

# HYDROLOGICAL RESPONSE OF CLIMATE-SMART AGROFORESTRY FOR UPSTREAM WATERSHED CONSERVATION IN STEEP TROPICAL LANDSCAPES, CENTRAL JAVA, INDONESIA

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This study evaluates hydrological responses under different land uses in the Merawu Sub-Watershed, Central Java, and to update the climate-smart agroforestry (CSAF) strategies for upstream conservation in steep tropical landscapes. A paired small-catchment approach compared a vegetable-dominated slope (Leksana, 16.39 ha) and a coffee-based agroforestry slope (Binangun, 2.63 ha), monitored during consecutive wet seasons (2024–2025). Each catchment was instrumented with 90° V-notch weirs and automated rainfall recorders to quantify event-scale direct runoff, runoff coefficients, and suspended sediment yield (SSY). Despite its steeper terrain, smaller size, and higher circularity, Binangun exhibited a higher runoff coefficient (8.7%) than Leksana (2.3%), indicating faster rainfall–runoff conversion under comparable monsoonal conditions. However, SSY in the coffee-based agroforestry catchment was substantially lower (46 t·ha<sup>-1</sup>) than in the intensive vegetable system (156 t·ha<sup>-1</sup>), representing a reduction of approximately 110 t·ha<sup>-1</sup>. This contrast reflects the effectiveness of dense multi-strata canopy cover and integrated soil and water conservation (SWC) practices in enhancing infiltration and sediment retention, even where runoff volumes remain high due to catchment-scale controls. Farmer surveys and field observations revealed widespread adoption of CSAF-aligned practices supported by active local institutions. Overall, the findings demonstrate that in steep tropical uplands, the primary climate-smart benefit of agroforestry lies in erosion and sediment control rather than runoff volume reduction alone. Integrated CSAF packages combining vegetative cover with mechanical and agronomic SWC measures and sustained through strong farmer institutions offer a scalable pathway for resilient upstream watershed conservation while maintaining smallholder livelihoods.

Keywords: Climate-smart agroforestry, hydrological response, sediment yield, soil and water conservation, watershed conservation

## INTRODUCTION

Upstream watersheds underpin downstream water security, hydropower reliability, and sediment regulation in monsoonal tropical regions. In Indonesia's Serayu Basin, accelerated hillslope cultivation on steep latosols has elevated erosion rates and sediment delivery to the Mrica Reservoir, threatening reservoir storage capacity and long-term hydropower generation. These pressures are increasingly compounded by climate change, which has intensified rainfall extremes and increased the frequency of high-intensity storm events across tropical Southeast Asia, amplifying runoff generation and erosion risks on cultivated slopes.

Soil and water conservation (SWC) measures have long been promoted to mitigate erosion and regulate hydrological responses in upland

watersheds. Climate-smart agroforestry (CSAF), in particular, has been widely advocated as a land-use strategy capable of restoring “forest-like” hydrological functions within agricultural landscapes (Naharuddin et al. 2018, Sidle et al. 2006, Suprayogo et al. 2020). Multi-strata canopies intercept rainfall, surface litter reduces raindrop impact, and deep, active root systems enhance soil macroporosity, thereby increasing infiltration and delaying runoff generation (Ranieri et al. 2004, Tschardt et al. 2011). Such processes are widely assumed to reduce both runoff volume and sediment export, especially on steep tropical slopes.

However, recent studies have shown that agroforestry or tree-based interventions alone do not consistently deliver hydrological benefits,

particularly where they are not complemented by slope-adapted mechanical and agronomic SWC measures. Field and modeling studies in tropical and subtropical uplands demonstrate that tree cover without terraces, infiltration structures, or proper soil management can fail to reduce surface runoff and, in some cases, may even accelerate flow concentration under intense rainfall (Basha et al. 2024, Scharrón 2023, Cerretelli et al. 2023, Türk et al. 2025, Dharmawan et al. 2023). These findings highlight a critical limitation of single-intervention approaches that treat agroforestry as a stand-alone solution rather than as part of an integrated conservation package (Brempong et al. 2023, Reddy et al. 2025).

Moreover, hydrological responses in small, steep catchments are strongly influenced by structural controls such as catchment size, slope, and shape, which can override land-use effects on runoff generation. While agroforestry may substantially reduce soil erosion through improved ground cover and soil structure, runoff volumes can remain high where steep slopes, short flow paths, and compact catchment morphometry promote rapid rainfall–runoff translation. This decoupling between runoff and erosion responses remains underexplored in empirical field studies, particularly in intensively managed smallholder landscapes.

Despite extensive promotion of agroforestry in Indonesia, there is still limited field-based evidence that simultaneously evaluates hydrological responses, sediment dynamics, and the role of integrated SWC practices under real smallholder management conditions, despite the long-standing recognition of watershed management as a holistic and multifaceted approach (Kumar et al. 2025). In addition, few studies explicitly incorporate social–institutional dimensions, such as farmer organisations and collective maintenance practices, as functional components influencing the long-term effectiveness of hydrological interventions. Addressing this gap is essential for translating CSAF concepts into scalable and resilient watershed management strategies.

This study addresses these gaps by integrating paired small-catchment hydrological monitoring with field-based assessment of conservation practices and farmer institutions in the Merawu Sub-Watershed, Central Java. Using consecutive wet-season observations (2024–2025), the study compares a vegetable-

dominated catchment (Leksana) and a coffee-based agroforestry catchment (Binangun) to examine how land use, catchment structure, and integrated SWC practices jointly influence runoff and sediment responses. By explicitly linking biophysical outcomes with management practices and institutional support, this study reframes CSAF not as a single land-cover intervention but as an integrated, slope-adapted conservation strategy.

