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An Integrative SWAT-Based and Epistemological Framework for Sustainable Management of the Alo-Molamahu SubWatershed, Gorontalo, Indonesia

Bontor L. Tobing[1], Mahludin A. Baruwadi[2], Hasim[3]
[1]Doctoral Program in Environmental Science, Universitas Negeri Gorontalo, Gorontalo, Indonesia
[2]Postgraduate Program, Universitas Negeri Gorontalo, Gorontalo, Indonesia
Email: [1]707625006@mahasiswa.ung.ac.id, [2]mahludinbaruwadi@ung.ac.id, [3]ehasimgtlo@gmail.com

Abstract

Sustainable watershed management requires decision-making frameworks that are both scientifically robust and socially legitimate. This study develops an integrative management model for the Alo-Molamahu Sub-Watershed, part of the Limboto Watershed in Gorontalo Province, Indonesia, by combining hydrological modeling, spatial analysis, and social–institutional assessment within an epistemological framework. A mixed-methods design was employed, integrating biophysical data derived from Geographic Information Systems (GIS) and the Soil and Water Assessment Tool (SWAT) with qualitative data obtained from interviews, questionnaires, and policy document analysis. Model calibration and validation using observed discharge data from River Flow Monitoring Stations demonstrate strong agreement between simulated and observed hydrological responses. The results indicate that land-use change on steep slopes and limited vegetation cover significantly increase runoff and sediment yield, while socio-economic pressures and weak policy instruments constrain effective conservation practices. Through systematic data triangulation, biophysical model outputs were interpreted alongside stakeholder perceptions and regulatory conditions to generate an evidence-based and adaptive watershed governance model. The study demonstrates that integrating validated hydrological simulations with social knowledge enhances both the scientific credibility and policy relevance of watershed management strategies. The proposed framework provides a replicable approach for sustainable management of complex socio-ecological watersheds in Indonesia and comparable contexts.

Keywords*: Integrative Watershed Management, SWAT Modeling, Data Triangulation, Socio-Ecological Systems, Evidence-Based Environmental Governance, Scientific Epistemology.*

1. INTRODUCTION

Watershed management has evolved into a complex challenge involving intertwined ecological, socio-economic, and institutional dimensions. In Indonesia, this complexity is evident in the degradation of critical watersheds, including the Limboto Watershed in Gorontalo Province, where unsustainable land-use practices, weak institutional coordination, and insufficient community engagement contribute to environmental decline. Existing interventions have predominantly employed technocratic approaches, emphasizing physical rehabilitation and structural engineering without adequately integrating community knowledge or addressing institutional fragmentation. Consequently, these solutions often fail to achieve lasting impact or social legitimacy.

An epistemological approach offers a paradigm shift in addressing these limitations by emphasizing the co-production of knowledge between scientific and societal actors. Rather than treating science as detached from its social context, this perspective integrates empirical validity with social legitimacy. In watershed governance, it enables the construction of knowledge that reflects both the biophysical dynamics of ecosystems and the sociocultural realities of affected communities (Wang et al., 2022; Dong et al., 2022; Parlee et al., 2021). Such integration is vital in regions like the Alo-Molamahu Sub-Watershed in the Limboto Watershed, where local practices, perceptions, and institutional policies jointly shape environmental outcomes.

Previous studies on the Limboto Watershed have focused largely on biophysical degradation and proposed sectoral mitigation strategies, often overlooking the systemic interplay between ecological degradation and governance failure. For example, while spatial planning and land rehabilitation have been emphasized, limited attention has been given to institutional coherence and participatory governance mechanisms. This presents a critical gap: the lack of a decision-making model that incorporates both scientific robustness and community legitimacy. By adopting an epistemological lens, this research bridges that gap and proposes a governance framework grounded in both scientific evidence and socio-political realities.

Compared to purely technocratic models, the epistemological approach employed here offers two key advantages. First, it strengthens the scientific validity of environmental decisions through multi-source data triangulation, including hydrological modeling (SWAT), spatial analysis (GIS), and field validation. Second, it ensures social legitimacy by involving communities in the knowledge-generation process, thereby enhancing the ethical and contextual relevance of environmental governance (Elkadiri et al., 2023; Weh, 2025; Huntington, 2000).

