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From Deforestation to Resilience: Pathways for Sustainable Community Development in Ratuwa River Basin Nepal

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ABSTRACT

The Churia region of Nepal represents one of the most ecologically fragile landscapes in the Himalayan foothills, providing critical ecosystem services including water regulation, soil conservation, carbon sequestration, and biodiversity habitat. This study examined land cover alterations and their effects on ecosystem services in the Ratuwa River System from 1990 to 2025, employing an integrated approach combining remote sensing analysis, ecosystem service modeling using InVEST and RUSLE, hydrological modeling with SWAT, and socio-economic surveys with 300 households. Findings reveal significant land cover transformations: forest cover declined by 35%, wetlands by 20%, while agricultural land expanded by 25% and settlements more than doubled. These changes severely degraded water regulation services with a 40% increase in surface runoff, 30% reduction in groundwater recharge, and 50% rise in flood frequency. Soil erosion increased from 18.7 to 32.4 t ha^{-1} $year^{-1}$, with agriculture contributing 76.5% of total soil loss. Carbon storage declined by 30.5% from 12.8 to 8.9 million tons, and habitat quality decreased from 0.72 to 0.51. Communities face declining agricultural yields, water scarcity, and heightened flood vulnerability, with marginalized households disproportionately affected. While community-led restoration demonstrates promise, long-term sustainability requires sustained institutional support. The study concludes that an integrated landscape governance framework prioritizing forest restoration, sustainable agriculture, and community engagement is essential for building resilience and achieving sustainable development in Nepal's Churia region.

Keywords: Land cover change, ecosystem services, Ratuwa River Basin, Churia region, sustainable development

INTRODUCTION

The Churia region of Nepal represents one of the most ecologically fragile yet socio-economically significant landscapes in the Himalayan foothills. Covering approximately 12.76% of Nepal's total land area, this region serves as a critical transition zone between the Himalayan mountains and the Terai plains, regulating hydrological flows, recharging groundwater, and sustaining biodiversity across multiple ecosystems [23, 27]. Composed of sandstone, mudstone, and shale, the Churia hills form porous alluvial and colluvial soils that are highly susceptible to erosion [22]. This geologically fragile landscape faces extreme human pressure from land conversion, infrastructure development, sand and boulder mining, and extraction of firewood and timber [12]. Combined with extreme rainfall, earthquakes, and porous geology, these pressures have made the Churia region highly vulnerable to floods, soil erosion, and landslides [19, 28]. The Churia hills provide critical ecosystem services, notably regulating surface water flows and recharging groundwater a main source of water for more than 14 million people inhabiting the downstream Terai plains [26, 20]. With the clearance of most forest areas in the Terai over the last century, the Churia hills are now the primary source of timber, fuelwood, fodder, and other forest products for both upland and downstream communities [1, 21].

Originating from the Siwalik foothills, the river traverses' forests, wetlands, agricultural plains, and rural settlements, supporting diverse flora and fauna with several endemic and threatened species [5, 16, 25]. The river system underpins subsistence and commercial livelihoods through agriculture, fishing, domestic water supply, and cultural practices, with fertile floodplains producing staple crops such as rice, maize, wheat, and vegetables [3, 4, 21].

Despite its importance, the Ratuwa basin has experienced rapid land cover changes over the past three decades. Research employing multi-temporal Landsat and Sentinel-2 imagery revealed that forest cover declined by 35% and wetlands by 20%, while agricultural land increased by 25% between 1990 and 2020 [14, 13]. These transformations fundamentally altered hydrological functioning, resulting in a 40% increase in surface runoff, a 30% reduction in groundwater recharge, and a 50% rise in flood frequency, with economic valuation indicating a 25% decline in water regulation service value [13]. Similar patterns across the broader Churia region show forest cover decreasing at 0.39% and riverine areas at 1.06% per year, while agricultural land and built-up areas expand at 1.13% and 4.18% per year respectively [14]. These changes are driven by deforestation, agricultural expansion, sand and gravel mining, infrastructure development, and urbanization [22, 12]. The Chure landscape suffers from logging, grazing, fuelwood collection, encroachment, forest fires, and excavation of boulders [23, 1], with intensified human activities primarily responsible for ecological imbalance [2, 27]. Climate change further exacerbates these dynamics through altered precipitation, increasing drought frequency, and extreme flood events [25, 11].

Land cover degradation has cascading impacts on ecosystem services sustaining biodiversity and human livelihoods [15, 6]. Local stakeholders have identified 42 forest-based ecosystem services: 16 provisioning, 15 regulating, and 11 cultural services [1]. Water regulation the most critical service has been severely compromised [19, 13]. Reduced forest cover diminishes water retention capacity, leading to increased flooding during monsoons and water scarcity during dry seasons, undermining agricultural productivity and food security [21, 20, 3, 12]. Forest-based ecosystem services play a vital role in improving livelihoods, the environment, and the economy, with priorities varying among users [7, 1]. Soil conservation services have also been significantly affected, with unsustainable farming on steep slopes accelerating erosion and sedimentation [28, 19, 12]. The fragile Churia geology, combined with forest loss, has intensified sediment deposition in rivers, degrading water quality and threatening aquatic biodiversity [26, 20]. The Terai, considered Nepal's granary, faces serious threat from siltation originating from the Churia hills due to deforestation and watershed degradation [26, 19]. Biodiversity conservation has been undermined by habitat fragmentation and loss of ecological connectivity, adversely affecting wildlife populations [27, 5]. Communities are experiencing declining agricultural yields, increasing water scarcity, and heightened flood risks, disproportionately affecting marginalized households [21, 12, 2, 4]. This degradation perpetuates a cycle of vulnerability, undermining livelihood security and constraining communities' capacity to invest in sustainable land management [7, 10].

