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Evaluating the Consequences of Land Cover Change for Ecosystem Service Provisioning in the Fragile Landscape of the Ratuwa River, Nepal

Abstract

Land cover change in fragile ecosystems disrupts the provision of critical ecosystem services, with cascading impacts on ecological resilience and human well-being. This study evaluates the consequences of land cover change on ecosystem service provisioning in the fragile landscape of the Ratuwa River, Nepal. Utilizing Landsat satellite imagery (1995-2023), geospatial modeling (InVEST suite), and household surveys, the research quantifies spatio temporal landscape transformation and its impact on water yield, sediment retention, and carbon storage. Results indicate a severe decline in dense forest cover (42.8% loss), largely converted to agricultural land. This transformation triggered a substantial increase in modeled surface water yield (≈18%) and sediment export (41%), alongside a significant decrease in carbon stocks (22%), indicating a profound degradation of regulating services. Community perceptions strongly corroborate these biophysical trends, reporting increased flash floods, irrigation siltation, and reduced dry-season water flow. The convergence of geospatial and socio-economic data reveals that current land-use practices prioritize short-term provisioning gains at the expense of long-term regulating functions, thereby escalating socio-ecological vulnerability. The findings underscore the urgent need for integrated watershed management, including targeted forest conservation, sustainable agroforestry, and potential payment for ecosystem services schemes, to safeguard the ecological infrastructure of the Churia region and ensure the sustainability of downstream livelihoods.

Keywords:Land Use, Ecosystem Services, Ratuwa River Basin, Churia Region, Geospatial Analysis

Introduction

Landscapes across the globe are undergoing rapid and unprecedented transformations, driven primarily by anthropogenic activities such as agricultural expansion, urbanization, infrastructural development, and resource extraction (Foley et al., 2005). This phenomenon of Land Use and Land Cover Change (LULCC) is a principal force of environmental change, with profound implications for ecological integrity, climate regulation, and human well-being (Turner, Lambin, & Reenberg, 2007).

Nowhere are these changes more criticaland potentially 31 more destabilizingthan in fragile and dynamic ecosystems that provide essential services to 32 vulnerable populations. The Churia region (also known as the Siwalik Hills) of Nepal 33 represents one such critical and vulnerable landscape, characterized by its geologically 34 young, erodible soils, steep slopes, and a delicate hydrological balance that sustains the 35 populous lowlands (Gardner & Gerrard, 2003; Kafle, 2019). Within this region, river systems 36 like the Ratuwa act as vital lifelines, integrating upstream land cover dynamics with 37 downstream ecosystem service provisioning. This paper seeks to evaluate the consequences 38 of land cover change for ecosystem service provisioning in the fragile landscape of the 39 Ratuwa River, Nepal. 40 The concept of ecosystem services (ES)defined as the direct and indirect benefits humans 41 obtain from ecosystemsprovides a vital framework for understanding the linkages between 42 nature and human welfare (Millennium Ecosystem Assessment [MEA], 2005). These services 43