Accordingly, this study aims not merely to formulate a management strategy but to test the validity of an integrative decision-making model that unites biophysical and social data in the context of watershed governance. Specifically, the research investigates how triangulated data and epistemological reasoning can yield actionable and inclusive strategies for sustainable management of the Alo-Molamahu Sub-Watershed.

The novelty of this research lies in the formulation of an adaptive watershed governance model that combines scientific epistemology and participatory processes. Unlike conventional frameworks that prioritize technical solutions, this model is built on co-produced knowledge, acknowledging both empirical rigor and stakeholder legitimacy. It contributes not only to academic discourse but also to practical policy innovation, offering a replicable model for other complex watershed systems facing socio-ecological challenges.

2. METHODOLOGY

This study adopts a sequential exploratory mixed-methods design grounded in scientific epistemology, aimed at generating actionable and context-sensitive knowledge through rigorous interdisciplinary integration. The methodology encompasses three core domains: biophysical simulation using SWAT, qualitative social-institutional analysis, and triangulated synthesis to construct an adaptive watershed governance model.

2.1 Epistemological Basis

The epistemological foundation asserts that valid environmental knowledge must be systematically constructed through empirical observation, rational analysis, and cross-validation among data sources (Bekhet & Zauszniewski, 2012; Kusumo & Kurnianto, 2019). Triangulation functions not only as a method for verification but also as an ontological commitment to plural knowledge domains, where hydrological simulation, local perspectives, and policy narratives intersect.

2.2 Study Area and Research Design

Research was conducted in the Alo-Molamahu Sub-Watershed, part of the Limboto Watershed in Gorontalo Province. The site is characterized by steep slopes (>25%), annual rainfall exceeding 2000 mm, and land conversion dominated by maize monoculture. Given its designation as a national ecological priority area, it provides a critical testbed for integrative governance models.

2.3 Biophysical Data Collection and SWAT Configuration

SWAT (Soil and Water Assessment Tool) was employed to model surface runoff and erosion dynamics. The input data included:

a) Digital Elevation Model (DEM): 30 m resolution from SRTM, hydrologically corrected using ArcHydro tools.
b) Land Use and Land Cover (LULC): Derived from Landsat 8 OLI imagery (2020), classified with maximum likelihood algorithm, and validated using ground truth points.
c) Soil Data: Obtained from Harmonized World Soil Database (HWSD), incorporating hydrological group, soil depth, bulk density, and texture class.
d) Climate Data: Daily rainfall, temperature, solar radiation, humidity, and wind speed from BMKG station.

SWAT model setup included defining Hydrologic Response Units (HRUs) by overlaying slope, LULC, and soil maps. Model calibration and validation were conducted using river discharge data from SPAS stations at inlet and outlet points.

Validation Metrics:
Model predictions were evaluated using standard statistical indicators:

a) Nash-Sutcliffe Efficiency (NSE):

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n}(Q_{obs,i}-Q_{sim,i})^2}{\sum_{i=1}^{n}(Q_{obs,i}-\overline{Q}_{obs})^2}$$

b) Coefficient of Determination (R^2):

$$\mathbf{R^2} = \frac{\left[\sum_{i=1}^{n}(Q_{obs,i}-\overline{Q}_{obs})(Q_{sim,i}-\overline{Q}_{sim})\right]^2}{\sum_{i=1}^{n}(Q_{obs,i}-\overline{Q}_{obs})^2\sum_{i=1}^{n}(Q_{sim,i}-\overline{Q}_{sim})^2}$$

2.4 Social and Institutional Data Collection

Semi-structured interviews and structured questionnaires were conducted to assess stakeholder perspectives on land use, watershed governance, and institutional constraints. Key informants included farmers, local leaders, and government officials. Policy analysis focused on coherence among national (Permen-LHK No. 26/2020), provincial, and district-level regulations.

2.5 Triangulation and Integration Protocol

Triangulation was conducted through a three-stage process:

a) Quantitative Simulation: SWAT outputs were spatially analyzed to identify critical erosion zones.
b) Qualitative Synthesis: Interview data were coded using NVivo 12 to extract thematic patterns (e.g., regulatory gaps, participatory challenges).
c) Cross-Validation: Spatial findings were cross-referenced with stakeholder narratives to confirm or challenge model predictions.

