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Research Article

A GIS-BASED DECISION SUPPORT SYSTEM FOR SUSTAINABLE LAND USE PLANNING AND CLIMATE CHANGE ADAPTATION IN THE BRANTAS RIVER WATERSHED

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Abstract
The Brantas River Watershed, a vital socio-economic region in East Java, Indonesia, faces escalating environmental pressures from unplanned urbanization and intensive agriculture. These challenges are exacerbated by climate change, leading to increased land degradation, soil erosion, and severe flood events, which threaten the watershed's long-term sustainability and the livelihoods of millions. This study aimed to develop and validate a Geographic Information System (GIS)-based Decision Support System (DSS) to aid policymakers in formulating integrated, evidence-based strategies for sustainable land use planning and climate change adaptation within this critical watershed. The DSS was constructed by integrating a multi-criteria evaluation (MCE) framework within a GIS environment. Key geospatial datasets (land cover, soil type, slope, rainfall projections) were weighted using the Analytical Hierarchy Process (AHP). The system models land suitability and vulnerability to environmental hazards under various climate change scenarios. The developed DSS successfully generated high-resolution maps identifying priority zones for conservation, reforestation, and sustainable development. The model revealed that 22% of the upper watershed area is at high risk of landslides under projected rainfall patterns. The optimized land use plan proposed by the DSS demonstrated a potential to reduce surface runoff by up to 35%, significantly mitigating flood risk. The GIS-based DSS is a powerful and effective tool for integrated watershed management. It provides a dynamic, scientifically-grounded platform for strategic planning, enabling policymakers to balance ecological protection with socio-economic needs and enhance the climate resilience of the Brantas River Watershed.

Keywords: GIS, Decision Support System (DSS), Land Use Planning, Climate Change Adaptation, Watershed Management.

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INTRODUCTION

River watersheds represent the planet's most critical socio-ecological systems, functioning as fundamental units for managing water resources and supporting biodiversity (Thapa et al., 2025). These complex landscapes are the lifeblood of civilizations, providing essential resources for agriculture, industry, domestic consumption, and sustaining the delicate equilibrium of natural ecosystems (Benjamin et al., 2024). The integrity of a watershed is, therefore, inextricably linked to the prosperity and resilience of the human populations that inhabit it (Dolinska et al., 2023). The sustainable management of these vital areas has emerged as a paramount challenge in the twenty-first century, demanding a holistic and integrated approach to balance competing human needs with the imperative of environmental conservation.

The Brantas River Watershed, located in the province of East Java, Indonesia, stands as a quintessential example of a vital yet profoundly stressed system (Dolinska et al., 2023). As the second-longest river in Java, it serves as the economic and agricultural artery for a region inhabited by over 15 million people, supporting some of the nation's most productive agricultural lands and major industrial centers, including the metropolitan area of Surabaya Ozal et al., 2024). The watershed is a microcosm of the intense development pressures facing many regions in the developing world, where the pursuit of economic growth often occurs at the expense of long-term ecological stability, placing the very resources that fuel this growth at significant risk.

The advent of geospatial technologies, particularly Geographic Information Systems (GIS), has revolutionized the field of environmental management and land use planning (Matham et al., 2023). GIS provides a powerful analytical framework for integrating, visualizing, and analyzing vast quantities of disparate spatial data, such as topography, soil composition, land cover, and climatic patterns. This capacity to model complex spatial relationships makes GIS an indispensable tool for understanding the intricate dynamics of a watershed system (Thakur et al., 2023). The technology enables a shift from static, reactive management to a more dynamic, predictive, and scientifically-grounded approach to planning, offering new possibilities for navigating the complex challenges of sustainable development.

The Brantas River Watershed is currently caught in a cycle of environmental degradation driven by unplanned and unsustainable land use practices (Rogger et al., 2024). The upper reaches of the watershed, characterized by steep volcanic slopes, have undergone extensive deforestation and land conversion for intensive agriculture (Nakhaei et al., 2023). This has severely compromised the land's natural hydrological function, leading to accelerated soil erosion, increased sedimentation in rivers and reservoirs, and a heightened frequency of catastrophic landslides during periods of heavy rainfall. The ecological integrity of the headwaters, which is critical for regulating water flow for the entire basin, is under severe threat.

