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Application of Remote Sensing and Geographic Information System for Evaluating Morphological Changes in East Rapti River

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Abstract

Rivers are a vital part of ecosystems as well as components in sustaining countless communities. They are dynamic systems that are susceptible to morphological changes caused by factors like flood and sedimentation. Such changes can lead to increased flood risks, erosion, damage to structures, and changes in water quality. River geomorphological changes play a significant part in flood risk management. This study focuses on the East Rapti River in Nepal, a region vulnerable to riverbed alterations due to natural and human-induced factors. The study evaluated the patterns of erosion and accretion between 1995 AD and 2023 AD. Through the analysis of satellite imagery and the Water Ratio Index (WRI), this study reveals a significant accretion in the Lothar-Sauraha section of the river. This section has experienced a rise in riverbed elevation. Likewise, river path shifts have been observed in the same section, with the river now flowing in proximity to the East Rapti Dike, posing risks to its integrity. This study underscores the need for proactive measures to manage river morphological changes and protect vulnerable communities and infrastructures.

Keywords

Accretion, Aggradation, East Rapti River, Erosion, GIS, WRI

1. Introduction

Rivers, vital components of ecosystems and lifelines for many communities, undergo continuous changes [1, 2], shaping landscapes and influencing communities' well-being [3, 4, 5]. It has been shown that the effects of floods have increased significantly over the years [6]. In recent years, the issue of morphological changes has become a major concern for communities living along the riverside. It has been identified as one of the major causes of flooding [7]. This can lead to several problems, including increased flood risk, river bank erosion, and changes in water quality [8]. The causes of riverbed changes are complex and can include natural factors such as changes in climate and vegetation cover, as well as human activities such as deforestation, agriculture, and sand mining [9, 10]. These changes are emerging as a significant concern for riverside communities, contributing to heightened flood risks, riverbank erosion, and alterations in water quality [7, 8].

In striving for equilibrium, where sediment transport matches output, rivers undergo morphological changes, manifesting as accretion, erosion, aggradation, meandering, cutoffs, increased slope, or degradation [11, 12]. When a river, by some modification or influencing factors, increases its capability to carry more sediment, the river tries to reach equilibrium by picking up extra sediment and vice-versa [12]. This equilibrium, disrupted by imbalances, prompts morphological changes that impact river systems.

Riverbed accretion, the gradual buildup of sediment over time, results from factors like sediment supply, channel morphology, and hydrological conditions [11, 13]. In contrast, riverbed erosion involves the removal and transport of sediment, influenced by natural events and anthropogenic activities [14]. Aggradation and degradation, while resembling accretion and erosion, differ in terms of land elevation increase or decrease due to sediment deposition or removal [14]. Generally, erosion and accretion occur simultaneously as accretion is often caused by erosion from upstream [15].

The impacts of riverbed accretion, erosion, and aggradation are varied and significant. Excessive river bed accretion can lead to channel avulsion, backwater effects, and increased flood risk. It can also reduce channel capacity, increase the risk of sedimentation in reservoirs and water intakes, alter the ecological functioning of the river system; and decrease the agricultural output [16, 17]. On the other hand, severe riverbed erosion can cause channel incision, bank instability, and habitat degradation. It can also lead to increased sediment transport downstream, sedimentation in reservoirs, and infrastructure damage [18].

Against this backdrop, this study aimed at quantifying river geomorphological changes in the East Rapti River. These changes, influenced by factors ranging from climate shifts to human activities, have raised concerns about the escalating flood risk in the region. Historical flood events, notably the catastrophic flood of 1993, have prompted proactive measures, including the construction and maintenance of dikes and spurs, supported by local communities and the Government of Nepal in collaboration with international donors [19]. The specific problem addressed in this research stems from the notable sediment buildup observed in the Lothar-Sauraha section of the East Rapti River [19]. This sediment accumulation is feared to exacerbate over time, potentially intensifying flood propagation and causing damage to critical infrastructures such as the Rapti Dike.

2. Study Area

Nepal, situated in the central Himalaya region, shares its borders with India on three sides and China to the north. The country's steep topography, coupled with heavy rainfall, leads to frequent flash floods. Nepal is characterized by three major river basins: Koshi, Gandaki, and Karnali, along with numerous smaller watersheds in the southern plains. Notably, the East Rapti River, a tributary of the Gandaki River basin, originates in the Mahabharat mountain range and eventually joins the Narayani River. This basin is densely populated, with a growing urban population in the key cities of east Bharatpur and Hetauda. The East Rapti River plays a vital role as a water source for irrigation, drinking, and other domestic uses in the Chitwan Valley [20]. However, significant changes in the river's morphology have occurred over recent decades due to a combination of natural and anthropogenic factors [21].

