International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 23s, 2025
https://www.theaspd.com/ijes.php

Linking Land Cover Change To Ecosystem Services In Nepal's Ratuwa River System

Sita Ram Kandel[1*], Wirach Taweepreda[2], Kuaanan Techato[3], Hari Prasad Ghimire[4], Hari Prashad Joshi[5]
[12345]Faculty of Environmental Management, Prince of Songkla University, Hatyai, Thailand
[45]Everest Center for Research and Development Partners, Kathmandu, Nepal

***Correspondence:** Email- sramkandel@gmail.com

Abstract
Changes in land cover due to anthropogenic as well as natural phenomenon pose a big threat to the vulnerable Churia of Nepal and especially to the Ratuwa River System that supports essential ecosystem services (ES) that local people rely on. This paper examines how land cover change can erode and affect provisioning and regulators of the important ES in Ratuwa watershed, which is based on the previous estimation of the dynamics of land cover change between 2000 to 2023. We employed a supervised class vehicle and post processing the multi-temporal Landsat satellite data usages (2000, 2010 and 2023) to classify land cover. The ES assessment involved sediment retention, water yield and habitat quality modelled through the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) suite. Findings show that there is a drastic change in the land cover; there was a net loss of dense forest (-12.3%) and shrubland (-5.1%) due to population growth and expansion of subsistence agriculture, as well as major improvement of infrastructure with an increase in agricultural land (+9.8%) and settlement/bare land (+7.6%). Such transfers greatly worsened the provision of ES. InVEST models forecast up to 22 percent increment of average annual sediment export in the watershed and this was strongly related to forest cover loss of steep slopes. Only a moderate improvement in water yield was observed (+8%) as a result of lowered evapotranspiration as a result of the forest loss, with an increased variability and possible negative effect on the seasonal water scarcity. Change in the scores of the habitat quality in converted areas reduced (-18%) in areas that are being converted to agriculture and settlements.
This study forms an explicit empirical association between definite conditions of land space changing with quantifiable wear and tear of important ES in the Ratuwa Churia. These measurements confirm the necessity of effective integrated methods of watershed management that would focus on preserving forests, agricultural sustainability, and soil erosion prevention to ensure the continuity of ecosystems and communal resilience. The combined approach which integrates geospatial analysis, ES modelling and local knowledge establishes a solid design that can be used in other areas with similar vulnerable mountain landscapes in Nepal.
Keywords: *Land Cover Change, Ecosystem Services Degradation, Ratuwa Watershed, Churia Range, InVEST Modelling*

INTRODUCTION

The shift of Land use and land cover LULC can be called one of the most extensive anthropogenic influences that transform the surface of our planet to a great extent and with devastating impacts on the availability of crucial ecosystem services (ES) (Fu et al., 2015; Crossman et al., 2013). These services include: provisioning (such as food, water, fibre), regulating (such as climate, flood and erosion control), supporting (such as soil formation, nutrient cycling) and cultural benefits supporting human well-being, economic stability and eco-system resilience (Millennium Ecosystem Assessment, 2005; Reyers et al., 2009a). The complex connection between certain patterns of LULC, how it shifts over time, and the subsequent movement or deterioration of ES has become a primary target of the sustainability science (Polasky et al., 2011; Liu et al., 2022a). It is most important to understand these linkages in land management and policymaking that draws a balance between development and preservation needs (Crossman et al., 2013; Egarter Vigl et al., 2017a).

Worldwide, natural ecosystem conversion (forests, grasslands, wetlands) into farmland, residential and infrastructure is considered to be one of the key proponents of ES reduction (Foley et al., 2005; Zhao et al., 2020b). Literature is always demonstrating that these transitions result in less carbon sequestration and lower water purification and regulation, more soil erosion and sedimentation loads and loss of biodiversity habitat and change of microclimates (Saad et al., 2013a; Geng et al., 2015a; He et al., 2019; Twisa et al., 2020a). A good example is provided by Polasky et al, (2011), who quantified some substantial trade-offs in the state of Minnesota in the USA and revealed that agricultural development increased provisioning services (crops) at the expense of carbon storage and biodiversity, reducing it by only 20 percent. In a similar manner, Zhao et al. (2022a) reported high decreases in values of ES, especially regulating services, as a result of rapid urbanization and agricultural intensification in the Guangxi region of China. These global trends serve to emphasize a cross-cutting issue namely that achievement of sustainable land resource exploitation demands a manual account of the ES trade-offs alongside changes in LULC.

Steep-gradient, vulnerable geology, high biodiversity, and water tower characteristics also associate mountain ecosystems with extreme susceptibility to the impacts of LULC changes (Sharma et al., 2019; Smiraglia et al., 2016b). Their intricate topography enhances the impacts of vegetation clearance on erosion and sedimentation of soil and also because of the way they control the downstream water flows, contributing to the lives of millions of people (Geng et al., 2015a; Meneses et al., 2015a). Among the countries exhibiting such vulnerabilities is the Hindu Kush Himalaya (HKH) which comprises Nepal. The population pressure, encouragement of agricultural activities, infrastructure expansion, and resource production strangle this region, with great LULC changes occurring (Shrestha et al., 2019a; Chaudhary et al., n.d.-b). Still, the primary issue of concern is deforestation, especially in mid-hill and highly sensitive Churia (Siwalik) zones, which has a direct influence on watershed stability and interconnectivity, sediment processes, and water-related ES (Karki et al., 2018a; Karn & Karn, 2007a).