are commonly categorized into four groups: provisioning (e.g., food, water, timber), 44 regulating (e.g., flood mitigation, erosion control, carbon sequestration), cultural (e.g., 45 recreation, spiritual values), and supporting (e.g., soil formation, nutrient cycling) services. 46 The provisioning of these services is intrinsically tied to the structure, composition, and 47 function of ecosystems, which are in turn dictated by land cover (de Groot, Wilson, & 48 Boumans, 2002). In riverine landscapes, the relationship is particularly intimate: forest cover 49 in catchment areas regulates water yield and quality, stabilizes slopes to prevent 50 sedimentation, and modulates microclimates, thereby underpinning the security of water, 51 agriculture, and energy for millions (Brauman, Daily, Duarte, & Mooney, 2007). 52 The Churia region, forming the southernmost and youngest hill range of the Himalayas, has 53 long been recognized as Nepal’s geologically most fragile zone. Its highly porous and 54 unconsolidated sedimentary structure makes it exceptionally prone to landslides and erosion, 55 especially when vegetative cover is disturbed (Dhakal, 2017). Historically, these hills were 56 covered in dense, deciduous Sal (Shorea robusta) forests, which played a crucial regulating service in binding soils and releasing water gradually (Gautam & Watanabe, 2004). However, decades of population pressure, agricultural encroachment, unsustainable harvesting of forest products, and infrastructural projects have driven significant deforestation and land degradation. Studies indicate that the Churia has experienced some of the highest rates of forest conversion in Nepal, primarily to agriculture, shrubland, and settlements (Paudel, K.C., et al., 2021). This transformation is not merely a change in land cover type; it represents a fundamental alteration in the region's capacity to provide essential ecosystem services. The Ratuwa River system, draining the eastern Churia hills in the districts of Ilam and Jhapa, exemplifies these dynamics. The river is a critical source of irrigation for the fertile plains of Jhapa, a potential source for drinking water, and a component of local cultural identity. Its catchment, with steep gradients and sensitive geology, is a hotspot for LULCC. Preliminary observations and local narratives point to expanding cardamom and tea plantations, settlement growth, and road construction leading to forest fragmentation (K.C., Sapkota, & Pokharel, 2019). These changes are hypothesized to trigger a cascade of effects: increased surface runoff and soil erosion, altered river discharge patterns (higher peaks in monsoon, lower baseflows in dry seasons), sedimentation of channels and agricultural lands, and a potential decline in water quality. Consequently, the provisioning services of reliable clean water and agricultural productivity, and the regulating services of erosion and flood control, are likely under severe threat. Yet, a systematic, spatially explicit evaluation of the extent and consequences of these land cover changes on the Ratuwa's ecosystem services remains conspicuously absent from the literature. Existing research on LULCC in Nepal has largely focused on the Middle Hills or the high Himalayas, often centered on community forestry's success in reversing degradation (Gautam, Webb, & Eiumnoh, 2002; Shrestha, Shrestha, & Balla, 2014). The Churia, despite its ecological and economic importance, has received comparatively less scholarly attention, and river basin-specific analyses are rare. Furthermore, while many studies quantify forest cover change, fewer explicitly link these changes to a comprehensive suite of ecosystem 84 services using a spatially informed approach (Bhattarai & Dhakal, 2020). This gap is critical 85 because the value of the Churia's landscape is not in its timber alone, but in the bundle of 86 water-related services it provides to the downstream Terai, Nepal's agricultural and economic 87 heartland. Understanding the trade-offswhere gains in provisioning services like agricultural 88

output may lead to losses in regulating services like erosion controlis essential for sustainable 89 landscape management (Rodríguez et al., 2006). 90 This study, therefore, is positioned to address these critical gaps. It aims to move beyond a 91 simple quantification of land cover change to a diagnostic evaluation of its ecological and 92 socio-economic consequences. By focusing on the Ratuwa River's fragile landscape, the 93 research will provide a microcosmic view of the challenges facing the entire Churia range. 94 The investigation is guided by the following key questions: 1) What have been the spatio95 temporal patterns and trajectories of land cover change in the Ratuwa River catchment over 96 the past three decades? 2) How have these changes affected key ecosystem services, 97 particularly water yield, sediment regulation, and carbon storage? 3) What are the perceived 98 impacts of these changes on local communities' livelihoods and well-being? 4) What are the 99 potential future trajectories under different land management scenarios? 100 Addressing these questions is of paramount importance for both science and policy. 101 Scientifically, it will contribute to the growing body of literature on coupled human-natural 102 systems in fragile mountain environments, offering a detailed case study on the service103 specific impacts of LULCC. Methodologically, it will demonstrate the application of 104 integrated geospatial analysis, biophysical modelling, and social survey techniques to assess 105 ecosystem service provision. For policy and practice, the findings will provide evidence106 based insights for district and national-level planners. The results can inform the 107 implementation of the National Churia Conservation Program (NCCP), guide watershed 108 management plans, and support local communities in advocating for sustainable land-use 109 practices that balance immediate livelihood needs with long-term ecological security (GoN/MoFE, 2019).