This research focuses on the East Rapti River from its confluence point with Sameri Khola, (see Figure 1) from which it avoids narrow channels of Mahabharat and Churia hills and begins flowing in wider channels, from Hetauda to its confluence with the Narayani River, covering the years from 1995 to 2023. The objective of this study is to quantify historical changes in river morphology, in terms of accretion and erosion level, path shifts; and level of aggradation.

The study area encompasses the East Rapti River, which traverses most of the Chitwan Valley. Its tributaries originate from the Siwaliks and Mahabharat Range. Based on the 30-meter Shuttle Radar Topographic Mission (SRTM) Digital Elevation Model (DEM) data, the elevation of the watershed ranges from 75m to 2500m. Likewise, most of the East Rapti Watershed is covered by forest, encompassing 68 percent of the total land area [22]. The basin receives roughly 2250 mm of rainfall annually, 90 percent of it during the monsoon season [23].

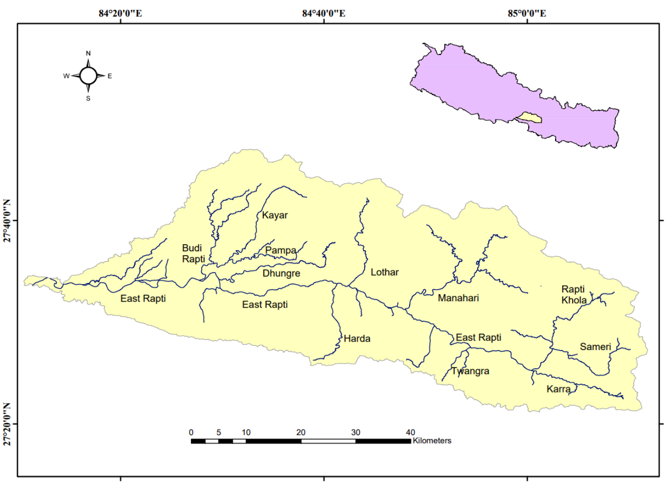

Figure 1: East Rapti River Watershed with its Major Tributaries and Location in Nepal

This region is highly agricultural, with one-quarter of the land comprising cultivated land [22]. Notable tributaries of the East Rapti include Pampa Khola, Dungre Khola, Lothar Khola, Budi Rapti, Manahari, and more. The watershed encompasses the majority of Chitwan and Makwanpur districts, covering an area of 2529 sq. km.

The East Rapti River Basin has witnessed a series of severe flood events in its history, most notable one in 1993 AD (2050 BS), resulting in the loss of many lives along with extensive property damage [19]. In response to this event, local communities and the Government of Nepal (GoN), with financial support from international agencies like Swiss Aid and Asian Development Bank (ADB), have taken proactive measures for the construction and maintenance of river dike in Rapti and Lothar rivers [19].

3. Methods

Morphological changes in East Rapti River were realized in terms of accretion and erosion areas, level of aggradation, and path shifts between years 1995 and 2023. The January of 1995 was taken for study for being just over a year since the devastating monsoon of 1993 AD, which occurred in July/August and contributed to serious landform changes [19], while the January was for clearer satellite images due to less cloud cover. Areas of erosion and accretion between the years 1995 and 2023 were obtained using remote sensing data, raster calculations, and other Geographic Information System (GIS) tools. Rivers for the years 1995 and 2003 were extracted by calculating the Water Ratio Index (WRI). The Water Ratio Index (WRI) in GIS is a quantitative tool used to assess the distribution and relative abundance of water bodies within a given geographic area [24]. Landsat satellite imageries of 30m resolution were used in calculating WRI. In GIS, a WRI map can be generated by using the following raster calculations.

$$\text{WRI} = \frac{\text{Green} + \text{Red}}{\text{NIR} + \text{SWIR}}$$

Where, Green, Red, NIR, and SWIR are all bands. NIR and SWIR stand for Near Infrared and Short-Wave Infrared respectively [24].

For, raster calculation using Landsat 5 imagery,

$$\text{WRI} = \frac{\text{Band 2} + \text{Band 3}}{\text{Band 4} + \text{Band 5}}$$

Whereas, for Landsat 9,

$$\text{WRI} = \frac{\text{Band 3} + \text{Band 4}}{\text{Band 5} + \text{Band 6}}$$

WRI values range from 0 to above, where higher values indicate a larger proportion of water bodies relative to the total area. A WRI close to 0 suggests a scarcity of water bodies, while a WRI close to 1 indicates a high concentration of water bodies within the study area. The satellite and bands used are summarized here in the following table.

