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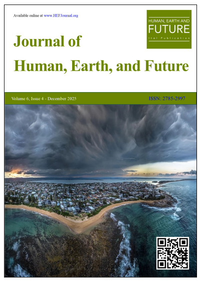

Optimization of Water Resources Management for Widening the Green Area

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Abstract

This study aims to develop an integrated optimization model for water resources management in the Jatigede Reservoir by incorporating the influence of land cover dynamics on hydrological processes. The objectives are to improve the reliability of water allocation for irrigation, raw water supply, and hydropower while simultaneously enhancing ecological sustainability through land use planning. The methodology combines hydrological analysis using rainfall–runoff and dependable flow estimation, spatial assessment of land cover change based on the satellite imagery, and optimization modeling with multi-objective programming. Simulation scenarios were constructed to represent the existing conditions, spatial planning policies (RTRW), and optimized land cover management. The findings reveal that incorporating land cover factors into the optimization model increases water supply reliability by 5–10% and reduces the risk of sedimentation, thereby extending the effective lifetime of the reservoir. Moreover, the optimization scenario demonstrates that expansion of dry land forest cover contributes positively to water regulation, although it requires trade-offs with plantation forest areas. The novelty of this research lies in bridging the gap between technical water allocation models and spatial ecological considerations, offering a more comprehensive decision-support tool. This improvement provides valuable insights for policymakers in integrating reservoir operation strategies with land use planning to achieve sustainable water resources management.

Keywords: Optimization; Jatigede Reservoir; Water Resources; Management.

1. Introduction

Reservoirs are multifunctional infrastructures that simultaneously supply irrigation and raw water, generate hydropower, and provide flood buffering [1-3]; yet their long-term performance strongly depends on watershed condition and land-use dynamics [4, 5]. In the Jatigede/Cimanuk system, heavy sedimentation, fluctuating inflows, and upstream land-use conversion have been identified as key threats to reservoir services and lifetime, making integrated management urgent. The present manuscript documents and optimization approach for Jatigede that explicitly links upstream land-cover allocation with reservoir operation and sectorial water benefits.

Previous research has advanced reservoir operation and irrigation allocation models [6, 7] using a range of deterministic and stochastic optimization methods (linear programming [8, 9], dynamic programming, and chance-constrained models), and some studies applied the production functions tailored to crop water–yield relations [10, 11] (e.g., the sine-product formulation). However, while optimization studies improve sectorial allocation, separate

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streams of literature demonstrate that land-use/land-cover (LULC) change has first-order effects on runoff [12], sediment yield, and inflow reliability—effects that will alter the validity of operational rules if ignored. Empirical and modeling studies therefore argue for embedding dynamic LULC into hydrological assessments [13] to capture long-term changes in inflow regimes. The sine-product model remains a commonly used production function to link applied irrigation water with crop yield in optimization frameworks.

Recent methodological advances also open new possibilities for reservoir management: deep reinforcement learning and transformer-based DRL have been applied to multi-reservoir operation problems to handle dimensionality and sequence decision-making under uncertainty, and hybrid physics–AI frameworks have improved the representation of internal hydrological fluxes by combining process models and neural corrections. These developments indicate the feasible pathways to combine the process understanding (hydrology, sediment) with data-driven predictive skill for operation and planning.

Despite these distinct advances, a persistent literature gap remains: relatively few operational optimization studies incorporate spatially explicit LULC scenarios (derived from satellite classification and/or policy scenarios) directly into the reservoir operation optimization loop, and even fewer translate optimization outputs into spatial planning instruments (e.g., RDTR/RTRW). As a result, many optimization solutions risk being technically optimal under historical hydrology but suboptimal or infeasible under plausible land-use transitions. This paper addresses that gap by integrating satellite-based land-cover reallocation, stochastic rainfall–runoff representation, crop production (sine-product), and multi-objective reservoir optimization—then translating results into spatially explicit recommendations (area maps, C-composite changes, and economic valuation) intended to support spatial planning and policy.

Contributions of this study are threefold. First, it demonstrates an operational workflow that links land-cover change scenarios to the inflow generation and reservoir optimization, allowing the assessment of trade-offs between ecological restoration (widening green area) and sectoral benefits [14, 15] (irrigation, raw water, PLTA/hydroelectric power). Second, it provides quantitative outcomes for Jatigede (e.g., reduction of composite runoff coefficient from 0.13 to 0.10 under the optimized land-use allocation and an associated increase in total function value), which can be translated into RDTR guidance for upstream zoning. Third, it situates the approach within contemporary methodological advances (stochastic simulation; possible future hybrid ML/process enrichments), clarifying where the future improvements (e.g., DRL for adaptive operation, hybrid physics–AI flux corrections) can be integrated.

The Jatigede Dam in West Java is a national strategic infrastructure that functions as an irrigation water supply, raw water source, hydroelectric power plant (PLTA), and flood control system in the Cimanuk River region [16]. Since its full operation began in 2015, the dam has faced serious problems, including increasing sedimentation, declining water quality, and unstable discharge fluctuations. A number of studies show that the conversion of forest areas into agricultural land and residential zones in the upstream Cimanuk watershed has increased surface runoff and erosion, thereby accelerating reservoir sedimentation [17, 18]. Other studies emphasize the importance of mathematically based water management optimization to support the efficiency of irrigation and hydropower water allocation. However, most existing research remains limited to technical–hydrological aspects of the reservoir and does not integrate land cover factors as strategic variables in water resources management optimization.

This research gap highlights the necessity of an integrated approach that links land-use dynamics with reservoir operation optimization models. By utilizing satellite imagery, spatial analysis, and hydrological simulation, the effects of land cover changes on dependable discharge can be modeled more accurately. The integration of spatial and ecological factors makes it possible to formulate land conservation strategies that are directly related to the sustainability of reservoir operations. Therefore, this study proposes the development of an optimized water resources management model for the Jatigede Dam that incorporates land cover aspects, with the aim of increasing water allocation efficiency, extending the technical lifetime of the reservoir, and supporting conservation-based spatial planning (RTRW).

The structure of this paper is organized as follows: Section 2 describes the study area and the collected data for the analysis. Section 2 explains the methodology applied, including hydrological analysis, land cover change assessment, and the formulation of the optimization model. Section 3 presents the results that are obtained from the simulation and optimization scenarios and provides a discussion that compares the findings with previous studies and elaborates on the ecological and policy implications. Finally, Section 4 concludes the study with key findings and recommendations for sustainable water resources management and spatial planning.