Accordingly, this study aims to evaluate hydrological and erosion responses under contrasting land-use systems, focusing on event-scale direct runoff and suspended sediment yield; and formulate a CSAF-based upstream watershed conservation strategy that integrates vegetative, mechanical, agronomic, and institutional components to enhance watershed resilience under increasing climatic and anthropogenic pressures.

## MATERIALS AND METHODS

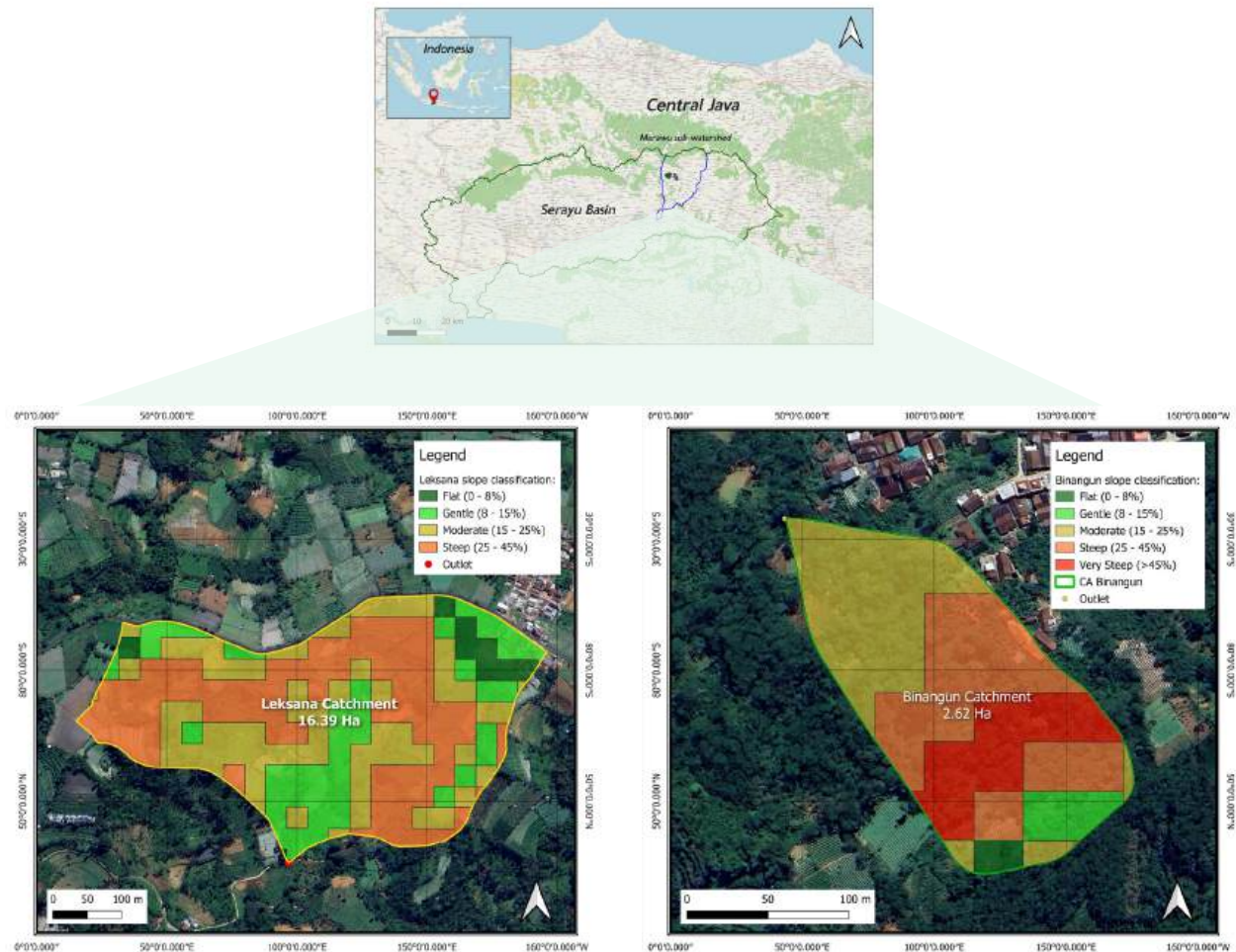
### Study area

Research was conducted in two small catchments within the Merawu Sub-Watershed, Karangobar District, Banjarnegara Regency, Central Java Province. The terrain is mountainous with steep slopes (>25–40%) (Figure 1). Land use is dominated by smallholder agriculture, consisting of mixed vegetable-based systems in the Leksana catchment and coffee-based agroforestry systems in the Binangun catchment, developed on reddish to dark-brown latosols under high annual rainfall.

The Leksana catchment covers an area of 16.39 ha, while the Binangun catchment is substantially smaller at 2.63 ha. These contrasting sizes, together with differences in slope and catchment shape, provide an opportunity to examine how structural catchment controls interact with land-use and conservation practices to influence hydrological responses.

### Research design

A mixed-methods approach was adopted, combining instrumented small-catchment hydrological monitoring, suspended sediment measurements, and farmer surveys complemented by field observations. Hydrological monitoring was conducted during consecutive wet seasons,



**Figure 1** Paired micro-catchment of Leksana and Binangun catchments

with Leksana monitored in 2024 and Binangun in 2025.

Since the catchments were not monitored simultaneously, the study does not apply a strict paired-catchment calibration framework. Instead, the design emphasizes comparative, event-scale hydrological behavior under comparable monsoonal conditions, allowing mechanistic interpretation of runoff and sediment responses while minimising sensitivity to inter-annual rainfall variability.

