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Land Use Land Cover Change and River Dynamics in Khageri Sub-Watershed, Chitwan, Nepal

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Abstract

Land use and land cover (LULC) is one of the important measures which shows how human activities are changing the environment. These changes reshape earth's physical surface, and also influence its ecosystem and hydrological process. This study examined LULCC and river sinuosity in the Khageri Sub-Watershed in Chitwan, Nepal. Pre-classified 10-meter Sentinel-2 land use land cover data from ESRI (Environmental Systems Research Institute) was used to create LULC maps for 2017, 2019, 2021, and 2023 in ArcGIS. Standard GIS methods were used for the change detection analysis. Sentinel-2 satellite imagery from the Copernicus Space Data Ecosystem was used to manually digitize river centerlines. River sinuosity was analysed at six segments of the Khageri River for 2017 and 2023. The selection of the study period was based on the availability of consistent, high-resolution, 10-meter Sentinel-2 data for the area. The results showed a clear trend of urbanization and land change, as the built-up areas was increased by 7% and crop and forest areas was declined by 19.60% and 4.19% respectively, from 2017 to 2023. Change in river sinuosity indicated morphological *changes that could increase flood risks and influence habitat stability in the area. The results highlight the close relationship between land use changes and river behaviour and thus emphasize the need of integrated watershed management and sustainable development planning.*

Introduction

Land use is defined as human activities carried out on land, like agriculture, settlements, or conservation zones (FAO, 2000), while land cover is the physical characteristics of the surface like forests, grasslands, and water bodies (Briassoulis, 2006; CIESIN, 2002). Human actions directly alter land cover and results in measurable land use and land cover change (LULCC). This is increasingly recognized as an important factor of environmental change (Phong, 2004; Lamichhane, 2008). According to the Intergovernmental Panel on Climate Change (IPCC, 2022), land use change, including deforestation and urban expansion, is one of the major contributors to global environmental degradation and regional climate vulnerability.

LULCC is a major global concern in areas undergoing rapid and unplanned development. These changes cause resource depletion, environmental degradation and unsustainable land-use practices (Niyogi et al., 2009; Schürmann et al., 2020; Rasool et al., 2021). Anthropogenic variables like population growth (Tiwari, 2008), their growing resource demand (Qasim et al., 2013), urban expansion (Zubair, 2006), deforestation (Lambin, 1997) and agricultural intensification (Berihun et al., 2019; Desta & Fetene, 2020) are the primary drivers of LULC. These changes are important for the development. But unplanned urbanization and development will disturb natural systems and long-term ecological stability (Riebsame et al., 1994; Betrua et al., 2019).

Biodiversity, climate patterns and hydrological cycle are influenced by LULC (Rawat et al., 2013; Kumari et al., 2014). Change in land use shift water flow, sediment transport, and river morphology (Debnath et al., 2017). Rivers naturally change its course as a result of erosion and deposition. With the growing LULC change, these processes increase the risk of flooding, habitat loss (Deb & Ferreira, 2015), and geomorphological instability (Noorazuan et al., 2003; Khan et al., 2021).

Remote sensing and Geographic Information System (GIS) are used to detect LULC patterns. Remote sensing helps to monitor surface changes over large areas. GIS helps to analyse changes across different time periods. (Lillesand et al., 2015; Foody, 2002). Medium-resolution satellite imagery, like Sentinel-2 helps to map land changes and river features accurately. This makes these technologies highly useful for watershed studies in areas with limited data.

Nepal is a developing country. This indicates how rapid population growth and economic development cause changes in land use and land cover. Anthropogenic activities have growing impact on LULCC in different ecosystems of the country (Lamichhane, 2008). According to the Ministry of Land Management, Cooperatives and Poverty Alleviation of Nepal, around 45% of the forest cover in the 1990s, has declined to approximately 29% due to timber extraction, agricultural expansion, and urbanization (Dhakal, 2014). Although urbanization has increased in recent time, the lack of region-specific studies hinders the successful implementation of mitigation strategies (Paudel et al., 2016).

The Khageri Sub-Watershed in Chitwan reflects the national trends of LULCC. Before the resettlement programs in the mid-20th-century, which include a major relocation to the Padampur area in 1995, the area was primarily covered by the forest (Dhakal, 2010; DSCO, 2017; Shrestha et al., 2020). At present, mining, land-use conversion, invasive species, unmanaged dumping, and population growth in the area have caused rapid environmental degradation.

The aim of the study is to assess trend of LULC changes and river sinuosity in the Khageri sub-watershed. This study will help to understand how the change in land use and land cover shifts river dynamics. Monitoring of LULC in the watershed area and its impact on river hydrology is helpful to develop sustainable strategies for land use, water resource management, biodiversity conservation, and disaster risk reduction in the area.

Methods and Materials

Study area

The Khageri Sub-Watershed is located in the Chitwan district of Bagmati Province, Nepal. It lies between latitudes 27º45'30" N and 27°37'04" N, and longitudes 84°27'37" E and 84°35'06" E. It covers an area of 159.74 square km, with elevation ranging between 180 and 1307 meters above sea level. Administratively, the study area covers Ichhakamana Rural Municipality (Ward 7), Ratnanagar Municipality (Wards 8-12), Kalika Municipality (Wards 1-8), and Bharatpur Metropolitan City (Wards 1, 8, 11, 12, and 29). It is subdivided into eight micro-watersheds (DSCO, 2017).