Table 1: Satellite Imagery Data Used in this Study

Year	Satellite Mission	Bands Used	Remarks
1995	Landsat 5 Level 2	2, 3, 4, 5	Image Quality = 9; Ground Control Points = 5
2023	Landsat 9 Level 2	3, 4, 5, 6	

The WRI maps were generated for the years 1995 AD and 2023 AD as follows.

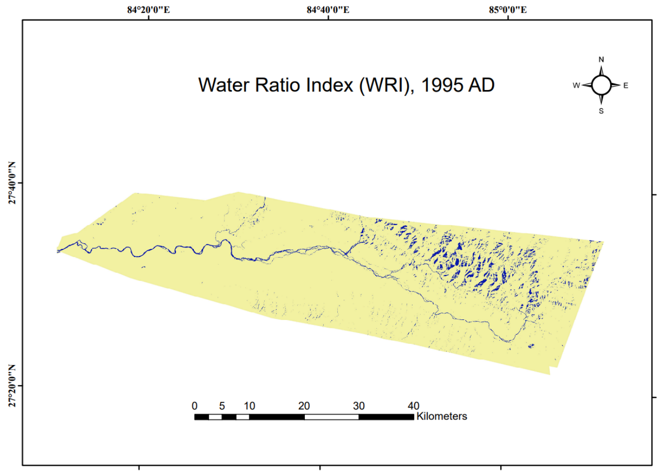

Figure 2: WRI for the Year 1995 AD

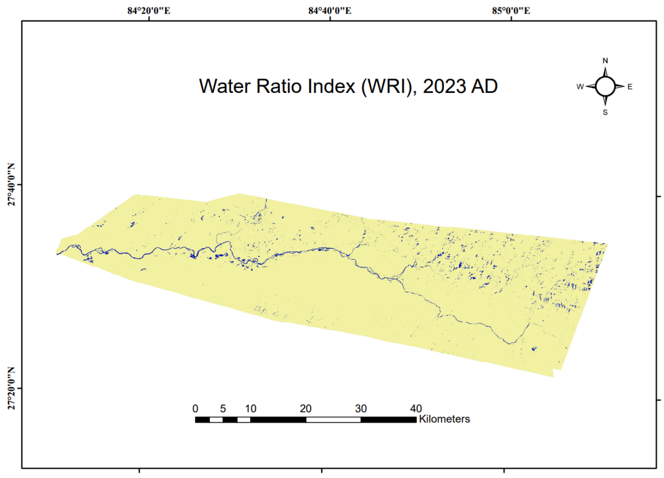

Figure 3: WRI for the Year 2023 AD

Once, converted to polygons using the 'raster to polygon' function, the WRI map helped in the extraction of the river for the required years. The river was broken down into 4 sections.

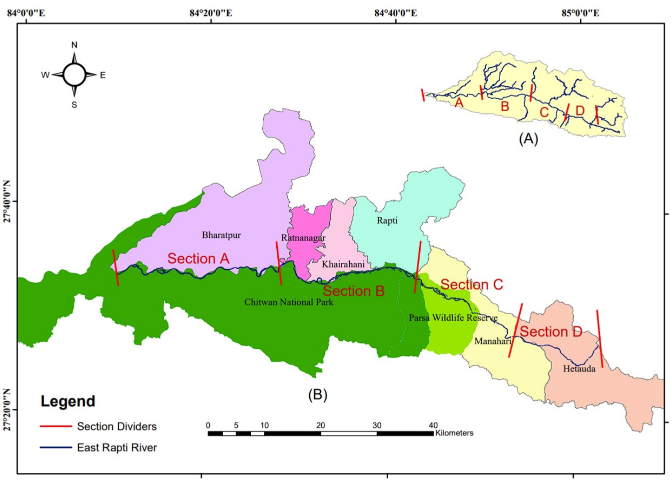

Figure 4: (A) East Rapti River Divided into Sections, (B) The Sections Corresponding to Different Administrative Zones

Section A from the confluence point with Budi Rapti to the confluence point with Reu Khola just near Narayani River. This section lies wholly on the border between Chitwan National Park and Bharatpur Metropolitan City. Similarly, Section B of the river flows in East Chitwan, between confluence points with Lothar Khola and Budi Rapti. Sections C and D lie in Makwanpur districts and flow through Manahari Municipality and Hetauda Sub-Urban Municipality respectively.