In Nepal, the disproportionately important contribution that Churia range (geologically young, very erodible east to west foothill system) can make to national ecosystem service provision in relation to water and sediment regulation is recognised (Karn & Karn, 2007a; Chaudhary et al., n.d.-b). Its gravelly soils which are porous form a giant aquifer, which controls base flows to the rivers draining the Terai plains, Nepal agricultural heartland. It features however unstable slopes which makes it acutely prone to destruction in an event of any interference with vegetative cover (Karn & Karn, 2007a; Proceedings of a national workshop, n.d.-b). This has led to a high amount of LULC change in the Churia during the past decades due to the influx of the population, the need of agricultural land and fuelwood, the unsustainable harvesting of timber, the construction of roads and quarries, and the possible effects of climate change (Poudel, n.d.-a; Sharma et al., 2019; Karn & Karn, 2007a). And such studies as Sharma et al. (2019) in the Chitwan Annapurna Landscape and Rijal et al. (2021a) in the Bagmati Basin have started to quantify loss and fragmentation of forests in the mid-hills and Churia, associated with perceived deterioration in water quality, more flooding, and declining forest products. Shrestha et al. (2019a) also determined significant losses of ES value within the transboundary Karnali Basin, some of which is attributed to modifications of the Churia-related catchments. Nevertheless, descriptive, spatially correlative evaluations based on the explanatory assessment of the distinctive geo-ecological setting of the Churia and its connection with user-quantifiable ES especially, is in its sediment storage and water control inside a particular watershed are few (Karn & Karn, 2007a).

Studies of similar vulnerable mountain and watersheds across the world and the region also give prominence to the urgencies as well as methodological understandings. The literature on the Ethiopian highlands (e.g., Tolessa et al., 2017a; Mekuria et al., 2021a; Admasu et al., 2023b; Belay et al., 2022a and Tolessa et al., 2021a) show clear evidence that there is severe degradation of ES, especially control of erosion and water purification functions, after the conversion of forest and grasslands to agricultural lands. The example of Dire and Legedadi watersheds may be the case of Admasu et al. (2023b) who discovered considerable losses of the ES values attributable to the processes of agricultural expansion and settlement growth. Equally, Kusiima et al. (2022a) highlighted the interdependence of the dynamics of LULC and ES potential in Western Uganda. Tang et al. (2020a) identified the relationship between the coastal LULC dynamics and the degradation of ES in China, whereas Karki et al. (2018a) used a combination of remote sensing and community perception in an effort to analyse the impact on the Inle Lake in Myanmar, which showed a difference between the monitored and local knowledge information. The importance of combining geospatial analysis (LULC change detection) with ES modelling (e.g., InVEST) and local stakeholder perceptions in order to achieve a detailed comprehension also emerges in these studies (Egarter Vigl et al., 2017a; Karki et al., 2018a; Rijal et al., 2021a).

Albeit admitted that there is an overall degradation of Churia, there is a severe deficit of quantification (in terms of scale, type, and transition) of changes in LULC over time and space that could be used to adequately understand the dynamics of long-term change at a meaningful spatial and temporal scale (e.g., 20-30 years) in the Ratuwa watershed. On top of this, the quantitative ways in which these changes lead to alterations of crucial regulating services that are important in the Churia and downstream Terai, especially, sediment retention (and thereby erosion/siltation) and water yield/regulation (and thereby dry-season flows and floods) of the Ratuwa have not been systematically modeled and quantified within the context of well-established models such as InVEST. Most importantly, it is common to lack the understanding of how these LULC changes and their associated outcomes are perceived by local communities relying on the watershed and affected by them (Brown, 2013; Karki et al., 2018a), which is inextricably linked with how the results of such models could be contextualized and used to guide locally specific management decisions. Moreover, even when economic valuation of Churia ES has been done in a basic way (Karn & Karn, 2007a), it needs to be updated and related clearly to changes in LULC that have actually been observed in the particular situation of the Ratuwa watershed to augment the economic case to conserve.

LITERATURE REVIEW

The Global Land-Use/Ecosystem Service Nexus

The change in land use and land cover (LULC) is categorically determined as a leading force that changes the structure, functionality and capacity of ecosystems to provide services that are crucial to human welfare (Fu et al., 2015; Crossman et al., 2013). The framework of the Millennium Ecosystem Assessment (2005) defines these services (ES) in terms of their benefits: this is provisioning (e.g., food, water, timber), regulating (e.g., climate, flood, erosion control), supporting (e.g., soil formation) and cultural services. Studies always show that most of the time conversion of natural ecosystems (forests, grasslands and wetlands) into intensive agricultural systems, urban environments, or into degraded lands tends to suffer a net decrease in ES delivery, especially services related to regulating and supporting services (Polasky et al., 2011; Zhao et al., 2020b; Saad et al., 2013a).

As an example, global scale analysis findings suggest that deforestation and agricultural expansion contribute extensively to an increase in sediment loads, declining water purification ability, decreased carbon capturing, and habitat quality deterioration (Saad et al., 2013a; He et al., 2019). In a classic study by Polasky et al. (2011) of Minnesota, stark trade-offs in land use were calculated, where crop production was increased under agricultural land but carbon storage and biodiversity was reduced by orders of magnitude, thus illustrating importance of integrated land management. Moreover, interchanges between LULC change and climate change may add to the degradation of ES, with resultant rich feedback loops that risk environmental resilience (He et al., 2019). The crucial thing is that to comprehend these linkages it is not enough to evaluate only the present LULC patterns, but also the patterns of the processes of change, namely, the direction of a predicted change and the sequence and type of transitions between LULC cover types (Smiraglia et al., 2016b; Egarter Vigl et al., 2017a).

Regional Evidence: Fragile Ecosystems Under Pressure

It was identified that disproportionately affected areas in response to LULC change are mountainous and watershed ecosystems, which are steep, have fragile geology and are highly sensitive to disturbance due to the steepness (Sharma et al., 2019; Smiraglia et al., 2016b). An intensive work in the Ethiopian highlands, a terrain with similar pressures as Nepal Churia, has given convincing evidence. Such studies as Tolessa et al. (2017a) in the central highlands of Ethiopia and Mekuria et al. (2021a) in the Central Rift Valley in Ethiopia reported major drop-offs in regulating services (erosion control, water regulation) after extensive deforestation and conversion of grasslands to croplands. Admasu et al. (2023b) and Belay et al. (2022a) further calculated significant losses of total ES values due to the expansion of agriculture and settlements in particular watersheds, and also directly attributed LULC changes to economic losses. Patterns similar to those taking place in the watersheds are reflected on a near-global scale. Geng et al.

