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CASE STUDY

Integrated system dynamics modeling for sustainable fisheries provisioning services

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ABSTRACT

BACKGROUND AND OBJECTIVES: Fisheries provisioning services deliver food production, livelihoods and ecosystem functions, but are increasingly under pressure from environmental degradation, declining fishery resources and socio-economic stressors. Traditional paradigms in fisheries governance often exhibit a deficiency in accounting for the multidirectional feedback loops linking ecological systems with socio-economic dynamics. The objectives of this study were to develop an integrated system dynamics model to assess interactions between these dimensions and identify management options to improve fisheries provisioning services through long-term scenario simulations.

METHODS: A system dynamics model was integrated, consisting of social, environmental, and economic sub-models using primary and secondary data from 2018-2023. The model includes population, fishermen, floating net cages, alternative employment, willingness to be a fisher, water quality and aquatic conditions, fish restocking, capture fisheries production, fisheries productivity, fish processing innovations, income, costs, and fisher's income. The model was verified and validated using the mean absolute error and average variation error metrics. Subsequently, predictive simulations were projected to 2045 under current, moderate, and optimistic scenarios.

FINDINGS: Actual capture fisheries production declined by 88.9 percent, from 588,100 kilograms in 2018 to 65,035 kilograms in 2023 and was projected to decline to 31,179 kilograms by 2045 under current conditions. Under the moderate and optimistic scenarios, the number of floating net cages was modeled with an annual reduction rate of 30% and 35%, respectively. Production recovery commenced in 2027 under the moderate scenario and in 2026 under the optimistic scenario. Furthermore, target water quality conditions were achieved by 2041 and 2037, respectively, while fisher's net income reached positive values by 2034.

CONCLUSION: The integrated system dynamics model underscores the potential for the sustainability of fishery production services through coordinated actions across social, environmental, and economic dimensions. The faster realization of target outcomes under the optimistic scenario highlights that proactive, coordinated interventions effectively expedite ecological restoration, fisheries output, and socioeconomic progress. This model offers a decision-support framework for assessing long-term fisheries management strategies.

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INTRODUCTION

Reservoir fisheries are an important part of the inland food system, providing fish for human consumption, employment, income and ecosystem services, especially for communities with limited alternative livelihoods. Inland fisheries are critical for global food security and livelihoods and are associated with freshwater ecosystem functions and several sustainable development goals (SDGs) (Smith and Bennett, 2019; Lynch *et al*., 2020). In South and Southeast Asia, capture fisheries and aquaculture, encompassing supply and consumption dynamics—are progressively recognized as integral subsystems within the wider food matrix, moving away from traditional treatments as standalone productive domains (Tezzo *et al*., 2021). Thus, the sustainability of reservoir fisheries is not only about fish abundance and fishing practices, but also about the relationships among environmental conditions, community livelihoods, resource use and governance, and economic incentives. Characterized as intricate socio-ecological matrices, reservoirs accommodate competing sectors such as fisheries, aquaculture, hydropower, agriculture, and urban infrastructure, which collectively generate pronounced anthropogenic pressures on aquatic ecosystems. Reservoir fisheries in tropical Asia result from a complex interaction among aquatic ecology, resource users, watershed processes, and institutional decision-making. Therefore, an integrated and transdisciplinary management approach is required (Schiemer *et al*., 2024; Solomon *et al*., 2020). Socio-ecological feedback loops are also important, as changes in fish abundance and catch opportunities may influence human behavior, while fishing decisions and resource use patterns, in turn, influence fish populations and ecosystem conditions (Wilson *et al*., 2020). Consequently, fisheries management frameworks reliant exclusively on biological metrics risk disregarding critical socioeconomic feedback, potentially precipitating unintended adverse consequences. Another significant pressure on reservoir ecosystems is aquaculture. Floating net cage (FNC) operations can increase food production and local income, but high stocking densities, overfeeding, and poor waste management can lead to increased nutrient and organic matter loads. Aquaculture effluents may contain nutrients, suspended solids, organic matter, and other contaminants that can cause eutrophication and environmental degradation (Ahmad *et al*., 2021; Liu *et al*., 2024). Consequently, evaluations of aquaculture carrying capacity must extend beyond physical production limits to explicitly incorporate ecological, social, and economic dimensions (Weitzman and Filgueira, 2020). A holistic assessment should also consider stakeholders, spatial and temporal variability, environmental changes and interactions between ecological and socioeconomic factors (Kluger and Filgueira, 2021; Weitzman *et al*., 2021). These complexities are particularly acute in reservoir ecosystems characterized by spatial competition and resource rivalry between cage aquaculture operations and capture fisheries. The Jatigede Reservoir is an artificial freshwater ecosystem that provides fisheries products and livelihood opportunities to the surrounding communities. The fisheries provisioning services of Jatigede Reservoir were recently classified as moderate due to anthropogenic pressures from residues of FNC, river waste, boat activities, and domestic activities (Iskandar *et al*., 2024). These results suggest that management should consider ecosystem conditions and community resource-use activities simultaneously to sustain fisheries provisioning services. One of the problems in Jatigede Reservoir is the management of FNC activity. FNC aquaculture can generate fish production and economic benefits, but overdevelopment can increase nutrient loads and degrade water quality. A study of the trophic status and carrying capacity of FNC in Jatigede Reservoir revealed significant nutrient enrichment, highlighting the need to

control the growth of FNC within the reservoir's carrying capacity (Marsela *et al*., 2023). findings align with broader evidence demonstrating that intensive aquaculture can generate environmental externalities when production and waste discharge exceed the assimilative capacity of aquatic ecosystems (Ahmad *et al*., 2021; Liu *et al*., 2024). Consequently, evaluating FNC management must extend beyond sectoral aquaculture policies to incorporate comprehensive assessments of water quality, capture fisheries productivity, and local socioeconomic well-being. The capture fisheries in Jatigede Reservoir have a very strong influence on the condition of the aquatic ecosystem. Plankton communities are used as indicators of reservoir environmental conditions, reflecting the importance of aquatic ecological processes in evaluating fish habitats (Dahlan *et al*., 2020; Rosadi, 2020). Recent studies (Iskandar *et al*., 2024) also indicate that the provision of sustainable fisheries services within the Jatigede Reservoir is fundamentally governed by complex interactions between environmental dynamics and anthropogenic stressors. Environmental degradation can affect fish stocks and the production of capture fisheries. Reduced catch and income in the future can affect fishing behavior, livelihood choices, and pressure on resource use; similar feedback loops have been described in freshwater fisheries, where human decisions and fish population dynamics are coupled over time (Wilson *et al*., 2020). The single variable-based management approaches are inadequate for ensuring the long-term viability of fisheries. Because these socio-ecological interactions are inherently complex, they necessitate analytical frameworks capable of capturing feedback loops, time delays, and temporal dynamics. System dynamics provides such a method. It models feedback structures and interrelated variables, and mimics their behavior under different conditions. Its application to environmental and sustainability challenges can assess nonlinear interactions and potential consequences of management actions. Systems modeling is regarded as beneficial for tackling interconnected environmental, social, and economic goals, as well as for evaluating the interactions among the SFGs (Moallemi *et al*., 2021). Integrated socio-economic-ecological models have been used in fisheries management to describe the relationships among fishery resources, communities, economic activities, and environmental conditions (Failler *et al*., 2021). Furthermore, system dynamics modeling has been widely applied in fisheries management to evaluate alternative policy strategies and examine the intricate interactions among biological, social and economic dimensions (Ismail *et al*., 2022). The paper demonstrates the potential of system dynamics as a decision-support tool rather than as a forecasting method. The importance of integrated modeling lies in the fact that fisheries management involves a trade-off between ecological conservation and socio-economic objectives. Application of the European sea bass fishery model demonstrates that management performance is fundamentally governed by the interplay between biological conditions and economic drivers, highlighting the necessity of simultaneously evaluating multiple objectives (Tidbury *et al*., 2021). Similarly, modeling system dynamics in socio-ecological systems can represent feedback loops among human activities, environmental processes, and ecosystem services, and evaluate alternative management pathways (Berrio-Giraldo *et al*., 2021). This enables a shift from separate environmental or economic assessments to a more integrated framework for assessing alternative interventions. However, previous studies on Jatigede Reservoir have focused mainly on specific aspects, including plankton communities, environmental factors, trophic status, fisheries provisioning services, and the carrying capacity of FNC (Dahlan *et al*., 2020; Marsela *et al*., 2023; Iskandar *et al*., 2024). Long-term management strategies frequently overlook the dynamic interactions among environmental variables, fishing practices, social dynamics,