2. Materials and Methods

Xu et al. [19] suggested the use of Deep Reinforcement Learning (DRL) to optimize the operation of parallel dams under discharge uncertainty. This method is highly relevant for increasing the flexibility and efficiency of traditional reservoir operation models. Rivera-Fernandez et al. [20] analyzed land cover changes from 1990 to 2024 and applied hydrological modeling (SWAT) to assess the impacts of land-use change on river discharge under future climate scenarios. Their results are well suited for comparison in terms of spatial methodology and research context. Abdi et al. [21] introduced a hybrid bRNN–CNN–GRU model for predicting reservoir inflow patterns. This deep learning architecture combination is effective in improving the accuracy of dependable discharge estimation in reservoir operation contexts. Huynh et al. [3] demonstrated a hybrid approach that integrates physical models with machine learning, including the regionalization of neural networks for high-resolution flash flood modeling. This research is highly relevant to the integration of spatial data with optimization models.

2.1. Theoretical Approach

2.1.1. Theory of Water Resources Management

The water resources management is based on the principle of Integrated Water Resources Management (IWRM) that emphasizes the integration between the aspects of hydrology, ecology, social, and economy. In the context of Jatigede Dam, this research refers to the theory that reservoir management is not only dependent on the hydrology parameters (inflow, storage volume, and irrigation requirement), but it is also dependent on the ecology parameter of water catchment (land cover, erosion, and sedimentation). Theoretically, it confirms that the function of upstream ecology determines the sustainability of upstream technical function.

2.1.2. Theory of Optimization Model

The optimization model employed in this study is based on operations research (OR) theory, primarily Linear Programming (LP) and Multi-Objective Linear Programming, which are used to determine optimal water allocation among various sectors (raw water supply, irrigation, and hydroelectric power) while considering water resource constraints. Multi-objective optimization is applied to resolve trade-offs among competing objectives (e.g., irrigation supply versus electrical energy generation versus water conservation). Based on this theoretical framework, the study formulates the reservoir operation system as a mathematical optimization problem that incorporates spatial constraints.

2.1.3. Theory of Hydrology and Dependable Discharge

The theoretical basis of dependable discharge analysis is grounded in reliability-based streamflow analysis. Dependable discharge is analyzed using the Weibull method to determine water availability at a specified reliability level. This approach emphasizes that reservoir operation planning should be based on discharge reliability rather than average discharge, making it more suitable for risk management applications.

2.1.4. Theory of Conservation and Land Cover

The research approach is also founded on soil and water conservation theory, which emphasizes that vegetation cover functions as a natural buffer by reducing surface runoff, increasing infiltration, and suppressing sedimentation. Therefore, the optimization model should not be limited to operational and technical aspects alone but must also integrate the ecological functions of the upstream area.

2.1.5. System Theory

All research schemes in this study are based on systems theory, which emphasizes the interaction between inputs, processes, and outputs. The inputs include rainfall, land cover, and water demand data; the processes consist of hydrological simulation and reservoir optimization models; and the outputs are water allocation strategies and recommendations for RTRW policy. This system is dynamic and adaptive; therefore, integration with spatial technologies (GIS and satellite imagery) strengthens the validity of the results.

2.1.6. AI/Deep Learning

Although this research is based on classical optimization approaches, it can theoretically be expanded by incorporating machine learning and deep learning techniques, as suggested by Huynh et al. [3], such as Long Short-Term Memory (LSTM) for hydrological time-series prediction, Convolutional Neural Networks (CNN) for satellite imagery–based land cover classification, and Deep Reinforcement Learning for adaptive reservoir operation optimization. Theoretically, these methods expand the optimization framework toward a more robust predictive and adaptive approach.

2.2. Research Location

The Cimanuk River originates at the foothills of Mount Papandayan in Garut Regency at an elevation of approximately +1,200 m above sea level. It flows northward for about 180 km and discharges into the Java Sea in Indramayu Regency. The river flow is supplied by the Cimanuk Watershed. Land use within the Cimanuk Watershed consists of: (1) agricultural land covering approximately 2,736 km^2 or 66% of the watershed area, comprising 41% rice fields, 8% plantations, and 17% dry farming; (2) forest and shrubland areas covering 1,044 km^2 or 29% of the watershed; and (3) residential, commercial, and industrial areas covering approximately 180 km^2 or 5% of the watershed. In 2006, the critical land area within the Cimanuk Watershed was recorded at approximately 178,794 ha, of which 46,129 ha were forested and the remainder located outside forest areas. The largest proportion of critical land was found in Garut Regency, covering approximately 90,000 ha.

The Jatigede Reservoir is located in West Java Province and has a watershed area of approximately 3,740.764 km², spanning the regencies of Garut, Sumedang, Majalengka, Cirebon, Indramayu, and Brebes. The upstream area of the Cimanuk River is located on Mount Papandayan, while its estuary is in the Java Sea in Indramayu Regency. Figure 1 presents the map of the Cimanuk Watershed.

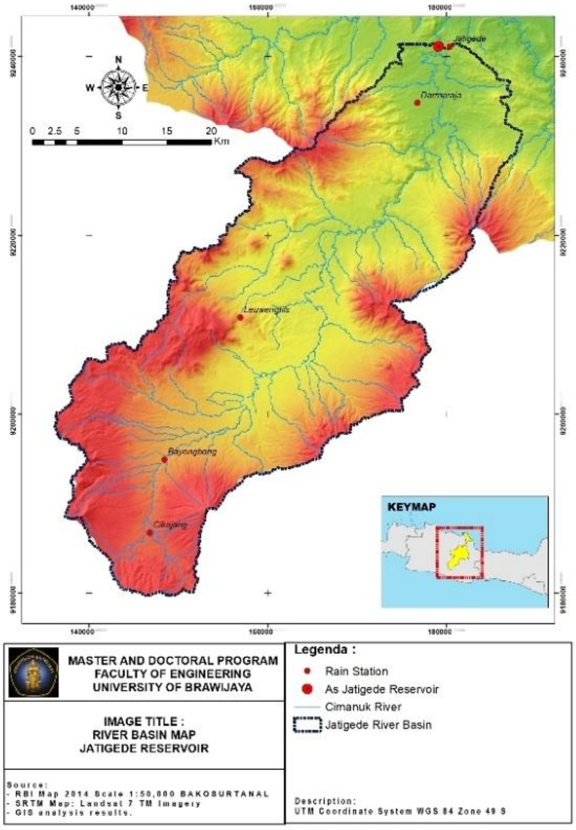

Figure 1. Map of Cimanuk Watershed

2.3. Methodology

The methodology of this research consists of as follows (Flow chart of study is presented in Figure 2):

a) Data collecting that intends to carry out the data collecting in field by seeing the constraints that becomes as the determination of the test-variables. This research carries out the test for 3 variables that are raw water, irrigation, and conservation.

