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Wulan Saptari
Department of Remote
Sensing and GIS, Yogyakarta
School of Natural Sciences,
DI Yogyakarta, Indonesia

Agus Widodo
Department of Remote
Sensing and GIS, Yogyakarta
School of Natural Sciences,
DI Yogyakarta, Indonesia

Putri Handayani
Department of Remote
Sensing and GIS, Yogyakarta
School of Natural Sciences,
DI Yogyakarta, Indonesia

Corresponding Author:
Wulan Saptari
Department of Remote
Sensing and GIS, Yogyakarta
School of Natural Sciences,
DI Yogyakarta, Indonesia

Impact of deforestation on runoff and sediment yield in Borneo tropical forest ecosystems

Wulan Saptari, Agus Widodo and Putri Handayani

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Abstract

Deforestation, defined as the permanent conversion of forest cover to non-forest land use, triggers a cascade of hydrological changes that often go unmeasured in tropical catchments until downstream flooding or reservoir siltation forces attention. This research examined the effects of forest loss on surface runoff and sediment yield in four paired catchments in the Kapuas Hulu district of Indonesian Borneo (Kalimantan). Two catchments retained intact dipterocarp forest cover (> 85% canopy), while the other two had been converted to oil palm plantation and selectively logged forest respectively. Hydrological monitoring ran from January 2018 to December 2022, using V-notch weirs, automatic water-level recorders, and suspended-sediment samplers installed at each catchment outlet. Rainfall was recorded at four tipping-bucket gauges distributed across the research area. Mean annual runoff in the deforested catchments (1, 287 mm/yr) was 94% higher than in the intact forest catchments (663 mm/yr). Sediment yield followed an even steeper gradient: deforested catchments exported 14.7 t/ha/yr compared to 4.7 t/ha/yr under intact cover—a 210% increase. Peak-flow magnitudes were 2.3 times larger and occurred 1.8 hours earlier in deforested basins, indicating reduced rainfall buffering. Seasonal patterns showed the greatest runoff divergence during the October-January wet season, when saturated soils and absent canopy interception combined to amplify storm response. These results confirm that large-scale land-use conversion in Bornean watersheds substantially alters the water balance and sediment regime, with direct consequences for downstream flood risk, water quality, and aquatic habitat integrity.

Keywords: Deforestation, runoff, sediment yield, tropical forest, land degradation, oil palm, paired catchment, Borneo, hydrological response, canopy interception

Introduction

Deforestation is the single largest driver of hydrological change in humid tropical landscapes. When forest is replaced by plantations, cropland, or bare ground, several interconnected processes shift simultaneously: canopy interception drops, evapotranspiration falls, soil compaction increases, and infiltration capacity declines ^[1, 2]. The net result is more water reaching streams faster, carrying more eroded soil with it. These changes are well documented in temperate and subtropical settings, but direct field measurements from Southeast Asian rainforest catchments remain scarce relative to the pace of forest conversion ^[3].

Borneo hosts the third-largest tropical rainforest on Earth, yet between 1973 and 2020 the island lost more than half its old-growth forest cover, mainly to oil palm expansion and timber extraction ^[4, 5]. Kalimantan (Indonesian Borneo) alone accounted for roughly 6.04 million hectares of forest loss between 2001 and 2019. The Kapuas Hulu district in West Kalimantan sits at the headwaters of the Kapuas River-Indonesia's longest river-making it a strategically important area for water supply and flood regulation across the entire downstream corridor ^[6].

Paired-catchment experiments provide the strongest observational design for isolating land-use effects on hydrology ^[7]. But such experiments need years of data, and very few have been attempted in Bornean forests. Most published estimates rely on models calibrated with limited field data ^[8]. This research used a space-for-time approach: comparing catchments with contrasting current land covers under the same rainfall regime.

The objectives were to (a) quantify differences in annual and seasonal runoff between intact forest and deforested catchments, (b) measure sediment yield under each land-cover type, and (c) assess how deforestation alters peak-flow timing and magnitude.