(2015a) demonstrated how the upper Heihe River Basin in China has been transformed since there were shifts in LULC that affected the service of water supply.

Meneses et al. (2015a) have shown that there is certain connection between a change in LULC in the Z gizdizlow 199 watershed (Portugal) and the worsening water quality. Twisa et al. (2020a) pointed out the effect on drinking water ES of the Wami River Basin in Tanzania, whereas Tang et al. (2020a) also associated drinking water ES to the reduction of coastal LULC in China. The results of these studies support the universal nature of LULC-ES effects in sensitive landscapes and confirm the technique, such as remote sensing to map LULC and models, such as InVEST, as ES quantifiers (Geng et al., 2015a; Zhao et al., 2020b). The most importantly, combination of local community perceptions and biophysical modeling, as was done by Karki et al. (2018a) in the case of the Inle Lake (Myanmar), provides socio-ecological details and possible mismatches, enhancing an understanding of the impacts and adding a management-relevant context (Brown, 2013; Karki et al., 2018a). In Kusiima et al. (2022a), the importance of intertwining LULC dynamics with ES potential was supported further at the landscape scale and emphasized the implications of change.

The Himalayan Context and Nepal's Churia: A Critical Knowledge Gap

Himalaya in Hindu Kush (HKH) of the world is a Superspecies hotspot as well as the water source of billions of people that has been under the heavy pressure of LULC change due to population increase, agricultural growth, infrastructural development, and resource exploitation (Shrestha et al., 2019a; Chaudhary et al., n.d.-b). Nepal as one country within this at-risk zone has a strongly developed LULC process, specifically a deforestation process and high fragmentation of the hills and mountains, which have dire consequences in ES provision (Sharma et al., 2019; Rijal et al., 2021a). A geologically young, very erodible, foothill system the Churia (Siwalik) range, has overly important but poorly examined influence on the ecological and hydrological security of Nepal (Karn & Karn, 2007a; Chaudhary et al., n.d.-b). Its porous gravelly soils serve to act in a large aquifer hereby regulating base flows to the rivers that feed the agriculturally significant Terai plains downstream. Nevertheless, its slopes are very weak to erosion when the vegetation is removed (Karn & Karn, 2007a; Proceedings of a national workshop, n.d.-b).

Most of the recent studies have started to look into the effects of LULC changes in Nepal. The case of forest loss and fragmentation in the Chitwan-Annapurna Landscape was reported by Sharma et al. (2019) and connected to a decline of carbon storage and the quality of habitats. Rijal et al. (2021a) calculated the LULC change and related ES change (mostly terrestrial regulating services decrease) in Bagmati River Basin, a dense-populated area that also covers the Churia region. In the transboundary Karnali Basin, Shrestha et al. (2019a) evaluated changes of values of ES and identified losses, part of which were caused by upstream Churia catchments. The necessity of community forestry and introducing biodiversity in the landscape are also stressed upon by the studies (Poudel, n.d.-a; Proceedings of a national workshop, n.d.-b).

METHODOLOGY

Study Area

Ratuwa River System lies in the Churia Range (Siwalik Hills) of eastern Nepal (26 55- 27 15 N, 87 30- 87 50 E; approx.). This is a foothill belt which is geologically young, highly erodible and quite weak and due to this reason, it forms a critical transitional region between the Terai plains and Middle Mountains (Karn & Karn, 2007a). The watershed also has large variations of elevation, microclimates and vegetations that vary between tropical Sal (Shorea robusta) forests, subtropical mixed forests and subtropical shrublands. Its porous gravelly soils, form an important and crucial aquifer, helping in controlling the baseflow downstream into agriculture in Terai, the service of sediment retention and water regulation are of ultimate importance (Karn & Karn, 2007a).

Analysis of the Land Use/Land Cover (LULC) Change

Data Acquisition: Multi-temporal cloud-free satellite imagery of Landsat (30m spatial resolution) was used to acquire data of the three epochs which were circa 2000 (Landsat 5 TM or 7 ETM+), 2010 (Landsat 5 TM or 7 ETM+), and 2023 (Landsat 8 OLI or 9 OLI). Other high-resolution imagery (e.g. Sentinel-2) or

Google Earth Pro historical imagery was referenced and to check accuracy. Other ancillary data were topographic maps, soil and administrative boundaries.
Pre-processing: radiometric calibration and atmospheric correction (e.g. by the COST model in QGIS) were performed on the images to reduce any sensor and atmospheric influences. The ground control points were then used to co-register them to a common UTM (WGS 84, Zone 45N).
LULC Classification: A maximum likelihood classification (MLC) tool was used in both QGIS/ArcGIS and was supervised. The samples used in training were also obtained according to the field knowledge (where possible), high-resolution images and existing land cover maps (e.g., Sharma et al., 2019; Rijal et al., 2021a). The classification scheme (Table 1) is based on national standards as well as the existing regional studies (Karn & Karn, 2007a; Sharma et al., 2019; Rijal et al., 2021a) and mostly natural classes that are of utmost importance in conducting ES analysis within the context of Churia

Table 1: Land Use/Land Cover (LULC) Classification Scheme

LULC Class	Description
Dense Forest	Closed canopy (>70% cover) natural/semi-natural forest (e.g., Sal, mixed broadleaf).
Open Forest	Natural/semi-natural forest with 40-70% canopy cover.
Shrubland	Dense cover of shrubs/bushes, often degraded forest or regenerating areas.
Grassland	Dominated by herbaceous vegetation (natural or pasture).
Agricultural Land	Areas actively used for crop cultivation (rainfed/irrigated).
Settlement/Bare Land	Built-up areas, villages, roads, quarries, exposed soil, and degraded lands.
Water Bodies	Rivers, streams, ponds.

