Review Article

Are Oil Palm Plantations the Primary Cause of the Late 2025 Hydrometeorological Disasters in Sumatra? A Review

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Research in Environment Science and Ecology (RESE)

Volume 3 Issue 1, 2026

Article Information
Received date: March 30, 2026
Published date: April 13, 2026

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DOI: 10.65070/RESE.2026.304

Keywords
Hydrometeorological disasters; Oil palm plantations; Watershed management; Climate change adaptation; Land use change; Tropical Cyclone Senyar; Sumatra; Flood attribution; Sustainable agriculture; Forest degradation

Abstract

The devastating hydrometeorological disasters that struck Aceh, North Sumatra, and West Sumatra in late November 2025, triggered by Tropical Cyclone Senyar, resulted in over 1,200 deaths and displaced hundreds of thousands of people. Public discourse rapidly attributed these disasters primarily to the expansion of oil palm plantations, intensifying debates about the sector's environmental impacts. This qualitative literature review critically examines whether oil palm plantations are the primary causal factor in these disasters by synthesizing evidence from meteorological analyses, hydrological studies, land-use change research, and disaster reports published between 2020 and 2025. Employing thematic analysis methodology, this study identifies six key themes:

a) Exceptional meteorological events as primary triggers.
b) Upper watershed forest degradation as critical amplifying factors.
c) Context-dependent hydrological impacts of oil palm plantations.
d) Multi-sectoral contributions to deforestation.
e) Climate-land use interaction effects.
f) Socioeconomic vulnerabilities.

Findings demonstrate that while oil palm plantations contribute to watershed vulnerability by replacing forests in critical locations, they are not the singular or primary cause of the 2025 disasters. Instead, disasters result from the interaction of climate-change-amplified extreme rainfall (primary trigger), multi-sectoral forest degradation (secondary amplifier), and variable management practices (tertiary factors). The study concludes that simplistic attribution to oil palm obscures a multi-causal reality and recommends integrated approaches that emphasize upper watershed protection, climate adaptation, improved land management across all sectors, and evidence-based spatial planning to distinguish suitable from unsuitable locations for agricultural development.

JEL Classification : Q15 (Land Ownership and Tenure; Land Reform; Land Use; Irrigation; Agriculture and Environment), Q24 (Land; Natural Disasters), Q54 (Climate; Natural Disasters and Their Management; Global Warming), Q56 (Environment and Development; Environment and Trade; Sustainability; Environmental Accounts and Accounting; Environmental Equity; Population Growth)

Introduction

Background and Context

On November 25-26, 2025, Tropical Cyclone Senyar formed in the Strait of Malacca, generating unprecedented rainfall across northern Sumatra. This rare meteorological phenomenon—only the second documented tropical cyclone in the Malacca Strait after Tropical Storm Vamei in 2001—delivered cumulative precipitation exceeding 1,843

How to cite this article: Judijanto L (2026) Are Oil Palm Plantations the Primary Cause of the Late 2025 Hydrometeorological Disasters in Sumatra? A Review. Res Env Sci & Eco 3.

millimeters over three days, with daily intensities surpassing 300 millimeters in numerous locations. The resulting floods and landslides across Aceh, North Sumatra, and West Sumatra provinces killed between 812 and 1,454 people, left 143-509 missing, heavily damaged 53,412 homes, and affected 37-53 districts and cities. Infrastructure destruction included 2,057 roads, 786 bridges, 4,546 educational facilities, and 215 health facilities, with economic losses exceeding IDR 1 trillion [1-3].

In the immediate aftermath, public discourse rapidly attributed these disasters primarily to the expansion of oil palm plantations, with environmental advocacy groups highlighting 1.4 million hectares of forest loss across the three provinces between 2016 and 2025. Media coverage of massive quantities of logs swept away during floods—described as "lautan kayu" (sea of logs)—reinforced narratives of deforestation-driven vulnerability. The Indonesian government responded by revoking 28 company permits covering 750,000 hectares following post-disaster environmental audits. However, meteorological experts and hydrologists have questioned oversimplified causal attribution, emphasizing the complexity of disaster causation, which involves interactions among extreme weather events, multi-sectoral land-use change, climate-change amplification, and socioeconomic vulnerabilities [4,5].

This tension between public perception and scientific evidence raises critical questions: Are oil palm plantations the primary cause of the late 2025 hydrometeorological disasters in Sumatra? Or do these disasters result from more complex interactions requiring nuanced analysis? Addressing these questions holds significant scientific, policy, and socioeconomic implications for Indonesia's sustainable development trajectory.

Research Urgency and Significance

Scientific urgency emerges from the need to distinguish correlation from causation in land use-disaster relationships. While spatial correlation between plantation expansion and increased flood frequency has been documented in some Indonesian watersheds, correlation does not prove causation, particularly when multiple confounding factors operate simultaneously. Critical evaluation is needed to determine whether oil palm plantations are uniquely problematic or whether forest conversion generally—regardless of subsequent land use—constitutes the key hydrological risk factor [6].

Policy implications are substantial. Indonesia's palm oil sector contributes significantly to the national economy while also accounting for approximately 20% of the country's greenhouse gas emissions. Government decisions to revoke permits and restrict expansion require a sound evidence base to avoid misdirecting limited resources away from interventions with the greatest potential for disaster risk reduction. Spatial planning reforms and land-use classification changes depend on an accurate understanding of how different land uses at different watershed positions affect hydrological regimes [7].

Socioeconomic significance concerns impacts on over 3.1 million people affected by the 2025 disasters, and on millions more whose livelihoods depend on plantation agriculture. Justice considerations arise when evaluating differential impacts on smallholder versus industrial operations and whether policies disproportionately burden vulnerable populations. An evidence-based understanding of actual causal mechanisms is essential for designing interventions that balance environmental protection, disaster risk reduction, economic development, and social equity [8,9].