b) Analyse Existing Conditions

   The analysis of existing reservoir management conditions aims to:

   a. Identify differences between actual operations and optimal/ideal operations;

   b. Evaluate the reservoir's success rate in meeting water demand;

   c. Assess the impact of climate change, land conversion, and sedimentation on reservoir capacity;

   d. Provide a basis for planning future management optimization. Validation and verification are used for evaluating the simulation result to prove the truth of a data and to agree the truth (validation) from the result that is obtained.

c) Building a model

   A reservoir management and operation optimization model are a mathematical representation designed to determine the best water management strategy within a reservoir system to achieve the specific objectives (e.g., meeting irrigation, drinking water, electricity, and flood control needs) while taking into account technical, hydrological, and environmental constraints.

d) Integration of Land Cover in Optimization Models

   In reservoir planning and operational management, optimization models generally consider hydrological parameters such as inflow, water demand, storage capacity, and evaporation. However, in practice, land cover in a watershed has a significant influence on the runoff patterns into the reservoir.

Changes in land cover, such as deforestation, urban expansion, and the conversion of land to agricultural use, can significantly increase surface runoff, reduce soil infiltration, and intensify erosion and sedimentation processes. These impacts ultimately decrease reservoir efficiency and shorten its operational lifespan. Therefore, integrating land cover characteristics into reservoir management optimization models enhances the accuracy of inflow estimation and supports more responsive and adaptive decision-making to watershed environmental changes.

2.4. Optimization Model

Optimization is closely related to maximization but is constrained by limitations. To optimize is essentially to maximize an objective under limited resources. However, optimization in water management can be categorized into two types: optimization conducted before the water infrastructure is completed and optimization performed after the water infrastructure has been constructed.

System analysis is a method used to study and analyze the various aspects of a system. Water resources system analysis aims to modify flow behavior by utilizing existing constraints and natural conditions. The application of system analysis methods is expected to enable reliable and optimal water resource management in relation to existing infrastructure and facilities [22]. A system consists of a collection of functional components that are interconnected in various ways, requiring inputs and producing outputs. In this context, simulation applies the water balance law for reservoirs or storage systems, which is expressed as follows:

$$S_{t+1} = S_t + I - O \quad (1)$$

where, S_{t+}= Storage at the end period of t; St= storage at the beginning period; I= inflow discharge during t period; and O= outflow discharge during t period.

A. The Model of Sine-Product

The objective function of the optimization model for a reservoir operation that supplies irrigation demand is to maximize the average monetary annual production. Basically, the production in the irrigation area is the crop yield. However, the relationship between the crop yield production and irrigation water delivery has been presented by English et al. [23], and it has been differentiated in the mathematical model by Soetopo [24, 25] as follows:

$$Yri = [\sin \{([AWri - a \sin (AWri \cdot 2\pi)] \cdot [1 - b \sin (AWri\ \pi)]c)\ d\ \pi/2\}]\ e \quad (2)$$

where, Yri = the representation of Yr (crop production/yield) at each period/stage; AWri = the applied water at the corresponding period/stage.

The behaviour of crop productivity can be simulated by the mathematical model of Sine-Product. However, the Sine–Product method can produce the crop production/ yield at each period by the input is applied water at corresponding period.

The base concept of Sine-Product is discharge and water requirement often show the seasonal pattern (up-down every year). It is represented as the sinusoidal function as follows:

$$Q(t) = A\sin(\omega t + \phi) + C \quad (3)$$

where, A = amplitude (fluctuation), ω = frequency of annual cycle, φ = phase, C = annual mean.

The objectives are as follows: (1) to simplify the seasonal patterns of inflow and demand; and (2) to control water release so that the deviation between supply and demand is minimized, while avoiding both shortages and flooding. The calibration of the sinusoidal function is conducted as follows: (1) the parameters A, ω, φ, and C are determined through time series analysis of historical discharge data and irrigation water requirements; and (2) irrigation water demand is analyzed using a multiplication–sinus model, for example, to estimate harvest benefits and actual irrigation requirements. The validation of the sinus method is carried out as follows: (1) the results of the sinus method are verified using existing discharge data, the RTRW, and optimal conditions; and (2) the inflow discharge graph produced by the sinus method is compared with observed data and shows a consistent pattern.

B. Model of Stochastic Simulation

The main assumptions are that inflow discharge, water demand (irrigation, hydroelectric power, and domestic use), and losses (evaporation and seepage) are modeled as random variables, with discharge probabilities based on historical data from the last 10 years. Climate variability (wet, normal, and dry years) is represented through probabilistic scenarios, namely Q_{80} (dry), Q_{50} (normal), and Q_{20} (wet).

Calibration is performed using hydrological data from 2013 to 2022, including rainfall, river discharge, and evaporation. In addition, land cover coefficient (C) values are fitted based on the 2022 RTRW and satellite imagery to reflect actual land conditions. Validation is conducted using consistency tests for rainfall data, including outlier tests, RAPS, and double mass curve analysis. The simulated discharge results are then compared with observed data from hydrological stations, yielding an R^2 value greater than 0.95, which indicates a high level of agreement.

The advantages of this approach are as follows: (1) stochastic simulation is robust to uncertainties arising from climate variability and land-use change; (2) the sinus product method is simple, easy to calibrate, and effective in illustrating seasonal patterns with limited data; and (3) both approaches can be integrated with numerical optimization techniques (e.g., LINDO Solver, Genetic Algorithms, and Linear Programming) to identify optimal solutions.