fisheries production, and fisher's income. This is an important gap in literature as interventions targeting one component may have implications for other components. Reducing activities in FNC may relieve environmental pressure. Nonetheless, it will impact livelihoods, while increasing capture fisheries production without restoring environmental conditions may not yield sustainable outcomes in the long run. The innovation of this study lies in the creation of an integrated system dynamics model that connects social, environmental, and economic sub-models to evaluate the long-term sustainability of fisheries provisioning services. The model includes interactions between FNC activities, water conditions, capturing fisheries production, fisheries productivity, innovations in fish processing, fisher income, and social variables. To evaluate the effects of varying management intensities on fisheries provisioning services through 2045, three distinct trajectories were modeled: current, moderate, and optimistic. Quantitative social-ecological modeling can help reveal feedback between human actions and ecological dynamics and offer a basis for assessing alternative fisheries management strategies (Restrepo-Gómez *et al*., 2022). Whereas earlier evaluations typically examined individual indicators in isolation, the present study establishes a scenario-based decision-support framework to trace the systemic management variables through interconnected social, environmental, and economic feedback loops (Schiemer *et al*., 2024). The study examines alternative interventions that affect the activities of FNC, water conditions, fisheries production, and fisher's income. Results of this study are expected to provide a framework to support scientific decision-making for evaluating alternative fisheries management strategies and to support sustainable management of aquatic resources. To improve the long-term sustainability of fisheries provisioning services, this study aims to develop an integrated system dynamics framework designed to parse multidimensional interactions across social, environmental, and economic sectors and identify optimal management pathways. The data used in the study were primary and secondary data obtained in 2018-2023, as well as model projections and scenario simulations until 2045. The study was conducted at the Jatigede Reservoir in West Java, Indonesia. The study was conducted in Jatigede Reservoir, Sumedang Regency, West Java, during 2022 to 2024.

MATERIALS AND METHODS

Data collection method and data analysis

Primary data were collected through field observations, interviews with fishermen and other reservoir stakeholders, and field and laboratory measurements, whereas secondary data were collected from relevant literature and government agencies. Environmental samples were collected at seven stations, and water samples were collected twice during the sampling period; water sampling was conducted only at a depth of 10 meters (m) from the surface. Fishery related data were compiled using field observation and semi-structured interviews. The system dynamics model was parameterized using six years of historical data (2018-2023) and incorporated dedicated sub-models for social, environmental, and economic indicators. The model was constructed and simulated using Powersim software to examine the temporal dynamics of fisheries provisioning services and to evaluate alternative scenarios.

System dynamics model concept

System dynamics analysis was used to understand the model and to simulate a complex system in a simple way, with variables that are reciprocally interconnected (Sterman, 2002). The analytical procedure was conducted in a sequential, stepwise manner. The initial phase focused on objective analysis and problem formulation, identifying core system requirements and defining structural problems to establish pathways toward overarching system goals. The

next step is system identification, which presents the system as a causal loop diagram (CLD) showing the feedback loops between variables in a model. CLDs were constructed by illustrating the feedback loops among variables in the system (Firmansyah *et al*., 2019). This study used three sub-models following aspects of fisheries and sustainability (Charles, 2001):

1) Social sub-model, which accounts for human population dynamics, the scale of FNC cultivation, alternative employment opportunities, total fishermen, and individual willingness occupational preference to enter the fishing sector. 2) The ecological or environmental sub-models, which track water quality status and general aquatic environmental conditions. 3) The economic sub-models, which simulates capture fisheries production, fish restocking rates, overall productivity, the total surface water area of the Jatigede Reservoir, processing volumes, product innovation in fish processing, fisher's income, aggregate revenues and costs, and total revenues generated from fisheries processing.

a. CLD: A CLD l loop diagram was made after system identification. In this study, there will be three sub-models. The variables in each sub-model are described as reciprocal relationships.
b. Data Collection: After making CLD, data collection related to each variable in the system was carried out. The data collected will be included in the stock flow diagram.
c. Stock Flow Diagram: The variables taken come from CLD. Then, classify which variables are included in the level, parameters, and initial conditions.

Model verification and Validation: The subsequent phase involved verifying the logical and mathematical integrity of the conceptual implementation to ensure that the integration of model formulation into the stock-flow diagram variables produced no runtime or computational errors. There are two metrics to validate the model: Absolute mean error (AME) and average variation error (AVE). The acceptable deviation is limited to <10 percent (%). Model validation was conducted using AME and AVE tests for each variable, yielding AME values of 1-7% and AVE values of 2-5%, both within the acceptable threshold of <10%, indicating that the model adequately reproduces the historical patterns within the adopted criteria, for AME and AVE, using Eqs. 1 and 2 (Walukow, 2011):

$$AME = \frac{Si-Ai}{Ai} \quad (1)$$

Where:
Si = Si/N
Ai = Ai/N
A = Actual value
Si = Simulation value
N = Observation time interval

$$AVE = \frac{Ss-Sa}{Sa} \quad (2)$$

$Ss = ((Si-Si)^2N)$
$Sa = ((Ai-Ai)^2N)$
Sa= Deviation of actual value
Ss= Deviation of simulated value

d. Sensitivity analysis: Sensitivity analysis was conducted to evaluate the robustness of the model outcomes to variations in key scenario parameters. The evaluated parameters comprised the reduction of floating net-cage capacity, water-quality intervention, occupational preference for commercial fishing, and technological innovation in fish processing. Each parameter varied by -20%, -10%, baseline, +10%, and +20% relative to the corresponding scenario baseline. The resulting changes in key model outputs, including capture fisheries production, fisher's income, fish catch productivity, processed fish products, water condition, and FNC stocks, were compared across the sensitivity ranges. The sensitivity analysis retained the structural architecture and simulation horizon of the primary scenario

analysis, evaluating model projections evaluated through the year 2045.

e. Projection, Simulation, and Scenario: At this stage, system behavior is studied because of scenario settings. During the simulation phase, model outputs were generated using Powersim initialized with empirical baseline data. The simulation time step was configured to be one year, with model outputs being recorded annually. In the stock flow diagram, several scenarios were run, generating annual variable data from 2025 until 2045. The year 2045 was selected to align with the government program, Indonesia Emas, and the achievement of the SDGs in Indonesia. The scenario parameters were derived, which pertains to the regional management framework, including the Regional Regulation of Sumedang Regency Number 4 of 2018 concerning the Regional Spatial Plan of Sumedang Regency for the period of 2018-2038, as well as the capacity and environmental management context of the Jatigede Reservoir. These parameters were built as policy assumptions, not statistical forecasts. The levels of the FNC s reduction and water-condition intervention were selected to represent varying degrees of management intensity within the local socio-ecological setting. Whereas the moderate scenario represents a lower-intensity intervention pathway, the optimistic scenario is designed as a more stringent policy stress-test. Thus, these values were used to explore system response to different levels of intervention, not to describe empirically predicted future behavior. The scenarios simulated in this study were:

1) Floating net cages: FNC decreased by 30% (moderate scenario) and decreased by 35% (optimistic scenario).

2) Water condition: FNC decreased by 8% (moderate) and decreased by 10% (optimistic). 3) Capture fisheries: The willingness to become a fisherman variable increased by 0.002% (moderate scenario) and the willingness to become a fisher variable by 0.003% (optimistic scenario).

4) Fisher's income: Increases willingness to become a fisher by 0.002% and increases the number of processed fishery product innovations by 6% (Moderate). Increase willingness to become a fisher by 0.003% and increase the number of processed fishery product innovations by 8% (optimistic).

