Integrating biophysical and socio-institutional inventories to reduce sedimentation in the Limboto watershed, Indonesia

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Abstract. This investigation sought to furnish a comprehensive bio-physical, hydrological, socioeconomic, and institutional inventory of the Limboto Watershed Area (DAS Limboto), specifically to forge a robust foundation for integrated management and the stabilization of Lake Limboto against relentless sedimentation. Operating through a Socio-Environmental Systems (SES) lens, this research masterfully synthesized remote sensing inputs, advanced GIS analytics, and granular social survey data. The empirical distillation reveals that DAS Limboto, sprawling over 89,385 hectares, possesses a characteristically elongated morphology (Rf 0.35; Re 0.46) coupled with a drainage density of 1.84 km/km², signaling an inherent predisposition towards moderate-to-severe surface runoff. Furthermore, the high mean annual precipitation 2.478 mm (with an 25,7 mm/days intensity) significantly amplifies erosion risk, particularly pronounced on slopes >25%. The alarming rate of forest loss (3.1% annually) directly translates into an annual sediment load of 1.2 million m3, catastrophically shallowing the lake to depths under 2.5 meters. Socially, this environmental stress is compounded by 365.000 individuals, a substantial population density of 408 jiwa/km² (supporting lives), and a severely fragmented institutional landscape that exacerbates degradation. These convergent findings compellingly argue for aggressive, cross-sectoral policy integration anchored by the "One Watershed, One Management Plan" directive, necessitating the immediate adoption of "evidence-based watershed management" drawing deeply from fused biophysical and social indicators to fortify conservation effectiveness. Ultimately, this study delivers a critical, empirical model for developing sustainable WSM strategies in Indonesia, positioning its results as the essential calculus for formulating adaptive policies resilient to ongoing climate change and anthropogenic strain.

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1. Introduction

Watershed management (WSM) in tropical regions, including Indonesia, is grappling with intricate challenges stemming from intense land use pressure and the evolving climate scenario. As an integrated ecological and hydrological system, a watershed plays a vital role in sustaining the delicate equilibrium between water resources, soil integrity, and vegetation cover [Hamel et al., 2017]. The adoption of Integrated Watershed Management (IWM) has emerged as a promising pathway to ameliorate environmental degradation in these rapidly developing tropical zones, characterized by swift rates of deforestation and land cover transformation. IWM fundamentally stresses cross-sectoral coordination and community participation in the sustainable utilization of natural resources, aiming to preserve the watershed's ecological functions while simultaneously advancing societal well-being [Narendra et al., 2021]. Empirical studies compellingly demonstrate that effective IWM implementation can lead to significant vegetation cover recovery and an erosion rate reduction of up to 89%, resulting in a direct, positive impact on hydrological stability and subsequent sedimentation levels.

The pervasive conversion of forests into agricultural land, plantations, and human settlements is a dominant theme across many Indonesian watersheds. This conversion precipitates hydrological imbalances, evidenced by increased surface runoff, diminished infiltration rates, and a greater frequency of both floods and droughts [Pasapan et al., 2024]. The long-term consequence of this trend is the erosion of the watershed's ecological capacity and a marked increase in sedimentation within downstream lakes or reservoirs. Prior research consistently reveals that watershed degradation directly compromises agricultural productivity, clean water availability, and the socioeconomic resilience of local populations. Consequently, effective management demands more than mere biophysical restoration; it requires synergistic collaboration among all stakeholders to govern natural resources under core principles of sustainability [Zafirah et al., 2017].

The One Watershed, One Management Plan principle, mandated by Indonesian Government Regulation (PP) No. 37 of 2012 concerning Watershed Management, serves as the strategic policy framework that underscores the necessity of integrating management across sectors and administrative boundaries. This mandate actively promotes policy coordination between forestry, agriculture, spatial planning, and water resource agencies, ensuring that all developmental activities are harmonized with the hydrological limits of the watershed [Sulistyaningsih et al., 2021]. Such integration facilitates a comprehensive, headwater-to-mouth approach to environmental problem-solving, while simultaneously mitigating conflicts over land and water use. In the context of highly dynamic tropical watersheds, adherence to this principle demonstrably enhances the effectiveness of adaptation strategies concerning climate change and hydrological uncertainty.

A paramount management concern throughout Indonesia is the alarming rate of sedimentation and ecosystem function degradation in tropical lakes, exemplified by Lake Limboto in Gorontalo Province. In the DAS Limboto catchmen the amount of sheet erosion was 122.24 ton/ha/year. Sediment yield in Alu-Polu was affected to a large extent by runoff rate, the width of the watershed, percentage of wasteland, and drainage density [Lihawa, 2009]. The rapid sedimentation phenomenon observed in this lake signals a severe disruption to the hydrological regulatory functions of the DAS Limboto catchment. Numerous studies correlate sedimentation rates with upstream land conversion and deficiencies in soil and water conservation practices. The influx of sediment material from upper catchments causes progressive lake shallowing, reduces water storage capacity, and exacerbates downstream flood risk. Furthermore, intensive use of fertilizers and pesticides in agricultural activities contaminates the water and accelerates eutrophication processes [Lee et al., 2021]. This confluence of biophysical and anthropogenic factors necessitates an integrative intervention strategy that prioritizes not just conservation measures, but also the crucial enhancement of institutional systems and water resource governance [Sulistyaningsih et al., 2021].

National and regional policies, such as PP No. 37/2012, are instrumental in reshaping WSM approaches toward greater participation and scientific evidence-based decision-making. This regulation underscores the need for comprehensive inventory assessments of watershed characteristics—covering both biophysical and social aspects—to formulate adaptive and measurable management plans [Basuki et al., 2022; Supangat et al., 2023]. Furthermore, policy execution inherently demands the active engagement of diverse stakeholders, ranging from local government to community members, ensuring that management actions possess both technical soundness and socio-ecological legitimacy [Pambudi, 2019]. Nevertheless, considerable research indicates that policy implementation is frequently impeded by institutional bottlenecks, such as overlapping inter-agency authority and poor cross-sectoral coordination [Sulistyaningsih et al., 2021]. Thus, a more systematic method is required to bridge established policy with tangible field realities.

The biophysical degradation of a watershed has an immediate and tangible effect on the wellbeing of downstream communities. Declining water quality, rising sedimentation, and compromised ecosystem services directly threaten the agricultural, fisheries, and local economic sectors. Reduced land productivity resulting from erosion and flooding elevates poverty risk and often catalyzes rural-to-urban migration. This inequity intensifies social and environmental stress, fostering a negative feedback loop that accelerates watershed deterioration [Yulianto et al., 2022]. These studies reassert that successful WSM hinges not only on technical conservation measures but equally on strengthening institutional capacity and empowering local communities to actively engage in resource planning and implementation.

Previous research has proposed several conceptual solutions to address these mounting challenges, including the adoption of ecohydrological approaches, risk-based adaptive management, and participatory models in watershed planning. The ecohydrological perspective emphasizes maintaining the ecological-hydrological balance essential for watershed sustainability. Concurrently, risk-based adaptive management allows for flexible control strategies tailored to socio-economic and climatic uncertainties. Participatory models, conversely, build social legitimacy and reinforce accountability mechanisms between the government and the public during conservation program execution. However, the practical application of these solutions remains constrained by insufficient integrated data and inadequate cross-sectoral coordination.

It is within this demanding context that the study of DAS Limboto gains high scientific and practical urgency. A comprehensive inventory approach—one that cohesively integrates biophysical, socio-economic, and institutional dimensions—is critical for grasping the system's dynamics as a unified whole. This research centers on mapping the specific characteristics of the DAS Limboto to form a foundation for targeted policy formulation and management interventions. The study also seeks to resolve a known research gap where physical and social analyses have historically been treated separately. By embracing the One Watershed, One Management Plan paradigm, this work offers an integrative framework to support national policies aimed at controlling sedimentation in Lake Limboto. The novelty of this study lies in merging spatial and non-spatial data within a unified planning system, positioning it as a potential model for other Indonesian watersheds. Moreover, these findings will contribute to scientific grounding for evidence-based planning, monitoring, and performance evaluation of watershed management, all oriented towards ecological sustainability and community welfare.

2. Methodology

This research employed an integrated inventory approach to characterize the biophysical, hydrological, social, and institutional parameters within the Limboto Watershed Area (DAS). This methodology is fundamentally grounded in the Socio-Environmental Systems (SES) framework, or the *Watershed-Human System*, which necessitates the holistic integration of biophysical and social datasets to comprehend the underlying dynamics of the watershed system. This framework facilitates comprehensive analysis of the interplay between hydrological components, land use patterns, geomorphology, and the prevailing socioeconomic conditions of the study area's population. Crucially, this approach ensures the research extends beyond mere biophysical profiling to assess the institutional capacity and community participation essential for maintaining watershed health.