### Catchment instrumentation and hydrological analysis

Each catchment was equipped with a 90° V-notch weir monitoring station (Figure 2), consisting of an automatic water-level recorder (AWLR) with a 10-minute recording interval, an automatic rainfall recorder (ARR), and a rising-stage suspended sediment sampler array. Stage–

discharge rating curves were developed for each weir to convert water level (stage) into discharge.

Hydrographs were separated to estimate direct runoff (DRO), and runoff coefficients (C) were calculated as the ratio of event-based direct runoff to rainfall depth. Suspended sediment yield (SSY) was determined by integrating measured sediment concentrations with discharge over time for each rainfall event.

In order to ensure comparability between monitoring periods, hydrological analyses focused on event-scale relationships rather than annual totals. Event-based regression analyses were conducted to relate peak discharge ( $Q_p$ ), direct runoff (DRO), and SSY to rainfall characteristics, including rainfall depth (P), duration (D), and mean rainfall intensity (I). This approach allows comparison of hydrological response mechanisms while reducing the influence of inter-annual variability associated with consecutive monitoring years.



**Figure 2** 90° V-notch weir monitoring stations in the Leksana catchment (left) and Binangun catchment (right)

### Rainfall characteristics

Rainfall data recorded by the ARR at each catchment were used to characterise storm events during the monitoring periods. Basic rainfall characteristics, including event rainfall depth, mean intensity, and number of monitored events, were summarized to confirm that both wet seasons fell within comparable monsoonal ranges typical of the Upper Serayu region.

Rather than statistically normalising runoff coefficients across years, rainfall comparability was evaluated descriptively to support cautious interpretation of relative hydrological responses.

### Farmer conservation practices

Structured interviews followed by field observations were conducted in both catchments to assess farmers' perceptions of climate variability and their adoption of soil and water conservation (SWC) practices. Conservation measures were classified into vegetative, mechanical, and agronomic practices. Interviews involved 16 landowners from the Wonosari and Mekarsari farmer groups in Leksana and 30 coffee farmers from the Gondoarum Farmer Group in Binangun. Field observations were subsequently carried out to verify and document the implementation of conservation practices across each catchment.

Quantitative and qualitative analyses were applied to evaluate the adoption, perceived benefits, and limitations of conservation practices. In Leksana, adoption rates and perceived effectiveness were assessed using farmer feedback and field observations. Given resource constraints, quantitative hydrological data were not collected at the plot scale; therefore, qualitative indicators were used to complement catchment-scale hydrological findings. In Binangun, interview data were analyzed in relation to socio-demographic variables such as age, education level, and landholding size using Microsoft Excel and SAS OnDemand for Academics.

### SWOT analysis

A SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis was conducted to synthesise biophysical findings, field observations, and interview results into a structured framework supporting CSAF strategy development. Strengths and weaknesses reflect internal catchment and management characteristics, while opportunities and threats represent external climatic, economic, and institutional factors. The results of this analysis are presented in a SWOT matrix (Table 2) and used to guide the formulation of integrated CSAF strategies.

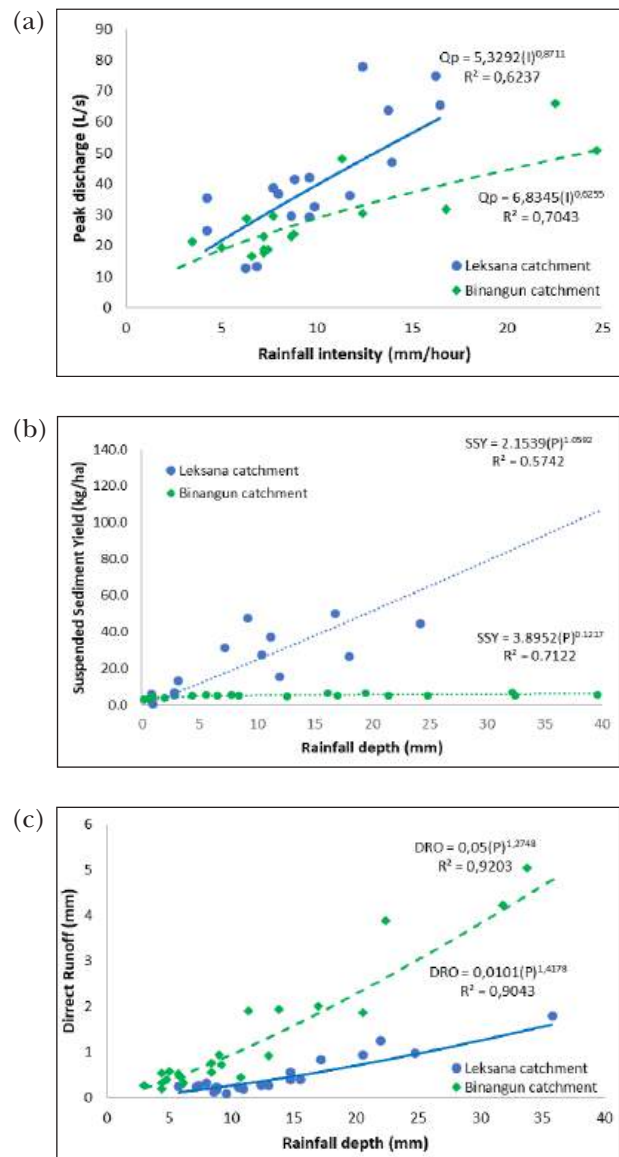
## RESULTS AND DISCUSSION

### Hydrological responses and sediment dynamics

Hydro-sediment monitoring revealed stark performance differences between Leksana and Binangun catchments. Leksana catchment has higher peak discharge ( $Q_p$ ) than Binangun catchment (Figure 3a). In Leksana,  $Q_p$  showed a strong positive correlation with rainfall intensity following the equation with an , indicating that discharge response increases sharply with rainfall intensity, reflecting a more responsive hydrological system. Conversely, in the Binangun catchment, the relationship followed with a slightly higher, suggesting a more moderate increase in discharge with rainfall. Despite the lower slope, Binangun’s intercept was higher, indicating a greater baseline discharge under similar rainfall conditions. This higher baseline  $Q_p$  reflects not only land-use characteristics but also structural catchment controls, particularly the smaller catchment size, steeper average slope, and higher circularity of Binangun. Higher baseline  $Q_p$  in Binangun’s coffee-based agroforestry reflects canopy-driven flow concentration and soil compaction beneath shade trees.

