational Faculty, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia
[3]Brantas River Basin Authority, Alumnus of the Applied Bachelor's Program, Department of Civil Infrastructure Engineering, Vocational Faculty, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia

DOI: https://doi.org/10.5281/zenodo.15530054

Corresponding Author: kuntjoro@ce.its.ac.id

Abstract

Pidekso Dam Reservoir, located in Wonogiri Regency, Central Java, Indonesia is designed to fulfil the needs for raw water, irrigation, and to support a Micro Hydro Power Plant. Additionally, the reservoir aims to mitigate flooding during the rainy season and water scarcity during the dry season in the upstream area of the Bengawan Solo River. This study aims to optimize the water resource management of Pidekso Reservoir using a dynamic programming approach. The method employed is Richard Bellman's dynamic programming optimization, which takes into account variables such as water availability, raw water demand, irrigation needs, and micro-hydro power utilization. The model was developed as a one-year simulation under various planting start time scenarios to determine the most efficient water allocation.

The optimization results indicate that the most optimal planting start time is in the second period of September. Under this scenario, potential increases in irrigated land area include 1,852 ha for the first rice planting season, 6,105 ha for the second rice season, and 5,776 ha for the secondary crop season. Moreover, the utilization of the Micro Hydro Power Plant also improves, with a dependable flow rate (95%) of 6.911 m^3/s. These findings demonstrate that a dynamic programming-based optimization approach can offer a more adaptive and efficient alternative for water resource management.

Keywords: Raw water, irrigation, micro hydro power plant, optimization, reservoir

Introduction

Pidekso Dam Reservoir is located in Wonogiri Regency, Central Java Province. The study area of the reservoir is shown in Figure 1 (PT. Mettana Engineering, 2011) [15]. Reservoir management is a key strategy for optimizing water resource utilization. Regardless of the size or intended purpose of the reservoir, its fundamental function is to store water; therefore, the primary parameter of any reservoir is its storage capacity (Linsley *et al*., 1994) [10].

Pidekso Reservoir was developed to address recurring problems in the upstream section of the Bengawan Solo River, where excessive flow during the rainy season often leads to flooding, while significantly reduced flow in the dry season causes water shortages (PT. Mettana Engineering, 2011; Darmawan, A., & Nugroho, S. 2023) [15, 2]. Under these hydrological conditions, regulating water release from the reservoir in an optimal manner is critical to meet competing demands for raw water supply, irrigation, and electricity generation from a Micro Hydro Power Plant (MHPP) within the service area.

In line with population growth, water demand continues to rise each year. This increasing demand affects the availability of discharge in the reservoir and the capacity to meet future needs for domestic use, agriculture, and power generation (Dabhade, P., & Regulwar, D. 2021) [1]. Consequently, accurate calculation of release volumes is essential (Moradi, H., & Ghassemi, H., 2019) [12].

This study aims to develop an optimal water allocation model for Pidekso Reservoir that can balance multiple water uses throughout the year. To achieve this, an optimization technique based on Richard Bellman's dynamic programming method is applied. This method is particularly suitable for water resource management due to its ability to handle multistage decision-making processes under constraints. Compared to other techniques, dynamic programming is more effective in managing systems with time-dependent variables and sequential decisions-characteristics that closely reflect reservoir operations.

The optimization model is designed with varying planting start times based on months and periods, while incorporating constraints such as water availability and reservoir storage capacity. The resulting analysis is expected to provide a practical guideline for efficient water utilization from the effective storage of Pidekso Reservoir for the upcoming year.

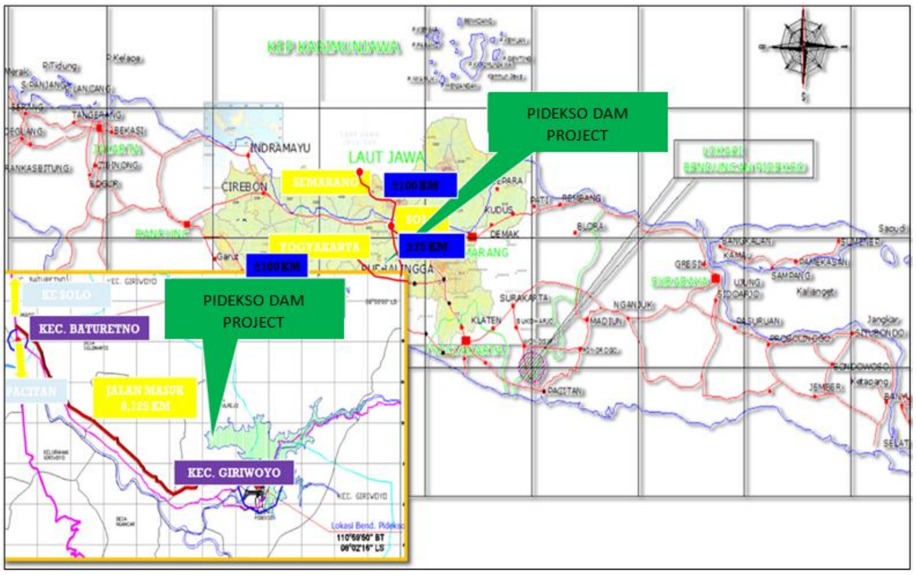

Fig 1: Location of the Pidekso Reservoir Dam Study Area

Materials and Methods

The optimization of water utilization at Pidekso Reservoir involves several stages, including:

Hydrological Analysis

Rainfall data used for the hydrological analysis were sourced from the B. Ngancar Station, which recorded daily rainfall over a 19-year period (2001–2019) (Rainfall and Climatology Data, 2019). The annual rainfall data was divided into two 15-day periods for detailed analysis (Rainfall and Climatology Data, 2019). Hydrological analysis was performed to estimate the effective rainfall, which serves as a critical input for determining irrigation water requirements (Indriyani, 2009; KP-01 Irrigation Network Planning Standards, 2013; Linsley *et al*., 1994) [6, 7, 10, 8]. Effective rainfall, or dependable rainfall, refers to the portion of total precipitation that is effectively available to meet crop water demands (Indriyani, 2009; KP-01 Irrigation Network Planning Standards, 2013) [6, 7, 8]. The effective rainfall, denoted as R80, can be calculated using Equation (1) (KP-01 Irrigation Network Planning Standards, 2013; Linsley *et al*., 1994; Mays, 1992) [8, 10, 11]:

$$R_{80} = \frac{n}{5} + 1 \quad (1)$$

where R80 is the 80% effective rainfall, n/5 + 1 is the rank of the smallest order, and n is the number of years of observation.

Climatological analysis

Climatological data were obtained from the W. Ngancar Climatology Station, which recorded data over a 19-year period (2001–2019) (Indonesian Meteorology, Climatology and Geophysics Agency [BMKG], 2019) [5]. The data were processed to calculate evaporation, which plays a crucial role in water resource development, including streamflow, reservoir capacity, and consumptive water use for crops (Doorenbos & Pruitt, 1977; KP-01 Irrigation Network Planning Standards, 2013; Linsley, Franzini, Freyberg, & Tchobanoglous, 1994; Soemarto, 1999) [3, 8, 10, 17].

Evaporation is influenced by several climatological parameters, such as solar radiation, wind speed, relative humidity, and air temperature (KP-01 Irrigation Network Planning Standards, 2013; Linsley *et al*. 1994) [8, 10]. To estimate the potential evapotranspiration (ET_0), the Modified Penman Method is used, as it integrates the effects of these variables into a single predictive model (Doorenbos & Pruitt, 1977) [3]. The calculation is expressed in Equation (2).

$$ETo = c[W.Rn + (1 - W)\, x\, f(u).(ea - ed)] \quad (2)$$

where *ETo* is the potential evapotranspiration, *c* is the Penman correction factor, *W* is the weighting factor, Rn is the net solar radiation, f(u) is the wind function, and (ea − ed) is the difference between the saturated vapor pressure (ea) and the actual vapor pressure (ed).

FJ Mock Model

The FJ Mock model is employed to estimate the available streamflow entering the reservoir. Dr. Mock's water balance model provides a simplified method for calculating various hydrological components based on extensive research on river basins across Indonesia. The average rainfall is determined from observed measurements, while evapotranspiration is derived from climatological data using the Penman equation. Combined with the hydrological characteristics of a given watershed, this model produces the streamflow discharge as output (KP-01 Irrigation Network Planning Standards, 2013) [8].

Synthetic Data Generation Using the Thomas-Fiering Method

The Thomas-Fiering model is a widely used stochastic model for generating streamflow forecasts. Stochastic methods in hydrology are time-dependent, representing sequences of events where each is influenced by preceding conditions (Gunawan, 2006) [4]. The Thomas-Fiering equation is expressed in Equation (3):

$$q_{i+1,j} = \overline{q_j} + bj\left(q_{i,j-1} - \overline{q_{j-1}}\right) + tiSd_j(1 - rj)^{1/2} \quad (3)$$

where $q_{i+1,j}$ is the generated flow data for month j in year $(i+1)$, rj is the correlation coefficient between month $(j-1)$ and month j, bj is the regression coefficient between the flow in month j and $(j-1)$, ti is a standard normal random variable, and Sd_j is the standard deviation for month j.