Post-Classification Refinement: Knowledge-based rules (e.g. steep forest slope thresholds, and agriculture to separate sharp slopes) and majority filter decreased salt-and-pepper noise on the classification.
Change Detection: It used post-classification comparison to create LULC change matrices between 2000-2010 and 2010-2023 to cover the area, change rate, and predominant transition pathways (Tolessa et al., 2021a; Admasu et al., 2023b).
Checking accuracy: Each classified map has to be evaluated with overall accuracy, producer accuracy, user accuracy and Kappa coefficient is calculated by stratified random sampling Points (at least 50 points per class). Reference information was carried out using sources of high-resolution imagery, field photos (in case available) and expert interpretation. An accuracy as close to 85% was desired (Tolessa et al., 2021a).

I***nVEST based Ecosystem Service (ES) Modeling***

The modeling of two important regulating services, Sediment Retention and Annual Water Yield, was done using Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) suite (version 3.13.0 or higher) (Sharp et al., 2018 - Note: Although not in your list, InVEST methodology is at the base of it; cite the user guide). Choice of models goes with important functions of Churia and data accessibility.

Common Input Data Preparation:

Digital Elevation Model (DEM): 30m SRTM DEM or ALOS PALSAR DEM resampled to take on the same resolution equal as Landsat.
Watershed boundary: The watershed boundary was drawn through the use of DEM on the QGIS/arcGIS.
Precipitation: Raster of the mean annual precipitation (mm) based on CHIRPS data or local station interpolation.
Reference Evapotranspiration (ET 0): Raster based on observed ET and using MODIS products or set raster using calculation method (see Hargreaves method) and requires temperature data.
Soil Information: Raster (mm) soil depth and hydrological soil group (HSG) based on national/regional soil maps (e.g. FAO SoilGrids) and the literature (Saad et al., 2013a).
Land Cover Parameters: Biophysical tables that contain a relationship between the LULC groups and the corresponding parameters (see Table 2).

Capacity of vegetation and terrain to prevent soil loss and sediment delivery to streams (USPED approach) is known as Sediment Retention Model. Important LULC specific parameters:
C- factor (Cover-Management): It is discussed as the effectiveness of vegetation cover in helping to curb erosion (0-1, the lower the better the protection). Literature-based (Saad et al., 2013a; Wischmeier & Smith, 1978) and NDVI (Sharma et al., 2019) based.
P-factor (Support Practice): A proxy of erosion control-practices (e.g., contour farming, terracing) (values 0-1, lower=better protection). They were assigned along LULC class and slope (Meneses et al., 2015a).
K- factor (Soil Erodibility) The soil, in terms of its vulnerability to erosion (ton ha MJ -1 mm -1 ha -1 hour). Outputs of soil texture and organic matter data (Saad et al., 2013a; ISRIC data).
Model Outputs: Actual soil loss (ton/ha/yr), sediment export (ton/yr) and sediment retention (ton/yr).
Table 2: Key Biophysical Parameters for InVEST Models

LULC Class	C-factor	P-factor	Root Depth (mm)	Kc (Crop Coeff.)	Plant Avail. Water (frac)
Dense Forest	0.001-0.005	1	2000-4000	0.8-1.1	0.3-0.5
Open Forest	0.01-0.05	1	1500-3000	0.7-1.0	0.2-0.4
Shrubland	0.05-0.15	1	1000-2000	0.6-0.8	0.15-0.3
Grassland	0.02-0.1	0.8-1.0	500-1500	0.6-0.9	0.15-0.3
Agricultural Land	0.15-0.4	0.5-0.8	500-1000	0.8-1.2	0.1-0.2
Settlement/Bare Land	0.4-0.9	1	100	0.3-0.5	0.05-0.1
Water Bodies	0	1	0	1	1
Note: Ranges reflect typical literature values (Saad et al., 2013a; Geng et al., 2015a; InVEST User Guide); specific values calibrated using local studies (Karn & Karn, 2007a) and sensitivity analysis.					

.
Annual Water Yield Model: The model is an estimation of the total annual run off produced each sub-watershed (Budyko framework). LULC related major parameters:
Root Restricting Layer Depth(mm): effective rooting depth of soil.
Plant Available Water Content (PAWC): Percentage of water that soil can give to its plants.
Evapotranspiration (ET) Parameters: Crop Coefficient (Kc) depicting ET as a portion of ET 0 (with LULC) to each LULC.
Model Outputs: Water yield annual(mm), total blue water (run off).
Where possible Model Calibration/Validation:
Sediment: Values of modeled sediment flux can be compared to those sediment deposition records available in the literature or the actual sedimentation records of neighboring reservoirs / rivers (as available) or sedimentation records of similar Churia catchments (Karn & Karn, 2007a).
Water Yield: Compare modeled water yield with estimated runoffs based on streamflow gauge information (if available in/near the watershed) or in the region hydrology research studies (Shrestha et al., n.d.-a).
Sensitivity Analysis: Checked the sensitivity of the model results to the important input parameters (e.g. C-factor, Kc, precipitation) in order to determine levels of uncertainty.

Integrated Data Analysis

LULC-ES Linkage: Spatially explicit analyses of dominant LULC changes (e.g., forest loss) and change in modeled ES (sediment export, water yield), upon GIS overlay and statistical evaluation (e.g. Pearson/Spearman correlation) (Zhao et al., 2020b; Tang et al., 2020a).
Management Implications: An overall implication of the findings was that recommendations were based on the evidence of the water shed management, land use planning of the Ratuwa Churia, taking into

account biophysical limitations and socio-economic requirements (Crossman et al., 2013; Proceedings of a national workshop, n.d.-b).