Higher peak discharge indicates a flashier hydrological response and reduced regulation capacity, driven by limited infiltration and shallow soil storage. Rapid surface runoff and limited infiltration is typical of mixed vegetable-based agroforestry with frequent soil disturbance. Disturbed or modified basins tend to produce sharper and higher flow peaks, increasing the energy available to erode channel banks and scour beds (McDonald et al. 2018). Shallow storage layers and reduced infiltration capacity further accelerate runoff generation, as precipitation intensity rapidly converts to overland flow with minimal subsurface retention (Türk et al. 2025). Because hydrological monitoring was conducted during consecutive wet seasons (2024–2025), these results are interpreted as relative, event-scale hydrological responses under comparable monsoonal conditions rather than as strict inter-annual statistical comparisons.

The rainfall depth (P) and direct runoff (DRO) relationship shows distinct hydrological behaviors between the two monitored catchments (Figure 3b). Despite similar rainfall inputs,



**Figure 3** Hydrological response of Leksana dan Binangun catchments in: (a) rain mean intensity (I) and peak discharge ( $Q_p$ ); (b) rainfall depth (I) and direct runoff (DRO); and (c) rainfall depth (I) and suspended sediment yield (SSY)

Binangun produced substantially higher direct runoff response, indicating a faster rainfall to runoff conversion. Ideally, tree cover will optimise groundwater recharge and infiltration as well as root-induced macroporosity in well-managed agroforestry systems that promote preferential flow and reduce surface runoff (Bargués Tobella et al. 2014, Ilstedt et al. 2016). In addition to root effects, the litter layer in tree-based systems plays a critical role in regulating near-surface water storage, as its effective water-retention capacity can delay runoff generation

and enhance subsurface retention under high rainfall conditions (Auguis et al. 2025).

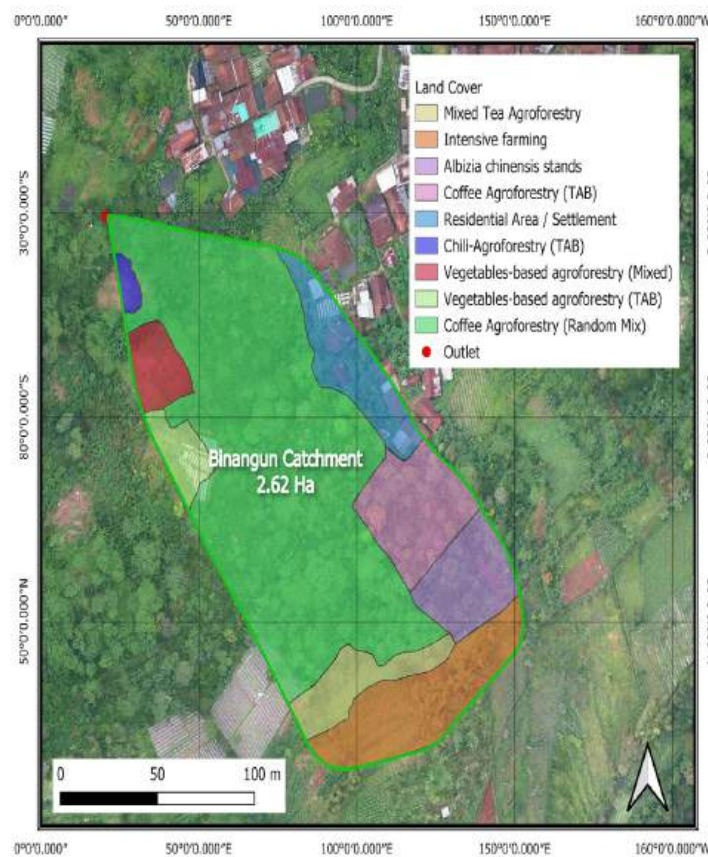
However, this hydrological response is strongly influenced by catchment morphometry (Table 1). Binangun catchment is characterised by a higher average slope (31.7%), with 56.7% of its area exceeding 25% slope and higher circularity (0.74), which tend to produce faster hydrological responses due to steeper terrain and a more compact shape that facilitates rapid flow concentration toward the outlet. In contrast, the Leksana catchment has gentler terrain with an average slope of 23.5%, 40.5% of its area steeper than 25%, and lower circularity (0.63), allowing longer flow paths and greater opportunities for infiltration and subsurface storage. Consequently, despite the presence of agroforestry cover, the steeper and more circular Binangun catchment is more susceptible to enhanced gravitational flow,

reduced infiltration, and accelerated surface runoff and erosion (Lei et al. 2020). Catchment size further amplifies these differences, as the substantially smaller Binangun catchment (2.63 ha) inherently exhibits shorter response times and reduced storage capacity compared to the larger Leksana catchment (16.39 ha).