Research Objectives

This study's primary objective is to critically examine, through a qualitative literature synthesis, whether oil palm plantations are the primary causal factor in hydrometeorological disasters in Aceh, North Sumatra, and West Sumatra in late 2025. Specific objectives include:

a) Analyzing meteorological characteristics and climate change dimensions of tropical cyclone senyar as the triggering event.
b) Evaluating hydrological impacts of oil palm plantations compared to other land use changes and forest conversion.
c) Assessing the role of upper watershed forest degradation in amplifying disaster severity.
d) Examining spatial heterogeneity and location-specific impacts.
e) Investigating management practices that mitigate or exacerbate hydrological risks.
f) Providing evidence-based recommendations distinguishing primary triggers from secondary amplifying factors.

Literature Review: Conceptual and Theoretical Foundations

Hydrometeorological Disasters: Conceptual Framework

Hydrometeorological disasters encompass weather- and climate-related hazards, including floods, landslides, droughts, and tropical cyclones. Indonesia's disaster profile is dominated by such events, with 92-99% of disasters classified as hydrometeorological. This concentration reflects the country's tropical climate, monsoon dynamics, complex topography, extensive coastal exposure, and rapid land-use change and urban expansion [10].

Contemporary disaster science conceptualizes disasters not as purely natural phenomena but as outcomes of interactions between natural hazards and human-created vulnerabilities. The widely-adopted risk equation posits that Disaster Risk = (Hazard × Vulnerability × Exposure) ÷ Capacity. This framework distinguishes between the hazard itself (e.g., extreme rainfall from Cyclone Senyar), vulnerability factors that amplify impacts (e.g., deforested watersheds with reduced infiltration capacity), exposure patterns (e.g., communities settled in flood-prone areas), and capacity factors that moderate impacts (e.g., early warning systems, flood defenses) [11,12].

Recognition of compound disasters-where multiple hazards interact or where extreme events encounter pre-existing environmental degradation-has advanced understanding of the complexity of disaster causation. The late 2025 Sumatra disasters exemplify this compound nature: a rare meteorological extreme interacted with decades of accumulated watershed degradation to produce impacts that exceeded what either factor alone would have generated. Effective attribution, therefore, requires differentiating proximate causes (immediate triggers) from underlying causes (structural vulnerabilities) [13-15].

Climate Change and Tropical Cyclone Dynamics

Tropical cyclone formation in Indonesian waters represents a relatively rare phenomenon due to the country's equatorial location, where the Coriolis force-essential for cyclonic rotation—is minimal. Historical records document only limited cyclone impacts, with Tropical Storm Vamei (2001) previously representing the only well-documented case in the Malacca Strait region. Cyclone Senyar's formation at approximately 5°N latitude, generating sustained winds of 85 km/h with gusts to 110 km/h, therefore constitutes a meteorologically exceptional event [16].

Climate change attribution studies have established that anthropogenic warming is altering tropical cyclone dynamics globally, including in Southeast Asia. The World Weather Attribution research consortium analyzed Cyclone Senyar and associated storms in November 2025, concluding that climate change "supercharged" these events by elevating sea surface temperatures and increasing atmospheric moisture capacity. Sea surface temperatures in the formation region were measured at 1-2°C above the 1991-2020 average and approximately 1°C above the pre-industrial baseline. This warming enabled the atmosphere to hold approximately 7% more moisture per degree Celsius of temperature increase, directly intensifying precipitation rates [17].

Climate projections for Indonesia indicate continued intensification of extreme rainfall events. Modeling studies project increases of 15-25% in extreme precipitation across most Indonesian regions under SSP2-4.5 and SSP5-8.5 emission scenarios, with Sumatra identified as particularly vulnerable to wet-season intensification. Return period compression represents a critical consequence: flood events of a given magnitude that historically occurred once per century may occur once per 50 years or more frequently as the climate continues to warm. This baseline hazard escalation occurs independently of land-use decisions, implying that even optimal forest conservation cannot eliminate rising flood risk without concurrent climate mitigation [18].

Forest Hydrology and Watershed Ecosystem Services

Tropical forests provide multiple hydrological functions that regulate water flows and reduce flood risk. Canopy interception captures 15-30% of precipitation, reducing the volume and kinetic energy of water reaching the ground surface. Complex root systems and high soil organic matter content enhance infiltration rates, facilitating groundwater recharge rather than immediate surface runoff. Vegetation roughness and litter layers slow overland flow, extending the time-to-peak during rainfall events and reducing peak discharge magnitudes [19].

The watershed ecosystem services framework conceptualizes these functions within broader categories: supporting services (soil formation, nutrient cycling); regulating services (water flow regulation, erosion control, water quality maintenance); provisioning services (freshwater supply, timber); and cultural services (recreation, spiritual values). Among these, water flow regulation represents a critical service for disaster risk reduction, as it determines how rapidly precipitation is converted to streamflow and whether flow occurs gradually or in destructive pulses [20-22].

Forest conversion to any alternative land use fundamentally alters these hydrological processes. Meta-analyses of paired watershed studies globally demonstrate that forest clearing increases annual water yield (total discharge) while also increasing peak flows and reducing dry-season baseflow. The magnitude of impact depends on what replaces the forest: conversion to impervious urban surfaces generates the greatest hydrological disruption, while conversion to well-managed perennial plantations with conservation practices yields intermediate impacts, and conversion to annual crops or bare soil generates severe impacts through erosion and compaction [23].