RESULT AND DISCUSSION

Integrated system structure and baseline dynamics

A CLD maps the feedback structures and component interactions underlying capture fisheries sustainability, thereby delineating the causal pathways necessary to achieve management goals. The CLD is then translated into an input-output diagram. A CLD illustrates the correlations among variables in a system with feedback (Firmansyah *et al*., 2019). The causal loop represents the system being modeled; later, it serves as the basis for formulating the stock-flow diagram. The system identification carried out identified 17 interconnected variables that can affect the management system, leading to the creation of a CLD. The CLD depiction is based on quantitative variables identified in the input-output system. The CLD diagram is structured into social, environmental, and economic sub-models. This classification is designed to organize variables according to the core dimensions under investigation, specifically highlighting policy levers governed by public authorities acting as controllers of the fisheries provisioning services management system. The CLD is presented in Fig. 1. Fig. 1 illustrates the feedback structure underlying the interactions among the principal components of the fisheries system and serves as the basis for interpreting the model dynamics. Six major reinforcing feedback systems (R1-R6) are identified to capture the dominant pathways through which changes in fisher participation, FNC activities, environmental conditions, fish

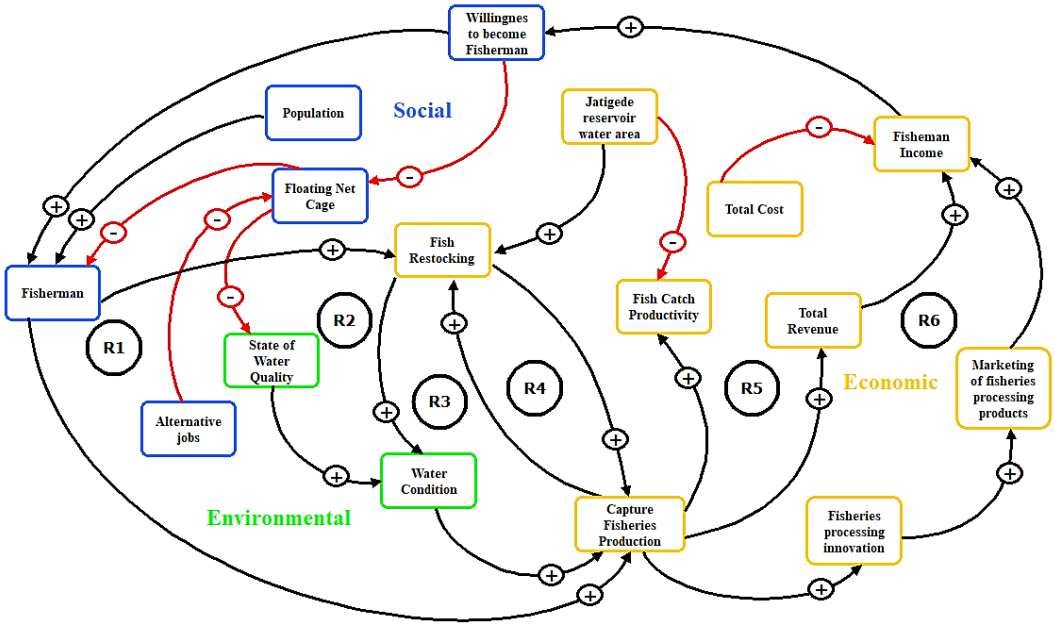

Fig. 1. The CLD for fisheries provisioning services in Jatigede Reservoir

restocking, capture fisheries production and economic performance propagate throughout the system. The polarity symbols (+/−) show the direction of causal influence between variables and the reinforcing loops show feedback processes that amplify changes in the system. Consequently, the CLD establishes a conceptual foundation for exploring the feedback dynamics embedded within the model. These causal pathways are subsequently operationalized and expanded according to the specific objectives of each sub-model.

The *number of FNC decreases*

This objective is the goal of the social sub-model related to anthropogenic pressure or community activities that harm the environment. Given the ongoing annual expansion of floating net-cage aquaculture and its compounding pressures on aquatic environmental quality, this sub-model is designed to simulate and evaluate strategies for mitigating cage density. When viewed from the CLD, the number of FNC is influenced by the variable of alternative jobs and the variable of willingness to become a fisher. System feedback mechanisms link FNC density to socio-economic and ecological variables. Labor market shifts—such as the expansion of alternative employment and fluctuations in occupational preference—exert a negative feedback effect on FNC proliferation. Ecologically, reductions in FNC scale mitigate organic waste accumulation, enhancing water quality scores in the Jatigede Reservoir. Socio-economically, FNC expansion acts as a driver of livelihood diversification, which inversely affects the total number of active fishermen by reducing reliance on capture fisheries (Béné *et al*., 2016; Allison and Ellis, 2001; Stacey *et al*., 2021). Furthermore, the increase in FNC has a negative impact on water quality, as organic waste from fish feed and excrement can increase eutrophication and degrade the ecological condition of the water (FAO, 2009; Cao *et al*., 2007; Liu *et al*., 2024).

Water conditions are in a good category

The environmental sub-model aims to find water conditions that fall into the good category.

Jatigede Reservoir is heavily polluted, requiring a management model that focuses on improving water conditions. Water condition variables are influenced by water quality status (positive relationship). If the water quality status is good, the water condition is also good. In addition, variables that can affect water conditions are fish restocking variables (positive relationship). Aquatic health is determined not only by physicochemical water quality parameters but also by the biological abundance within the ecosystem. Consequently, fish stocking initiatives can enhance aquatic biodiversity and foster equilibrium between biotic communities and water quality conditions. Therefore, the water conditions will also be good if the fish restocking variable increases. Good water conditions can affect fisher's catch (positive relationship). If this variable is in good condition, it supports fish in living, developing, and adapting, which increases the amount of fish life. Successful fish recruitment and reproduction drive population growth, which in turn enhances aggregate harvest rates and tota capture fisheries production. Improved water quality has a positive impact on capturing fisheries production, as habitat quality directly influences the abundance and health of wild fish stocks (Lorenzen, 2008; Welcomme and Bartley, 1998; Smith and Bennett, 2019). On the other hand, fish restocking activities can also improve water conditions by enhancing ecological balance, particularly if the released fish species play an ecological role in controlling certain aquatic organisms or plants (Bell *et al*., 2006; Silva, 2003).

Increased capture fisheries production

The economic sub-model has two objectives, one of which is capturing fisheries production. The restocking variable (positive relationship) influences the capture fisheries production variable. Although the model assumes that increased fish restocking can enhance capture fisheries production, the magnitude and persistence of this contribution remain. This uncertainty stems from the lack of explicit quantification for post-stocking survival, recruitment, ecological interactions, and fishing pressure are not explicitly quantified. This aligns with observed variations in stocking efficacy and reinforces the necessity of treating its contribution as probabilistic rather than assuming a uniform effect on future catch (Stewart and Long, 2016). Another variable that affects the number of fish caught is water conditions (positive relationship). Good water conditions will increase the survival of organisms, increasing the quantity of fish in the waters and the amount of catch. Another variable that affects capture fisheries production is the number of fishermen (positive relationship). The overall catch or capture fisheries production will increase if the number of fishermen increases. The variable influenced by capture fisheries production is the number of restocked fish (positive relationship). Annual fish restocking rates are dynamically linked to total commercial catch volumes. Consequently, an increase in aggregate harvest yields drives a corresponding expansion in subsequent stocking quantities. Another variable influenced by fisher's catch is the innovation of processed fishery products (positive relationship). If the capture fisheries production increases, the processed products of fishermen who do processing business will also increase. The total revenue variable is influenced by fisheries production (positive relationship). The more fishermen catch, the more fish are sold, and the more total revenue increases. The last variable influenced by capturing fisheries production is the fish productivity variable (positive relationship). Elevated catch rates correspond directly with enhanced fisheries productivity. Furthermore, growth in the active fishing population stimulates fish restocking efforts, driven by the critical role of community participation in sustaining stock enhancement programs. This active local involvement simultaneously reinforces the social and institutional capacities necessary for successful restocking interventions (Lorenzen, 2008; Garaway *et al*., 2006; Katre *et al*., 2024). Accordingly, the increase in the number of

fishermen is also positively correlated with capture fisheries production, as increased fishing effort directly boosts total catch up to the optimal capacity limit (Hilborn and Walters, 1992; Charles, 2001). Fish restocking itself has a clear positive relationship with capture fisheries production, as the addition of stock directly increases the fish biomass available for harvest (Lorenzen, 2008; Lorenzen, 2005). This production growth subsequently improves catch productivity, as rising stock abundance facilitates higher catch per unit effort for fishers (Hilborn, 2007; Haddon, 2007; Schiemer *et al*., 2024).