In addition, the Binangun catchment is not purely coffee-based agroforestry; it also includes areas of intensive vegetable cultivation, especially on the higher slopes above the catchment (Figure 4). These open, intensively tilled plots reduce surface cover and soil permeability, contributing significantly to the elevated direct runoff (DRO) observed at this site. Conversely, Leksana’s gentler terrain provides longer residence time for water infiltration and temporary storage, contributing to lower runoff response.

**Table 1** Morphometric characteristics of both catchments

Catchment	Drainage area (ha)	Catchment circularity	Catchment average slope (%)
Binangun	2.63	0.74	31.7
Leksana	16.39	0.63	23.5



**Figure 4** Land cover in Binangun catchment

Land cover and soil water conservation practices further amplify these differences. Binangun catchment, which is characterised by coffee-based agroforestry systems already integrated with conservation practices such as terraces, vegetative strips, and infiltration pits, could increase infiltration and delay runoff peaks. These practices should ideally maintain soil structure and canopy interception, reducing peak discharge and direct runoff. However, the combined effects of steep slope, compact catchment size, and intensive cultivation in upper slopes override some of these land-use benefits, resulting in higher runoff response in Binangun. Leksana, by contrast, demonstrates the hydrological benefits of gentler slopes and longer flow paths despite more intensive cultivation.

In accordance with direct runoff, Leksana also exhibited a lower direct runoff coefficient (2.3%) than that in Binangun catchment (8.7%), but substantially higher erosion risk across the monitored wet season (155.6 t ha<sup>-1</sup>) compared to Binangun catchment (46.2 t ha<sup>-1</sup>). The elevated sediment yield in Leksana corresponded with the positive relationship between rainfall depth (P) and suspended sediment yield (SSY) (Figure 3c), indicating that erosion processes were more sensitive to rainfall under intensive vegetable-based agroforestry systems with frequent soil disturbance.

Deforestation and land-use conversion to intensive agriculture can increase surface runoff and erosion (Scharrón 2023). Accordingly, despite the implementation of several SWC measures in Leksana, erosion potential remained high due to the predominance of temporary annual crops and vegetable cultivation involving frequent tillage. In contrast, coffee agroforestry systems, characterised by dense canopy cover and minimal soil disturbance, were more effective in controlling soil erosion. Although Binangun exhibited a higher direct runoff response (Figure 3b) due to its steeper slopes, its overall erosion response was lower because of the dominance of coffee-based agroforestry (57% of land cover). This contrast indicates a decoupling between runoff volume and sediment yield, where high runoff does not necessarily translate into high erosion under well-managed agroforestry systems.

The effectiveness of coffee agroforestry in reducing erosion increases with higher

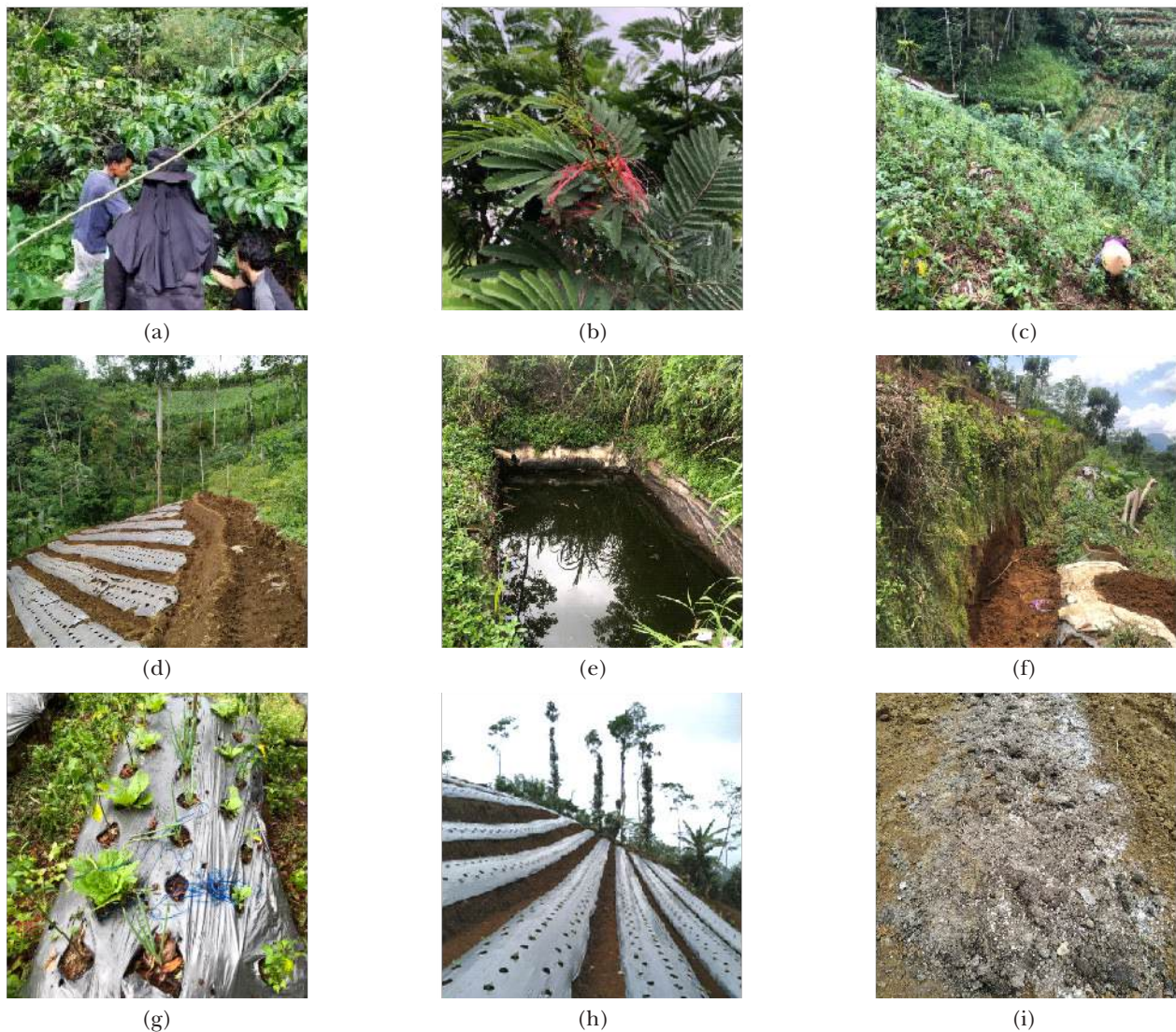
vegetation cover and well-maintained SWC practices (Cerretelli et al. 2023). In Binangun, coffee agroforestry systems provided nearly full ground cover (up to 100%) through the combination of shade trees, coffee plants, and understory vegetation. The integration of vegetative and mechanical SWC techniques within these agroforestry systems collectively enhanced infiltration and sediment retention while reducing surface runoff, thereby strengthening their capacity to control erosion. These findings highlight that both topographic conditions and sustainable land management play critical roles in determining erosion outcomes. Well-managed and infiltration-enhancing agroforestry systems can significantly reduce surface runoff and sediment loss in sloping tropical landscapes (Ngaba et al. 2024, Suprayogo et al. 2020).

