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Review Paper

Beyond Coverage: Evidence-Based Prioritization of High-Quality SLM Interventions for Sustained Nutrient Retention

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ABSTRACT

The degradation of land resources across East African watersheds, most acutely evidenced in Ethiopia, presents a substantial threat to agricultural viability and water security due to rampant soil erosion and nutrient depletion. This research introduces a rigorous, evidence-based prioritization framework for Sustainable Land Management (SLM). This framework synergistically integrates empirical field observations, nuanced local knowledge, and advanced SWAT+ modeling tethered to the Analytic Hierarchy Process (AHP). Our findings reveal substantial spatial heterogeneity in erosion and nutrient export, where croplands bear the disproportionate burden of degradation, while designated exclosures demonstrate the most pronounced mitigation effects. Crucially, the calibration and validation of the SWAT+ model were significantly refined through the incorporation of community-derived data and empirical field metrics, leading to substantially more accurate spatial identification of erosion hotspots and subsequent conservation prioritization. Furthermore, the analysis strongly suggests that the intrinsic quality and consistent maintenance of SLM/Soil and Water Conservation (SWC) interventions supersede the impact volume of spatial coverage alone. Economically analyzed, prospective SLM practices exhibit favorable cost–benefit ratios, providing justification for their strategic adoption as durable, long-term restoration strategies. This study ultimately contributes a scientifically robust, yet socially contextualized, bio-physical-social framework for comprehensive watershed stewardship, furnishing actionable scientific insights alongside pragmatic policy directives for ecological restoration.

Keywords: Sustainable Land Management (SLM); Soil and Water Conservation (SWC); SWAT+; Analytic Hierarchy Process (AHP); soil erosion; nutrient loss; local knowledge.

INTRODUCTION

The trajectory of land resource degradation across the watersheds of East Africa, with Ethiopia serving as a critical archetype, remains a dominant impediment to resilient agricultural productivity and sustained water security. This decline is manifestly driven by surface runoff-induced erosion, sporadic, drought-linked soil loss, and the subsequent leaching of vital nutrient capitals (N, P, cations) carried away through surface flow and discharge outlets (Grum et al., 2016;

Girmay et al., 2020; Zhang et al., 2016). To effectively map the zones of maximal susceptibility, classical erosion models, notably USLE/RUSLE, have been routinely deployed across Ethiopian catchments, including specialized studies in regions like Agewmariyam and Basaka. This extensive modeling effort decisively illuminates the non-negotiable demand for immediate, hotspot-centric mitigation strategies (Girmay et al., 2020; Dinka, 2020).

The core of the research gap surfaces when assessing the long-term viability of conservation programs. While Soil and Water Conservation (SWC) and Sustainable Land Management (SLM) initiatives unquestionably correlate with reduced erosion and nutrient export, their mid-to-long-term success is profoundly tethered to two non-negotiable factors: sustained funding mechanisms and rigorous infrastructure maintenance (Schmidt & Tadesse, 2019). Existing scholarship forcefully argues for the synergistic integration of water harvesting techniques, field-level soil protection, and climate adaptation strategies required to lock in nutrient retention and augment durable productivity within Ethiopia's challenging semi-arid context (Grum et al., 2016; Schmidt & Tadesse, 2019; Ewunetu et al., 2025). This recognition culminates in the contemporary call for a fully holistic evaluation—one that seamlessly weaves empirical field data, tacit local ecological knowledge, and integrated predictive modeling to ensure that SLM implementation achieves surgical precision (Abere et al., 2025).

Perhaps the most striking realization emerging from contemporary empirical investigation is the elevated importance of technical implementation quality over mere coverage metrics. Evidence from Ethiopian watersheds emphatically demonstrates that the incidence of severe erosion is much more closely indexed to parameters such as slope gradient, existing land cover integrity, and especially, the *consistent installation and subsequent diligent maintenance* of conservation features, rather than just the spatial expanse of the program (Schmidt & Tadesse, 2019; Abere et al., 2025). Technological benchmarks like the USLE/RUSLE framework effectively guide resource allocation toward sustainable practices—such as planting protective buffer strips, constructing effective water retention structures, and enforcing SWC infrastructure upkeep—yielding superior results in curtailing severe erosion and nutrient leaching compared to broad, unmaintained campaigns (Girmay et al., 2020; Dinka, 2020). Ultimately, the enduring legacy of SLM hinges not on the frequency of new program launches, but on the steadfast guardianship of physical assets and the embedding of community understanding (Schmidt & Tadesse, 2019; Abere et al., 2025).