Upper-watershed positioning confers disproportionate hydrological importance. Headwater catchments function as "water towers," capturing, storing, and gradually releasing precipitation. Forest degradation in these critical zones generates cascading downstream effects: increased sediment loads that fill reservoirs and river channels, elevated peak flows that exceed channel capacity, and reduced dry-season flows that impair water security. Consequently, upper-watershed forest conservation is among the most cost-effective flood mitigation strategies, with benefits far exceeding those of equivalent conservation in lowland areas [24].

Land Use Change and Flood Frequency Relationships

Empirical evidence from Indonesian watersheds documents relationships between land use change and flood frequency. In the Bekasi Watershed (Java), a 43% increase in built-up area between 1990 and 2018 was associated with a 4.13% increase in surface discharge. The Tembesi River watershed in Jambi (Sumatra) experienced a 21% increase in surface runoff and 16.9% increase in sediment yields following forest-to-plantation conversion. Community perception studies in Jambi documented an increase in flood frequency from 0.5 events per year in 2011 to 2.5 events per year in 2018 as plantation expansion progressed [25].

However, temporal dynamics reveal important nuances. Analysis of the Citarum Watershed in West Java demonstrated that while land use change effects are detectable in long-term flood statistics, extreme rainfall variability dominates during individual storm events. This finding suggests that attribution differs by timescale: event-level disasters are primarily driven by meteorological extremes, while decadal trends in flood frequency reflect cumulative land degradation [26].

Spatial heterogeneity further complicates simple generalizations. A critical insight from hydrological modeling is that "contribution of palm oil cannot be generalized; impact depends heavily on initial land conditions". Forest-to-plantation conversion generates substantial negative hydrological impacts due to the loss of mature forest functions. In contrast, establishing plantations on degraded land or grassland may yield neutral or even positive impacts if proper conservation practices are implemented, as plantations provide superior vegetative cover relative to the degraded baseline. Watershed position matters critically: upper-catchment conversions generate disproportionate impacts compared to lower-catchment changes due to cascading downstream effects [27].

Oil Palm Plantations: Hydrological Characteristics and Management Variables

Oil palm (Elaeis guineensis) exhibits specific biophysical characteristics relevant to hydrological function. Mature plantations (8+ years) achieve nearly 100% canopy cover, providing rainfall interception capacity. Root systems extend to depths of 5 meters, creating biopores that facilitate water infiltration. Annual evapotranspiration ranges from 1,000-1,500 millimeters, lower than that of the primary tropical forest (1,200-1,800 mm) but substantially higher than most annual crops. These characteristics suggest that oil palm possesses inherent capacities for soil and water conservation when compared to more intensive agricultural systems [28].

However, the establishment and management of plantations critically determine actual hydrological outcomes. Soil compaction from heavy machinery during site preparation, planting, and harvesting operations can increase bulk density by 30% and reduce total porosity by 15%, substantially impairing infiltration capacity. Young plantations (0-5 years) before canopy closure exhibit maximum erosion rates and runoff generation, particularly on sloped terrain. Drainage infrastructure constructed for estate water management—channels and dams designed to prevent waterlogging in plantations—can redirect runoff into surrounding communities, exacerbating downstream flood risk [29].

Conservation practices can substantially mitigate these negative impacts. Terracing on slopes above 6% reduces runoff velocity and soil loss by up to 70%. Leguminous cover crops (Mucuna, Pueraria, Calopogonium) protect the soil surface, enhance infiltration, and add organic matter. Mulching with empty fruit bunches and palm fronds reduces raindrop impact and increases water retention. Silt pits capture sediment and increase infiltration; when combined with frond pile management, they reduce surface runoff by 31%. Well-managed plantations that implement comprehensive Good Agricultural Practices can mimic natural hydrological functions, whereas poorly managed operations exhibit severe degradation [30].

Land suitability criteria provide a scientific basis for spatial planning. The optimal slope for oil palm cultivation is below 8%, with 8-15% considered suitable, 15-25% marginal, and above 25-40% unsuitable. Soil requirements include well-drained mineral soils, pH 4.5-6.5, and depth exceeding 100 centimeters. Climate suitability encompasses annual rainfall of 2,000-3,000 millimeters, evenly distributed, a temperature range of 24-32°C, and an elevation below 400 meters above sea level. Indonesia's Sumatra and Kalimantan regions possess favorable biophysical characteristics within these parameters, with spatial analyses indicating that 79.56% of some districts are classified as highly suitable (S1) or suitable (S2). Critically, substantial areas of degraded land, grassland, and unproductive plantations could accommodate expansion without further deforestation if appropriate spatial planning mechanisms were implemented [31].

Methodology: Qualitative Literature Review Approach

Methodological Rationale

This study employs a qualitative literature review methodology, distinguished from a systematic literature review by its flexible, interpretive approach, which enables exploration of complex, multidimensional topics across disciplines. Qualitative literature reviews provide broad contextual understanding without the standardized protocols, rigid inclusion criteria, and quantitative synthesis characteristic of systematic reviews. This methodological choice is appropriate for disaster attribution research that requires integrating diverse evidence types—meteorological data, hydrological modeling, land-use remote sensing, policy documents, field reports—that resist reduction to standardized effect sizes [32].

The primary advantage of qualitative approaches for this topic lies in their flexibility in accommodating heterogeneous evidence while maintaining analytical rigor through systematic thematic analysis. Disaster causation involves meteorology, hydrology, land-use science, social vulnerability, and governance dimensions that cannot be adequately captured by narrow systematic review protocols designed primarily to evaluate clinical interventions. Qualitative synthesis enables conceptual exploration and theoretical development of multi-causal frameworks rather than hypothesis testing, appropriate for emerging research domains where causal mechanisms remain contested [33].