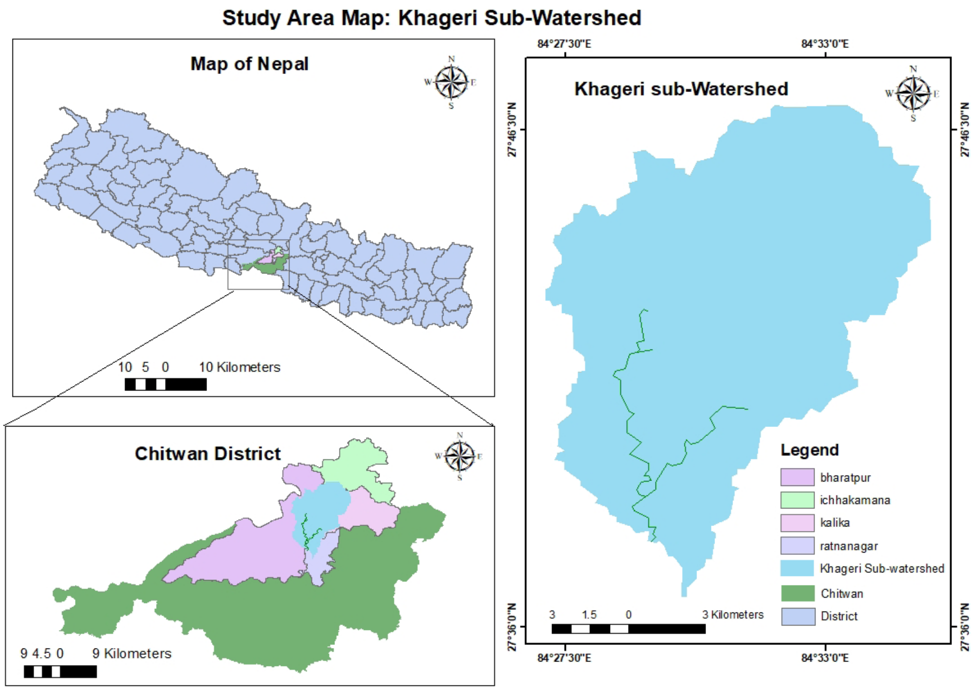

Figure 1. Location map of the study area

Land use and land cover (LULC) data of the year 2017, 2019, 2021, and 2023 were obtained from the ESRI Sentinel-2 Land Cover Explorer. The datasets have a spatial resolution of 10 meters and include pre-classified LULC categories (ESRI, 2023). The 10-meter resolution are better than the 30-meter resolution for distinction of land cover features under vegetation. The selected years were based on the availability of cloud-free and high-resolution 10-meter Sentinel-2 imagery. LULC maps were prepared for 2017, 2019, 2021, and 2023, and a change matrix was created for the period 2017 to 2023. Even though the longer-term analyses can reveal broader trends, this study mainly focuses on recent, high-resolution data to provide an accurate understanding of current land use patterns.

Satellite imagery for river sinuosity analysis

Sentinel-2 imageries were downloaded from the Copernicus Space Data Ecosystem (Copernicus, 2023). It was used to derive river centerlines for the years 2017 and 2023. The 10-meter spatial resolution of these images enabled accurate digitization of river morphology and assessment of sinuosity changes at six segments of the Khageri River. The years 2017 and 2023 were selected to align with the LULC analysis and to ensure the use of high-quality, cloud-free satellite data for both land cover and river dynamics assessment.

Field survey for river verification

In mid-June and late July 2024, field-based GPS points were collected at intervals of 200 m, 300 m, and 500 m along both riverbanks to assist in visual verification of sinuosity interpretation. River widths were also recorded at each location. All coordinates were referenced to the WGS 84 UTM Zone 45N coordinate system. These data were not used for quantitative analysis but supported the remote sensing-based centerline extraction.

Delineation of the watershed and Image classification

The watershed shapefile was obtained from the Global Watershed tool available from MG Hydro (MGHydro, 2023) and used to define the spatial boundaries for analysis in ArcGIS.

Sentinel-2 LULC data, pre-classified by ESRI, were used for analysis, utilizing specific spectral bands included in the dataset.

Table 1. Description of LULC classes

Value	Color	Label	Description
1		Water	Areas where water was predominantly present throughout the year, like rivers, ponds, and lakes
2		Tree	Any significant clustering of tall(~15 feet or higher) dense vegetation, typically with a closed or dense canopy
5		Crop	Humans planted/plotted cereals, grasses, and crops not at tree height
7		Built-up Area	Human-made structures like houses, dense villages, towns/cities, paved roads
8		Bare Ground	Areas of rock or soil with very sparse to no vegetation for the entire year, examples: exposed soil or rocks
11		Other Land	Open areas covered in homogenous grasses with little to no taller vegetation, examples: natural meadows, sparse to moderate grasses, bushes, and shrubs

The same LULC classes and color codes were used in all LULC maps.

Some portions of the area in 2019 and 2021 remained unclassified due to cloud cover, slightly affecting total percentage values in those years.

Detection of change in LULC classes

The spatial distribution and relationships of land use types were represented by LULC maps (Dhakal, 2010). Change detection, a common method in environmental studies, compares satellite imagery from different time points to analyse land cover changes (Kiage et al., 2007). In this study, Sentinel-2 LULC data from the years 2017, 2019, 2021, and 2023 were used to detect and analyse the pattern of change in the study area.