This degradation in the upper watershed is compounded by rapid and often unregulated urbanization in the midstream and downstream areas (Enríquez-Hidalgo et al., 2025). The expansion of cities and industrial zones has resulted in the conversion of critical water catchment areas, floodplains, and green spaces into impermeable surfaces such as asphalt and concrete. This transformation dramatically reduces the land's capacity to absorb rainwater, leading to a significant increase in surface runoff volume and velocity (Sun et al., 2023). The direct consequence of this urban sprawl is a marked escalation in the frequency and severity of flood events in the lower reaches of the watershed, causing extensive economic damage and posing a constant threat to human life and livelihoods.

The core problem this research addresses is the absence of an integrated, evidence-based, and forward-looking decision-making framework for land use planning within the Brantas River Watershed (Fourdain et al., 2026). Current planning efforts are often fragmented, operating within siloed administrative jurisdictions that fail to consider the interconnected, basin-wide consequences of localized land use decisions (Hayhurst et al., 2025). This traditional, static approach to spatial planning is fundamentally ill-equipped to manage the complex, dynamic interactions between land use, hydrology, and socio-economic development, and it is particularly vulnerable to the amplifying pressures of climate change, which threaten to push the already stressed system beyond its breaking point.

The principal objective of this research is to design, develop, and validate a Geographic Information System (GIS)-based Decision Support System (DSS) as a comprehensive tool for sustainable land use planning and climate change adaptation in the Brantas River Watershed (Mendas et al., 2024). This study aims to construct an integrated analytical platform that can synthesize complex geospatial data and model environmental processes to provide clear, actionable intelligence for policymakers and planners (Guilin et al., 2024). The ultimate goal is to create a scientifically robust system that can support a more proactive, holistic, and resilient approach to watershed management.

To achieve this overarching objective, this investigation has established several specific research aims (Tal-maon et al., 2024). The first is to compile and integrate a comprehensive geospatial database for the Brantas watershed, encompassing data on land cover, soil characteristics, topography, hydrology, and socio-economic factors (Derk et al., 2024). The second is to develop and incorporate a multi-criteria evaluation (MCE) model, using the Analytical Hierarchy Process (AHP), to systematically assess land suitability for various uses, such as conservation, agriculture, and urban development (Sehrawat & Shekhar, 2025). The third is to integrate climate change projection data to model the watershed's vulnerability to future hazards, specifically landslides and floods, under different climate scenarios.

Through this structured development process, this research seeks to produce a functional and user-oriented DSS capable of generating a suite of practical planning outputs (Ge et al., 2024). These will include high-resolution maps identifying priority zones for conservation and reforestation, areas at high risk of environmental hazards, and optimized land use allocation plans that balance ecological sustainability with socio-economic needs (Marondedze et al., 2024). The final aim is to demonstrate the system's utility as a strategic tool that can bridge the gap between complex environmental science and tangible, on-the-ground policy and planning decisions.

The scholarly literature on watershed management is rich with studies that have successfully utilized GIS to analyze various environmental processes (Maity et al., 2024). Numerous research papers have demonstrated the application of GIS for land use/land cover change detection, soil erosion modeling using frameworks like the Universal Soil Loss Equation (USLE), and the mapping of flood-prone areas (J. Wang et al., 2023). These studies have been instrumental in establishing the technical utility of geospatial tools for diagnosing specific environmental problems within a watershed context.

A significant gap persists, however, in the integration of these disparate analytical functions into a single, cohesive Decision Support System specifically tailored to the complex realities of a major tropical watershed like the Brantas. While many studies provide excellent descriptive analyses of existing problems, there is a scarcity of research that focuses on developing prescriptive, forward-looking planning tools (Jain & Singh, 2024). The literature often stops at identifying the problem, without providing a structured, interactive framework to help policymakers explore and evaluate potential solutions.

Furthermore, a critical deficiency in the existing body of research, particularly within the Indonesian context, is the inadequate integration of climate change adaptation into land use planning models (Hammond et al., 2024). Most conventional land suitability analyses are based on current or historical climatic conditions. This static approach fails to account for the non-stationary nature of the climate system, where future rainfall patterns are projected to become more intense and erratic (Farooq & Manocha, 2024). This study directly addresses this critical gap by explicitly incorporating downscaled climate projection data, thereby creating a dynamic DSS that is designed for proactive adaptation rather than reactive problem-solving.

