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LAND USE AND HYDROENVIRONMENTAL RESPONSES IN AMAZONIAN WATERSHEDS: A SYSTEMATIC REVIEW FOCUSED ON PARÁ

USO DA TERRA E RESPOSTAS HIDROAMBIENTAIS EM BACIAS AMAZÔNICAS: REVISÃO SISTEMÁTICA COM FOCO NO PARÁ

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ABSTRACT
Land-use and land-cover changes alter water and sediment fluxes in tropical watersheds. This systematic review synthesized studies published from 2020 to 2025 on landscape transformation, riparian integrity, and hydroenvironmental responses, with a focus on Pará. Reporting of the selection process followed PRISMA 2020, and screening was organized in Rayyan. A total of 110 records were identified, four duplicates were removed, 106 titles, 26 abstracts, and six full texts were assessed, resulting in four included studies. The corpus covered Mato Grosso, the Gurupi River watershed, Rondônia, and Santarém, Pará. Direct evidence concentrated on the association between deforestation and hydroenvironmental fragility and between low riparian integrity and water-quality changes. Morphometric and hydrosedimentological studies added physical controls but did not isolate causal land-use effects. The small evidence base, heterogeneous designs, and the original geographic orientation of the search toward Pará limit regional generalization. The synthesis supports integrating riparian conservation, land-cover control, and hydrosedimentological monitoring, while highlighting the need for comparable studies and denser observations within the state.
Keywords: Deforestation. Sediments. Riparian vegetation. Water quality. Environmental fragility.

RESUMO
Alterações no uso e cobertura da terra modificam fluxos de água e sedimentos em bacias tropicais. Esta revisão sistemática sintetizou estudos publicados entre 2020 e 2025 sobre transformação da paisagem, integridade ripária e respostas hidroambientais, com foco no Pará. O relato do processo de seleção seguiu o PRISMA 2020, e a triagem foi organizada no Rayyan. Foram identificados 110 registros, removidas quatro duplicatas, avaliados 106 títulos, 26 resumos e seis textos completos, resultando em quatro estudos incluídos. O corpus abrangeu Mato Grosso, a bacia do rio Gurupi, Rondônia e Santarém, Pará. A evidência direta concentrou-se na associação entre desmatamento e fragilidade hidroambiental e entre baixa integridade ripária e alterações da qualidade da água. Estudos morfométricos e hidrossedimentológicos acrescentaram condicionantes físicos, mas não isolaram efeitos causais do uso da terra. O pequeno número de estudos, a heterogeneidade dos delineamentos e a orientação geográfica original da busca para o Pará limitam a generalização regional. A síntese sustenta a integração entre conservação ripária, controle das mudanças de cobertura e monitoramento hidrossedimentológico, mas evidencia a necessidade de estudos comparáveis e maior densidade de observações no estado.
Palavras-chave: Desmatamento. Sedimentos. Vegetação ripária. Qualidade da água. Fragilidade ambiental.

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1 INTRODUCTION

Conversion of forests to pasture, cropland, and urban areas changes how precipitation is partitioned among evapotranspiration, storage, infiltration, and runoff. It affects not only water volumes but also the seasonal distribution of flows that sustain tropical systems (D'Acunha et al., 2024; Chagas; Chaffe; Blöschl, 2022). In the Amazon, these effects extend beyond the converted area: forest loss disrupts moisture recycling and has been associated with reduced rainfall at regional scales, with consequences even for the productivity of agricultural landscapes (Leite-Filho et al., 2021; Cui et al., 2026).

The system, however, does not respond as a homogeneous surface. Shallow groundwater buffers some of the variability in discharge, and the precipitation response to deforestation varies across seasons and spatial scales. Consequently, the same percentage of forest loss can produce different hydrological signals depending on the physical and

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climatic setting (Bagheri et al., 2024; Qin et al., 2025). Attribution is equally complex for sediment dynamics: global observations and continental modeling indicate that deforestation, dams, and changes in precipitation can either increase or decrease sediment fluxes, depending on the location of the disturbance and the connectivity of the river system (Dethier; Renshaw; Magilligan, 2022; Fagundes et al., 2023).