Recognizing these challenges, national and international initiatives have promoted resilience-building approaches in the Churia region [20, 9]. The Government of Nepal established the President Chure-Terai Madhesh Conservation Development Board in 2014 for restoration and sustainable management [23, 20]. Community-led restoration initiatives have demonstrated promising outcomes, with a study in Phulbari, Dang District showing an 8.6% increase in forest cover over three decades and a 26.1% rise in restoration sites from 2015 to 2020 [8]. Sites with soil-water retention strategies significantly outperformed non-intervention areas [8]. Participatory forest restoration programs have contributed to forest recovery and improved ecosystem service provision [4, 23]. Synergistic outcomes emerged by integrating community choices, government support, and flexible donor aid [8].

Community forestry generates environmental services such as carbon sequestration, hydrological regulation, and landscape restoration as positive externalities [4, 11]. However, significant challenges remain, as effectiveness depends on institutional capacity, governance quality, and equitable benefit distribution [4, 22]. Donor-funded restoration initiatives face uncertain long-term sustainability, and locals fear gains may be lost once funding ends [8]. Restoration efforts must be integrated into government budgets with community involvement [9, 20]. Climate change compounds these challenges, requiring adaptive management approaches [25, 11]. Ecosystem-based adaptation is advocated as cost-effective and efficient, yet limited awareness exists among disaster risk reduction professionals and ecologists about linkages between ecosystem restoration and disaster risk reduction [20].

The Ratuwa River Basin presents a critical case for examining pathways from deforestation to resilience. Recent research has documented land cover change severity and hydrological implications [13, 14], yet comprehensive studies linking land cover dynamics to ecosystem service degradation and community-level outcomes remain limited [1, 27]. Assessments and quantification of ecosystem services in the Chure region are very limited [1, 20]. The Churia hills should be conserved for environmental services to the entire Terai region rather than for provisioning tangible forest products only [26, 19].

Numerous studies have documented significant land cover transformations across the Churia landscape over the past three decades. Research employing remote sensing and GIS techniques has revealed alarming rates of forest loss and land degradation. The drivers of these land cover changes are multifaceted and interconnected. The Chure landscape suffers severely from anthropogenic disturbances including logging, grazing, fuelwood collection, solid waste disposal, encroachment, forest fire, and excavation of sand, gravel, and boulders [1, 23]. Intensified human activities, particularly forest encroachment and deforestation, are mainly responsible for the ecological imbalance in the Chure region [2, 27]. Climate change, land-use transitions, and poorly planned road construction further compound these pressures, significantly impacting water quality and quantity. The excessive extraction of sand and boulders for construction is causing rapid degradation of the Chure region, leading to reduced infiltration and causing flash floods during the monsoon season, followed by water scarcity in the dry months [17].

Studies employing multi-temporal Landsat and Sentinel-2 imagery have documented that forest cover in the Ratuwa basin declined by 35% and wetlands by 20%, while agricultural land increased by 25% between 1990 and 2020 [13, 14]. Similar patterns across the broader Churia region show forest cover decreasing at 0.39% and riverine areas at 1.06% per year, while agricultural land and built-up areas expand at 1.13% and 4.18% per year respectively [14]. Research by Uddin et al. documented significant forest decline across the Hindu Kush Himalayan region from 1990 to 2010 [29]. The expansion of agricultural land and settlement areas reflects the intensive anthropogenic pressures that have been identified as primary drivers of land use transitions in Nepal's foothill regions [12, 21]. These changes are driven by deforestation, agricultural expansion, sand and gravel mining, infrastructure development, and urbanization [12, 22].

The Churia forests provide a wide array of ecosystem services that are critical to both local communities and downstream populations. More than 14 million people inhabiting the downstream Terai plains depend on water regulation and groundwater recharge services originating from the Churia hills [26, 20]. Local users and stakeholders in the Chure region have identified a total of 42 forest-based ecosystem services, including 16 provisioning, 15 regulating, and 11 cultural services [1]. However, land cover change has severely compromised these services. The economic valuation of water regulation services in the Ratuwa basin revealed a 25% overall decline in service value, with direct consequences for ecological stability and socio-economic resilience [13].

Water regulation the most critical service provided by the Churia forests has been severely compromised [19, 13]. Reduced forest cover diminishes water retention capacity, leading to increased flooding during monsoons and water scarcity during dry seasons, undermining agricultural productivity and food security [21, 20, 3, 12]. Forest-based ecosystem services play a vital role in improving livelihoods, the environment, and the economy, with priorities varying among users based on their proximity to forests and socio-economic status [1]. The disruption of hydrological cycles through deforestation reduces water availability for irrigation, drinking, and domestic use in the Terai region [26].

Soil conservation represents another critical ecosystem service under threat. The Churia hills, with their weakly consolidated rocks and thin soil cover, are particularly vulnerable to erosion [28]. Unsustainable land use practices, including farming on steep slopes without adequate conservation measures, have accelerated soil erosion and sedimentation [12, 28]. Deforestation and indiscriminate land clearance in the Chure Range contribute to soil erosion, leading to the loss of fertile topsoil and degradation of agricultural land in the Terai [19, 26]. The annual soil loss of approximately 3.69 million tons has severe implications for downstream sedimentation, water quality degradation, and loss of agricultural productivity in the Terai plains [13]. The Terai, considered the granary of Nepal, faces serious threat from siltation originating from the Churia hills due to deforestation and watershed degradation [26, 19].