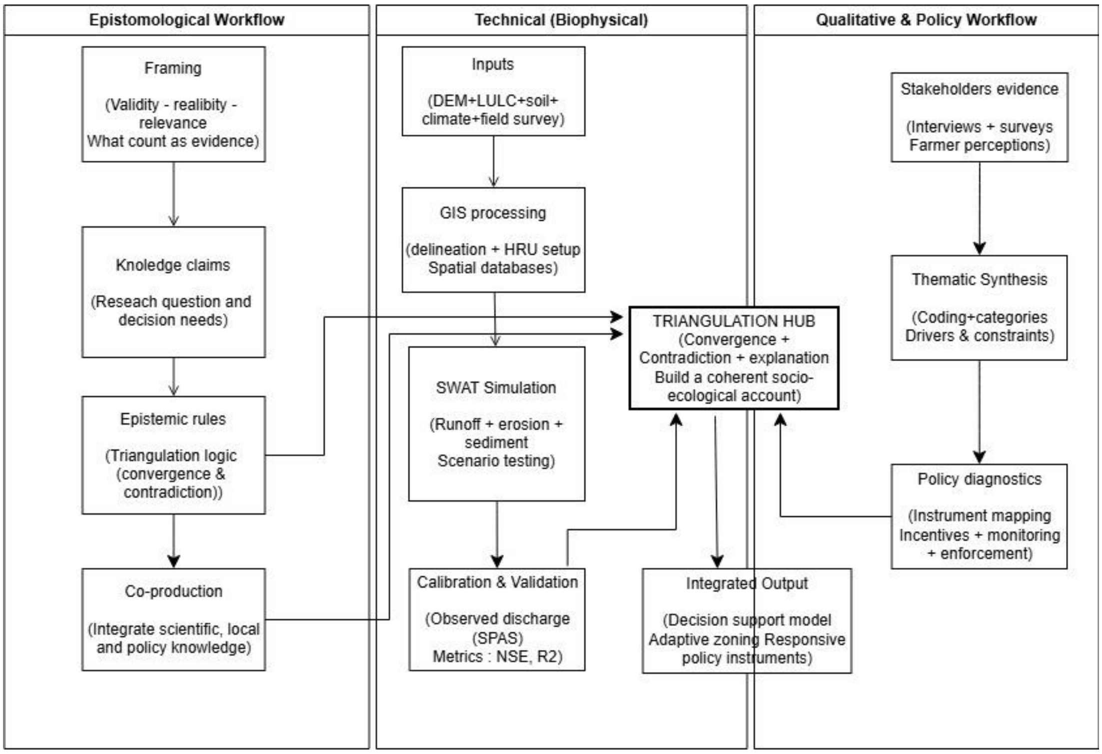


Figure 1. Integrated Epistemological-Technical Workflow

2.6 Model Development and Replicability

The triangulated insights inform the construction of an adaptive governance model comprising:

a) Zoning maps based on sediment yield and slope gradient.
b) Participatory platforms to engage communities in policy deliberation.
c) Feedback loops linking monitoring outcomes to regulatory reform.