The primary data corpus comprised biophysical components (geology, morphometry, topography, soil, hydrology, and land use) alongside socioeconomic and institutional data. Biophysical data were derived from a synergy of remote sensing techniques, Geographic Information Systems (GIS), and direct field observations. Social and institutional data were sourced from official institutional documents, household surveys, and in-depth interviews conducted with key stakeholders across the three administrative jurisdictions of DAS Limboto: Gorontalo Regency, North Gorontalo Regency, and Gorontalo City. All collected data were integrated within a spatial database system to enable synergistic cross-component analysis.

2.1 Data Sources

The primary data foundation utilized multi-resolution satellite imagery, including Landsat 8 OLI, SPOT, ALOS PALSAR, and SRTM 90 m data. These were instrumental in generating detailed maps of elevation, slope gradient, and land cover. Geometric and radiometric corrections were rigorously applied to ensure both spatial and temporal accuracy. Data integration was managed using specialized GIS software (ArcGIS and QGIS), with the official Indonesian Topographic Map (RBI) at a 1:25,000 scale designated as the principal geospatial reference. Socioeconomic and institutional data were compiled from governmental agencies (e.g., Bappeda, Environmental Agency, Forestry Agency, and Agriculture Agency), project conservation reports, and community surveys detailing land use practices and perceptions regarding natural resource management. Data amalgamation was executed via an overlay analysis approach to spatially correlate biophysical parameters with the distribution of social and institutional activities across the watershed.

2.2 Meteorological Parameters

The meteorological parameters analyzed included annual rainfall, intensity, and spatial distribution. Data were acquired from the BMKG Gorontalo Station and were used to classify rainfall intensity according to the categories established by Linsley (1975): very low (<13.60 mm/day), low (13.61–20.70 mm/day), moderate (20.71–27.70 mm/day), high (27.71–34.80 mm/day), and very high (≥34,81 mm/hari mm/day). The spatial distribution of rainfall was determined using the Thiessen polygon method for flat areas and the isohyetal method for hilly terrain, resulting in the production of isohyetal maps. This analysis was crucial for establishing the linkage between rainfall patterns and the watershed's hydrological response concerning surface runoff and soil erosion.

2.3 Geology and Geomorphology

Geological and geomorphological analysis was performed to delineate the influence of lithology on drainage patterns and potential erosion susceptibility. Rock classification referenced national geological maps and field data, identifying dominant rock types such as volcanic breccia, tuff, limestone, and alluvium. Impermeable rock structures, like lava and andesite, are known to produce sharper flow peaks compared to permeable rocks such as sedimentary rock or tuff [Theofanous & Myronidis, 2020]. Geomorphological mapping adhered to the BAKOSURTANAL classification format, characterizing landform units into slope, valley, and flood plain categories. This geological context supported the correlation analysis between rock structure, drainage patterns, and infiltration capacity in relation to the hydrological response.

2.4 Topography and Slope Gradient Analysis

The topography of DAS Limboto was analyzed utilizing the Digital Elevation Model (DEM) extracted from SRTM imagery. Key measured parameters included mean elevation, slope gradient, and slope direction (azimuth). Elevation values were computed using the hypsometric curve approach (Figure 1), while slope gradient was calculated using contour methodology based on the formulations proposed by Avery (1975) and Horton (1945). This analysis yielded a slope class map distributed as follows: 0–8% (41%), 8–15% (27%), 15–25% (18%), and >25% (14%). The mean watershed slope was calculated at 11,8%, indicating a **rolling terrain** morphology. This topographical data served as the bedrock for analyzing the relationship between terrain, erosion processes, and soil infiltration capacity [Rana & Suryanarayana, 2021].

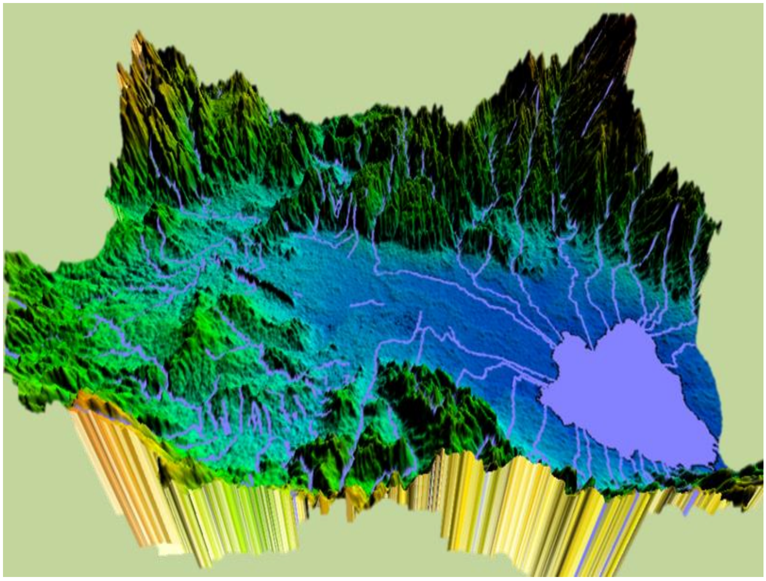

Figure 1. Illustrates the hypsometric map of DAS Limboto, revealing the spatial variation in elevation and mean slope across the area.

2.5 Soil and Hydrological Parameters

Soil characteristics, including texture, permeability, and solum depth, were identified following the Puslittanak classification system. Four dominant soil orders were present: Andisols (35%), Inceptisols (33%), Entisols (22%), and Vertisols (10%), exhibiting infiltration capacities ranging from <2 cm/hours to >10 cm/hours. This information was used to determine the potential for surface runoff and erosion based on infiltration capacity. The hydrological modeling employed the Soil and Water Assessment Tool (SWAT), integrated with GIS, to estimate flow discharge, sedimentation yield, and runoff coefficients. Hydrological parameters such as Qmin, Qavg, Qmax, and rasio Qmin/Qavg were sourced from the SPAS Limboto hydrological station data. Modeling results indicated a runoff coefficient value of 0.56, signifying a moderate runoff response.

2.6 Morphometric Analysis and River Network

Morphometric analysis was conducted to evaluate the watershed shape and potential surface flow using the parameters of form ratio (Rf), elongation ratio (Re), bifurcation ratio (Rb), and drainage density (Dd). The value of Rf as 0.35 and Re of denote an 0.46 elongated watershed shape, which typically results in a longer flow concentration time and thus a delayed flood peak. The value ranged between 3.2-4.8, suggesting control by normal geological structures, while the value of 1,84 km/km² indicates a moderate to high level of surface runoff potential. The river network was classified up to the 6th order, exhibiting a dendritic drainage pattern with secondary trellis influences, as illustrated in Figure 2 [Fahmi & Kusumandari, 2022]. The relationship between these morphometric characteristics and erosion potential was spatially analyzed through the correlation of morphological parameters with land use distribution.

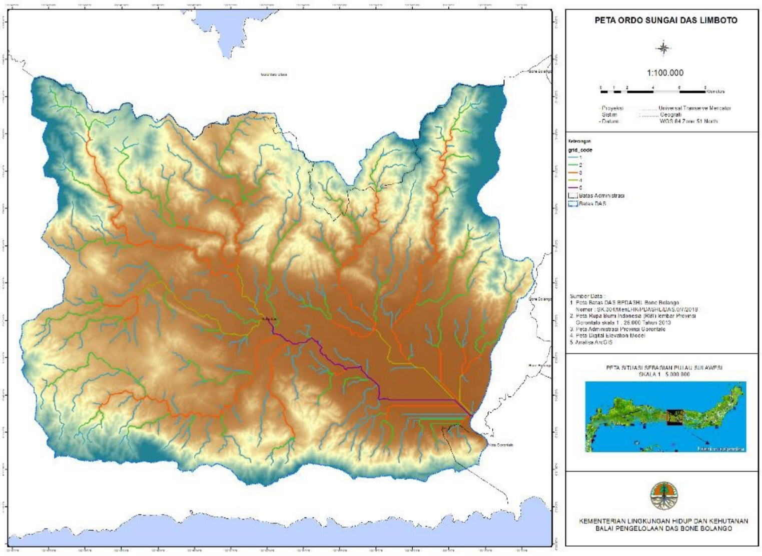

Figure 2. Depicts the pattern of the main flow network of DAS Limboto, classifying the river orders up to the 6th order.

2.7 Socioeconomics and Institutional Framework

Social and institutional data were gathered utilizing a community-based participatory approach. Data validity was ensured through triangulation of sources and methods, encompassing household surveys, Focus Group Discussions (FGDs), and interviews with relevant agency officials. A co-production process was implemented to confirm the social data's relevance to the biophysical context and to identify institutional indicators such as coordination effectiveness, community participation, and adaptive capacity to environmental changes. Reliability was maintained by juxtaposing survey results against secondary data from local government and watershed management bodies. This approach aligns with the principle of transparency and accountability inherent in ecosystem-based management [Ekawati et al., 2005].

