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Unveiling Nepal's River Dynamics: A Remote Sensing Exploration of Koshi, Narayani, and Karnali Rivers

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Abstract

Summer monsoon from Indian Ocean is the main source of precipitation in Nepal and its impact varies across regions. In the eastern Koshi Basin, the impact of the monsoon is stronger than in western Karnali Basin, leading to more soil erosion in the eastern hills. This is reflected downstream of the basin where river flow meets the low-lying flat terrain and exhibits dynamic river morphology. This paper thus explores the morphological changes within the three prominent rivers of Nepal: Koshi in the east, Narayani in the central region, and Karnali in the west, which are characterized by widths exceeding one kilometer and serve a critical role for the region's ecosystems and human settlements. The change in the river morphology was analyzed from the satellite images using Remote Sensing Techniques within Google Earth Engine (GEE) and GIS environment. Modified Normalized Difference Water Index (MNDWI) was used to extract waterbody to avoid the overestimation of extracted water obtained caused by land noise. To quantify the stability of these rivers, it was vital to assess the percentage of unchanged water area, thus, decadal comparison from 1990 to 2022 was performed. Narayani river is notably stable with maximum of 64.8% unchanged area, followed by Karnali River at 54.5% and Koshi River at 32.5%. This underscores Koshi's versatile morphology, a conclusion further supported by its higher westward channel shift in terms of planar water area of up to 3871 m. However, due to the larger valley area of the study reach of Karnali, it shows the highest average erosional rate of 2.322 km^2/year followed by Koshi River with 1.629 km^2/year and Narayani River with 1.602 km^2/year. This paper thus can be seen as a steppingstone for further research into river dynamics which can aid sustainable management plans for the basins.

Keywords

River Morphology, Koshi, Narayani, Karnali, Remote Sensing, GEE, JavaScript, GIS.

1. Introduction

Geomorphology provides comprehensive and methodical framework to understand river functioning that affects river biodiversity [1]. The ever changing and intricately woven process of channel development and modifications are more evident in braided rivers [2]. Bank erosion, down cutting, and bank accretion are very common phenomena within the floodplains that leads to a considerable shift of channel position along the river course [3] of braided rivers which results socioeconomic and environmental losses due to the deposition of high amount of eroded sediments into the downstream [4, 5]. Shifts in river channels are linked to diverse factors like characteristics of the drainage basin, climate, geology, hydrology, and human activities [6]. These include natural aspects such as soil composition, riverbank shapes, vegetation, and land use, along with flooding as major contributor. River shifts are a hazard to floodplain communities, necessitating strategies based on solid grasp of channel changes over time. Among the existing river planform types, braided rivers have one of the most complex bio morphologic structures that leads to more dynamic river functions [7]. Prediction of changes happening in the channel character of braided rivers due to change in discharge does not occur to be feasible [8] as its morphology exhibits a high degree of nonlinearity and complexity [9]. Since the concept of river channel morphology was offered by [10], the expression of morphological characteristics in rivers has begun to receive attention from different field.

Continuous efforts are required to ascertain if distinctive channel patterns that appear visually different can be consistently identified [11]. Therefore, using multiple satellite images over time became a practical solution to gain better insights into these rivers which has been performed in this study. Thus, the study seeks to explore the spatial variability of morphological changes in the Himalayan braided rivers and identify key areas where these changes occur. This spatial analysis is essential for identifying the locations most vulnerable to morphological transformations and understanding the factors influencing these changes. By determining the causes of morphological alterations, such as erosion, sedimentation, effective strategies can be proposed for river management and restoration.

2. Study Area

Three distinct study areas namely Koshi in the east, Narayani in the center, and Karnali in the west have been selected to represent Nepal's spatial distribution from east to west as shown in Figure1.

2.1 Koshi River

The Koshi river system is situated in the eastern region of Nepal, encompassing a drainage area originating from the Himalayan