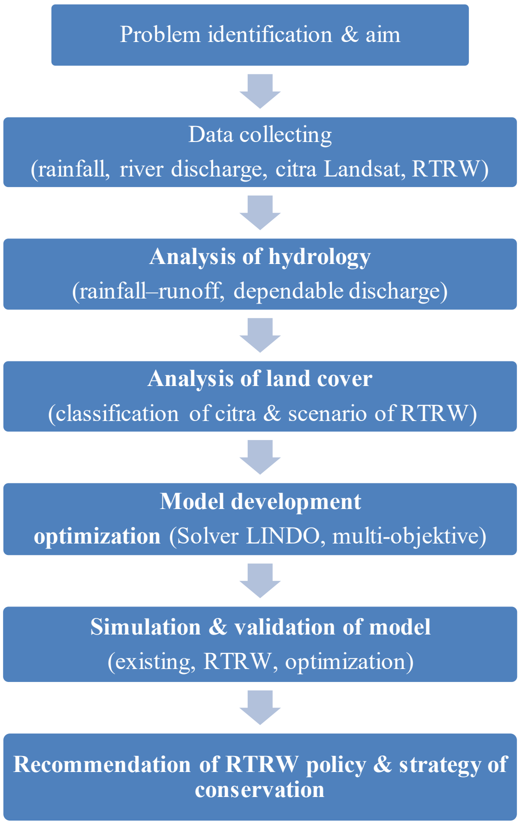

Figure 2. Flowchart of the Study

3. Results and Discussion

This research aims to optimize inflow discharge, primarily in relation to land-use patterns in the Jatigede Watershed, so that policy recommendations related to land-use change in the downstream area of the reservoir can be proposed [26]. Table 1 presents the optimization guidelines for land-use changes in the downstream area of the Jatigede Reservoir. Figure 3 shows a map of land use of existing and optimized conditions.

Table 1. Optimization Instruction for Land Use Change in the Upstream of Jatigede Reservoir

No.	Land Use	Area (km^2)	
		Existing	Optimization
1	Water body	34.70	34.70
2	Bush	9.41	1.52
3	Primary dry land forest	4.83	228.22
4	Secondary dry land forest	92.99	468.25
5	Vegetation forest	204.39	109.39
6	Residential	90.31	102.20
7	Plantation	8.58	8.58
8	Dry land agriculture	538.74	138.74
9	Mixed dry land agriculture	295.04	195.04
10	Ricefield	170.47	171.05
11	Opened land	15.76	7.52
	Total	**1,465.21**	**1,465.21**

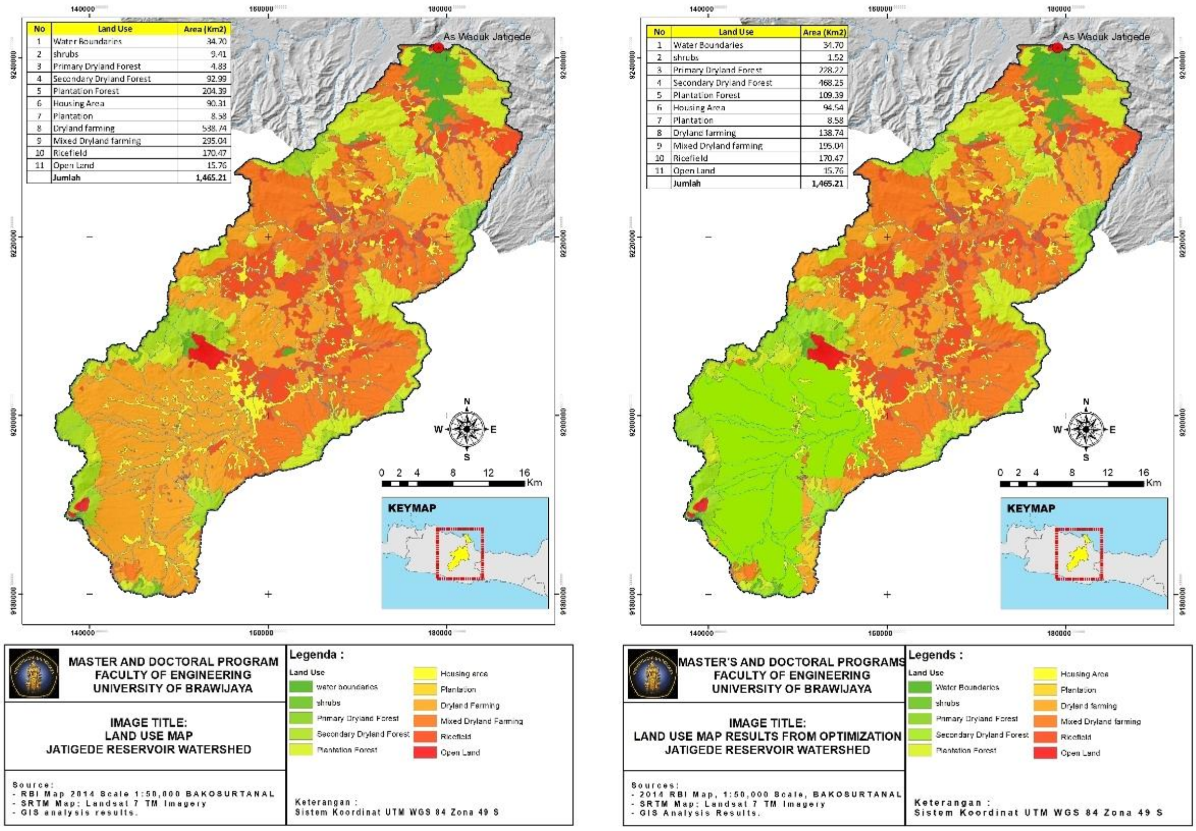

Figure 3. Land use map of existing and optimized conditions

Land-use changes influence the exposed surface parameter (m) [7, 8] in the analysis using the F.J. Mock method. Under existing conditions, the value of parameter m is 38.5%, while under the optimized condition it is reduced to 21.5%, as illustrated in Figure 4.