Table 1. Rainfall Annual

No	Station	Coordinates		Rainfall Annual	
		X	Y	mm	Classification
1	ARR Isimu Raya	0° 39' 94.2"	122° 51' 47.8"	1,240.1	Very Low
2	ARR Biyonga	0° 41' 16.2"	122° 59' 23.8"	1,162.8	Very Low

No	Station	Coordinates		Rainfall Annual	
		X	Y	mm	Classification
3	ARR Dulamayo	0° 41’ 16.2”	122° 59’ 23.8”	1,160.8	Very Low
4	ARR Iloponu	0° 42’ 30.6”	122° 51’ 19.6”	1,435.1	Very Low
5	ARR Tabongo Timur	0° 39’ 94.2”	122° 51’ 47.8”	1,516.9	Low
6	ARR Liyodu	0° 33’ 29.4”	122° 47’ 52.4”	1,700.3	Low

Rainfall intensity classification based on Linsley (1975): Very Low (<13.60 mm/day), Low (13.61–20.70 mm/day), Moderate (20.71–27.70 mm/day), High (27.71–34.80 mm/day), and Very High (mm/day). This comprehensive methodology facilitated a thorough mapping of the interactions among physical, hydrological, social, and institutional factors. The resulting inventory forms the empirical foundation for formulating integrated management policies for DAS Limboto, strictly adhering to the One Watershed, One Management Plan principle mandated by PP No. 37/2012. This integrative strategy not only substantiates a scientific evaluation of the existing conditions but also provides an empirical model for sustainable watershed management in Indonesian tropical settings.

3. Results

3.1 Morphometry and Physical Characteristics of the Limboto Catchment

The Limboto Watershed Area (DAS) spans hectares, encompassing three distinct administrative jurisdictions: Gorontalo Regency, North Gorontalo Regency, and Gorontalo City. Morphologically, the DAS exhibits an elongated configuration, evidenced by a low Form Factor (Rf) of 0.35 and an Elongation Ratio (Re) of 0.46, this geometry suggests a hydrological response characterized by a relatively long flow concentration time, yet it simultaneously signifies a high inherent erosion potential. Based on the lemniscate ratio analysis (>1), this elongated shape tends to temper peak discharge but critically elevates sedimentation risk in the lower reaches due to the cumulative runoff contribution from various sub-watersheds. The overall drainage pattern is dendritic, overlaid by secondary trellis influences, reflecting a moderate structural geological control over the drainage alignment.

The total stream length approximates 1,645 km, yielding a Drainage Density (Dd) of 1.84 km/km2. This moderate to high density strongly indicates significant surface runoff potential coupled with relatively low soil infiltration capacity, thereby amplifying the risk of seasonal flooding in the downstream areas [Zhang et al., 2019]. The Bifurcation Ratio (Rb) falls within the 3.2 to 4.8 range, consistent with normal geological structural control. Topographical analysis, derived from the SRTM-based Digital Elevation Model, established a mean elevation of (450m a.s.l.) and a Relief Ratio (Rh) of 0.034, indicating a moderate degree of landscape dissection and a moderate velocity of runoff. Critically, the morphometric signature reveals that the steeper headwater areas, particularly those with gradients exceeding >25%, significantly contribute to elevated erosion rates.

3.2 Precipitation Regime

The mean annual rainfall across DAS Limboto registered 2,478 mm, translating to a daily intensity of 25.7 mm/days, which falls within the moderate category according to Linsley's classification [Wagner, T., & Linsley, R. (1975]. The spatial distribution of precipitation displayed a marked decline from north to south, with the highest accumulation (2,800 mm) recorded in the northern hills and the lowest (2,200 mm) in the southern regions. This isohyetal pattern is heavily modulated by the orographic effect exerted by the northern highlands. High rainfall intensity in these uplands directly contributes to increased surface runoff, particularly over land surfaces characterized by diminished vegetative cover.

Climatically, the dominant drivers for discharge and runoff variability in DAS Limboto are the synergistic combination of high-intensity rainfall events and frequent occurrences of extreme precipitation [Wei et al., 2014]. This meteorological phenomenon is exacerbated by land use change, which simultaneously curtails infiltration capacity. Temporally, the peak rainy season occurs between November and April, coinciding with the western monsoon phase, which invariably triggers elevated peak river discharges. The low ratio of 0.24 highlights a pronounced seasonal imbalance, indicating a frail capacity for groundwater storage and baseflow maintenance during dry periods.

3.3 Land Cover Dynamics

The 2023 land cover inventory revealed that forest cover (34%) constitutes of the DAS area, followed by agriculture (28%), urban settlements (22%), plantations (9%), and open land (7%). Significant deforestation in the upper reaches has proceeded at an alarming rate of 3,1% per year since the year 2000, stemming primarily from the conversion of forest into dry agricultural fields and settlement expansion. Vegetation decline, quantified via NDVI analysis, showed a reduction 3.1% per year in the vegetation index between 2000 and 2023 year. This decrease exhibits a positive correlation with the rise in the runoff coefficient, escalating from 0.36 to 0.56, signaling a higher runoff response attributable to reduced canopy interception [Aslam et al., 2020; Zhang et al., 2019].

The expansion of built-up areas over 22% the last two decades has directly undermined infiltration capacity and increased the frequency of downstream flooding. Flood-prone areas were mapped across 6,432 ha, 72% representing the total DAS area, concentrated primarily within the low-lying zones adjacent to Lake Limboto. This land cover transformation trajectory aligns with global findings asserting that deforestation actively accelerates erosion and sedimentation processes in tropical lakes [Woldemariam & Harka, 2020; Jarray et al., 2023].

Table 2. Composition of Land Cover in DAS Limboto, 2023

No	Land Cover Type	Area (Ha)	Percentage (%)
1	Parking areas and fields	2.05	0,00
2	Industrial and commercial buildings	60.05	0,07
3	Other non-residential buildings	15.45	0,02
4	Village residential buildings (associated with vegetation)	6.28	0,01
5	Urban residential buildings	3,371.99	3,77
6	Natural lakes (unspecified)	2,687.67	3,01
7	Primary high-altitude forest, medium density	1,366.80	1,53
8	Primary high-altitude forest, high density	9,949.92	11,13
9	Secondary high-altitude forest, medium density	3,732.94	4,18
10	Asphalt/concrete/soil roads	69.89	0,08
11	Mixed gardens	22,800.98	25,51
12	Fields/dry land with secondary crops	6,714.77	7,51
13	Other open land	63.73	0,07
14	Runways and taxiways	17.77	0,02
15	Oil palm plantations	304.72	0,34
16	Other plantations	10,521.40	11,77
17	Continuous paddy fields	6,524.34	7,30

No	Land Cover Type	Area (Ha)	Percentage (%)
18	Shrubs	118.18	0,13
19	Scrubland/Bush	20,956.20	23,44
20	Stadiums	2.05	0,00
21	Rivers	94.65	0,11
22	Airport terminals	1.67	0,00
23	Other water bodies (unspecified)	2.09	0,00
	Total	**89,385.61**	100,00

3.4 Geology, Soil, and Topography

Geological interpretation identifies the dominant lithologies in DAS Limboto as volcanic breccia (45%), alluvium (30%), tuff (15%), and limestone (10%). The heterogeneity of these rock properties directly influences infiltration capacity and runoff speed. Specifically, impermeable rock types, such as volcanic breccia, generate quicker flow peaks compared to permeable sedimentary rocks or tuff [Theofanous & Myronidis, 2020]. The underlying geological structure thus dictates both the distribution of stream networks and the vulnerability of the surface to erosion.

The primary soil orders identified were Andisols (35%), Inceptisols (33%), Entisols (22%), and Vertisols (10%). The prevalence of fine texture and shallow solum in the headwaters amplifies erosion potential. Conversely, soils in the lower plains exhibit low permeability (<2cm/hours), significantly increasing flood hazards. With an average slope of 11.8%, the area is classified as rolling terrain, featuring slope classes distributed as 0-8% (41%), 8-15% (27%), 15-25% (18%), and >25% (14%). This distribution underscores the finding that the steep upper slopes are major contributors to sediment mobilization and transport [Regasa & Nones, 2023].

3.5 Hydrological Characteristics

Hydrological analysis confirms that DAS Limboto exhibits a moderate runoff response, characterized by a runoff coefficient (C) of 0.56. Measured flow rates included a minimum discharge (Qmin) of 5,7 m^3/sec, a mean discharge (Qavg) of 23,4 m^3/sec, and a maximum discharge (Qmax) of 68,9 m^3/sec. The ratio of signifies a substantial intra-annual imbalance, pointing toward an attenuated capacity for groundwater storage due to compromised recharge areas upstream.

These hydrological traits reinforce the morphometric observation: The elongated watershed geometry delays peak flow timing, yet intense rainfall events drive higher peak discharges [Battista et al., 2020]. SWAT model projections estimate that a mere increase in land conversion in the upper 10% reaches could escalate sediment yield by 18% annually. Furthermore, RUSLE model outputs indicate that areas with slopes >25% exceeding are responsible for 54% of the total sediment load entering Lake Limboto. Consequently, the estimated annual sediment volume reaching the lake is 12 million m3 annual, driving the mean lake depth below <25%.