## Conservation practices as mitigation and adaptation strategy and in Leksana and Binangun

### *Leksana catchment*

Farmers in Leksana catchment implement integrated conservation practices combining multi-strata agroforestry (timber/fruit trees over annual crops), bench terraces, contour planting, and small ponds for runoff harvesting and irrigation. Agronomic practices include intercropping, crop rotations, mulching, and selective use of plastic mulch, complemented by mixed organic and chemical fertilization (Figure 5). Traditional methods, such as *embungs* (small reservoirs) and terracing, when integrated with modern conservation approaches, enhance resilience and adaptability. These methods have been proven effective in improving sediment and water retention, which are crucial for disaster prevention and land conservation (Haryanto 2013, Limantara 2011).

However, despite relatively low runoff coefficients, Leksana exhibited high sediment yield, indicating that existing conservation practices were insufficient to offset the effects of frequent soil disturbance associated with intensive vegetable cultivation. Practices related to contour alignment, permanent ground cover, and canopy continuity still require further improvement to enhance erosion control under high-intensity rainfall.



**Figure 5** Vegetative techniques (a) coffee plantation, (b) tree cover, and (c) cover crop; Mechanical techniques (d) bunds, (e) reservoir, and (f) terracing; and Agronomic practices (g) mulching, (h) contour planting, (i) fertilization in Leksana catchment

### *Binangun catchment*

Following the conservation effectiveness findings in Leksana catchment, similar integrated practices were also observed in Binangun catchment. Coffee farmers have implemented diverse and integrated soil and water conservation (SWC) practices as adaptive and climate-smart measures that align with CSAF (Figure 6). Coffee agroforestry serves as the core strategy, practiced by all farmers and regarded by 63% as the most beneficial system both economically and ecologically.

Vegetative techniques include multi-strata shade tree systems (e.g. *Albizia chinensis*, *Artocarpus heterophyllus*, *Calliandra calothyrsus*) that enhance

microclimatic regulation, erosion control, and income diversification. Farmers also maintain undergrowth and cover crops (*Arachis pintoi*, grasses, taro), apply organic residues as mulch, construct terraces (76%) and rorak/infiltration pits (55%), and adopt agronomic measures such as contour planting, organic fertilization (87%), and crop rotation (67%). The application of rorak between coffee rows (Figure 7) effectively retains runoff, enhances infiltration, and provides sites for organic matter accumulation (Djufry et al. 2022).

Adequate shade cover, when combined with other SWC measures, can reduce erosion risk by 17–40% in coffee agroforestry systems (Cerretelli et al. 2023). The ecological and