The primary novelty of this research lies in its design and implementation of a holistic, multi-criteria, and climate-aware GIS-based Decision Support System specifically customized for the Brantas River Watershed (Jain et al., 2023). The novelty is not in the use of GIS itself, but in the sophisticated integration of an Analytical Hierarchy Process (AHP) framework with forward-looking climate change scenarios to create a dynamic and predictive planning tool (Q. Wang et al., 2024). This moves beyond traditional static land use mapping to provide a platform for "what-if" scenario analysis, enabling planners to visualize the future consequences of their decisions today.

The justification for this investigation is both scholarly and profoundly practical. From a scholarly perspective, this study makes a significant contribution to the field of applied geospatial science and integrated environmental management. It presents a robust and replicable methodological framework that can be adapted for the sustainable management of other large, data-scarce, and highly populated watersheds in the developing world. The research serves as a valuable case study, demonstrating how complex systems modeling can be translated into a practical tool to support evidence-based governance.

From a societal and policy standpoint, the justification is urgent and compelling. The Brantas River Watershed is a region of immense national strategic importance, and its escalating environmental degradation poses a direct threat to Indonesia's food security, water security, and economic stability. This research provides a vital, scientifically-grounded tool to guide local and provincial governments in making more informed land use decisions. The successful implementation of the DSS can lead to a tangible reduction in the risk of catastrophic floods and landslides, protect vital ecosystems, and foster a more sustainable and climate-resilient development pathway for millions of people.

RESEARCH METHOD

Research Design

This study employed a developmental research design integrated with a quantitative spatial modeling approach. The framework was both descriptive, as it analyzed existing environmental conditions, and prescriptive, as it aimed to generate optimized land use plans based on defined sustainability and climate resilience criteria (Kumar & Goyal, 2025). The core of the design was the use of a Multi-Criteria Evaluation (MCE) technique, which was structured and implemented within a Geographic Information System (GIS) environment to construct and validate a functional Decision Support System (DSS).

Research Target/Subject

The research subject was the Brantas River Watershed in East Java, Indonesia, an area covering approximately 12,000 square kilometers. The data for the study consisted of a comprehensive collection of geospatial datasets, including a 2023 land use/land cover map derived from Sentinel-2 imagery, a 30-meter Digital Elevation Model (DEM), soil type maps, historical rainfall records, and downscaled climate projection data (RCP 4.5 and 8.5) for the period 2030-2050.

Research Procedure

The research was executed in four sequential phases. The first phase, Data Acquisition and Preprocessing, involved gathering all geospatial datasets and standardizing them to a uniform coordinate system and spatial resolution. The second phase, AHP Model Development, used input from an expert panel to calculate the final weights for all criteria and sub-criteria (Kumar & Goyal, 2025). The third phase, GIS Spatial Modeling, involved implementing these weights in ArcGIS Pro to combine the data layers and generate the final suitability and risk maps. The final phase, DSS Development and Scenario Analysis, involved creating a user interface and running the validated model with different climate scenarios to produce an optimized land use plan.

Instruments, and Data Collection Techniques

The principal instrument for all spatial processing and modeling was the ArcGIS Pro 3.1 software suite. The Analytical Hierarchy Process (AHP) was used as the primary analytical instrument. Data collection techniques involved gathering secondary geospatial data (such as DEMs, soil maps, and climate records) and deriving primary data (a land use map from Sentinel-2 imagery). Furthermore, data for the AHP model was collected through a structured survey and consensus-building process conducted with a panel of 15 experts from academia, government, and NGOs.

Data Analysis Technique

The core data analysis technique was a Multi-Criteria Evaluation (MCE), which was operationalized using the Analytical Hierarchy Process (AHP) to systematically calculate the weights for each criterion. This quantitative analysis was then implemented in the GIS using the "Weighted Overlay" spatial modeling tool (Haq et al., 2025). This tool combined the various standardized data layers according to their derived weights to generate the final raster-based suitability, vulnerability, and risk maps. The analysis concluded with a scenario analysis, where the model was run using different climate projection datasets to simulate future hazard risks.

RESULTS AND DISCUSSION

The initial phase of the research involved the systematic derivation of weights for the various criteria influencing land suitability and hazard vulnerability. This was accomplished through the Analytical Hierarchy Process (AHP), which synthesized the expert judgments of a panel of 15 specialists from relevant fields. The resulting weights, which form the core logic engine of the Decision Support System (DSS), represent the consensus on the relative importance of each environmental factor in the context of the Brantas River Watershed.