Limitations of this approach are acknowledged. Subjectivity in source selection and theme identification can introduce bias compared with protocol-driven systematic reviews. Limited reproducibility due to the absence of standardized procedures may lead to inconsistent results when conducted by different researchers. The risk of confirmation bias—preferentially including sources that support prior expectations—requires active mitigation through negative-case analysis and triangulation. Despite these limitations, a qualitative literature review is the most appropriate methodology for addressing this study's research questions, given the heterogeneity of the current evidence and its multidisciplinary scope [34].

Literature Search and Source Selection Strategy

Literature search encompassed multiple database platforms: Google Scholar, Scopus, Web of Science, PubMed, and ScienceDirect for peer-reviewed academic publications; CGIAR repositories, CIFOR publications, and university institutional repositories for specialized research; government reports from BNPB (National Disaster Management Agency), BMKG (Meteorology, Climatology, and Geophysical Agency), and Ministry of Environment and Forestry for official data; NGO reports from environmental organizations for policy context; and credible journalism from Mongabay, Jakarta Post, Tempo, and Channel News Asia for event documentation.

Temporal scope prioritized literature published between 2020 and 2025 to capture the most recent evidence, with selective inclusion of foundational studies from 2010-2019 establishing hydrological principles. Event-specific sources from November-December 2025 documenting the impacts of Cyclone Senyar were systematically collected. The geographic focus was on Indonesian contexts, particularly Sumatra, with comparable tropical-region studies included when findings demonstrated transferability. Keywords and search terms included: disaster-related ("hydrometeorological disaster," "flooding," "landslides," "Tropical Cyclone Senyar," "Sumatra floods 2025"), land use-related ("oil palm plantation," "deforestation," "land use change," "forest conversion," "watershed degradation"), hydrological ("surface runoff," "infiltration," "soil erosion," "water regulation," "hydrological services"), and geographic ("Aceh," "North Sumatra," "West Sumatra," "Sumatra," "Indonesia").

Inclusion criteria encompassed: publications accessible in English or Indonesian; studies addressing hydrological impacts of land use change in tropical contexts; sources providing empirical data, conceptual frameworks, or policy analysis relevant to research questions; and Indonesian contexts or transferable findings from comparable regions. Exclusion criteria removed: purely anecdotal accounts without verifiable evidence; studies from temperate or arid zones with limited tropical transferability; and outdated methodologies superseded by recent approaches.

Analytical Framework: Thematic Analysis

Thematic analysis-systematic identification, analysis, and reporting of patterns within data—provided the analytical framework. This iterative process involved repeated reading, coding, theme development, and refinement to identify meaningful patterns that address the research questions. An inductive approach allowed themes to emerge from data rather than being imposed by predetermined frameworks [35].

The six-stage process followed established protocols:
a) Data familiarization through immersive reading of collected literature.
b) Initial coding generating preliminary codes representing significant features.
c) Theme identification collating codes into potential themes representing patterned meanings.
d) Theme review and refinement checking coherence against coded extracts and entire dataset.

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e) Theme definition and naming refining specifics and generating clear definitions.
f) Report production synthesizing themes into compelling narrative addressing research questions [36].

Quality assurance employed multiple strategies to enhance trustworthiness. Triangulation cross-referenced findings across multiple sources and methodological approaches. Peer debriefing involved consultations with subject-matter experts in hydrology, forestry, and disaster management. Negative case analysis actively sought evidence that contradicted emerging conclusions to avoid confirmation bias. Audit trail maintenance documented literature search, selection decisions, and analytical processes. Reflexivity acknowledged the researcher's positionality and potential biases. Data saturation guided the continuation of the literature review until no new themes or insights emerged [37].

Results: Thematic Findings on causes of Late 2025 Hydrometeorological Disasters

Theme 1: Exceptional Meteorological Event as Primary Trigger

Tropical Cyclone Senyar represents a rare and intense meteorological phenomenon. Formation occurred on November 25-26, 2025, in the Malacca Strait at approximately 5°N latitude, making it only the second documented tropical cyclone in this region after Tropical Storm Vamei in 2001. Maximum sustained winds reached 85 km/h with gusts to 110 km/h. The cyclone's quasi-stationary behavior—remaining over the Strait of Malacca for 2-3 days—led to persistent moisture convergence and prolonged extreme rainfall. Global Precipitation Measurement satellite data recorded cumulative precipitation of 1,843 millimeters over November 25-27, 2025 UTC, with daily intensities exceeding 300 millimeters in numerous locations across North Sumatra [38].

Climate change attribution analysis demonstrates hazard amplification. The World Weather Attribution study concluded that anthropogenic climate change "supercharged" Cyclone Senyar's intensity and associated rainfall through elevated sea surface temperatures. Waters in the formation region measured 0.2°C warmer than the 1991-2020 average and approximately 1°C above the pre-industrial baseline. This warming enabled the atmosphere to hold 7% more moisture per degree of temperature increase, directly intensifying precipitation rates. Atmospheric dynamics involving interaction with La Niña conditions, the Northeast Monsoon, Typhoon Koto, and the Indian Ocean Dipole created exceptional convergence conditions [39-41].

Dr. Edi Riawan from Institut Teknologi Bandung's Meteorology program described the event as the "largest rainfall in 20 years" for the affected region, emphasizing its historical exceptionality. BMKG classified Cyclone Senyar as a "rare phenomenon," with extreme rainfall exceeding historical norms and established return-period estimates. Comparative analysis with previous cyclones indicates that Senyar's intensity and persistence exceeded Cyclone Vamei (2001), Cyclone Robyn (November 2024), and other recent events in Indonesian waters [9,42,43].