The ecological consequences of this reorganization extend beyond streamflow. The integrity of Amazonian aquatic ecosystems depends on hydrological connectivity and on maintaining processes operating from the channel to the watershed scale. Meanwhile, global freshwater biodiversity loss has reached levels that cannot be adequately assessed using isolated physical variables alone (Castello; Macedo, 2016; Sayer et al., 2025). In eastern Amazonian streams, land-use patterns influence fish assemblage organization and may result in species absences even when observed richness appears largely unchanged, demonstrating why ecological responses should not be reduced to a single indicator (Lobato et al., 2022; Cantanhêde et al., 2023).

Official monitoring reported 5,731 km² of deforestation in the Brazilian Legal Amazon in 2025, and local analyses in Pará show that agricultural expansion follows distinct conversion pathways, including the replacement of pasture with cropland in already-established agricultural areas. This requires distinguishing the opening of new agricultural frontiers from intensification of existing land use (INPE, 2026; Conceição et al., 2025). This distinction also matters hydrologically: monitoring of eight small watersheds in the Cerrado–Amazon transition found that a higher proportion of deforestation was associated with higher annual and daily streamflow, greater seasonality, and more intense flood peaks, while reducing dry-season baseflow. Thus, land-cover conversion alters both water volumes and the temporal distribution of flows (Almada et al., 2026).

The scientific challenge, therefore, is not merely to demonstrate that landscapes matter, but to identify which responses were actually measured, at what scale, and to what extent they can be attributed to land use. To address this gap, this systematic review critically synthesized literature published from 2020 to 2025 on land use, land cover, and hydroenvironmental responses in watersheds of the Brazilian Amazon, with a focus on Pará, distinguishing direct evidence of associations, morphometric controls, and inferences supported by external literature.

2 MATERIALS AND METHODS

2.1 REVIEW DESIGN AND RESEARCH QUESTION

A systematic review with qualitative synthesis was conducted and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses 2020 (PRISMA 2020), used as a transparency guideline for study identification, screening, eligibility assessment, and inclusion (Page et al., 2021). Records were organized and screened using Rayyan, a platform for managing titles, abstracts, duplicates, and eligibility decisions (Ouzzani et al., 2016). The research question was: How are changes in land use, land cover, and riparian vegetation integrity associated with hydrological, hydrosedimentological, and water-quality responses in Amazonian watersheds, considering studies retrieved through a search strategy focused on Pará?

The PECO framework was adapted to the environmental scope of the review. The population or context comprised watersheds, subwatersheds, small watersheds, and streams in the Brazilian Amazon; exposure included land-use and land-cover change, deforestation, anthropogenic disturbance, or riparian degradation; comparators, where available, were gradients in vegetation cover, integrity, or land use; and outcomes included streamflow, runoff, sediments, erosion, hydroenvironmental fragility, drainage

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characteristics, and water-quality parameters. Morphometric or hydrosedimentological studies without an explicit land-use contrast were retained only when they provided physical controls directly relevant to interpreting responses within the evidence base.

2.2 INFORMATION SOURCES AND SEARCH STRATEGY

The publication period covered 2020 through 2025. The preserved review documentation recorded searches of Scopus, Springer Nature Link, PubMed, the Journals Portal of the Brazilian Coordination for the Improvement of Higher Education Personnel (CAPES), the Directory of Open Access Journals (DOAJ), JSTOR, and the Scientific Electronic Library Online (SciELO). The quantitative selection record contained 108 results from Scopus and two from Springer Nature Link, with no additional records from the other sources. These were treated as information sources rather than equivalent databases: Scopus was the principal bibliographic retrieval source, whereas Springer Nature Link served as a supplementary publisher platform. The documentation did not reliably preserve the exact date of each search; therefore, those dates were not retrospectively reconstructed. Search string: ("land use change" OR "land-use change" OR "land cover change" OR "land-use and land-cover change" OR "land use" OR "land cover" OR desmatamento OR "mudança de uso da terra" OR "mudanças de uso da terra" OR "cobertura da terra" OR "uso e cobertura da terra") AND ("hydrological regime" OR streamflow OR "river discharge" OR runoff OR "water yield" OR "flow regime" OR "hydrologic response" OR "regime hidrológico" OR vazão OR escoamento OR "resposta hidrológica") AND ("small catchment*" OR "headwater stream*" OR microbacia* OR "bacia de cabeceira" OR "small watershed*" OR "headwater basin*") AND (Pará OR "Para State" OR "State of Pará" OR "estado do Pará"). The syntax was adapted to each source's search functionality while retaining the four conceptual blocks. Because the final evidence base contained studies from other parts of the Brazilian Amazon, these were retained as comparative evidence, and the scope of the synthesis was made explicit without changing the recorded counts in the selection process.