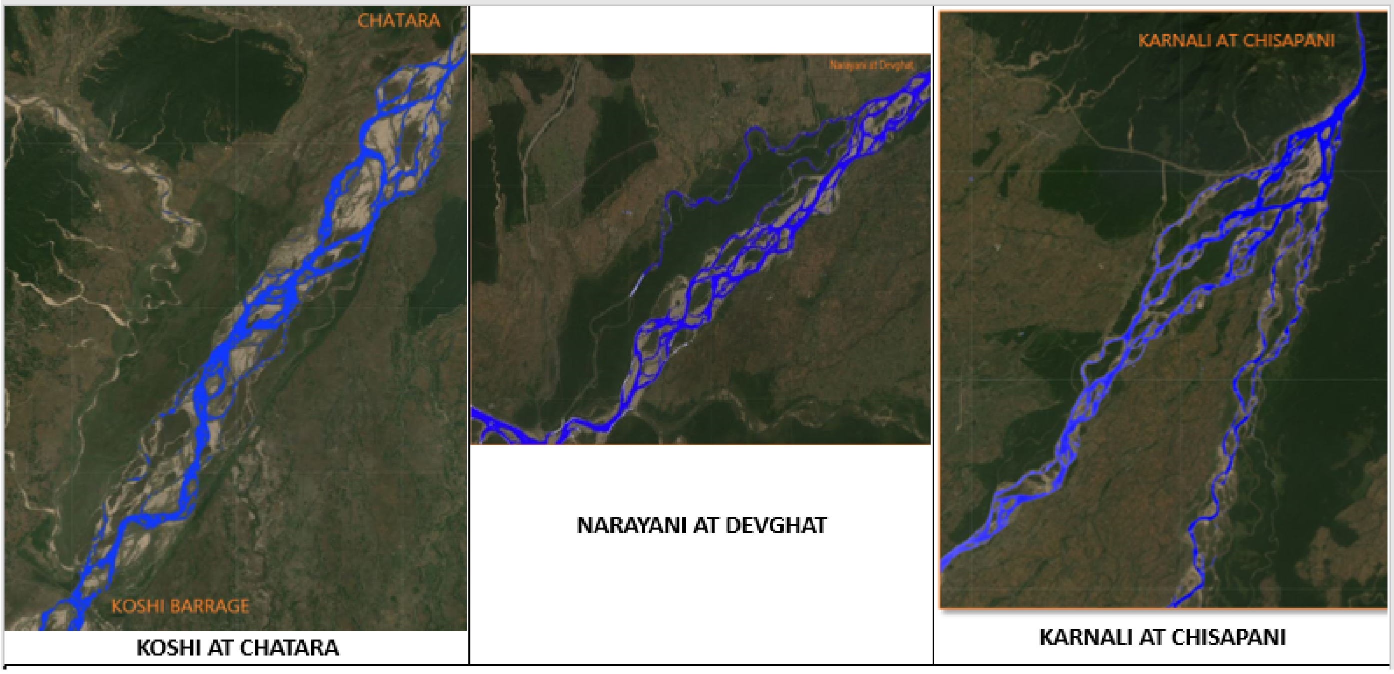

Figure 1: Study sites: Koshi at Chatara(left), Narayani at Devghat(middle) and Karnali at Chisapani(right)

territories of both China and Nepal. The river system spans between Longitudes 86°53'00" E to 87°11'000" E and Latitudes 26°31'00" N to 26°50'00" N. The tributaries of the Koshi traverse the diverse terrain of the Himalayan, Mahabharat, and Siwalik ranges, conversing in the extensive lower alluvial plains. Given its immediate downstream positioning at the confluence of the three primary tributaries namely Sunkoshi, Arun and Tamor at Tribeni, Chatara has been identified as the focal study area. Thus, the study river reach has been selected spanning from Chatara to the Koshi barrage extending 42 km in length with remarkably gentle gradient of merely 1:2000 [12].

2.2 Narayani River

The Narayani River system also referred as Gandaki River, is situated in the central region of Nepal, spanning latitudes 25.49° to 29.28° N and longitudes 85.02° to 85.83° E. Operating as a transboundary river basin, it originates from the southern fringes of China, courses through Nepal and finally contributes to the Ganges River in India encompassing a total area of 46,300 Km^2 [13], 31100 Km^2 of which lies within Nepal. The Narayani River basin boasts a complex network of tributaries, among them are Marsyandi, Daraudi, Seti, Madi, Kali Gandaki, Budhi Gandaki, and Trishuli. The study river reach has been selected spanning from Devghat to Baguban extending 54 km in length.

2.3 Karnali River

The karnali River, situated in the western region of Nepal stretches across latitudes 28°26' N to 28°67' N and longitudes 80°97' E to 81°28' E which covers an area of approximately 789 Km^2 with about 522 Km^2 within Nepal [13]. The catchment area of Karnali basin is 45440 Km^2 [14]. The karnali Megafan is demarcated by Churiya Range in north, to its east lies Bardiya National Park, while its western boundary is enclosed by Mohana watershed.The study river reach has been selected spanning from Karnali Bridge to Kailashpuri Dam extending 45 km in length. The fan shaped topography has an approximate elevation of 260 m above msl and extends into 139m above msl along Indo-Nepal border [15]

3. Methodology

In this research, same methodologies are applied for all three study area. Throughout the study, the Google Earth Engine (GEE) platform and Geographic Information Systems (GIS) were instrumental in performing the necessary tasks for the findings. GEE offers a convenient and efficient way to extensively use remote sensing data, including Landsat imagery, which can be directly accessed, filtered, and analyzed using the Earth Engine Code Editor using JavaScript.