Climate projections indicate an increase in baseline flood risk independent of land use. Modeling studies project 15-25% increases in extreme precipitation across Indonesia under SSP2-4.5 and SSP5-8.5 emission scenarios. Return period compression implies that flood events of a given magnitude will occur more frequently, reducing intervals between disasters. Sumatra is identified as particularly vulnerable to intensifying wet-season extreme rainfall. Critically, this baseline hazard escalation operates independently of land management decisions, implying that climate-driven flood risk continues increasing even with optimal forest conservation [44].

Theme 2: Upper Watershed Forest Degradation as Critical Amplifying Factor

Forest loss across the three affected provinces has been substantial. Environmental monitoring documented the clearing of 1.4 million hectares of forest cover across Aceh, North Sumatra, and West Sumatra between 2016 and 2025. Province-specific data show: Aceh lost 177,000 hectares over seven years, including 16,000 hectares in 2024 alone; the Batang Toru watershed in North Sumatra (covering flood-stricken Tapanuli districts) lost 73,000 hectares between 2016 and 2024; and West Sumatra lost 1,550 hectares of forest vegetation cover in directly affected flood zones [45].

Expert assessments emphasize upper catchment degradation as a critical amplifying factor. Dr. Suryatmojo from Universitas Gadjah Mada's hydrology program stated: "Extreme weather was only the initial trigger. The weakened natural defenses in the upper watershed greatly exacerbated the destructive impact". Indonesia's Deputy Minister of Public Works explained that "loss of vegetation has diminished the land's ability to absorb rainfall, resulting in rainwater flowing directly into rivers". Professor Ahmad Maryudi from UGM Forestry attributed upper watershed deforestation to "anthropogenic factors, including human actions and negligence...poor-quality policies compounded by weak implementation capacity" [8,46].

Hydrological mechanisms explain this amplification. Deforested slopes lose soil structure and organic matter, decreasing water absorption rates and infiltration capacity. Without forest interception and retention, rainfall converts more rapidly to surface flow rather than infiltrating into soil and groundwater. Destabilized slopes produce sediment that fills river channels, reducing conveyance capacity and exacerbating flooding. Erosion and topsoil loss lead to compacted surfaces with limited infiltration capacity, perpetuating degradation cycles [47].

Spatial analysis reveals a correlation between degraded watersheds and the worst disaster impacts. The Batang Toru watershed, which experienced the highest casualties in Central Tapanuli, South Tapanuli, and Sibolga City, correlates with 73,000 hectares of documented forest loss. Aceh Singkil district recorded 6,100+ affected households—the highest in Aceh—and exhibits extensive deforestation since 1990. Areas with degraded headwater forests experienced greater flood severity than lowland areas with intact or moderately degraded forest cover [48].

Multiple economic sectors drive forest loss. Activities implicated include oil palm plantations, rubber plantations, legal and illegal logging operations, mining, and infrastructure development. In Aceh, specific drivers include illegal logging in wildlife corridors, patchouli oil cultivation, and mining encroachment in the Leuser Ecosystem. North Sumatra faces pressure from the Martabe gold mine and the Batang Toru hydropower project, both of which are linked to the degradation of landslide-prone terrain. The policy context includes 31 active mining permits covering 156,741 hectares in Aceh, and four forestry concessions exceeding 207,000 hectares [49-52].

Theme 3: Oil Palm Plantations - Context-Dependent Hydrological Impacts

Evidence documents both negative hydrological impacts and important contextual variables. Studies in the Tembesi River watershed (Jambi, Sumatra) found that forest-to-oil-palm conversion increased surface runoff by 21%, sediment yields by 16.9%, total nitrogen by 78%, and total phosphorus by 144%. Similar findings in the Kais River watershed showed a 21% increase in surface runoff and dramatic deterioration in water quality associated with oil palm expansion. Community perception studies in Jambi reported flood frequency increasing from 0.5 events per year in 2011 to 2.5 events per year in 2018 following plantation establishment. An NTU-led study in Aceh found flood-prone areas had fewer trees, more oil palm coverage, and higher poverty rates, with over 2,000 flood events documented between 2011 and 2018 [53].

Mechanisms of hydrological impact include soil compaction from heavy machinery, which increases bulk density by 30% and reduces total porosity by 15%, thereby impeding infiltration. Plantation drainage infrastructure—channels and dams designed for estate water management—can redirect runoff to surrounding communities. While oil palm reaches 100% canopy cover at maturity, it intercepts less rainfall than a multi-strata tropical forest because of its simpler canopy architecture. Root systems, though deep, create less complex soil structure than diverse forest systems do, thereby reducing infiltration heterogeneity [54-56].

The evidence indicates critical spatial heterogeneity. Hydrologically, the contribution of palm oil cannot be generalized. Impact depends heavily on initial land conditions. Forest-to-oil-palm conversion generates the most severe negative impacts due to the loss of mature forest hydrological functions. In contrast, establishing plantations on degraded land or bare soil may yield neutral or positive impacts if proper conservation practices are implemented, as plantations provide superior vegetative cover relative to degraded baseline conditions. Watershed position critically affects the magnitude of impacts: upper-catchment oil palm conversions generate more substantial hydrological consequences than lower-catchment placements due to cascading downstream effects [57-59].

Plantation age and management quality determine actual outcomes. Young plantations (0-5 years) exhibit the highest erosion and runoff rates during the establishment phase before canopy closure. Mature plantations (8+ years old) with proper management can achieve moderate soil and water conservation. Well-managed plantations implementing Good Agricultural Practices—including terracing, cover crops, mulching, and silt pits—show 31-40% runoff reduction compared to unmanaged systems. Certification standards (RSPO, ISPO, MSPO) require conservation measures, but implementation heterogeneity creates variable outcomes [60-62].