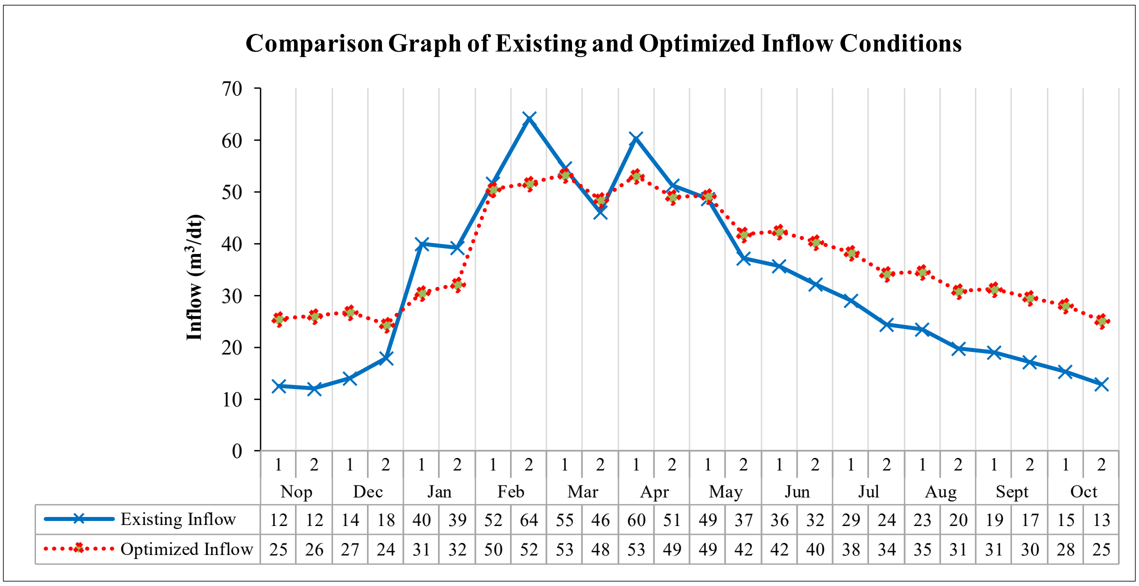

Figure 4. Curve Comparison of Half Monthly Flow Discharge between Existing and Optimization Conditions

3.1. Reservoir Simulation on the Optimization Condition and Component Analysis of Each Outflow

Based on the availability of discharge data and water demand data, simulations related to the reservoir operation pattern were conducted. This research models the operation pattern of the Jatigede Reservoir by balancing storage, dependable discharge, and demand discharge. Table 2 presents the simulation results of the Jatigede Reservoir under post-optimization conditions. The post-optimization analysis results for each component are presented as follows: irrigation in Table 3, hydro-electric power (PLTA) in Table 4, and raw water supply in Table 5.

Table 2. Simulation Result in Jatigede Reservoir for Optimization Condition

No of Period	Month	Period	Number of days	Active Storage in end Period	Inflow of reservoir		Initial Total Storage	Volume of Reservoir Release	Raw water demand		Volume of Irrigation Release	Volume of Hydro power Release
				(million m³)	(m³/s)	(million m³)	(million m³)	(million m³)	(m³/s)	(million m³)	(million m³)	(million m³)
1	Nov	1	15	64.0000	25.40	32.9188	774.2000	43.119	3.50	4.5360	38.583	43.119
2		2	15	58.3788	26.10	33.8238		39.445	3.50	4.5360	34.909	39.445
3	Dec	1	15	52.2594	26.86	34.8156		40.935	3.50	4.5360	36.399	40.935
4		2	16	58.3909	24.40	33.7298		27.598	3.50	4.8384	22.760	27.598
5	Jan	1	15	58.2512	30.50	39.5334		39.673	3.50	4.5360	35.137	39.673
6		2	16	60.3781	32.18	44.4892		42.362	3.50	4.8384	37.524	42.362
7	Feb	1	15	89.6182	50.43	65.3570		36.117	3.50	4.5360	31.581	36.117
8		2	13	130.1227	51.65	58.0083		17.504	3.50	3.9312	13.573	17.504
9	Mar	1	15	177.0652	53.29	69.0693		22.127	3.50	4.5360	17.591	22.127
10		2	16	218.4000	48.41	66.9280		25.593	3.50	4.8384	20.755	25.593
11	Apr	1	15	280.0000	53.03	68.7239		7.124	3.50	4.5360	2.588	7.124
12		2	15	280.0000	49.09	63.6163		63.616	3.50	4.5360	59.080	63.616
13	May	1	15	240.0000	49.24	63.8126		103.813	3.50	4.5360	99.277	103.813
14		2	16	188.0000	41.87	57.8742		109.874	3.50	4.8384	105.036	109.874
15	Jun	1	15	121.0000	42.42	54.9805		121.980	3.50	4.5360	117.444	121.980
16		2	15	120.0000	40.30	52.2314		53.231	3.50	4.5360	48.695	53.231
17	Jul	1	15	120.0000	38.29	49.6199		49.620	3.50	4.5360	45.084	49.620
18		2	16	120.0000	34.10	47.1389		47.139	3.50	4.8384	42.300	47.139
19	Aug	1	15	110.0000	34.55	44.7819		54.782	3.50	4.5360	50.246	54.782
20		2	16	90.0000	30.77	42.5428		62.543	3.50	4.8384	57.704	62.543
21	Sep	1	15	80.0000	31.18	40.4157		50.416	3.50	4.5360	45.880	50.416
22		2	15	70.0000	29.63	38.3949		48.395	3.50	4.5360	43.859	48.395
23	Oct	1	15	70.0000	28.14	36.4752		36.475	3.50	4.5360	31.939	36.475
24		2	16	74.2000	25.07	34.6514		30.451	3.50	4.8384	25.613	30.451