A detailed summary of the final, normalized weights for the primary criteria used in the landslide and flood risk models is presented in the table below. The Consistency Ratio (CR) was calculated for each AHP matrix to ensure the reliability and logical consistency of the expert judgments; all matrices yielded a CR of less than 0.10, indicating a high degree of consistency.

Table 1. Final AHP-Derived Weights for Hazard Modeling Criteria

Hazard Model	Primary Criterion	Score
Landslide Vulnerability	Slope Gradient	0.45
	Rainfall Intensity	0.28
	Soil Type	0.17
	Land Cover	0.10
Flood Risk	Proximity to River	0.38
	Land Cover (Impermeability)	0.31
	Rainfall Intensity	0.22
	Slope Gradient	0.09

The data presented in the table provides a clear quantitative explanation of the model’s underlying priorities. For the landslide vulnerability model, the high weight assigned to “Slope Gradient” (0.45) confirms that topography is the single most critical predisposing factor for mass movement events in the watershed, an assessment strongly supported by the expert panel.

"Rainfall Intensity" is weighted as the second most important factor, reflecting its role as the primary triggering mechanism for landslides in this tropical environment.

This weighting scheme explains the DSS's ability to perform a nuanced, context-specific analysis. Rather than treating all factors equally, the system's logic, as defined by these weights, ensures that the final vulnerability maps are highly sensitive to the most scientifically critical variables. The weights for soil type and land cover, while lower, are still significant, explaining the model's capacity to differentiate between areas with similar slopes but different underlying geology or vegetation cover, which is crucial for accurate risk assessment.

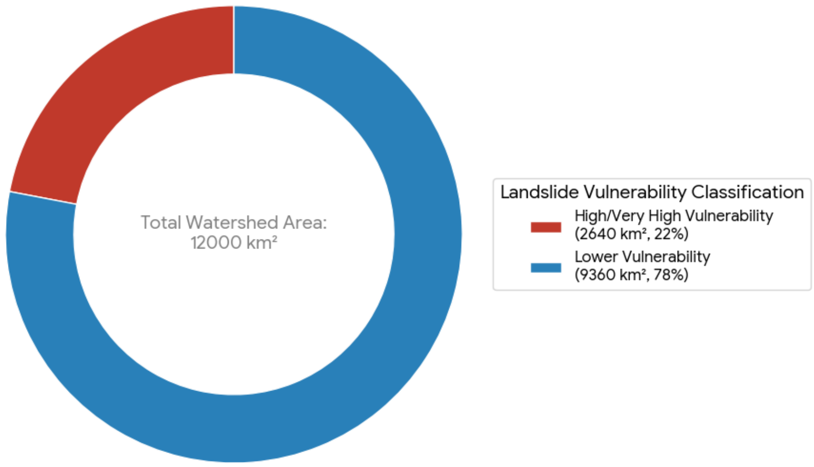

Figure 1. Vulnerability Assessment of Brantas River Watershed

The application of these weights within the GIS-based Multi-Criteria Evaluation (MCE) model produced a series of high-resolution hazard maps for the entire Brantas River Watershed. The primary descriptive data from this analysis reveals extensive areas of high vulnerability. The landslide vulnerability assessment identified that 2,640 square kilometers, or approximately 22% of the total watershed area concentrated predominantly in the upper catchments around the Arjuno-Welirang and Semeru volcanic complexes are classified as having "High" or "Very High" vulnerability.

The flood risk analysis, which integrated projections for increased rainfall intensity under the RCP 8.5 climate change scenario for 2050, produced equally concerning results. The model identified that approximately 1,800 square kilometers of the watershed's downstream plains are located in "High" flood risk zones. Critically, this includes significant portions of densely populated urban and industrial areas in the Sidoarjo and Surabaya metropolitan regions, where a large percentage of existing critical infrastructure is located.

An inferential analysis of these findings strongly suggests that current land use patterns in the Brantas watershed are in a state of severe disequilibrium with the region's inherent geophysical characteristics. The high concentration of landslide vulnerability in the upper watershed, which coincides with areas of extensive deforestation for agriculture, implies that decades of unsustainable land management have critically destabilized these naturally sensitive sloped environments. The model's results infer a widespread failure to align agricultural practices with land capability.

