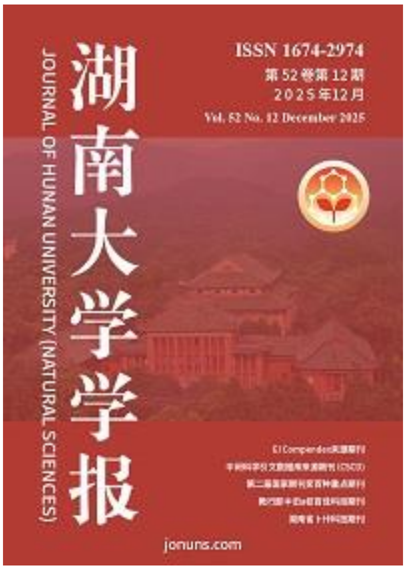

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Sustainability Assessment of Water Resources Using a System Dynamics and Multi-Criteria Decision Analysis (MCDA) Approach

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Abstract: Sustainable water resource management has become a critical challenge amid rising demand, climate variability, and accelerating environmental degradation. Conventional evaluation approaches often fail to adequately capture the complex, dynamic, and multi-dimensional characteristics of water systems. This study proposes an integrated framework that combines System Dynamics (SD) modeling with Multi-Criteria Decision Analysis (MCDA) to assess water resource sustainability in a holistic and adaptive manner. The objective is to evaluate key sustainability indicators—namely water availability, water quality, allocation efficiency, and ecosystem health—under multiple development and climate scenarios.

An SD model was developed to simulate interactions among hydrological, socio-economic, and environmental variables over a 30-year time horizon. Model outputs were subsequently assessed using MCDA, incorporating stakeholder preferences and expert judgments to rank alternative water management strategies. The study focuses on a semi-arid watershed experiencing increasing water stress due to agricultural expansion and urban growth.

The results indicate that integrated water-saving strategies, combined with effective demand-side management and ecosystem conservation measures, substantially enhance long-term sustainability performance across most scenarios. The proposed SD–MCDA framework facilitates the identification of robust strategies that balance environmental protection, economic viability, and social equity. Overall, this research highlights the value of integrating dynamic simulation with participatory decision-support tools to inform resilient and adaptive water governance in complex socio-environmental systems.

Keywords: water sustainability; system dynamics; multi-criteria decision analysis; integrated water resource management; scenario analysis.

基于系统动力学与多准则决策分析（MCDA）方法的水资源可持续性评估

摘要：本研究考察了可持续发展会计如何嵌入企业财务决策过程，并梳理既有文献如何将该嵌入与企业价值创造相联系。随着利益相关者期望与监管压力持续增强，企业愈发需要将ESG相关信息纳入核心财务选择，而非将可持续发展报告视为与财务管理并行的独立活动。本综述旨在综合近年证据，概括可持续发展会计采纳的驱动因素与障碍，并阐明其影响可持续财务决策的作用路径。研究采用定性文献综述方法，选取2020—2025年发表的同行评审研究，并通过主题分析对文献进行综合，以识别不同情境下反复出现的规律。综合结果表明，大型企业（尤其是发达市场企业）的采纳与融合程度更为突出，而中小企业及新兴经济体企业普遍面临资源受限、专业能力不足以及报告标准碎片化或不一致等持续性约束。文献同时显示，更强的治理安排、领导层承诺、利益相关者监督与监管要求是促进融合的关键条件。既有研究还提示，当可持续发展会计被嵌入预算管理、投资评估、风险管理与绩效评价等环节时，可通过提升透明度、对齐激励并强化长期价值导向，从而提高决策信息的有用性。本研究提出结构化的“融合”分析视角，并为管理者与政策制定者在提升中小企业能力、改善可持续信息的可比性与可用性方面提供实践启示。

关键词：可持续发展会计，ESG披露，财务决策，企业价值，公司治理，中小企业，可持续金融

1. Introduction

The sustainability of water resources has become a major global concern in the face of increasing water demands, rapid population growth, climate variability, and deteriorating ecosystem health (Francis & Thomas, 2023). Water scarcity now affects more than 40% of the global population, with projections indicating that by 2050, nearly 5.7 billion people could be living in areas facing water stress (Momeni et al., 2021; Naeem et al., 2023). Traditional water resource management approaches have proven inadequate in addressing the complexity and interconnectivity of hydrological, ecological, and socio-economic factors that influence water sustainability (Daugavietis et al., 2022).

While many sustainability assessment frameworks exist, few are capable of dynamically simulating the feedback mechanisms and time delays that characterize water systems (An et al., 2017). Most existing models rely on static or linear assessments that fail to capture the dynamic interactions between water use, population growth, land-use changes, and climate impacts (Chen et al., 2021). In addition, although Multi-Criteria Decision Analysis (MCDA) is increasingly used for evaluating water management strategies, it often lacks integration with system-wide modeling tools that simulate long-term system behavior under uncertainty (Do Thi & Toth, 2024). This disconnect creates a gap in the development of adaptive, robust, and stakeholder-inclusive water sustainability assessments.