3.1 Data Processing Workflow

The data processing workflow consists of numerous steps to analyze Landsat surface reflectance imagery:

1. Delineation of the Region of Interest (ROI) using prescribed variables.
2. Establishment of specific start and end dates to form the Landsat surface reflectance collection.
3. Refinement of the collection to obtain the least cloudy image.
4. Selection of red, green, and blue bands, with their median values used to generate a true-color composite.
5. Selection of the Modified Normalized Difference Water Index (MNDWI) to identify water bodies.

The MNDWI is a variation of the NDWI designed to improve the detection of water bodies in satellite imagery. It is calculated

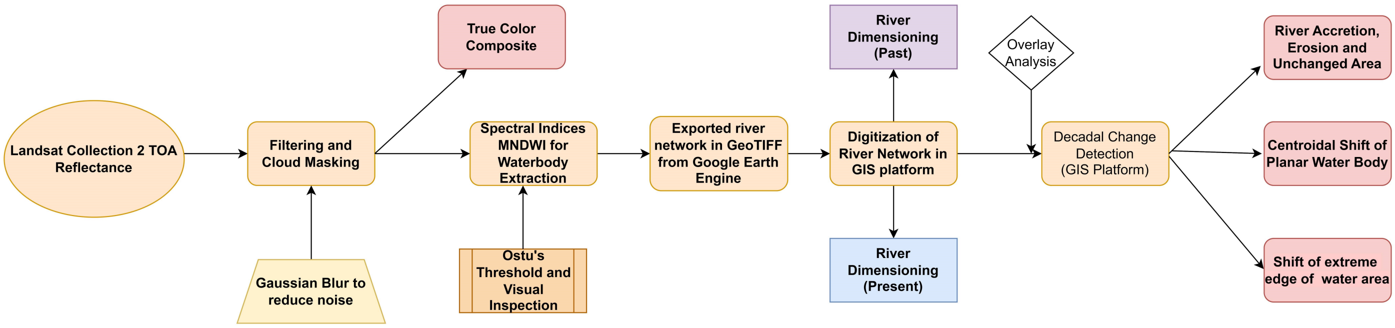

Figure 2: Methodology for Research

using the green and shortwave infrared (SWIR) bands of a sensor, typically using the following equation [16]:

$$MNDWI = \frac{Green - SWIR}{Green + SWIR} \quad (1)$$

Compared to the Normalized Difference Water Index (NDWI) originally proposed by [17], the MNDWI assigns a positive value to water and a negative index to built-up land, enhancing the contrast between these features for more accurate water body extraction [18]. Therefore, the MNDWI algorithm, being widely applied and robust [19], is used in this study.

3.2 Data Filtering

Filtering of the MNDWI was performed using Otsu's threshold method, along with visual inspection of overlayed MNDWI layers over true-color images. The stretch function was applied to enhance image contrast, and Gaussian blur was used to reduce noise. The MNDWI layer was then clipped to the ROI and added as a transparent overlay. The final MNDWI layer, obtained after further thresholding, was exported as a GeoTIFF file to Google Drive.

3.3 River Network Digitization

Further processing of the obtained file was performed in the GIS platform to digitize the river network. Overlay analysis was conducted to detect decadal changes, determining river accretion, erosion, and unchanged areas. Unchanged areas were identified using the intersection tool in GIS. Accretion and erosion areas were calculated as follows:

$$\text{Accretion Area} = \text{Previous Year Area} - \text{Unchanged Area} \quad (2)$$

$$\text{Erosional Area} = \text{Next Year Area} - \text{Unchanged Area} \quad (3)$$

Centroidal shift of planar water bodies and channel shift of the extreme edge of the riverbank were determined by dimensioning the river shapefile within the AutoCAD environment.

4. Results

The outcomes of the results are displayed herein as seen in Figure 3, depicting distinct colors for delineating accretion, erosion, and unchanged areas as specified in the legend. The comparative timeline spans from 1990 to 2022.