Fisher's income increases

Another purpose of the economic sub-model is to increase fisher's income. The results of interviews with 40 captured fishermen in Jatigede Reservoir show that fisher's income has decreased from previous years. The primary objective of this model is to inform the sustainable management of fisheries and aquatic environments, thereby fostering community well-being through the enhancement of fisher's income. Total revenue (positive relationship) influences the fisher's income variable. The more total revenue fishermen receive from fish sales, the higher their income. The total cost variable is also a variable that affects income (negative relationship). If the total costs incurred by fishermen increase, the net income of fishermen decreases. The variable that affects fisher's income is the marketing variable of processed fishery products (positive relationship). An expansion in the processing of fishery products drives proportional growth in product distribution and commercialization, which consequently enhances household incomes within the fishing community. Increased capture fisheries production also has a direct impact on the total revenue of the fisheries sector, given the linear relationship between production output and fisher's economic income (Lorenzen, 2008; Charles, 2001; Smith *et al*., 2005). This increase in production subsequently spurred innovation in fisheries processing, as the greater availability of raw materials encouraged market actors to develop new processing methods with higher added value (Delgado *et al*., 2003; FAO, 2016). Furthermore, the expansion of the Jatigede Reservoir's surface area has also spurred an increase in restocking activities, as the provision of a larger aquatic space creates ecological opportunities for the development of restocking-based fisheries (FAO, 1998; Lorenzen *et al*., 2001). Economically, expansions in total sectoral revenue directly augment fishers' incomes, reflecting the strong interdependence between individual financial returns and the broader performance of the fisheries sector (Lorenzen, 2008). Within the fisheries value chain, innovations in fish processing drive increased marketing of these innovative products, as a growing variety of value-added products opens new market opportunities (Allison and Ellis, 2001; Smith *et al*., 2005; Stacey *et al*., 2021). Ultimately, this increase in marketing activities for innovative fish products positively influences fishers' earnings, as market expansion and elevated price points for processed products enhance the economic benefits received by fishing households (Béné *et al*., 2016; FAO, 2016).

Baseline projection of fisheries provisioning services

Stock flow diagrams were constructed and expanded based on the variables identified in the CLD. Subsequently, the model was parameterized using empirical primary data and secondary datasets compiled from relevant agencies and previous literature. The resulting stock-flow diagram for the fisheries provisioning services model is presented in Fig. 2. Stock flow diagrams are used to project data trends through 2045 and to create scenarios using the sub-model to inform policy related to the Jatigede reservoir water environment and sustainable fisheries. The actual data used in this study are 2018-2023 data. The data projection on the stock-flow diagram shows the model's projection for variables related to fisheries provisioning services. Projection data in the stock-flow diagram relate to variables for FNC,

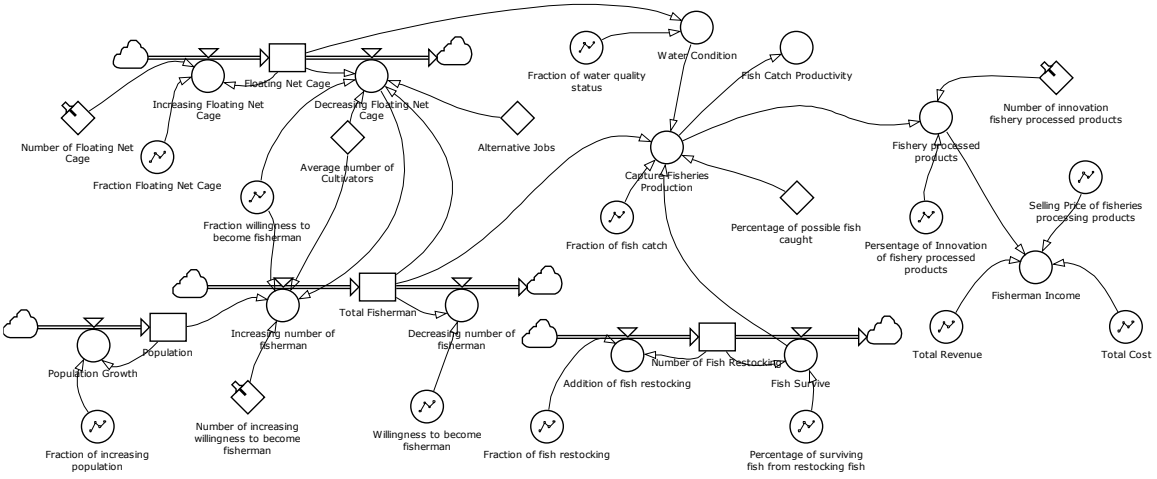

Fig. 2. Stock flow diagram of fisheries provisioning services in Jatigede Reservoir

fishermen, water conditions, capture fisheries production, the number of fish processed into fisheries products, and fisher's income. Projections and data trends for 2018-2045 are shown in Table 1. The trend observed in Table 1 shows the projection increases or decreases in data for each variable until 2045. The FNC data show an increase, indicating that without intervention from economic drivers, public awareness, government intervention, and so on, the number of FNC will continue to rise. As detailed in the preceding data, the total active fishing population exhibits a declining trend that corresponds inversely with the expansion of FNC. According to the results of interviews with 40 fishermen, there are some fishermen who do not want to be fishermen and turn their profession into cultivators in FNC. The condition of Jatigede Reservoir waters shows a trend of increasing pollution, with STORET scores in the hundreds, indicating it has entered the heavily polluted category. This is also in line with the number of FNC, which are a source of pollutants in the waters, and, as described in the causal loop and stock flow diagrams, FNC affect the condition of the waters of Jatigede Reservoir. Aquatic environmental conditions directly influence the viability of aquatic organisms, subsequently constraining aggregate harvest yields in capture fisheries. Furthermore, this dynamic is compounded by the ongoing contraction of the active fishing workforce. Historical and projected simulation data spanning from 2024 to 2045 indicate that capture fisheries production has experienced a declining trend since the initial inundation of the Jatigede Reservoir. The results of interviews with people living in and around the Jatigede Reservoir and fishermen who work in its waters show that only 1 fisher processes his catch into dried fish products, which adds to the fish's selling value. Annual data demonstrates a progressive decline in the volume of fish allocated for value-added processing. Without targeted interventions such as capacity-building programs to increase the number of fishers engaged in product processing, this downward trajectory is projected to persist. Model projections indicate that while capture fisheries yields will rise through 2045, the volume of processed fishery products will experience a continuous decline. Total household income for fishers is calculated as the aggregate revenue generated from both fresh fish harvest sales and processed fishery commodities. Consequently, as processing output contracts over time, annual income exhibits a steady downward trend, reflecting declining production capacity, reduced value addition, and increasing livelihood vulnerability.

Table 1: The number of fish processed into fisheries products, and fisher's income and projections data for 2018-2045

Year	Floating net cage (unit)	Total fishermen (People)	Water condition	Capture fisheries production in kilograms (kg)	Number of fish processed (kg)	Fisher income (USD)
Actual data						
2018	250	123	-7	588,100	1,800	140,849
2019	625	122	-15	489,675	1,800	138,132
2020	750	123	-25	275,125	180	84,400
2021	333	110	-45	238,705	180	55,454
2022	816	111	-52	169,365	90	34,986
2023	885	110	-94	65,035	90	13,270
Projection data						
2024	891	106	-94	62,328	86	13,278
2025	897	101	-95	59,762	82	13,286
2026	904	97	-96	57,331	79	13,294
2027	910	93	-96	55,030	76	13,301
2028	916	90	-97	52,853	73	13,307
2029	922	86	-98	50,796	70	13,314
2030	929	83	-98	48,855	67	13,320
2031	935	80	-99	47,025	65	13,325
2032	942	77	-100	45,301	63	13,331
2033	948	74	-100	43,680	60	13,336
2034	955	72	-101	42,159	58	13,340
2035	961	69	-102	40,734	56	13,345
2036	968	67	-103	39,402	54	13,349
2037	974	65	-103	38,160	53	13,352
2038	981	63	-104	37,006	51	13,356
2039	988	61	-105	35,936	50	13,359
2040	995	59	-105	34,949	48	13,362
2041	1,002	58	-106	34,041	47	13,365
2042	1,008	56	-107	33,213	46	13,368
2043	1,015	55	-108	32,460	45	13,370
2044	1,022	54	-108	31,783	44	13,372
2045	1,029	53	-109	31,179	43	13,374

Initial conditions

The system dynamics model was formulated using the Stock-Flow diagram and the functional relationships among the social, environmental, and economic variables. The initial conditions of the principal stock variables were defined using the 2018 observed values, including 250 FNC, 123 fishermen, a water-condition score of -7, 588,100 kg of capture fisheries production, and 1,800 kg of processed fishery products. Model parameters were derived from official statistics, field observations, interviews, and secondary data sources, as detailed in Table 2.