2.3 ELIGIBILITY CRITERIA

Eligible studies were peer-reviewed articles published within the specified period, available in full text for assessment, conducted in the Brazilian Amazon, and reporting extractable data at the watershed, subwatershed, small-watershed, or watercourse scale. Studies had to link land use, land cover, deforestation, riparian integrity, or landscape condition to at least one hydrological or hydroenvironmental outcome, or provide morphometric or hydrosedimentological characterization essential to interpreting the sensitivity of a hydrographic unit. Field studies, time-series analyses, remote sensing, geospatial analysis, and hydroenvironmental modeling were eligible.

Studies were excluded if they were conducted outside the Brazilian Amazon without a directly comparable component, lacked assessable full text, were theses, dissertations, undergraduate monographs, or gray literature as the primary evidence base, were reviews without primary data, were exclusively laboratory-based, or lacked a clear connection to inland drainage systems. Records were also excluded when outcomes could not be extracted or when land use was mentioned only incidentally, without relevant hydroenvironmental or structural information.

2.4 STUDY SELECTION, DATA EXTRACTION, AND SYNTHESIS

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After records were imported into Rayyan, four duplicates were removed. Titles and abstracts were then screened, followed by full-text assessment of potentially eligible studies. The extracted information comprised publication year, authorship, location, hydrographic unit, study design, variables, methods, main findings, and contributions to an integrated interpretation. Heterogeneity in spatial scales, metrics, and designs precluded meta-analysis or calculation of a common effect size. Accordingly, the qualitative synthesis distinguished findings directly associated with land use from morphometric or hydrosedimentological controls. The numerical consistency of the selection process was checked before final drafting: 110 records identified, four duplicates removed, 80 excluded at title screening, 20 excluded at abstract screening, two excluded after full-text review, and four studies included. No formal risk-of-bias or methodological quality assessment instrument was applied, a limitation considered when interpreting the strength of the evidence. Publications outside the included evidence base, including studies from 2026 consulted during drafting, were used only for conceptual context and comparison in the introduction and discussion; they were not included in study selection and did not alter the synthesis of the four included studies.