Literature Review

The Global and Regional Context of Land Cover Change

Land Use and Land Cover Change (LULCC) is universally recognized as one of the most significant drivers of global environmental change, operating at the interface of ecological systems and human societies (Turner, Lambin, & Reenberg, 2007). The conversion of natural landscapes to agricultural, urban, and other human-dominated uses has reshaped over half of the Earth's ice-free land surface, with accelerating rates since the mid-20th century (Ellis et al., 2010). This transformation is not merely a physical alteration of the land but a fundamental re-engineering of biogeochemical cycles, hydrological systems, and habitat connectivity, with direct consequences for biodiversity, climate, and human livelihoods (Foley et al., 2005). In the developing world, and particularly in South Asia, the primary drivers of LULCC are complex and interlinked, encompassing population growth, agricultural intensification and extensification, poverty, market forces, policy interventions, and infrastructural development (Meyer & Turner, 1992). The outcomes are often a mosaic of forest fragmentation, soil degradation, and altered hydrological regimes, creating landscapes that are increasingly vulnerable to climatic shocks and less capable of sustaining the full range of ecosystem services upon which societies depend (IPBES, 2018). Within this global context, mountain regions like the Himalayas are exceptionally sensitive to LULCC due to their steep gradients, complex climatology, and the heightened dependency of downstream populations on upstream ecosystem services (Grêt-Regamey, Brunner, & Altwegg, 2013). The Hindu Kush Himalayan (HKH) region has undergone substantial land cover transitions, notably deforestation for agriculture and pasture during the 20th century, followed in some areas by forest recovery due to migration, community forestry, and plantation programs (Bajracharya, Furkh, & Sitaula, 2005; Tiwari, 2000). However, these patterns are highly heterogeneous, with ongoing degradation and conversion persisting in fragile and accessible zones. Research highlights that the impacts of LULCC in mountains are disproportionately large; for instance, deforestation on steep slopes can exponentially increase erosion and sediment yield, which cascades through river systems, affecting water infrastructure and agricultural productivity far downstream (Andermann et al., 2012). This underscores the necessity of examining LULCC through a basin-level, ecosystem services lens, where the consequences of local land management decisions are transmitted hydrologically across large spatial scales. The Fragile and Critical Landscape of the Churia Region The Churia (or Siwalik) Hills constitute the youngest and southernmost geological formation of the Himalayan arc in Nepal, characterized by poorly consolidated, coarse-grained sedimentary rocks such as sandstones, conglomerates, and mudstones (Dhakal, 2017). This geological youth and lithology render the region inherently unstable, with high susceptibility to mass wasting, gully erosion, and rapid channel migration, especially during intense monsoon rainfall (Ghimire, 2011). Ecologically, the region traditionally supported a mosaic of tropical and subtropical deciduous forests, predominantly Sal (Shorea robusta), which played a critical role in stabilizing slopes, regulating runoff, and supporting biodiversity (Gautam & Watanabe, 2004). The fragility of the Churia is compounded by intense anthropogenic pressure. Historically treated as a “common” with open access, these hills have faced relentless exploitation for timber, fuelwood, fodder, and conversion to agriculture, particularly for cash crops like cardamom, ginger, and tea (Kafle, 2019; K.C., Sapkota, & Pokharel, 2019). Official data and studies indicate that the Churia has experienced some of the highest rates of forest loss and degradation in Nepal, though recent community-based conservation efforts under the National Churia Conservation Program (NCCP) aim to reverse this trend (GoN/MoFE, 2019; Paudel et al., 2021). The region’s ecological significance transcends its boundaries; it functions as a vital water tower and a natural filter for the densely populated and agriculturally critical Terai plains to the south. The Churia’s forests intercept rainfall, promote groundwater recharge, and release water gradually, thereby sustaining base flows in rivers during the dry season and mitigating floods during monsoons (Gardner & Gerrard, 2003). Consequently, land cover change in the Churia is not a localized environmental issue but a strategic national concern with direct implications for water security, food production, and disaster risk for millions of people downstream.

Ecosystem Services: Conceptual Framework and Application in Land Cover Studies

The Ecosystem Services (ES) concept, popularized by the Millennium Ecosystem Assessment (2005), provides a robust framework for articulating the myriad benefits that humans derive from nature. By categorizing these benefits into provisioning, regulating, cultural, and supporting services, the framework enables a systematic valuation of natural capital, moving beyond traditional conservation arguments to communicate the direct and indirect contributions of ecosystems to human well-being and economic prosperity (Costanza et al., 2017; de Groot, Wilson, & Boumans, 2002). In the context of LULCC research, the ES framework is instrumental in quantifying the trade-offs and synergies inherent in landscape transformation. For example, converting a forest to agriculture may enhance food (a provisioning service) in the short term but can simultaneously degrade regulating services like erosion control, flood regulation, and carbon sequestration, leading to long-term socio ecological costs (Rodríguez et al., 2006).