Verification and validation

Verification and validation were conducted to ensure that the dynamic model adequately represented the 2018-2023 historical system. Model verification involved checking the stock flow diagram and input data, while validation used AME and AVE to compare simulated and actual outputs. The validation results were below 10% for FNC (AME 1%, AVE 5%), water condition (2%, 4%), capture fisheries production (3%, 2%), and fisher's income (7%, 2.6%), indicating that the model was suitable for subsequent scenario analysis (Walukow, 2011).

Scenario simulation and management implications

The scenarios created in this study aim to achieve the objectives of the three sub-models developed in the problem identification section. The sub-models are the social, environmental, and economic sub-models. These three sub-models interact to capture the complex dynamics of the fisheries system and evaluate its broader

Table 2: Variable, unit, and data source of stock flow diagram

Variable	Unit	Stock flow diagram symbol
Population	People	level
Population growth	People/year	Rate
Fraction of increasing population	%	Auxiliary
FNC	FNC	Level
Increasing FNC	FNC	Rate
Fraction of FNC	%	Auxiliary
Decreasing FNC	FNC	Rate
Alternative jobs	%	Constant
Average number of cultivators	People/Floating net cage	Constant
Fraction's willingness to become a fisher	%FNC	Auxiliary
An increasing number of fishermen	People	Rate
Total Fisher	People	level
Decreasing number of fishers	People	Rate
Willingness to become a fisher	%	Auxiliary
Fraction of water quality status	-	Auxiliary
Water Condition	-	Rate
Capture fisheries production	Kg	Rate
Fraction of fish catch	Kg/people	Auxiliary
Percentage of possible fish caught	%	Constant
Fish that survive restocking	Kg	Rate
Number of fish restocking	Kg	level
Addition of fish restocking	Kg	Rate
Fraction of fish restocking	%	Auxiliary
Jatigede Reservoir water area	M^2	Constant
Fish catch productivity	Kg/M^2	Rate
Fishery processed products	Kg	Rate
Percentage of fishery processed products	%	Auxiliary
Selling price of fisheries processing products	Rp	Auxiliary
Total revenue	Rp	Auxiliary
Total cost	Rp	Auxiliary
Fisher income	Rp	Rate

socioeconomic and environmental consequences. Data simulations for each sub-model are conducted across three comparison aspects: actual data trends, trends from moderate simulations, and trends from optimistic simulations. The moderate scenario embodies a lower-intensity policy intervention, whereas the optimistic scenario functions as a more stringent policy stress-test. Optimistic simulation is a data scenario that uses more optimistic variable assumptions, set with the aim of achieving the best results and desired conditions.

Sensitivity analysis

Sensitivity analyses were conducted by perturbing key model parameters across a range of -20%, -10%, +10%, and +20% relative to their baseline values. Model responses were quantified as percent change from baseline and a normalized sensitivity index (SI). The results showed very different sensitivity of the intervention parameters. The sensitivity of FNC reduction was very low, with projected 2045 capture fisheries production changes of less than 0.04 % under the moderate scenario and less than 0.03 % under the optimistic scenario, with absolute SI values less than 0.002. Similarly, water-condition improvement led to less than 0.07% change in projected 2045 production, with absolute SI values below 0.004. The results demonstrate that long-term production exhibit high stability in response to variations in FNC reduction and water-quality improvement across the tested ranges. Conversely, the coupled shift in occupational inclination toward fishing and innovations in fish processing generated substantially greater system sensitivity. The projected 2045 production changed by about ±13% under the moderate

scenario and ±14% under the optimistic scenario for a ±20% change in parameters. The combined SI values ranged from 0.635 to 0.636 and 0.723 to 0.724, respectively. The results show that socioeconomic participation and value-added processing are more powerful leverage points in the modelled system than FNC reduction or water-condition improvement. However, because the inclination toward commercial fishing and fish processing innovation varies simultaneously, their individual contributions cannot be fully isolated, necessitating dedicated one-at-a-time sensitivity analyses.

Sensitivity to milestone year

Sensitivity analysis of the milestone year showed that the robustness of the projected transition timing varied across system outcomes. In the moderate scenario, FNC elimination occurred in 2041-2045, and Water Condition > -30 moved from 2045 to 2038. While production recovery exhibited relative stability between 2027 and 2030, income recovery proved significantly more sensitive. Specifically, non-negative income levels were not achieved under the baseline, -10%, and -20% conditions; however, under the +10% and +20% parameter variations, positive income recovery was attained by 2045 and 2041, respectively. In the optimistic scenario, FNC elimination and the water-condition threshold were reached earlier, varying from 2035 to 2042 and 2035 to 2041, respectively. Production recovery proved exceptionally robust, with 2026 recovery levels remaining consistent across all parameter variations. In contrast, income recovery exhibited the highest temporal sensitivity, spanning a recovery window from 2027 to 2044. Overall, the results show that production recovery is relatively robust to changes in parameters, whereas the timing of environmental and, especially, socio-economic recovery is more sensitive. This milestone year analysis is in addition to the endpoint sensitivity analysis and illustrates the robustness of the timing of the projected transition to uncertainty in the parameters.

Social dimension

The social sub-model includes aspects related to the behavior, activities, and interactions of the community around Jatigede Reservoir, as well as the impact of fisheries on social life. The variables included in the social sub-model in this study are population variables, fishermen, FNC, alternative jobs, and willingness to become a fisher. Within the social sub-model, scenario generation is driven by FNC density, as a primary objective of this module is to simulate the targeted reduction of net-cage infrastructure. In the simulation of the reduction of FNC, scenarios were developed in which the number of FNC in Jatigede Reservoir decreased by 30% annually (moderate scenario) and by 35% annually (optimistic scenario). The simulated reduction in FNC capacity was initiated in 2025. The resulting trajectories of FNC reduction are illustrated in Fig. 3. The simulation results of the FNC after two scenarios, such as the moderate and optimistic scenarios, provide data on the decline in FNC. In both scenarios, it is expected that there will not only be a decrease in the number of FNC but also that there will be no FNC in Jatigede Reservoir following government directives, as FNCs are not allowed in Jatigede Reservoir. As illustrated in Fig. 3, the moderate scenario projects that the complete eradication of FNC in the Jatigede Reservoir will be achieved by 2045. Simulation results under the optimistic scenario indicate that all FNC operations in the Jatigede Reservoir will be fully phased out by 2042. Structurally, the social sub-model interacts dynamically with the economic and environmental sub-models. Specifically, social dynamics such as FNC prevalence influence community occupational choices (i.e., willingness to enter the fishing workforce) and subsequent harvest efficiency. Concurrently, shifts within the environmental and economic subsystems collectively drive overall community welfare.