The relationship between specific land use practices and the resultant loss of sediment and precious nutrient loads is both powerful and deeply contextual. Land parcels characterized by sparse ground cover, unchecked cultivation on steep inclines, and intensive farming regimes exhibit a marked propensity to elevate surface runoff, thereby channeling sediment and nutrient plumes (N, P, K) into adjacent river systems and catchment outlets (Grum et al., 2016; Abere et al., 2025). Conversely, the committed application of physical soil protection methods, slope contouring, and agroforestry consistently yields a measurable deceleration of erosion and nutrient egress (Adimassu et al., 2020; Schmidt & Tadesse, 2019). The USLE/RUSLE driven hydrological framework proves indispensable in pinpointing these erosion hotspots relative to topography and land type, enabling far more precisely targeted interventions (Girmay et al., 2020). This scientific insight is magnified through the integration of local knowledge: community expertise provides essential temporal context, seasonality patterns, and established traditional methods for model calibration, while the model supplies the necessary risk evaluation scaffolding, prioritization architecture, and projection of short- and long-term impacts (Abere et al., 2025; Schmidt & Tadesse, 2019). Thus, achieving sustainable adoption and infrastructure longevity in this semi-arid setting demands a finely tuned balance between rigorous field evidence, model sophistication, and active community participation (Grum et al., 2016; Abere et al., 2025; Schmidt & Tadesse, 2019).

LITERATURE REVIEW

The core of this research strategy is nested within a powerful, hybrid methodology that fuses the predictive capabilities of the Soil and Water Assessment Tool Plus (SWAT+) with the structured decision-support framework of the Analytic Hierarchy Process (AHP) to delineate critical land conservation priority areas.

Integration of SWAT+ and AHP for Risk Spatialization

The AHP was strategically employed to systematically assign relative weights to key environmental proxies, specifically erosion indicators, sediment loss estimates, nutrient balance metrics, current land cover status, and topographic slope. These weighted criteria were then synthesized to formulate a comprehensive Risk Scoring Layer. This layer serves as the critical bridge, integrating directly with the output generated by the SWAT+ simulations. The SWAT+ module itself was tasked with physically simulating surface runoff dynamics, soil erosion flux, and the resulting transport of sediments and nutrients across each defined watershed delineation unit (DAS). This spatial modeling capability allows for the precise identification of high-risk zones, providing an empirically grounded foundation for intervention prioritization (Abere et al., 2025). This integrative approach has been empirically validated to yield superior accuracy in prioritization decision-making compared to methodologies reliant upon any single modeling instrument.

SWAT+ Parameterization: Calibrating for Nutrient and Sediment Flux

The calibration pathway for the SWAT+ model mandated the precise adjustment of highly sensitive parameters governing both erosional processes and nutrient cycling dynamics. Primary parameters targeted for tuning included the established erosion factor (derived from RUSLE/RUSLE2 schematics), slope steepness, potential for *land slip*, soil depth profiles, extant land cover conditions, and key hydrological routing parameters (e.g., flow routing and infiltration rates). The resulting model outputs comprise quantified simulations of nutrient loss (N, P, K) and sediment yield. The fidelity of these simulations is directly contingent upon the resolution and quality of input data, encompassing the Digital Elevation Model (DEM) accuracy, the defined spatial grid resolution, and meticulous preprocessing of hydrological datasets (Girmay et al., 2020; Ewunetu et al., 2025).

Field Validation and the Incorporation of Local Ecological Knowledge (LEK)

To rigorously fortify the model's predictive validity, field data acquisition involved comprehensive procedures, specifically utilizing *runoff plots*, extensive soil surveying, and Focused Group Discussions (FGDs) with local community stakeholders. This collected field data provides the essential ground truth necessary for locally scaling the calibration of erosion, sediment, and nutrient parameters. Furthermore, the invaluable insights gleaned from the community—concerning traditional conservation practices, localized erosion indicators, and their perception of land degradation severity—were employed to cross-verify the spatial hotspots identified by the model. Consequently, this methodology advances beyond mere technical simulation; it orchestrates a robust triangulation involving empirical observation, engineered simulation, and indispensable local knowledge to forge conservation scenarios that are both profoundly adaptive and verifiably evidence-based (Abere et al., 2025).