Comparison with other land uses provides important context. Forest consistently outperforms oil palm in infiltration capacity, erosion control, and flood mitigation. However, oil palm can provide superior hydrological services compared to severely degraded bare land. Rubber plantations exhibit hydrological impacts similar to those of oil palm; both are inferior to forests but superior to annual crops. A key insight is that forest conversion to ANY monoculture degrades hydrological functions; oil palm is not uniquely problematic but shares common impacts with other conversion crops [63].

In the specific context of the 2025 disaster zones, oil palm distribution requires spatially explicit analysis. Aceh Singkil shows extensive oil palm replacement of forests and a strong correlation with flood occurrence. In North Sumatra's Tapanuli region, while the Batang Toru watershed experiences forest loss, oil palm is one

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of several drivers, alongside mining, hydropower, and illegal logging. West Sumatra shows less oil palm dominance than Aceh and North Sumatra, with deforestation driven by various agricultural conversions. The evidence indicates that simplistic "palm oil caused floods" narratives oversimplify a multi-causal reality that requires spatially explicit attribution analysis [4].

Theme 4: Multi-Sectoral Land Use Activities and Illegal Operations

Evidence of illegal logging emerged prominently in post-disaster investigations. The "lautan kayu" (sea of logs) phenomenon—massive quantities of logs swept away during floods—indicated substantial illegal timber operations. The environmental organization Apel Green Aceh discovered 30 cubic meters of illegally felled logs in Babah Suak Village, Nagan Raya, one day before the floods began on November 25, 2025. Nagan Raya experienced 5,127 hectares of forest loss between 2018 and 2024, with 2024 recording the highest annual loss at 1,052 hectares. Illegal logging was documented in wildlife corridors connecting the Leuser and Ulu Masen ecosystems [64].

Mining sector contributions are substantial. Aceh alone hosts 31 active mining permits covering 156,741 hectares. Illegal gold mining operations cover an estimated 3,500 hectares, with 2,300+ hectares within the protected Leuser Ecosystem. In North Sumatra, the Batang Toru region faces pressure from the Martabe gold mine expansion and the construction of the NSHE (North Sumatra Hydro Energy) hydropower dam, both of which are linked to slope instability and increased landslide vulnerability. Environmental monitoring indicates that mining and industrial plantations together accelerate forest loss, with 860,000 hectares of tree cover lost in Aceh between 2021 and 2024 [24,65].

Multi-sector attribution presents analytical challenges. Environmental advocacy group Walhi reported the 1.4 million hectares of forest loss (2016-2025) as attributed to "plantations AND mining"—not oil palm exclusively. Four forestry concessions spanning over 207,000 hectares contribute to forest fragmentation. Infrastructure development, including roads, dams, and settlements, fragments watersheds and alters drainage patterns. Agricultural diversity includes patchouli oil cultivation, rubber plantations, coffee, and other crops also driving deforestation in affected areas [66].

The government's enforcement response included permit revocations for 28 companies covering 750,000 hectares, following post-disaster environmental audits that identified violations. Importantly, companies targeted represent a mix of timber, mining, and plantation operations—not exclusively palm oil companies. Specific prominent cases include North Sumatra Hydro Energy (hydropower) and Agincourt Resources (Martabe gold mine). Legal proceedings were initiated against six companies for alleged watershed damage involving 2,516 hectares of clearance in North Sumatra [7,65].

Theme 5: Climate Change and Land Use Interaction Effects

An integrative conceptual framework from various articles articulates dual pathways:
(1) land use change increases discharge primarily for small return period floods (T1-T10), while (2) climate change increases extreme rainfall across ALL return periods, including large magnitude events (T50-T100). The compound effect of land-use change and climate change jointly amplifies flood risk beyond what either factor alone would. Relative contributions vary by temporal scale: event-level disasters are dominated by meteorological extremes, while decadal trends in flood frequency reflect cumulative land degradation [26].

Attribution differs between short-term and long-term perspectives. For the specific 2025 disaster event, Cyclone Senyar's extreme rainfall constitutes the PRIMARY trigger, with land degradation functioning as a SECONDARY amplifier. Over medium-term timescales (2011-2025), increasing flood frequency reflects both land-use change and climate variability, with communities perceiving escalating risk. Long-term, multi-decadal perspectives reveal a fundamental watershed transformation, with 1.4 million hectares of deforestation restructuring baseline hydrological regimes [16].

Return period dynamics illustrate differential impacts. Land-use change primarily affects frequent, low-magnitude floods (T1-T10), whereas climate change affects extreme, high-magnitude floods (T50-T100). Given the 2025 disaster's T50-T100 level rainfall intensity, meteorological factors dominate causality even in degraded landscapes. This implies that even with perfect land management, climate-driven extreme events continue to pose escalating risk [67].

Nevertheless, land use change remains critical for resilience. Degraded watersheds experience disproportionate damage relative to intact systems under a given rainfall intensity, demonstrating vulnerability amplification. Deforestation removes natural buffering capacity that could moderate disaster severity, eroding resilience. Future risk trajectory analysis indicates that, without land restoration, climate change-driven hazard increases interact with increases in vulnerability to exponentially escalate disaster risk [9,19,68].

The Zero Artificial Runoff (ZARo) framework offers an integrative management approach. This concept proposes managing excess discharge to approach natural hydrological conditions regardless of specific land use. Implementation involves:

a) Delineating watersheds and characterizing land cover changes.
b) Estimating discharge changes via monitoring and modelling.
c) Implementing control measures.

The ZARo application in Bandung demonstrated effectiveness by reducing surface runoff up to 40%. This framework offers a pathway to accommodate economic development while managing hydrological risks through a combination of engineered and nature-based solutions [69-71].