Biodiversity conservation has also been undermined through habitat fragmentation and loss of ecological connectivity, adversely affecting wildlife populations dependent on forest ecosystems [27]. Habitat quality declined from a mean index of 0.72 in 1990 to 0.51 in 2025, with forest fragmentation increasing substantially as the number of forest patches rose from 347 to 892, while mean patch size decreased from 170 ha to 43 ha [13]. Carbon storage declined by 30.5% from 12.8 to 8.9 million tons, with forest areas experiencing the greatest absolute losses [13].

Despite the challenges, community-based forest management has emerged as a promising approach to addressing land degradation in the Churia region. Nepal has increased its forest cover from 29% in 1994 to over 46% in 2022, thanks largely to community-based forest management. Community forestry programs have been shown to dominate recent land greening amid climate change in Nepal, with forest management accounting for 40% of leaf area index temporal variability [4].

A study evaluating a donor-backed, community-led restoration initiative within Nepal's Terai Arc Landscape in the Churia Hills of Phulbari, Dang District, showed an 8.6% increase in forest cover over three decades, with a 26.1% rise in restoration experiment sites from 2015 to 2020 [8]. Sites with soil-water retention strategies significantly outperformed non-intervention areas, proving effective in reclaiming denuded slopes and conserving water in the face of climate change [8]. Participatory forest restoration programs, involving community forest user groups and buffer zone management committees, have contributed to forest recovery and improved ecosystem service provision in several areas [4, 23]. Synergistic outcomes emerged by integrating community choices, government support, and flexible donor aid [8]. Effective policy alignment enhanced ecosystem services, social capital, and ecological functions [8]. Studies have shown that community forestry not only reforests degraded land but also generates environmental services such as carbon sequestration, hydrological regulation, and landscape restoration as positive externalities [4, 11]. The Government of Nepal established the President Chure-Terai Madhesh Conservation Development Board in 2014 for restoration and sustainable management [23, 20].

However, significant challenges remain. Despite being part of over 30 international environmental agreements, Nepal's forest degradation rate exceeded 1.5% annually [17]. While donor-funded projects have initiated restoration activities, their long-term sustainability is uncertain, and locals fear that restoration gains may be lost once funding ends [8]. Restoration efforts must be integrated into government annual budgets and plans to ensure lasting success, with community involvement to promote shared responsibility and ownership [9, 20]. The effectiveness of community forestry and restoration programs depends heavily on institutional capacity, governance quality, and the equitable distribution of benefits [4, 22]. Moreover, the impacts of climate change including increasing frequency of extreme weather events and shifting agricultural suitability compound these challenges, requiring adaptive management approaches that can respond to evolving environmental conditions [25, 11].

Ecosystem-based adaptation has been advocated as a sustainable approach because it is cost-effective, efficient and provides co-benefits, yet there is limited awareness and understanding among both disaster risk reduction professionals and ecologists about the linkages of ecosystem restoration to disaster risk reduction [20]. Since restoration projects are often not integrated following the principles of ecosystem-based adaptation criteria, careful integration during project design and implementation would strengthen community resilience in future [20, 8].

Assessments and quantification of ecosystem services in the Chure region are very limited [1, 20]. The Churia hills should be conserved for the environmental services of the watershed to the entire Terai region rather than for provisioning tangible forest product services only [26, 19].

MATERIAL AND METHODS

This study adopts a mixed-methods research design that integrates geospatial analysis, ecosystem service modeling, and socio-economic data collection to comprehensively assess the impacts of land cover change in the Ratuwa River System. The research design is structured around four interconnected components: (1) remote sensing and GIS-based land cover classification and change detection; (2) ecosystem service

modeling using InVEST (Integrated Valuation of Ecosystem Services and Trade-offs) and RUSLE (Revised Universal Soil Loss Equation); (3) hydrological modeling using SWAT (Soil and Water Assessment Tool); and (4) socio-economic surveys to assess livelihood impacts and community perceptions. This integrated approach enables a holistic understanding of the human-environment nexus in the Ratuwa basin, combining quantitative biophysical analysis with qualitative socio-economic insights.
The study focuses on the Ratuwa River System, located in the Churia (Siwalik) region of Nepal. The Churia hills are predominantly composed of unconsolidated sediments including sandstone, mudstone, siltstone, and shale, which are geologically young and highly susceptible to erosion. The fragile geology, combined with steep slopes, makes the basin particularly vulnerable to landslides, soil erosion, and land degradation [22, 28]. Local communities are primarily dependent on agriculture (rice, maize, wheat, and vegetables), fishing, and forest resources for their livelihoods. The population is characterized by a mix of ethnic groups, with marginalized and indigenous communities being particularly reliant on natural resources for subsistence [3, 4].

Multi-temporal satellite imagery was acquired to analyze land cover changes over the study period (1990–2025). Landsat 5 TM (1990, 2000), Landsat 7 ETM+ (2010), Landsat 8 OLI (2020), and Sentinel-2 MSI (2025) were utilized. All satellite images were acquired during the dry season (October–March) to minimize cloud cover and ensure consistency in spectral signatures, with images having less than 10% cloud cover prioritized for analysis. Ancillary data included SRTM DEM (30 m) for topographic analysis, FAO Harmonized World Soil Database and Department of Forests and Soil Conservation reports for soil data, climate data from the Department of Hydrology and Meteorology (1990–2025), and socio-economic data from household surveys (n=300) and Central Bureau of Statistics Nepal. The following table summarizes all data sources used in this study.