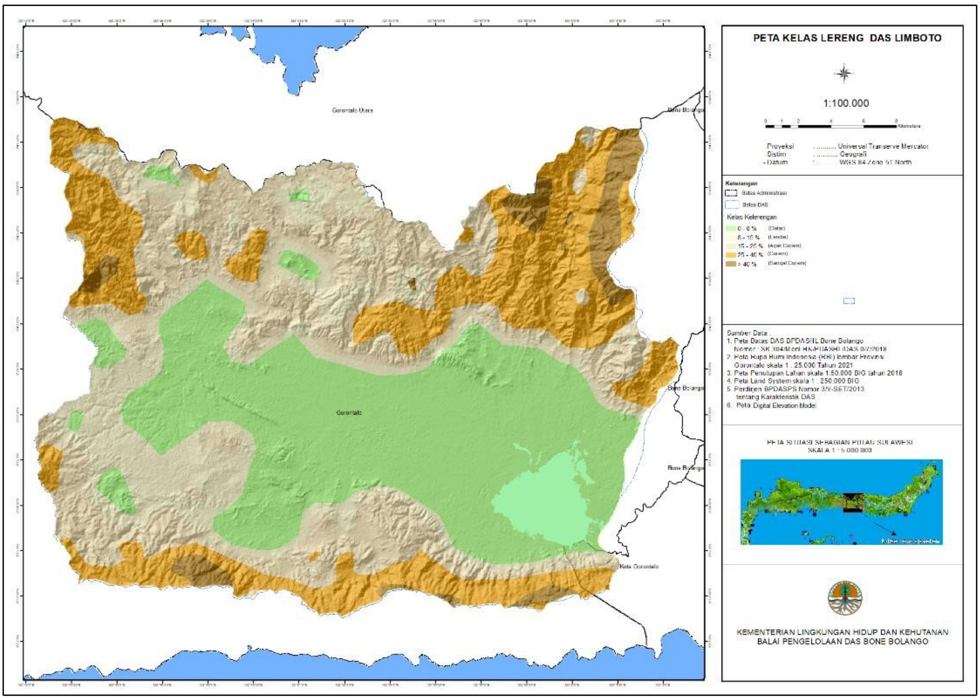

Figure 3. Hypsometric Map of DAS Limboto showing elevation variation and slope gradient is referenced here

3.6 Socioeconomic and Institutional Status

The population within DAS Limboto is estimated at 365.000 individuals, yielding an average density of 408 jiwa/km2. The primary economic drivers are agriculture (47%), followed by fisheries (21), trade (18), and services (14). The annual population growth rate of 1.9% per year is increasing land use pressure and hastening the conversion of forestland to cultivated areas. This socioeconomic impetus solidifies the link between human activity and environmental degradation, paralleling findings in other tropical watersheds [Spracklen & Garcia-Carreras, 2015; Ma et al., 2023].

Institutionally, WSM governance in DAS Limboto is characterized by fragmented authority, involving at least five major agencies operating without transparent coordination. Involved bodies include the Bone Limboto BPDAS, Sulawesi II BWS, the local

Environmental and Forestry Agency, the Public Works and Spatial Planning Agency (PUPR), and Bappeda. This institutional structure lacks an integrated coordination mechanism capable of synergizing cross-sectoral management policies. Such fragmentation directly compromises the effective implementation of forest rehabilitation and soil conservation programs [Chappell, 2010; Koirala et al., 2014].

Community participation in natural resource management remains notably low, despite the active roles played by existing farmer groups and NGOs in rehabilitation schemes. Empirical evidence confirms that conservation success rates increase significantly when local communities are involved in planning and monitoring [Capon et al., 2013; Visweshwaran et al., 2022]. Within DAS Limboto, the watershed forum, facilitated by local government, represents a crucial and potentially developable platform for participatory coordination.

3.7 Integrated Synthesis

Collectively, the research findings underscore that the complex hydrological system of DAS Limboto is a product of intricate interactions between morphometric, geological, land cover, and institutional factors. Land use alterations upstream directly trigger higher runoff, erosion, and sedimentation downstream, critically accelerating the shallowing of Lake Limboto. The accompanying social and institutional context either amplifies or mitigates these physical impacts based on the efficacy of coordination and community engagement. This synthesis emphatically validates the necessity of implementing the One Watershed, One Management Plan principle within an evidence-based WSM framework. The successful reduction of hydrological pressures and enhancement of future environmental resilience depend upon the judicious integration of policy directives, precise spatial data, and the inherent socio-ecological dynamics of the catchment.

4. Discussion

The comprehensive inventory of DAS Limboto’s biophysical conditions and institutional landscape illuminates a complex nexus between ecosystem integrity and evolving socioeconomic dynamics, mandating a multi-sectoral and multi-scalar management approach. Relative to comparable studies in Southeast Asia, DAS Limboto exhibits characteristics typical of tropical stream systems under dual pressures: high land use intensity and significant rainfall variability, compounded by documented weaknesses in institutional coordination [Schiemer et al., 2024]. The morphological assessment, quantified by a low Form Factor (0.35) and Elongation Ratio (0.46), confirms an elongated basin shape that delays hydrological response times. Crucially, this elongation does not mitigate flood risk; rather, increasing land conversion in the headwaters enhances this danger. This finding is corroborated by Zhang et al. (2019) and Nasirzadehdizaji & Akyüz (2022), who note that elongated catchments with high drainage density exhibit sluggish response times but generate substantial runoff volumes when protective vegetation cover is compromised. Consequently, the DAS Limboto’s morphology clearly predisposes the steeply sloped areas (>25%) to high erosion potential, concentrating mobilized sediment in the lowland plains and driving the persistent sedimentation of Lake Limboto.

Hydrologically, the mean annual rainfall of 2.478 mm and a daily intensity of 25.7 mm position the region within the moderate-to-high hazard range, sufficient to induce significant surface runoff, especially across areas of low infiltration. The observed north-to-south decline in spatial rainfall distribution strongly suggests an influential orographic effect that accentuates hydrological disparities among sub-basins. This scenario mirrors conditions in other humid tropical catchments across Southeast Asia, where intense rainfall contributes heavily to peak discharge increases and heightened erosion, particularly in deforested tracts [Wei et al., 2014]. The hydrological impact of land cover change further validates conclusion: the loss of natural vegetation diminishes canopy interception capacity, leading to increased direct runoff. In the Limboto context, the decline in vegetation index 24% over the last two decades signifies substantial degradation of groundwater storage capacity, resulting in reduced baseflow and heightened frequency of seasonal flooding downstream.

The land cover analysis and erosion projections establish a direct causality between upstream deforestation and accelerating sedimentation within Lake Limboto. SWAT and RUSLE model outputs indicate that 54% of the total sediment contribution originates from areas with slopes steeper than 25% and composed of fine-textured soils (Inceptisols and Entisols). The increase in sediment yield linked 18% to land use conversion substantiates findings by Jarray et al. (2023) and Xie & Liang (2024) that progressive land conversion escalates soil erodibility and the overall rate of sedimentation in tropical lakes. With an estimated annual sediment load of 1.2 million m3 entering the lake, the average depth is diminishing to under meters—a classic manifestation of shallowing lake phenomena common in tropical regions facing intense anthropogenic stress [Woldemariam & Harka, 2020]. This trend unequivocally confirms that strengthening headwater-based forest rehabilitation and soil conservation programs must be treated as a priority mitigation measure.

Geologically and geomorphologically, the dominance of volcanic breccia (45%) and alluvium (30%) dictates the dynamics of infiltration and flow routing. Impermeable bedrock structures in the upper reaches promote rapid surface flow, while alluvial zones downstream act as primary sediment accumulation sinks. This observation aligns with [Theofanous & Myronidis, 2020], who emphasize that the combination of impermeable lithology and open land cover creates the most vulnerable scenario for rapid runoff and high sedimentation loads. Despite a moderate average relief of (11.8%), the geomorphological stability of DAS Limboto is being actively undermined by human activities, notably land clearance and construction on steep slopes.

In the institutional and social domain, this study reveals that governance fragmentation presents one of the most significant impediments to effective DAS Limboto management. The five key agencies involved in oversight suffer from overlapping authority without any established, integrated coordination mechanism. This deficiency forces conservation activities to remain either partial or purely reactive. Such coordination deficiencies are widely documented in Southeast Asia, where watershed decentralization without mandated cross-sectoral frameworks compromises rehabilitation effectiveness [Chakraborty & Mukhopadhyay, 2014; Krutov, 2018]. In Limboto's context, this weakness is compounded by restricted access to shared data platforms among institutional actors, leading to policy duplication and a critical divergence between planning aspiration and on-the-ground implementation.

