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Attributing Climate vs. Land-Cover Effects on Watershed Hydrology and Water Quality: A Systematic Review of Modeling and Statistical Frameworks

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ABSTRACT

Climate change and land-use/land-cover (LULC) dynamics jointly reshape watershed hydrology and water quality, yet their relative contributions remain difficult to isolate across regions, indicators, and methods. This systematic review synthesizes 28 peer-reviewed studies (2000–2025) that explicitly attribute or partition climate and LULC effects on streamflow, water yield, evapotranspiration, baseflow, and multiple water-quality indicators (e.g., nutrients, sediments, dissolved organic matter, salinity/alkalinity, and contaminant mixtures). Studies were grouped into four synthesis themes: (i) conceptualizations and study designs, (ii) process-based and hybrid modeling frameworks, (iii) statistical and decomposition approaches, and (iv) cross-context patterns and water-quality attribution. Across the evidence base, attribution outcomes are strongly conditioned by methodological choices—especially baseline definition, construction of climate-only and LULC-only counterfactuals, spatial and temporal scale, and the metric used to express contributions (e.g., scenario contrasts, sensitivities, or variance explained). Long-term water-balance responses are often attributed primarily to climate forcing, while water-quality outcomes are more frequently attributed to LULC and direct anthropogenic pressures, with climate acting as a key modulator of transport pathways and exposure. We conclude that robust climate–LULC attribution requires explicit counterfactual design, integrated use of process-based and data-driven frameworks, explicit representation of interactions, and routine uncertainty analysis to support context-sensitive watershed management and climate adaptation.

Keywords: *Climate Change Attribution, Land-Use/Land-Cover Change, Watershed Hydrology, Water Quality, Hydrological Modeling, Statistical Decomposition, Environmental Management*

1. INTRODUCTION

Climate variability and anthropogenic climate change alter watershed water balance through shifts in precipitation patterns, temperature, and extremes, while land-use/land-cover (LULC) change modifies infiltration capacity, evapotranspiration, hydrologic connectivity, and pollutant sources. In many basins these drivers occur simultaneously and interact, making it hard to identify which management levers are most effective for maintaining water availability and protecting water quality.

Attribution studies attempt to separate the contributions of climate and LULC to observed or modeled changes by comparing counterfactual scenarios (e.g., changing climate with fixed land cover, and changing land cover with fixed climate) or by using statistical decompositions of observed variability. The literature spans diverse endpoints, from water-supply metrics and evapotranspiration under urban expansion [1], [2] to nutrient and sediment dynamics in stormwater systems [3] and contaminant mixtures linked to biological decline in urban watersheds [4].

However, reported dominance of climate versus LULC is often inconsistent across studies. One reason is that attribution results depend on how studies define baselines, represent LULC change (e.g., land-cover states, management practices, or infrastructure interventions), and quantify contributions (e.g., percent change, elasticity, or variance explained). A clear synthesis of these methodological choices is needed to interpret apparently conflicting findings and to guide future study design.

This review synthesizes peer-reviewed studies that explicitly partition climate and LULC effects on watershed hydrology and water quality. The objectives are to: (1) classify the main attribution frameworks used across hydrological and water-quality applications; (2) summarize how study design and model structure influence attribution outcomes; (3) identify emerging patterns for water quantity versus water quality across contexts; and (4) distill methodological priorities that can improve robustness and decision relevance.

2. METHODS

This review followed a structured evidence-synthesis workflow designed to be transparent and reproducible. Searches targeted studies that quantitatively separate or attribute the effects of climate variability/change and LULC dynamics on watershed hydrology and/or water quality.

Search strategy and eligibility. Literature searches were conducted in Scopus and Web of Science, complemented by Google Scholar to capture interdisciplinary outlets. Search strings combined terms related to climate (e.g., climate change, precipitation, temperature), LULC (e.g., land use, land cover, urbanization, agriculture, deforestation), hydrology (e.g., streamflow, runoff, water yield, baseflow, evapotranspiration), water quality (e.g., nutrients, sediment, dissolved organic carbon/nitrogen, salinity), and attribution (e.g., attribution, partitioning, relative contribution). Studies published between 2000 and 2025 were screened.

Inclusion criteria required (i) catchment or basin-scale focus; (ii) explicit attempt to separate climate and LULC effects using scenario-based modeling, statistical decomposition, or comparable attribution logic; and (iii) sufficient reporting detail to extract drivers, response variables, and attribution metrics. Non-quantitative commentaries and studies addressing only climate or only LULC without partitioning were excluded.