4.1 Koshi River

The comparison begins with the period from 1990 to 2000, where an erosion area of 16.349 Km^2 and an accretion area of 17.734 Km^2 were observed in the Koshi region. Additionally, 8.545 Km^2 of land remained unchanged during this time. Moving on to the period from 2000 to 2010, the erosion area increased to 18.138 Km^2, while the accretion area also saw an increase to 21.773 Km^2. The unchanged area measured was 6.756 Km^2. In the most recent comparison from 2010 to 2022, the erosion area was recorded as 17.657 Km^2, with an accretion area of 29.633 Km^2. The unchanged area during this period was measured to be 10.872 Km^2. These measurements highlight the dynamic nature of the Koshi region's landscape, with areas experiencing a significant amount of both erosion and accretion over time.

Centroidal shift of planar water body in meters in the Koshi river at Chatara reveals changing dynamics. Between 1990 and 2022, the centroid shifted northward by 2718 meters in 2000, then southward by 5154 m in 2010, before again moving northward by 2721 m in 2022. These shifts highlight the river's evolving nature over time.

The sections taken vary for different time periods, as illustrated in Figure 4. This approach was undertaken to effectively capture the most significant shifts in the outermost bank line, thus providing a better representation of the maximum channel shift. The eastward movement towards the left bank has been considered as positive, and negative value signifies westward movement. The channel shift from 1990 to 2000 as well as between 2010 to 2022 predominantly reveals westward shift in the mid-section with relatively less shift towards upstream and downstream near the barrage. This may be due to the controlling of the river channel by the construction of a barrage and levees constraining the floodplain, as indicated by [12]. However, notable westward channel migration occurred from 2000 to 2010, particularly evident in a significant movement of -3871 m at section 5 with eastward movement of up to 566 m at section 3

Summary of the decadal comparison of erosion and accretion areas for the Koshi River is presented in Table 1

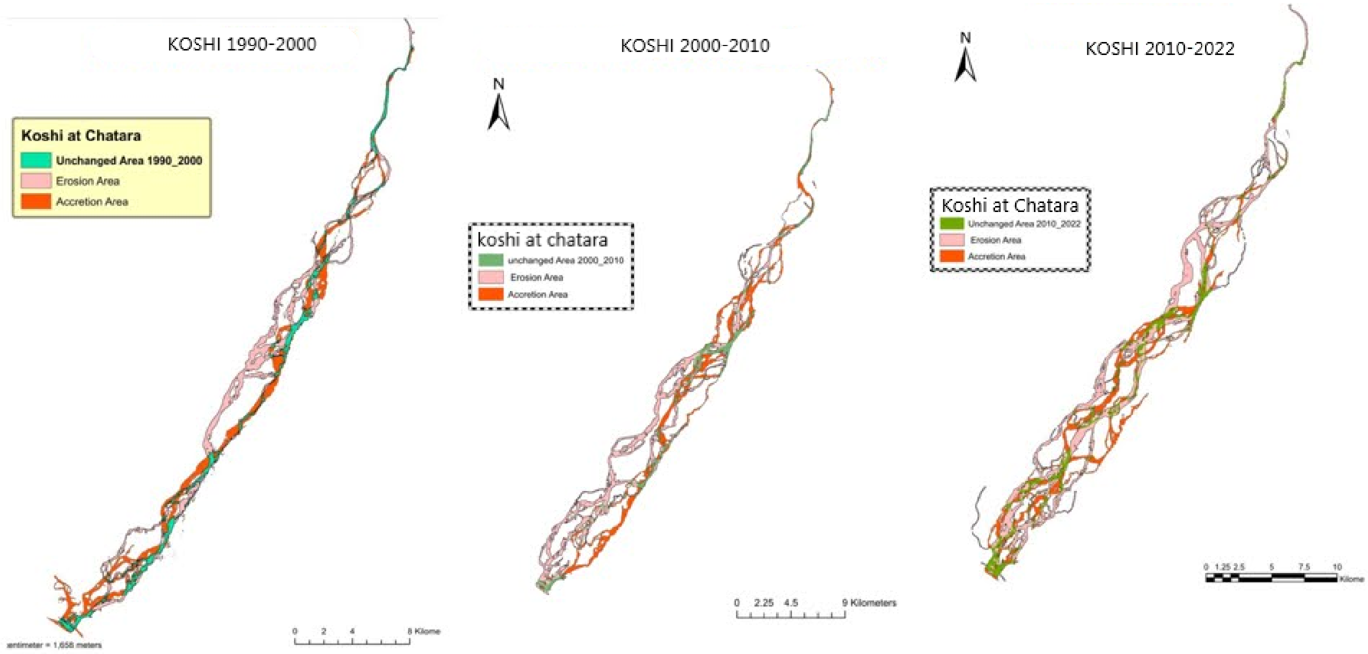

Figure 3: Koshi River at Chatara: Decadal Comarison from 1990-2022.