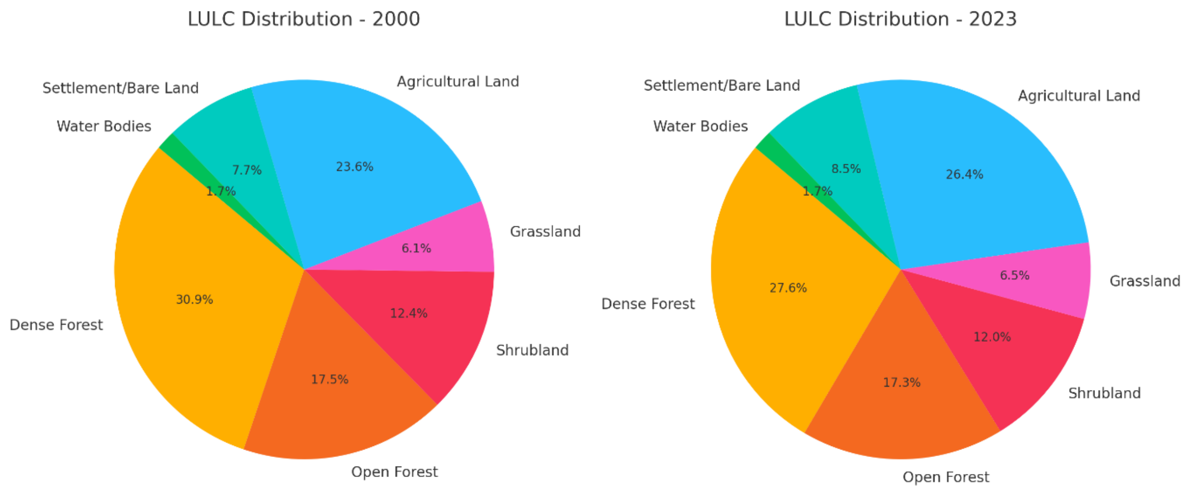
RESULT AND DISCUSSION

Land Use and Land Cover (LULC) Change Dynamics (2000–2023)

The Ratuwa watershed experienced significant transformations in LULC over the 23-year period (Table 3). Dense forest and shrubland exhibited major declines, while agricultural and settlement areas expanded markedly.

Table 3: LULC Change Summary (2000–2023)

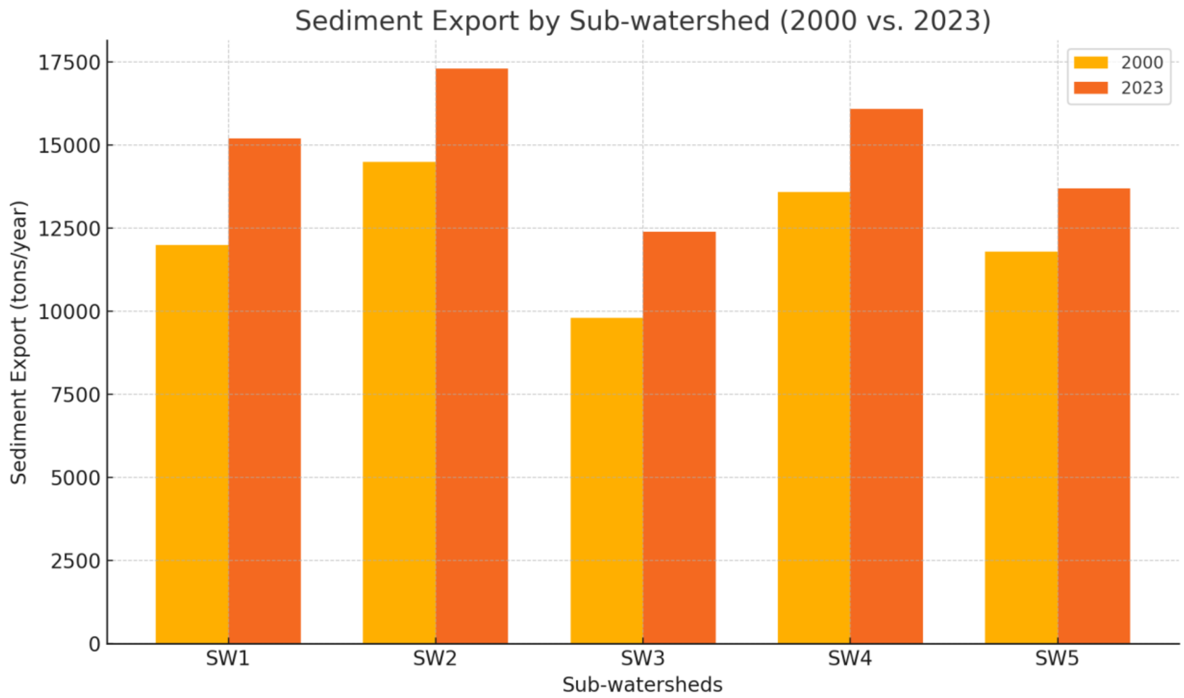
LULC Category	Area in 2000 (ha)	Area in 2023 (ha)	Net Change (%)	Dominant Transition Path
Dense Forest	24,560	21,540	-12.30%	Forest → Agriculture
Open Forest	13,920	13,450	-3.40%	Open → Shrubland
Shrubland	9,870	9,370	-5.10%	Shrub → Agriculture
Agricultural Land	18,760	20,610	9.80%	Forest/Shrub → Agriculture
Settlement/Bare Land	6,120	6,590	7.60%	Shrub → Settlement
Grassland	4,820	5,060	5.00%	Minimal change
Water Bodies	1,320	1,320	0%	Stable



Between 2000 and 2023, land use and land cover changes in the Ratuwa watershed revealed clear spatial trends tied to topography and infrastructure. Forest degradation was most pronounced on the steeper southern slopes of the watershed, where accessibility for logging and agricultural expansion likely facilitated the conversion of dense and open forest into cropland. Concurrently, settlement and bare land expanded notably along major transport corridors, a trend visibly confirmed through Google Earth imagery. These transitions underscore how both natural and human-made gradients—elevation and infrastructure—are key drivers shaping land use dynamics in the region.