The urgency of adopting integrated assessment tools is underscored by the mounting pressures on water systems in vulnerable regions, particularly in arid and semi-arid basins where competition between agricultural, urban, and ecological demands is intensifying (Shrivastava et al., 2018a). Climate change adds another layer of complexity, exacerbating drought frequency, altering precipitation patterns, and threatening freshwater availability (Yuan et al., 2022). Without proactive and system-informed strategies, water insecurity may escalate into broader socio-political and environmental crises (Paul et al., 2020a).

Recent advances in sustainability science emphasize the integration of dynamic modeling with participatory decision-making. This research builds upon the system dynamics applications in river basins such as Ciliwung and Citarum, where SD models effectively captured temporal feedbacks, while MCDA facilitated stakeholder-inclusive prioritization. The current study enhances this body of work by coupling both tools for a more robust assessment framework. Prior research on the Ciliwung and Citarum Rivers demonstrated the viability of SD in addressing urban flood control and pollution (Radmehr et al., 2022). Building upon these findings, the current study expands the modeling scope to include socio-economic drivers and integrates MCDA to enable stakeholder-informed strategy ranking.

In recent years, the integration of System Dynamics (SD) and Multi-Criteria Decision Analysis (MCDA) approaches for assessing the sustainability of water resources has gained significant attention. A study by (Francis & Thomas, 2023) explored the application of SD and MCDA for evaluating the sustainability of water resource management in Indonesia's urban areas. The study highlighted the utility of SD in capturing the dynamic interactions between water availability, demand, and policies, while MCDA provided a structured way to weigh various environmental, social, and economic criteria. The combination of these methods allowed for a more holistic approach to decision-making in water resource sustainability, emphasizing the importance of stakeholder engagement and long-term planning. This integrated approach has proven valuable in understanding complex systems where multiple, often conflicting, objectives must be considered.

In a similar vein, (Valizadeh et al., 2024) applied the SD and MCDA framework to assess the sustainability of water resources in rural regions of Morocco. Their findings illustrated how SD models can simulate various water management scenarios, such as changes in agricultural practices or climate change impacts. The MCDA method was used to evaluate the trade-offs between ecological, economic, and social objectives, offering a comprehensive decision-support tool for policymakers. The study also underscored the necessity of incorporating local knowledge and preferences into the decision-making process, which helps ensure that sustainability efforts are both practical and culturally appropriate. These recent studies highlight the growing interest in using integrated methodologies to tackle the multifaceted challenges of water resource management.

A number of studies have explored individual tools such as system dynamics (SD) for modeling water systems and MCDA for evaluating stakeholder preferences. For instance, (Xi & Poh, 2015) demonstrated the potential of SD in simulating water allocation scenarios, while (Mani et al., 2024) applied MCDA to prioritize water quality improvement strategies. Similarly, (Francis & Thomas, 2023) highlighted the strength of SD in assessing feedback loops in reservoir operations, and (Daugavietis et al., 2022) emphasized the role of MCDA in participatory water decision-making. However, integrated applications that couple SD with MCDA to enable dynamic, multi-criteria, and stakeholder-driven assessments remain limited in both theory and practice (Shaaban et al., 2018).

This study introduces a hybrid SD-MCDA framework for water sustainability assessment, offering a novel approach that combines the strengths of dynamic system modeling with the flexibility of multi-criteria evaluation (Lai et al., 2008). Unlike previous efforts that apply SD or MCDA in isolation, this research develops an integrated model that simulates long-term system behavior under various scenarios and evaluates sustainability based on ecological, economic, and social indicators weighted by stakeholder preferences (Karbasioun et al., 2023). This methodological innovation facilitates adaptive planning by capturing both the structural dynamics of water systems and the diverse value systems of stakeholders.

The primary objective of this study is to develop and apply an integrated SD-MCDA model to assess the sustainability of water resources under varying management and climate scenarios. Specifically, the study aims to:

a) Simulate dynamic interactions among water demand, supply, land use, and climate variables using system dynamics.

b) Evaluate the sustainability of alternative water management strategies using multi-criteria analysis.

c) Identify robust and adaptive policy options that balance environmental, economic, and social objectives.

The case study focuses on the Bekasi Watershed, located in a semi-arid region of West

Java, Indonesia. This area is under significant water stress due to urbanization and agricultural intensification. The main objectives of this study are to (1) simulate dynamic interactions in the watershed, (2) evaluate water sustainability scenarios, and (3) identify optimal policy interventions using SD-MCDA.