Domestic Water Demand Analysis

The domestic (raw) water demand is the top priority in the operation plan of the Pidekso Reservoir. The calculation of domestic water demand begins with population projection for the year 2020 using the Geometric Growth Method (Gunawan, 2006; Setiyanto, B., & Adhi, B. W. 2022) [4, 16], as shown in Equation (4).

Reference (APA Style)

Gunawan, A. (2006) [4]. *Hidrologi untuk perencanaan dan evaluasi sumber daya air*. Andi Offset.

$$Pn = Po\,(1 + r)^t \quad (4)$$

Raw Water Demand Analysis

The raw water supply is the primary priority in the operational planning of the Pidekso Reservoir. The projection of domestic water demand begins with estimating the population for the year 2020 using the Geometric Growth Method (Gunawan, 2006) [4], as expressed in Equation (4).

where Pn is the projected population at the end of the target year, P_0 is the initial population, r is the annual population growth rate (in percentage), and t is the number of projection years.

Based on the results of the population projection for the upcoming year, the service area for raw water demand is classified as a small town.

Irrigation Water Demand Analysis

The majority of irrigation water demand in the study area is met using surface water sources. Several factors affecting agricultural water requirements vary over time and space (Taha, 1996; Triatmodjo, B. 2010.; Zhang, Y., Li, X., Wang, Y., & Chen, J. 2021) [18, 19, 20]. Irrigation demand analysis is conducted based on the cropping pattern implemented in the study area. The crops cultivated include rice and secondary crops (*palawija*), with a rice–rice–*palawija* rotation across an irrigated area of 1,500 hectares. Effective rainfall with 80% reliability is considered in the analysis.

The water demand calculation is simulated using different planting start times to provide input for the optimization model using the Richard Bellman method. The irrigation water demand is calculated using Equation (5).

$$KAI = \frac{(Etc + IR + WLR + P - Re)}{IE} x\,A \quad (5)$$

where KAI is the irrigation water demand, ETc is the crop evapotranspiration (consumptive use), IR is the net irrigation requirement at the farm level, WLR is the water layer replacement requirement, P is percolation, Re is effective rainfall, IE is the irrigation efficiency, and A is the irrigated area (Mays, 1992; Taha, 1996; Triatmodjo, 2010) [11, 18, 19].

Micro-Hydro Power Plant (MHPP) Analysis

A Micro-Hydro Power Plant (MHPP) is a small-scale power generation system that utilizes the streamflow entering the intake and the elevation drop (head) to produce electricity (Morena & Tika, 2017) [13]. The actual power output from the generator accounts for the efficiency of both the turbine and the generator and is calculated using Equation (6).

$$P = \eta\,.\rho.Q.g.H_{eff} \quad (6)$$

where P is the electrical power output (in watts), g is the gravitational acceleration (9.81 m/s^2), H_{eff} is the effective head (in meters), η is the efficiency of the turbine-generator system (dimensionless), and ρ is the density of water (typically 1000 kg/m^3).

Optimization Modelling Using the Richard Bellman Method: The fundamental concept of the Richard Bellman optimization method is the principle of optimality, which states that a properly formulated problem can be solved in a step-by-step manner (Morena & Tika, 2017) [13]. In the context of irrigation, optimization problems are often nonlinear in nature. One effective approach to addressing these nonlinearities is the use of optimization techniques. This theory is applicable in more general regulatory settings and can be implemented for hydroelectric power systems with dams (Olofsson *et al*., 2002; Mays, 1992) [11], using the Richard Bellman method (Indriyani, 2009) [6, 7].

The optimization model aims to determine the optimal decision for a particular action based on state-determining factors (Indriyani, 2009; Küster *et al*., 2021) [6, 7, 9].

According to Mays (1992) [11], the core characteristics of all optimization problems using the Richard Bellman method are as follows:

1. The problem is divided into multiple stages, with decision variables at each stage.
2. Each stage is associated with a number of possible states.
3. Decisions at each stage yield returns, defined by a stage return function, and transition the system from the current state to the next stage's state. Given the current state, an optimal policy for the remaining stages is independent of the policy adopted in previous stages. This is known as Bellman's principle of optimality, which serves as the backbone of the Bellman dynamic

programming technique.

4. The solution process begins by identifying the optimal decision for each possible state, either from the last stage (backward recursion) or from the first stage (forward recursion).
5. A recursive relationship is established in which the optimal policy at stage *n* is developed based on the known optimal policy for stage *n+1*.

The schematic diagram of the decision-making process for the optimization model applied to the Pidekso Reservoir is shown in Figure 2.

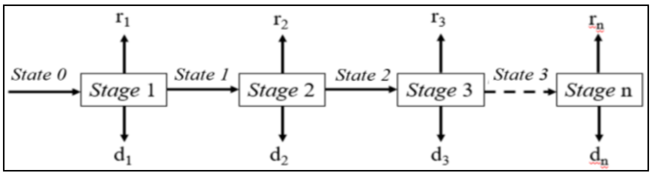

Fig 2: Decision Flowchart of the Dynamic Programming Model for Pidekso Reservoir

The formulation of the optimization technique using Richard Bellman's method for the Pidekso Reservoir is based on the following elements:

1. **Stage:** A stage represents the time period under consideration. Within one year, there are 24 stages, consisting of 12 months with two sub-periods (15-day intervals) each.
2. **State:** The state represents the reservoir storage at stage *i,ji,ji,j*. At the beginning of the initial period, the reservoir storage is assumed to be full, which is 25.165 million cubic meters.
3. **Decision Variable:** The decision variable is the release required to meet raw water and irrigation demands. For the Micro Hydro Power Plant (MHPP), the release depends on the combined releases for raw water and irrigation during each period.
4. **Return:** The return is the ratio value between release and demand for raw water, irrigation, and MHPP needs in each period, expressed as a factor kkk ranging from 0 to 1, as given by Equation (7).

$$k_{i,j} = \frac{R_{i,j}}{D_{i,i}} \qquad (7)$$

5. **Objective Function:** The objective function in this study is to find the average value of the factor kkk over one complete cycle, as expressed in Equation (8).

$$OF = \frac{1}{n}\sum_{i=1}^{n} k \qquad (8)$$

6. **State Transformation Function:** This function is used to determine the reservoir condition that links one stage to the next, as described by Equation (9).

$$ST_{t+1}=ST_1+Q_t+PP_t-EV_t-R_t \qquad (9)$$

7. **Forward Recursive Formula:** This equation represents the relationship between optimal policies for each problem at stage nnn and the previous stage. It indicates that decisions taken consider the state resulting from the decisions made at the previous stage.

$$r_{t+1}(ST_{t+1}) = \underset{Rt}{Max}[r_t(R_t, ST_{t+1}) + (r_t(ST_t)],$$
$$for\ t = 2, \dots, T$$
$$r_{t+1}(ST_{t+1}) = \underset{Rt}{Max}[r_t(R_t, ST_t)],$$
$$\text{for } t = 1 \qquad (10)$$

8. **Constraints in Reservoir Storage:** The reservoir has a minimum storage capacity that must be maintained (dead storage). Therefore, at each stage, the reservoir's ending storage volume must not fall below the minimum capacity, which is 8.095 million cubic meters. Based on the explanation above, the constraint can be expressed as equation (11).

$$K_d \leq ST_t \leq K \qquad (11)$$

Simulation of the Richard Bellman Optimization Technique for Pidekso Reservoir

The optimization simulation using the Richard Bellman method for Pidekso Reservoir was conducted with several alternatives, namely irrigation water demand calculations with different planting start times based on months and periods, resulting in 24 simulations.

The optimization technique was solved stage by stage. The steps to complete the optimization process are as follows:

1. Calculate and review reservoir inflow data, water losses due to potential evapotranspiration, precipitation, and water demand in each period.
2. Set the initial storage volume *ST* with $K_d \leq ST_t \leq K$ for the current and subsequent periods.
3. Determine the optimal factor *k* value for each water demand.
4. Calculate the ending storage volume using the predetermined state transformation function. If the storage volume does not meet constraints, repeat step 3 by using the recursive equation to adjust *k* until the ending storage volume satisfies the constraint. The ending storage at stage 1 becomes the initial storage for stage 2.
5. Repeat steps 3 and 4 for all stages.
6. After calculating the final stage, compute the average factor k value to determine the optimal result for each water demand in one simulation. Repeat for each planting start time.

The large number of calculations required for this simulation was facilitated using Visual Basic for Applications (VBA) in Microsoft Excel.

Results and Discussion

Optimal Results: Table 1 and Figure 3 show that in September, the water demand for raw water and irrigation has the most optimal average factor *k* value of 1. This indicates that the Pidekso Reservoir can fully meet the raw water, and irrigation demands in the service area over one year. Meanwhile, from the two periods in September, the most optimal result for the Micro Hydro Power Plant (MHPP) 1 is in Period II, with an average factor *k* value of 0.89, followed by MHPP 2 with an average factor k of 0.74 also in September Period II.