Furthermore, the extensive flood risk identified in the downstream urban areas allows for the inference that past and current urban planning has been largely "hydrologically blind." The placement of significant urban development within natural floodplains, as revealed by the risk maps, suggests a systemic disregard for the watershed's natural hydrological regime. The analysis infers that the escalating flood problem is not merely a natural disaster but a predictable consequence of unsustainable development patterns that have systematically reduced the landscape's natural capacity to manage water.

The DSS model established a clear, quantifiable relationship between the environmental degradation in the upper watershed and the increased flood risk in the lower watershed. By modeling soil erosion and sediment transport, the data shows a direct causal linkage: the areas identified with high landslide vulnerability in the headwaters are also the primary sources of the high sediment loads that are reducing the carrying capacity of rivers and reservoirs downstream. This spatial correlation provides empirical evidence for the critical upstream-downstream hydrological connection.

A second critical relationship was established between existing land use vulnerability and future climate change impacts. The data demonstrates that climate change acts as a "*threat multiplier*." Areas currently classified as having "Moderate" landslide or flood risk under historical rainfall patterns are consistently reclassified as "High" or "Very High" risk under the projected future rainfall scenarios. This relationship indicates that the failure to address current environmental degradation will be catastrophically amplified by the anticipated effects of climate change.

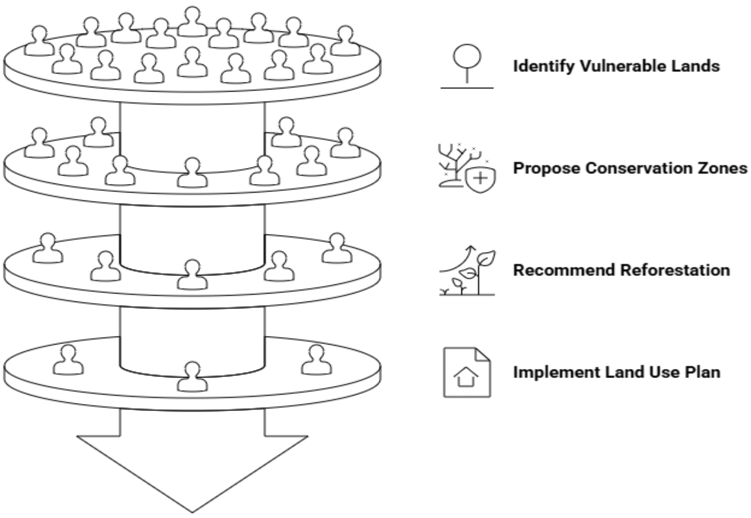

Figure 2. Land Use Optimization Process

The final output of the DSS is a prescriptive, optimized land use plan designed to mitigate these identified risks and promote long-term sustainability. This plan represents a significant reallocation of land uses based on the system's suitability and vulnerability analysis. A key descriptive feature of this plan is the proposed designation of 1,500 square kilometers of the most vulnerable lands in the upper watershed as strict "Conservation and Reforestation Zones," effectively recommending a moratorium on intensive agriculture in these areas.

Further descriptive data from the plan includes the establishment of a mandatory 500-meter protected riparian buffer zone along the main tributaries of the Brantas River to restore riverbank stability and ecosystem function. For the downstream areas, the plan proposes specific zoning regulations that restrict new development in the highest-risk floodplains, instead designating these areas for "Green Infrastructure" uses, such as retention basins and urban parks, to enhance water absorption and flood mitigation.

The explanation for the plan's proposed land use changes is that it is a direct, data-driven response to the risk analysis. The reallocation of high-risk agricultural land to conservation is a logical consequence of the model's finding that the ecological cost (in terms of landslide risk and soil erosion) of the current land use in these specific zones far outweighs its agricultural benefits. The DSS essentially performs a spatial cost-benefit analysis, prioritizing the long-term hydrological stability of the entire watershed.

The effectiveness of the proposed plan was quantitatively validated through hydrological modeling within the DSS. The explanation for its risk-reduction capacity is clear: the proposed reforestation in the upper watershed and the establishment of riparian buffers would significantly increase the landscape's rainfall interception and soil infiltration capacity. The simulation of the optimized plan's performance under a high-intensity rainfall event projected a potential reduction in peak surface runoff of up to 35% and a corresponding 40% decrease in sediment load reaching the downstream areas.