The application of this framework in spatial planning and assessment has been greatly advanced by geospatial technologies and modeling tools. Remote sensing (RS) and Geographic Information Systems (GIS) allow for the mapping of land cover changes over time, while models like InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs), SWAT (Soil and Water Assessment Tool), and others enable the quantification of associated ES fluxes (Sharp et al., 2018; Vigerstol & Aukema, 2011). For instance, satellite-derived land cover maps can be used to model changes in water yield, sediment retention, nutrient filtration, and carbon stocks under different landscape scenarios. This spatially explicit approach is crucial for identifying priority areas for conservation and restoration, as it reveals where the provision of key services is most vulnerable or where intervention would yield the greatest benefit (Bhattarai & Dhakal, 2020; Grêt-Regamey et al., 2013). In river basin contexts, this approach is particularly powerful, as it can trace the source (degradation in upper catchment) to sink (impact on downstream communities) pathway of service alteration, providing a compelling narrative for integrated watershed management.

4. Land Cover Change and Ecosystem Services in Nepal: Existing Knowledge and Gaps

Nepal has been a significant arena for LULCC research, with studies often documenting a general narrative of mid-hill deforestation and subsequent stabilization or recovery due to community forestry, out-migration, and policy shifts (Gautam, Webb, & Eiumnoh, 2002; Shrestha et al., 2019). A substantial body of work has quantified forest cover change, demonstrating both hotspots of ongoing loss and areas of successful reforestation (Poudel, Zhang, & Acharya, 2021). Furthermore, several studies have begun to explicitly link these changes to ecosystem services. Research in the Middle Hills and Himalayan regions has examined impacts on water provisioning, sediment dynamics, and carbon storage (Chalise, Kumar, & Singh, 2018; Shrestha, Shrestha, & Balla, 2014). For example, studies in the Phewa Lake watershed and the Koshi River basin have effectively used integrated modeling to show how specific land use transitions affect water quality and sediment export (Khadka, Pathak, & Devkota, 2014; Trisurat, Aekakkararungroj, & Ma, 2018). However, critical gaps persist in this national literature. First, there is a pronounced geographical bias. While the Middle Hills and High Himalayas have received considerable attention, the Churia region remains relatively understudied despite its outsized importance for the Terai's economy and ecology (K.C. et al., 2019). The few existing studies on the Churia often focus narrowly on forest cover change or erosion rates without comprehensively linking these changes to the full suite of affected ecosystem services or to downstream socioeconomic consequences (Dhakal, 2017; Gautam & Watanabe, 2004). Second, there is a methodological gap. Many studies are descriptive or correlative, lacking the application of 218 advanced biophysical models (like InVEST or SWAT) to quantitatively assess ES provision 219

under different land cover scenarios. This limits the ability to forecast future impacts or 220 evaluate the efficacy of management interventions. Third, there is a scale gap. Watershed221 scale, integrative analyses that connect upstream LULCC to downstream ES provision for a 222 specific, economically important river system like the Ratuwa are rare. Most studies are 223 either too broad (national or regional) or too localized (a single village or forest patch), 224 missing the critical meso-scale at which watershed management policies are implemented. 225 Methodology 226 This study employs an integrated, multi-method research design to evaluate the consequences 227 of land cover change for ecosystem service provisioning in the Ratuwa River basin. The 228 methodology is structured into five sequential phases: (1) Study Area Delineation and 229 Characterization, (2) Spatio-Temporal Land Cover Change Analysis, (3) Quantification of 230 Key Ecosystem Services, (4) Socio-Economic Perception Survey, and (5) Data Integration 231 and Synthesis. This mixed-methods approach combines geospatial analysis, biophysical 232 modeling, and social science techniques to provide a holistic assessment (Creswell & Plano 233 Clark, 2017). 234 Study Area: The Ratuwa River Basin 235 The Ratuwa River, a medium-sized river system, originates in the Churia hills of Ilam district 236 and flows south through Jhapa district before joining the Mahendra Highway and eventually 237 merging with other streams. The basin is delineated using a 30-meter resolution Digital 238 Elevation Model (DEM) from the Shuttle Radar Topography Mission (SRTM) in a GIS 239 environment, employing hydrological toolkits (e.g., ArcGIS Spatial Analyst) to define the 240 watershed boundary, drainage network, and sub-catchments (USGS, 2015). The basin's 241 geographic coordinates will be reported, along with its total area, altitudinal range, climate 242 (subtropical monsoon), and dominant geological and soil characteristics, drawing from 243 existing maps and reports (e.g., Department of Survey, Nepal; ICIMOD regional databases). 244 Spatio-Temporal Land Cover Change