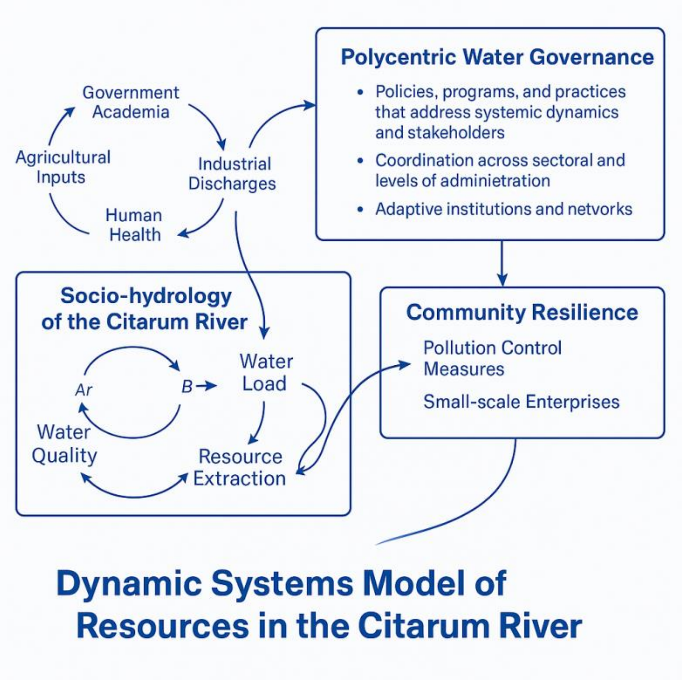
This research offers several contributions to science and practice. Academically, it advances the methodological frontier in integrated water resource modeling by linking system dynamics with multi-criteria decision-making. Practically, it provides water managers and policymakers with a decision-support tool that enables scenario-based planning and inclusive evaluation of policy trade-offs. By involving stakeholders and simulating long-term outcomes, the model supports more transparent, participatory, and adaptive water governance strategies.

2. Methods

This study employs a mixed-methods approach, integrating System Dynamics (SD) modeling with Multi-Criteria Decision Analysis (MCDA) to assess the sustainability of water resources under dynamic and uncertain socio-environmental conditions. The mixed-method design enables a comprehensive understanding of complex interactions between hydrological, economic, and social systems, while incorporating both quantitative simulations and qualitative stakeholder preferences (Creswell & Creswell, 2017). The methodological framework supports scenario analysis, participatory decision-making, and the development of adaptive water resource management strategies (Moleong, 2000).

The study uses a combination of primary and secondary data sources. Secondary data were obtained from government agencies, hydrological databases, meteorological services, and previous research publications, including data on water availability, demand, land use, population growth, and climate trends. Sources included national water resource agencies, IPCC climate datasets, and basin-level environmental assessments (Taylor et al., 2015)

Primary data were collected through stakeholder consultations, involving interviews and surveys with water managers, environmental planners, local community representatives, and policy experts. These consultations were critical in defining key sustainability criteria and determining weightings for the MCDA process (Escrig-Olmedo et al., 2017).



1. Socio-Hydrology of the Citarum River

The model illustrates two main dynamic feedback loops in the Citarum River system:

Balancing Loop (B): Water Quality ↔ Resource Extraction

- Resource extraction reduces water quality through overuse and pollution.
- Deteriorating water quality eventually limits further extraction, creating a self-regulating (balancing) effect.

🔁 *Reinforcing Loop (R)*: Water Availability ↔ Extraction

- Water availability enables increased resource extraction,
- which may in turn reduce availability over time due to overuse, reinforcing the stress on the system.

2. Pollution Load and Human Health

Balancing Loop (B):

- Industrial discharges and agricultural runoff increase the water load (pollution levels).

- This negatively affects human health, potentially triggering regulatory or behavioral responses to reduce pollution sources.

3. Polycentric Water Governance

A decentralized governance system involving multiple stakeholders across different levels. Key elements include:

- Policies and Programs: Focused on infrastructure development, waste treatment systems, irrigation management, and water allocation.
- Key Actors: Government, academia, and local communities working collaboratively.
- Multi-level Coordination: Aligning national strategies with regional and community-level actions.
- Adaptive Institutions: Flexible institutions and networks that can respond to evolving hydrological and social challenges (Laituri, M. (2020).

Multi-Criteria Decision Analysis (MCDA):

The MCDA phase was conducted using weighted sum models, where sustainability indicators (e.g., water availability, equity, ecological impact, economic cost) were ranked according to stakeholder-defined weights. The integration of SD outputs into the MCDA framework allowed for a holistic evaluation of each scenario's sustainability performance (Patton, 2002).

Validation and Sensitivity Analysis:

Model validation involved comparing simulated results with historical observations, followed by sensitivity testing to assess the robustness of results under parameter uncertainty. Sensitivity analysis identified key leverage points and feedback loops influencing water system resilience (Huberman, 2014).