LULC maps were created for these years using ArcGIS, with the "Extract by Mask" tool applied to the Sentinel-2 imagery. The land use categories were pre-classified which include water, tree crop, built-up area, bare ground, and other land. The area of each class was calculated by the Field Calculator with the use of the formula, Area = [Count]*10*10.

Changes in area per class from one year to another was calculated using the "Calculate Geometry" tool. The rate of change was calculated using the formula, [A2-A1]/A1*100.

Change detection was performed for the period between 2017 and 2023. Map representation of change between each classes were prepared using the "Raster to Polygon" tool, followed by Geoprocessing techniques such as "Dissolve" and "Union" in ArcGIS. The area of change from one class to another was calculated using the "Calculate Geometry" tool, and the percentage of change was calculated using the formula, Area/Sum of Area *100.

Change in river dynamics

The assessment of river changes was carried out using remote sensing techniques (Sapkale et al., 2016; Yang et al., 2015). Sentinel-2 satellite images were obtained from the Copernicus Space Data Ecosystem. For 2023, a cloud-free image from October was used. Since no cloud-free October image was available for 2017, the image with the lowest possible cloud cover from a nearby date was selected. River shapefiles for both years were manually digitized from these images. All the shapefiles were geo-referenced to the WGS_84 datum and UTM Zone 45N coordinate system prior to analysis.

The sinuosity of a river is calculated to understand its meandering pattern (Schumm, 1963; Singh et al., 2013). It measures how far a river deviates from a straight path, providing valuable insights into river behaviour and the associated hydrological processes. The channel index, also known as the total sinuosity index, is defined as the ratio of the river's actual channel length and the direct straight-line distance from its source to its mouth (Mueller, 1968; Friend & Sinha, 1993).

Sinuosity Index = CL/Air

CL = the river channel's length under study

Air = the shortest air distance between the river channel's source and mouth

Channel and straight-line distances were measured from the river centerlines of 2017 and 2023. The river within the Khageri Sub-Watershed was divided into six segments of approximately 3 km each to analyse the change in sinuosity.

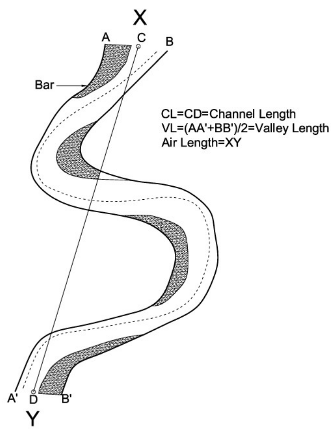

Figure 2. Mueller's sinuosity index parameters (Modified after Ghosh & Mistri, 2012)

Rivers were classified according to their sinuosity index values. An index value below 1.05 indicates a straight river, between 1.05 and 1.3 suggests a sinuous river, between 1.3 and 1.5 indicates a moderately meandering river, and an index value above 1.5 denotes a meandering river (Horacio, 2015).

Results and Discussion

Land use and land cover patterns

The LULC classification for 2017 revealed that tree was the most common land use class, covering 71.60% of the area. Crop followed this at 16.91%, Built-up Area at 9.26%, other land at 1.88%, Water at 0.26%, and Bare Ground at 0.09% respectively (Fig. 3).

In 2019, tree remained the most prevalent land use class, covering 70.56% of the area, followed by Crop, Built-up Area, Other Land, Water and Bare Ground at 14.92%, 11.82%, 2.43%, 0.20%, and 0.06% respectively.

The 2021 classification indicated that trees still dominated, covering 70.21% of the area. However, Built-up Area overtook crop, covering 14.06% of the area, while crop's coverage decreased to 13.09%. Other land, Water, and Bare Ground covered 2.27%, 0.31%, and 0.04% respectively.

Similarly, in 2023, tree was still the major land use class covering 68.60% of the area. Crop, Built-up Area, Other Land, Water, and Bare Ground covered 13.60%, 13.57%, 3.90%, 0.28%, and 0.05% respectively.

While this study focuses on the period from 2017 to 2023 and uses 10-meter pre-classified Sentinel-2 data, the analysis captures important shifts in land use land cover and provide valuable insights for local planning. These findings also provide a basis for future studies to extend the analysis over longer periods and explore more detailed classification approaches.