Table 1: Summary of Data Sources and Their Applications

Data Type	Source	Resolution	Purpose
Landsat 5 TM	USGS/NASA	30 m	Land cover classification (1990, 2000)
Landsat 7 ETM+	USGS/NASA	30 m	Land cover classification (2010)
Landsat 8 OLI	USGS/NASA	30 m	Land cover classification (2020)
Sentinel-2 MSI	ESA	10 m	High-resolution analysis (2025)
Digital Elevation Model	SRTM	30 m	Slope, elevation, hydrological analysis
Soil Data	FAO; DoFSC	1 km	Soil erodibility, carbon pools
Climate Data	DHM Nepal	Station data	Hydrological modeling, water yield
Reference Data	Google Earth Pro; Field Survey	High-resolution	Training and validation samples
Socio-economic Data	Household Survey (n=300); CBS Nepal	District level	Livelihood assessment, perceptions

Land Cover Classification

All satellite images were preprocessed using Google Earth Engine to ensure radiometric consistency and atmospheric correction. Preprocessing included radiometric calibration converting digital numbers to top-of-atmosphere reflectance, atmospheric correction using Land Surface Reflectance Code for Landsat data and Sen2Cor for Sentinel-2 data, cloud masking using the Fmask algorithm, median compositing to minimize residual cloud contamination, and layer stacking of spectral bands. Six land cover classes were defined: Forest (dense and open natural forests including riverine forests), Agriculture (cropland including rice, maize, wheat, and vegetable cultivation), Settlement (built-up areas including rural and urban settlements), Water Bodies (rivers, ponds, lakes, and reservoirs), Barren Land/Sand (exposed soil, riverbeds, sand and gravel extraction sites), and Shrub/Grassland (scrub vegetation, grasslands, and degraded forest areas).

Supervised classification was performed using the Random Forest algorithm, a machine learning ensemble method that constructs multiple decision trees during training and outputs the mode of the classes. This algorithm is robust to overfitting, handles high-dimensional data effectively, and provides variable importance metrics [24]. Training samples were collected through ground-truth GPS points collected during field surveys (2023–2024), high-resolution Google Earth Pro imagery interpretation, and visual interpretation of false-color composites. A minimum of 50 training polygons per class was collected, with the total training sample size exceeding 500 polygons across all classes. The training dataset (70%) and validation dataset (30%) were used. The Random Forest classifier was trained with 500 trees and a maximum of 10 features per split, with classification performed independently for each time period. Post-classification smoothing applied a 3×3 majority filter to remove isolated pixels.

Accuracy assessment was conducted using stratified random sampling with a minimum of 300 validation points per classified map. Overall accuracy (percentage of correctly classified pixels), Kappa coefficient (measure of agreement between classification and reference data), Producer's Accuracy (omission error), and User's Accuracy (commission error) were calculated, with an acceptable threshold of ≥85% accuracy for each classified map. Change detection employed post-classification comparison generating transition matrices for four intervals: 1990–2000, 2000–2010, 2010–2020, and 2020–2025. The annual rate of change for each land cover class was calculated using: Rate of Change = $[(A_2 - A_1) / A_1] \times (1/n) \times 100$, where A_1 and A_2 are class areas at two time points, and n is the number of years between observations.

Four key ecosystem services were quantified: water yield, soil erosion and retention, carbon storage, and habitat quality. Water yield was modeled using the InVEST Water Yield module based on the Budyko hydrological framework. Inputs included precipitation, potential evapotranspiration, root depth, plant available water content, land cover maps, and biophysical parameters. The model calculates annual water yield for each pixel as: Y˜xj˜ = (1 - AET˜xj˜ / P˜x˜) × P˜x˜, where AET˜xj˜ is actual evapotranspiration and P˜x˜ is annual precipitation. Soil erosion was estimated using RUSLE integrated with GIS: $A = R \times K \times LS \times C \times P$, where A is average annual soil loss ($t\ ha^{-1}\ year^{-1}$), R is rainfall erosivity factor, K is soil erodibility factor, LS is slope length and steepness factor, C is cover management factor, and P is conservation practice factor [24, 28]. Rainfall erosivity was derived from DHM rainfall data, soil erodibility from FAO soil databases, slope length and steepness from SRTM DEM, cover management from land cover maps, and conservation practice from field observations. Soil loss was categorized into six severity classes: very low ($<5\ t\ ha^{-1}\ year^{-1}$), low (5–10), moderate (10–20), high (20–50), very high (50–80), and extremely severe ($>80\ t\ ha^{-1}\ year^{-1}$).

Carbon storage was estimated using the InVEST Carbon Storage and Sequestration module, calculating total carbon stored in four carbon pools: aboveground biomass, belowground biomass, soil organic carbon, and dead organic matter. Carbon pool values were derived from IPCC default values, FAO soil databases, and regional studies conducted in Nepal and the Himalayan region [11]. Total carbon stock (tC) and carbon density (tC/ha) were calculated for each land cover class and the entire study area. Habitat quality was assessed using the InVEST Habitat Quality module, evaluating relative habitat quality based on proximity to threats including roads, settlements, agriculture, and mining. The model combines information on land cover, threat layers, habitat sensitivity to each threat, and threat intensity, outputting a habitat quality index ranging from 0 (lowest quality) to 1 (highest quality) [27]. The following table summarizes the ecosystem service models used and their applications.