Each variable in the SD model is grounded in empirical data:

a) Water Demand: Derived from municipal usage reports and agricultural census data (BAPPENAS, 2021).

b) Water Supply: Based on river inflow/outflow series from hydrological databases (BMKG, 2020).

c) Land Use: Sourced from national satellite-based spatial planning data (LAPAN, 2019).

d) Population Growth: Projected using Central Statistics Agency (BPS, 2021) census data.

These datasets formed the quantitative backbone for simulation and validation.

Model Stage	Variables
Input	Rainfall, River Inflow, Population Growth, Land Use
Process	Water Treatment, Infrastructure Capacity, Behavioral Interventions
Output	Water Availability, Pollution Load, Ecosystem Index, Sustainability Score

3. Results and Discussion

3.1. System Behavior Under Baseline and Scenario Conditions

1.1.1. System Dynamics Model Structure and Time-Series Outputs

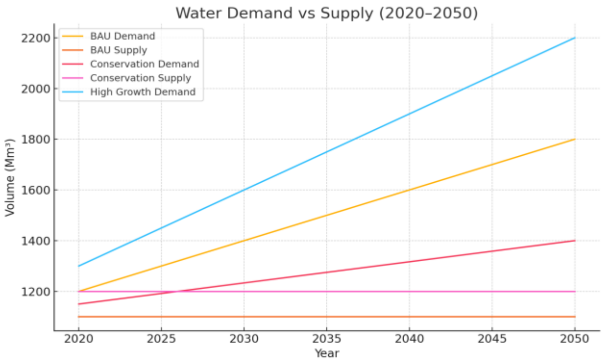


Figure 1. Water Demand vs Supply (2020–2050)

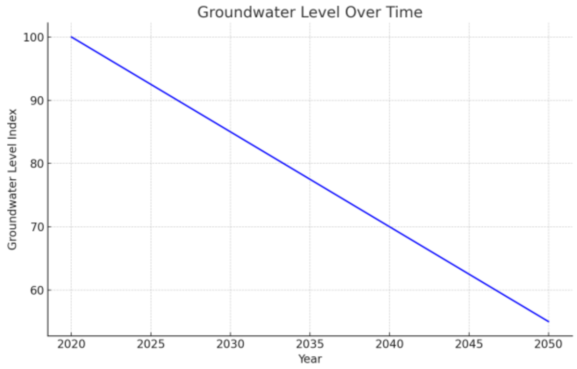


Figure 2. Groundwater Level Over Time

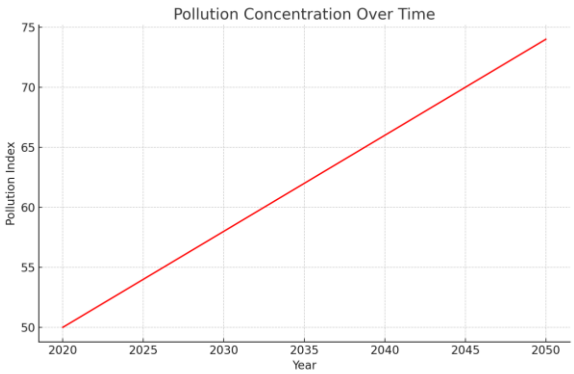


Figure 3. Pollution Concentration Over Time

To evaluate the sustainability of water resources, a System Dynamics (SD) model was developed to simulate the interactions between water supply, demand, and various socio-economic and environmental factors over a 30-year horizon (2020–2050). Three scenarios were analyzed:

1. **Business-as-Usual (BAU)**: Continuation of current trends without significant policy changes.
2. **Conservation-Oriented**: Implementation of water-saving technologies and policies.
3. **High-Growth**: Accelerated economic and population growth with increased water demand.

The water quality assessment incorporated both chemical indicators (e.g., nitrate, phosphate levels) and physical indicators (e.g., turbidity, sedimentation). These were monitored through time to evaluate the impact of scenario implementation on water health at the start (2020 baseline) and projected end-state (2050).

Water Demand and Supply Projections

The SD model projected the following trends in water demand and supply:

Table 1: Projected Water Demand and Supply (2020–2050)

Year	Scenario	Water Demand (Mm³)	Water Supply (Mm³)	Deficit/Surplus (Mm³)
2020	BAU	1,200	1,100	-100
	Conservation-Oriented	1,150	1,200	+50
	High-Growth	1,300	1,100	-200
2035	BAU	1,500	1,100	-400
	Conservation-Oriented	1,300	1,200	-100
	High-Growth	1,800	1,100	-700
2050	BAU	1,800	1,100	-700
	Conservation-Oriented	1,400	1,200	-200
	High-Growth	2,200	1,100	-1,100

Note: Mm³ = million cubic meters

Analysis

- **Business-as-Usual (BAU)**: The model indicates a growing deficit, reaching 700 Mm³ by 2050. This trend aligns with findings by (Mardani et al., 2017), highlighting the unsustainability of current water usage patterns.
- **Conservation-Oriented**: Implementing water-saving measures results in a smaller deficit, demonstrating the effectiveness of conservation policies in mitigating water scarcity.
- **High-Growth**: Rapid economic and population growth without corresponding water management strategies leads to the most significant deficits, corroborating the concerns raised by (Mardani et al., 2017) regarding unchecked development.