Sociologically, public participation in conservation and rehabilitation efforts remains insufficiently developed, despite clear potential residing within local forest groups and the existing watershed forum. Studies by Capon et al. (2013) and Dai et al. (2009) emphasize that community involvement is a lynchpin for ensuring long-term conservation success. The limited public engagement in Limboto stems largely from the technical and economic constraints placed upon the community, alongside a lack of effective incentives to adopt conservation practices. Nevertheless, positive indicators emerge from several community-based local initiatives successfully integrating conservation with sustainable livelihoods, such as agroforestry and conservation agriculture. Scaling up these successful local models requires robust cross-sectoral policy support and dedicated financing pathways.

The interaction between the biophysical state and the social structure in DAS Limboto demonstrates a powerful reciprocity between environmental deterioration and community welfare. The degraded upper reaches are typically inhabited by lower-income groups heavily dependent on land resources for agriculture [Ma et al., 2023]. Disparities in access to conservation technology and weakened local institutional capacity intensify this predicament. Therefore, strengthening local governance and enhancing participation mechanisms become crucial priorities for embedding socioeconomic dimensions into cohesive WSM policy. Stas et al. (2022) affirm that conservation success critically relies on the synergy between key biophysical indicators (land cover, discharge, erosion) and social indicators (participation, welfare, institutional capacity). In essence, effective watershed governance necessarily requires a multi-dimensional approach that simultaneously addresses ecological, social, and institutional facets.

From a policy standpoint, these results emphatically reinforce the mandate for implementing the One Watershed, One Management Plan, as stipulated by PP No. 37/2012. Synergy across sectors—forestry, agriculture, spatial planning, and water resources—must be formalized within a distinct governance structure featuring coordination mechanisms oriented toward open data access and multi-risk indicator evaluation [Pirani & Mousavi, 2016]. Cross-sectoral performance indicators must span biophysical metrics (discharge, water quality, land cover), social metrics (participation, welfare), and institutional metrics (coordination efficiency, budget allocation) [Capon et al., 2013]. This layered approach aligns perfectly with the global trajectory toward evidence-based watershed management, which synthesizes remote sensing inputs, social survey data, and hydrological modeling to yield adaptive, proofed policies [Dahliansyah et al., 2020].

When benchmarking DAS Limboto against other major Indonesian systems, such as Brantas or Citarum, Limboto faces formidable obstacles regarding data integration and monitoring capability. The Brantas basin, for instance, has established a robust real-time monitoring system for discharge and water quality linked to the SWAT model, whereas Limboto remains reliant on limited, periodically acquired spatial hydrological data. This deficiency inhibits rapid, evidence-backed decision-making for disaster mitigation and rehabilitation planning [Schiemer et al., 2024]. Therefore, the immediate necessity is the deployment of an open-data monitoring system to enhance planning efficiency and governance transparency.

Policy coherence at the regional level must also be buttressed by sustainable financing mechanisms capable of guaranteeing long-term forest rehabilitation and soil conservation efforts. International experience in ASEAN countries suggests that WSM success is heavily contingent upon financial stability and the provision of incentives for local communities contributing to ecosystem protection [Bruns & Meinzen-Dick, 2000]. For Limboto, mechanisms such as Payment for Ecosystem Services (PES) or results-based revolving funds could serve as powerful incentives, actively promoting continued community engagement in sustaining rehabilitation achievements.

Ultimately, the findings from the DAS Limboto inventory offer a significant contribution to developing data-driven watershed management models nationally. By integrating biophysical and socioeconomic data through the lens of evidence-based watershed management, this study provides high-fidelity input for calibrating models like SWAT to simulate the cascading effects of land cover change and assess the efficacy of conservation interventions on discharge, sedimentation, and water quality. This analytical approach has proven effective in various developing nations for engineering climate-adaptive policies in the face of anthropogenic stress [Pirani & Mousavi, 2016]. Within the Indonesian framework, this methodology can serve as a blueprint for advancing the national Watershed Management Information System (SIPDAS), ensuring it accommodates regional variability, guarantees local participation, and bolsters the transparency and accountability of water resource stewardship based on watershed boundaries.

5. Conclusion

This investigation conclusively demonstrates that the pervasive degradation of the Limboto Watershed Area (DAS) is not attributable to a singular cause, but rather emerges from the complex interplay among biophysical, hydrological, socioeconomic, and institutional variables. The inventory results confirm that the watershed's elongated morphology (Rf 0,35; Re 0,46) and moderate drainage density (1,84 km/km^2) dictate surface runoff patterns and consequently heighten flood potential downstream. High annual rainfall (2.478 mm/year) coupled with upstream deforestation (3,1%/year) synergistically drives sedimentation 1.2 million m^3 annually, reaching an alarming level, which forces the progressive shallowing of Lake Limboto to depths less than 2.5 meters. Socially, the system is strained by significant population pressure (growing at 1.9%) and the overwhelming dominance of the agricultural sector (45%), while institutional fragmentation acts as a critical brake on necessary cross-sectoral coordination.

Adding layers to this challenge, the socioeconomic landscape is buckling under the weight of nearly 400 people per square kilometer, fueled by a 1.9% population surge and deep reliance on the agricultural economy (47% employment share). Perhaps most damningly, the entire environmental response is critically hobbled by a fragmented institutional apparatus incapable of achieving necessary cross-sectoral alignment. Essentially, the data paints a clear picture: environmental collapse here is a failure of governance as much as it is a failure of land stewardship

These findings strongly affirm the urgent need for the robust implementation of the "One Watershed, One Management Plan" principle, as codified in PP No. 37/2012. Effective mitigation of degradation and evidence-based decision-making necessitate the comprehensive integration of biophysical, social, and institutional data within a unified "evidence-based watershed management" framework. This study contributes an empirical, integrated model for data-driven WSM development within Indonesia, highlighting the indispensable role of open monitoring systems, enhanced inter-agency collaboration, and active community engagement in securing sustainable land and water conservation. Future research is strongly recommended to focus on developing simulation scenarios—utilizing dynamic models such as SWAT and GeoWEPP—to project the impact of future land cover shifts on watershed discharge and water quality, thereby solidifying the basis for adaptive DAS policy formulation.

References

[1] D. Ainunisa, G. Halik, W. Y. Widiarti, Pemodelan perubahan tataguna lahan terhadap debit banjir DAS Tanggul, Jember menggunakan model SWAT (Soil and Water Assessment Tool). *Rekayasa Sipil* **14**, 154–161 (2020). https://doi.org/10.21776/ub.rekayasasipil.2020.014.02.10
[2] A. B. Aneseyee, E. Elias, T. Soromessa, G. L. Feyisa, Land use/land cover change effect on soil erosion and sediment delivery in the Winike watershed, Omo Gibe Basin, Ethiopia. *Sci. Total Environ.* **728**, 138776 (2020). https://doi.org/10.1016/j.scitotenv.2020.138776
[3] S. Arciniega-Esparza, J. A. Breña-Naranjo, P. A. Troch, On the connection between terrestrial and riparian vegetation: The role of storage partitioning in water-limited catchments. *Hydrol. Process.* **31**, 489–494 (2017). https://doi.org/10.1002/hyp.11071
[4] C. Asdak, Y. Yulizar, S. Subiyanto, A national policy on Indonesia's integrated water resource conservation management. *Indones. J. For. Res.* **10**, 151–162 (2023). https://doi.org/10.59465/ijfr.2023.10.2.151-162
[5] B. Aslam, A. Maqsoom, Shahzaib, Z. A. Kazmi, M. Sodangi, F. Anwar, M. H. Bakri, R. F. Tufail, D. Farooq, Effects of landscape changes on soil erosion in the built environment: Application of geospatial-based RUSLE technique. *Sustainability* **12**, 5898 (2020). https://doi.org/10.3390/su12155898
[6] D. Astiani, L. M. Curran, M. Mujiman, R. Salim, Throughfall quantity and carbon input beneath canopy gaps of varying size in degraded tropical peatland forest of West Kalimantan, Indonesia. *Biodiversitas* **18**, 1258–1264 (2017). https://doi.org/10.13057/biodiv/d180351
[7] H. Avery, The nature of abrasive wear. *SAE Trans.* (1975). https://www.jstor.org/stable/44718073
[8] G. T. Ayele, A. Kuriqi, M. A. Jemberrie, S. M. Saia, A. M. Seka, E. Z. Teshale, M. H. Daba, S. A. Bhat, S. S. Demissie, J. Jeong, A. M. Melesse, Sediment yield and reservoir sedimentation in highly dynamic watersheds: The case of Koga Reservoir, Ethiopia. *Water* **13**, 3374 (2021). https://doi.org/10.3390/w13233374
[9] T. M. Basuki, H. Y. S. H. Nugroho, Y. Indrajaya, I. B. Pramono, N. P. Nugroho, A. B. Supangat, D. R. Indrawati, E. Savitri, N. Wahyuningrum, P. Purwanto, S. A. Cahyono, P. B. Putra, R. N. Adi, A. Nugroho, D. Auliyani, A. Wuryanta, H. D. Riyanto, B. Harjadi, C. Yudilastyantoro, D. P. Simarmata, Improvement of integrated watershed management in Indonesia for mitigation and adaptation to climate change: A review. *Sustainability* **14**, 9997 (2022). https://doi.org/10.3390/su14169997
[10] G. Battista, P. Molnár, P. Burlando, Modelling impacts of spatially variable erosion drivers on suspended sediment dynamics. *Earth Surf. Dyn.* **8**, 619–635 (2020). https://doi.org/10.5194/esurf-8-619-2020
[11] W. Berghuijs, M. Sivapalan, R. Woods, H. H. G. Savenije, Patterns of similarity of seasonal water balances: A window into streamflow variability over a range of time scales. *Water Resour. Res.* **50**, 5638–5661 (2014). https://doi.org/10.1002/2014WR015692