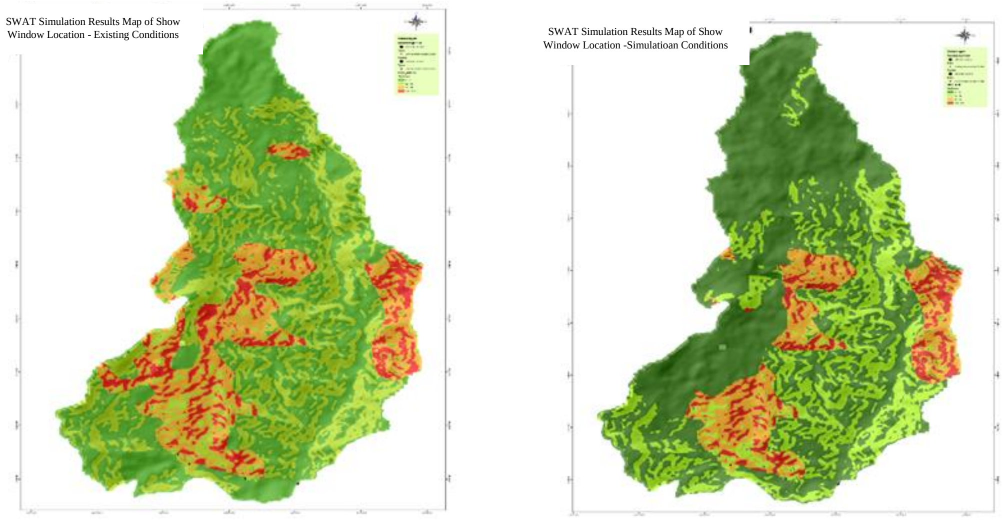
3. RESULTS AND DISCUSSION

This combined visualization is critical epistemologically, as it makes explicit the correspondence between simulated knowledge and empirical reality. Rather than presenting model outputs as abstract numerical results, the side-by-side comparison situates SWAT-derived “scientific truth” within observable hydrological behavior, reinforcing its credibility for decision-making.

This section integrates biophysical evidence generated through SWAT modeling with qualitative stakeholder insights and institutional–policy assessment. Following an epistemological framework, “scientific truth” (model-based, empirically grounded outputs) is interpreted alongside “social truth” (stakeholder rationalities and constraints) to produce actionable, legitimate, and adaptive watershed governance recommendations.

3.1 SWAT-Based Biophysical Characterization and Input Parameterization

The SWAT model required systematic preparation of spatial and climatic inputs. Key parameter groups included soil properties, land use/land cover (LULC), and climate records. LULC was derived from remote interpretation and field verification, then harmonized with SWAT land-use codes to ensure functional equivalence (e.g., canopy structure, rooting depth, and management characteristics). This harmonization is critical epistemologically because it links observed landscape reality to the representational categories used by the model, reducing interpretive bias.



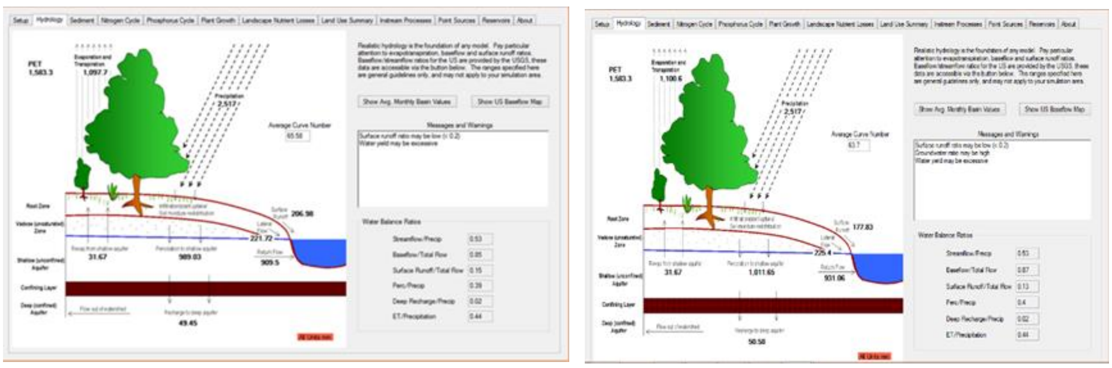
(2.a). Existing condition (2.b). Simulation condition

Figure 2. SWAT simulations indicate that land-use conversion from monoculture farming to mixed vegetation (BPDASHL, 2019)

Based on the land-use inventory used in the SWAT setup, the study area was dominated by shrub/secondary vegetation (RNGB) and dryland agriculture (AGRR), with smaller proportions of forest (FRST) and cultivated plots approximated as corn (CORN). This composition indicates a watershed system where conservation capacity is spatially uneven, and where land management practices become decisive drivers of runoff and sediment dynamics.

3.2 Surface Runoff Simulation Under Current and Rehabilitation Scenarios

Surface runoff was simulated under two scenarios: (i) a baseline scenario reflecting current/actual land use, and (ii) a rehabilitation scenario representing land management changes associated with revegetation and conservation actions. The runoff outputs were classified into five classes based on the minimum–maximum range to support spatial prioritization (Figures 3).