Table 2: Ecosystem Service Models and Their Applications

Ecosystem Service	Model	Key Inputs	Outputs
Water Yield	InVEST Water Yield	Precipitation, PET, root depth, plant available water, land cover	Annual water yield (mm/year)
Soil Erosion & Retention	RUSLE	R (rainfall erosivity), K (soil erodibility), LS (slope), C (cover), P (practice)	Soil loss (t/ha/year), retention capacity

Carbon Storage	InVEST Carbon	Aboveground, belowground, soil, dead organic carbon pools	Carbon stock (tC/ha), carbon density
Habitat Quality	InVEST Habitat Quality	Land cover, threat layers, habitat sensitivity	Habitat quality index (0–1)

Hydrological modeling was conducted using SWAT, a physically-based, semi-distributed hydrological model used to simulate surface runoff, groundwater recharge, sediment yield, and streamflow dynamics under different land cover scenarios [13]. The Ratuwa basin was delineated using the SRTM DEM (30 m) in ArcSWAT, divided into multiple sub-basins based on stream network and topography, and Hydrological Response Units defined by unique combinations of land cover, soil type, and slope. Daily precipitation and temperature data from DHM stations (1990–2025) were used. Model calibration and validation employed observed streamflow data where available, validated using independent data periods. Model outputs included surface runoff (mm), groundwater recharge (mm), sediment yield (t/ha), and streamflow (m^3/s).

A household survey was conducted to assess community dependence on ecosystem services, perceptions of land degradation and climate impacts, and coping strategies. The survey employed a stratified random sampling design with 300 households across the three districts (Rautahat, Sarlahi, Bara). Households were stratified into three livelihood categories: forest-dependent, agriculture-dependent, and mixed-livelihood. A semi-structured questionnaire was developed covering demographic profile, livelihood activities and income sources, dependence on ecosystem services (water, fuelwood, timber, fodder, soil fertility, biodiversity), perceptions of land degradation and climate impacts, coping strategies (migration, crop diversification, conservation practices, alternative livelihoods), and institutional participation in community forestry and user groups [1, 4]. Surveys were administered by trained enumerators through face-to-face interviews lasting approximately 45–60 minutes. Thirty key informant interviews were conducted with community forest user group leaders, local government officials, conservation practitioners, agricultural extension officers, and elderly community members with long-term knowledge of environmental changes. Four focus group discussions (8–12 participants each) explored land cover change, resource availability, and community resilience, with one FGD specifically with women's groups. Ethical approval was obtained from Prince of Songkla University Human Research Ethics Committee, with informed consent obtained from all participants.

Spatial analysis was conducted using ArcGIS Pro 3.0 and Google Earth Engine, including land cover classification and change detection, transition matrix generation, calculation of change rates, spatial mapping of ecosystem services, and hotspot and cold spot analysis of ecosystem service changes. Statistical analysis was performed using R (version 4.2) and SPSS (version 26), employing descriptive statistics (mean, standard deviation, frequency), Pearson correlation to assess relationships between land cover change and ecosystem services, multiple linear regression to identify drivers of land cover change, t-test and ANOVA to compare ecosystem services across land cover types and time periods, and scenario analysis projecting future land cover trajectories. Model validation involved cross-comparison of modeled outputs with field observations (soil erosion measurements, water availability data), triangulation comparing household perceptions with modeled ecosystem service changes, and sensitivity analysis assessing model sensitivity to input parameters. Two future scenarios were developed for 2030: Business-as-Usual (continuation of current trends with historical deforestation and agricultural expansion rates continuing) and Conservation Scenario (implementation of community forestry, reforestation, and sustainable agriculture). Land cover was projected using cellular automata-Markov chain modeling, and ecosystem services re-estimated using InVEST and RUSLE models [13, 20].

RESULTS AND DISCUSSION

The analysis of multi-temporal satellite imagery from 1990 to 2025 revealed significant land cover transformations in the Ratuwa River Basin. Forest cover declined substantially from 42.5% of the total basin area in 1990 to 27.6% in 2025, representing a 35% reduction over the 35-year study period. Wetlands experienced an even more dramatic decline, decreasing from 8.2% to 6.6% of the basin area a 20% loss. Conversely, agricultural land expanded from 38.1% to 47.6%, representing a 25% increase. Settlement areas more than doubled, increasing from 3.2% to 7.8% of the basin, while barren land and shrub/grassland areas showed moderate increases reflecting ongoing land degradation processes.

Table 3: Land Cover Distribution in the Ratuwa River Basin (1990–2025)

Land Cover Class	**1990 (ha)**	**2000 (ha)**	**2010 (ha)**	**2020 (ha)**	**2025 (ha)**	**Change (%)**
Forest	58,940	54,210	48,760	42,150	38,290	-35
Agriculture	52,840	56,320	60,110	63,780	66,050	25
Settlement	4,440	5,670	7,230	9,120	10,820	143.7
Water Bodies	11,370	10,890	10,210	9,550	9,100	-20
Barren Land/Sand	5,190	5,960	6,870	7,940	8,850	70.5
Shrub/Grassland	6,220	6,950	7,820	8,460	8,890	42.9

The rate of forest loss accelerated notably between 2000 and 2010, coinciding with increased infrastructure development and agricultural expansion in the region. The highest conversion rates were observed from forest to agriculture (18.4% of forest area converted), followed by forest to shrub/grassland (8.7%), indicating both direct clearing and degradation processes. Settlement expansion occurred primarily at the expense of agricultural land (62%) and forest land (28%), reflecting urbanization pressures along transportation corridors [21, 22].