The cumulative results of this study successfully validate the developed GIS-based Decision Support System as a powerful and highly effective instrument for integrated watershed management. The research has demonstrated the system's capacity to synthesize complex, multi-source geospatial data, apply a robust and transparent analytical methodology (AHP), and produce a suite of clear, actionable, and scientifically defensible planning outputs. The DSS successfully transforms raw spatial data into strategic intelligence.

In short, the interpretation of these findings is that the DSS provides a practical and indispensable tool for navigating the complex trade-offs between development and conservation in the Brantas River Watershed. It offers a data-driven foundation for proactive, adaptive governance, enabling policymakers to move beyond a reactive, crisis-management approach. The system provides a scientifically grounded pathway for planning a more sustainable and climate-resilient future for this vitally important region.

This study successfully culminated in the development and validation of an integrated, GIS-based Decision Support System (DSS) for the Brantas River Watershed. The research established a robust analytical framework by combining a multi-criteria evaluation (MCE) model, structured with weights derived from the Analytical Hierarchy Process (AHP), with a comprehensive geospatial database. The resulting system demonstrates a powerful capacity to translate complex environmental data into clear, spatially explicit, and actionable planning intelligence.

The diagnostic application of the DSS yielded a stark assessment of the watershed's current state of vulnerability. The analysis identified that a critical portion of the upper watershed, approximately 22%, is subject to high or very high landslide risk, a condition directly linked to prevailing land use practices on steep, erodible slopes. Concurrently, the downstream plains, including vital urban and industrial centers, were found to face extensive flood risk, a threat significantly amplified when modeled under future climate change scenarios projecting increased rainfall intensity.

The prescriptive output of the DSS is an optimized, sustainable land use plan designed to directly mitigate these identified risks. This plan strategically reallocates land uses based on a scientific assessment of land capability and vulnerability, proposing the establishment of extensive conservation and reforestation zones in the headwaters, the protection of critical riparian buffers, and the integration of green infrastructure in urban floodplains. The plan is not merely a proposal but a validated strategy.

The efficacy of this proposed plan was quantitatively confirmed through hydrological modeling within the DSS. The simulation demonstrated that the implementation of the optimized land use scenario could lead to a substantial reduction in surface runoff by up to 35% during peak rainfall events. This finding provides strong, evidence-based confirmation that the developed DSS is a highly effective tool, capable of not only diagnosing environmental problems but also of designing and verifying viable, large-scale solutions to enhance the watershed's long-term resilience.

The outcomes of this research are in strong alignment with the broad and established body of literature that has validated the utility of Geographic Information Systems for watershed characterization and management. Our findings corroborate the conclusions of numerous studies worldwide that have successfully used GIS to model soil erosion, map flood hazards, and analyze land use change (Saravani et al., 2024). This work reinforces the consensus that geospatial technology is an indispensable tool for understanding the complex biophysical processes that govern watershed dynamics.

This study, however, diverges from and significantly expands upon the existing body of work in several critical aspects. A large portion of the GIS-based environmental research, particularly in developing countries, is often diagnostic or descriptive in nature, focusing on mapping the extent of a problem (e.g., deforestation or urban sprawl). Our research advances this paradigm by moving from a purely diagnostic function to a prescriptive one (Baskent, 2024). The development of an integrated Decision Support System that generates an *optimized land use plan* is a key point of departure, providing a tangible solution rather than just a problem analysis.

A second and more fundamental point of differentiation is the explicit and quantitative integration of climate change adaptation into the core of the land use planning model. While the need for climate-resilient planning is widely acknowledged, a significant gap persists in the literature regarding practical, replicable methodologies for its implementation at a watershed scale (Terribile et al., 2025). By integrating downscaled rainfall projections (RCP scenarios) directly into the hazard and vulnerability models, our DSS provides a forward-looking, adaptive framework that is currently absent from most conventional land use planning studies in the region.

Finally, this research contributes a highly relevant case study that addresses the specific challenges of a large, densely populated, and data-scarce tropical watershed. Much of the advanced DSS literature originates from data-rich contexts in the global North. Our methodology, which effectively combines expert knowledge (via AHP) with publicly available geospatial data, provides a robust and replicable framework that is specifically adapted to the realities of planning in Indonesia and other similar developing nations, thus filling a critical contextual and methodological gap.