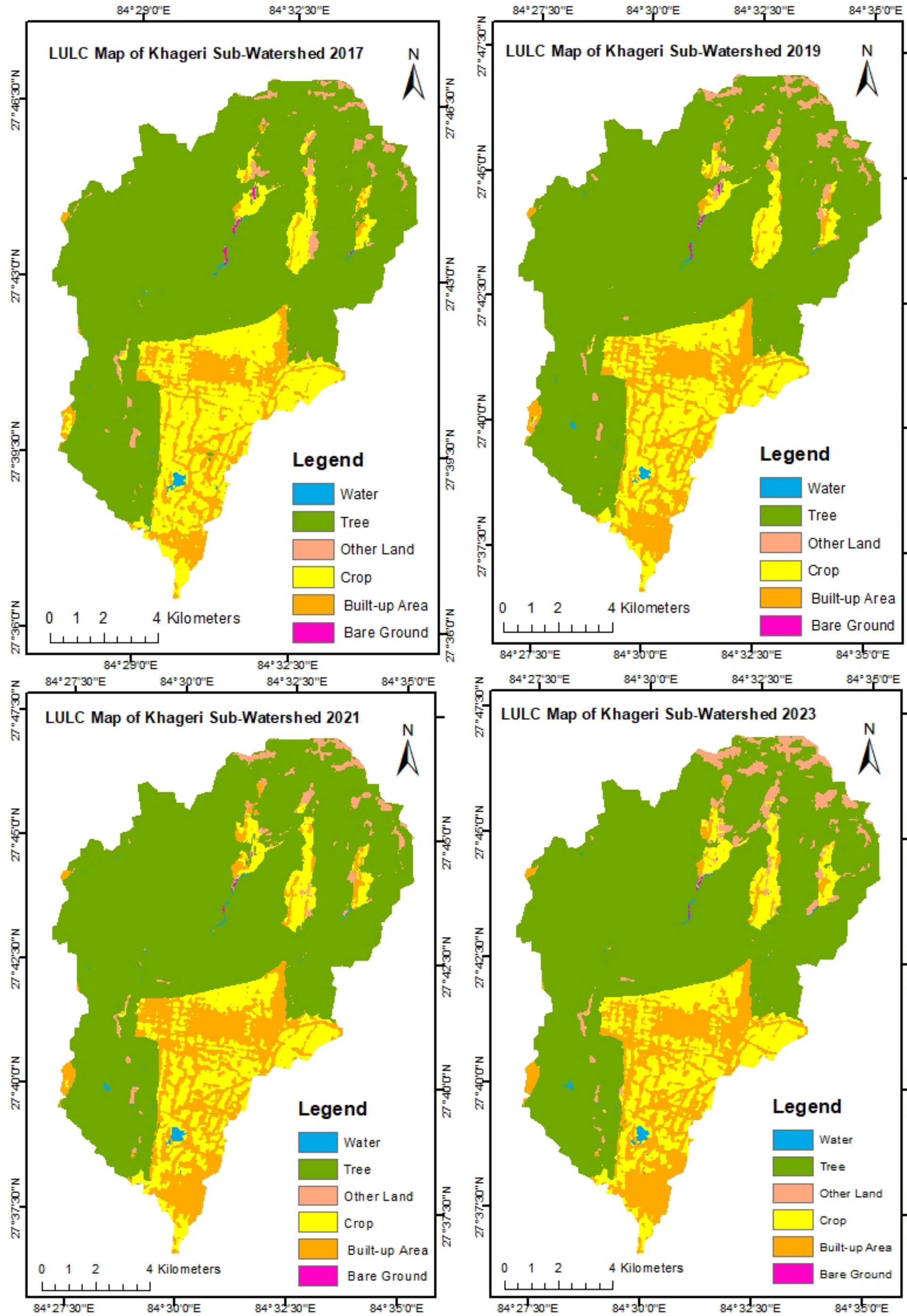

Figure 3. Land use land cover maps for 2017, 2019, 2021, and 2023

LULC dynamics over the period 2017 to 2023

The result showed that the Built-up area, other land, and water areas increased, whereas crop, tree, and bare ground areas declined over the time period of 6 years from 2017 to 2023 (Table 2).

The highest change is seen in built-up area increased by 627.92 hectares followed by an increase of 295.06 hectares in Other Land. Similarly, Water area is also increased, with a growth rate of 7.07 % over the period. Bare Ground has shown the highest relative decline at 40.15%. Crop and tree cover also have decreased by 482.98 hectares with the rate of 19.60 % and 4.19 % respectively.

Table 2. LULC Change Matrix (2017-2023)

Class		2023						
		Bare Ground	**Built-up Area**	**Crop**	**Other Land**	**Tree**	**Water**	**Grand Total**
2017	**Bare Ground**	0.048		0.014	0.006	0.0053	0.017	0.089
	Built-up Area	0	8.613	0.560	0.058	0.021	0.000	9.252
	Crop	0.002	4.591	11.993	0.263	0.038	0.025	16.911
	Other Land	0.003	0.040	0.319	1.288	0.211	0.010	1.871
	Tree	0.001	0.303	0.674	2.278	68.298	0.064	71.618
	Water	0.001	0.021	0.031	0.002	0.044	0.159	0.258
	Grand Total	0.053	13.569	13.590	3.895	68.617	0.276	100

The LULC change matrix shows that a large amount of crop land i.e 4.59 % has been converted into built-up area. Similarly, 0.0005%, 0.3%, 0.67%, 2.27%, and 0.064% of tree was converted into bare ground, build area, crop, other land, and water respectively. 0.04% of other land and 0.021 % of water has been converted into built-up area.