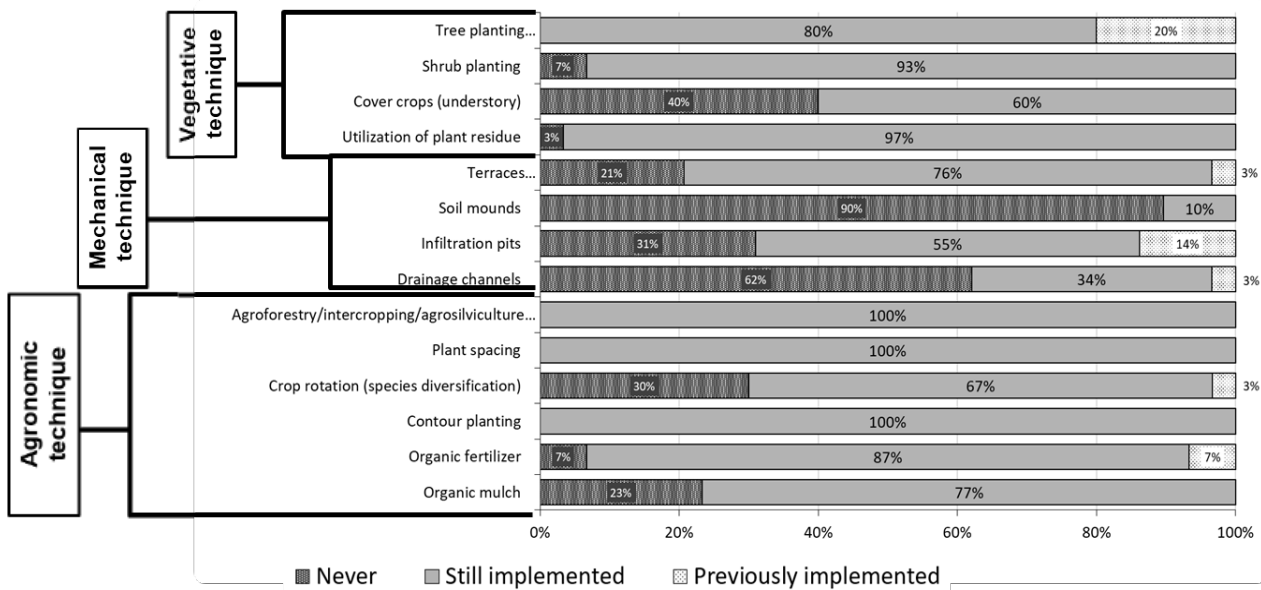


Figure 6 Soil and water conservation strategies implemented by coffee farmers in Binangun catchment

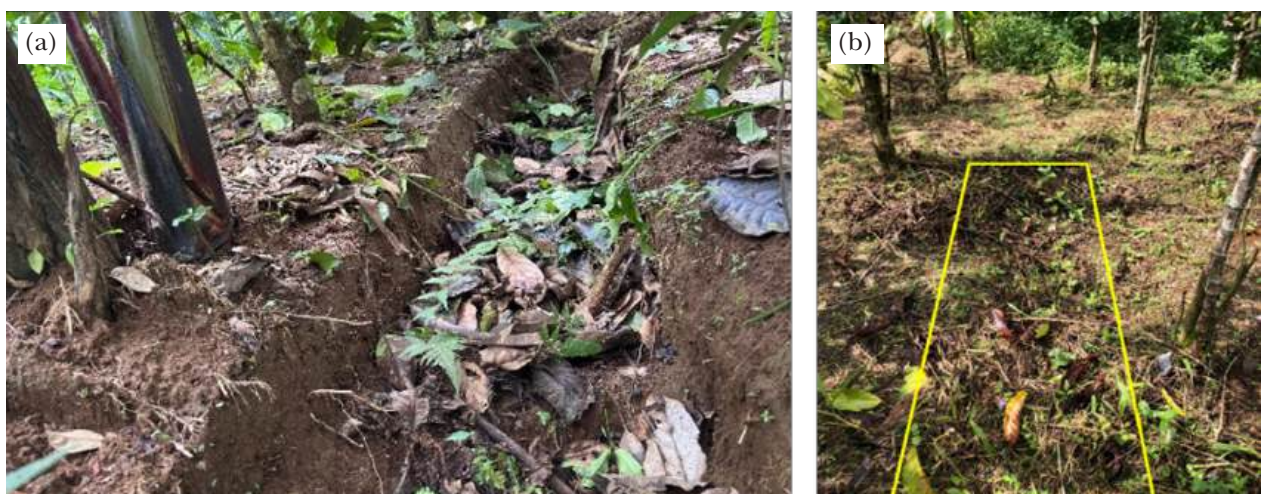


Figure 7 Implementation of *rorak* (infiltration pit) in coffee agroforestry plots: (a) newly constructed *rorak* and (b) *rorak* filled with litter and requiring maintenance. The *rorak* dimensions vary (approximate depth and width of 50 cm and a length of 1–2 m)

economic values of coffee agroforestry motivate farmers to maintain trees, enhancing both livelihood resilience and ecosystem conservation (Kay et al. 2019).

The effectiveness of SWC practices in Binangun is further strengthened by farmers’ knowledge of climate change and adaptive responses, supported by extension services and active farmer institutions. Although statistical correlations between climate knowledge and age or education level were weak, extension agents played a dominant role in shaping adaptive land management decisions. These findings

reinforce that CSAF effectiveness depends on the full integration of vegetative, mechanical, and agronomic measures, rather than tree presence alone.

### A CSAF strategy for upstream watershed conservation

Synthesising the conservation effectiveness assessment and SWOT analysis, both Leksana and Binangun exhibit strong potential to advance upstream watershed conservation through integrated, adaptive management that

builds upon traditional practices refined over generations. The key findings from the SWOT analysis are summarized in Table 2, providing a strategic framework for integrated CSAF implementation.

**Table 2** SWOT Analysis for CSAF Strategy

Strengths	Weakness
<ul style="list-style-type: none"> <li>Dense canopy cover and integrated SWC practices</li> <li>Strong farmer institutions and local knowledge</li> <li>Proven erosion control in coffee agroforestry</li> </ul>	<ul style="list-style-type: none"> <li>Partial adoption of contour planting in Leksana</li> <li>Intensive tillage in vegetable plots (Leksana)</li> <li>Smaller catchment flashiness (Binangun)</li> </ul>
Opportunities	Threats
<ul style="list-style-type: none"> <li>PES schemes and hydropower incentives</li> <li>Strengthening farmer groups and peer learning</li> <li>Tailored site-specific CSAF strategies</li> </ul>	<ul style="list-style-type: none"> <li>Increasing rainfall intensity and climate risks</li> <li>Market fluctuations and economic uncertainties</li> <li>Land-use pressure and tenure insecurity</li> </ul>

The SWOT analysis (Table 2) identifies the internal strengths and weaknesses, as well as external opportunities and threats, that shape the effectiveness of CSAF in the Merawu Sub-Watershed. This matrix provides a strategic foundation for the four-pillar integrated approach proposed. A four-pillar integrated strategy is proposed to guide upstream watershed management across the Merawu Sub-Watershed:

(1) *SWC Practice Integration at Farm and Hillslope Scales*

Integrated SWC practices (vegetative, mechanical, and agronomic measures) can significantly reduce soil erosion. Recommended practices including: (a) contour-aligned planting and bed orientation, organic practices, use of ground covers, and proper tree management; (b) construction of bench terraces and rorak (infiltration pits) on slopes exceeding 15% to minimize runoff and erosion; and (3) establishment of strategically located

runoff-harvesting ponds to reduce surface runoff and peak discharge, while providing supplementary irrigation during the dry season.