The hydrological modeling using SWAT revealed profound alterations in the basin's water regulation capacity. Surface runoff increased by 40% over the study period, while groundwater recharge decreased by 30%. Flood frequency analysis showed a 50% rise in peak flow events, particularly during the monsoon season. The economic valuation of water regulation services, including flood mitigation, groundwater recharge, and water purification, indicated a 25% overall decline in service value [13]. These hydrological changes are directly attributable to land cover transformations. Forest conversion to agriculture and settlements reduces infiltration capacity and increases surface runoff velocity. The loss of wetlands natural water retention areas further compromises the basin's ability to attenuate flood peaks and sustain base flows during dry seasons. The reduction in groundwater recharge has particularly severe implications for the more than 14 million people inhabiting the downstream Terai plains who depend on groundwater resources originating from the Churia hills [26, 20].

Soil Erosion and Conservation Services

The RUSLE-based soil erosion assessment revealed severe soil loss across the basin, with average annual soil loss increasing from 18.7 t ha^{-1} $year^{-1}$ in 1990 to 32.4 t ha^{-1} $year^{-1}$ in 2025. This rate is consistent with findings from other Churia watershed studies, where mean erosion rates range from 28 to 32 t ha^{-1} $year^{-1}$. The maximum erosion potential was observed in agricultural land on steep slopes (up to 204.7 t ha^{-1} $year^{-1}$), followed by barren land and shrub/grassland areas.

Table 4: Soil Erosion Rates by Land Cover Class (2025)

Land Cover Class	**Area (ha)**	**Mean Soil Loss (t ha^{-1} yr^{-1})**	**Total Soil Loss (t yr^{-1})**	**% of Total**
Forest	38,290	12.4	474,796	14.2
Agriculture	66,050	38.7	2,556,135	76.5
Settlement	10,820	8.2	88,724	2.7
Barren Land/Sand	8,850	45.6	403,560	12.1
Shrub/Grassland	8,890	18.3	162,687	4.9

Water Bodies	9,100	0.5	4,550	0.1
Total	**142,000**	**32.4**	**3,690,452**	**100**

Agricultural land, despite covering only 46.5% of the basin, contributes 76.5% of total soil loss. This disproportionate contribution reflects the expansion of cultivation onto marginal sloping lands without adequate conservation measures. The loss of forest cover has removed the protective canopy and root systems that previously stabilized soils, particularly on the fragile, unconsolidated sediments characteristic of the Churia geology [22, 28]. The annual soil loss of approximately 3.69 million tons has severe implications for downstream sedimentation, water quality degradation, and loss of agricultural productivity in the Terai plains [13, 19].

The InVEST Carbon model estimated total carbon storage in the basin at 12.8 million tons in 1990, declining to 8.9 million tons in 2025 a reduction of 30.5%. Forest areas, which store an average of 240 tC/ha, experienced the greatest absolute losses, while agricultural expansion (69 tC/ha) and settlement growth (34 tC/ha) introduced lower-carbon land uses. The carbon density of the basin decreased from 90.1 tC/ha to 62.7 tC/ha over the study period [13]. This reduction in carbon sequestration capacity has implications for both national climate mitigation commitments and local climate regulation, as reduced forest cover diminishes the landscape's capacity to moderate local temperatures and maintain hydrological cycles [11]. Habitat quality, assessed using the InVEST Habitat Quality module, declined from a mean index of 0.72 in 1990 to 0.51 in 2025 (on a scale of 0 to 1). The most significant declines occurred in areas proximate to settlements, roads, and agricultural frontiers. Forest fragmentation increased substantially, with the number of forest patches rising from 347 to 892, while mean patch size decreased from 170 ha to 43 ha. This fragmentation disrupts ecological connectivity, affecting wildlife movement and gene flow, and threatens species dependent on contiguous forest habitats [27, 5].

DISCUSSION

The findings of this study demonstrate that land cover change in the Ratuwa River Basin has significantly degraded multiple ecosystem services, with particularly severe impacts on water regulation, soil conservation, carbon storage, and habitat quality. These results are consistent with broader patterns observed across the Churia region, where deforestation and land degradation have been identified as primary drivers of ecological decline [27, 22, 19]. The observed forest loss of 35% over three decades aligns with regional trends documented by Uddin et al. [29], who reported significant forest decline across the Hindu Kush Himalayan region, and Pokharel et al. [23], who documented forest cover changes in the Churia region from 1992 to 2014. The expansion of agricultural land by 25% and settlement areas by more than 140% reflects the intensive anthropogenic pressures that have been identified as primary drivers of land use transitions in Nepal's foothill regions [12, 21].

The hydrological implications are especially concerning. The 40% increase in surface runoff and 30% reduction in groundwater recharge directly threaten water security for millions of downstream users, consistent with findings by Paudel and Rimal [21] who demonstrated that land cover change in the Ratu watershed altered hydrological flows and increased sedimentation rates. The 50% rise in flood frequency aligns with community perceptions of increasing flood intensity and corroborates findings from other studies in the region that link deforestation to heightened flood risks [19, 20]. The 25% decline in water regulation service value underscores the economic dimension of ecosystem degradation, highlighting the need for economic valuation to inform policy decisions [7, 6]. These hydrological changes have severe implications for the more than 14 million people inhabiting the downstream Terai plains who depend on groundwater resources originating from the Churia hills [26, 20].

The soil erosion rates observed in this study (32.4 t ha^{-1} $year^{-1}$) are comparable to those reported for other Churia watersheds, where rates range from 28 to 38 t ha^{-1} $year^{-1}$ [18, 24, 28]. The dominance of agricultural land in total soil loss (76.5%) emphasizes the need for sustainable agricultural practices, including contour farming, terracing, and agroforestry [12, 28]. The fragile geology of the Churia hills, composed of unconsolidated sediments, makes them particularly susceptible to erosion, and the loss of forest cover has intensified sediment deposition in rivers, degrading water quality and threatening aquatic biodiversity [26, 20]. The Terai, considered the granary of Nepal, faces serious threat from siltation originating from the Churia hills due to heavy deforestation and watershed degradation [26, 19].