(3.a). Existing outputs (3.b). Simulation outputs

Figure 3. The SWAT outputs (BPDASHL, 2019)

The SWAT outputs show a modest but consistent reduction in minimum runoff values under the rehabilitation scenario (0.55 mm in the baseline scenario versus 0.54 mm following rehabilitation). Although the absolute difference is small, the direction of change is epistemologically meaningful: it demonstrates that the model is sensitive to vegetation and land management interventions and thus can serve as a decision-support instrument for evaluating policy-relevant scenarios.

The runoff response is consistent with hydrological reasoning in which increasing vegetative cover and reducing effective imperviousness increase infiltration and reduce overland flow. However, an epistemological reading emphasizes that the magnitude of modeled improvement should be interpreted cautiously and contextually: small numerical reductions may still translate into meaningful outcomes when concentrated in critical sub-units where runoff generation is disproportionate.

3.3 Erosion and Sediment Yield: Quantifying Degradation and Intervention Effects

SWAT simulations for sediment yield indicate a measurable reduction after the rehabilitation scenario. Total sediment output decreased from 9,249 tons/year (baseline) to 9,188 tons/year (rehabilitation), a reduction of 61 tons/year (≈0.66%). This result supports the interpretation that land-cover improvements and conservation measures can reduce erosion rates.

From an epistemological standpoint, the model-derived sediment yield constitutes “scientific truth” in the sense that it is systematically produced from a transparent hydrological–erosion representation and can be evaluated against field observations and spatial plausibility. Yet, this truth is partial unless integrated with social and institutional explanations for why erosion-prone land uses persist.

3.4 Water Yield and Trade-Offs: Evidence of System-Level Consequences

Beyond runoff and sediment reduction, SWAT outputs also reveal trade-offs related to water yield. The modeled annual water supply decreased from 32,802,483 m³ (baseline) to 32,735,942 m³ (rehabilitation), a reduction of 66,541 m³ (≈0.20%). The most plausible mechanism is increased evapotranspiration associated with additional vegetation cover under rehabilitation.

This finding is important for decision-making because it shows that conservation actions may generate co-benefits (erosion reduction) while also shifting water balance components. Under an epistemological approach, such trade-offs should not be treated as model “errors” but as interpretable consequences that require deliberation with stakeholders and planners, especially in contexts where water availability has competing demands.

3.5 Model–Observation Alignment and Epistemic Credibility

Hydrological modeling gains epistemic credibility when its outputs align with observed discharge behavior. In this study, simulated discharge was compared directly with observations from River Flow Monitoring Stations (SPAS) in a single figure (hydrograph overlay), enabling inspection of temporal agreement between simulation and field records. Consistent alignment between simulated and observed patterns supports the use of SWAT outputs as scientifically valid inputs for evidence-based watershed planning (Satterwhite et al., 2020).

3.6 Epistemological Interpretability: Linking Model Truth to Farmer Rationalities

Model results indicate that runoff and sediment are sensitive to vegetation cover and land management; however, interviews and stakeholder engagement reveal that land-use decisions are frequently driven by short-term economic needs. Farmers may recognize erosion risks yet continue cultivating steep or exposed areas due to livelihood constraints and limited access to incentives, technical support, or alternative income.

This interaction illustrates a key epistemological insight: hydrological simulation provides a rigorously constructed account of “what happens” biophysically, while farmer perceptions and constraints explain “why it happens” socially. Scientific truth and social truth are therefore not competing narratives; they represent complementary knowledge domains that, when triangulated, yield a more complete and ethically relevant understanding of watershed degradation (Salam, 2020; Wang et al., 2022).

3.7 Policy Effectiveness and Evidence-Based Critique of Governance Instruments

Policy assessment indicates that formal planning instruments (including spatial plans/RTRW) can be strengthened by SWAT outputs to improve targeting and accountability. The model can identify problematic sub-units (sub-watersheds) and support priority-setting for intervention. However, policy implementation effectiveness depends on instrument design and institutional capacity.

Consistent with stakeholder evidence, weak policy performance is most plausibly linked to deficits in (i) incentives (limited economic support for conservation adoption), and (ii) monitoring and enforcement (insufficient oversight and evaluation mechanisms). Under an epistemological framework, policy weakness should be diagnosed not only normatively but empirically—i.e., whether policy instruments demonstrably shift the biophysical indicators that matter (runoff and sediment yield).