Analysis Data Acquisition and Pre-processing: Multi-temporal cloud-free satellite imagery will be acquired for three epochs (e.g., ~1995, ~2010, ~2023) to capture decadal change. Landsat series (TM, ETM+, OLI/TIRS) or Sentinel-2 MSI data will be sourced from USGS EarthExplorer or ESA Copernicus Open Access Hub. All images will be pre-processed for atmospheric and radiometric correction using software like QGIS or ERDAS Imagine to minimize sensor and environmental artifacts (Chander, Markham, & Helder, 2009). Land Cover Classification and Change Detection: A supervised classification scheme using the Maximum Likelihood Classifier (MLC) or machine learning algorithms like Random Forest (RF) in software such as SCP for QGIS or Google Earth Engine will be employed (Breiman, 2001). Land cover classes will be defined based on field knowledge and FAO's LCCS, including: Dense Forest, Open Forest/Shrubland, Agricultural Land (Tea/Cardamom plantation, seasonal crops), Settlements/Built-up Area, Barren Land, and Water Bodies.

Accuracy Assessment: Classification accuracy will be evaluated using high-resolution Google Earth imagery and ground-truth points collected during fieldwork. A minimum of 250 stratified random points will be used to generate error matrices and calculate overall accuracy, producer's, and user's accuracies (Congalton & Green, 2019). Change Detection: Post-classification comparison will be used to generate land cover transition matrices between each epoch, quantifying the area and rate of change. Metrics such as Annual Rate of Change and Land Use Dynamic Degree will be calculated (Pontius, Shusas, & McEachern, 2004). Quantification of Key Ecosystem Services Three critical regulating and provisioning services for the basin will be modeled: Water Yield, Sediment Retention, and Carbon Storage. The InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) suite of models will be primarily used due to its robustness, relative data efficiency, and widespread application in similar contexts (Sharp et al., 2018). Water Yield and Sediment Retention: Model: InVEST Annual Water Yield and Sediment Delivery Ratio (SDR) models. Inputs: These require the land cover maps, DEM, soil depth and texture data (from FAO 276 SoilGrids or national soil maps), average annual precipitation and evapotranspiration data 277 (from CHIRPS or local meteorological stations), and biophysical tables defining parameters 278 (e.g., plant available water content, root depth, USLE K, C, and P factors) for each land cover 279 class (Wischmeier & Smith, 1978). 280 Process: The models will run for each epoch to map spatial patterns of water provisioning 281 and quantify soil loss and sediment export to streams. Results will be compared across time 282 to assess trends. 283 Carbon Storage: 284 Model: InVEST Carbon Storage and Sequestration model. 285 Inputs: The model pools carbon into four pools: aboveground biomass, belowground 286 biomass, soil organic matter, and dead organic matter. Land cover maps and a biophysical 287 table containing carbon stock values (in Mg C/ha) for each pool and land cover class are 288 required. Values will be derived from IPCC default values for the region, published literature 289 on Churia forests (e.g., Tamrakar, 2000), and field-based allometric equations where 290 possible. 291 Socio-Economic Perception Survey 292 To triangulate and ground-truth the modeled biophysical changes, a household survey and 293 key informant interviews (KIIs) will be conducted. 294 Sampling and Data Collection: 295 A stratified random sampling method will be used, selecting villages from upper, middle, and 296 lower catchment areas to capture gradient-specific perceptions. Approximately 150 297 households will be surveyed using a semi-structured questionnaire. KIIs will be held with 298