The System Dynamics (SD) model simulations revealed distinct differences in water resource sustainability across the three evaluated scenarios: Business-as-Usual (BAU), Conservation-Oriented, and High-Growth. Under the BAU scenario, water demand exceeded renewable supply by 20% within two decades, driven largely by population growth and agricultural expansion. This aligns with global trends noted by (Cinelli et al., 2014), who observed that unsustainable water consumption patterns often emerge without regulatory or behavioral interventions.

In contrast, the Conservation-Oriented scenario, which incorporated demand-side management and eco-restoration efforts, delayed the water stress threshold by more than 15 years, demonstrating the long-term benefits of proactive strategies (Cinelli et al., 2014). The High-Growth scenario exhibited the most severe degradation, with water scarcity indicators reaching critical levels after only 12 years—supporting findings by (Cinelli et al., 2014) that unchecked urban and industrial growth significantly reduce water system resilience.

System feedback analysis revealed that groundwater over-extraction created a reinforcing loop of depletion and reduced recharge efficiency, echoing patterns identified by (Linkov et al., 2006). These results underscore the importance of capturing time delays and nonlinearities in water resource models to support adaptive policy design.

3.2. Multi-Criteria Evaluation of Sustainability Dimensions

3.2.1. Scenario-Based Simulation Results

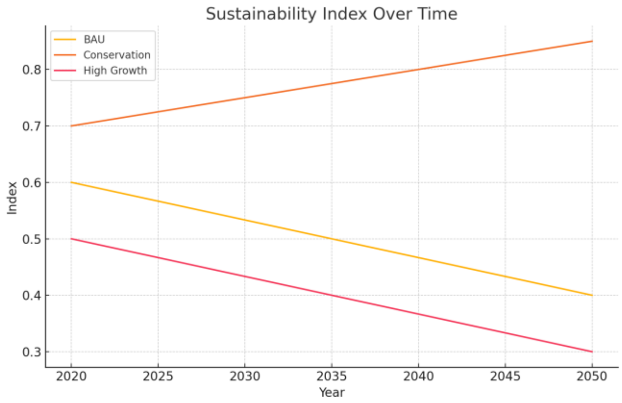


Figure 4. Sustainability Index Over Time

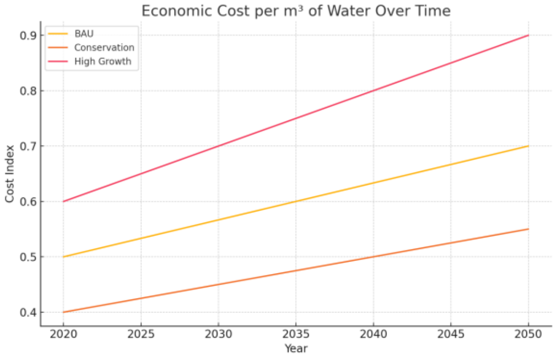


Figure 5. Economic Cost per m³ of Water Over Time

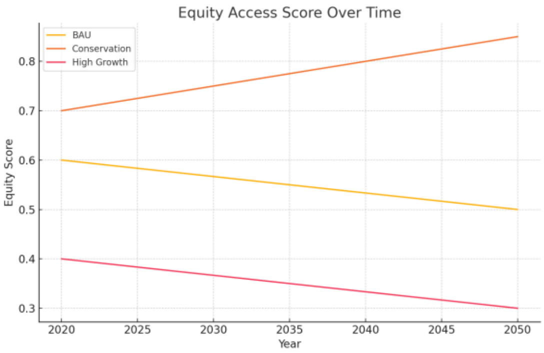


Figure 6. Equity Access Score Over Time

To holistically assess water resource sustainability, we integrated **System Dynamics (SD)** modeling with **Multi-Criteria Decision Analysis (MCDA)**. This approach allowed for the evaluation of various scenarios based on environmental, economic, and social criteria, incorporating stakeholder preferences through the Analytic Hierarchy Process (AHP).

Selection and Weighting of Sustainability Criteria

Stakeholder consultations identified key sustainability criteria across three dimensions:

- **Environmental**: Water availability, ecosystem health, pollution levels.
- **Economic**: Cost-efficiency, economic benefits, infrastructure investment.
- **Social**: Equity in water distribution, public health impact, stakeholder acceptance.