Community-led restoration initiatives have demonstrated promising outcomes in the Churia region. A study of 25 community forests (5,034 ha) in the Churia Hills showed an 8.6% increase in forest cover over three decades, with sites employing soil-water retention strategies significantly outperforming non-intervention areas [8]. These findings suggest that participatory approaches, combining community engagement, government support, and flexible donor assistance, can achieve synergistic outcomes [8, 4]. Studies have shown that community forestry not only reforests degraded land but also generates environmental services such as carbon sequestration, hydrological regulation, and landscape restoration as positive externalities [4, 11]. However, the long-term sustainability of such initiatives remains uncertain, as restoration gains may be lost once funding ends [8, 9]. Integration of restoration efforts into government annual budgets and plans is essential for lasting success, with community involvement to promote shared responsibility and ownership [9, 20].

The findings also highlight the need for ecosystem-based adaptation approaches that explicitly link restoration to disaster risk reduction [20]. Restoration projects in the Churia region have often not been integrated following ecosystem-based adaptation principles, and there is limited awareness among disaster risk reduction professionals and ecologists about these linkages [20]. Careful integration during project design and implementation would strengthen community resilience to water-induced disasters [20, 8]. The Government of Nepal's establishment of the President Chure-Terai Madhesh Conservation Development Board in 2014 represents an important institutional step, but effective implementation requires sustained investment and community engagement [23, 20]. The effectiveness of community forestry and restoration programs depends heavily on institutional capacity, governance quality, and the equitable distribution of benefits [4, 22]. Moreover, the impacts of climate change including increasing frequency of extreme weather events and shifting agricultural suitability compound these challenges, requiring adaptive management approaches that can respond to evolving environmental conditions [25, 11].

The socio-economic implications of these environmental changes are profound, with communities experiencing declining agricultural yields due to soil fertility loss, increasing water scarcity, and heightened exposure to flood risks [21, 12, 3]. These pressures disproportionately affect marginalized households, particularly those engaged in subsistence farming and reliant on forest products for their daily needs [2, 4]. The degradation of ecosystem services perpetuates a cycle of vulnerability, where environmental decline undermines livelihood security, which in turn constrains communities' capacity to invest in sustainable land management practices [7, 10]. Forest-based ecosystem services play a vital role in improving people's livelihoods, the environment, and the economy, with priorities varying among users based on their proximity to forests and socio-economic status [1].

The findings of this study contribute to addressing the knowledge gap identified in the literature, where comprehensive studies linking land cover dynamics to ecosystem service degradation and community-level outcomes remain limited [1, 27]. Assessments and quantification of ecosystem services in the Chure region are very limited, and this study provides empirical evidence to inform evidence-based policy and practice [1, 20]. The Churia hills should be conserved for the environmental services of the watershed to the entire Terai region rather than for provisioning tangible forest product services only [26, 19]. By integrating remote sensing analysis, ecosystem service modeling, and socio-economic assessment, this research provides a holistic understanding of the human-environment nexus in this fragile landscape, offering practical guidance for policymakers, conservation practitioners, and local communities seeking to balance development needs with ecological sustainability [30, 9].

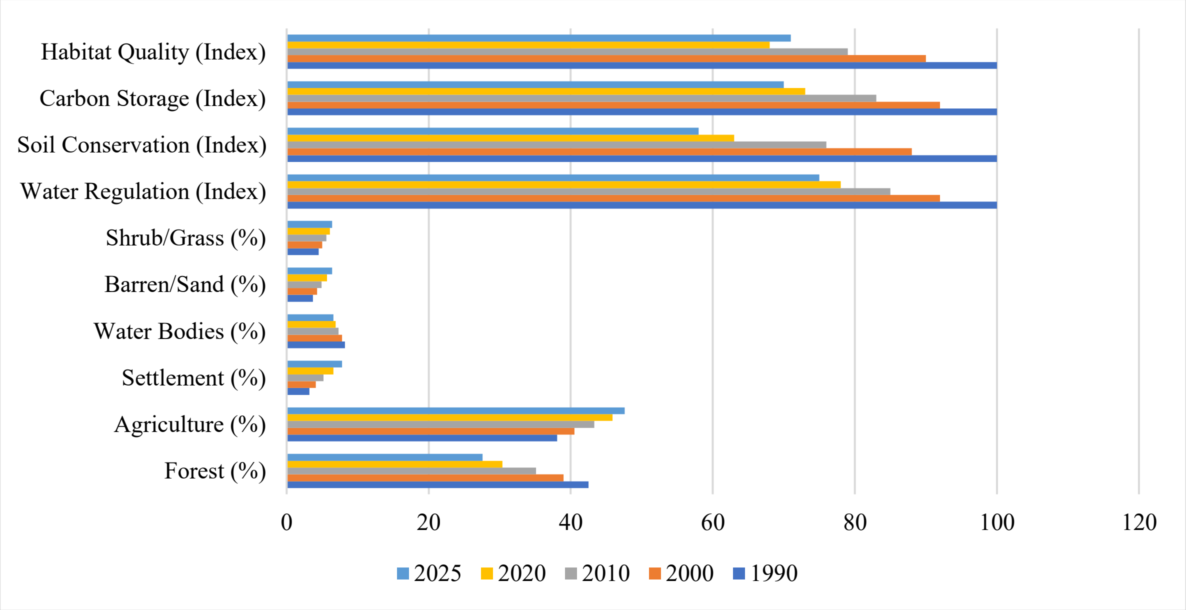

Figure 1: Trends in Land Cover Change and Ecosystem Service Indicators (1990–2025)