Table 1(a): Average Factor *k* Values for Each Planting Start Time

Month	Period	Average Value of *k* Factor			
		Raw Water Demand	Irrigation Demand	MHPP1 Demand	MHPP2 Demand
Nov	I	1,000	0,920	0,862	0,747
	II	1,000	0,876	0,882	0,749
Dec	I	1,000	0,847	0,864	0,682
	II	1,000	0,814	0,828	0,639
Jan	I	1,000	0,847	0,867	0,693
	II	1,000	0,867	0,876	0,677
Feb	I	1,000	0,878	0,891	0,719
	II	1,000	0,881	0,886	0,750
Mar	I	1,000	0,879	0,880	0,720
	II	1,000	0,880	0,886	0,692
Apr	I	1,000	0,891	0,892	0,675
	II	1,000	0,896	0,877	0,682

Table 1(b): Average Factor *k* Values for Each Planting Start Time

Month	Period	Average Value of *k* Factor			
		Raw Water Demand	Irrigation Demand	MHPP1 Demand	MHPP2 Demand
May	I	1,000	0,896	0,898	0,659
	II	1,000	0,889	0,874	0,661
Jun	I	1,000	0,912	0,861	0,704
	II	1,000	0,939	0,862	0,695
Jul	I	1,000	0,957	0,892	0,714
	II	1,000	0,955	0,885	0,680
Aug	I	1,000	0,964	0,901	0,677
	II	1,000	0,994	0,897	0,750
Sept	I	1,000	1,000	0,876	0,773
	II	1,000	1,000	0,896	0,735
Oct	I	1,000	0,957	0,874	0,740
	II	1,000	0,941	0,869	0,747

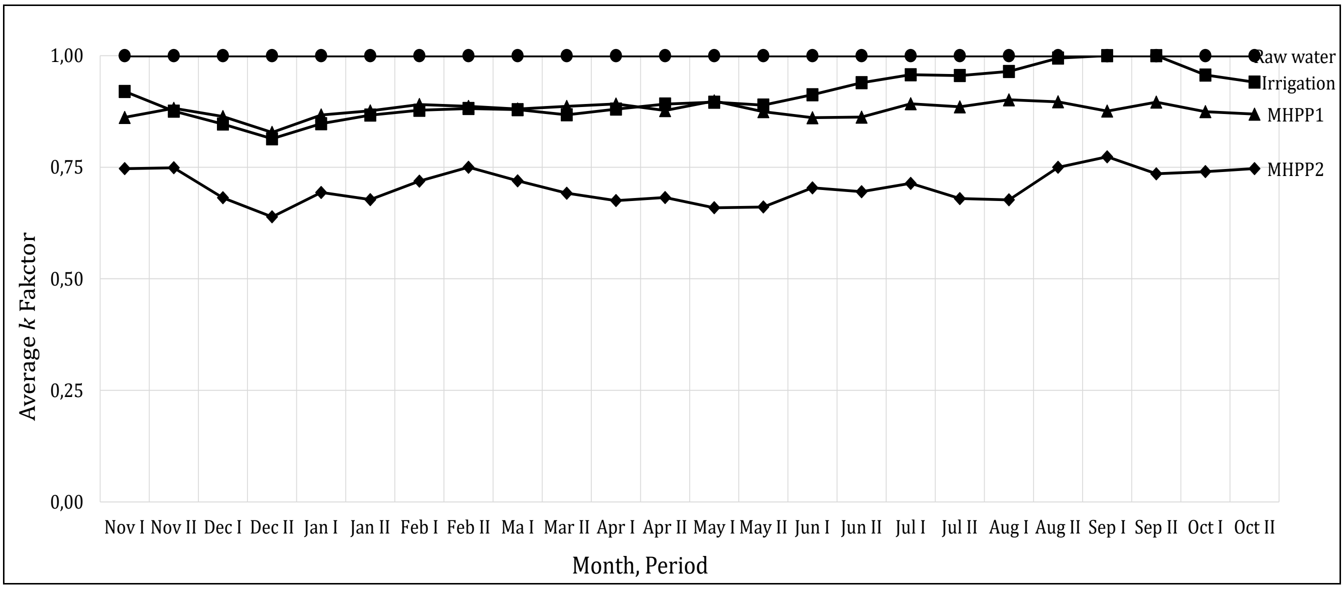

Fig 3: Average Factor *k* Values for Each Planting Start Period – Optimization Results

Optimization Solution

Table 2 presents the release values during September (Period II) for each time interval. Figure 4 illustrates the cumulative inflow and outflow during the same period, indicating that the water availability in the Pidekso Reservoir remains abundant. This suggests that the current water usage has not yet fully utilized the reservoir's effective storage capacity.

To address this, an optimization solution is proposed by adjusting the irrigated planting area. By increasing the irrigated area proportionally, the excess available water in the effective reservoir storage can be fully utilized, thus enhancing overall water use efficiency in the Pidekso Reservoir operation.

Table 2: Summary of Inflow and Outflow for Planting Start Time in September – Period II

Waktu awal tanam	Bulan	Periode	Jumlah hari	ΔS	Inflow				Outflow				
					Qt	PPt	Total Inflow	Inflow Kumulatif	EVt	Air Baku	Irigasi	Total Outflow	Outflow Kumulatif
				juta m^3	juta m^3	juta m^3	juta m^3	juta m^3	juta m^3	juta m^3	juta m^3	juta m^3	juta m^3
1	2	3	4	5	6	7	8	9	10	11	12	13	14
September Periode II	Sep	II	15	25.165	1.994	0.280	27.439	0.000	0.560	0.052	0.000	0.613	0.000
	Okt	I	15	25.165	2.602	0.319	28.086	27.439	1.357	0.052	2.538	3.947	0.613
		II	16	24.139	2.344	0.241	26.724	55.525	1.447	0.056	5.415	6.918	4.560
	Nov	I	15	19.806	1.688	0.009	21.503	82.249	0.571	0.052	4.014	4.637	11.478
		II	15	16.865	3.303	0.524	20.692	103.751	0.571	0.052	3.968	4.592	16.115
	Des	I	15	16.100	3.225	0.400	19.726	124.444	0.550	0.052	3.700	4.302	20.707
		II	16	15.423	4.525	0.632	20.581	144.169	0.587	0.056	0.898	1.541	25.009
	Jan	I	15	19.040	1.665	0.158	20.863	164.750	0.633	0.052	0.482	1.167	26.550
		II	16	19.696	3.172	0.445	23.313	185.613	0.675	0.056	0.000	0.731	27.717
	Feb	I	15	22.582	5.272	0.834	28.688	208.926	0.657	0.052	1.117	1.827	28.448
		II	14	25.165	5.417	0.850	31.432	237.614	0.614	0.049	2.658	3.320	30.275
	Mar	I	15	25.165	1.397	0.000	26.562	269.046	0.589	0.052	4.321	4.961	33.595
		II	16	21.601	1.133	0.000	22.734	295.608	0.628	0.056	2.213	2.896	38.556
	Apr	I	15	19.838	4.386	0.648	24.871	318.342	0.666	0.052	2.656	3.375	41.453
		II	15	21.496	1.690	0.025	23.211	343.213	0.666	0.052	3.044	3.763	44.828
	Mei	I	15	19.448	3.351	0.452	23.252	366.424	0.905	0.052	1.574	2.531	48.591
		II	16	20.720	3.119	0.282	24.122	389.676	0.965	0.056	0.976	1.997	51.122
	Jun	I	15	22.125	1.419	0.029	23.574	413.798	0.665	0.052	1.129	1.847	53.119
		II	15	21.727	1.669	0.183	23.579	437.372	0.665	0.052	2.495	3.213	54.966
	Jul	I	15	20.366	0.877	0.056	21.300	460.950	0.620	0.052	3.308	3.981	58.178
		II	16	17.320	1.053	0.055	18.427	482.251	0.661	0.056	3.600	4.317	62.159
	Agu	I	15	14.110	0.499	0.023	14.632	500.678	0.741	0.052	3.947	4.741	66.476
		II	16	9.892	1.302	0.036	11.229	515.310	0.790	0.056	1.787	2.634	71.217
	Sep	I	15	8.595	1.867	0.054	10.516	526.539	0.560	0.052	0.429	1.041	73.850

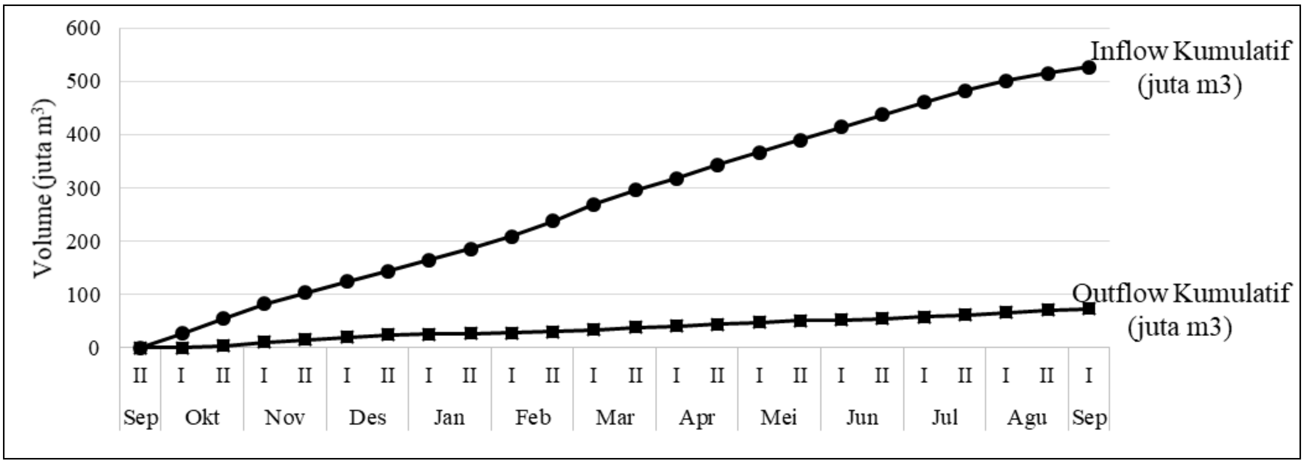

Fig 4: Cumulative Inflow and Outflow Volumes for the Planting Start Time in September – Period II

Initial calculations were conducted by maximizing the utilization of water available in the effective storage of the Pidekso Reservoir using the Richard Bellman Method.