Table 1: Decadal Comparison of Erosion and Accretion Areas for the Koshi River

Image Source	Date Acquired	Decadal Comparison	Erosion Area (Km^2)	Accretion Area (Km^2)	Unchanged Area (Km^2)
Landsat-5	1990-01-12	Koshi	-	-	-
Landsat-5	2000-12-09	1990-2000	16.349	17.734	8.545
Landsat-5	2010-12-05	2000-2010	18.138	21.773	6.756
Landsat-9	2022-11-28	2010-2022	17.657	29.633	10.872

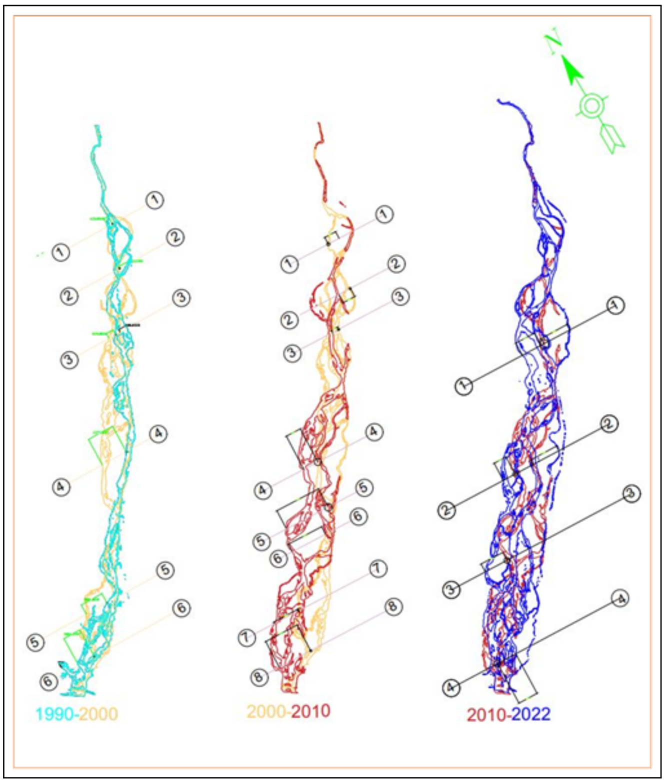

Figure 4: Koshi Reach with varying X-sections

Figure 5: Graph of Shift of extreme edge water body for 1990-2022

4.2 Narayani River

The figure 6 shows the river network of Narayani River at Devghat and up to Baguban about 54 Km downstream of Devghat. The comparison starts from 1990 to 2000, where an erosion area of 12.892 Km^2 and an accretion area of 9.278 Km^2

Table 2: Decadal Comparison of Erosion and Accretion Areas for Narayani River

Image Source	Date Acquired	Decadal Comparison	Erosion Area (Km^2)	Accretion Area (Km^2)	Unchanged Area (Km^2)
Landsat-5	4/16/1990	Narayani	-	-	-
Landsat-7	2/17/2000	1990-2000	12.892	9.278	10.774
Landsat-5	2/18/2010	2000-2010	9.373	13.411	10.256
Landsat-9	11/10/2022	2010-2022	28.942	6.894	12.735