[12] I. G. Boëchat, A. B. D. M. De Paiva, S. Hille, B. Gücker, Land-use effects on river habitat quality and sediment granulometry along a 4th-order tropical river. *Ambiente Agua* **8** (2013). https://doi.org/10.4136/ambi-agua.1232
[13] BPDAS Bone Bolango, Karakteristik DAS Limboto. Laporan Kegiatan (2024).
[14] A. Brath, A. Montanari, G. Moretti, Assessing the effect on flood frequency of land use change via hydrological simulation (with uncertainty). *J. Hydrol.* **324**, 141–153 (2006). https://doi.org/10.1016/j.jhydrol.2005.10.001
[15] P. D. Brooks, P. A. Troch, M. Ďurčík, E. L. Gallo, M. Schlegel, Quantifying regional scale ecosystem response to changes in precipitation: Not all rain is created equal. *Water Resour. Res.* **47**, W00J08 (2011). https://doi.org/10.1029/2010WR009762
[16] B. Bruns, R. Meinzen-Dick, Back matter—Negotiating water rights. In: *Negotiating Water Rights* (2000), 381–394. https://doi.org/10.3362/9781780445526.015
[17] S. J. Capon, L. E. Chambers, R. M. Nally, R. J. Naiman, P. Davies, N. Marshall, J. Pittock, M. Reid, T. Capon, M. M. Douglas, J. A. Catford, D. S. Baldwin, M. J. Stewardson, J. Roberts, M. Parsons, S. E. Williams, Riparian ecosystems in the 21st century: Hotspots for climate change adaptation? *Ecosystems* **16**, 359–381 (2013). https://doi.org/10.1007/s10021-013-9656-1
[18] D. Chakraborty, K. Mukhopadhyay, Status of water pollution in India and other countries of Asia. In: *Water Resources Management* (2014), 23–45. https://doi.org/10.1007/978-94-017-8929-5_2
[19] N. A. Chappell, Soil pipe distribution and hydrological functioning within the humid tropics: A synthesis. *Hydrol. Process.* **24**, 1567–1581 (2010). https://doi.org/10.1002/hyp.7579
[20] S. Collins, M. Thoms, J. Flotemersch, Hydrogeomorphic zones characterize riverbed sediment patterns within a river network. *River Syst.* (2015).
[21] D. Dahliansyah, D. Hanim, H. Halimo, Hubungan berat badan lahir (BBLR) dan inisiasi menyusu dini (IMD) dengan perkembangan motorik pada 1000 hari pertama kehidupan. *Pontianak Nutr. J.* **3**, 29 (2020). https://doi.org/10.30602/pnj.v3i1.628
[22] A. Dai, T. Qian, K. E. Trenberth, J. D. Milliman, Changes in continental freshwater discharge from 1948 to 2004. *J. Clim.* **22**, 2773–2792 (2009). https://doi.org/10.1175/2008JCLI2592.1
[23] G. Destouni, F. Jaramillo, C. Prieto, Hydroclimatic shifts driven by human water use for food and energy production. *Nat. Clim. Chang.* **3**, 213–217 (2013). https://doi.org/10.1038/nclimate1719
[24] J. Dietz, D. Hölscher, C. Leuschner, H. Hendrayanto, Rainfall partitioning in relation to forest structure in differently managed montane forest stands in Central Sulawesi, Indonesia. *For. Ecol. Manag.* **237**, 170–178 (2006). https://doi.org/10.1016/j.foreco.2006.09.044
[25] S. Ekawati, P. Paimin, P. Puwanto, Monitoring dan evaluasi kondisi sosial ekonomi dalam pengelolaan daerah aliran sungai: Studi kasus di Sub DAS Progo Hulu. *J. Penelit. Sos. Ekon.* (2005).
[26] F. Fahmi, A. Kusumandari, Sensitivity to erosion based on morphometry and the erosion rate in Blongkeng Watershed. In: *Proc. 2nd Int. Conf.* (2022).
[27] C. R. Ford, S. H. Laseter, W. T. Swank, J. M. Vose, Can forest management be used to sustain water-based ecosystem services in the face of climate change? *Ecol. Appl.* **21**, 2049–2067 (2011). https://doi.org/10.1890/10-2246.1

[28] A. A. Gedefaw, M. A. Desta, R. Mansberger, Impacts of integrated watershed management interventions on land use/land cover of Yesir Watershed in Northwestern Ethiopia. *Land* **13**, 918 (2024). https://doi.org/10.3390/land13070918

[29] P. Hamel, K. Falinski, R. Sharp, D. A. Auerbach, M. Sánchez-Canales, P. J. Dennedy-Frank, Sediment delivery modeling in practice: Comparing the effects of watershed characteristics and data resolution across hydroclimatic regions. *Sci. Total Environ.* **580**, 1381–1388 (2017). https://doi.org/10.1016/j.scitotenv.2016.12.103

[30] G. J. A. Hansen, K. E. Wehrly, K. Vitense, J. R. Walsh, P. C. Jacobson, Quantifying the resilience of coldwater lake habitat to climate and land use change to prioritize watershed conservation. *Ecosphere* **13**, e4172 (2022). https://doi.org/10.1002/ecs2.4172

[31] L. Hao, G. Sun, Y. Liu, J. Wan, M. Qin, H. Qian, C. Liu, J. Zheng, R. John, P. Fan, J. Chen, Urbanization dramatically altered the water balances of a paddy field-dominated basin in Southern China. *Hydrol. Earth Syst. Sci.* **19**, 3319–3331 (2015). https://doi.org/10.5194/hess-19-3319-2015

[32] R. E. Horton, Erosional development of streams and their drainage basins; Hydrophysical approach to quantitative morphology. *Geol. Soc. Am. Bull.* **56**, 275–275 (1945). https://doi.org/10.1130/0016-7606(1945)56%5B275:EDOSAT%5D2.0.CO;2

[33] H. Y. S. H. Nugroho, Y. Indrajaya, S. Astana, M. Murniati, S. Suharti, T. M. Basuki, T. W. Yuwati, P. B. Putra, B. H. Narendra, L. Abdulah, T. Setyawati, S. Subarudi, H. Krisnawati, M. H. Saputra, Y. Lisnawati, R. Garsetiasih, R. Sawitri, I. A. S. L. P. Putri, O. Setiawan, Y. I. Rahmila, A chronicle of Indonesia's forest management: A long step towards environmental sustainability and community welfare. *Land* **12**, 1238 (2023). https://doi.org/10.3390/land12061238

[34] T. Hwang, L. E. Band, T. C. Hales, Ecosystem processes at the watershed scale: Extending optimality theory from plot to catchment. *Water Resour. Res.* **45**, W11417 (2009). https://doi.org/10.1029/2009WR007775

[35] T. Hwang, L. E. Band, J. M. Vose, C. Tague, Ecosystem processes at the watershed scale: Hydrologic vegetation gradient as an indicator for lateral hydrologic connectivity of headwater catchments. *Water Resour. Res.* **48**, W06514 (2012). https://doi.org/10.1029/2011WR011301

[36] E. Istanbulluoglu, R. L. Bras, On the dynamics of soil moisture, vegetation, and erosion: Implications of climate variability and change. *Water Resour. Res.* **42**, W06418 (2006). https://doi.org/10.1029/2005WR004113

[37] F. Jarray, T. Hermassi, M. Mechergui, C. Zucca, Q. B. Le, Long-term impact of soil and water conservation measures on soil erosion in a Tunisian semi-arid watershed. *Land* **12**, 1537 (2023). https://doi.org/10.3390/land12081537

[38] M. Kalcic, J. Frankenberger, I. Chaubey, Spatial optimization of six conservation practices using SWAT in tile-drained agricultural watersheds. *JAWRA J. Am. Water Resour. Assoc.* **51**, 956–972 (2015). https://doi.org/10.1111/1752-1688.12338