Discussion and Analysis

Multi-Causal Attribution Framework: Answering the Core Question

Analysis reveals a hierarchy of causation. The primary trigger (Level 1) is Tropical Cyclone Senyar's extreme rainfall event during November 25-27, 2025. Evidence includes an unprecedented cumulative rainfall of 1,843 millimeters, daily rainfall intensities exceeding 300 millimeters, and quasi-stationary cyclone behavior. Expert consensus from BMKG, UGM hydrologists, and international meteorologists identifies meteorological extremes as the initiating factor in the disaster. Climate change attribution demonstrates that warmer sea surfaces (+1°C above pre-industrial) and enhanced atmospheric moisture (+7% per degree Celsius) amplified cyclone intensity [72].

The secondary amplifier (Level 2) comprises upper watershed forest degradation. Evidence documents 1.4 million hectares of forest loss (2016-2025) in affected provinces, with concentration in upper catchments. Mechanisms include loss of infiltration capacity, rainfall interception, and soil stabilization, which exacerbate surface runoff and erosion. Spatial correlation shows degraded watersheds (Batang Toru, Aceh Singkil, Nagan Raya) experienced the most severe impacts [73].

Tertiary factors (Level 3) include specific land management practices, among which oil palm plantation operations constitute one component. Evidence demonstrates context-dependent impacts that vary with prior land use, plantation age, management quality, and watershed position. Critically, oil palm represents ONE component of broader forest loss driven by multiple sectors including logging, mining, other agriculture, and infrastructure [4].

Answering the core research question: NO—oil palm plantations are NOT the singular or primary source of late 2025 hydrometeorological disasters. This conclusion rests on four pillars of reasoning. First, primary causation resides in a rare, climate-change-amplified extreme meteorological event that would have caused flooding regardless of land use. Second, forest degradation across multiple sectors—not just oil palm—weakened watershed resilience, amplifying disaster severity. Third, oil palm contributes to hydrological vulnerability it replacing forests in critical upper watersheds, but this contribution cannot be isolated from concurrent logging, mining, infrastructure, and other agricultural activities. Fourth, spatial heterogeneity means that oil palm impacts vary dramatically by location, age, and management; simplistic generalizations obscure context-dependent reality [74].

Oil Palm's Contributory Role: Nuanced Understanding

While not the primary cause, oil palm's role requires nuanced characterization. The sector is contributory but not determinative—oil palm expansion is ONE factor among multiple drivers of forest loss and hydrological degradation. The mechanism involves forest conversion rather than oil palm per se: evidence indicates that ANY forest-to-monoculture conversion degrades hydrological functions, whether to oil palm, rubber, coffee, or other plantations [6,75,76].

Management practices determine actual outcomes. Well-managed plantations implementing conservation practices (terracing, cover crops, ZARo principles) can substantially mitigate hydrological impacts, with studies documenting reductions of 31-40% in runoff. Conversely, poorly managed plantations lacking conservation measures exhibit severe erosion, compaction, and increased runoff. This variability implies that management quality is as important as land use type itself [61,75-79].

Geographic specificity requires attention. Aceh Singkil shows a strong correlation between oil palm and flood coverage. North Sumatra Tapanuli shows mining and hydropower as prominent factors alongside plantations. West Sumatra shows mixed agricultural drivers. These spatial differences underscore the importance of location-specific analysis rather than blanket generalizations [80,81].

Climate Change as Dominant Long-term Driver

Projection consensus indicates a 15-25% increase in extreme rainfall across Indonesia, regardless of land management decisions. Return period compression means T50 floods become T25 floods, T100 floods become T50 floods, driven by climate change independent of surface conditions. Policy implication:

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even with optimal forest conservation and plantation management, climate-driven hazards continue escalating [82].

Climate-land use interaction creates compound vulnerability. Climate change increases hazard magnitude; land degradation increases landscape vulnerability; their interaction multiplies disaster risk exponentially. Future trajectories suggest that without addressing BOTH climate mitigation AND landscape restoration, Indonesian Sumatra faces recurring catastrophic floods. The framework of "Avoiding the Unmanageable, Managing the Unavoidable" applies: climate adaptation requires reducing controllable vulnerabilities (e.g., land degradation) while building resilience to unavoidable hazards (e.g., intensifying rainfall) [18,27].

Spatial Planning and Management Recommendations

Upper watershed protection emerges as the highest priority. Upper-catchment forest loss generates downstream flood amplification effects that exceed those from lower-catchment changes by orders of magnitude. Watersheds currently below 25% forest cover—characteristic of many Sumatran river basins—exhibit severely compromised water regulation capacity. Evidence-based policy recommends a moratorium on land conversion in the upper watershed across sectors (palm oil, mining, logging, and infrastructure) [83,84].

Suitable land exists for oil palm expansion without further deforestation. Spatial analysis demonstrates vast areas of degraded land, grassland, and existing unproductive plantations could accommodate expansion. For example, 79.56% of Ketapang Regency is classified as suitable (S1/S2) for oil palm, with substantial overlap of "Other Use Areas" and "Conversion Production Forests" rather than primary forest. Indonesian law provides mechanisms for land reclassification to enable plantation expansion on appropriate sites while conserving forests. Sumatra's extensive unproductive plantations offer replanting opportunities, generating economic benefits without new deforestation [31,44].

Slope-based restrictions possess a scientific foundation. Oil palm on slopes of 15-25% or greater experiences dramatically increased erosion and runoff, making it unsuitable for sustainable production. Evidence suggests that plantations established on unsuitable steep slopes contribute disproportionately to watershed degradation. Rigorous application of existing suitability criteria (slopes below 8% optimal, below 15% acceptable) would prevent most problematic conversions [85, 86].