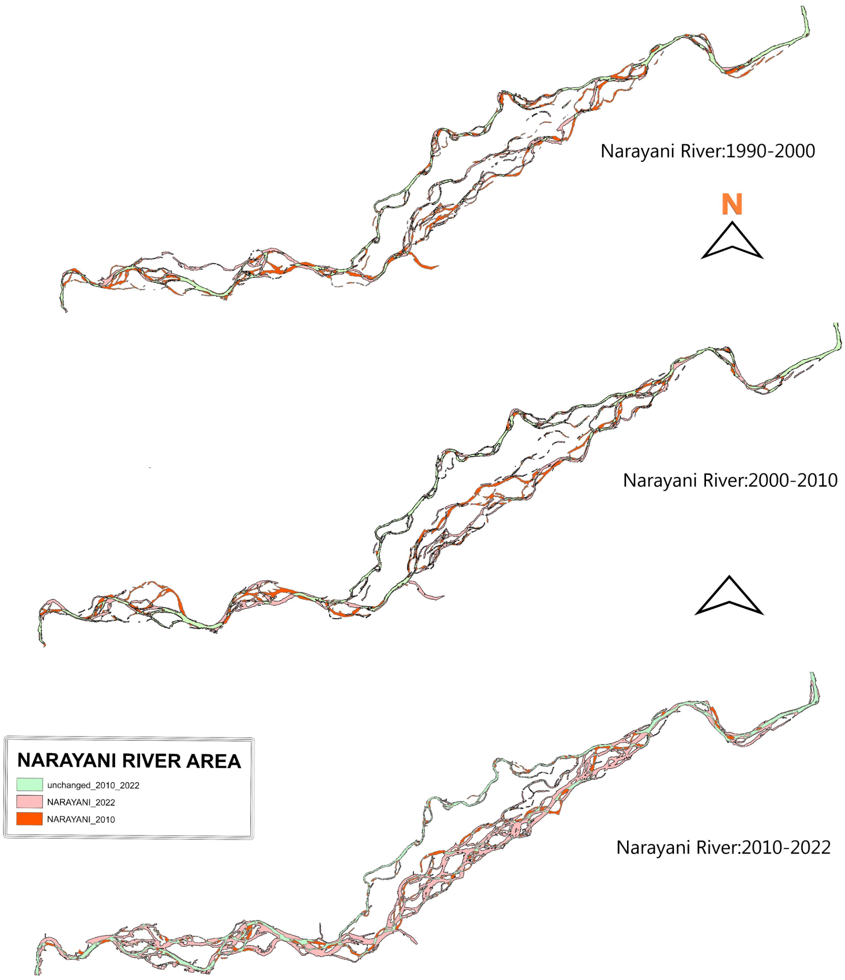

Figure 6: Decadal Comparison of Narayani River from 1990-2022

were observed, with 10.774 Km^2 remaining unchanged. From 2000 to 2010, an erosion area of 9.373 Km^2 and an accretion area of 13.411 Km^2 were recorded, while 10.256 Km^2 remained unchanged. In the most recent comparison from 2010 to 2022, the erosion area increased to 28.942 Km^2, with an accretion area of 6.894 Km^2, and 12.735 Km^2 remaining unchanged.

The Planar water body of Narayani River in the studied reach has experienced a minimum centroidal shift, with its maximum shift of 682 meters occurring between 2010 and 2022.

The outermost riverbank, considered as the extreme edge of the wetted area, has exhibited a northward shift in the upstream reach, particularly prominent with a maximum shift of 1001 meters between 2010 and 2022. Sections 2 and 3, however, show a more oscillatory pattern. From 1990 to 2000, there seems to be a southward shift of -1253 meters, followed by a subsequent northward shift of 1446 meters between 2000 and 2010. The trend reverses from 2010 to 2022, leading to a southward shift of -657 meters.

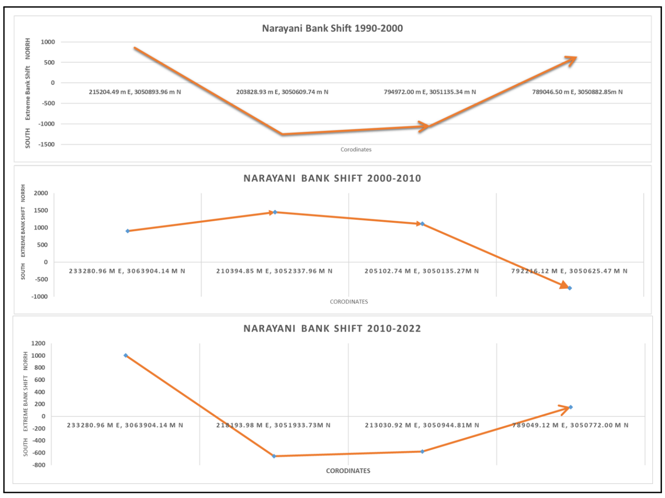

Figure 7: Narayani River:Channel Shift of river bank

4.3 Karnali River

The figure 9 presents the erosion and accretion areas of the Karnali River reach starting from Chisapani and up to Kailashpuri Dam which is further summarized in table 3.

From 1990 to 2000, the river experienced erosion covering an area of 21.559 Km^2, while accretion extended over 15.123 Km^2, and 15.517 Km^2 remained unchanged. The trend persisted between 2000 to 2010, where erosion expanded to 30.37 Km^2, surpassing 15.62 Km^2 of accretion. However, between 2010 and 2022, accretion increased to 28.249 Km^2, while erosion covered 22.405 Km^2. Notably, the unchanged area grew from 15.517 Km^2 to 21.456 Km^2 and finally to 23.577 Km^2 between 1990 to 2022, indicating a developing permanent flow path in recent years.