MATERIALS & METHODS

The foundation of this study rests upon integrating established hydrological science with socio-ecological insights to address pervasive land degradation dynamics in vulnerable watersheds.

Land Degradation and Nutrient Export Flux

The core concept underpinning land degradation centers on the critical nexus between surface erosion, sediment transport mechanisms, and the resultant nutrient efflux. Surface erosion generates sediment loads that are subsequently mobilized via surface runoff and riverine flow, directly precipitating the loss of essential soil nutrients, including N, P, K, and Ca, out to the catchment outlet. Factors such as effective slope gradient, prevailing land cover conditions, and the implementation level of conservation practices serve as crucial moderators governing the rate of this nutrient attrition (Zhang et al., 2016; Schmidt & Tadesse, 2019).

The Theory of Nutrient Balance

The theory of Nutrient Balance provides the analytical lens through which agricultural sustainability is assessed. This involves meticulously accounting for nutrient inputs (fertilization, organic matter addition), losses via runoff mechanisms, and overall soil accumulation (Mulualem et al., 2023; Schmidt & Tadesse, 2019; Adimassu et al., 2020). A persistent negative nutrient balance signals an impending risk of nutrient depletion, which inevitably leads to a long-term decline in productive capacity. Conversely, strategic SLM practices—those that maintain robust ground cover, effectively stabilize slopes, and incorporate crop rotation—actively enhance nutrient retention while simultaneously curtailing nutrient losses. The synthesis achieved by integrating empirical field data (e.g., runoff plot measurements, soil surveys, and FGD outcomes) with erosion/nutrient export models significantly bolsters model validity, ensures alignment between input assumptions and community reality, and underpins the development of truly evidence-based policy (Abere et al., 2025; Adimassu et al., 2020).

Integrating Local Ecological Knowledge (LEK)

Local Ecological Knowledge (LEK) is not merely supplementary but plays an essential, foundational role in effective slope management strategies. Traditional practices, established seasonal rhythms, and community risk perceptions regarding erosion must inform and enrich the conservation design, rendering it highly adaptive to semi-arid climatic volatility. Field evidence compellingly demonstrates that this localized knowledge aids researchers in correctly diagnosing underlying erosional drivers and prioritizing conservation actions that possess genuine socio-ecological relevance (Grum et al., 2016; Adimassu et al., 2020; Abere et al., 2025). Therefore, the methodical integration of LEK enhances the inherent legitimacy of conservation interventions while simultaneously maximizing the probability of long-term ecological sustainability.

The Hybrid Conceptual Model

A robust conceptual model uniting traditional knowledge system with formal scientific modeling is indispensable for bridging the gap between community practices and evidence-based prediction. Hybrid frameworks, such as the fusion of nutrient balance theory with community-driven adaptation approaches, can accurately elucidate both nutrient flow pathways and land response to specific conservation measures. This integration sharpens the accuracy of risk identification, empowers more contextually relevant decision-making, and generates policy recommendations finely tuned to local socio-economic realities (Mulualem et al., 2023).

The Role of SWAT+ in Biophysical Simulation

The SWAT+ model is employed to simulate the complex dynamics of surface flow, erosion intensity, sedimentation processes, and nutrient transport (N, P, K). Model inputs rigorously encompass precipitation data, slope characteristics, soil texture profiles, current land cover classification, and established conservation measures. Furthermore, parameter adaptation rooted in the RUSLE framework facilitates the estimation of erosional variability and nutrient export across differing land-use types. Crucially, calibration grounded in site-specific field data, including in-situ measurements of flow and sediment concentration, profoundly enhances simulation accuracy, thereby assuring alignment with localized site conditions (Abere et al., 2025).

Efficacy of AHP in Prioritization Structuring

The Analytic Hierarchy Process (AHP) has proven highly efficient in establishing robust weighting for conservation factors via consistent pairwise comparisons across critical criteria, including erosion severity, sediment flux, nutrient status, land cover type, and slope topography (Girmay et al., 2020). Consequently, AHP facilitates the construction of a risk scoring mechanism that is both transparent and empirically verifiable. When coupled with SWAT+ simulation outcomes, this mechanism yields demonstrably more accurate priority hotspot mapping. This synergistic approach streamlines the allocation of scarce resources and significantly enhances stakeholder acceptance across the management spectrum.