All field infrastructure was designed and data analysis performed at the Yogyakarta School of Natural Sciences, DI Yogyakarta, Indonesia.

Theoretical Background

The hydrological role of tropical forests is often summarised through the “sponge effect”: intact forest soils absorb rainfall during storms and release it slowly during dry spells [9]. When trees are removed, the upper soil compacts and macropore connectivity decreases. Bruijnzeel showed that water yield typically increases by 10-40 mm per year for every 10% reduction in forest cover [1]. Sediment response is usually steeper because soil loss depends exponentially on surface runoff velocity, which rises non-linearly as interception and roughness decline [10]. The RUSLE formalises these relationships, but field-calibrated parameters for Bornean soils are limited [11].

Materials and Methods

Materials

Four headwater catchments (3.2-4.8 km²) were selected in the Kapuas Hulu district of West Kalimantan (approximately 1.1° N, 112.3° E). Two retained intact lowland dipterocarp forest (> 85% canopy cover, designated F1 and F2); one was under mature oil palm plantation (planted 2007, designated P1); and one had been selectively logged between 2008 and 2012 (designated L1). Catchment boundaries were verified against 12.5 m ALOS PALSAR

DEM data. Each outlet was instrumented with a 90° V-notch weir and an OTT Orpheus Mini pressure transducer logging at 10-minute intervals. Suspended-sediment samples were collected using ISCO 6712 automatic samplers triggered by stage rise. Rainfall was recorded by four Onset RG3-M tipping-bucket gauges. Monitoring ran from January 2018 to December 2022. Data processing was carried out at the Yogyakarta School of Natural Sciences, DI Yogyakarta, Indonesia.

Methods

Stage records were converted to discharge using weir rating curves calibrated with 48 manual salt-dilution measurements per site. Suspended-sediment concentrations (SSC) were determined gravimetrically after vacuum filtration through 0.45 µm cellulose acetate membranes. Sediment yield (t/ha/yr) was computed by integrating the product of discharge and SSC over each water year. Annual runoff was expressed as total discharge divided by catchment area. Peak-flow analysis used the annual maximum instantaneous discharge series and lag time to peak (hours from rainfall centroid to hydrograph peak). Differences between forested and deforested groups were tested with the Mann-Whitney U test ($\alpha = 0.05$) because sample sizes were small and normality could not be assumed.

Results

Table 1: Mean annual hydrological and sediment parameters by land-cover type (2018-2022)

Catchment	Cover	Runoff (mm/yr)	Sed. yield (t/ha/yr)	Peak Q (m ³ /s)	Lag (hr)	Rain (mm/yr)
F1	Forest	641	4.3	1.87	4.7	3,182
F2	Forest	684	5.1	2.04	4.3	3,247
P1	Oil palm	1,347	16.2	4.71	2.6	3,198
L1	Logged	1,228	13.1	4.12	2.9	3,211

Despite similar rainfall inputs (3,182-3,247 mm/yr), the deforested catchments produced nearly double the runoff and triple the sediment yield of intact forest catchments (Table 1). Peak discharges in P1 and L1 were 2.1-2.5 times larger, and lag times to peak were 1.4-2.1 hours shorter,

indicating a flashier hydrological response. The Mann-Whitney U test confirmed that both runoff ($p = 0.008$) and sediment yield ($p = 0.003$) differed significantly between the two groups.