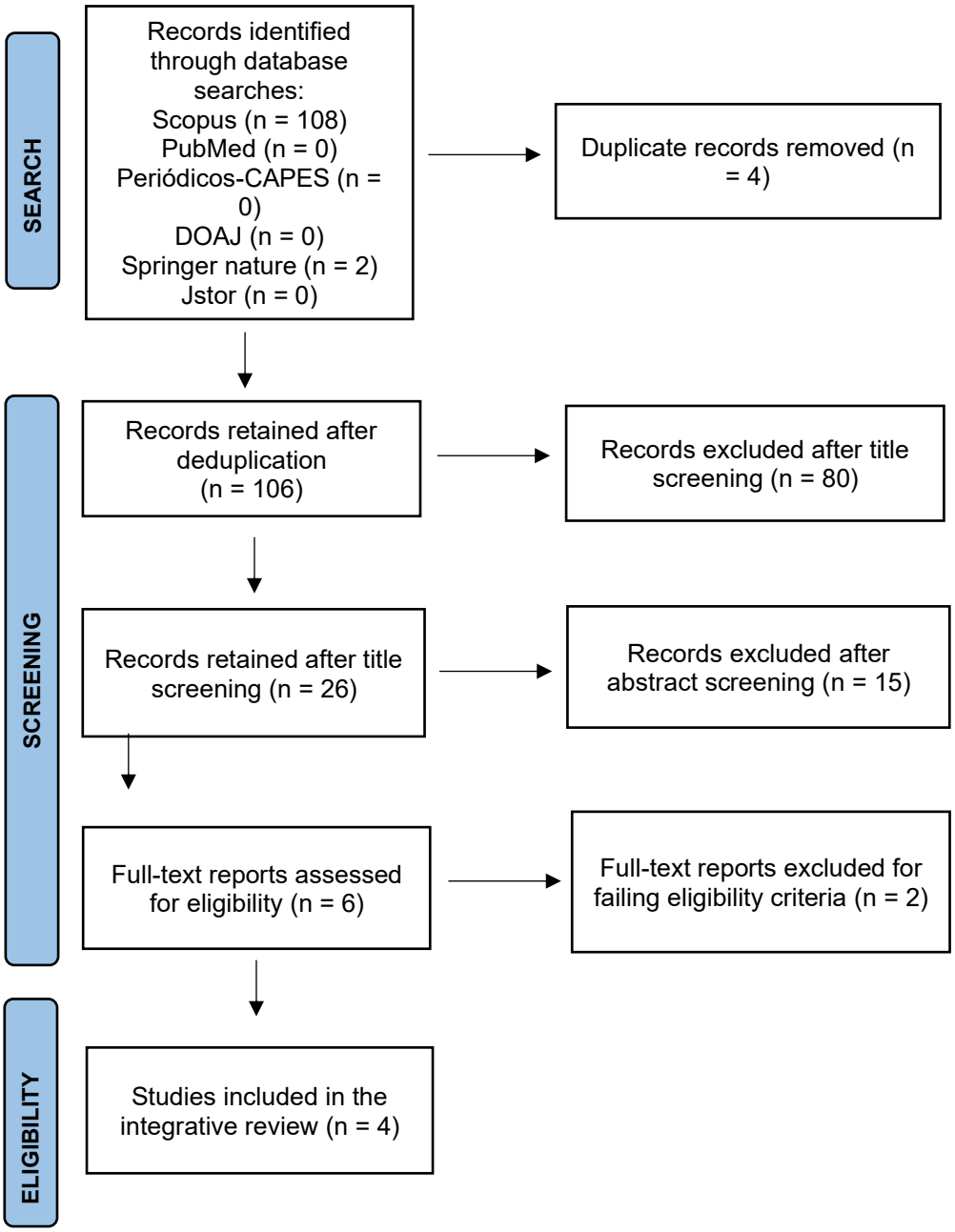
3 RESULTS

3.1 STUDY SELECTION

The searches identified 110 records, including 108 from Scopus and two from Springer Nature Link. Four duplicates were removed, leaving 106 records for title screening; 80 were excluded at that stage. Of the 26 abstracts assessed, 20 failed to meet the eligibility criteria, leaving six full texts for eligibility assessment. Two were excluded after full-text review, and four studies were included in the qualitative synthesis (Figure 1). Table 1 summarizes the analytical characteristics of the four included studies.

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Figure 1 - PRISMA flow diagram showing study identification, screening, eligibility assessment, and inclusion.



Source: Prepared by the authors using the PRISMA 2020 flow and data from the present review.

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Table 1 - Characteristics of studies included in the systematic review.

ID	Year	Study	Lead authors	Area/environment	Study design	Variables	Methods	Main findings	Integrative interpretation
E1	2024	Morphometry, Water Availability and Sediment Transport in the River Renato Watershed, Southern Amazon	Almeida; Souza; Borella; Castagna; Garcia; Alves; Zolin	Renato River watershed, middle Teles Pires, Mato Grosso	Hydrosedimentological monitoring and morphometry	Water level, discharge, suspended and bedload sediments, topography, drainage	Monthly measurements; rating curves; QGIS	Elongated shape, regular drainage, and low morphometric flood susceptibility; satisfactory fit for water discharge and weaker fit for sediment discharge	Structural and hydrosedimentological evidence. The study describes a landscape with approximately 69% natural vegetation but does not isolate a causal land-use effect.
E2	2023	Influence of climatic phenomena and deforestation on hydroenvironmental fragility, Gurupi River watershed, Northern Brazil	Gomes; Beltrão; Lima	Gurupi River watershed, northern Brazil	Spatial scenario analysis	Precipitation, deforestation, drainage, slope, soils, geomorphology, and geology	CHIRPS, MapBiomas, and official datasets; AHP; geospatial analysis	Deforestation increased during the study period; scenarios combining extreme rainfall, greater land conversion, and natural controls produced greater hydroenvironmental fragility	Direct evidence of an association among deforestation, climate, and fragility, without reducing the response to a single driver.
E3	2021	Caracterização morfométrica da Sub-bacia do Rio Ribeirão, Amazônia Ocidental, Brasil	Marinho; Vendruscolo; Vasconcelos; Cavalheiro; Stachiw	Nova Mamoré and Porto Velho, Rondônia	Morphometric characterization	Geometry, elevation, slope, stream order, drainage and stream densities, time of concentration	QGIS, TauDEM, and SRTM	50 small watersheds; dendritic drainage; predominantly flat to gently rolling terrain; principal units elongated and of low flood susceptibility	Structural evidence. Defines physical controls needed to distinguish land-use signals from morphometric predisposition.