Table 3. Analysis of Irrigation Water Component in the Optimization Condition

Analysis of irrigation component													
Cropping season		Irrigation demand		Irrigation	MODEL OF SINUS-MULTIPLICATION							Objective function of irrigation	
				Release	AWri	Component				Yri	Yr	Max harvest	Real harvest
On-	Period	(m³/dt)	(million m³)	(million m³)	(0 ~ 1)	Formulation of sinus-multiplication				(0 ~ 1)	(0 ~ 1)	(million Rp*)	(million Rp*)
CP1	1	19.504	25.2772	38.583	1.000	0.00000	0.00000	1.00000	1.00000	1.00000	1.00000	3,689,280	3,689,280.00
	2	26.936	34.9091	34.909	1.000	0.00000	0.00000	1.00000	1.00000	1.00000			
	3	27.264	35.3341	36.399	1.000	0.00000	0.00000	1.00000	1.00000	1.00000			
	4	16.464	22.7598	22.760	1.000	0.00000	0.00000	1.00000	1.00000	1.00000			
	5	27.112	35.1372	35.137	1.000	0.00000	0.00000	1.00000	1.00000	1.00000			
	6	27.144	37.5239	37.524	1.000	0.00000	0.00000	1.00000	1.00000	1.00000			
	7	24.368	31.5809	31.581	1.000	0.00000	0.00000	1.00000	1.00000	1.00000			
	8	1.792	2.0128	13.573	1.000	0.00000	0.00000	1.00000	1.00000	1.00000			
CP2	1	9.392	12.1720	17.591	1.000	0.00000	0.00000	1.00000	1.00000	1.00000	0.98453	3,689,280	3,632,218.09
	2	6.856	9.4777	20.755	1.000	0.00000	0.00000	1.00000	1.00000	1.00000			
	3	1.232	1.5967	2.588	1.000	0.00000	0.00000	1.00000	1.00000	1.00000			
	4	18.608	24.1160	59.080	1.000	0.00000	0.00000	1.00000	1.00000	1.00000			
	5	63.512	82.3116	99.277	1.000	0.00000	0.00000	1.00000	1.00000	1.00000			
	6	60.776	84.0167	105.036	1.000	0.00000	0.00000	1.00000	1.00000	1.00000			
	7	69.816	90.4815	117.444	1.000	0.00000	0.00000	1.00000	1.00000	1.00000			
	8	58.776	76.1737	48.695	0.639	-0.76758	-0.09166	0.78164	0.42162	0.98453			
CP3	1	56.84	73.6646	45.084	0.612	-0.64713	-0.07728	0.77370	0.38864	0.98163	0.87534	2,635,200	2,306,694.69
	2	61.368	84.8351	42.300	0.499	0.00867	0.00104	0.75893	0.26873	0.96583			
	3	41.768	54.1313	50.246	0.928	-0.43586	-0.05205	0.94610	0.86617	0.99954			
	4	80.768	111.6537	57.704	0.517	-0.10546	-0.01259	0.75926	0.28620	0.96882			
	5	67.088	86.9460	45.880	0.528	-0.17304	-0.02066	0.75984	0.29694	0.97051			
	6	54.688	70.8756	43.859	0.619	-0.67910	-0.08110	0.77553	0.39672	0.98238			
	7	13.168	17.0657	31.939	1.000	0.00000	0.00000	1.00000	1.00000	1.00000			
	8	11.608	16.0469	25.613	1.000	0.00000	0.00000	1.00000	1.00000	1.00000			

* 1000Rp = 0.060 USD (20 November 2025)

The optimization results for the irrigation component, as presented in Table 3, indicate that the harvest yield for CP 1 (MT 1) is 3,689,280 million rupiah, for CP 2 (MT 2) is 3,689,280 million rupiah, and for CP 3 (MT 3) is 2,625,200 million rupiah.

Table 4. Analysis of Hydro Power Component in the Optimization Condition

Analysis of Hydro Power Component													
No of Period	Month	Period	Number of days	End Total Storage	Elevation of End MAW	End head	Average Head1	Hydro power Release	Continue discharge	Used discharge	Generated power	Generated energy	Value of Hydro power generated
				(million m³)	(m)	(m)	(million m³)	(million m³)	(m³/dt)	(m³/dt)	(GW)	(GWh)	(million Rp*)
1	Nov	1	15	764.0000	255.79	165.79	165.904	43.119	33.271	33.271	0.046	16.553	16,552.59
2		2	15	758.3788	255.67	165.67	165.730	39.445	30.436	30.436	0.042	15.126	15,126.42
3	Dec	1	15	752.2594	255.53	165.53	165.600	40.935	31.586	31.586	0.044	15.685	15,685.42
4		2	16	758.3909	255.67	165.67	165.600	27.598	19.964	19.964	0.028	10.575	10,575.07
5	Jan	1	15	758.2512	255.66	165.66	165.666	39.673	30.612	30.612	0.042	15.208	15,208.06
6		2	16	760.3781	255.71	165.71	165.689	42.362	30.644	30.644	0.042	16.241	16,241.05
7	Feb	1	15	789.6182	256.35	166.35	166.030	36.117	27.868	27.868	0.039	13.875	13,875.22
8		2	13	830.1227	257.19	167.19	166.770	17.504	15.584	15.584	0.022	6.754	6,754.47
9	Ma	1	15	877.0652	258.12	168.12	167.656	22.127	17.073	17.073	0.024	8.584	8,583.84
10		2	16	918.4000	258.90	168.90	168.510	25.593	18.514	18.514	0.026	9.979	9,979.12
11	Apr	1	15	980.0000	260.00	170.00	169.450	7.124	5.497	5.497	0.008	2.793	2,793.19
12		2	15	980.0000	260.00	170.00	170.000	63.616	49.087	49.087	0.070	25.024	25,024.16
13	May	1	15	940.0000	259.29	169.29	169.647	103.813	80.102	73.000	0.103	37.138	37,137.77
14		2	16	888.0000	258.33	168.33	168.812	109.874	79.481	73.000	0.103	39.419	39,418.68
15	Jun	1	15	821.0000	257.01	167.01	167.668	121.980	94.121	73.000	0.102	36.705	36,704.53
16		2	15	820.0000	256.98	166.98	166.995	53.231	41.074	41.074	0.057	20.569	20,569.03
17	Jul	1	15	820.0000	256.98	166.98	166.985	49.620	38.287	38.287	0.053	19.172	19,172.31
18		2	16	820.0000	256.98	166.98	166.985	47.139	34.099	34.099	0.047	18.214	18,213.69
19	Aug	1	15	810.0000	256.78	166.78	166.881	54.782	42.270	42.270	0.059	21.154	21,153.72
20		2	16	790.0000	256.36	166.36	166.567	62.543	45.242	45.242	0.063	24.105	24,105.07
21	Sep	1	15	780.0000	256.14	166.14	166.249	50.416	38.901	38.901	0.054	19.394	19,393.95
22		2	15	770.0000	255.92	165.92	166.033	48.395	37.342	37.342	0.052	18.592	18,592.40
23	Oct	1	15	770.0000	255.92	165.92	165.924	36.475	28.144	28.144	0.039	14.004	14,003.89
24		2	16	774.2000	256.02	166.02	165.970	30.451	22.028	22.028	0.030	11.694	11,694.42