[39] P. H. Kirana, M. Farid, M. B. Adityawan, A. A. Kuntoro, W. Widyaningtyas, Study of flood risk assessment on Banyumas and Cilacap District in downstream Serayu River Basin, Indonesia. *J. Tek. Sipil* **30**, 149–156 (2023). https://doi.org/10.5614/jts.2023.30.2.2

[40] F. Kizito, J. Gicheha, N. A. Rahman, L. Tamene, K. Ng'ang'a, N. Koech, Are landscape restoration interventions sustainable? A case for the Upper Tana Basin of Kenya. *Sustainability* **13**, 10136 (2021). https://doi.org/10.3390/su131810136

[41] S. Koirala, P. J. Yeh, Y. Hirabayashi, S. Kanae, T. Oki, Global-scale land surface hydrologic modeling with the representation of water table dynamics. *J. Geophys. Res.: Atmos.* **119**, 75–89 (2014). https://doi.org/10.1002/2013JD020398

[42] A. Krutov, Experience in improvement of the water sector institutional structures. *Water Sect. Russ. Probl. Technol. Manag.* **1**, 5 (2018). https://doi.org/10.35567/1999-4508-2018-1-5

[43] S. Launiainen, M. Guan, A. Salmivaara, A. Kieloaho, Modeling boreal forest evapotranspiration and water balance at stand and catchment scales: A spatial approach. *Hydrol. Earth Syst. Sci.* **23**, 3457–3480 (2019). https://doi.org/10.5194/hess-23-3457-2019

[44] Y. Lee, T. Yoon, F. A. Shah, Economics of integrated watershed management in the presence of a dam. *Water Resour. Res.* **47**, W10502 (2011). https://doi.org/10.1029/2010WR009172

[45] M. Lega, M. Wahid, C. Darminto, Institutional capacity and sustainability of customary forests: Customary forest management in Rantau Kermas Village. *J. Local Gov. Issues* **7**, 83–99 (2024). https://doi.org/10.22219/logos.v7i1.31717

[46] I. P. Lestari, Interaksi sosial komunitas Samin dengan masyarakat sekitar. *Komunitas Int. J. Indones. Soc. Cult.* **5** (2013). https://doi.org/10.15294/komunitas.v5i1.2376

[47] Q. Li, X. Wei, M. Zhang, W. Liu, H. Fan, G. Zhou, K. Giles-Hansen, S. Liu, Y. Wang, Forest cover change and water yield in large forested watersheds: A global synthetic assessment. *Ecohydrology* **10**, e1838 (2017). https://doi.org/10.1002/eco.1838

[48] F. Lihawa, The effect of watershed environmental conditions and land use on sediment yield in Alo-Pohu Watershed. *Indones. J. Geogr.* (2009).

[49] Y. Lin, C. Chen, W.-Y. Lien, W. Chang, J. R. Petway, L.-C. Chiang, Landscape conservation planning to sustain ecosystem services under climate change. *Sustainability* **11**, 1393 (2019). https://doi.org/10.3390/su11051393

[50] R. Linsley, Flood plain mapping (1975).

[51] Y. Ma, D. Sun, Z. Niu, X. Wang, Contribution of climate change and human activities to runoff and sediment discharge changes based on Budyko theory and water–sediment relationships during 1960–2019 in the Taohe River Basin, China. *Atmosphere* **14**, 1144 (2023). https://doi.org/10.3390/atmos14071144

[52] T. Nakaegawa, M. Hosaka, Potential predictability of seasonal mean river discharge in dynamical ensemble prediction using MRI/JMA GCM. *SOLA* **2**, 112–115 (2006). https://doi.org/10.2151/sola.2006-029

[53] J. Nalbant, L. Schneider, R. Hamilton, S. Connor, H. Biester, H. Stuart-Williams, O. V. Bergal-Kuvikas, G. Jacobsen, J. Stevenson, Fire, volcanism and climate change: The main factors controlling mercury (Hg) accumulation rates in tropical Lake Lantoa, Sulawesi, Indonesia (16,500–540 cal yr BP). *Front. Environ. Chem.* **4**, 1241176 (2023). https://doi.org/10.3389/fenvc.2023.1241176

[54] B. H. Narendra, C. A. Siregar, I. W. S. Dharmawan, A. Sukmana, P. Pratiwi, I. B. Pramono, T. M. Basuki, H. Y. S. H. Nugroho, A. B. Supangat, P. Purwanto, O. Setiawan, R. Nandini, N. A. Ulya, V. B. Arifanti, T. W. Yuwati, A review on sustainability of watershed management in Indonesia. *Sustainability* **13**, 11125 (2021). https://doi.org/10.3390/su131911125

[55] R. Nasirzadehdizaji, D. E. Akyüz, Application of SWAT hydrological model to assess the impacts of land use change on sediment loads. *Int. J. Agric. Environ. Food Sci.* **6**, 108–120 (2022). https://doi.org/10.31015/jaefs.2022.1.15

[56] A. Negese, Impacts of land use and land cover change on soil erosion and hydrological responses in Ethiopia. *Appl. Environ. Soil Sci.* **2021**, 6669438 (2021). https://doi.org/10.1155/2021/6669438

[57] J. D. Niel, P. Willems, Climate or land cover variations: What is driving observed changes in river peak flows? A data-based attribution study. *Hydrol. Earth Syst. Sci.* **23**, 871–882 (2019). https://doi.org/10.5194/hess-23-871-2019

[58] M. R. Olii, I. Ichsan, Assessment of critical land using geographic information systems—A case study of Limboto Watershed, Gorontalo. *IOP Conf. Ser.: Earth Environ. Sci.* **437**, 012053 (2020). https://doi.org/10.1088/1755-1315/437/1/012053

[59] A. Pambudi, Watershed management in Indonesia: A regulation, institution, and policy review. *Indones. J. Dev. Plan.* (2019).

[60] R. Pandit, J. A. Parrotta, A. K. Chaudhary, D. L. Karlen, D. L. M. Vieira, Y. Anker, R. Chen, J. Morris, J. A. Harris, P. Ntshotsho, A framework to evaluate land degradation and restoration responses for improved planning and decision-making. *Ecosyst. People* **16**, 1–18 (2020). https://doi.org/10.1080/26395916.2019.1697756

[61] P. Pasapan, M. Wahid, A. Saleng, Conservation of the Mount Bawakaraeng water resources area as a form of water resources management through sustainable and environmentally sound approaches. *J. Lifestyle Sustain. Dev.* (2024).

[62] A. Peñuela, H. Sellami, H. G. Smith, A model for catchment soil erosion management in humid agricultural environments. *Earth Surf. Process. Landf.* **43**, 608–622 (2018). https://doi.org/10.1002/esp.4271

[63] F. J. Pirani, S. A. Mousavi, Integrating socio-economic and biophysical data to enhance watershed management and planning. *J. Hydrol.* **540**, 727–735 (2016). https://doi.org/10.1016/j.jhydrol.2016.05.072

[64] A. N. A. Ramadan, W. K. Adidarma, B. A. Riyanto, K. Windianita, Penentuan hydrologic soil group untuk perhitungan debit banjir di daerah aliran sungai Brantas Hulu. *J. Sumber Daya Air* **13**, 69–82 (2018). https://doi.org/10.31028/jsda.v13.i2.69-82

[65] V. Rana, T. Suryanarayana, Estimation of flood influencing characteristics of watershed and their impact on flooding in data-scarce region. *Ann. GIS* **27**, 349–364 (2021). https://doi.org/10.1080/19475683.2021.1960603

[66] D. J. Rapport, Sustainability science: An ecohealth perspective. *Sustain. Sci.* **2**, 77–84 (2007). https://doi.org/10.1007/s11625-006-0016-3

[67] K. Rathwell, G. Peterson, Connecting social networks with ecosystem services for watershed governance: A social-ecological network perspective highlights the critical role of bridging organizations. *Ecol. Soc.* **17**, 24 (2012). https://doi.org/10.5751/ES-04810-170224

[68] M. S. Regasa, M. Nones, SWAT model-based quantification of the impact of land use land cover change on sediment yield in the Fincha Watershed, Ethiopia. *Front. Environ. Sci.* **11**, 1146346 (2023). https://doi.org/10.3389/fenvs.2023.1146346

[69] M. C. Roa-García, S. Brown, H. Schreier, L. M. Lavkulich, The role of land use and soils in regulating water flow in small headwater catchments of the Andes. *Water Resour. Res.* **47**, W05510 (2011). https://doi.org/10.1029/2010WR009582

[70] F. B. Saroinsong, A. Hernández-Salinas, Y. Purwanto, Practical applications of sustainability science in landscape planning preliminary stage of Bunaken-Tangkoko-Minahasa Biosphere Reserve. *IOP Conf. Ser.: Earth Environ. Sci.* **940**, 012013 (2021). https://doi.org/10.1088/1755-1315/940/1/012013