RESULT

Differential Erosion and Nutrient Export Across Land Use Typologies

A primary outcome of this investigation reveals significant disparity in soil loss and nutrient export rates directly attributable to prevailing land use/land cover (LULC) categories within the Ethiopian study area. Croplands emerged as the dominant efflux source, frequently exhibiting erosion rates that significantly breach established national tolerance thresholds. In contrast, grazing lands registered moderately lower rates of erosion and nutrient loss compared to croplands, though their impact remained statistically important. Most notably, designated *exclosure* areas—a testament to restorative ecological processes catalyzed by increased vegetation cover—demonstrated the most pronounced, quantifiable reductions in surface erosion and nutrient leaching (Adimassu et al., 2020; Girmay et al., 2020).

Biophysical Drivers of Nutrient Mobilization

The rate of erosion and subsequent nutrient mobilization is inherently governed by a matrix of bio-physical parameters, including slope steepness, the density of vegetative cover, soil depth profiles, and physico-chemical soil characteristics such as texture and cation exchange capacity. The intensity of precipitation serves as a significant kinetic driver, where high-intensity rainfall events amplify surface runoff, thereby accelerating nutrient transport toward receiving rivers and catchment outlets (Saggau et al., 2021). Mechanistically, USLE-based erosion modeling explicitly confirms that slope morphology and ground cover status are the foremost determinants dictating the magnitude of sediment and nutrient excretion (Girmay et al., 2020).

Empirical Erosion Rates Relative to National Benchmarks

Field observations confirmed that erosion rates within Ethiopian croplands frequently approached, or even surpassed, the recommended national erosion threshold for sustainable agriculture. On unmanaged agricultural plots, particularly those situated on steeper slopes, annual erosion rates were quantified within the concerning range of 100–300 t ha^{-1} $year^{-1}$, a level substantially exceeding recommended limits and underscoring the critical imperative for consistent, on-the-ground soil conservation adherence (Girmay et al., 2020).

Convergence Between Field Observation and Model Simulation

Overall, the SWAT+ model demonstrated commendable proficiency in replicating the observed trends in hydrological output, erosion, and nutrient export, particularly subsequent to calibration utilizing site-specific field data. Measurements derived from *runoff plots* and detailed soil surveys substantially reinforced the model's predictive validity in delineating specific erosion hotspots. This convergence between hard empirical observation and bio-physical modeling serves as powerful evidence reinforcing the accuracy of the resulting conservation intervention prioritization schema (Girmay et al., 2020; Ewunetu et al., 2025).

Effectiveness of SLM Interventions

Most Efficacious Conservation Practices

Empirical evidence across the Ethiopian study sites firmly establishes that conservation strategies characterized by consistency and structural rigor—including enhanced ground cover management, slope protection engineering, agroforestry implementation, and *exclosure* establishment—result in significant reductions across both erosion rates and nutrient losses. The *exclosure* technique, specifically, proved superior in mitigating the loss of N, P, and K relative to adjacent open agricultural lands. Furthermore, the synergistic combination of engineered SWC/SLM practices coupled with proactive infrastructure maintenance and localized adaptation yielded a more durable outcome than conservation programs focused solely on increasing spatial coverage (Adimassu et al., 2020; Schmidt & Tadesse, 2019; Grum et al., 2016; Mulualem et al., 2023).

The Temporal Dimension: SLM Implementation Duration

The chronological duration of SLM deployment directly correlates with tangible improvements in soil quality indices and overall harvest yields. Research indicated that medium-to-long-term implementation facilitated an observable increase in soil organic matter, concentrations of nitrogen and phosphorus, stable soil pH, and enhanced soil structure. While positive impacts on agricultural productivity were evident, the *longevity* of these benefits is highly susceptible to the continuity of financial support, diligent infrastructure maintenance, and sustained community engagement. Critically, a deficit in consistent maintenance risks the rapid erosion of long-term ecological gains (Schmidt & Tadesse, 2019; Abere et al., 2025).