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ID	Year	Study	Lead authors	Area/environment	Study design	Variables	Methods	Main findings	Integrative interpretation
E4	2022	Efeitos da integridade ambiental da zona ciliar e sua influência na qualidade da água de igarapés urbanos em Santarém-PA, Amazônia, Brasil	Santos; Mortati; Canani; Oliveira	Six urban streams, Santarém, Pará	Ecological observational study	Habitat integrity, vegetation cover, discharge, width, depth, pH, conductivity, dissolved oxygen, turbidity, and temperature	Habitat Integrity Index; hydrological and physicochemical measurements; correlations and between-site comparisons	Five degraded streams; habitat integrity significantly correlated with dissolved oxygen and conductivity	Direct evidence concerning riparian degradation and water quality in an urban Amazonian setting.

Source: Prepared by the authors based on the four studies included in the review.

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3.2 CHARACTERISTICS OF INCLUDED STUDIES

The four included studies were published between 2021 and 2024 and represented different parts of the Amazon region. To distinguish direct evidence from contributions describing physical controls, they are designated E1 through E4 in Table 1: E1 examined the Renato River watershed in the middle Teles Pires region of Mato Grosso; E2 assessed hydroenvironmental fragility in the Gurupi River watershed; E3 characterized the Ribeirão River subwatershed in Rondônia; and E4 investigated six urban streams in Santarém, Pará. This distribution confirms that the evidence base does not support a review restricted to Pará and does not consist exclusively of small watersheds.

The most direct evidence linking landscape transformation to hydroenvironmental responses came from E2 and E4. In E2, increasing deforestation, combined with years of extreme precipitation and geoenvironmental controls, was associated with scenarios of greater fragility. In E4, five of six streams were classified as degraded, and the Habitat Integrity Index was significantly correlated with dissolved oxygen and conductivity. Although these studies measured different relationships, both linked landscape condition to observable hydroenvironmental outcomes.

E1 and E3 provided complementary evidence without independently testing land-use causality. E1 described an elongated watershed, regular drainage, and low morphometric susceptibility to extreme flooding; discharge rating curves performed better than sediment-discharge estimates, indicating greater uncertainty in the sediment component. E3 delineated 50 small watersheds with dendritic drainage, predominantly flat to gently rolling terrain, and low morphometric flood susceptibility in the principal units. In both cases, morphometry defines physical controls that must be considered before attributing hydrological variation exclusively to land cover.

3.3 INTEGRATIVE SYNTHESIS

The synthesis identifies two levels of evidence. E2 and E4 explicitly linked landscape condition, deforestation, or riparian integrity to hydroenvironmental outcomes; E1 and E3 provided morphometric and hydrosedimentological controls needed to interpret the sensitivity of hydrographic units. This distinction was retained because treating all four studies as if they supported the same causal relationship would overstate the evidence provided by their study designs.

There was insufficient common evidence to estimate a pooled effect on infiltration, surface runoff, streamflow, or sediment export. Among the four included studies, the review also found no directly comparable time series that would permit statistical separation of forest-loss effects from those of precipitation, topography, drainage networks, and antecedent conditions. The results therefore support an interpretation of increasing hydroenvironmental sensitivity under landscape degradation, but not a single or universal response magnitude for Amazonian watersheds.

4 DISCUSSION

The synthesis does not support a simplistic interpretation in which less forest automatically and uniformly leads to more runoff, greater sediment transport, and poorer water quality. In the Gurupi watershed, Gomes, Beltrão, and Lima (2023) identified hydroenvironmental fragility shaped by interactions among deforestation, extreme precipitation, and geoenvironmental characteristics. In Santarém, Santos et al. (2022) documented a different, more localized signal, in which loss of riparian-zone integrity accompanied changes in dissolved oxygen and conductivity. Both studies demonstrate the

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importance of landscape condition, but they do not measure the same process and therefore cannot establish a single causal pathway for Amazonian watersheds.