Conservation practice effectiveness is well-documented. Quantified benefits include: frond pile management and silt pits reduce runoff by 31%; ZARo approaches reduce runoff by 40%; terracing reduces erosion by 70%. Best management practices combining terracing, leguminous cover crops, empty fruit bunch mulching, silt pits, and riparian buffer preservation can approach forest-level hydrological function. Certification standards (RSPO, ISPO, MSPO) require such measures, though compliance monitoring and enforcement need strengthening [48,87].

Conclusion

Substantive Conclusions

This qualitative literature review demonstrates that oil palm plantations are not the primary or singular source of late 2025 hydrometeorological disasters in Aceh, North Sumatra, and West Sumatra. Primary causation lies in a rare, climate-change-amplified Tropical Cyclone Senyar, which generated unprecedented rainfall (1,843 mm cumulative, 300+ mm daily) that would have caused flooding under any land-use scenario. Secondary amplification stems from upper-watershed forest degradation across multiple sectors—logging, mining, plantations, infrastructure—that has weakened hydrological resilience and exacerbated disaster severity. Oil palm plantations contribute to forest loss and hydrological degradation when they replace forests in critical locations. Still, this contribution is context-dependent and cannot be isolated from concurrent multi-sectoral activities.

Spatial heterogeneity is critical. Oil palm impacts vary dramatically by prior land use (forest versus degraded land), plantation age (young versus mature), management quality (with versus without conservation practices), and watershed position (upper versus lower catchment). Well-managed plantations implementing comprehensive conservation best practices can substantially mitigate hydrological impacts, approaching natural system function under certain conditions. Conversely, poorly-managed plantations on unsuitable slopes in critical upper catchments exacerbate vulnerability.

Climate change emerges as the dominant long-term driver, independent of land-use decisions. Projections indicate 15-25% increases in extreme rainfall and return period compression regardless of surface land management. This implies that even optimal forest conservation cannot eliminate escalating flood risk without concurrent climate mitigation, though land restoration remains essential for building resilience to unavoidable climate-driven hazards.

Policy Recommendations

Evidence-based recommendations emphasize integrated approaches. Upper watershed protection is the highest priority and requires a moratorium on land conversion in critical catchments across all sectors. Spatial planning reform should direct oil palm expansion to degraded lands, grasslands, and unproductive plantations rather than forest conversion, utilizing Indonesia's substantial suitable non-forest land. Slope restrictions (below 8% optimal, below 15% acceptable) should be rigorously enforced to prevent establishment on erosion-prone terrain.

Management practice enhancement through mandatory conservation standards—terracing, cover crops, mulching, silt pits, riparian buffers-applies to all plantations regardless of certification status. Zero Artificial Runoff framework implementation at the watershed scale requires all land uses (plantations, mines, urban areas) to manage runoff a approximate natural hydrological conditions. Smallholder technical support through subsidized access to conservation practices and conditional cash transfers that link financial support to practice adoption address equity considerations.

Multi-sectoral accountability requires equitable enforcement across ALL sectors—palm oil, rubber, logging, mining, infrastructure—not selective targeting. Corporate liability frameworks should hold companies accountable for downstream flood damages attributable to verified watershed degradation. Climate adaptation integration must incorporate climate projection data into spatial planning, infrastructure design, and land-use decisions, while prioritizing nature-based solutions that provide both mitigation and adaptation benefits.

Research Priorities and Limitations

Future research should prioritize watershed-specific attribution studies that conduct detailed spatial analyses to quantify the relative contributions of oil palm versus other land uses in specific disaster-affected watersheds. Long-term hydrological monitoring using permanent stations to track discharge, sediment, and water quality in watersheds with varying plantation densities and management practices would strengthen the evidence base and inform adaptive planning.

Management effectiveness evaluation through rigorous field studies quantifying runoff reduction from different combinations of conservation practices under Indonesian tropical conditions remains essential. Climate-land-use interaction modeling is developing integrated projections of future flood risk across different scenarios.

Study limitations include methodological challenges in disentangling meteorological extremes, climate change, land use change, and socioeconomic vulnerabilities. Spatial resolution gaps limit the availability of watershed-specific data on oil palm location, age, and management practices to the required precision. Counterfactual impossibility means quantifying what 2025 disasters would have been with pristine forests relies on modeling assumptions. Data quality issues, including inconsistent reporting, dominance of grey literature, and publication lags, affect the robustness of the evidence.

Final Synthesis

The late 2025 hydrometeorological disasters in Sumatra represent a tragic confluence of climate-change-amplified extreme weather interacting with decades of multi-sectoral forest degradation. While oil palm plantations have contributed to watershed vulnerability by replacing forests in critical locations, the evidence does not support a simplistic attribution to the palm oil sector. Rather, disasters result from systemic interactions: inadequate climate mitigation that allows rainfall intensification; weak governance that enables forest loss across the logging, mining, plantation, and infrastructure sectors; insufficient enforcement of land-use planning and conservation standards; and socioeconomic vulnerabilities that concentrate poor communities in hazard zones.

Moving forward requires integrated approaches that address ALL contributing factors through upper watershed protection, climate adaptation, improved land management across sectors, and support for vulnerable populations. Scapegoating oil palm provides a politically convenient explanation but fails to address root causes and risks misdirecting resources away from interventions with the greatest potential for disaster risk reduction. Evidence-based policy grounded in hydrological science, spatial analysis, and multi-causal attribution frameworks offers a credible path toward resilient, sustainable, and equitable development in Sumatra's critical watersheds. With appropriate spatial planning directing development to suitable locations, rigorous implementation of conservation practices, and integrated climate adaptation strategies, Indonesia can balance economic development with environmental protection and disaster risk reduction.

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