(2) *Revitalisation of Farmer Institutions and Extension Ecosystems*

Beyond biophysical and engineering measures, this study demonstrates that the effectiveness and persistence of soil and water conservation (SWC) practices are strongly mediated by social-institutional factors. High levels of social capital manifested through active farmer groups, intergenerational knowledge transfer, and collective maintenance norms function as a form of *soft engineering* that sustains hydrological performance at the catchment scale. These institutional dynamics underpin the long-term functionality of “hard” SWC measures and help explain the superior hydrological regulation observed in the Binangun catchment.

Importantly, this finding extends hydrological analysis beyond conventional plot- or structure-based evaluations by positioning farmer institutions as an integral component of watershed hydrology. Strengthening farmer institutions thus constitutes a hydrological intervention, as it directly influences the maintenance, effectiveness, and continuity of infiltration-enhancing structures and land management practices. Practical strategies include: (a) reactivating and empowering farmer groups (e.g., the *Gondoarum* Farmer Group) as platforms for collective learning, co-maintenance, and shared decision-making; (b) promoting peer-to-peer learning through demonstration plots to accelerate adaptive practice uptake; and (c) integrating simple participatory monitoring tools (e.g., rainfall and event-based runoff records, visual sediment yield indicators) to reinforce farmer engagement and long-term stewardship.

By explicitly linking institutional strength to hydrological outcomes, this study highlights farmer institutions as a critical yet under-recognised “soft engineering” mechanism for climate-smart watershed management in steep tropical landscapes.

- (3) *Economic Resilience and Incentive Mechanisms*  
Diversify agroforestry products (timber, coffee, fruit, and fodder) and develop post-harvest value addition to buffer income against climate and pest risks. Alignment of these efforts with Payment for Ecosystem Services (PES) or hydropower sediment-reduction incentives can sustain SWC maintenance in upstream areas that benefit downstream areas.
- (4) *Risk-Informed Landscape Governance*  
*Integrate community-based disaster risk management (DRM) into watershed planning for landslides and flash floods.*  
Strengthen tenure security and micro-credit access for SWC retro fitting, and prioritize high-erosivity sub-catchments (high risk zones) for accelerated implementation of terraces and infiltration pit.

### Implications for tropical forest science and policy

These findings underscore that forest-in-farms (agroforestry) produce measurable hydrological co-benefits when coupled with SWC engineering and maintained through strong institutions. Policy frameworks that treat agroforestry as a single land-cover intervention will likely underperform on steep smallholder hillslopes without co-investment in terraces, infiltration pits, and ponds, as well as social mechanisms to maintain their functionality.

### Limitations and future research

Catchments were monitored in consecutive (not simultaneous) wet seasons. Although rainfall characteristics were comparable, strict inter-annual normalization was not possible, and interpretations therefore emphasise event-scale hydrological behavior. Moreover, belowground ecological processes such as fine-root dynamics, litterfall, and soil biological activity exhibit strong temporal variability and may influence infiltration pathways (Jeyanny et al. 2025). The sediment budgets primarily represent suspended load, while bedload contributions warrant further investigation.

## CONCLUSIONS

Upstream watershed conservation in steep tropical agroecosystem landscapes requires integrated climate-smart agroforestry (CSAF) approaches that combine multi-strata tree systems with soil and water conservation (SWC) measures such as terraces, infiltration pits, ponds, mulching, and contour farming, and that are implemented and maintained through strong farmer institutions. In the Merawu Sub-Watershed, the integration of these practices influenced hydrological and erosion responses under contrasting land-use systems.

The results demonstrate that coffee-based agroforestry systems, when combined with integrated SWC practices, were effective in substantially reducing sediment yield but did not necessarily reduce runoff volume in smaller and steeper catchments. Although the Binangun catchment exhibited a higher runoff coefficient than Leksana, it produced significantly lower suspended sediment yield, highlighting the effectiveness of dense canopy cover, continuous ground cover, and infiltration-enhancing practices in controlling erosion.

Accordingly, the initial hypothesis that agroforestry would reduce both runoff and sediment was only partially supported. While agroforestry-based CSAF did not reduce runoff volume under conditions dominated by strong catchment-scale controls (small size, steep slope, and compact shape), it markedly reduced sediment export. This finding underscores a decoupling between runoff volume and erosion response in steep tropical catchments and identifies erosion control as the primary hydrological benefit of CSAF in such settings.

Beyond biophysical outcomes, this study also shows that the persistence and effectiveness of CSAF practices depend strongly on social-institutional factors. Active farmer groups, knowledge exchange, and collective maintenance norms function as a form of soft engineering that sustains the long-term functionality of SWC measures and enhances catchment-scale hydrological regulation.

Overall, this study highlights that CSAF should not be treated as a single land-cover intervention but as an integrated, slope-adapted

management package that combines vegetative, mechanical, agronomic, and institutional components. Such integrated approaches offer a practical and scalable pathway for improving watershed resilience, reducing sediment delivery, and sustaining smallholder livelihoods in steep tropical landscapes.

## ACKNOWLEDGEMENT

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