Synergy of Physical and Biological Techniques

Conservation effectiveness is demonstrably augmented when physical techniques—such as *bunding*, terracing, and specific slope management—are strategically conjoined with biological measures, including revegetation, agroforestry, the strategic use of *fodder shrubs*, and *exclosures*. This synergistic application yields a significantly greater reduction in both erosion and nutrient efflux than implementing any single practice isolation. Field data further nuance this finding, indicating that efficacy exhibits variability modulated by local land type and micro-climatic conditions, thereby necessitating that conservation designs be explicitly tailored to the specific context (Adimassu et al., 2020; Mulualem et al., 2023; Schmidt & Tadesse, 2019).

Economic Considerations: BCR, NPV, and ROI

Economic feasibility analyses confirm that many SLM practices yield substantial long-term financial advantages derived from productivity enhancements, cost avoidance due to mitigated erosion, and overall fertility improvement. Key economic indicators, including the Benefit-Cost Ratio

(BCR), Net Present Value (NPV), and Return on Investment (ROI), generally offer strong support for the viability of these practices. However, the realization of this economic effectiveness is entirely dependent on sustained funding streams, continuous maintenance commitments, and robust local community adoption. Therefore, any rigorous economic assessment must explicitly factor in long-term maintenance costs against prospective long-term benefits to ensure programmatic sustainability (Schmidt & Tadesse, 2019; Abere et al., 2025).

Model Performance and Empirical Validation: SWAT+ Fidelity

Biophysical Simulation Performance of SWAT+

Studies across tropical watersheds, including those in Ethiopia, attest to SWAT+'s capacity to reliably simulate the dynamics of streamflow debit, sediment erosion, and nutrient transport, provided that hydrological parameters, land cover, slope data, and conservation measures are precisely parameterized. The integration of RUSLE-based erosion factors serves to fortify the estimation of erosivity indices. Validation against field metrics—gauged via *runoff plots*, sediment measurements, and water quality sampling—effectively elevates model performance metrics such as NSE, R^2, and Kling-Gupta Efficiency (KGE), thereby streamlining the final identification of erosion hotspots (Abere et al., 2025; Girmay et al., 2020). Nevertheless, model accuracy is observed to diminish when applied to very small spatial scales if the grid resolution is insufficient or if the input DEM and preprocessing protocols lack necessary detail (Saggau et al., 2021).

Calibration via Field Data and Localized Insight

The calibration of SWAT+ relied heavily upon obtaining high-fidelity data—namely streamflow debit, sediment yield, and nutrient concentrations—sourced from *runoff plots* and intensive soil surveys. Crucially, direct interviews with local residents served to confirm seasonal runoff patterns, prevailing land management behaviors, and key anthropogenic influences (Abere et al., 2025; Girmay et al., 2020). Such qualitative information enriches the model's input parameters, rendering the simulated conservation efforts, land cover scenario, and soil management practices a more faithful reflection of local realities (Abere et al., 2025).

Limitations in Small- to Medium-Scale Watersheds

In small-to-medium scale watersheds, the primary methodological hurdles involve managing inherent bio-physical heterogeneity, navigating observational data sparsity, and addressing the nonuniformity of the established grid scale. SWAT+ may exhibit reduced sensitivity to micro-landscape variations when input data granularity is inadequate, necessitating a cautious and nuanced interpretation of resultant maps (Saggau et al., 2021).

Synthesizing SWAT+ and AHP for Prioritization

The combination of SWAT+ simulations with AHP weighting proves essential for refining conservation priority mapping. AHP establishes the risk weights based on criteria (erosion, nutrient loss probability, land cover, slope), while SWAT+ provides the underlying physical process modeling. This integrated output delivers a vastly superior priority map compared to standalone approaches, solidifying the scientific basis for targeted resource allocation and precise conservation intervention (Abere et al., 2025; Girmay et al., 2020).

DISCUSSION

The Indispensable Symbiosis: Scientific Modeling and Local Expertise

The findings robustly substantiate the hypothesis that the integration of geospatial scientific models with localized, context-specific ecological knowledge yields substantial multiplicative benefits for effective land conservation planning. In the context of East African watersheds, the explicit co-utilization of field observation data (derived from runoff plots, sedimentation monitoring, and water quality assessments) alongside community-held expertise ensures a superior resolution in mapping erosion and nutrient efflux hotspots. The hybrid SWAT+/AHP modeling architecture was shown not merely to enhance the predictive validity across flow, erosion, and nutrient dynamics, but fundamentally to elevate the legitimacy and practical adoption of conservation policies at the community level (Abere et al., 2025; Adimassu et al., 2020; Ewunetu et al., 2025). The nuanced perception held by local communities regarding the root causes of erosion, coupled with their traditional land management practices, functions as a vital enrichment layer for parameter calibration, ensuring that subsequent policy recommendations are deeply embedded in local socio-economic reality.