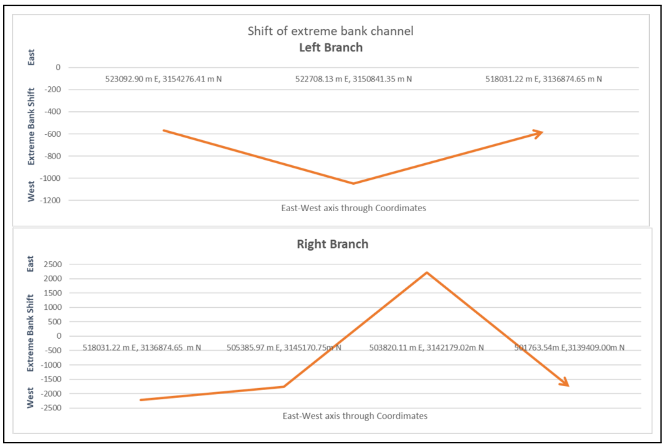

Figure 8: Karnali River Prominent Channel Shift(2010-2022)

The centroidal shift of planar water body exhibits a notable value of 6874 m between 1990-2000, which reduced to 2936 m from 2000 to 2010 and further to 1533 m from 2010 to 2022. This decreasing trend highlights the diminishing centroidal shift, yet it remains substantial, reflecting the dynamic nature of the Karnali River.

The channel shift analysis of Karnali mega fan reveals higher shift of right branch compared to the left branch .The right branch exhibits a general dominant westward shift, particularly evident in the upstream and middle section with value as high as 2125 m. Notably, a substantial eastward shift of 1732 m occurs near the confluence of the two branches between year 2010 to 2022. This distinctive shift pattern is attributed to the meandering behavior of the river in that specific reach. Conversely, the left branch demonstrates a consistent westward shift, reaching as high as 1048 m.The overall trend of the Karnali river is thus seen to be shifting in westward This detailed account of channel shifts underscores the dynamic nature of the channel shifts within the Karnali mega fan region.

It's worth noting that this increased shifting observed from 2010 to 2022 may be attributed, in part, to significant flooding events that occurred during this period, including those in 2010-2013, as documented by the (DHM). Also, the 2014 flooding event led to significant erosion of riverbanks due to the impact of the floodwaters.Preliminary analyses conducted [20]suggest that this particular flood event may have been an extremely rare occurrence, with an estimated probability of just one in a thousand years for such an event to happen. The combination of this exceptional flood event in 2014 and the ongoing fluctuations in river discharge has led to substantial alterations in the river's planform throughout the period of 2010 to 2022.

5. Discussion on Comparative Study of Three Rivers

The comparison between the river morphology of the three rivers, Koshi, Narayani, and Karnali, in Nepal yields valuable insights into the divergent pattern that they exhibit.

The summer monsoon, which originates from the Indian Ocean, is the primary source of precipitation in Nepal [21]. However, the impact of this monsoon system varies across different regions of the country. In the case of the Karnali River Basin located in the western region, its interaction with the summer monsoon is comparatively weaker than in the Koshi Basin in the eastern part [22]. The soil erosion value in the eastern hills is known to be considerably higher due to a major chunk of the annual precipitation being influenced by monsoon rain annually [23].

The average soil loss from Karnali was estimated to be 9.85 t $ha^{-1}year^{-1}$, with a total of 48,279,696 tons of soil being lost per year [23]. This is way less than the Koshi basin, which was estimated to be 22 t $ha^{-1}year^{-1}$ [24]. This data suggests a more dynamic river morphology in the downstream low-lying flat areas of the Koshi river than the Karnali river.

This study also supports this result, which is magnified with active water area. To gain a more comprehensive perspective on their instability, considering the percentage of unchanged water area is crucial. In this regard, the Narayani River stands out as the most stable, with a maximum unchanged area of 64.8%. The Karnali River follows at 54.5%, and the Koshi River at 32.5%. This underscores Koshi's versatile morphology, a conclusion further supported by its higher channel shift in terms of planar water area, up to 3871 m.

The higher trend in the shift in the Koshi river might also have to do with the large number of rainfall-triggered landslides within the Koshi Basin, 5858 in total, where the Gorkha earthquake triggered more than 25,020 landslides, with 14,127 located in the Koshi River basin alone [25]. Also, a significant amount of outermost planar water area shift of Koshi at section 5 between 2000 to 2010 could be contributed by the August 2008 flooding when the river breached at Kusaha, Sunsari, 12 km upstream of the Koshi Barrage.

Since the valley area for the study reach of the Karnali megafan is bigger than that of the Koshi river reach, the Karnali megafan has the highest average erosional rate, reaching a value of 2.322 Km^2/year throughout the study period, while the Koshi River, lying in the eastern region, follows with a rate of 1.629 Km^2/year, and the Narayani River in the central region with 1.602 Km^2/year. These findings underscore the highly dynamic and unstable nature of the flow patterns within these prominent river systems across Nepal.