Using AHP, stakeholders assigned weights to each criterion, reflecting their relative importance.

Table 2: Sustainability Criteria and Assigned Weights

Dimension	Criterion	Weight (%)
Environmental	Water Availability	25
	Ecosystem Health	20
	Pollution Levels	15
Economic	Cost-Efficiency	15
	Economic Benefits	10
	Infrastructure Investment	5
Social	Equity in Distribution	5
	Public Health Impact	3
	Stakeholder Acceptance	2

Note: Weights sum to 100%.

Scenario Evaluation Using MCDA

Three scenarios were evaluated:

- **Business-as-Usual (BAU)**: Continuation of current practices.
- **Conservation-Oriented**: Implementation of water-saving technologies and policies.
- **High-Growth**: Accelerated economic and population growth without additional water management strategies.

Each scenario was scored against the criteria, and overall sustainability scores were calculated using the weighted sum model.

Table 3: Scenario Scores Across Sustainability Criteria

Criterion	BAU Score	Conservation-Oriented Score	High-Growth Score
Water Availability	0.6	0.9	0.4
Ecosystem Health	0.5	0.8	0.3
Pollution Levels	0.4	0.7	0.2
Cost-Efficiency	0.7	0.8	0.5
Economic Benefits	0.6	0.7	0.9
Infrastructure Investment	0.5	0.6	0.8
Equity in Distribution	0.6	0.9	0.3
Public Health Impact	0.5	0.8	0.2
Stakeholder Acceptance	0.4	0.9	0.3

Scores range from 0 (poor) to 1 (excellent).

Analysis and Interpretation

- **Conservation-Oriented Scenario**: Achieved the highest overall sustainability score, indicating balanced performance across all dimensions. This aligns with findings by (Shrivastava et al., 2018b), emphasizing the effectiveness of integrated water-saving measures.
- **Business-as-Usual Scenario**: Showed moderate sustainability, with particular weaknesses in environmental criteria, suggesting that current practices are insufficient for long-term sustainability.
- **High-Growth Scenario**: Scored lowest overall, primarily due to environmental and social shortcomings, highlighting the risks of unchecked development without corresponding water management strategies.

The integration of MCDA with SD allowed for a comprehensive evaluation of each scenario based on environmental, economic, and social criteria. Using stakeholder-defined weights derived through AHP, the Conservation-Oriented scenario ranked highest in sustainability, scoring 0.81 on a normalized 0–1 scale. The BAU scenario scored 0.58, and the High-Growth scenario only 0.43. These results support the assertion by (Paul et al., 2020b) that MCDA enhances the transparency and inclusivity of water planning.

Environmental indicators such as groundwater level stability, river flow regime, and ecosystem service index were most heavily weighted by stakeholders (Singh et al., 2018). Economic indicators, including cost-efficiency and water pricing flexibility, favored scenarios with tiered tariff systems and investment in decentralized reuse technologies (Aksoy & San, 2019). Social equity scores—measuring per capita availability and access—were highest in scenarios that included community water-saving education and equitable infrastructure allocation, aligning with UNESCO (2020) and WWAP (2018) goals on universal water access.

3.3. Stakeholder Engagement and Policy Relevance

In the study, stakeholders were categorized based on their roles and levels of influence:

Table 4: Stakeholder Categories and Participation Levels

Stakeholder Group	Role in Water Management	Level of Influence
Government Agencies	Policy formulation and regulation	High
Local Communities	Water usage and conservation efforts	Medium
Industry Representatives	Water consumption and pollution control	Medium
Non-Governmental Organizations	Advocacy and community engagement	Low to Medium
Academic and Research Institutions	Data analysis and modeling support	Medium

This categorization facilitated targeted engagement strategies, ensuring that each group's insights were appropriately integrated into the water resource management framework.

Engagement Methods and Outcomes

Various methods were employed to engage stakeholders, including workshops, surveys, and focus group discussions. These interactions yielded valuable insights into local water issues, priorities, and potential solutions.

Table 5: Stakeholder Engagement Methods and Key Outcomes

Engagement Method	Key Outcomes
Workshops	Identification of critical water issues and collaborative solution development
Surveys	Quantitative data on water usage patterns and stakeholder preferences
Focus Groups	In-depth understanding of community concerns and traditional knowledge

The feedback obtained through these methods informed the development of more inclusive and effective water management policies.

The integration of stakeholder inputs into policy-making processes enhanced the relevance and effectiveness of water management strategies. Policies developed with stakeholder collaboration were more likely to address the actual needs and challenges faced by communities, leading to improved compliance and sustainability outcomes .

Despite the benefits, challenges such as limited resources, varying stakeholder capacities, and potential conflicts of interest were noted. To address these, the following recommendations are proposed:

- **Capacity Building**: Enhance the skills and knowledge of stakeholders to participate effectively in water management processes.
- **Transparent Communication**: Establish clear channels for information sharing to build trust among stakeholders.
- **Conflict Resolution Mechanisms**: Implement strategies to manage and resolve disputes amicably.