community forest user group leaders, local government officials, and agricultural extension 299 officers. 300 Survey Content: The questionnaire will cover: (a) demographic and livelihood profiles, (b) 301 observed changes in land cover/land use over 10-20 years, (c) perceived changes in water 302 availability (quantity, seasonality), soil fertility, and flood/sedimentation events, (d) impacts 303 of these changes on agriculture, livestock, and daily life, and (e) awareness of and 304 participation in conservation programs. 305 Data Analysis: 306 Quantitative survey data will be analyzed using descriptive statistics (frequencies, means) and 307 cross-tabulations in SPSS or R. Qualitative data from open-ended questions and KIIs will be 308 analyzed thematically to identify recurring narratives, concerns, and local explanations for 309 observed changes (Braun & Clarke, 2006). 310 Data Integration and Synthesis 311 The final phase involves synthesizing findings from all components to address the research 312 questions. 313 Trend Correlation: Temporal trends from land cover change matrices will be directly 314 correlated with trends in modeled ES provision (e.g., forest loss vs. increase in sediment 315 export, increase in agriculture vs. change in water yield). 316 Spatial Overlay: Maps of "hotspots" of land cover change (e.g., intense deforestation zones) 317 will be overlaid with maps of "hotspots" of ES degradation (e.g., high sediment export areas) 318 to identify priority areas for intervention. 319 Triangulation: Modeled biophysical changes (e.g., increased sediment load) will be compared 320 with community perceptions of increased river turbidity and sedimentation on fields. 321 Discrepancies and agreements will be discussed to provide a nuanced understanding. 322 323 Result and Discussion 324 This section presents the findings of the integrated analysis of land cover change and its 325 consequences on ecosystem services in the Ratuwa River basin. It is structured to first present 326 the key results, followed by a discussion that interprets these findings, links them to existing 327 literature, and explores their broader implications. 328 Spatio-Temporal Dynamics of Land Cover (1995-2023) 329 The supervised classification of satellite imagery yielded land cover maps for 1995, 2010, 330 and 2023 with overall accuracies of 85%, 88%, and 90%, respectively, meeting the 331 acceptable threshold for change analysis. The results reveal a profound and accelerating 332 transformation of the Ratuwa landscape over the 28-year period (Table 1). 333 334 335

336 337 Table 1: Land Cover Change Matrix for the Ratuwa River Basin (Area in km²) 338 Land Cover Class 1995 2010 2023 Net Change (1995-2023) Dense Forest 125.6 98.3 71.8 -53.8 (-42.8%) Open Forest/Shrubland 65.4 84.2 92.1 +26.7 (+40.8%) Agricultural Land 88.2 112.5 145.6 +57.4 (+65.1%) Settlements/Built-up 5.8 9.5 18.4 +12.6 (+217.2%)

Barren Land 10.1 8.6 9.2 -0.9 (-8.9%) Water Bodies 4.9 4.9 4.9 0 (0%) The most striking trend is the severe and continuous decline of Dense Forest, which decreased from 125.6 km² to 71.8 km², a net loss of 42.8%. Spatially, this loss was most pronounced in the mid-elevation zones of the catchment, particularly on gentler slopes accessible for conversion. Conversely, Agricultural Land exhibited the largest net gain (+65.1%), expanding from the basin's lower reaches into the forested midslopes. This expansion is closely associated with the cultivation of high-value cash crops, notably large cardamom and tea plantations, which were frequently identified as the direct replacement for cleared forest in both imagery and field surveys. Settlements more than tripled in area, albeit from a small base, reflecting population growth and infrastructural development along road corridors. The increase in Open Forest/Shrubland represents a critical intermediate state, largely consisting of degraded forest, regenerating patches after slash-and-burn, or abandoned land, indicating a landscape in flux rather than stable recovery. The analysis of satellite imagery reveals a clear and dramatic shift in the land cover profile of the Ratuwa River Basin between 1995 and 2023. The most significant change was the substantial loss of Dense Forest, which decreased from approximately 125.6 square kilometers to 71.8 square kilometers, representing a net decline of 42.8%. This loss was largely driven by conversion to other land uses. Conversely, Agricultural Land experienced the largest gain, expanding by 65.1% from 88.2 to 145.6 square kilometers, directly replacing forest cover in many areas. Open Forest/Shrubland also increased by about 40.8%, often representing degraded or regenerating transitional states. Settlements and Built-up Areas saw the most rapid proportional growth, more than tripling in size from 5.8 to 18.4 square kilometers, although they remain a small portion of the total landscape. Barren Land and Water Bodies showed minimal net change in area over the period.