* 1000Rp = 0.060 USD (20 November 2025)

Parameter of	**p**	0.0632
Capacity	**c**	168.5425
Curve	**d**	30.3454
Max head [m]		170.00
Max MAW elevation [m]		260.00

Discharge of hydro power [m³/s]	73
Efficiency of hydro power [%]	85
Output of hydro power [Rp/kWh]	1000

Hydro power energy In a year
[million Rp]
436,558.07

The optimization results for the PLTA component, as presented in Table 5, show that the PLTA discharge is 73 m³/s with an efficiency of 85%. With an output value of Rp. 1,000 per kWh, the annual energy revenue generated by PLTA is 493,523.40 million rupiah.

Table 5. Analysis of Raw Water Component in the Optimization Condition

Raw Water Components Calculation						
No of. Period	Month	Period	Number of day	Raw water Release	Raw water Release	Value of Raw water
				(million m³)	(m³/s)	(million Rp*)
1	Nov	1	15	4.5360	3.500	195.37
2		2	15	4.5360	3.500	195.37
3	Dec	1	15	4.5360	3.500	195.37
4		2	16	4.8384	3.500	208.39
5	Jan	1	15	4.5360	3.500	195.37
6		2	16	4.8384	3.500	208.39
7	Feb	1	15	4.5360	3.500	195.37
8		2	13	3.9312	3.500	169.32
9	Mar	1	15	4.5360	3.500	195.37
10		2	16	4.8384	3.500	208.39
11	Apr	1	15	4.5360	3.500	195.37
12		2	15	4.5360	3.500	195.37
13	May	1	15	4.5360	3.500	195.37
14		2	16	4.8384	3.500	208.39
15	Jun	1	15	4.5360	3.500	195.37
16		2	15	4.5360	3.500	195.37
17	Jul	1	15	4.5360	3.500	195.37
18		2	16	4.8384	3.500	208.39
19	Aug	1	15	4.5360	3.500	195.37
20		2	16	4.8384	3.500	208.39
21	Sep	1	15	4.5360	3.500	195.37
22		2	15	4.5360	3.500	195.37
23	Oct	1	15	4.5360	3.500	195.37
24		2	16	4.8384	3.500	208.39

* 1000Rp = 0.060 USD (20 November 2025)

Table 6. Comparison of Function Value between Existing and Optimization Conditions

Condition	Hydro Power	Raw Water	Irrigation	Benefit Total
	(Million Rp*)	(Million Rp*)	(Million Rp*)	(Million Rp*)
Existing	392,654.11	4,753.89	8,892,469.63	9,289,877.64
Optimization	436,558.07	4,753.89	9,628,192.79	10,069,504.75

* 1000Rp = 0.060 USD (20 November 2025)

Based on the results of the function analysis (Table 6), it is evident that under the optimized condition, there is an increase in the dam's function value from Rp. 9,289,877,640,000 to Rp. 10,069,504,750,000, representing an increase of Rp. 779,627,110,000. The value of approximately 780 billion rupiah reflects the potential gross benefit; however, the costs associated with conservation implementation have not yet been calculated. To obtain more comprehensive results, it is necessary to conduct an economic feasibility analysis (BCR/NPV) that considers reforestation costs, community incentives, and land-use change costs. Table 7 presents a comparison of the run-off coefficient (C) between the existing and optimized conditions.

Table 7. Comparison of Run-off Coefficient between Existing and Optimization Conditions

No.	Land use	Area (km^2)		Value of C	C composite	
		Existing	Optimization		Existing	Optimization
1	Water body	34.70	34.70	0.05	1.74	1.74
2	Bush	9.41	1.52	0.07	0.66	0.11
3	Primary dry land forest	4.83	228.22	0.03	0.14	6.85
4	Secondary dry land forest	92.99	468.25	0.03	2.79	14.05
5	Vegetation forest	204.39	109.39	0.05	10.22	5.47
6	Residential	90.31	102.20	0.6	54.19	61.32
7	Plantation	8.58	8.58	0.4	3.43	3.43
8	Dry land agriculture	538.74	138.74	0.1	53.87	13.87
9	Mixed dry land agriculture	295.04	195.04	0.1	29.50	19.50
10	Ricefield	170.47	171.05	0.15	25.57	25.66
11	Opened land	15.76	7.52	0.2	3.15	1.50
	Total	**1,465.21**	**1,465.21**		**0.13**	**0.10**

As shown in Table 7, the run-off coefficient (C) decreases from 0.13 to 0.10 under the optimized condition. This result indicates that land-use management in the upstream area should focus on increasing primary and secondary dryland forest areas while reducing dryland agricultural land.

3.2. Validation Model

The optimization model is validated by comparing the simulation result of inflow discharge and outflow discharge (raw water, irrigation, and hydro-electric power) to the observation data from 2013 until 2022. The validation is carried out as follows:

1. The comparison of inflow discharge is as the model result and field data on the control point of Jatigede Dam. The statistical indicators that can be used is Nash-Sutcliffe Efficiency (NSE), Root Mean Square Error (RMSE), and Mean Absolute Percentage Error (MAPE). The results show that the NSE is > 0.70 (good category) with the average MAPE is about 8-12% that is still in the tolerance limit for watershed scale hydrology model
2. The validation of reservoir storage and outflow sectors: discharge of irrigation water supply, raw water, and hydro-electric power as the simulation result is compared with the reservoir operational record from the River Region Big Institution (BBWS) of Cimanuk-Cisanggarung. The difference of irrigation supply average is only about ±**7%**, and the hydro-electric power energy is about ±9%.
3. The sensitivity analysis is carried out by variating the key parameters as follows: a) coefficient of run-off (C) based on the land cover type; b) forest cover area in the RTRW scenario and optimization; c) dependable discharge (Q_{80} and Q_{90}) as the base of water allocation. The result show that about ±10% change on the run-off coefficient can influence the dependable discharge until about ±6%, however, the variation about ±5% of forest area influences the effective storage capacity change until ±8%.