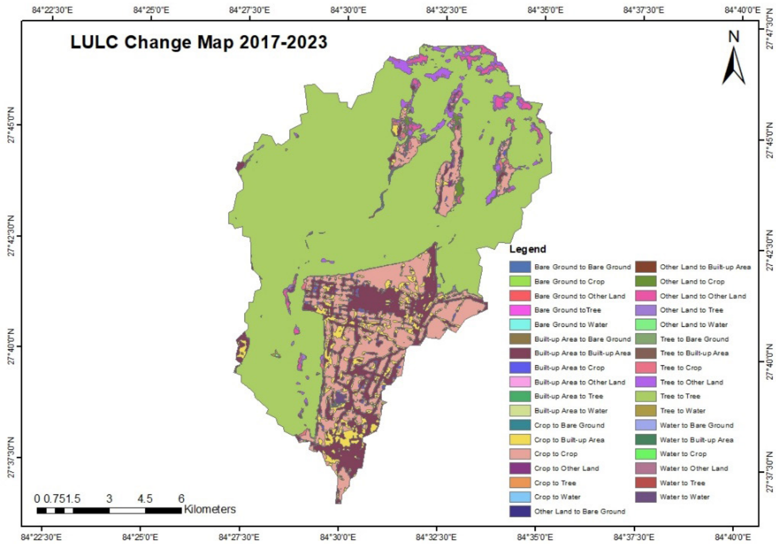

Figure 4. LULC Change Map 2017-2023

Sinuosity of the Khageri river

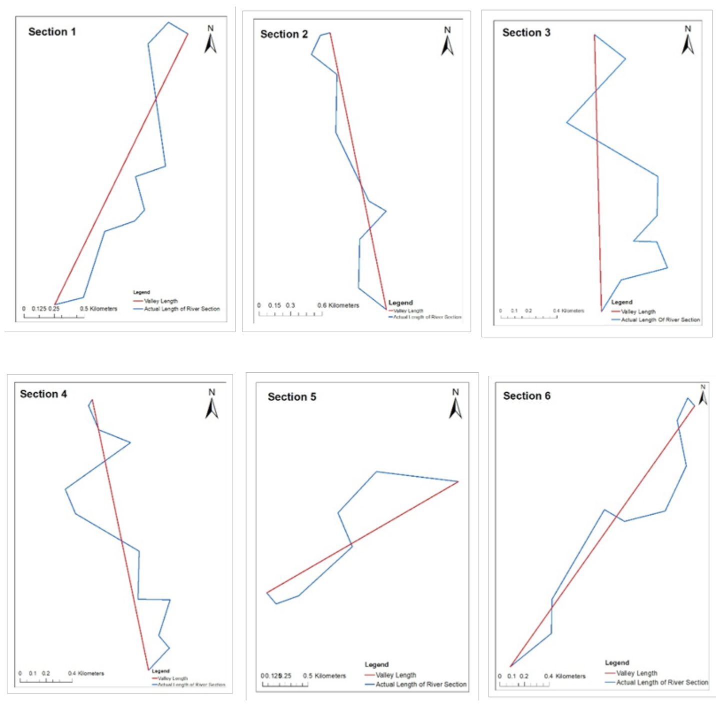

Figure 5. Sections of Khageri River

A straight stream has sinuosity 1.0 and as this number increases the stream departs from a straight line (Schumm, 1963). The sinuosity index value of the Khageri River ranges from 1.24 to 1.53 in 2017 and from 1.26 to 1.70 in 2023. The average sinuosity index was found to be 1.36 and 1.44 in 2017 and 2023 respectively. The river was found to be moderately meandering over the six years.

Table 3. Sinuosity index in 2017 and 2023

Section	Sinuosity Index in 2017	Sinuosity Index in 2023
1	1.303	1.317
2	1.241	1.263
3	1.532	1.695
4	1.338	1.691
5	1.339	1.388
6	1.421	1.302
Average	1.362	1.443

In 2017, most of the sections (1, 3, 4, 5, and 6) were found to be moderately meandering, while section 2 was found to be sinuous. In 2023, sections 1, 5, and 6 remained moderately meandering, section 2 also remained in sinuous form, and sections 3 and 4 developed into fully meandering channel. In between the years 2017 and 2023, section 4 experienced the greatest increase in sinuosity index (0.353), whereas section 6 experienced the greatest decrease (-0.119).

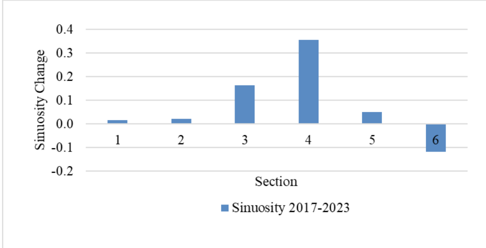

Figure 6. Graph for Sinuosity index change for 2017-2023

Interpretation of land use and land cover change

The Khageri sub-watershed shows significant changes across all land cover classes, including water, trees, crop, built-up area, bare ground, and other land. These changes draw attention to the growing urbanization and agricultural expansion. Thus understanding these changes are important for maintaining the ecological health of the watershed, as well as developing sustainable management plans so that the adverse effects of human activities on the natural environment can be mitigated.

Increased rainfall patterns and local initiatives of water conservation could be the reason for the increment of 7.07 % in the water class. The increased water bodies provide vital ecological services such as flood regulation and water purification and support regional biodiversity (Foley et al., 2020). However, runoff from surrounding land uses can cause flooding and water quality decline. There is the need of monitoring the long- term effects of these changes.

The study area experienced a decrease of 4.19% in the tree area. Tree is the major land use class of the study area. Equivalent results were observed by (Ministry of Land Management, Cooperatives and Poverty Alleviation, 2019) which shows similar decline of 45% of the forest cover of Nepal in the 1990s to approximately 29% in recent. Loss of tree cover increases soil erosion and reduction in carbon sequestration capacity. This findings raise the need of reforestation to reduce the effects of climate change (Khan et al., 2021).