Table 3: Decadal Comparison of Erosion and Accretion Areas for Karnali River

Image Source	Date Acquired	Decadal Comparison	Erosion Area (Km^2)	Accretion Area (Km^2)	Unchanged Area (Km^2)
Landsat-5	1990-03-13	Karnali Chisapani	-	-	-
Landsat-7	2000-11-11	1990-2000	21.559	15.123	15.517
Landsat-5	2010-10-14	2000-2010	30.37	15.62	21.456
Landsat-9	2022-12-10	2010-2022	22.405	28.249	23.577

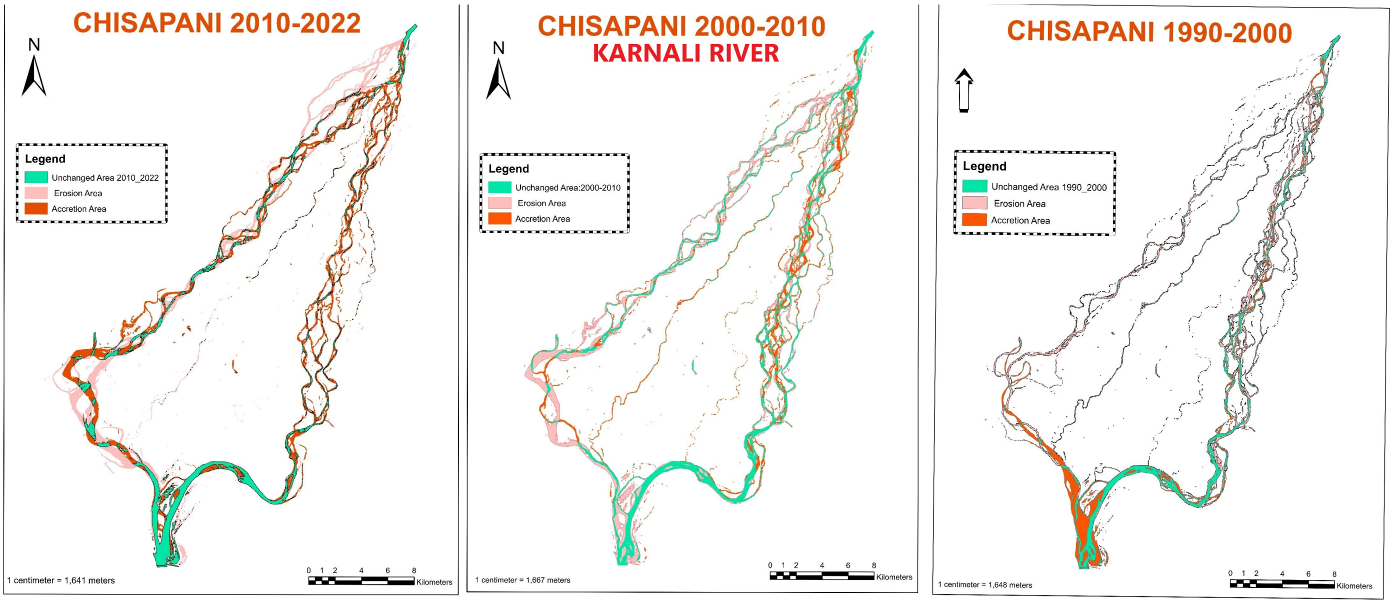

Figure 9: Decadal Comparison of Karnali megafan Channel Shift (1990-2022)

6. Conclusion

This study offers valuable insights into the intricate river dynamics of Nepal's major rivers—Koshi, Narayani, and Karnali. Remote Sensing techniques and a GIS environment were employed to analyze the changes in the rivers based on satellite images. The Modified Normalized Difference Water Index (MNDWI) was utilized for decadal comparison from 1990-2022 within the GEE platform to extract water bodies. The results were obtained through a planimetric approach that considered planar water body shift, erosion, and accretion, along with the unchanged area of all three rivers.

When quantifying the stability perspective, the Narayani River emerges as the most stable, boasting an unchanged area of 64.8%. The Karnali River follows at 54.5%, while the Koshi River records 32.5%.This highlights Koshi's flexible morphology, further supported by its substantial channel shift of up to 3871 m. Notably, the valley area for the study reach of the Karnali megafan is larger than that of the Koshi river, contributing to the higher average erosional rate of 2.322 Km^2/year, followed by Koshi at 1.629 Km^2/year, and Narayani at 1.602 Km^2/year. These findings collectively underscore the dynamic and unstable nature of these prominent river systems distributed across Nepal. Conducting reconnaissance surveys, field-level investigations, along with comprehensive data collection could offer deeper insights into the physical factors contributing to the channel shifts.

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