By the validation approach, this model is evaluated reliable and robust enough, and can represent the performance of Jatigede Dam in the various scenarios of management.

3.3. Ecology Trade-off from the Land Cover Moving

The research result shows the increasing of primary/secondary dry land of forest area; however, on the other side, there happens the decreasing of vegetation forest (plantation forest). This moving takes a number of ecology trade-offs as follows:

1. The advantage of ecology (positive): a) the increasing of natural ecosystem function: primary/ secondary dry land forest has the higher biodiversity than the mono-culture vegetation forest. It strengthens the ecological function as the carbon sink, preparation of animal habitat, and the resilience of ecosystem to the climate disturb; b) the decreasing of erosion and run-off: natural forest cover with litter layer and various root system that is more effective to hold the erosion than the industry or plantation vegetation; c) the ecosystem resilience is stronger: the secondary forest can be still naturally self-recovery, however, the vegetation forest tends vulnerable to the pest attack.
2. The ecological consequences (negative): a) the decreasing of production ecosystem service: the decreasing of vegetation forest means the decreasing too of wood potency, plantation yield, or direct economic service that is usually reliable by the local society; b) conflict of land utilization: conversion from vegetation forest to natural

forest can decrease the income from commercial forestry sector, so it causes the socio-economic resistance; c) dynamic change of ecology: although the natural forest is richer of biodiversity, the increasing of secondary forest is too fast and it can also change the composition of local species and causes the competition of new ecology.

3. The implication for Jatigede Dam: a) From the hydrology trade-off, it is more profitable because the increasing of primary/secondary forest improves the infiltration, decreases the sedimentation, and lengthens the lifetime of the effective reservoir; b) from the socio-economic trade-off, there is the loss of potency of short-term economic value from the vegetation forest that is needed to be balanced with the policy of conservation incentive or environmental service cost (PES).

3.4. Integration of Public Participations in Optimization Model

The optimization model in this research is mathematical-technique-based; however, it can expand by entering the variables of social and society preference through some mechanisms as follows:

1. Determination of Multi-Objective Optimization Weight: a) in the model, every aim (raw water, irrigation, hydro-electric power, and conservation) has the interest weight; b) this weight can be determined together with the society water users through the preference survey, focus group discussion (FGD), or village consensus; c) therefore, the water allocation that is produced can reflect the local priority and not only the technocrat decision.
2. Integration of socio-economic data: a) the model can accommodate the water demand level of households, society, agricultural areas, and micro business that are usually escaped in the reservoir technical model; b) it makes the optimization not only focus on the big sector (hydroelectric power and area-scaled irrigation), but also on the little society interest.
3. Scenario-Based Decision Making: a) The model can be addressed with some scenarios (for example, priority of hydroelectric power, priority for irrigation, and priority for conservation); b) the society can be involved in selecting the most suitable scenario with the local demand through the participative mechanism.
4. Decision Support System (DSS): a) the model result can be transformed into the interactive dashboard that can be accessed by the society and local decision maker; b) by this transparency, the society has the base to supervise and give input in reservoir management.
5. The incentive policy for conservation participation: a) The model can enter the land cover variable that is influenced by the society's activities (for example, reforestation and agroforestry); b) payment for environmental service (PES) can be entered as the factor in optimization, so the society feels it has a direct role in maintaining the sustainable reservoir.

There are 8 planned steps to implement the model in Indonesia as follows: 1) translating the model output into the policy map; 2) cross-sectorial dialog and participative validation; 3) input to the process of RTRW arrangement; 4) framework of conservation funding; 5) instrument of law and regulating executor; 6) pilot and phasing; 7) monitoring, evaluation, and adaptive management (M & E); and 8) institutionalize and scale up.

4. Conclusion

The problem that appeared due to the watershed damage in Jatigede Reservoir can be seen from the aspects of water allocation, utilization, and management that become disturbed, which is caused by the deforestation, morphology damage, and sedimentation in the river; degradation and shallowing due to the uncontrolled mining; the decreasing of raw water quantity from water sources; and the potencies of drought and flood in some areas. Therefore, the optimization of water resources in Jatigede Reservoir is carried out for decreasing the runoff coefficient in the upstream of Jatigede Reservoir, so there is obtained a wider green area than the existing condition. The optimization result shows that the benefit is Rp. 10.069.504.750.000 (about 10 billion rupiahs) for the existing condition before being optimized. Based on the analysis that has been carried out, there is an increase of primary dry land forest from 4.83 km² (existing condition) to 228.42 km² (after optimization) and secondary dry land forest from 92.99 km² (existing condition) to 468.25 km² (after optimization). Although the vegetation forest is decreasing from 204.39 km² (existing condition) to 109.39 km² (after optimization), the C composite is decreasing from 0.13 (existing condition) to 0.10 (after optimization). It shows that the green area is getting wide, and it will be decreasing the surface run-off. The results of the optimization model need to be directly linked to the regional spatial planning and watershed conservation strategies to ensure that the model recommendations can be implemented in real and measurable policies.

Furthermore, the model can be tested at other reservoir locations, particularly regarding spatial planning in the upstream areas of the dam, both at the pattern planning stage and within existing systems. Further research is recommended to develop an optimization model that integrates more variables, such as biodiversity and climate change. This approach will provide more holistic and applicable results for land-use planning.

This model is tough enough to face the scenario of extreme climate because it can adapt to the strategy of water allocation and release by integrating the variables of hydrology, land cover, and simulation of multi-scenarios. However, this research also suggests further development by entering the variable of climate change explicitly so the result is more comprehensive.

5. Declarations

5.1. Author Contributions

Conceptualization, A.H. and M.B.; methodology, P.T.J.; software, A.H.; validation, R.A., A.H., and R.A.; formal analysis, A.H.; investigation, A.H.; resources, R.A.; data curation, A.H.; writing—original draft preparation, L.M.L.; writing—review and editing, M.B.; visualization, P.T.J.; supervision, P.T.J.; project administration, A.H.; funding acquisition, A.H. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

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5.4. Institutional Review Board Statement

Not applicable.

5.5. Informed Consent Statement

Not applicable.

5.6. Declaration of Competing Interest

The authors declare that there are no conflicts of interest concerning the publication of this manuscript. Furthermore, all ethical considerations, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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