Based on these calculations, the optimum irrigated planting areas for each period were determined. The results are presented in Table 3.

As illustrated in Figure 5, the utilization of water in the effective reservoir storage is already optimal, which is indicated by the overlapping lines of the cumulative inflow and outflow volume graphs. The coincidence of these lines signifies that all available water in the effective storage has been efficiently used.

From these results, the maximum optimum irrigated area was found to be:

- 24,030 ha for the first rice planting season,
- 22,378 ha for the second rice planting season, and
- 26,542 ha for the secondary crops (*palawija*) season.

Meanwhile, the minimum optimum irrigated area was

- 3,352 ha for the first rice planting season,
- 7,605 ha for the second rice planting season, and
- 7,276 ha for the secondary crops season.

The graph of optimum irrigated areas for each planting period is presented in Figure 6.

The first simulation was carried out using the maximum optimum irrigated areas to determine whether the effective reservoir storage could meet the total water demand. The results of inflow and outflow calculations based on the maximum irrigated areas are shown in Table 4.

Table 3: Computed Results Based on the Optimum Irrigation Area

Planting Start Time	Month	Period	number of days	Inflow					Outflow					Irrigation
				ΔS	Qt	PPt	Total Inflow	Cumulative Inflow	EVt	Raw Water	Irrigation	Total Outflow	Cumulative Outflow	
				10^6 m^3	10^6 m^3	10^6 m^3	10^6 m^3	10^6 m^3	10^6 m^3	10^6 m^3	10^6 m^3	10^6 m^3	10^6 m^3	Ha
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
September Period II	Sep	II	15	17,070	1,994	0,280	19,344	0,000	0,560	0,052	18,732	19,344	0,000	4132
	Oct	I	15	17,070	2,602	0,319	19,991	19,344	1,357	0,052	18,582	19,991	19,344	3661
		II	16	17,070	2,344	0,241	19,655	39,335	1,447	0,056	18,152	19,655	39,336	3352
	Nov	I	15	17,070	1,688	0,009	18,767	58,990	0,571	0,052	18,143	18,767	58,991	6781
		II	15	17,070	3,303	0,524	20,897	77,757	0,571	0,052	20,274	20,897	77,758	7663
	Dec	I	15	17,070	3,225	0,400	20,696	98,654	0,550	0,052	20,093	20,696	98,655	8146
		II	16	17,070	4,525	0,632	22,228	119,350	0,587	0,056	21,585	22,228	119,351	24030
	Jan	I	15	17,070	1,665	0,158	18,894	141,578	0,633	0,052	18,209	18,894	141,579	18898
		II	16	17,070	3,172	0,445	20,687	160,471	0,675	0,056	19,957	20,688	160,473	8257
	Feb	I	15	17,070	5,272	0,834	23,176	181,158	0,657	0,052	22,467	23,176	181,160	7889
		II	14	17,070	5,417	0,850	23,337	204,335	0,614	0,049	22,675	23,337	204,337	7605
	Mar	I	15	17,070	1,397	0,000	18,467	227,671	0,589	0,052	17,826	18,467	227,674	8695
		II	16	17,070	1,133	0,000	18,204	246,138	0,628	0,056	17,520	18,204	246,141	8928
	Apr	I	15	17,070	4,386	0,648	22,104	264,342	0,666	0,052	21,385	22,104	264,345	10834
		II	15	17,070	1,690	0,025	18,785	286,446	0,666	0,052	18,067	18,786	286,449	13250
	May	I	15	17,070	3,351	0,452	20,874	305,231	0,905	0,052	19,917	20,874	305,234	22378
		II	16	17,070	3,119	0,282	20,472	326,105	0,965	0,056	19,451	20,472	326,108	26542
	Jun	I	15	17,070	1,419	0,029	18,519	346,577	0,665	0,052	17,802	18,519	346,581	15765
		II	15	17,070	1,669	0,183	18,922	365,096	0,665	0,052	18,205	18,923	365,100	10945
	Jul	I	15	17,070	0,877	0,056	18,004	384,018	0,620	0,052	17,332	18,004	384,022	7859
		II	16	17,070	1,053	0,055	18,178	402,022	0,661	0,056	17,461	18,178	402,027	7276
	Aug	I	15	17,070	0,499	0,023	17,592	420,200	0,741	0,052	16,799	17,592	420,205	6384
		II	16	17,070	1,302	0,036	18,407	437,792	0,790	0,056	17,290	18,136	437,797	9674
	Sep	I	15	17,070	1,867	0,054	18,991	456,199	0,560	0,052	18,378	18,991	455,933	21437

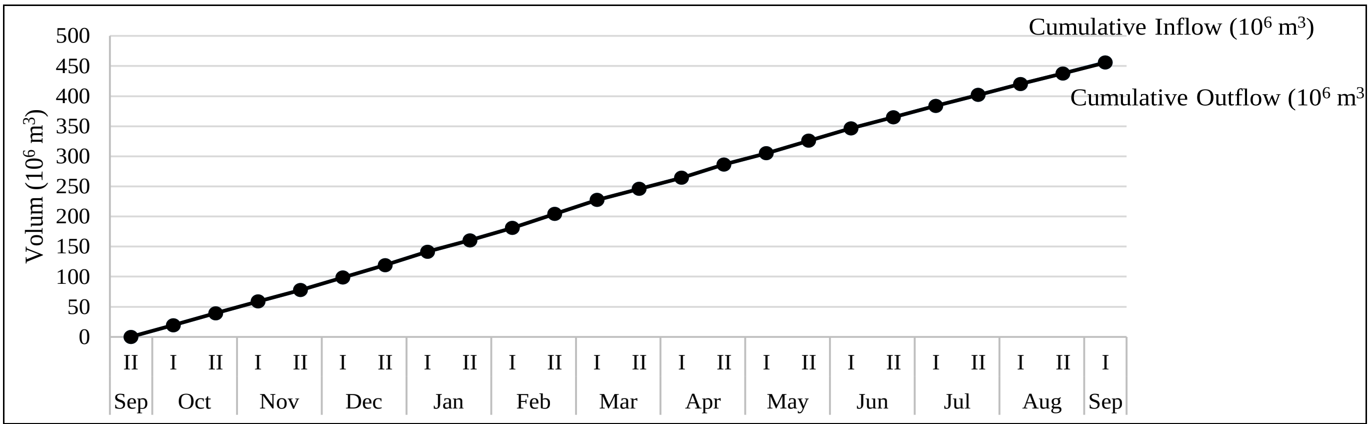

Fig 5: Cumulative Inflow and Outflow Volumes for the Optimum Irrigated Area

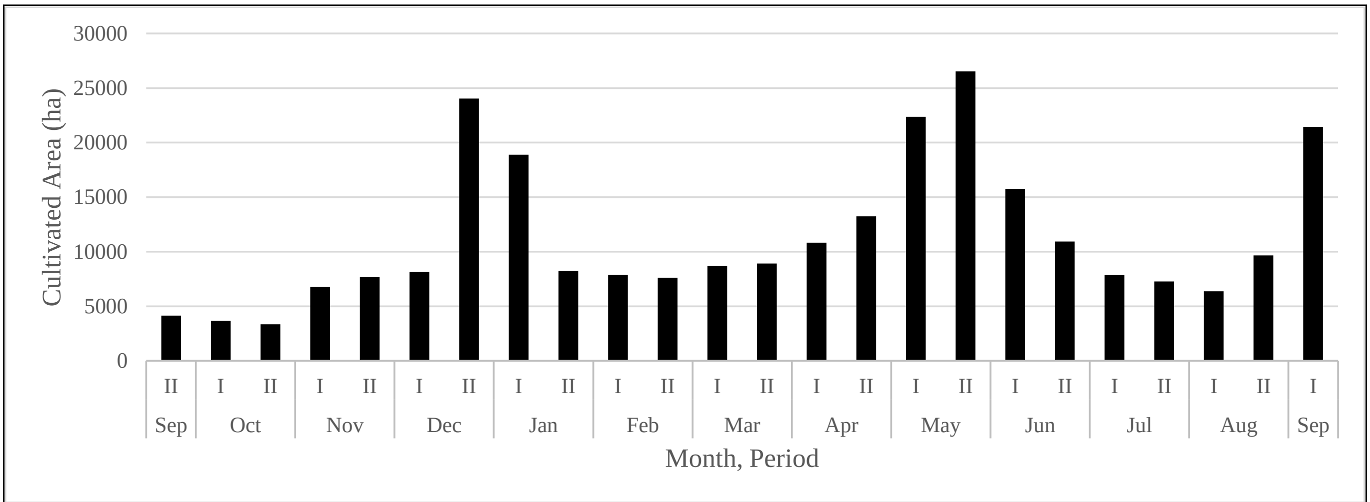

Fig 6: Optimum Planting Area for Each Period

Table 4: Calculation Results of Inflow and Outflow with the Largest Optimum Planting Area