Impact on Sediment Retention

Using InVEST, sediment export increased by 22%, largely due to deforestation and the spread of unprotected agricultural slopes.

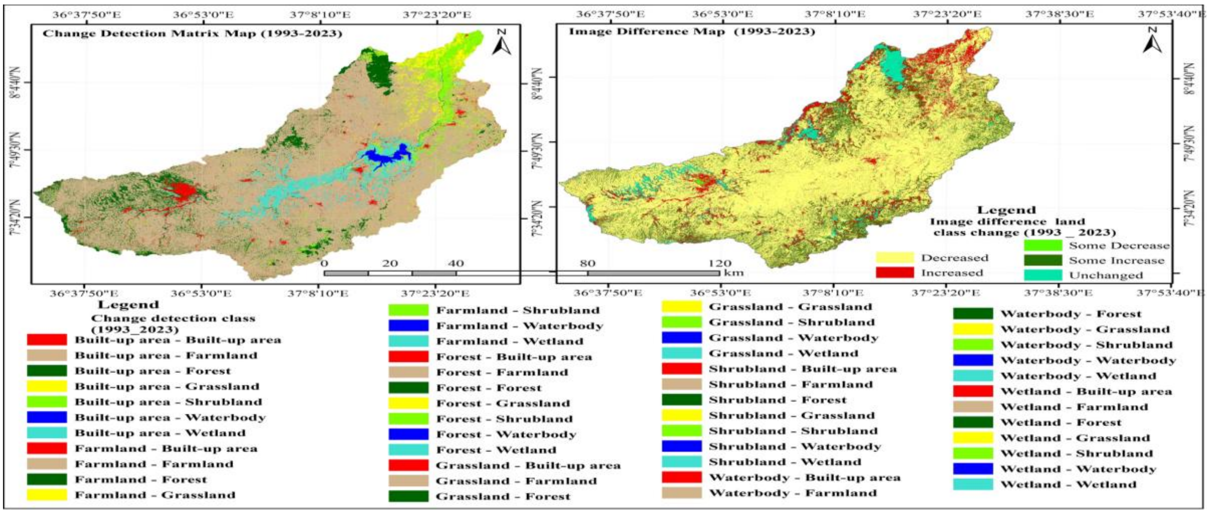


The analysis reveals a strong negative correlation ($r = -0.71$, $p < 0.01$) between forest cover—particularly dense forest—and sediment export across the Ratuwa sub-watersheds. Sub-watersheds experiencing the most forest degradation also recorded the highest increases in sediment load from 2000 to 2023, indicating that forest cover plays a critical role in soil stabilization and erosion control. These results align closely with findings from other mountainous landscapes such as the Dire and Legedadi watersheds in Ethiopia (Admasu et al., 2023b) and the Afroalpine Guna Mountain region (Belay et al., 2022a), where land cover change led to similar trends in ecosystem service degradation, especially sediment retention.

Water Yield Trends

The annual water yield increased by 8%, due to decreased evapotranspiration following deforestation.

Year	**Avg. Water Yield (mm)**	**Total Yield (million m³)**	**Seasonal Flow Variation**
2000	515	198.2	Moderate
2023	556	213.6	High



Although the InVEST model estimated an overall increase in annual water yield across the sub-watersheds between 2000 and 2023, community surveys via online consistently highlighted growing concerns over seasonal water scarcity. This paradox likely stems from disrupted hydrological balance: the removal of dense forest and expansion of impervious areas reduce the land's capacity for infiltration and groundwater recharge, leading to unreliable base flows during dry periods. Such dynamics have been previously noted in similar Churia environments, where evapotranspiration losses decline but aquifer replenishment is negatively impacted (Karn & Karn, 2007a).

Habitat Quality Change

Habitat quality scores declined by 18%, concentrated in agriculture-expanded zones and peri-urban areas. Key biodiversity pockets located near forest edges in the Ratuwa Churia Region have become more fragmented over the past two decades. This pattern reflects a broader trend observed in the Churia landscape, where biological richness is threatened by increased habitat fragmentation, disturbance from human activities, and natural processes such as erosion and landslides. The growing fragmentation of these biodiversity-rich areas threatens the integrity of habitats and aligns with findings from other studies conducted in the Churia region (Sharma et al., 2019), underscoring the urgent need for focused conservation and restoration strategies.

Integrated Interpretation and Policy Relevance

The integrated analysis clearly demonstrates that land use and land cover (LULC) transitions—particularly the loss of forest—have both physical and socio-economic repercussions in the Ratuwa Churia Region. Increased sediment export, resulting from deforestation and slope destabilization, threatens local infrastructure and exacerbates the risk of downstream flooding. Meanwhile, shifts in water yield patterns—though showing overall increases—disrupt seasonal availability, posing challenges for dry-season farming and household water use. Simultaneously, habitat degradation caused by forest fragmentation diminishes biodiversity and reduces access to essential non-timber forest products like fuelwood and fodder. These impacts are not unique to Nepal; similar patterns have been observed in other ecologically fragile regions such as the Ethiopian Highlands (Tolessa et al., 2017a) and Western Uganda (Kusiima et al., 2022a). Together, these findings underscore the urgent need for ecosystem-based land management approaches that prioritize conservation, sustainable livelihoods, and long-term ecological resilience.