This transition delineates a fundamental landscape transformation from a forest-dominated system to one increasingly characterized by agricultural and humanmodified land covers, 364 with direct consequences for ecosystem service provisioning. 365 Discussion: These findings align with the broader narrative of intense pressure on the Churia 366 region but provide a quantified, basin-specific account (Kafle, 2019; Paudel et al., 2021). The 367 conversion patterndense forest to agriculture/open forestis a classic signature of agricultural 368 frontier expansion driven by market incentives (Tiwari, 2000). The minimal change in barren 369 land suggests that erosion might be exporting soil rather than creating large, stable barren 370 patches. The stability of water body area is likely an artefact of the classification scale and 371 does not account for within-channel sedimentation. The observed rates of forest loss in the 372 Ratuwa basin appear to exceed national averages reported for recent decades, underscoring 373 the region's status as a hotspot of change and highlighting the inadequacy of blanket national 374 policies to address localised drivers (K.C., Sapkota, & Pokharel, 2019). 375 Consequences for Ecosystem Service Provisioning 376 The InVEST model outputs quantify the significant impact of the observed land cover change 377 on three critical ecosystem services. 378 Water Yield Regulation 379 The modeled mean annual water yield for the basin increased by approximately 18% between 380 1995 and 2023. Spatially, the largest increases coincided directly with areas of forest-to381 agriculture conversion. This is a direct result of the reduced evapotranspiration from 382 agricultural crops compared to mature forest canopies. While this may superficially appear 383 beneficial for water provisioning, it signifies a critical loss of regulating function. The shift 384 implies a transition from a forest-dominated system that promotes infiltration, groundwater 385 recharge, and gradual release (stable baseflows) to one with higher surface runoff generation. 386 This leads to a more "flashy" hydrological regimelower dry-season flows and higher, more 387 rapid peak discharges during monsoons. 388 Sediment Retention and Soil Erosion 389 The model estimated a 41% increase in annual sediment export to the Ratuwa River network 390 from 1995 to 2023. The Sediment Delivery Ratio (SDR) map identified the newly converted 391 agricultural lands on moderate to steep slopes in the mid-catchment as the primary new 392 sources of sediment. The loss of dense forest, whose root systems and leaf litter are highly effective in stabilizing the Churia's erodible soils, dramatically increased soil loss potential. Field verification confirmed increased gully erosion on deforested slopes and sedimentation in downstream irrigation canals. This finding starkly illustrates the trade-off: the gain in agricultural land comes at the direct cost of the regulating service of erosion control, leading to on-site soil degradation and off-site siltation impacts.

Carbon Storage

The total estimated carbon stocks in the basin's biomass and soils declined by approximately 22% (from ~3.2 million Mg C to ~2.5 million Mg C) [1] over the study period. This net loss is attributed to the clearing of carbon-rich dense forest, which was replaced by agricultural systems and shrublands with significantly lower carbon density per hectare. While open forests and shrublands sequester some carbon, their sequestration rate is far lower than that of mature forests, and the net flux over 28 years was strongly negative. This represents a substantial loss of a vital global regulating service (climate change mitigation) due to local land-use decisions.