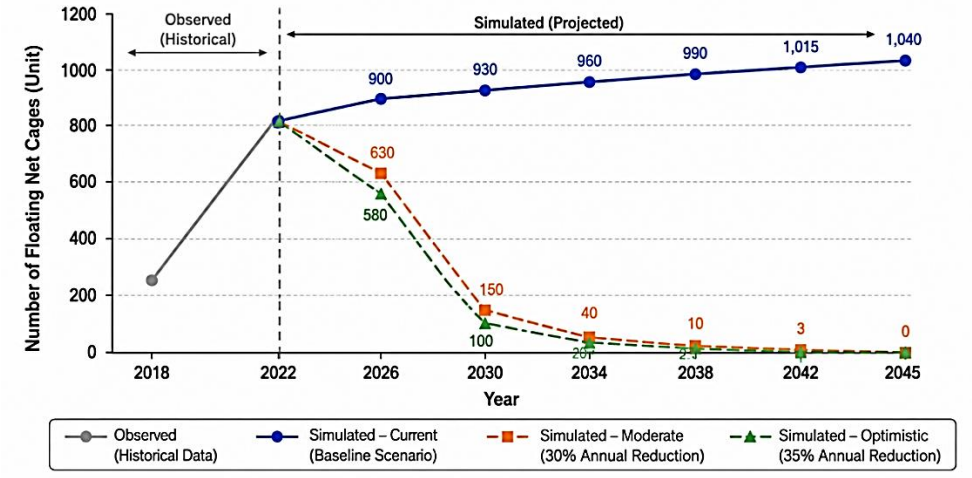

Fig. 3: Graphic simulation of FNCs

Environmental dimension

The Environmental Sub-Model represents ecological aspects related to fisheries provisioning services in Jatigede Reservoir. Variables that become environmental sub-models in this study are water quality and water conditions. The data simulation used in the environmental sub-model is data on the water condition variable, which is influenced by the FNC variable, one of the factors that contributes pollutants to water bodies and affects the condition of Jatigede Reservoir waters. The water-quality scenarios were designed to simulate management interventions aimed at restoring the ecological health of the Jatigede Reservoir to optimal conditions, specifically achieving a STORET index score exceeding -30. The scenario of water conditions is carried out with a controlled input variable of the number of FNC: a decrease of 8% (moderate) and a decrease in FNC by 10% (optimistic). The simulated water-quality trajectories are presented graphically in Fig. 4. Simulation of Jatigede Reservoir water condition data by the moderate scenario, where the number of FNC is reduced by 8% annually; the results of water conditions each year are getting better, and the target to achieve the goal of Jatigede Reservoir water conditions above a score of -30 is achieved in 2041. In the optimistic scenario, where the number of FNC is reduced by 10%, the water conditions improve every year, and the goal of water conditions above -30 is achieved in 2037. The environmental sub-model affects other sub-models (the economic sub-model), which is fish catches to fisher's income.

Economic dimension

In this dynamic system model, the third sub-model is the economic aspect of fisheries and fisheries resource management in Jatigede Reservoir, which includes production, marketing, and income. Variables included in the economic sub-model category in this study are fish restocking, Jatigede Reservoir area, capturing fisheries production, fish catch productivity, fisheries processing innovation, marketing of fisheries processing products, total cost, total revenue, and fishers' income. The economic sub-model simulation focuses on two primary output variables: the volume of capture fisheries production and fishers' incomes. The capture fisheries production variable is simulated under two scenarios: a moderate scenario with controlled inputs, using an increase of 0.002% in the willingness to become a fishers' variable, and an optimistic scenario with an increase of 0.003% over the simulation period. The simulation of the production data of the capture fisheries is illustrated in Fig. 5.

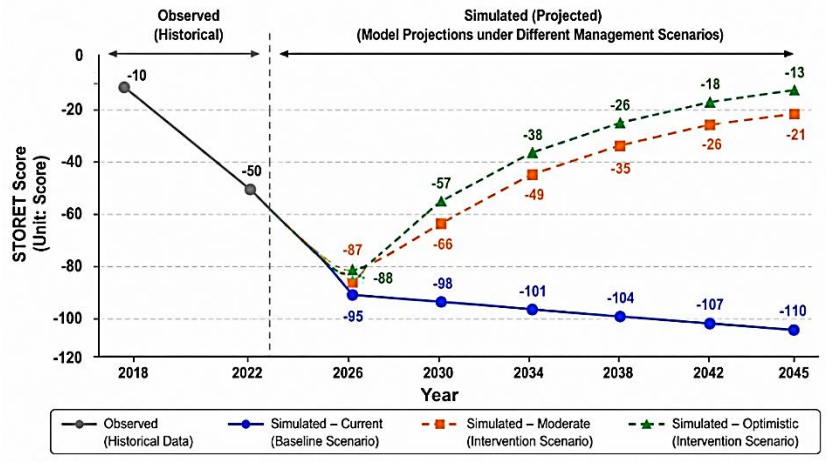

Fig. 4: Graphic simulation of water condition

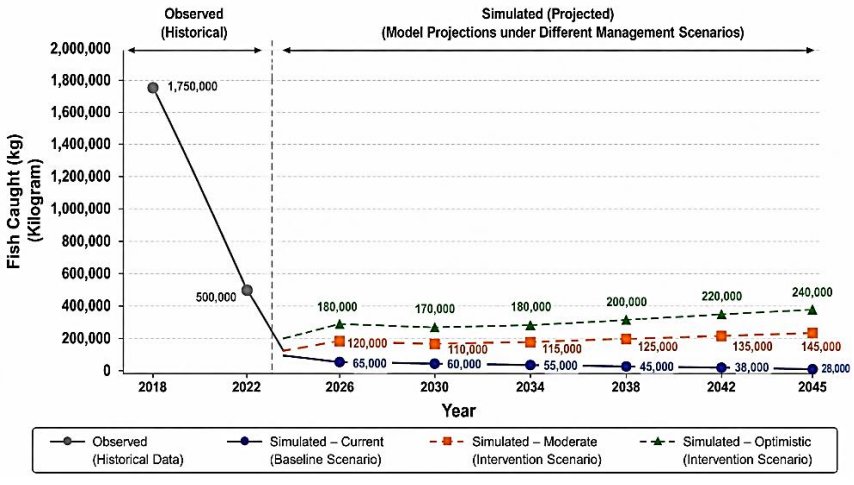

Fig. 5: Graphic simulation of capture fisheries production

The results of the comparison between the trend of actual data and data from the moderate and optimistic scenarios show that when the scenario is applied to increase the willingness to become a fishers variable in 2025, capture fisheries production increases annually. The moderate scenario shows an increase in data starting from 2027, and when the optimistic scenario is applied, fisheries production increases starting in 2026. Fishers' income constitutes a primary target output within the economic sub-model. Total earnings are governed by aggregate revenue, which is directly determined by total revenue, whereas total revenue is influenced by capture fisheries production alongside secondary economic variables, such as innovation in processed fishery products. In the simulation of increased fisher's income, the moderate scenario used is an increase in willingness to become fishermen by 0.002% and an increase in the number of processed fishery product innovations by 6%. The optimistic scenario is an increase in willingness to become a fisher by 0.003% and an increase in the number of innovations in processed fishery products by 8% for improved long-term sustainability. The simulated trajectories of fishers' income are presented in Fig. 6 under scenarios.

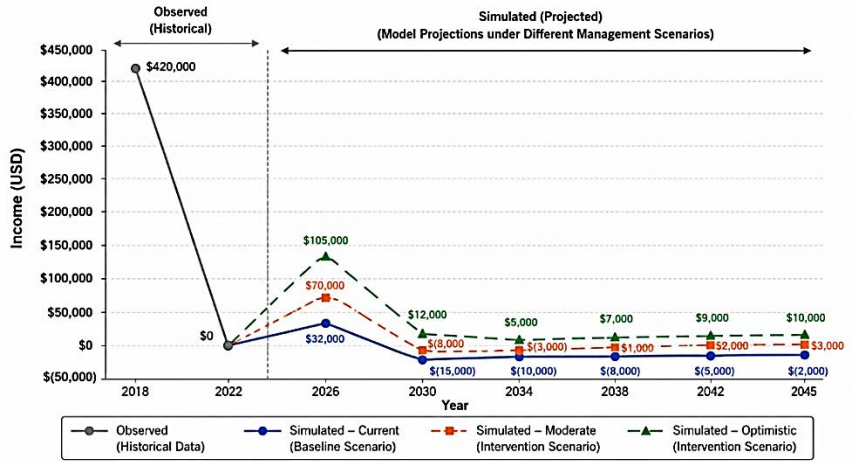

Fig. 6: Graphic simulation of fisher's income

The income of fishermen obtained from 2018 to 2023 is the total income of 40 fishermen for a year. The fisher's income in Jatigede Reservoir indicates community welfare in the economic sector. In 2023, aggregate net income for fishers on the Jatigede Reservoir yielded a negative balance. This deficit was driven by critically low daily catch rates—frequently falling below 3 kg per day or resulting in total zero-catch days—coupled with continuous operational expenditures. These fixed and variable costs encompassed fuel expenses, daily sustenance, and unforeseen losses, such as gear damage caused by submerged structural remnants within the reservoir basin. The results of the dynamic system model for fisher's income, shown in Fig. 6, indicate that under a moderate scenario, fisher's income increases, and in 2042 the total income of fishermen in Jatigede Reservoir is still negative. Under the optimistic scenario, fishers' incomes demonstrated a consistent upward trajectory, with net financial returns shifting from deficit to positive by 2034. The economic sub-model is highly dependent on environmental and social conditions. Environmental degradation can reduce fish stocks, resulting in lower catches and income for fishermen. Conversely, economic changes, such as increases in fisher's income, will affect people's desire to become fishermen and market demand.