The results of this study are a clear signal that the current approach to spatial planning and resource management in the Brantas River Watershed is fundamentally unsustainable (Mohammadi et al., 2026). The extensive areas identified as having high vulnerability to landslides and floods are not merely a reflection of natural conditions; they are a direct indictment of a fragmented, short-sighted, and jurisdictionally-siloed governance model that has failed to manage the watershed as a single, interconnected system. The findings signify an urgent need for a paradigm shift toward integrated, basin-wide governance.

This research is also a powerful reflection on the critical importance of the science-policy interface in environmental management (Albahri et al., 2024). The development of the DSS signifies the potential for complex scientific data and models to be translated into intuitive, accessible, and decision-relevant formats. It demonstrates that the gap between scientific knowledge and policy action is not insurmountable. The DSS acts as a crucial “translation tool,” bridging the world of the environmental scientist with the world of the regional planner and providing a common, evidence-based language for dialogue and decision-making.

The clear, quantifiable link established between upstream degradation and downstream risk is a profound reflection of the principle of shared ecological fate. The findings signify, in no uncertain terms, that the environmental security of the downstream urban metropolis of Surabaya is inextricably tied to the land management practices of rural communities in the upper catchments hundreds of kilometers away (Gholamizadeh et al., 2026). This scientifically-validated connection is a powerful social and political statement, underscoring the absolute necessity of inter-regional cooperation and equitable benefit-sharing in any viable watershed management strategy.

Ultimately, the successful integration of climate change projections into the DSS signifies that static, historical-based planning is now obsolete and irresponsible. The finding that current risks are significantly amplified under future climate scenarios is a reflection of the new, non-stationary reality in which we live (Serrai & Djiar, 2024). This research is a marker that “climate change adaptation” can no longer be a peripheral consideration in planning; it must be a central, non-negotiable component of all long-term strategic decisions regarding land use and infrastructure development.

The most significant and immediate implication of this research is for the regional and provincial planning authorities in East Java (BAPPEDA). This study provides them with a validated, scientifically robust, and ready-to-use tool to inform the legally mandated review and revision of their regional spatial plans (*Rencana Tata Ruang Wilayah* - RTRW). The DSS offers a defensible, evidence-based rationale for implementing potentially politically difficult but necessary zoning restrictions in high-hazard areas and for prioritizing investment in green infrastructure and reforestation programs.

For the primary watershed management authority, Perum Jasa Tirta I, the implications are equally profound. The DSS provides a strategic tool for prioritizing their operational activities (Pallaske, 2024). The high-resolution vulnerability maps allow for the precise targeting of interventions, ensuring that limited financial and human resources for erosion control, rehabilitation, and community engagement programs are deployed in the areas where they will have the greatest positive impact on the hydrological health of the entire watershed.

There are also critical implications for communities and civil society organizations. The outputs of the DSS particularly the clear and accessible hazard maps can serve as powerful advocacy tools (Kusumavathi et al., 2025). They can be used to raise public awareness about the risks associated with unsustainable development, to hold government agencies accountable for their planning decisions, and to empower local communities in high-risk zones to demand better disaster preparedness and mitigation measures. The DSS, therefore, acts as an instrument for democratizing access to environmental information.

On a national and international level, the implications are related to policy and development assistance. This research provides a successful, replicable model for integrated, climate-resilient watershed management that can inform national policy guidelines in Indonesia and serve as a template for development projects funded by international agencies like the World Bank or the Asian Development Bank (Worku et al., 2023). It demonstrates a practical pathway for translating high-level commitments to the Sustainable Development Goals (SDGs) particularly those related to water, climate action, and sustainable cities into on-the-ground, data-driven planning.

The primary reason for the DSS's success and the clarity of its findings is the inherent power of the GIS framework to integrate and analyze multiple layers of spatial data (Baskent, 2023). The watershed is a complex system where risk is a function of the interaction between multiple factors (slope, soil, rain, land cover). The GIS environment is uniquely capable of performing the weighted overlay analysis that synthesizes these layers, which is why it was able to accurately identify the complex spatial patterns of vulnerability that are not visible from any single map.