Initial Planting Time	Month	Period	Jumlah hari	ΔS	Inflow				Outflow					Remaining Storage	Storage Condition
					Qt	PPt	Total Inflow	Cumulative Inflow	EVt	Raw Water	Irrigation	Total Outflow	Vumulative Outflow	(8) - (14)	
				10^6 m^3	10^6 m^3	10^6 m^3	10^6 m^3	10^6 m^3	10^6 m^3	10^6 m^3	10^6 m^3	10^6 m^3	10^6 m^3	10^6 m^3	$K_d \leq ST_t \leq K$
1	2	3	4	5	6	7	8	9	10	11	12	14	15	16	17
September Period II	Sep	II	15	17,070	1,994	0,280	19,344	0,000	0,560	0,052	36,315	36,928	0,000	-17,584	NOT OK
	Oct	I	15	17,070	2,602	0,319	19,991	19,344	1,357	0,052	81,326	82,734	36,928	-62,743	NOT OK
		II	16	17,070	2,344	0,241	19,655	39,335	1,447	0,056	130,121	131,624	119,662	-111,969	NOT OK
	Nov	I	15	17,070	1,688	0,009	18,767	58,990	0,571	0,052	64,298	64,922	251,286	-46,155	NOT OK
		II	15	17,070	3,303	0,524	20,897	77,757	0,571	0,052	63,574	64,197	316,208	-43,300	NOT OK
	Dec	I	15	17,070	3,225	0,400	20,696	98,654	0,550	0,052	59,271	59,874	380,405	-39,178	NOT OK
		II	16	17,070	4,525	0,632	22,228	119,350	0,587	0,056	14,390	15,033	440,279	7,195	NOT OK
	Jan	I	15	17,070	1,665	0,158	18,894	141,578	0,633	0,052	7,718	8,403	455,312	10,491	OK
		II	16	17,070	3,172	0,445	20,687	160,471	0,675	0,056	18,028	18,759	463,715	1,928	NOT OK
	Feb	I	15	17,070	5,272	0,834	23,176	181,158	0,657	0,052	42,489	43,199	482,474	-20,023	NOT OK
		II	14	17,070	5,417	0,850	23,337	204,335	0,614	0,049	66,722	67,384	525,673	-44,047	NOT OK
	Mar	I	15	17,070	1,397	0,000	18,467	227,671	0,589	0,052	45,882	46,523	593,057	-28,056	NOT OK
		II	16	17,070	1,133	0,000	18,204	246,138	0,628	0,056	43,916	44,599	639,579	-26,396	NOT OK
	Apr	I	15	17,070	4,386	0,648	22,104	264,342	0,666	0,052	44,173	44,891	684,179	-22,788	NOT OK
		II	15	17,070	1,690	0,025	18,785	286,446	0,666	0,052	20,343	21,062	729,070	-2,276	NOT OK
	May	I	15	17,070	3,351	0,452	20,874	305,231	0,905	0,052	6,639	7,596	750,132	13,278	OK
		II	16	17,070	3,119	0,282	20,472	326,105	0,965	0,056	12,968	13,988	757,728	6,484	NOT OK
	Jun	I	15	17,070	1,419	0,029	18,519	346,577	0,665	0,052	29,971	30,688	771,716	-12,169	NOT OK
		II	15	17,070	1,669	0,183	18,922	365,096	0,665	0,052	44,147	44,864	802,405	-25,942	NOT OK
	Jul	I	15	17,070	0,877	0,056	18,004	384,018	0,620	0,052	58,536	59,209	847,269	-41,205	NOT OK
		II	16	17,070	1,053	0,055	18,178	402,022	0,661	0,056	63,696	64,413	906,478	-46,235	NOT OK
	Aug	I	15	17,070	0,499	0,023	17,592	420,200	0,741	0,052	46,566	47,359	970,891	-29,767	NOT OK
		II	16	17,070	1,302	0,036	18,407	437,792	0,790	0,056	15,813	16,659	1018,250	1,748	NOT OK
	Sep	I	15	17,070	1,867	0,054	18,991	456,199	0,560	0,052	0,000	0,613	1034,909	18,378	OK

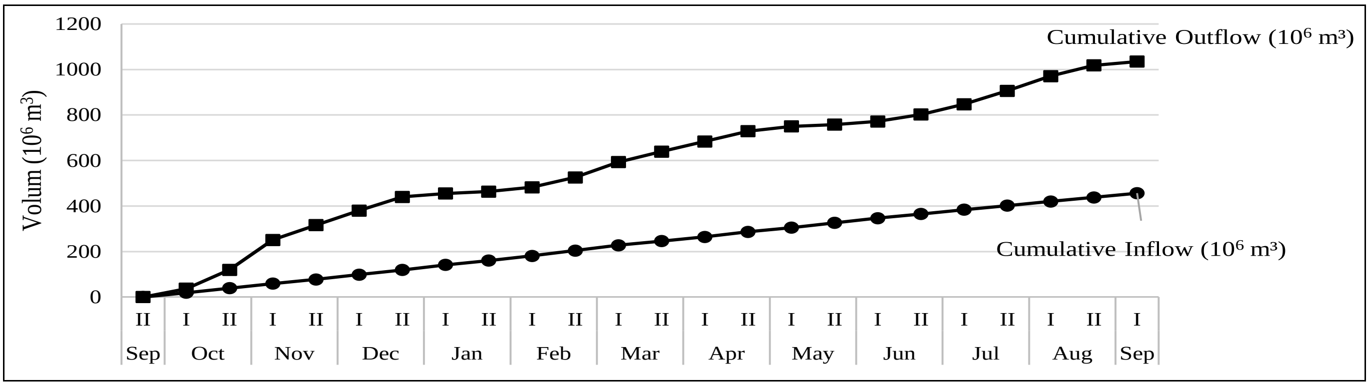

Fig 7: Cumulative Inflow and Outflow Volume with the Largest Optimum Planting Area.

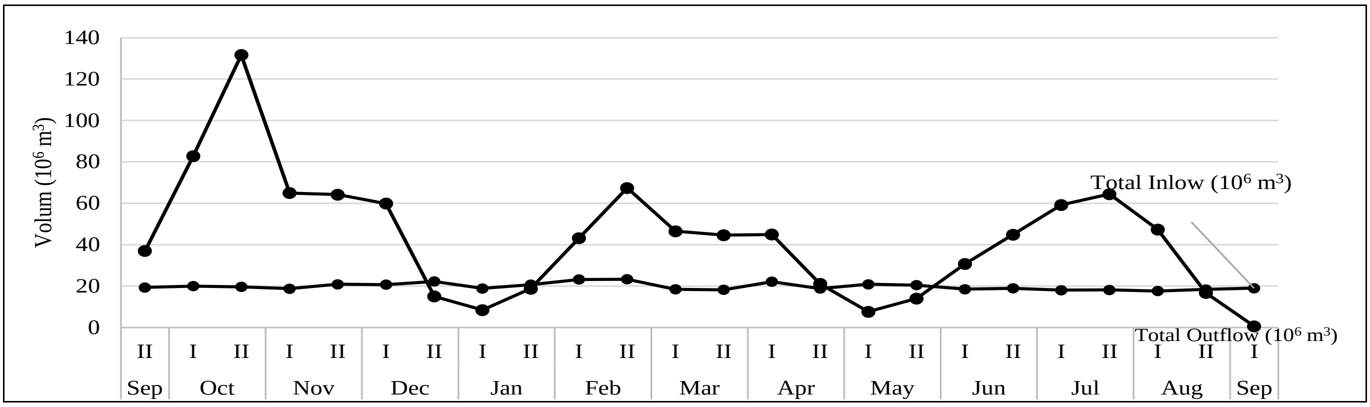

Fig 8: Inflow and Outflow Volume with the Largest Optimum Planting Area

Based on Figure 7, it can be observed that when utilizing the maximum optimum irrigated area, the cumulative outflow volume exceeds the cumulative inflow volume, and the reservoir storage condition falls below the dead storage level. The inflow and outflow volume graph is presented in Figure 8. Under these conditions, it is evident that applying the maximum optimum irrigated area is not feasible for the targeted irrigation area, as certain periods cannot be adequately irrigated.

The second calculation was carried out using the minimum optimum irrigated area to determine whether the reservoir's effective storage can fulfil the required water demand under this scenario. The results of inflow and outflow calculations based on the minimum optimum irrigated area are shown in Table 5, while the cumulative inflow and outflow volume graph is presented in Figure 9, and the inflow and outflow volume graph is presented in Figure 10.