Integrated management implications

The simulation results demonstrate strong interconnections among the social, environmental, and economic sub-models, indicating that fisheries provisioning services require an integrated management approach. Three scenarios were evaluated: the current condition, moderate scenario, and optimistic scenario. While the baseline condition maintains the trajectory of current trends absent significant intervention, the moderate and optimistic scenarios reflect realistic and intensive mitigation measures, respectively. A summary of the simulation outcomes is summarized in Table 3. The results show that the current situation is causing the continuous deterioration of environmental quality, fishery resources, and fisher's income. Conversely, while the optimistic scenario attains the primary management objectives ahead of schedule, the moderate scenario achieves them by 2045. Under the optimistic scenario, FNC reaches zero in and the target hydrological condition is attained by 2037, accompanied by an accelerated recovery in capture fisheries production and a transition to positive net income for fishers by 2034. These findings indicate that intensified interventions can significantly accelerate the recovery of fisheries provisioning services.

Table 3: General results of the simulation

Intervention	Scenario	Scenario assumption	Model outcome	Milestone
FNCs reduction	Moderate	30% reduction	FNCs decrease progressively	FNCs reach 0 in 2045
FNCs reduction	optimistic	35% reduction	FNCs decrease more rapidly	FNCs reach 0 in 2042
Water-condition improvement	Moderate	8% FNCs reduction	Water condition improves progressively	Water condition > -30 in 2041
Water-condition improvement	optimistic	10% FNCs reduction	Water condition improves more rapidly	Water condition > -30 in 2037
Integrated socioeconomic intervention	Moderate	0.002% willingness to become fishermen and 6% fish-processing innovation	Capture fisheries production and fisher's income recover gradually	Income becomes still negative in 2045 but getting better
Integrated socioeconomic intervention	optimistic	0.003% willingness to become a fisher and 8% fish processing innovation	Capture fisheries production and fisher's income recover more rapidly	Income becomes non-negative by 2034

This study also reveals that environmental restoration, social engagement, and economic diversification should be developed in parallel. Mitigating FNC alleviates environmental stress, improves hydrological conditions, and enhances aquatic resources alongside capturing fisheries production. Consequently, increased fishery yields, coupled with innovations in fish processing and improved marketing strategies, serve to strengthen fishers' incomes. This means that fisheries management should address feedback interactions among environmental conditions, social behavior, and economic performance, rather than relying on isolated interventions. The model was designed to achieve sustainable fisheries, a healthy aquatic ecosystem, and community welfare by 2045. This long-term vision aligns with the Indonesia Emas 2045 vision and the National Long-Term Development Plan 2025-2045. Thus, the model provides a decision-support framework for evaluating alternative management strategies for the SDGs. Although the optimistic scenario yields the most rapid environmental recovery, it necessitates more stringent policy enforcement and heightened public buy-in, particularly concerning the reduction of FNC. Therefore, successful implementation demands participatory planning, compensation mechanisms, alternative livelihood programs, adequate budget allocation, and cross-agency coordination. Furthermore, the integrated model provides a versatile framework applicable to other reservoirs, provided that model parameterizations are calibrated to reflect local socio-ecological conditions. Overall, the results suggest that coordinated interventions across the social, environmental, and economic dimensions are more likely to accelerate ecological recovery, fisheries production, and community welfare than isolated management actions.

Comparison with previous system dynamics studies

Consistent with prior system dynamics literature, the present model employs feedback-based simulation to evaluate fisheries sustainability and the efficacy of management interventions. Previous studies have mainly considered the environmental capacity of cage-aquaculture, fishing effort, stock management, or biological and economic interactions. For instance, Gunawan *et al.,* (2011) investigated sustainable FNC aquaculture in Cirata Reservoir, integrating cage production, environmental quality, and farm profitability into their analysis (Château *et al.,* 2015). Moreover, Martins *et al.* (2015) and Ismail *et al.,* (2022) showed the usefulness of system dynamics in assessing fisheries management and socioeconomic impacts. A comparison of these studies with the present framework is provided in Table 4. The current study extends these approaches by incorporating environmental

Table 4: Comparison of the present study with previous system dynamics studies on fisheries sustainability and management

Study system / location	Main modelling focus	Dimensions	Management / scenario analysis	Main contribution relative to the present study	Source
FNC aquaculture, Cirata Reservoir, Indonesia	Sustainable management of FNC aquaculture	Ecological: fish productivity, water quality, and eutrophication. Social: limited consideration of social/fisher participation. Economic: fish price and environmental costs.	FNCA regulation, aeration, and stocking-density interventions.	Demonstrated the usefulness of SD for reservoir cage aquaculture management. However, the model primarily focused on aquaculture sustainability and did not integrate capture fisheries, fishermen participation, and livelihood outcomes as explicitly as the present study.	Gunawan *et al.* (2011)
Marine cage culture, Magong Bay, Taiwan	Environmental carrying capacity and farm profitability	Ecological: nutrient enrichment, dissolved oxygen, phytoplankton, and water quality. Social: not explicitly represented. Economic: farm profitability and harvest.	Production-level scenarios and environmental limits.	Integrated environmental and economic consequences of cage production. However, the focus was mainly on cage aquaculture, whereas the present study links FNC reduction with capture fisheries, fishermen participation, processing innovation, income, and environmental recovery.	Château *et al.* (2015)
Artisanal dredge fisheries, southern Portugal	Sustainable fisheries management	Ecological: fish stocks and biological sustainability. Social: fishing activity and fishing effort. Economics: fisheries revenue.	Fishing-effort reduction and temporary closure.	Demonstrated how SD can evaluate regulatory interventions and socioeconomic consequences. However, it did not explicitly integrate reservoir water conditions, FNC management, fish processing innovation, and fishermen participation within one framework.	Martins *et al.* (2015)
Managed fisheries under transferable quota systems	Fisheries management and stock rebuilding	Ecological: fish stocks and stock rebuilding. Social: fishermen incentives and management behavior. Economic: economic incentives associated with quota management.	Individual transferable quotas (ITQ), total allowable catch (TAC), and adaptive management.	Highlighted the importance of feedback between management incentives and fisheries sustainability. However, it focused on quota-based fisheries management rather than reservoir-specific environmental degradation and livelihood transition.	Garrity (2011)
Indian mackerel fishery, Malaysia	Open-access fishery management	Ecological: biological and fishery dynamics. Social: fisher behavior and fishing activity. Economic: economic factors affecting the fishery.	Alternative fisheries-management options.	Provided an integrated biological, social, and economic SD framework for fisheries management. The present study extends this framework by integrating water condition, FNC pressure, fisher participation, processing innovation, restocking, and income within a reservoir fisheries provisioning-service framework.	Ismail *et al.* (2022)
Jatigede Reservoir, West Java, Indonesia	Integrated fisheries provisioning-service sustainability	Ecological: FNC pressure, water condition, capture fisheries production, and restocking. Social: fishermen participation and livelihood transition. Economic: fishermen income and fish-processing innovation.	Moderate and optimistic integrated interventions, including FNC reduction, water-condition improvement, socioeconomic interventions, and milestone assessment.	Develops an integrated social, environmental, economic SD model for reservoir fisheries provisioning services and evaluates intervention intensity, sustainability milestones, parameter sensitivity, and long-term leverage points through 2045.	Present study

degradation and FNC pressure into a comprehensive reservoir fisheries provisioning-service framework that simultaneously accounts for capture fisheries production, fishers' participation, fish processing innovation, restocking, and fishers' income. The comparison suggests that important combinations of ecological, social, and economic dimensions in fisheries management have been addressed in prior system dynamics studies, albeit with different system boundaries and intervention mechanisms than the present study. Whereas scholarship in cage aquaculture has predominantly centered on environmental carrying capacity and economic performance, conventional fisheries management models have largely focused on fish stocks, harvesting dynamics, fishing effort, or economic incentives. The present study extends these approaches by incorporating environmental conditions, FNC pressure, capture fisheries production, fishermen participation, restocking, fish-processing innovation, and income into a single social-environmental-economic framework. Furthermore, the model evaluates alternative intervention intensities, sustainability milestones, and parameter sensitivity through 2045, thereby offering a comprehensive appraisal of long-term fisheries provisioning-service sustainability.