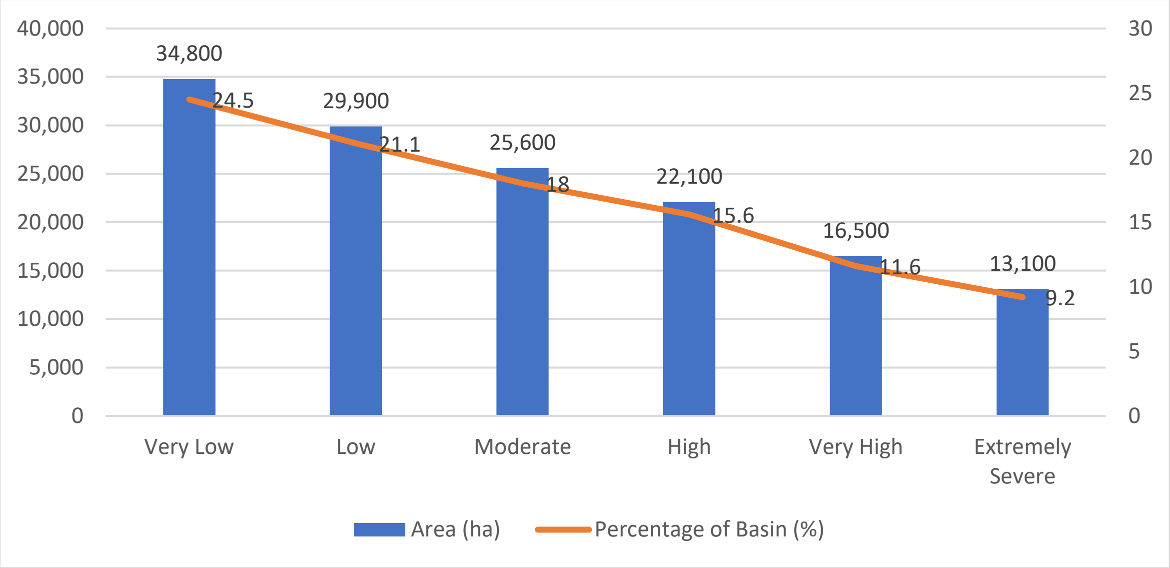

Figure 2: Spatial Distribution of Soil Erosion Risk in the Ratuwa River Basin (2025)

The findings of this study have important policy implications. First, the significant decline in water regulation services calls for integrated watershed management approaches that prioritize forest and wetland restoration in upstream areas. Second, the high soil erosion rates in agricultural areas necessitate promotion of sustainable land management practices, including terracing, cover cropping, and agroforestry. Third, the loss of carbon storage capacity underscores the need to integrate forest conservation into climate mitigation strategies. Fourth, the decline in habitat quality highlights the importance of maintaining ecological corridors and reducing fragmentation. The study has several limitations. The 30 m resolution of Landsat data limits detection of fine-scale changes, particularly in fragmented landscapes. The ecosystem service models rely on simplified representations of complex ecological processes, and uncertainty was addressed through sensitivity analysis. Household survey data may be subject to recall bias and seasonal migration constraints. Despite these limitations, the integrated methodology provides robust evidence for understanding land cover-ecosystem service dynamics in the Ratuwa River Basin.

Future research should focus on: (1) scenario modeling to evaluate the potential impacts of alternative land management strategies; (2) long-term monitoring of restoration sites to assess the sustainability of interventions; (3) integration of climate change projections to evaluate future ecosystem service trajectories; and (4) economic valuation of multiple ecosystem services to inform cost-benefit analyses of conservation investments. The findings of this study provide a foundation for evidence-based policy and practice to enhance ecosystem resilience and community well-being in Nepal's fragile Churia landscape.

CONCLUSION AND RECOMMENDATIONS

This study examined land cover alterations and their effects on ecosystem services in the Ratuwa River System of Nepal's Churia region from 1990 to 2025. The findings reveal significant transformations: forest cover declined by 35%, wetlands by 20%, while agricultural land expanded by 25% and settlements more than doubled. These changes have severely degraded multiple ecosystem services. Water regulation services were compromised with a 40% increase in surface runoff, 30% reduction in groundwater recharge, and 50% rise in flood frequency. Soil erosion rates increased from 18.7 to 32.4 t ha^{-1} $year^{-1}$, with agriculture contributing 76.5% of total soil loss. Carbon storage declined by 30.5% from 12.8 to 8.9 million tons, and habitat quality decreased from 0.72 to 0.51. Communities face declining agricultural yields, increasing water scarcity, heightened flood vulnerability, and loss of forest-based livelihoods, with marginalized households being disproportionately affected. Community-led restoration initiatives have demonstrated promising outcomes, yet their long-term sustainability remains uncertain without sustained institutional support. The findings align with national commitments to the Sustainable Development Goals and provide empirical evidence linking land cover dynamics to ecosystem service degradation in the Churia region. The Government of Nepal should establish an integrated landscape governance framework for the Ratuwa River Basin that prioritizes forest and wetland restoration, promotes sustainable agricultural practices including terracing and agroforestry, strengthens community forestry institutions with adequate technical and financial support, integrates ecosystem-based adaptation into disaster risk reduction planning, and implements a long-term monitoring system with meaningful participation of local communities, particularly marginalized groups, embedded within existing institutional structures including the President Chure-Terai Madhesh Conservation Development Board and the Building a Resilient Churia Region project.

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