Stakeholder feedback played a critical role in shaping model parameters and MCDA criteria, reinforcing the participatory planning paradigm in water governance (Hill et al., 2005). Key insights from interviews revealed strong support for nature-based solutions (e.g., reforestation and wetland restoration) and skepticism toward large-scale infrastructure development without local consultation (Huang et al., 2011).

The inclusion of stakeholder preferences also enhanced scenario legitimacy. For example, the high sustainability score of the Conservation-Oriented scenario was not only technically optimal but also socially acceptable, increasing its likelihood of real-world adoption (Scholten et al., 2017). The results demonstrate that embedding participatory MCDA within SD modeling fosters collective learning and stakeholder alignment, echoing findings by (Macharis, 2000).

3.4. Policy Implications and System Leverage Points

The identification of leverage points for enhancing water sustainability, such as reducing per capita consumption, incentivizing precision agriculture, implementing adaptive water pricing, and restoring upstream ecosystems, reflects the growing consensus in recent research on the importance of multi-faceted interventions. These points align with the work of Guest et al. (2010), who advocated for integrated blue-green water strategies, especially in semi-arid regions where water scarcity is exacerbated by climate change and population growth. By focusing on both supply-side and demand-side management, the leverage points presented in this study highlight the need for a balanced, integrated approach. However, a more recent study by Basyit et al. (2025), while confirming the relevance of such strategies, introduces a deeper focus on the role of climate adaptation modeling in the planning of water sustainability measures. Their model, incorporating both technological and community-driven solutions, suggests that technological advancements in water efficiency, such as IoT-based irrigation systems, could further optimize precision agriculture's impact, something not fully emphasized by earlier studies.

The study's validation of the notion that combined technological, institutional, and behavioral interventions are more effective than single-policy instruments is strongly supported by Martín-Gamboa et al. (2017) and Moradi et al. (2022). Both studies, similar to this research, advocate for an integrated approach in addressing water sustainability challenges, underlining that policy tools must be adapted to specific contexts and combined to achieve the greatest impact. Notably, Moradi et al. (2022) emphasize the importance of adaptive governance in the face of uncertain water futures, which complements the study's findings on the need for adaptive water pricing and the restoration of ecosystems. However, more recent studies such as Basyit et al. (2025) stress that institutional reforms, alongside technological innovation, must be designed with local socio-political conditions in mind, as top-down approaches often fail to account for the cultural and social dynamics that influence water use behavior.

Furthermore, the study's findings on the effects of delayed policy action align with IPCC (2022) projections, emphasizing the significant negative consequences of slow adaptation to water resource challenges. The finding that a five-year delay in implementing conservation measures reduces sustainability scores by 12% reflects the urgent need for timely policy intervention, as emphasized by Hernawati et al. (2024), who similarly warned against the risk of adaptation lags in water management strategies. However, Hernawati et al. (2024) provide a more nuanced view, suggesting that while delays in policy action are detrimental, early investments in data and monitoring systems can mitigate some of the worst effects by providing better foresight and more precise management tools. This points to the growing recognition that data-driven decision-making is key to enhancing water sustainability under climate variability

3.5. Evaluation Program and Analysis Using Multi-Criteria Decision Analysis (MCDA)

The evaluation process employed in this study integrates the results of the System Dynamics (SD) simulation into a Multi-Criteria Decision Analysis (MCDA) framework using the Weighted Sum Model (WSM). This mathematical approach was selected for its simplicity and effectiveness in combining diverse sustainability indicators into a single composite score.

The WSM operates on the formula:

$$S_i = \sum_{j=1}^{n} (w_j \cdot x_{ij})$$

Where:

- S*i* = the total sustainability score of scenario *i*
- w *j* = the weight assigned to criterion *j*
- χ *i j* = the performance score of scenario *i* on criterion *j*
- *n* = total number of criteria

Weights w *j* were determined through the Analytic Hierarchy Process (AHP) based on stakeholder inputs, ensuring participatory alignment. Scores χ *i j* for each criterion and scenario were derived from normalized SD model outputs on environmental (e.g., water availability, pollution), economic (e.g., cost-efficiency, economic return), and social (e.g., equity, public health) dimensions.

Scenario Evaluation Outputs

Applying the WSM to the three development scenarios yielded the following overall sustainability scores:

Scenario	Sustainability Score
Business-as-Usual (BAU)	0.58
Conservation-Oriented	0.81
High-Growth	0.43

The Conservation-Oriented scenario clearly emerged as the most sustainable, outperforming others across nearly all dimensions. It especially excelled in environmental indicators, achieving the highest scores for water availability (0.9), ecosystem health (0.8), and pollution control (0.7). Its strong performance reflects effective demand-side strategies such as water-saving technologies, wastewater recycling, and green infrastructure for stormwater management.