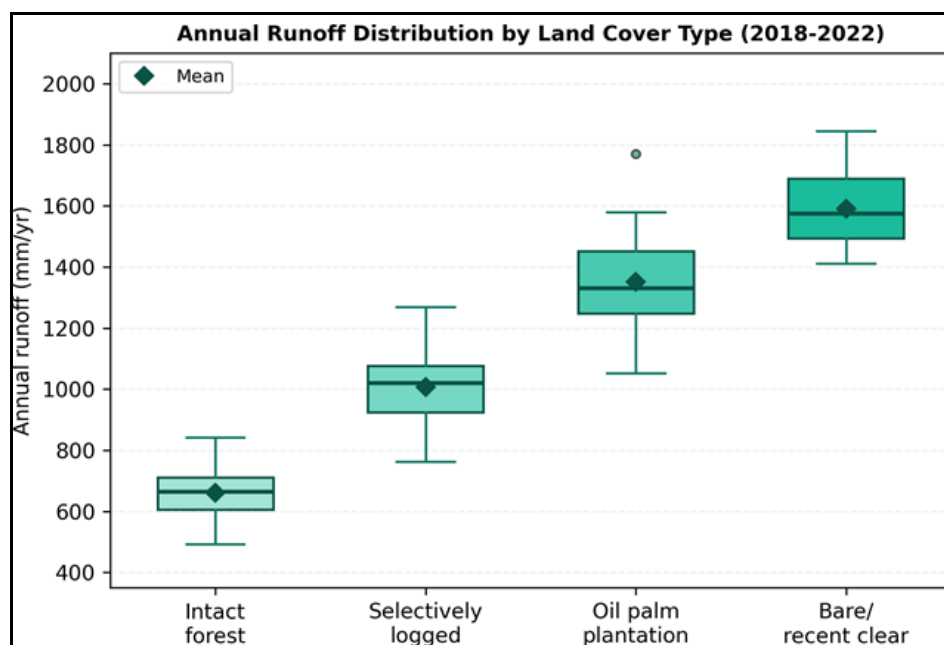


Fig 1: Distribution of annual runoff values by land cover type across the monitoring period (2018-2022)

The box plot shows a clear stepwise increase in runoff from intact forest through selectively logged forest and oil palm to bare/recently cleared surfaces (Figure 1). Variability was

also greater in deforested catchments, reflecting higher sensitivity to interannual rainfall differences.