Accordingly, SWAT-derived runoff and sediment indicators can be formalized as performance variables for policy evaluation, enabling an adaptive governance cycle: implement → monitor → evaluate → revise. This approach aligns with triangulation principles and supports evidence-based policymaking that integrates modeling outputs, institutional diagnostics, and stakeholder legitimacy (Miller et al., 2008; Moran-Ellis et al., 2006).

3.8 Synthesis Through Triangulation: Implications for Adaptive Watershed Management

Triangulation of SWAT outputs, stakeholder insights, and policy analysis yields a coherent explanation of watershed degradation dynamics and intervention limits. The rehabilitation scenario shows that technical measures can reduce runoff and sediment, but the scale of improvement depends on where interventions occur and whether governance instruments address socio-economic drivers.

a) Therefore, the results support an adaptive watershed management model that:
b) Prioritizes spatially explicit interventions in erosion-prone zones;
c) Couples conservation requirements with incentive mechanisms;
d) Institutionalizes monitoring using model-linked indicators; and
e) Embeds stakeholder engagement to ensure social legitimacy and compliance.

Overall, integrating SWAT-derived scientific validity with social and institutional knowledge strengthens both the explanatory power and the practical usability of the management strategy, consistent with the epistemological approach underpinning this study.

3.9 Discussion

This section discusses the research findings within the framework of scientific epistemology and their contributions to the development of a sustainable management strategy for the Alo-Molamahu Sub-Watershed in the Limboto Watershed. The discussion focuses on the validity of scientific knowledge obtained through data triangulation, multidisciplinary integration, and ethical and practical implications in implementing evidence-based environmental management.

Scientific epistemology plays a central role in addressing the limitations of scientific knowledge in tackling the complexity of socio-ecological systems. By promoting critical reflection on the fundamental assumptions of research, epistemology helps researchers comprehend the intricate interactions between humans and the environment. This approach enables the combination of various methods and perspectives within a holistic and transdisciplinary framework (Jabar et al., 2024). In the context of watershed management, this integration allows researchers to assess not only biophysical aspects but also the underlying social dynamics and policy contexts.

Findings indicate that watershed degradation is not solely driven by physical factors such as rainfall and slope but also by socio-economic conditions and institutional weaknesses. The epistemological approach acknowledges that a comprehensive understanding of watershed systems requires a synergy between empirical data and normative insights. In other words, analysis should go beyond numeric data or mathematical models and incorporate perceptions, community participation, and local values (Salam, 2020).

Neglecting epistemological validity in environmental science has serious ethical consequences. Managerial decisions based on inaccurate or partial data may lead to unsustainable policies, marginalize local communities, and exacerbate environmental and social injustices. Epistemology, therefore, demands accountability at every stage of research and policy implementation—from data collection to decision-making (Salam, 2020).

The triangulation method used in this study has proven effective in enhancing the validity of findings. Integrating biophysical, social, and policy data creates a more comprehensive representation of the watershed reality. This aligns with literature advocating for the inclusion of social data in ecosystem modeling to generate models that are both inclusive and field-relevant. Epistemology thus supports collaboration between social and natural scientists to produce solutions that are not only scientifically sound but also socially and ethically appropriate (Sari et al., 2025).

The use of the SWAT hydrological model also aligns with epistemological standards as a scientific validation tool. The model simulates water flow dynamics and illustrates how land-cover changes impact erosion and sedimentation. The model's validation involves assessing input accuracy, consistency between scenarios and outcomes, and its reliability in reflecting actual watershed conditions (Satterwhite et al., 2020).

Multidisciplinary data integration is viewed in epistemology as a collaborative process that enriches scientific knowledge. This approach requires openness to different paradigms—from natural sciences and social sciences to public policy. In this context, triangulation is not only a data verification technique but also a strategy for reinforcing holistic knowledge (Diyati & Nursikin, 2025). This is supported by transdisciplinary literature emphasizing the importance of cross-disciplinary collaboration in understanding and resolving complex environmental issues (Habaora, 2020).