The amount of Accretion and Erosion, in terms of Area, can be determined in a section by using the 'Intersect' tool. Intersect function was used for determining unchanged area. River areas for each year were obtained from attributes tables.

The area of accretion and erosion in a river can be determined as:

Area of Accretion
= Area of River Previous Year – Unchanged Area

Area of Erosion
= Area of River Next Year – Unchanged Area

A river section can be said to be in balance if the area of Accretion is comparable to the area of Erosion. But, if the area of accretion exceeds that of erosion, it can be concluded that this is an aggrading river whereas, if the area of erosion is larger, the river in that section is going degradation.

Key-informant interviews (KII) were also conducted in the Lothar-Sauraha section (Section-B) to get a rough estimate of the level of aggradation.

4. Results and Discussions

The river for years 1995 and 2023 is compared with each other for each section. River shapes for the years 1995 and 2023 along with unchanged areas for each section are shown below.

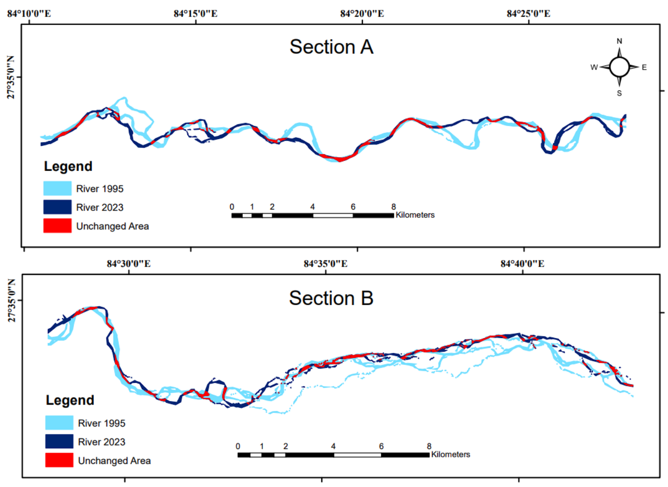

Figure 5: River Shapes for years 1995 and 2023 in Sections A and B

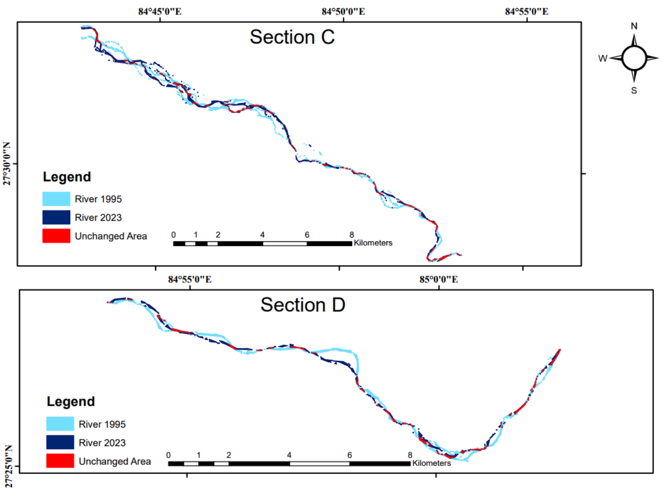

Figure 6: River Shapes for years 1995 and 2023 in Sections C and D

The erosion and accretion across the river were determined to be as follows.

Table 2: Erosion and Accretion Status Between Years 1995 AD and 2023 AD

Sections	Unchanged Area (ha)	Erosion (ha)	Accretion (ha)
A	109.92	293.43	479.56
B	84.66	196.16	436.57
C	25.42	105.71	140.01
D	19.20	48.25	92.84