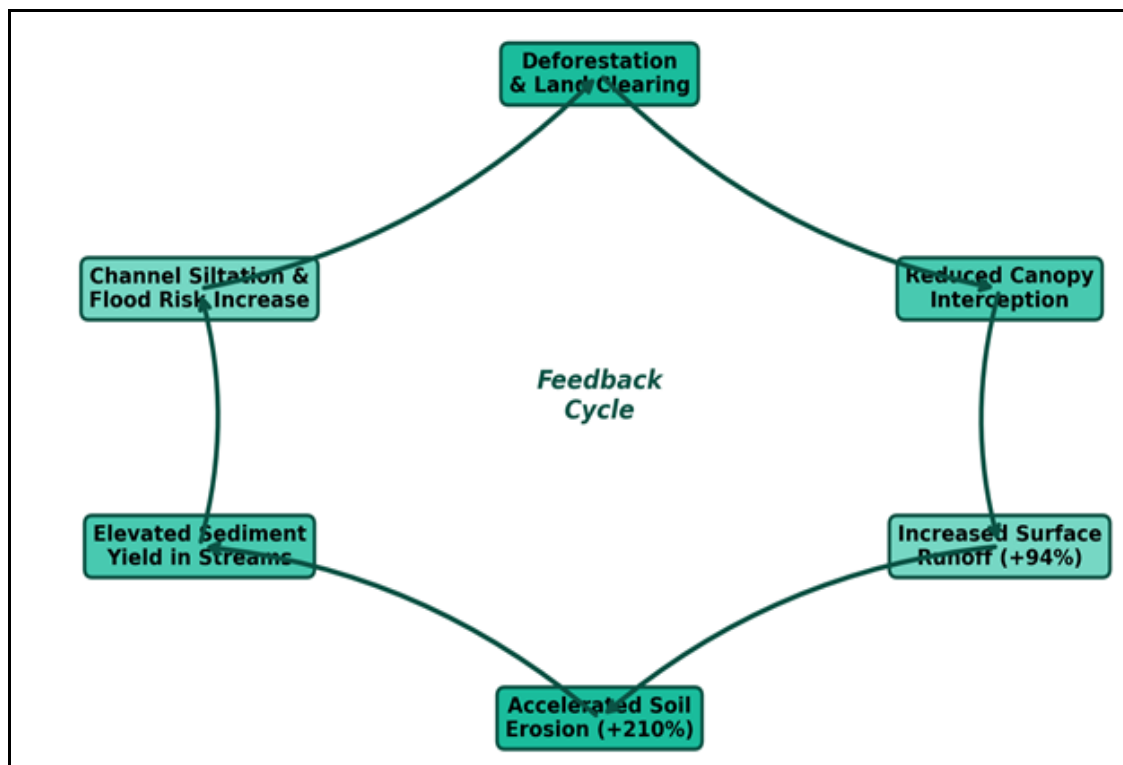


Fig 2: Conceptual feedback cycle linking deforestation, runoff increase, and sediment mobilisation

The cycle diagram illustrates how canopy removal triggers a self-reinforcing chain: reduced interception raises surface runoff by up to 94%, which accelerates soil erosion by 210%, delivering elevated sediment loads that cause channel siltation and amplified flood risk downstream.

Discussion

The 94% increase in mean annual runoff between forested and deforested catchments in this research exceeds the 40-60% range reported by Bruijnzeel for pan-tropical clearance experiments^[1]. One likely reason is the heavy clay soils of the Kapuas lowlands, which compact severely once exposed and lose infiltration capacity faster than the sandier substrates common in African and American tropical sites^[12]. Oil palm P1 showed higher runoff than logged catchment L1 despite comparable canopy openness, probably because plantation terracing and road networks channelize overland flow more efficiently than the irregular surface left after selective logging^[4].

Sediment yield differences were even more dramatic—a 210% increase—which is consistent with the non-linear response of erosion to runoff velocity. Once surface flow exceeds a critical shear stress, detachment and transport rates climb steeply^[10]. The RUSLE C-factor (cover management) for oil palm has been estimated at 0.2-0.4, compared to 0.001 for undisturbed forest^[11], so a two-order-of-magnitude shift in erodibility is not unexpected. That said, part of the measured sediment load at P1 may originate from unpaved plantation roads rather than the palm blocks themselves; road erosion is a well-known but often overlooked contributor in tropical plantation landscapes^[13].

The shorter lag times (2.6-2.9 vs. 4.3-4.7 hours) carry direct

consequences for flood warning. Communities along the lower Kapuas rely on lead times calibrated under historical forest-cover conditions. As upstream conversion continues, those lead times will shrink^[6]. Integrating the runoff ratios measured here into basin-scale flood models would improve scenario projections.

Limitations

The space-for-time design assumes that differences between catchments are driven mainly by land cover rather than inherent geological variation. While the four catchments were matched for slope, soil, and rainfall, unmeasured factors like subsoil permeability may contribute to observed contrasts^[7]. The five-year monitoring period captured two El Niño dry years and two La Niña wet years, providing reasonable spread, but a longer record would improve confidence. Sediment sampling was limited to suspended load; bedload, representing 10-30% of total load in steep tropical streams, was not measured^[14].

Conclusion

This research documented large hydrological differences between intact forest and deforested catchments in the Kapuas Hulu headwaters of Indonesian Borneo. Deforested catchments produced 94% more annual runoff and 210% more sediment than forested counterparts receiving the same rainfall. Peak flows were 2.3 times larger and arrived nearly two hours sooner, creating a flashier and more erosive regime.

The findings add field-calibrated evidence linking tropical deforestation with downstream flood amplification and water quality decline. Oil palm plantations showed a worse hydrological footprint than selectively logged forest, likely

due to soil compaction from terracing and roads. These results are relevant to land-use planning in West Kalimantan, where the Kapuas River supplies water to more than two million people.

Restoring riparian buffer strips and enforcing best-management practices on plantation roads are practical steps that could reduce runoff and sediment delivery without requiring full reforestation. Longer-term monitoring and inclusion of bedload measurements would strengthen future assessments.

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