The epistemological foundation of evidence-based management is evident in the development of watershed strategies based on empirical data from multiple sources. These models rely not on intuition or experience alone but on validated, testable data (Anam, 2023). By integrating biophysical data, community perceptions, and policy contexts, the resulting governance model is more prepared to handle implementation challenges and is scientifically justifiable.

Research literature also supports the design of governance models that combine scientific knowledge and community participation as increasingly critical in managing natural resources. This approach fosters constructive dialogue among scientists, policymakers, and local communities, resulting in policies that are not only effective but also just and sustainable (Salam, 2020).

In this study, community involvement is not limited to being a data source but extends to active participation in decision-making processes. This aligns with participatory epistemology, which recognizes that knowledge is not solely held by academics or experts but also by people who live in and interact with the environment daily.

In summary, this discussion affirms that epistemology is not merely a theoretical foundation but also a practical tool for shaping valid, just, and sustainable environmental management strategies. An epistemological approach enables the development of contextually appropriate and inclusive policies, enhancing the adaptive capacity of communities and the long-term sustainability of watershed ecosystems.

Based on the integrated model developed in this study, several concrete technical recommendations can be proposed for local and regional governments:

1) Spatial Zoning Based on Erosion Risk: SWAT-derived sediment yield and slope maps should be formally adopted as a basis for watershed zoning. Areas identified as high-risk zones (>25% slope with high sediment yield) should be designated as conservation or limited-use zones, where land conversion is restricted and agroforestry or reforestation is prioritized.
2) Targeted Vegetation and Land-Management Interventions: Sub-basins with the highest modeled runoff contribution should be prioritized for soil and water conservation measures, such as contour farming, vegetative buffer strips, and reforestation using locally adapted species. These interventions should be spatially explicit and aligned with model outputs rather than applied uniformly across the watershed.
3) Adaptive and Incentive-Based Policy Instruments: The findings indicate that weak incentives and limited monitoring capacity are key factors undermining policy effectiveness. Local governments are therefore encouraged to introduce incentive-based instruments—such as conditional subsidies or payment for ecosystem services (PES)—targeted at farmers operating in critical zones identified by the SWAT model.
4) Strengthening Monitoring and Feedback Mechanisms: Hydrological indicators generated by SWAT (e.g., runoff depth and sediment yield) can be operationalized as performance indicators for watershed management programs. Periodic monitoring and model updating should be institutionalized to support adaptive policy revision based on empirical evidence.
5) Institutionalizing Participatory Decision-Making: To bridge scientific and social knowledge, the spatial outputs of the model should be communicated to local stakeholders through participatory forums. This process supports co-production of knowledge and enhances compliance by aligning policy measures with local perceptions and capacities.

Theoretically, this research contributes to environmental science by demonstrating that epistemology can function not merely as a philosophical framework but as an operational approach for integrating models, data, and stakeholder knowledge into decision-making processes. Practically, the proposed evidence-based and adaptive governance model offers a replicable framework for other watersheds facing similar socio-ecological challenges.

4. CONCLUSION

This study demonstrates that an epistemological approach provides a robust and operational foundation for developing sustainable and evidence-based management strategies for the Alo-Molamahu Sub-Watershed within the Limboto Watershed system.

By integrating biophysical modeling (SWAT), social perception data, and policy analysis through triangulation, the research reveals that watershed degradation is driven not only by physical factors—such as steep slopes, high rainfall, and land-use change—but also by socio-economic pressures and institutional weaknesses.

From a scientific perspective, the SWAT simulations confirm that the expansion of monoculture farming on erosion-prone slopes significantly increases surface runoff and sediment yield, while scenarios incorporating vegetation restoration and land-use control substantially reduce these impacts. Social analysis further shows that farmers' land-use decisions are strongly influenced by short-term economic needs, highlighting the limits of purely technocratic interventions. Together, these findings reinforce the epistemological argument that sustainable watershed governance requires the integration of scientific validity with social legitimacy.

In conclusion, sustainable watershed management in the Alo-Molamahu Sub-Watershed can only be achieved when scientifically validated models are embedded within socially legitimate and institutionally responsive governance systems. The epistemological approach advanced in this study provides a pathway for aligning empirical evidence, policy instruments, and community engagement in pursuit of long-term watershed sustainability.

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