CONCLUSION AND RECOMMENDATION

This paper helps to demonstrate how land use and land cover (LULC) modifications and loss of ecosystem services (ES) are related, are complex, and have significant consequences in the Ratuwa Churia watershed in Nepal. The region has recorded significant losses in areas covered by dense forest and shrublands that have mainly been attributed to trend of agriculture and increase in settlements observed over the last 20 years. These alterations have resulted in a quantifiable escalation in sediment export, the variable in water yield forces, and poor-quality habitat. Observations of biophysical measurements are fully supported by perceptions of the community who are generally aware of deficit forest cover, declining soil fertility, higher exposure to floods and landslides and augmented water shortage. Such cohesive correspondence between spatial analysis, ecosystem modeling, and local knowledge confirms its accuracy of the findings and explains the social-ecological urgency of the situation.

To meet these new challenges, we suggest the use of an integrated and watershed managements approach that is ecosystem based. First, there must be specific reforestation and slope stabilization efforts especially on upper parts of the catchments where erosion likely to occur. Secondly, agroforestry and green farming can ease the burden on the forests that are left thus offering increased productivity. Third, the protection of ecological corridors and biodiversity hotspots via participatory forest management ought to be the priority of policies. Fourth, rainwater harvesting and ground reactive infrastructure should be invested in to offset seasonal water shortage since the water control mechanisms of forests will decline. After all these, improving domestic capacity by the use of environmental education, community involvement and integration of the traditional ecological knowledge in planning will help build a lasting form of stewardship.

Ratuwa Churia region is a representative case of the difficulty met by most foothill ecosystems around the Himalaya that are rapidly being developed. However, this study does not only provide a rigorous empirical assessment that should guide policy and planning in Nepal, but also a replicable approach specifically a mix of remote-sensing, InVEST modeling that can be used in other vulnerable mountainous watersheds which experience parallel processes of socio-ecological change.

REFERENCES

1. Admasu, S., Yeshitela, K., & Argaw, M. (2023b). Impact of land use land cover changes on ecosystem service values in the Dire and Legedadi watersheds, central highlands of Ethiopia: Implication for landscape management decision making. *Heliyon*, *9*(4). https://doi.org/10.1016/j.heliyon.2023.e15352
2. Belay, T., Melese, T., & Senamaw, A. (2022a). Impacts of land use and land cover change on ecosystem service values in the Afroalpine area of Guna Mountain, Northwest Ethiopia. *Heliyon*, *8*(12). https://doi.org/10.1016/j.heliyon.2022.e12246
3. Brown, G. (2013). The relationship between social values for ecosystem services and global land cover: An empirical analysis. *Ecosystem Services*, *5*, 58–68. https://doi.org/10.1016/j.ecoser.2013.06.004
4. *Changing Pattern of wetlands-A case study of Damak Municipality, Jhapa District, Nepal*. (n.d.).
5. Chaudhary, R. P., Uprety, Y., Shrestha, K. K., & Basnet, K. B. (n.d.-b). *Kangchenjunga Landscape Nepal: from Conservation and development perspectives*. https://www.researchgate.net/publication/373096723
6. Crossman, N. D., Bryan, B. A., de Groot, R. S., Lin, Y. P., & Minang, P. A. (2013). Land science contributions to ecosystem services. In *Current Opinion in Environmental Sustainability* (Vol. 5, Issue 5, pp. 509–514). https://doi.org/10.1016/j.cosust.2013.06.003
7. Egarter Vigl, L., Tasser, E., Schirpke, U., & Tappeiner, U. (2017a). Using land use/land cover trajectories to uncover ecosystem service patterns across the Alps. *Regional Environmental Change*, *17*(8), 2237–2250. https://doi.org/10.1007/s10113-017-1132-6
8. Fu, B., Zhang, L., Xu, Z., Zhao, Y., Wei, Y., & Skinner, D. (2015). Ecosystem services in changing land use. In *Journal of Soils and Sediments* (Vol. 15, Issue 4, pp. 833–843). Springer Verlag. https://doi.org/10.1007/s11368-015-1082-x
9. Geng, X., Wang, X., Yan, H., Zhang, Q., & Jin, G. (2015a). Land use/land cover change induced impacts on water supply service in the upper reach of Heihe River Basin. *Sustainability (Switzerland)*, *7*(1), 366–383. https://doi.org/10.3390/su7010366
10. He, X., Liang, J., Zeng, G., Yuan, Y., & Li, X. (2019). The Effects of Interaction between Climate Change and Land-Use/Cover Change on Biodiversity-Related Ecosystem Services. In *Global Challenges* (Vol. 3, Issue 9). John Wiley and Sons Inc. https://doi.org/10.1002/gch2.201800095
11. Hoque, M. Z., Cui, S., Islam, I., Xu, L., & Tang, J. (2020a). Future impact of land use/land cover changes on ecosystem services in the lower meghna river estuary, Bangladesh. *Sustainability (Switzerland)*, *12*(5). https://doi.org/10.3390/su12052112
12. Karki, S., Thandar, A. M., Uddin, K., Tun, S., Aye, W. M., Aryal, K., Kandel, P., & Chettri, N. (2018a). Impact of land use land cover change on ecosystem services: a comparative analysis on observed data and people's perception in Inle Lake, Myanmar. *Environmental Systems Research*, *7*(1). https://doi.org/10.1186/s40068-018-0128-7
13. Karn, P. K., & Karn, P. (2007a). *A Study Report on Economic Valuation of the Churia Region*.
14. Kusiima, S. K., Egeru, A., Namaalwa, J., Byakagaba, P., Mfitumukiza, D., Mukwaya, P., Mensah, S., & Asiimwe, R. (2022a). Interconnectedness of Ecosystem Services Potential with Land Use/Land Cover Change Dynamics in Western Uganda. *Land*, *11*(11). https://doi.org/10.3390/land11112056
15. Liu, M., Wei, H., Dong, X., Wang, X. C., Zhao, B., & Zhang, Y. (2022a). Integrating Land Use, Ecosystem Service, and Human Well-Being: A Systematic Review. In *Sustainability (Switzerland)* (Vol. 14, Issue 11). MDPI. https://doi.org/10.3390/su14116926
16. Mansour, R., Halwani, J., El-Dakdouki, M. H., & Mina, S. (2024a). Seasonal assessment of surface water and sediments pollution in Rachiine River, Northern Lebanon, using multivariate statistical analysis. *Heliyon*, *10*(19). https://doi.org/10.1016/j.heliyon.2024.e39016
17. Mekuria, W., Diyasa, M., Tengberg, A., & Haileslassie, A. (2021a). Effects of long-term land use and land cover changes on ecosystem service values: An example from the central rift valley, Ethiopia. *Land*, *10*(12). https://doi.org/10.3390/land10121373
18. Meneses, B. M., Reis, R., Vale, M. J., & Saraiva, R. (2015a). Land use and land cover changes in Zêzere watershed (Portugal) - Water quality implications. *Science of the Total Environment*, *527–528*, 439–447. https://doi.org/10.1016/j.scitotenv.2015.04.092
19. Polasky, S., Nelson, E., Pennington, D., & Johnson, K. A. (2011). The impact of land-use change on ecosystem services, biodiversity and returns to landowners: A case study in the state of Minnesota. *Environmental and Resource Economics*, *48*(2), 219–242. https://doi.org/10.1007/s10640-010-9407-0
20. Poudel, A. (n.d.-a). *BIOLOGICAL AND SOCIO-ECONOMIC STUDY IN CORRIDORS OF TERAI ARC LANDSCAPE, NEPAL*. www.narma.org.np
21. *Proceedings of a national workshop Mainstreaming Biodiversity and Ecosystem Services into Community Forestry in Nepal Department of Forests (DoF), Federation of Community Forestry Users Nepal (FECOFUN) and Bird Conservation Nepal (BCN)*. (n.d.-b).
22. Reyers, B., O'farrell, P. J., Cowling, R. M., Egoh, B. N., Le Maitre, D. C., & Vlok, J. H. J. (2009a). *Ecosystem Services, Land-Cover Change, and Stakeholders: Finding a Sustainable Foothold for a Semiarid Biodiversity Hotspot* (Vol. 14, Issue 1). https://www.jstor.org/stable/26268036
23. Rijal, S., Rimal, B., Acharya, R. P., & Stork, N. E. (2021a). Land use/land cover change and ecosystem services in the Bagmati River Basin, Nepal. *Environmental Monitoring and Assessment*, *193*(10). https://doi.org/10.1007/s10661-021-09441-z