Table 5: Inflow and Outflow Calculation Results Using the Minimum Optimum Irrigated Area

Initial Planting Time	Month	Period	Number of Days	ΔS	Inflow				Outflow					Remaining Storage	Storage Condition
					Qt	PPt	Total Inflow	Cumulative Inflow	EVt	Raw Water	Irrigation	Total Outflow	Outflow Kumulatif	(8) - (14)	
				10^6 m^3	10^6 m^3	10^6 m^3	10^6 m^3	10^6 m^3	10^6 m^3	10^6 m^3	10^6 m^3	10^6 m^3	10^6 m^3	10^6 m^3	$K_d \le ST_t \le K$
1	2	3	4	5	6	7	8	9	10	11	12	14	15	16	17
September Period II	Sep	II	15	17,07	1,99	0,28	19,34	0,00	0,56	0,05	5,07	5,68	0,00	13,67	OK
	Oct	I	15	17,07	2,60	0,32	19,99	19,34	1,36	0,05	11,35	12,75	5,68	7,24	OK
		II	16	17,07	2,34	0,24	19,66	39,34	1,45	0,06	18,15	19,66	18,43	0,00	OK
	Nov	I	15	17,07	1,69	0,01	18,77	58,99	0,57	0,05	8,97	9,59	38,09	9,17	OK
		II	15	17,07	3,30	0,52	20,90	77,76	0,57	0,05	8,87	9,49	47,68	11,40	OK
	Dec	I	15	17,07	3,23	0,40	20,70	98,65	0,55	0,05	8,27	8,87	57,17	11,82	OK
		II	16	17,07	4,52	0,63	22,23	119,35	0,59	0,06	2,01	2,65	66,05	19,58	OK
	Jan	I	15	17,07	1,67	0,16	18,89	141,58	0,63	0,05	1,08	1,76	68,70	17,13	OK
		II	16	17,07	3,17	0,44	20,69	160,47	0,68	0,06	6,13	6,86	70,46	13,83	OK
	Feb	I	15	17,07	5,27	0,83	23,18	181,16	0,66	0,05	14,44	15,15	77,32	8,03	OK
		II	14	17,07	5,42	0,85	23,34	204,33	0,61	0,05	22,67	23,34	92,46	0,00	OK
	Mar	I	15	17,07	1,40	0,00	18,47	227,67	0,59	0,05	15,59	16,23	115,80	2,23	OK
		II	16	17,07	1,13	0,00	18,20	246,14	0,63	0,06	14,92	15,61	132,03	2,60	OK
	Apr	I	15	17,07	4,39	0,65	22,10	264,34	0,67	0,05	15,01	15,73	147,64	6,37	OK
		II	15	17,07	1,69	0,02	18,79	286,45	0,67	0,05	6,91	7,63	163,37	11,15	OK
	May	I	15	17,07	3,35	0,45	20,87	305,23	0,90	0,05	2,26	3,21	171,01	17,66	OK
		II	16	17,07	3,12	0,28	20,47	326,10	0,96	0,06	3,55	4,58	174,22	15,90	OK
	Jun	I	15	17,07	1,42	0,03	18,52	346,58	0,67	0,05	8,22	8,93	178,79	9,59	OK
		II	15	17,07	1,67	0,18	18,92	365,10	0,67	0,05	12,10	12,82	187,73	6,10	OK
	Jul	I	15	17,07	0,88	0,06	18,00	384,02	0,62	0,05	16,05	16,72	200,55	1,29	OK
		II	16	17,07	1,05	0,05	18,18	402,02	0,66	0,06	17,46	18,18	217,27	0,00	OK
	Aug	I	15	17,07	0,50	0,02	17,59	420,20	0,74	0,05	12,76	13,56	235,44	4,03	OK
		II	16	17,07	1,30	0,04	18,41	437,79	0,79	0,06	4,33	5,18	249,00	13,23	OK
	Sep	I	15	17,07	1,87	0,05	18,99	456,20	0,56	0,05	0,00	0,61	254,18	18,38	OK

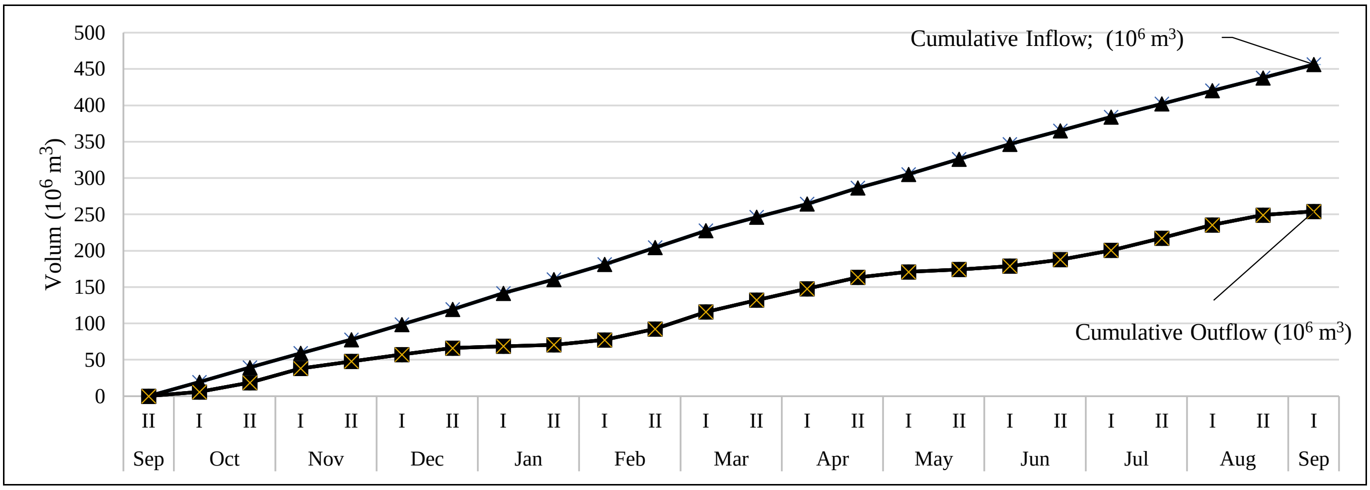

Fig 9: Cumulative Inflow and Outflow Volume with Optimum Irrigated Area

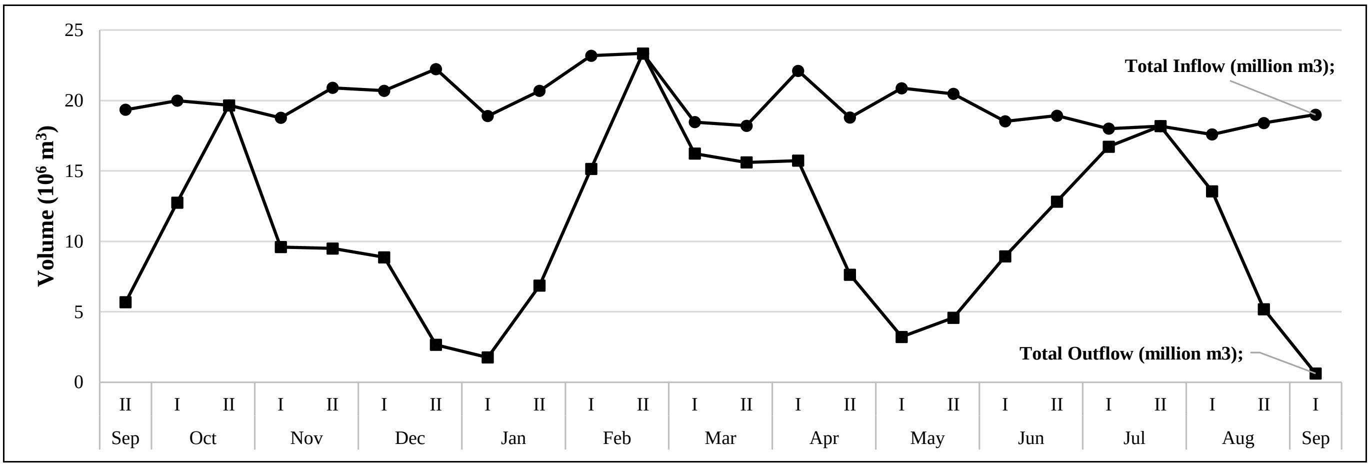

Fig 10: Inflow and Outflow Volumes Corresponding to the Maximum Optimum Irrigated Area

From the use of the smallest optimum planting area, it can be observed that the cumulative inflow volume exceeds the cumulative outflow volume, and the reservoir storage condition is greater than or equal to the dead storage. Therefore, the application of the smallest optimum planting area is feasible under the storage conditions of the Pidekso Reservoir and can serve as a reference for water usage in the designated cropping pattern.

The expansion of the irrigated planting area for a one-year cropping period, where initially the planting area at the study site was 1,500 ha, results in increases to 3,352 ha for the first rice planting season, 7,605 ha for the second rice season, and 7,276 ha for the dry-season crops (*palawija*). Thus, the increase in irrigated area amounts to 1,852 ha for the first rice season, 6,105 ha for the second rice season, and 5,776 ha for the *palawija* season. However, surplus water remains unused during 21 periods. This surplus will be utilized in the third calculation phase by optimizing the operation of the Micro Hydro Power Plant (MHPP).

The third calculation aims to maximize the use of remaining reservoir water from the second phase by increasing the utilization for MHPP. The water supply for MHPP comes from the release for domestic and irrigation water as well as the unused storage volume from the previous step. Based on the total available water supply, the dependable discharge at a 95% reliability level is calculated to be 6.911 m³/s. During PLTMH operation, when the discharge is in excess, the MHPP continues to operate, but the intake to the irrigation channel is limited to meet only the actual water demand. The results of the calculation for maximizing the use of reservoir water for MHPP are presented in Table 6, while the cumulative inflow and outflow volume graph is shown in Figure 11, and the inflow and outflow volume graph is presented in Figure 12.

Based on Table 6, it is shown that the average power generated by MHPP 1 and MHPP 2 exceeds 100 kW. Given this level of power generation, the system no longer qualifies as Micro Hydro Power (typically less than 100 kW) but rather can be classified as a Mini Hydro Power Plant (MHPP), with output ranging from 100 kW to 5,000 kW (Morena and Tika, 2017) [13].