The crop area showed a decrease of 19.60% between 2017-2023. According to (Neupane et al., 2019), decrease in crop area is due to urbanization and shift in farming practices. Likewise (Dhakal et al., 2014) revealed that such decrease in crop area raises food security issues in the area. This findings raise the need of sustainable farming practices to fulfil the food security of growing population.

Among all the classes, Built-up area showed the highest increase of 46.57%. According to (Rai et al., 2020), population growth and economic expansion are responsible for rapid increase in built-up area. Urbanization increase economic opportunities and infrastructure development but it also degrade natural resources and minimize green spaces. The findings raise the need of Sustainable urban planning strategies to reduce potential environmental risks. (Sharma et al., 2023).

The study area experienced a decrease of 40.15% in the bare ground area. This reflects a potential recovery of the degraded area or a shift towards more productive land uses. According to (Debnath et al., 2017), this decrease is generally positive, but monitoring of ecological health is necessary to ensure the area is safe from erosion and degradation from intensive land use practices.

The area which are not included in the above classes are termed as "other land". According to (Verburg et al., 2019), monitoring changes in Other Land provides insights on land use patterns and their potential effects habitat fragmentation and biodiversity loss.

Interpretation of river dynamics

Activities such as sand and gravel extraction, channel management, and riverbank mining cause change in river dynamics. These activities slow down the flow of river and change the slope of riverbed thereby, affecting the plan form of river and decrease its sinuosity (Ozturk & Sesli, 2015).

The sinuosity index of the Khageri River was calculated over six year period. The result showed that Section 4 experienced greatest increase of 0.353. This indicates increase in meandering. This is possibly related to the change in sediment transport, due to upstream land use activity (Langat et al., 2019). On the other hand, Section 6 went through a reduction in sinuosity of -0.119, possibly due to channelization or other human-made changes to control flood and protect infrastructure.

The change in the value of sinuosity index between 2017 and 2023 is an increase, which means a shift toward more meandering, possibly caused by the change of land use. Equivalent results were observed by (Adhikari et al., 2022) in the Seti River Sub-Basin which shows similar relationships between urbanization and river morphological changes. This validates the findings in the Khageri Sub-Watershed.

These all observed variation in sinuosity have ecological consequences. Increased meandering increases the heterogeneity of the habitat along the riverbanks, thus helps in improving biodiversity. Nevertheless, these changes also raise the threat of river bank erosion and local flooding if they are not managed properly (Shrestha et al., 2020). On the other hand, loss of sinuosity or a straight channel can also negatively affect the aquatic habitats and water quality by disrupting the sediment flow and natural hydrological patterns (Noorazuan et al., 2003).

Conclusion

This study provides insights on factors affecting land use land cover and river morphology in the Khageri Sub-Watershed, Chitwan. The results revealed the importance of integrated watershed management. This study also provides a base for future studies over longer time periods and evidence-based policy formulation.

The land use land cover maps showed the highest coverage in the area by tree in all four dates. The result shows that the built-up areas has remarkably increased by 46.57%. Similarly, the area of agricultural land and tree cover have been decreased by -19.60% and -4.19% respectively in the interval of six year (2017-2023). Crop (4.59%) is the major class contributing to the built-up area expansion.

The sinuosity index of the Khageri River was observed during the period of 2017-2023. The study was analyzed by dividing the river into 6 sections. Section 4 had a highest increase in sinuosity (0.353) and Section 6 had a decrease (-0.119). The average sinuosity index was 1.36 and 1.44 in 2017 and 2023 respectively. This represents the river to be moderately meandering over the six years.

References

Adhikari, A. R., Gurung, S. B., Adhikari, L., & Zhu, L. (2022). Assessment of land use land cover and river dynamics of Himalaya: Seti River sub-basin of Nepal. *The Geographic Base, 9*, 85–97

Berihun, M. L., Tsunekawa, A., Haregeweyn, N., Tsubo, M., Adgo, E., Meshesha, D. T., Sultan, D., Yibeltal, M., & Masunaga, T. (2019). Exploring land use/land cover changes, drivers and their implications in contrasting agro-ecological environments of

Ethiopia. Land Use Policy, 87, 104052. https://doi.org/10.1016/j.landusepol.2019.104052qasi

Betrua, T., Yimer, F., & Gashaw, T. (2019). Land use and land cover dynamics and their driving forces in the Muga Watershed, Ethiopia. *Environmental Systems Research, 8*, 1–15. https://doi.org/10.1186/s40068-019-0129-x

Briassoulis, H. (2006). Analysis of land use change: Theoretical and modeling approaches. In S. Loveridge (Ed.), *The Land Use Change Analysis (LUCA) Model: An Overview*. University of the Aegean.

CIESIN (2002). Center for International Earth Science Information Network. *Global Land Cover Data*. Columbia University.

Copernicus. (2023). Copernicus data space ecosystem: Sentinel-2 imagery access. European Space Agency. https://dataspace.copernicus.eu/

Deb, P., & Ferreira, C. M. (2015). Potential impacts of land use changes on future coastal flooding in the Chesapeake Bay. *Journal of Coastal Research, 31*(5), 1031–1043. https://doi.org/10.2112/JCOASTRES-D-14-00138.1

Debnath, M., Mukherjee, A., & Pal, S. C. (2017). Impact of land use/land cover change on morphometric parameters of drainage basin: A remote sensing and GIS based study. *The Egyptian Journal of Remote Sensing and Space Sciences, 20*(2), 263–272. https://doi.org/10.1016/j.ejrs.2016.12.003

Desta, H., & Fetene, M. (2020). Analysis of land use land cover dynamics and its impacts on the ecosystem services in northwestern Ethiopian highlands. *Journal of Environmental Systems Research, 9*(1), 1-14.