[71] F. Schiemer, U. S. Amarasinghe, D. Simon, J. Vijverberg, Sustainable aquatic resource management and inland fisheries in tropical Asia: Interdisciplinary and transdisciplinary approaches. *Ambio* **53**, 1050–1064 (2024). https://doi.org/10.1007/s13280-024-01996-8
[72] K. E. Schilling, T. M. Isenhart, J. A. Palmer, C. F. Wolter, J. Spooner, Impacts of land-cover change on suspended sediment transport in two agricultural watersheds. *JAWRA J. Am. Water Resour. Assoc.* **47**, 672–686 (2011). https://doi.org/10.1111/j.1752-1688.2011.00533.x
[73] D. L. Setyowati, Assessment of watershed carrying capacity and land use change on flood vulnerability areas in Semarang City. *Forum Geogr.* **35**, 158–170 (2021). https://doi.org/10.23917/forgeo.v35i2.15542
[74] S. Singh, S. Swarnkar, R. Sinha, Integrating sediment connectivity and stream power index with RUSLE for modelling soil erosion dynamics in a large Himalayan Basin under modern and future climate scenarios. *Earth Surf. Process. Landf.* **50**, 620–636 (2025). https://doi.org/10.1002/esp.70032
[75] H. G. Smith, W. Blake, A. Taylor, Modelling particle residence times in agricultural river basins using a sediment budget model and fallout radionuclide tracers. *Earth Surf. Process. Landf.* **39**, 1944–1959 (2014). https://doi.org/10.1002/esp.3589
[76] D. V. Spracklen, L. Garcia-Carreras, The impact of Amazonian deforestation on Amazon Basin rainfall. *Geophys. Res. Lett.* **42**, 9546–9552 (2015). https://doi.org/10.1002/2015GL066063
[77] S. M. Stas, B. D. Spracklen, P. Willetts, T. C. Le, H. D. Tran, T. T. Le, D. T. Ngo, A. V. Le, L. T. Hùng, E. Rutishauser, J. Schwendike, J. H. Marsham, M. van Kuijk, E. K. Jew, O. L. Phillips, D. V. Spracklen, Implications of tropical cyclones on damage and potential recovery and restoration of logged forests in Vietnam. *Philos. Trans. R. Soc. B* **378**, 20210081 (2023). https://doi.org/10.1098/rstb.2021.0081
[78] T. S. Steenhuis, A. S. Collick, Z. M. Easton, E. S. Leggesse, H. K. Bayabil, E. White, S. B. Awulachew, E. Adgo, A. A. Ahmed, Predicting discharge and sediment for the Abay (Blue Nile) with a simple model. *Hydrol. Process.* **23**, 3728–3737 (2009). https://doi.org/10.1002/hyp.7513
[79] T. Sulistyaningsih, A. Nurmandi, S. Salahudin, A. Roziqin, M. Kamil, I. T. Sihidi, A. A. Romadhan, M. J. Loilatu, Public policy analysis on watershed governance in Indonesia. *Sustainability* **13**, 6615 (2021). https://doi.org/10.3390/su13126615
[80] A. Supangat, T. Basuki, Y. Indrajaya, O. Setiawan, Sustainable management for healthy and productive watersheds in Indonesia. *Land* **12**, 1963 (2023). https://doi.org/10.3390/land12111963
[81] A. D. Teshager, P. W. Gassman, S. Secchi, J. T. Schoof, G. Misgna, Modeling agricultural watersheds with the soil and water assessment tool (SWAT): Calibration and validation with a novel procedure for spatially explicit HRUs. *Environ. Manag.* **57**, 894–911 (2016). https://doi.org/10.1007/s00267-015-0636-4
[82] N. Theofanous, D. Myronidis, A streamflow hydrograph analysis and simulation for a study case watershed. *Int. J. Sustain. Agric. Manag. Inform.* **6**, 1–16 (2020). https://doi.org/10.1504/IJSAMI.2020.106547
[83] P. A. Troch, G. Carrillo, M. Sivapalan, T. Wagener, K. A. Sawicz, Climate–vegetation–soil interactions and long-term hydrologic partitioning: Signatures of catchment co-evolution. *Hydrol. Earth Syst. Sci.* **17**, 2209–2217 (2013). https://doi.org/10.5194/hess-17-2209-2013

[84] V. Vanacker, A. Molina, G. Govers, J. Poesen, G. Dercon, S. Deckers, River channel response to short-term human-induced change in landscape connectivity in Andean ecosystems. *Geomorphology* **72**, 340–353 (2005). https://doi.org/10.1016/j.geomorph.2005.05.013
[85] R. Visweshwaran, R. Ramsankaran, T. I. Eldho, M. K. Jha, Hydrological impact assessment of future climate change on a complex river basin of Western Ghats, India. *Water* **14**, 3571 (2022). https://doi.org/10.3390/w14213571
[86] E. R. Vivoni, Diagnosing seasonal vegetation impacts on evapotranspiration and its partitioning at the catchment scale during SMEX04–NAME. *J. Hydrometeorol.* **13**, 1631–1638 (2012). https://doi.org/10.1175/JHM-D-11-0131.1
[87] T. Wagner, R. Linsley, Application of Stanford watershed model to an Indian watershed. *Water Resour. Bull.* (1975).
[88] G. Wang, S. L. Mang, H. Cai, S. Liu, Z. Zhang, L. Wang, J. L. Innes, Integrated watershed management: Evolution, development and emerging trends. *J. For. Res.* **27**, 967–994 (2016). https://doi.org/10.1007/s11676-016-0293-3
[89] W. Wei, L. Chen, H. Zhang, J. Chen, Effect of rainfall variation and landscape change on runoff and sediment yield from a loess hilly catchment in China. *Environ. Earth Sci.* **73**, 1005–1016 (2015). https://doi.org/10.1007/s12665-014-3451-y
[90] M. H. Wirayuda, Analisis karakteristik sub DAS Ci Jolang terkait muka air banjir berdasarkan parameter morfometri berbasis sistem informasi geografis. *J. Sumberd. Bumi Berkelanjutan (Semitan)* **1**, 401–407 (2022). https://doi.org/10.31284/j.semitan.2022.3221
[91] G. W. Woldemariam, A. E. Harka, Effect of land use and land cover change on soil erosion in Erer Sub-Basin, Northeast Wabi Shebelle Basin, Ethiopia. *Land* **9**, 111 (2020). https://doi.org/10.3390/land9040111
[92] X. Xie, X. Liang, Coupling soil erosion and sediment transport processes with the variable infiltration capacity model (VIC-SED) for applications suitable with coarse spatial and temporal resolutions. *J. Adv. Model. Earth Syst.* **16**, e2024MS004307 (2024). https://doi.org/10.1029/2024MS004307
[93] F. Yulianto, M. R. Khomarudin, E. Hermawan, N. P. Nugroho, G. A. Chulafak, G. Nugroho, U. C. Nugroho, S. Suwarsono, H. L. Fitriana, E. Priyanto, Spatial and temporal distribution of estimated surface runoff caused by land use/land cover changes in the upstream Citarum watershed, West Java, Indonesia. *J. Degrad. Min. Lands Manag.* **9**, 3293–3305 (2022). https://doi.org/10.15243/jdmlm.2022.092.3293
[94] N. Zafirah, J. Ilham, R. Mostapa, S. Muhammad, Isotopic (δ13C and δ15N) variations in tropical river sediments of Kelantan, Malaysia: A reconnaissance study of land use influence. *Appl. Ecol. Environ. Res.* **15**, 1101–1119 (2017).
[95] J. B. Zedler, S. Kercher, Wetland resources: Status, trends, ecosystem services, and restorability. *Annu. Rev. Environ. Resour.* **30**, 39–74 (2005). https://doi.org/10.1146/annurev.energy.30.050504.144248
[96] C. Zhan, S. Jiang, F. Sun, Y. Jia, C. W. Niu, W. Yue, Quantitative contribution of climate change and human activities to runoff changes in the Wei River Basin, China. *Hydrol. Earth Syst. Sci.* **18**, 3069–3077 (2014). https://doi.org/10.5194/hess-18-3069-2014
[97] M. Zhang, N. Liu, R. J. Harper, Q. Li, K. Liu, X. Wei, D. Ning, Y. Hou, S. Liu, A global review on hydrological responses to forest change across multiple spatial scales: Importance of scale, climate, forest type and hydrological regime. *J. Hydrol.* **546**, 44–59 (2017). https://doi.org/10.1016/j.jhydrol.2016.12.040

[98] S. Zhang, Z. Li, X. Lin, C. Zhang, Assessment of climate change and associated vegetation cover change on watershed-scale runoff and sediment yield. *Water* **11**, 1373 (2019). https://doi.org/10.3390/w11071373
[99] G. Zhou, X. Wei, X. Chen, P. Zhou, X. Liu, X. Yin, G. Sun, D. F. Scott, S. Zhou, L. Han, Y. Su, Global pattern for the effect of climate and land cover on water yield. *Nat. Commun.* **6**, 5918 (2015). https://doi.org/10.1038/ncomms6918