Table 6(a): Power Output Calculation Results for the Micro Hydro Power Plant (MHPP)

Month	Period	Number of days	Release		Remaining Storage	Total Suplai MHPP		MHPP 1				
			Raw Water	Irrigation				m³/dtk	juta m³	Demand	Release	P
			10^6 m³	10^6 m³	10^6 m³	10^6 m³	m³/dtk			10^6 m³	10^6 m³	kW
1	2	3	4	5	6	7	8	9	10	11	12	13
Sep	II	15	0,052	5,066	13,665	18,784	14,494	6,885	8,924	8,924	8,924	825,927
Oct	I	15	0,052	11,345	7,237	18,634	14,378	6,885	8,924	8,924	8,924	825,927
	II	16	0,056	18,152	0,000	18,208	13,171	6,885	9,518	9,518	9,518	825,927
Nov	I	15	0,052	8,970	9,173	18,195	14,040	6,885	8,924	8,924	8,924	825,927
	II	15	0,052	8,869	11,405	20,326	15,683	6,885	8,924	8,924	8,924	825,927
Dec	I	15	0,052	8,269	11,825	20,145	15,544	6,885	8,924	8,924	8,924	825,927
	II	16	0,056	2,007	19,577	21,640	15,654	6,885	9,518	9,518	9,518	825,927
Jan	I	15	0,052	1,077	17,132	18,261	14,090	6,885	8,924	8,924	8,924	825,927
	II	16	0,056	6,127	13,830	20,012	14,476	6,885	9,518	9,518	9,518	825,927
Feb	I	15	0,052	14,440	8,027	22,519	17,376	6,885	8,924	8,924	8,924	825,927
	II	14	0,049	22,675	0,000	22,723	18,786	6,885	8,329	8,329	8,329	825,927
Mar	I	15	0,052	15,592	2,234	17,878	13,795	6,885	8,924	8,924	8,924	825,927
	II	16	0,056	14,924	2,596	17,576	12,714	6,885	9,518	9,518	9,518	825,927
Apr	I	15	0,052	15,012	6,373	21,437	16,541	6,885	8,924	8,924	8,924	825,927
	II	15	0,052	6,913	11,153	18,119	13,981	6,885	8,924	8,924	8,924	825,927
May	I	15	0,052	2,256	17,661	19,969	15,408	6,885	8,924	8,924	8,924	825,927
	II	16	0,056	3,555	15,896	19,507	14,111	6,885	9,518	9,518	9,518	825,927
Jun	I	15	0,052	8,216	9,586	17,854	13,776	6,885	8,924	8,924	8,924	825,927
	II	15	0,052	12,102	6,103	18,257	14,087	6,885	8,924	8,924	8,924	825,927
Jul	I	15	0,052	16,046	1,285	17,384	13,414	6,885	8,924	8,924	8,924	825,927
	II	16	0,056	17,461	0,000	17,516	12,671	6,885	9,518	9,518	9,518	825,927
Aug	I	15	0,052	12,765	4,034	16,851	13,003	6,885	8,924	8,924	8,924	825,927
	II	16	0,056	4,335	13,226	17,617	12,744	6,885	9,518	9,518	9,518	825,927
Sep	I	15	0,052	0,000	18,378	18,430	14,221	6,885	8,924	8,924	8,924	825,927

Table 6(b): Power Output Calculations for the Micro-Hydro Power Plant (MHPP)

Month	Period	Total suplai - MHPP 1	MHPP 2					MHPP Cumulative Inflow	MHPP Cumulative Outflow	MHPP Total Inflow	MHPP Total Outflow
			m^3/dtk	juta m^3	Demand	Release	P				
		10^6 m^3			10^6 m^3	10^6 m^3	10^6 m^3	10^6 m^3	10^6 m^3	10^6 m^3	10^6 m^3
1	**2**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
Sep	**II**	9,860	6,885	8,924	8,924	9,860	712,98	0,000	0,000	18,784	18,784
Oct	**I**	9,711	6,885	8,924	8,924	9,711	702,18	18,784	18,784	18,634	18,634
	II	8,690	6,885	9,518	9,518	8,690	589,06	37,418	37,418	18,208	18,208
Nov	**I**	9,272	6,885	8,924	8,924	9,272	670,44	55,626	55,626	18,195	18,195
	II	11,402	6,885	8,924	8,924	11,402	824,48	73,822	73,822	20,326	20,326
Dec	**I**	11,222	6,885	8,924	8,924	11,222	811,44	94,147	94,147	20,145	20,145
	II	12,122	6,885	9,518	9,518	12,122	821,75	114,293	114,293	21,640	21,640
Jan	**I**	9,337	6,885	8,924	8,924	9,337	675,16	135,933	135,933	18,261	18,261
	II	10,494	6,885	9,518	9,518	10,494	711,37	154,194	154,194	20,012	20,012
Feb	**I**	13,595	6,885	8,924	8,924	13,595	983,07	174,206	174,206	22,519	22,519
	II	14,395	6,885	8,329	8,329	14,395	1115,20	196,725	196,725	22,723	22,723
Mar	**I**	8,955	6,885	8,924	8,924	8,955	647,51	219,448	219,448	17,878	17,878
	II	8,057	6,885	9,518	9,518	8,057	546,20	237,327	237,327	17,576	17,576
Apr	**I**	12,514	6,885	8,924	8,924	12,514	904,85	254,903	254,903	21,437	21,437
	II	9,196	6,885	8,924	8,924	9,196	664,92	276,340	276,340	18,119	18,119
May	**I**	11,045	6,885	8,924	8,924	11,045	798,69	294,459	294,459	19,969	19,969
	II	9,988	6,885	9,518	9,518	9,988	677,12	314,428	314,428	19,507	19,507
Jun	**I**	8,930	6,885	8,924	8,924	8,930	645,73	333,935	333,935	17,854	17,854
	II	9,333	6,885	8,924	8,924	9,333	674,89	351,789	351,789	18,257	18,257
Jul	**I**	8,460	6,885	8,924	8,924	8,460	611,77	370,046	370,046	17,384	17,384
	II	7,998	6,885	9,518	9,518	7,998	542,17	387,430	387,430	17,516	17,516
Aug	**I**	7,928	6,885	8,924	8,924	7,928	573,24	404,946	404,946	16,851	16,851
	II	8,098	6,885	9,518	9,518	8,098	548,98	421,797	421,797	17,617	17,617
Sep	**I**	9,507	6,885	8,924	8,924	9,507	687,42	439,414	439,414	18,430	18,430

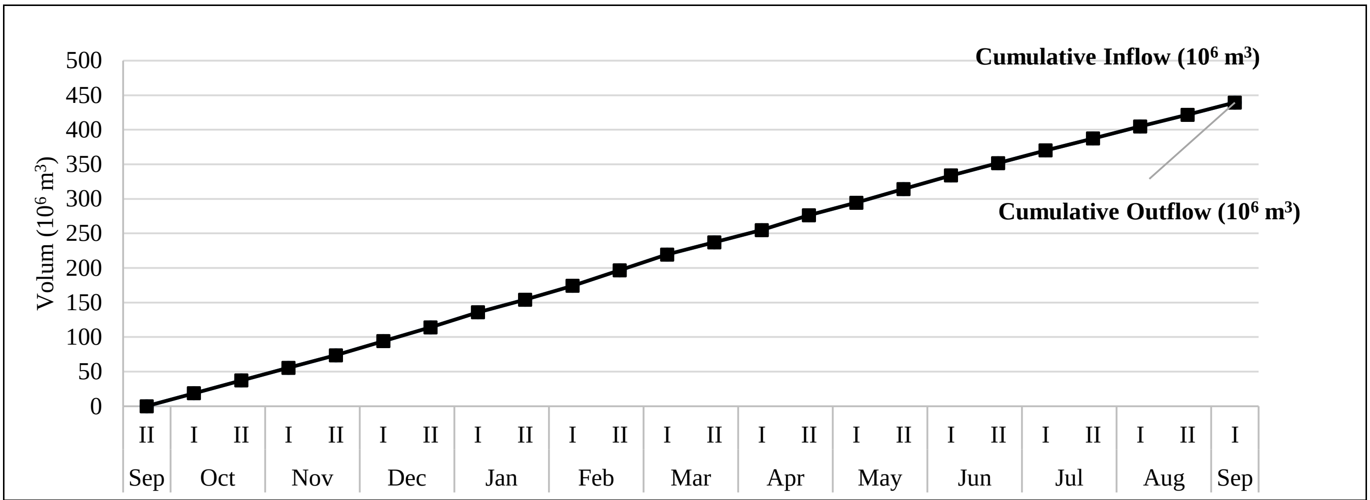

Fig 11: Cumulative Inflow and Outflow Volume Graph for Raw Water, Irrigation, and Mini Hydro Power Plant (MHPP)