Dhakal, B. (2014). Forest cover change in Nepal: A case of the Chure region. *Banko Janakari, 24*(1), 36–40. https://doi.org/10.3126/banko.v24i1.20672

Dhakal, B. N., & Khanal, N. R. (2018). Causes and consequences of fragmentation of agricultural land: A case of Nawalparasi District, Nepal. *The Geographical Journal of Nepal, 11*, 95–112.

Dhakal, S. (2010). *Land use and land cover change in the Padampur area of Chitwan District, Nepal* [Master's thesis]. Tribhuvan University, Central Department of Geography. DSCO Chitwan. (2017). *Annual Progress Report FY 2016/17*. Ministry of Forests and Environment, Government of Nepal.

DSCO Chitwan. (2017). *Watershed Management Plan of Khageri Sub-Watershed, Chitwan District (2017–2022)*. District Soil Conservation Office, Ministry of Forests and Soil Conservation, Government of Nepal.

ESRI. (2023). Sentinel-2 Land Cover Explorer. Environmental Systems

Research Institute. https://livingatlas.arcgis.com/landcover/

FAO. (2000). *Global Forest Resources Assessment*. Food and Agriculture Organization of the United Nations, Rome.

Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., ... & Zaks, D. P. M. (2020). Solutions for a cultivated planet. Nature, 478, 337–342. https://doi.org/10.1038/nature10452

Foody, G. M. (2002). Status of land cover classification accuracy assessment. *Remote Sensing of Environment, 80*(1), 185–201. https://doi.org/10.1016/S0034-4257(01)00295-4

Friend, P. F., & Sinha, R. (1993). Braiding and meandering parameters. In S. B. Marriott & J. Alexander (Eds.), *Floodplains: Interdisciplinary Approaches* (pp. 105–111). Geological Society, London, Special Publications, 75(1). https://doi.org/10.1144/GSL.SP.1993.075.01.06

Ghosh, S., & Mistri, B. (2012). Spatio-temporal change of river course in the Ajay River Basin, Eastern India: A Remote Sensing and GIS approach. *International Journal of Geomatics and Geosciences, 3*(2), 351–363.

Horacio García. (2015). River Sinuosity Index: Geomorphological Characterisation – Technical Note. *Wetlands International Europe*.

IPCC. (2022). Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, et al., Eds.). Cambridge University Press. https://doi.org/10.1017/9781009325844

Khan, M. A., Banerjee, R., & Thakur, P. K. (2021). Spatio-temporal analysis of river morphological changes using remote sensing and GIS techniques: A case study of the Ganga River, India. *Environmental Challenges, 4*, 100088. https://doi.org/10.1016/j.envc.2021.100088

Kiage, L. M., Walker, N. D., Ramsey III, E. W., & Huh, O. K. (2007). Remote sensing-based change detection at a regional scale: A case study of southeastern Louisiana. *Remote Sensing of Environment, 108*(3), 212–223. https://doi.org/10.1016/j.rse.2006.03.005

Kumari, R., Pandey, A. C., & Nathawat, M. S. (2014). Geospatial assessment of land use/land cover dynamics and its impact on hydrological regime in Gomti river basin, India. *Environmental Earth Sciences, 72*, 4279–4294. https://doi.org/10.1007/s12665-014-3333-5

Lambin, E. F. (1997). Modelling and monitoring land-cover change processes in tropical regions.

Progress in Physical Geography, 21(3), 375–393. https://doi.org/10.1177/030913339702100302

Lamichhane, S. (2008). A review on the impact of land cover changes. *Journal of Environmental Science*.

Lamichhane, S. (2008). *Land use and land cover change and its environmental implications in the Kathmandu Valley, Nepal* [Master's thesis]. Norwegian University of Science and Technology.

Langat, P. K., Kumar, L., & Koech, R. (2019). Monitoring river channel dynamics using remote sensing and GIS techniques. *Physics and Chemistry of the Earth, Parts A/B/C, 112*, 1–10.

Lillesand, T., Kiefer, R. W., & Chipman, J. (2015). *Remote Sensing and Image Interpretation* (7th ed.). Wiley.

MGHydro. (2023). Global Watersheds Tool. MG Hydro. https://mghydro.com/watersheds/

Ministry of Land Management, Cooperatives and Poverty Alleviation (MoLMCPA). (2013). *Land Use Policy, 2013*. Government of Nepal.

Ministry of Land Management, Cooperatives and Poverty Alleviation. (2019). *National Land Policy*.

Mueller, J. E. (1968). An introduction to the hydraulic and topographic sinuosity indexes. *Annals of the Association of American Geographers, 58*(2), 371–385. https://doi.org/10.1111/j.1467-8306.1968.tb00650.x

Niyogi, D., et al. (2009). Land-use change and its effects on water resources in the United States.

Noorazuan, M. H., et al. (2003). The relationship between river sinuosity and bank erosion in the Kinta River, Malaysia. *Journal of Environmental Hydrology, 11*(1), 1–10.