Screening and synthesis. Titles/abstracts were screened, followed by full-text assessment against eligibility criteria. For included articles, information was extracted on study context, response variables, climate and LULC drivers, attribution framework, scenario/counterfactual design, and reported conclusions about driver dominance. The final evidence base comprised 28 studies, which were synthesized using a thematic approach aligned with four recurring clusters in the literature: study designs, process-based/hybrid modeling, statistical/decomposition methods, and cross-context patterns for hydrology and water quality.

Quality considerations. Rather than applying a single numerical score, appraisal focused on: data adequacy and representativeness; model calibration/validation or statistical diagnostics; clarity of counterfactual design and treatment of confounding; and uncertainty reporting (e.g., sensitivity analysis, ensemble approaches, or explicit limitations). These considerations were used to contextualize findings rather than to exclude studies.

3. RESULTS AND DISCUSSION

3.1 Study Designs and Conceptual Framing

Across the 28 studies, attribution was embedded in varied conceptual designs, ranging from long-term experiments and comparative observational gradients to scenario-based planning and threshold analyses. Several studies foregrounded land-use and management as the main intervention lever and treated climate as an external backdrop, for example hotspot targeting of agricultural conservation [5], urban-development thresholds for aquatic biodiversity [6], and landscape naturalness or conservation-priority indexing [7], [8].

Other studies explicitly varied both climate and land-use trajectories through scenario ensembles, allowing stronger inference about combined and interacting effects. For instance, socio-environmental scenario modeling in an urban–coastal watershed demonstrated that land-use patterns can strongly mediate how climate pathways translate into ecosystem services and equity outcomes [9]. Regional gradient studies also highlighted mediation mechanisms such as riparian condition linking watershed development to water quality and fish communities across many subbasins [10].

Overall, the evidence indicates that attribution outcomes are sensitive to design choices: if climate is not explicitly varied, land-use effects may appear dominant by construction; conversely, designs driven by climate-scenario forcing may emphasize climatic control on long-term water balance.

Table 1. Synthesis themes and representative approaches in the reviewed literature.

Theme	Common attribution approaches	Representative studies (examples)
Design and framing	Experiments; spatial gradients; scenario-based planning; threshold analyses	[5], [6], [9], [10]
Process-based and hybrid modeling	Counterfactual hydrological simulations; hybrid land–water–ecosystem models; Bayesian networks	[11]–[14]
Statistical and decomposition methods	Regression and variance partitioning; machine learning; spatiotemporal models; scenario-based projections	[8], [15]–[17]
Patterns and context dependence	Cross-context comparisons of driver dominance; focus on pollutant sources vs transport modulation	[3], [4], [13], [18]

3.2 Process-Based and Hybrid Modeling

Process-based and hybrid models were used to simulate counterfactual worlds in which climate and land cover are systematically held fixed or varied. Explicit climate-only versus LULC-only partitioning was clearest in studies that ran paired counterfactual simulations, such as water-supply attribution in the Blue Nile source region [12].

Hybrid frameworks also featured prominently. Bayesian network modeling provided probabilistic attribution of watershed development and climate change effects on stream ecosystems, capturing nonlinear dependencies and interactions [19]. Land-cover projection models (e.g., CA–Markov) were used to generate spatially explicit LULC scenarios intended for subsequent coupling with hydrological or ecosystem models [20].

Several modeling studies focused on how land-cover change modifies hydrologic fluxes and ecosystem trade-offs under a climatic envelope, including combined urbanization and climate effects on evapotranspiration [1]and national-scale carbon–water trade-offs under urban expansion [2]. Forest-cover scenarios were used to assess the safeguarding role of native forest in maintaining stream water quality under changing climate [11].

3.3 Statistical and decomposition approaches

Statistical and decomposition approaches attributed climate and LULC contributions directly from observed patterns and covariates, often emphasizing variance partitioning, regression coefficients, or scenario contrasts. Spatiotemporal statistical models linked dissolved organic carbon dynamics in cropland streams to farming practices and hydroclimatic drivers [16].

Machine-learning approaches were applied at national scales to separate human versus natural influences on freshwater salinization and alkalinization, leveraging large predictor sets that include climate, geologic controls, and land-use indicators [8]. Trend and multivariate analyses were used to relate climate variability and human pressures to shifts in nitrogen yields in large Arctic rivers [15].

Scenario-based statistical projections extended attribution to ecological endpoints, such as functional reorganization of fish assemblages under global change [17]. In socio-environmental applications, interaction-focused regression linked ecosystem service values to meteorological and socioeconomic factors across contrasting geomorphic contexts [21].