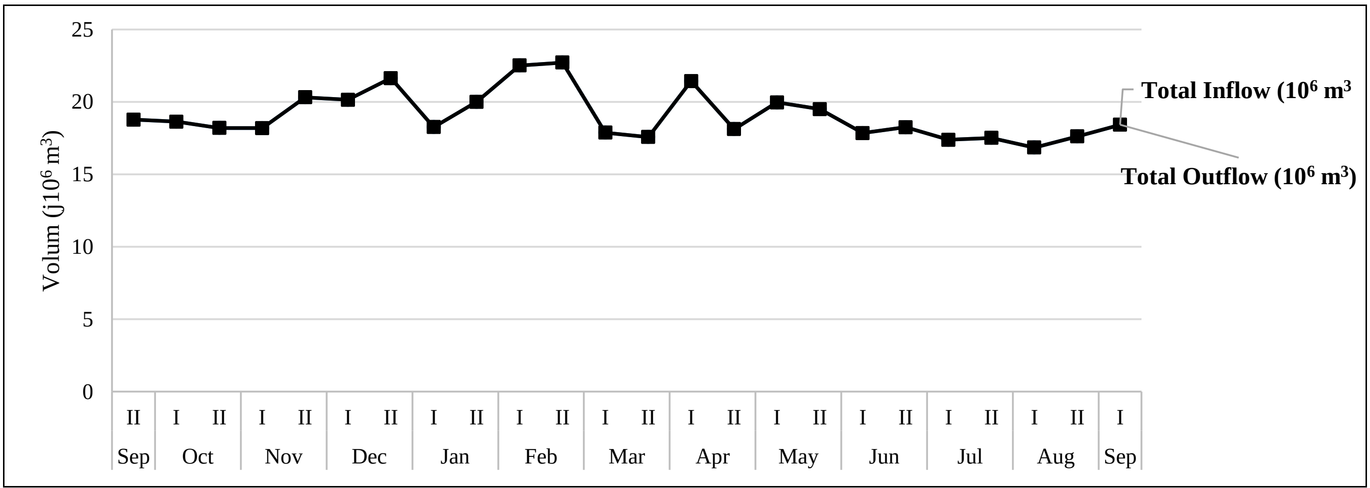

Fig 12: Inflow and Outflow Volume Graph for Raw Water, Irrigation, and Mini Hydro Power Plant

Conclusions and Recommendations

Conclusions

Based on the calculations and analysis conducted in this study, the following conclusions are drawn regarding the application of the Richard Bellman optimization method for Pidekso Reservoir in meeting raw water, irrigation, and Micro-Hydro Power Plant (MHPP) demands:

- The available water discharge for the year 2020 ranges from a minimum of 0.385 m^3/s to a maximum of 4.478 m^3/s.
- Raw water demand in 2020 is estimated at 0.023 m^3/s under average daily conditions, 0.026 m^3/s under peak daily conditions, and 0.040 m^3/s during peak hour demand.
- Irrigation water demand during the 2020 cropping season varies between 0 m^3/s and a maximum of 6.169 m^3/s.
- The MHPP water demand, based on a 95% dependable discharge of 1.152 m^3/s, produces power outputs of 58.707 kW and 48.865 kW, and energy generation of 5,144,273.9 kWh and 401,776.5 kWh for MHPP 1 and MHPP 2 respectively.
- The optimization simulation comprised 24 models varying in planting start time across different months and periods, constrained by water availability and reservoir storage capacity.
- The optimal planting start time identified is September, Period II, with irrigation area expansions of 1,852 ha (first rice season), 6,105 ha (second rice season), and 5,776 ha (dry season crops), alongside improved MHPP utilization with a dependable discharge of 6.911 m^3/s.

Recommendations

For better field application of this study's findings, the following recommendations are proposed:

- Update the input data regularly with the latest and most accurate information before implementation.
- Develop a comprehensive integrated model covering hydrological analysis to reservoir operation planning into a unified software system.
- Conduct further optimization simulations with alternative cropping patterns to refine water resource management.
- Utilize other programming languages or tools to enhance computational efficiency and ease of use in the optimization process.

Acknowledgements

The author gratefully acknowledges the support and data contributions from the Bengawan Solo River Basin Authority (*Balai Besar Sungai Bengawan Solo*) and the Department of Public Works and Spatial Planning – Water Resources Division. Their cooperation was invaluable to the completion of this research.

List of Symbols

A Irrigated area (ha)
bj Regression coefficient between data of month j and *j-1*
c Penman correction factor
D Water demand (m^3/s)
ea Saturated vapor pressure (mbar)
ed Actual vapor pressure (mbar)
ETo Potential evapotranspiration (mm/day)
EV_t Evapotranspiration volume at period t (m^3)
Etc Consumptive water requirement (mm/day)
f(u) Wind influence function
g Gravitational acceleration (m/s^2)
H_{eff} Effective head (m)
IE Irrigation efficiency (%)
IR Irrigation water requirement at paddy field level (mm/day)
k Ratio value between release and demand (Return)
KAI Irrigation water requirement (l/s)
K Reservoir capacity (m^3)
K_d Dead storage capacity (m^3)
n Number of observation years in Harza formula
OF Objective Function, average value of factor k in one cycle
P Percolation (mm/day)
P Electric power (kW)
Pn Projected population at the end of the year (persons)
Po Projected population at the beginning of the year (persons)
PP_t Precipitation volume at period t (m^3)
QF_t Reservoir inflow volume at period t (m^3)
$q_{i+1,j}$ Power generation data for month *j* in year (*i+1*)
R_{80} 80% effective rainfall (mm/day)
r Population growth rate (%)

R Release for water demand (m³/s)
Re Effective rainfall (mm/day)
rj Correlation between previous month (*j-1*) and month *j* data
Rn Net solar radiation (mm/day)
R_t Decision variable (water demand for raw water, irrigation, and micro-hydro power plant at period t) (m³/s)
Sd_j Standard deviation of month *j*
ST Reservoir storage volume (m³)
t Projection year count
ti Normal random variable
W Weighting factor
WLR Water requirement for soil water replacement (mm/day)
η Turbine efficiency (%)
ρ Water density (kg/m³)
palawija: secondary crops or dry-season crops like corn, soybeans, peanuts, mung beans, cassava etc.

References

1. Dabhade P, Regulwar D. Multi-reservoir optimization for maximization of releases for hydropower generation considering environmental flow. Journal of Water Resource and Protection. 2021;13(12):931–944. https://doi.org/10.4236/jwarp.2021.1312050
2. Darmawan A, Nugroho S. Dam-break risk analysis and mitigation at Pidekso Dam, Wonogiri Regency, Central Java, Indonesia [Internet]. ResearchGate; 2023 [cited 2025 May 27]. Available from: https://www.researchgate.net/publication/383319151
3. Doorenbos J, Pruitt WO. Guidelines for predicting crop water requirements. Rome: Food and Agriculture Organization; 1977. (FAO Irrigation and Drainage Paper No. 24).
4. Gunawan A. Hidrologi untuk perencanaan dan evaluasi sumber daya air. Yogyakarta: Andi Offset; c2006.
5. Indonesian Meteorology, Climatology and Geophysics Agency. Rainfall and climatological data, W. Ngancar climatology station. Jakarta: BMKG; c2019.
6. Indriyani A. Pengelolaan sumber daya air dengan metode dynamic programming. Yogyakarta: Universitas Gadjah Mada; c2009.
7. Indriyani L. Estimation of effective rainfall for irrigation planning. Surabaya: Institut Teknologi Sepuluh Nopember; c2009.
8. Ministry of Public Works, Indonesia. KP-01 Irrigation network planning standards: Irrigation planning criteria, planning section of irrigation networks. Jakarta: Ministry of Public Works; 2013.
9. Küster T, Klingler M, Weigt H. Optimal water management in reservoir systems using dynamic programming. Water Resources Management. 2021;35(2):455–470.
10. Linsley RK, Franzini JB, Freyberg DL, Tchobanoglous G. Water-Resources Engineering. 4th ed. New York: McGraw-Hill; c1994.
11. Mays LW. Hydrology and Hydraulic Systems. New York: McGraw-Hill; c1992.
12. Moradi H, Ghassemi H. Optimisation and economic modeling of micro hydropower plant installation in water distribution networks. Journal of Cleaner Production. 2019;239:118053. https://doi.org/10.1016/j.jclepro.2019.118053
13. Morena RP, Tika RN. Perencanaan pembangkit listrik tenaga mikrohidro. Yogyakarta: Graha Ilmu; c2017.
14. Olofsson M, Berntorp K, Lennartsson A. Optimal hydro power scheduling using dynamic programming. In: International Conference on Electric Utility Deregulation and Restructuring and Power Technologies; 2002 Mar 23–26; Beijing, China. IEEE; c2002. p. 241–245.
15. PT. Mettana Engineering. Feasibility Study of Pidekso Dam Project. Jakarta: PT. Mettana Engineering; c2011.
16. Setiyanto B, Adhi BW. Raw water supply system analysis at Randugunting Dam, Blora Regency, Province of Central Java [Internet]. ResearchGate; c2022 [cited 2025 May 27]. Available from: https://www.researchgate.net/publication/361848436
17. Soemarto CD. Hidrologi teknik. Jakarta: Erlangga; c1999.
18. Taha HA. Operations Research: An Introduction. 6th ed. Upper Saddle River (NJ): Prentice Hall; c1996.
19. Triatmodjo B. Hidrologi terapan. Yogyakarta: Beta Offset; c2010.
20. Zhang Y, Li X, Wang Y, Chen J. Optimal water allocation method for joint operation of a reservoir and pumping station under insufficient irrigation. Journal of Hydrology. 2021;598:126456. https://doi.org/10.1016/j.jhydrol.2021.126456