Watershed physical structure provides a second filter for interpretation. In the Ribeirão River subwatershed, Marinho et al. (2021) showed that shape, terrain, drainage density, and time of concentration define hydrological susceptibility even before any change can be attributed to land use. This does not diminish the importance of forest cover; rather, it requires its effects to be placed within the appropriate mechanism. Recent models suggest that feedback between forest loss and moisture recycling may reduce Amazonian climate stability at lower warming levels than estimated when deforestation feedback is ignored, whereas fluvial sediment responses may emerge rapidly in heavily disturbed areas, with their magnitude depending on system connectivity (Wunderling et al., 2026; Narayanan; Cohen; Gardner, 2024). The percentage of deforestation alone is therefore an inadequate descriptor: where conversion occurs, how water and sediments connect to the channel, and which surface and subsurface stores buffer the resulting pulse also matter.

Hydrosedimentology is particularly vulnerable to oversimplified interpretations. In the Renato River watershed, Almeida et al. (2024) obtained a more consistent fit for water discharge than for sediment discharge, highlighting the difficulty of representing sediment transport with the same confidence as hydraulic variables. At broader scales, trends in sediment concentration and flux reflect drivers that may act in opposite directions; on the Amazon floodplain, deposition depends jointly on inundation, suspended sediment concentration, and hydrodynamics (Sun et al., 2025; Feng et al., 2025). Uncertainty in sediment discharge is not a minor statistical detail: it affects the very variable commonly used to infer erosion and material transfer, calling for finer temporal resolution and more rigorous sediment-budget closure.

In riparian areas, the management implications are more direct and more demanding. Ecological thresholds may be crossed following relatively small losses of vegetation, and the effectiveness of tropical riparian buffers depends on their width, continuity, and habitat quality rather than a uniform buffer distance applied regardless of context (Dala-Corte et al., 2020; Luke et al., 2019). In the eastern Amazon, macroinvertebrate changes have been detected after small forest losses, while fish studies show that protecting only the immediate stream margin is insufficient when watershed-scale pressures persist (Brito et al., 2020; Leal et al., 2018). Brazil's Forest Code provides an essential legal basis for Permanent Preservation Areas, but mapped regulatory compliance should not be equated with effective hydroecological functioning (Brasil, 2012).

Water quality also has dimensions that cannot be captured by assessments focused solely on discharge and sediments. Global projections indicate that riverine nitrogen loads remain strongly dependent on fertilizer use and socioeconomic pathways, whereas phosphorus transport is being reshaped by fertilizers, dams, and deforestation, with substantial relative increases in small rivers and the Southern Hemisphere (Lee et al., 2024; Liu et al., 2025). In the Amazon, conversion from forest to pasture also alters physical stream structure and reduces functional dimensions of fish assemblages, reinforcing the need to assess hydrological and ecological conditions together (Cantanhêde et al., 2021).

The limitations of this review must remain explicit. Four studies, only one of which was conducted entirely within Pará, cannot establish a region-wide effect magnitude, and heterogeneity among physicochemical correlations, hydroenvironmental fragility analyses, morphometry, and rating curves precludes any defensible quantitative synthesis. The original geographic focus of the search on Pará, the absence of exact search dates, and the lack of a formal risk-of-bias assessment weaken the strength of inference. These constraints do not invalidate the findings, but they prevent them from being presented as a consensus for the entire Amazon. The most important methodological advance would be to combine synchronous time series of land cover, discharge, sediments, groundwater, and water

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quality in designs that control for rainfall, morphometry, and the location of land conversion. Without such controls, additional correlations may improve diagnosis but remain insufficient to estimate causality or management thresholds.

5 CONCLUSIONS

The four included studies associate deforestation with increased hydroenvironmental fragility and reduced riparian integrity with changes in water quality. Morphometric and hydrosedimentological findings provide relevant physical context but do not establish land-use causality.

Differences in study design and geography, the Pará-focused search strategy, and the absence of formal risk-of-bias assessment preclude regional generalization. The findings support riparian protection, land-cover management, and integrated water and sediment monitoring, while highlighting the need for comparable studies in Pará.

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