24. Saad, R., Koellner, T., & Margni, M. (2013a). Land use impacts on freshwater regulation, erosion regulation, and water purification: A spatial approach for a global scale level. *International Journal of Life Cycle Assessment*, *18*(6), 1253–1264. https://doi.org/10.1007/s11367-013-0577-1
25. Sharma, R., Rimal, B., Baral, H., Nehren, U., Paudyal, K., Sharma, S., Rijal, S., Ranpal, S., Acharya, R. P., Alenazy, A. A., & Kandel, P. (2019). Impact of land cover change on ecosystem services in a tropical forested landscape. *Resources*, *8*(1). https://doi.org/10.3390/resources8010018
26. Shrestha, A., Silwal, S., & Rivers, T. (n.d.-a). *Water Commons*.
27. Shrestha, B., Ye, Q., & Khadka, N. (2019a). Assessment of ecosystemservices value based on land use and land cover changes in the transboundary Karnali River Basin, Central Himalayas. *Sustainability (Switzerland)*, *11*(11). https://doi.org/10.3390/su11113183
28. Smiraglia, D., Ceccarelli, T., Bajocco, S., Salvati, L., & Perini, L. (2016b). Linking trajectories of land change, land degradation processes and ecosystem services. *Environmental Research*, *147*, 590–600. https://doi.org/10.1016/j.envres.2015.11.030
29. Tang, J., Li, Y., Cui, S., Xu, L., Ding, S., & Nie, W. (2020a). Linking land-use change, landscape patterns, and ecosystem services in a coastal watershed of southeastern China. *Global Ecology and Conservation*, *23*. https://doi.org/10.1016/j.gecco.2020.e01177
30. Tolessa, T., Kidane, M., & Bezie, A. (2021a). Assessment of the linkages between ecosystem service provision and land use/land cover change in Fincha watershed, North-Western Ethiopia. *Heliyon*, *7*(7). https://doi.org/10.1016/j.heliyon.2021.e07673
31. Tolessa, T., Senbeta, F., & Kidane, M. (2017a). The impact of land use/land cover change on ecosystem services in the central highlands of Ethiopia. *Ecosystem Services*, *23*, 47–54. https://doi.org/10.1016/j.ecoser.2016.11.010
32. Twisa, S., Mwabumba, M., Kurian, M., & Buchroithner, M. F. (2020a). Impact of land-use/land-cover change on drinking water ecosystem services in Wami River Basin, Tanzania. *Resources*, *9*(4). https://doi.org/10.3390/RESOURCES9040037
33. Zhao, Q., Wen, Z., Chen, S., Ding, S., & Zhang, M. (2020b). Quantifying land use/land cover and landscape pattern changes and impacts on ecosystem services. *International Journal of Environmental Research and Public Health*, *17*(1). https://doi.org/10.3390/ijerph17010126
34. Zhao, Y., Han, Z., & Xu, Y. (2022a). Impact of Land Use/Cover Change on Ecosystem Service Value in Guangxi. *Sustainability (Switzerland)*, *14*(17). https://doi.org/10.3390/su141710867