Policy Imperative: Shifting Focus to Technical Quality over Mere Coverage

A pivotal policy implication derived herein advocates for a fundamental reorientation away from prioritizing sheer spatial coverage toward an unwavering commitment to the technical quality (TQ) of Soil and Water Conservation (SWC) interventions. The long-term economic and productivity gains realized from initial investments are swiftly eroded in the absence of dedicated infrastructure maintenance schedules (Schmidt & Tadesse, 2019; Saggau et al., 2021). Consequently, policy mandates must strategically allocate mid-to-long-term funding streams dedicated explicitly to operational upkeep, continuous monitoring protocols, and the enhancement of community-level technical capacity (Abere et al., 2025). Furthermore, policies must actively foster the adoption of mixed-strategy designs that judiciously blend physical engineering techniques with biological restoration strategies, all hermetically sealed to the localized biophysical and socio-ecological context to maximize the effectiveness of nutrient and erosion retention (Adimassu et al., 2020; Mulualem et al., 2023).

Identified Key Practices: Accuracy Through Integration

The demonstrated efficacy of structuring conservation prioritization via SWAT+ modeling weighted by AHP analysis is unequivocal. This systematic approach yields conservation priority maps exhibiting superior fidelity because the risk weights are directly informed by both empirical evidence and community consensus (Abere et al., 2025; Girmay et al., 2020). This combinatorial power enhances resource allocation efficiency and guarantees far more targeted policy responses. The synergistic effect of community engagement and high-resolution field data fundamentally strengthens the relevance of model outputs, driving higher adoption rates for conservation practices and underpinning the ubiquitous application of evidence-based strategies from the plot level up to the entire watershed scale (Ewunetu et al., 2025).

Institutionalizing Evidence-Based Prioritization

The transition to an *evidence-based prioritization* paradigm is predicated on the accurate identification of erosion and nutrient loss risk hotspots via the triangulated approach of field observation, SWAT+/AHP modeling, and LEK integration. This methodological synthesis delivers a clear, accountable, and politically defensible priority map. By enabling policy to rigorously assess interventions based on quantifiable risk metrics and anticipated socio-economic consequence, resource deployment moves toward maximal efficiency (Abere et al., 2025; Adimassu et al., 2020). To sustain this momentum, institutional mechanisms for adaptive learning—incorporating continuous community feedback, iterative field surveys, and ongoing performance monitoring—must be embedded to ensure that dynamic SLM scenarios remain perpetually relevant and responsive.

Challenges to Scalability and Replication

The replication of the validated SWAT+/AHP approach across the broader landscape faces inherent constraints rooted in socio-ecological heterogeneity. Spatial heterogeneity and persistent limitations in observational data collection pose significant challenges to model calibration and validation, particularly in smaller or less accessible watersheds. The accuracy of resulting risk maps remains susceptible to the quality of input data, specifically the DEM resolution, hydrological preprocessing rigor, and the fundamental assumptions built into the conservation input layers (Saggau et al., 2021; Grum et al., 2016). Regional variations in climate, dominant land use matrices, and cultural paradigms necessitate continual adaptation of AHP weighting schemes and model parameters. Thus, the sustainable maintenance of predictive rigor is contingent upon the ongoing, diligent incorporation of updated field data and relevant local knowledge prediksi (Adimassu et al., 2020; Abere et al., 2025).

CONCLUSION

This research conclusively affirms that land degradation in Ethiopian watersheds, primarily driven by erosion and nutrient depletion, is best managed through a strategically deployed, evidence-based prioritization protocol. The integration of field observations, deep local insight, and the sophisticated SWAT+/AHP modeling framework yielded conservation priority maps noted for their enhanced accuracy and profound social relevance. The principal finding underscores that the ultimate success and sustainability of SLM/PSWC interventions reside in the technical execution and committed maintenance of infrastructure, rather than the sheer spatial footprint. Scientifically, this study advances the utility of an integrative bio-physical–social framework capable of substantially strengthening the legitimacy of conservation policy. Practically, these findings strongly advocate for a policy trajectory centered on technical excellence, long-term custodial care, and iterative local adaptation

Declaration by Authors

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