Limitations of the model

Certain limitations should be considered when interpreting the model's outputs. First, the calibration period is restricted to 2018-2023, which is a relatively short period for showing long-term socio-ecological dynamics. Second, because the social and behavioral relationships were informed in part by interviews with 40 fishers, the estimated behavioral parameters may not fully capture the heterogeneity of the broader fishing community. Third, parameters governing behavioral responses such as propensity toward entering the fishery and livelihood transition remain subject to uncertainty, as human behavior adapts dynamically to shifting economic, social, and institutional drivers. Fourth, the water quality component is modelled by a simplified model and may not fully encompass the inherent complexity of hydrological, biogeochemical and ecological processes in the reservoir. the model does not explicitly account for all potential pollution sources; external inputs—such as those from upstream reservoirs, domestic sewage, agricultural runoff, and catchment-wide activities—can substantially influence water quality. Sixth, restocking of fish is seen as a positive contribution to fisheries production. However, the scale and longevity of the effect on future catch is unknown, and might depend on survival, recruitment, ecological interactions and fishing pressure. Seventh, the projection extends to 2045, well beyond the historical calibration period, implying a large potential for uncertainty to grow over the long simulation horizon. Eighth, economic parameters are affected by uncertainty related to inflation, changes in fish prices, operating costs, market conditions, and general economic conditions, which are not fully accounted for in the model. Ninth, the proposed interventions lack explicit evaluation regarding their economic viability through a detailed cost–benefit analysis. Costs of intervention, implementation budgets, enforcement costs, compensation mechanisms, and costs related to markets are not fully included in the model. Consequently, the simulated scenarios should not be construed as cost-optimal investment strategies, or as definitive proof of economic viability. These financial dimensions require rigorous assessment prior to the formulation of practical investment and policy frameworks. Tenth, the aggregation of the relationships between fishers, FNC activities, alternative employment and willingness to become fishermen may oversimplify the livelihood transitions. It thus may not be representative of decision making at the individual level. Alternative employment is presented as a social mechanism for reducing dependence on FNC activities and for indirectly changing the fisher's participation. Nevertheless,

the scenario analysis did not isolate the independent quantitative contribution of this factor to fishing dependence. Finally, the sensitivity analysis is not probabilistic but deterministic, since parameters were varied in established ranges (-20%, -10%, +10% and +20%) rather than probability distributions. Consequently, these projections should be interpreted as output of scenario-based decision support rather than accurate predictions of future fishery trajectories. Longer time-series data could improve future model development on water quality and fish production, spatially resolved environmental measurements, fishing effort and catch-per-unit-effort data, individual-level livelihood and behavioral information, post-stocking survival and recapture data, and more detailed economic data on intervention costs, fish prices, operating costs, and market conditions. Such empirical data would facilitate enhanced model calibration, robust uncertainty quantification, and a more comprehensive appraisal of management feasibility.

CONCLUSION

The integrated system dynamics model developed in this study suggests that interactions among social, environmental, and economic factors highly influence the sustainability of fisheries services in Jatigede Reservoir. Model simulations indicate that fishery sustainability cannot be attained through isolated interventions, as FNC operations, water quality, fishery resources, community participation, and fishers' incomes are intrinsically linked via feedback loops. The baseline scenario indicates that the continued use of FNC is associated with declining water quality, decreasing capture fisheries production, and lower fisher's income. These results suggest the need for an integrated management approach that considers ecological conditions, fishery resources, and community livelihoods. Outputs from the scenario analysis demonstrate that reducing aquaculture pressures from FNC, intensity, improving water quality, enhancing community engagement in capturing fisheries, and fostering innovation in fish processing can collectively reverse the declining trajectory of fisheries provisioning services. In the optimistic scenario, management targets are achieved sooner than in the moderate scenario. In the optimistic scenario, the activities of FNC reach zero by 2042, the targeted water quality is achieved by 2037, and fisher's income, the optimistic scenario reaches non-negative income in 2034. In the moderate scenario, these targets are reached in 2045 and 2041 respectively. Furthermore, the optimistic scenario demonstrates that capture fisheries production undergoes an accelerated recovery, indicating that more intensive and coordinated interventions can significantly expedite both ecological restoration and harvest yields. Collectively, these findings suggest that mitigating the environmental pressure of FNC enhances water quality and establishes optimal conditions for the rehabilitation of captured fisheries. These findings also suggest that socio-economic interventions need to be integrated with ecological restoration. Increased production in capture fisheries does not necessarily improve community well-being if fishermen continue to rely on limited income sources. Important complementary strategies include improving fisher's participation, developing innovations in fish processing, expanding market opportunities, and providing alternative livelihoods. Specifically, the former strategy enhances the economic value of fishery resources, whereas the latter alleviates ecological stress on the reservoir ecosystem. Thus, the interaction between environmental improvement and economic diversification is an important factor in the long-term viability of fisheries. By offering a management-centric architecture for decision support, integrated system dynamics models facilitate the comparative analysis of policy alternatives and the structural trade-offs inherent among environmental, social, and

economic targets. The optimistic scenario would be a faster route to the sustainability horizon of 2045, but it would require greater institutional commitment and broader public acceptability. Any reduction in FNC activities must be accompanied by appropriate incentives, alternative livelihood opportunities, robust financial support, stakeholder engagement, and cross-sectoral coordination to mitigate unintended socio-economic repercussions. Also, there is a need for regular monitoring and occasional evaluation of water quality, fishery production, and welfare of fishermen to change management interventions as the conditions change. Ultimately, this study underscores the capacity of system dynamics modeling to advance the integrated and adaptive governance of fisheries provisioning services, achieving this by embedding ecological restoration, harvest productivity, stakeholder behavioral responses, and economic welfare within a comprehensive analytical framework. The proposed model affords decision-makers and stakeholders an analytical framework to examine alternative management trajectories and prioritize interventions that optimize trade-offs between environmental and socio-economic objectives. This framework may be adapted for use in other reservoir fisheries facing similar sustainability challenges through appropriate parameter adjustments and validation.

AUTHOR CONTRIBUTIONS

A.N.K.B.P. Iskandar, the corresponding author, contributed to conceptualizing and designed the study, acquisition of data, analysis and interpretation of data, drafted the manuscript, statistical analysis and developed the integrated system dynamics model. Sunardi contributed to critical revision of the manuscript for important intellectual content, supervision, and ecological and fisheries aspects. Zahidah contributed to critical revision of the manuscript for important intellectual content, supervision, and ecological and fisheries aspects. D. Iskandar contributed to analysis and interpretation of data, critical revision of the manuscript for important intellectual content, and supervision. R. Adji contributed to acquisition of data, critical revision of the manuscript for important intellectual content, socioeconomic and economic analysis. R. Sunaryanto contributed to acquisition of data, critical revision of the manuscript for important intellectual content, and fisheries processing and value-added analysis. S. S. Antarlina, contributed to acquisition of data, critical revision of the manuscript for important intellectual content, fisheries processing and value-added analysis. B. Marwoto contributed to acquisition of data, critical revision of the manuscript for important intellectual content, fisheries processing and value-added analysis. W. Basuki contributed to administrative, technical, or material support, policy analysis, and management implications. N. Ismail contributed to administrative, technical, or material support, policy analysis, and management implications. All authors reviewed and approved the final manuscript.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, have been completely observed by the authors.

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ABBREVIATIONS

%	Percent
AME	Absolute mean error
AVE	Average variation error
CLD	Causal loop diagram
FAO	Food and Agriculture Organization
FNC	Floating net cages
kg	Kilogram
SDGs	Sustainable development goals
STORET	STORET is a method
USD	US Dollar (American currency)
y	Year
m	meter

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