Noorazuan, M. H., Ruslan, R., Juaeni, M., & Ismail, A. Z. (2003). The relationship between land use and surface water quality in the Batang Pahat River Basin. *Proceedings of the International Conference on Water Resources Management in the Era of Climate Change*.

Ozturk, D., & Sesli, F. A. (2015). Determination of Temporal Changes in the Sinuosity and Braiding Characteristics of the Kizilirmak River, Turkey. *Polish Journal of Environmental Studies, 24*(5), 2095–2112.

Paudel, B., Fu, B., Khanal, R., & Acharya, B. S. (2016). An insight into the worsening situation of land degradation in Nepal. *Environmental Management, 58*, 472–489. https://doi.org/10.1007/s00267-016-0707-9

Phong, D. X. (2004). GIS and remote sensing integration for environmental studies. In *Proceedings of the International Symposium on*

Geoinformatics for Spatial Infrastructure Development in Earth and Allied Sciences (pp. 1–9). Hanoi, Vietnam.

Qasim, M., Hubacek, K., Termansen, M., & Khan, A. (2013). Spatial and temporal dynamics of land use pattern in District Swat, Hindu Kush Himalayan region of Pakistan. *Applied Geography, 34*, 210-219.

Rai, R., Zhang, Y., Paudel, B., Khanal, N. R., & Acharya, B. K. (2020). Satellite image-based monitoring of urban land use change and assessing the driving factors in Pokhara and Bharatpur metropolitan cities, Gandaki Basin, Nepal. Journal of Resources and Ecology, 11(1), 87–99. https://doi.org/10.5814/j.issn.1674-764x.2020.01.009

Rasool, I. B., et al. (2021). Land Use Change Detection Using Remote Sensing Techniques in India.

Rawat, J. S., & Kumar, M. (2013). Monitoring land use/cover change using remote sensing and GIS techniques: A case study of Hawalbagh block, district Almora, Uttarakhand, India. *The Egyptian Journal of Remote Sensing and Space Sciences, 16*(1), 111–117. https://doi.org/10.1016/j.ejrs.2013.01.002

Riebsame, W. E., Meyer, W. B., & Turner, B. L. (1994). Modeling land use and cover as part of global environmental change. *Climatic Change, 28*(4), 427–439. https://doi.org/10.1007/BF01094014

Sapkale, J. B., Mali, M. G., & Patil, K. A. (2016). Use of remote sensing and GIS for river channel change detection: A review. *International Journal of Engineering Sciences & Research Technology, 5*(1), 76–82.

Schumm, S. A. (1963). Sinuosity of alluvial rivers on the Great Plains. *Geological Society of America Bulletin, 74*(9), 1089–1100. https://doi.org/10.1130/0016-7606(1963)74[1089:SOAROT]2.0.CO;2

Schürmann, C. A., et al. (2020). The impact of land-use changes on carbon storage in forests.

Sharma, S. K., & Pathak, S. L. (2023). *Urbanization, Population, and Environment*. Rawat Publications.

Shrestha, B. B., Paudel, S., & Tiwari, A. P. (2020). Invasive alien plant species in Chitwan National Park buffer zone: Distribution, local use and management. *Nepal Journal of Environmental Science, 8*, 1–11. https://doi.org/10.3126/njes.v8i0.30980

Shrestha, S., et al. (2020). Assessment of Land Use Land Cover and River Dynamics of Himalaya: Seti River Sub-Basin of Nepal.

Singh, A., Yadav, M., & Gupta, R. D. (2013). Morphometric analysis of river catchments using GIS and remote sensing techniques: A case study of Kanhar river basin, India. *Journal of Water Resource and Protection, 5*(10), 953–961. https://doi.org/10.4236/jwarp.2013.510098

Tiwari, K. R., Balla, M. K., & Bajracharya, R. M. (2008). Spatial and temporal dynamics of land use/land cover changes in western Chitwan, Nepal. Himalayan Journal of Sciences, 5(7), 57–62. https://doi.org/10.3126/hjs.v5i7.1470

Verburg, P. H., et al. (2019). Beyond land cover change: Towards a new generation of land use models. *Journal of Land Use Science, 14*(1), 1–4.

Yang, X., Zhao, W., & Fu, B. (2015). Monitoring spatial and temporal variations of river channel migration using multi-temporal satellite images: A case study of the Yellow River, China. *Geomorphology, 228*, 303–313. https://doi.org/10.1016/j.geomorph.2014.09.017

Zubair, A. O. (2006). Change detection in land use and land cover using remote sensing data and GIS: A case study of Ilorin and its environs in Kwara State. *Remote Sensing Journal, 1*(2), 48–55.

Neupane, B. K., Acharya, A., & Thapa, L. (2019). Local People's Perception on Climate Change at Kamalamai Municipality, Sindhuli. The Geographic Base, 6, 21–31. https://doi.org/10.3126/tgb.v6i0.26164

Neupane, B. K., Mandal, U. K., Al-Quraishi, A. M. F., Ozdemir, M., & Rai, R. (2023). Environmental threat of soil erosion in the Gwang Khola Watershed, Chure Region of Nepal. Iraqi Geological Journal, 56(1E), 194– 206. https://doi.org/10.46717/igj.56.1E.14ms-2023-5-24.