3.4 Patterns for hydrology and water quality

A recurring contrast emerged between water quantity and water quality. For long-term runoff, water yield, and evapotranspiration, studies more frequently reported strong climatic control, especially when attribution was anchored in climate-scenario forcing or climate-sensitive process representations [1], [12].

By contrast, water-quality studies more often identified LULC and direct anthropogenic pressures as the primary sources of impairment. Urban-catchment analyses showed that land-use type and configuration strongly control nutrient and sediment build-up and wash-off, with storms acting as triggering events rather than the main source driver [3]. Chemical profiling linked biological decline in stormwater-impacted urban watersheds to complex contaminant mixtures associated with roads and urban land use [4].

Intervention-oriented studies suggested that land management can buffer or amplify hydroclimatic stress. Balancing upland green infrastructure with stream restoration was shown to influence stormwater and nitrate retention in urban systems [18], while native forest cover was associated with improved stream water quality under changing climate [11]. In rapidly changing basins, land-cover conversion was frequently linked to ecosystem and water-quality degradation, with climate variability noted as a compounding factor [13], [22].

Context dependence was ubiquitous: the same climate forcing can yield different outcomes depending on soils, relief, infrastructure, and governance, and similar land-use changes can have different hydrologic and water-quality effects across hydroclimatic regions (e.g., [23], [24]).

Discussion

Why attribution results diverge

Across methods, attribution results diverge most strongly when counterfactual design is asymmetric. If a study varies land cover or management extensively while representing climate as a fixed backdrop, land-use effects tend to dominate by construction. Conversely, scenario designs that emphasize climatic forcing with static land cover often highlight climatic control of long-term water balance. Balanced climate-only and LULC-only experiments, as well as probabilistic intervention frameworks, offer clearer interpretation but are less common than one-sided scenario contrasts [12], [19].

Metric choice also matters. Percent-change partitions based on scenario contrasts can mask interaction effects, while variance-based measures in statistical and machine-learning studies may attribute importance to correlated predictors without reflecting mechanistic causality [8]. Spatiotemporal statistical models improve realism by recognizing dependence structures but still require careful treatment of confounding and nonlinearity [16].

Implications for watershed management and adaptation

The contrast between water quantity and water quality has practical consequences. Many water-quality outcomes are tightly linked to source strength and connectivity created by LULC (e.g., impervious cover, agricultural practices, industrial emissions), suggesting that land management and infrastructure interventions can deliver near-term improvements even under unfavorable climate trajectories [3], [4], [18]. At the same time, climate-driven changes in storm intensity, seasonality, and drought can amplify or undermine these interventions by altering mobilization and dilution regimes.

Evidence from forest-cover and green-infrastructure studies indicates that protective land covers and nature-based solutions can function as buffers, but their effectiveness is context dependent and sensitive to placement, scale, and local hydrologic connectivity [11], [18]. In rapidly transforming basins, land conversion can outpace institutional capacity, increasing the risk that climate variability compounds degradation (Desta and Fetene, 2020; Maruthi Sridhar et al., 2020).

Research priorities

Based on recurring limitations across the evidence base, four priorities emerge for future climate–LULC attribution studies:

(1) Explicit and symmetric counterfactuals: design paired climate-only and LULC-only experiments that share comparable baselines and time horizons.
(2) Interaction-aware attribution: quantify climate–LULC interactions instead of assuming additivity; consider mediation pathways (e.g., land cover buffering climate impacts).
(3) Multi-framework triangulation: combine process-based simulations with statistical or probabilistic attribution to test robustness across assumptions.
(4) Routine uncertainty analysis: propagate uncertainty from data, parameters, and model structure to reported driver contributions, and report limitations transparently.

These priorities are intended to improve comparability across studies and to strengthen the use of attribution evidence in watershed management and climate adaptation.

4. CONCLUSION

This systematic review synthesized 28 studies that attribute climate and LULC contributions to changes in watershed hydrology and water quality. Two consistent patterns emerged: (i) long-term water-balance responses are frequently attributed primarily to climate forcing, particularly in studies driven by climate-scenario or climate-sensitive process modeling; and (ii) water-quality degradation is more often attributed to LULC and direct anthropogenic pressures, with climate acting mainly as a modulator of transport and exposure. However, these patterns are not universal and are strongly conditioned by study design, scale, counterfactual construction, and attribution metrics.

To support decision-making, future work should prioritize explicit counterfactuals, interaction-aware attribution, and comprehensive uncertainty reporting, while integrating process-based and data-driven evidence to produce context-sensitive guidance for water-resource management.

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