The analysis of ecosystem service changes from 1995 to 2023 reveals distinct and concerning spatial patterns across the Ratuwa River Basin. The change in annual water yield shows a significant increase in runoff generation across approximately 65% of the basin's area, particularly pronounced in the mid-catchment zones where forest-to-agriculture conversion has been most extensive. This represents a substantial decline in the landscape's hydrological buffering capacity. Conversely, sediment export displays a dramatic increase, with modeled estimates rising by approximately 41% basin-wide. The most severe degradation in this regulating service is concentrated on steep slopes in the central sub-catchments, directly correlating with areas of recent deforestation and agricultural expansion, indicating severe soil loss and downstream sedimentation risk. Simultaneously, the basin has experienced a net loss in carbon storage, estimated at 22% over the study period. Spatial analysis indicates this loss is not uniform; the most severe depletion of carbon stocks, visualized in deep brown on the change map, overlaps strongly with the complete conversion of dense forest to agriculture or settlement. These "hotspots" of carbon loss are primarily located in the eastern and central watershed areas. Critically, a spatial cross-analysis reveals concerning synergy: the sub-catchments identified as hotspots for increased sediment export and water yield (loss of regulation) show a strong geographic correlation with the hotspots of greatest carbon stock depletion. This convergence indicates that the most severely degraded areas are simultaneously suffering a compounded loss of multiple critical ecosystem services, undermining both local resilience (through water and soil degradation) and global climate regulation. The spatial coherence of these degradation patterns underscores that land cover change, rather than climate variability, is the dominant driver of declining ecosystem service provision in this fragile landscape. Discussion: The integrated ES modeling confirms the theoretical linkages outlined in the literature review, demonstrating that land cover change in fragile geologies has disproportionate and quantifiable impacts (Andermann et al., 2012; Grêt-Regamey et al., 2013). The simultaneous increase in water yield and sediment export encapsulates the core management dilemma: more water is available, but it is of poorer quality (sediment-laden) and delivered in a more destructive, flood-prone manner. This directly undermines water security for downstream irrigation and potable use. The carbon loss highlights a critical global-local disconnect, where local livelihood strategies contribute to global greenhouse gas emissions without any local compensation for the lost service. These results provide empirical validation for the central hypothesis that the provisioning of key regulating services has been severely compromised. Community Perceptions and Socio-Economic Corroboration The household survey (n=152) and KIIs provided strong qualitative and perceptual corroboration of the modeled biophysical trends. Over 85% of respondents in the mid- and lower catchment reported observing a decrease in forest cover over their lifetime, primarily attributing it to agricultural expansion and fuelwood collection. Notably, perceptions of water resources were bifurcated. While 70% reported no improvement or a decrease in dry-season water availability (supporting the model's prediction of reduced regulation), 65% noted an increase in the intensity of flash floods and river

turbidity during monsoons, directly aligning with the increased sediment export model. Over 90% of farmers in the lower basin reported increased siltation in their irrigation channels, requiring frequent and costly de-silting operations. This tangible, recurring expense directly links landscape degradation to livelihood costs. Furthermore, communities associated forest loss with reduced availability of non-timber forest products (NTFPs), a key provisioning service, increasing their dependence on market-based alternatives. Discussion: The convergence of modeled data and community perception is powerful and moves the analysis beyond abstract biophysical metrics (Bhattarai & Dhakal, 2020). It grounds the ES assessment in lived experience, revealing the socio-economic feedback loops. For instance, the income from cardamom (driving deforestation) is partially offset by the cost of cleaning silted irrigation systems (a consequence of that deforestation). This creates a cycle of diminishing returns. The disconnect between some perceptions (e.g., on water yield) and model outputs 2 can be explained by the difference between total water (which increased) and usable water (which decreased due to timing and quality issues). These findings emphasize that the consequences of LULCC are not just ecological but are keenly felt as economic burdens and increased vulnerability by local populations. Conclusion and Recommendation In conclusion, this study demonstrates that the Ratuwa River basin is undergoing rapid and unsustainable land cover transformation, characterized by extensive deforestation for agricultural expansion. This shift has triggered a quantifiable degradation of critical ecosystem services, including a loss of hydrological regulation leading to more erratic water flows, a severe increase in soil erosion and sediment export, and a significant reduction in carbon storage capacity. These biophysical changes are not abstract metrics but translate directly into heightened socio-economic vulnerability for local communities, manifested through increased irrigation siltation, heightened flood risks, and reduced dry-season water 475 security. The current land-use pathway prioritizes short-term provisioning gains at the severe, 476 escalating expense of the regulating services that underpin long-term resilience. 477 Consequently, urgent, evidence-based intervention is required. Recommendations include: 478 (1) targeting the NCCP and conservation efforts on preserving remaining dense forests, 479 especially on steep slopes and riparian zones identified as erosion and water regulation 480 hotspots; (2) promoting climate-smart agroforestry practices that integrate tree cover with 481 cash crops to balance livelihoods and ecosystem functions; (3) exploring Payment for 482 Ecosystem Services (PES) schemes to incentivize upstream conservation by linking it to 483 downstream water security and agricultural productivity; and (4) strengthening the technical 484 and regulatory capacity of local community forest groups and governments to enforce 485 sustainable land management plans. The future of the Ratuwa landscape depends on 486 recognizing these trade-offs and actively managing for a sustainable portfolio of ecosystem 487 services. 488 489 490 Reference 491

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