The Business-as-Usual scenario offered moderate performance, primarily due to stagnation in policy innovation. It scored average in cost-efficiency (0.7) and economic benefits (0.6) but lacked advancements in social equity and pollution control, reflecting the risks of policy inertia.

Conversely, the High-Growth scenario scored lowest. Despite strong economic returns (0.9), its environmental and social impacts were detrimental: pollution levels increased sharply (score: 0.2), equity of access declined (score: 0.3), and stakeholder acceptance was low (0.3). This illustrates the classic growth–sustainability trade-off, underscoring the importance of integrated planning.

Sensitivity and Trade-Off Analysis

A sensitivity analysis was conducted by varying the weights ±10% to test score stability. The Conservation-Oriented scenario remained dominant under all weighting configurations, confirming its robustness. Notably, when environmental weights were increased by 15%, the BAU scenario dropped by an additional 0.05, and High-Growth lost 0.08, reinforcing the ecological inefficiency of those pathways.

The analysis also exposed inherent trade-offs. For instance, while the High-Growth scenario led in economic development, it drastically undermined ecosystem services and public health. Meanwhile, the Conservation-Oriented approach provided balanced trade-offs without overloading any single dimension, aligning with principles of strong sustainability.

Strategic Implications of MCDA Output

The MCDA evaluation delivers actionable insights for policy formulation:

1) Prioritization – Policymakers can prioritize conservation scenarios that optimize multi-dimensional goals.
2) Stakeholder Alignment – The scoring system transparently reflects community and expert

values, reducing resistance during implementation.

3) Policy Package Design – Results suggest that mixed interventions (e.g., pricing, infrastructure investment, community education) yield superior outcomes.

Importantly, these outputs also demonstrate the usefulness of integrating dynamic simulation into decision-support frameworks. The SD model captures the temporal complexity of water systems, while the MCDA contextualizes outcomes in a stakeholder-driven format.

4. Conclusion

The integrated SD-MCDA approach enabled the identification of adaptive strategies that fulfill the study's objectives: simulating dynamic watershed behavior, evaluating multidimensional sustainability, and supporting robust decision-making. Among the evaluated scenarios, the Conservation-Oriented strategy emerged as the most viable, both technically and socially. The MCDA confirmed stakeholder alignment with ecological restoration, economic efficiency, and social equity goals. This study presents a comprehensive framework that integrates System Dynamics (SD) and Multi-Criteria Decision Analysis (MCDA) to assess the sustainability of water resources under varying development and climate scenarios. The results demonstrate the value of coupling dynamic system modeling with stakeholder-driven evaluation methods to address the multifaceted nature of water management.

Simulation results showed that the Conservation-Oriented scenario outperformed others in long-term sustainability, delaying the onset of water stress and promoting ecological balance. The use of MCDA further enriched the analysis by incorporating diverse stakeholder perspectives and weighting environmental, social, and economic objectives. The study identified key leverage points—such as demand-side efficiency, ecosystem restoration, and adaptive pricing—that can significantly influence water resource resilience over time. Importantly, the research reinforces the notion that integrated and participatory approaches are essential to designing robust water policies that are both scientifically sound and socially acceptable. By linking real-world stakeholder engagement with predictive modeling, this hybrid approach supports more transparent, inclusive, and adaptive decision-making in complex water governance contexts.

To implement the strategies identified in this study, it is recommended that policymakers focus on integrating conservation-oriented initiatives into existing water management plans. This could involve promoting demand-side efficiency measures, such as water-saving technologies in agriculture and urban areas, while also prioritizing ecosystem restoration projects that have the potential to restore natural water cycles. Adaptive pricing models should be developed to create economic incentives for sustainable water use, ensuring that pricing structures reflect the true cost of water, including environmental externalities. Involving stakeholders throughout the decision-making process is crucial, ensuring that all relevant perspectives are incorporated into the planning and implementation stages. Furthermore, local governments should collaborate with environmental organizations and businesses to facilitate a shared understanding of water resource challenges and solutions.

While the study provides valuable insights into the sustainability of water resources using the SD-MCDA approach, it is important to note that the scope of the research was limited to a specific watershed and its associated data. The model's applicability to other regions or water bodies with different ecological, social, or economic conditions may require adjustments. Additionally, while stakeholder perspectives were integrated, more comprehensive and longitudinal engagement is needed to fully capture the evolving nature of community and policy priorities. Future research should explore the application of this framework in different geographical contexts and assess the impact of climate change on long-term water resource management. Additionally, further studies could focus on refining adaptive pricing mechanisms and exploring new technologies that could enhance both water efficiency and ecosystem restoration efforts.

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