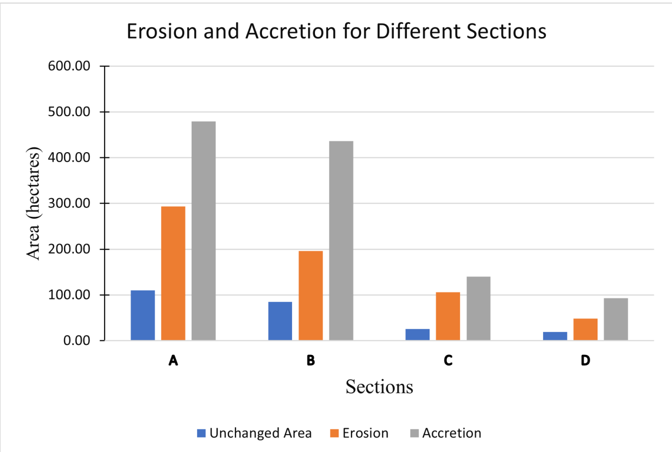

Figure 7: Accretion and Erosion Level in Different Sections

From Table 2 and Figure 7, it is quite clear that there is more accretion than erosion in all sections. Only Section C (Manahari section) seems a little bit balanced in terms of erosion and accretion. Significant accretion was observed in Section B (Lothar-Sauraha section) in comparison to erosion. Accretion being high throughout the river in comparison to erosion confirms the river is going aggradation throughout its length. Further, the KII survey conducted in the Lothar-Sauraha section gave a rough estimate that the river has aggraded 1.85m from 1995 AD till now at a rate of 0.066m per year in that section which is similar to that provided by Singh (2013)[19] i.e., 2m to 3m for 1989 to 2012. One of the major reasons for high accretion can be attributed to the high amount of sediment output from right bank tributaries Lothar and Manahari. The basins of Lothar and Manahari suffer high erosion due to landslides and other anthropogenic activities leading to high sediment output into the East-Rapti River.

Likewise, the river has witnessed path shifts, the most significant of which is in the Lothar-Sauraha section or Eastern Chitwan, which also has the presence of a river dike, of very critical importance for preventing floods in Eastern Chitwan.

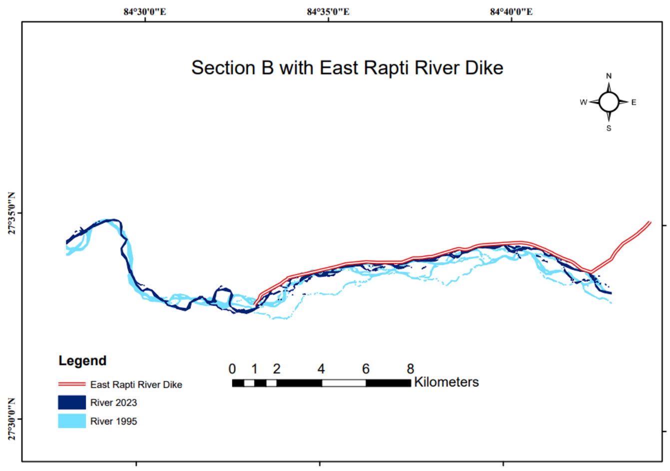

Figure 8: Section B of the River with East Rapti Dike

Figure 8 shows that the East Rapti river has moved very close to the dike almost 2 kilometers at some points. There are many braided channels in Section B in the year 1995 but there are almost no braided channels in the year 2023 and the river is flowing close to the dike eroding the bed around there.

This can have serious implications regarding the integrity of the dike as it puts the dike itself vulnerable to erosion. In fact, during the site visit, a few places in the East Rapti River dike were observed to have been slowly eroded by the river as shown in 9.

Figure 9: East Rapti River Eroding the Dike near Girijachowk

The river path shift in Section B can be attributed to the Harda Khola (see Figure 1) which joins Rapti in the easternmost part of this section on the left bank. During flooding events, Harda Khola can redirect the river's flow towards the north, closer to the dike.

5. Conclusions and Ways Forward

The study evaluated the morphological changes in terms of patterns of erosion and accretion between 1995 AD and 2023 AD by the use of satellite imageries and calculating WRI. The study revealed that there has been significant accretion in the East Rapti River, the most in the Lothar-Sauraha section. The riverbed in that same section was determined to have risen by around 1.85m in the year since 1995 AD. Moreover, the study has highlighted the shifting of the river path, particularly near the critical East Rapti Dike, which poses a potential threat to its integrity and, consequently, the safety of the surrounding communities. These findings underscore the importance of proactive measures to manage and mitigate the impacts of river morphological changes in this vulnerable region.

While moving forward, it is recommended that research efforts to monitor riverbed changes, sediment transport, and the impact of human activities on the East Rapti river system should be continued. Further, the collection of data regarding the cross-section of the river should be carried out at hydrological stations at Lothar, Manahari, and Rajaiya. This helps in better quantifying aggradation and degradation over time. Implementation of a robust river monitoring system to continuously assess the East Rapti River's morphological changes utilizing remote sensing and Geographic Information System tools for real-time data collection and analysis. Finally, conducting a comprehensive flood risk assessment, and prioritizing watershed management, especially in the Lothar and Manahari Khola to address the sediment output from those tributaries are other activities that can contribute to maintaining river morphology within acceptable form.

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