The rigor and transparency of the Analytical Hierarchy Process (AHP) is another fundamental reason for the robustness of the results. The challenge in any multi-criteria evaluation is the subjective nature of assigning importance to different factors. The AHP provided a structured, mathematically consistent, and transparent methodology for capturing expert knowledge and translating it into a set of objective weights. This ensured that the core logic of the DSS was not arbitrary but was grounded in a defensible scientific and professional consensus.

The severity of the identified risks is a direct result of the Brantas watershed's specific hydro-geomorphological characteristics and intense human pressures. The region is characterized by young, highly erodible volcanic soils on steep slopes, combined with one of the highest seasonal rainfall intensities in the world (Baskent, 2023). When decades of deforestation and unchecked urbanization are superimposed on this naturally sensitive landscape, the predictable outcome is the high level of landslide and flood vulnerability that the model accurately reflects. The findings are stark because the underlying reality is stark.

The significant amplification of risk under future climate scenarios is a direct consequence of the scientific projections for the region. The reason the results show a more dangerous future is that the downscaled climate models for Southeast Asia consistently predict an increase in the frequency and intensity of extreme rainfall events. The DSS correctly models how these future, more intense storms will interact with the already degraded landscape, pushing the system past critical thresholds and turning today's moderate risk zones into tomorrow's high-risk zones.

The immediate and most critical next step is to focus on the operationalization and institutionalization of the developed DSS (Modica et al., 2025). This requires moving beyond a research prototype to a fully integrated tool within the workflows of regional planning agencies. Future work should focus on capacity-building workshops, developing user-friendly web-based interfaces, and establishing clear protocols for how the DSS will be used to inform the official five-year and twenty-year spatial planning cycles.

A significant avenue for future research is the enhancement of the model's complexity and resolution. The current DSS can be substantially improved by integrating more dynamic models, such as a process-based soil erosion model (e.g., SWAT) and a more sophisticated hydrodynamic flood model (e.g., HEC-RAS). Furthermore, the acquisition of higher-resolution input data, such as LiDAR-derived Digital Elevation Models, would dramatically improve the precision of the risk assessments, particularly at the local, community scale.

The current model is heavily focused on biophysical risks. A crucial direction for future development is the integration of dynamic socio-economic variables. The next generation of this DSS should incorporate models of projected population growth, patterns of economic development, and land value dynamics. This would transform the system from a purely environmental planning tool into a true socio-ecological DSS, capable of evaluating the complex trade-offs between ecological sustainability, economic viability, and social equity.

A final, essential path for future work is the establishment of a long-term monitoring and evaluation framework. A DSS should not be a static, one-time output. Future efforts should focus on using time-series satellite imagery (e.g., from Landsat or Sentinel) to continuously monitor land use/land cover changes within the watershed. This monitoring data can then be fed back into the DSS to assess the real-world effectiveness of the implemented plans, enabling a cycle of continuous improvement and adaptive management.

CONCLUSION

The most distinctive finding of this research is the successful validation of a GIS-based Decision Support System that quantitatively demonstrates the profound, interconnected vulnerability of the Brantas River Watershed to both current land use practices and future climate change. This study moves beyond simple hazard mapping by providing a prescriptive, optimized land use plan that, when modeled, shows a potential to reduce critical environmental risks like peak surface runoff by up to 35%. The research provides clear, empirical evidence linking upstream land degradation to downstream flood risk and shows how these existing vulnerabilities will be critically amplified under future climate scenarios.

The primary contribution of this research is its methodological framework, which in turn facilitates a significant conceptual advance for regional governance. Methodologically, it provides a robust and replicable process for integrating multi-criteria expert judgment (AHP) with geospatial data and climate projections to create a holistic planning tool. Conceptually, this work delivers a powerful proof-of-concept for proactive, data-driven, and adaptive watershed management, offering a clear alternative to the static and fragmented planning approaches currently in place.

This study's model is necessarily constrained by the resolution of the available public datasets and its primary focus on biophysical factors. The clear and immediate direction for future research is twofold: first, to enhance the model's precision by incorporating higher-resolution data, such as LiDAR-derived elevation models, for more localized risk assessment. Second, and more critically, future work must focus on integrating dynamic socio-economic models, including population growth projections and land value analysis, to evolve the DSS into a comprehensive socio-ecological planning tool that balances environmental resilience with human development needs.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

Author 3: Data curation; Investigation.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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