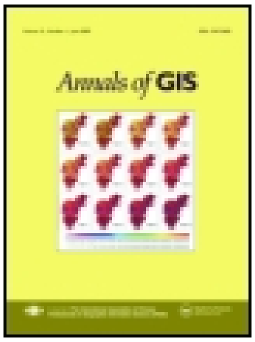

Annals of GIS

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tagi20

Assessment of channel shifting of Karnali Megafan in Nepal using remote sensing and GIS

Biplob Rakhal , Tirtha Raj Adhikari , Sanjib Sharma & Ganesh R. Ghimire

To cite this article: Biplob Rakhal , Tirtha Raj Adhikari , Sanjib Sharma & Ganesh R. Ghimire (2021): Assessment of channel shifting of Karnali Megafan in Nepal using remote sensing and GIS, Annals of GIS, DOI: 10.1080/19475683.2021.1871950

To link to this article: https://doi.org/10.1080/19475683.2021.1871950

Published online: 15 Jan 2021.

ANNALS OF GIS
https://doi.org/10.1080/19475683.2021.1871950

Taylor & Francis
Taylor & Francis Group

OPEN ACCESS Check for updates

Assessment of channel shifting of Karnali Megafan in Nepal using remote sensing and GIS

Biplob Rakhal[a], Tirtha Raj Adhikari[b], Sanjib Sharma[c] and Ganesh R. Ghimire[d]

[a]Engineering-GIS, World Food Programme, Lalitpur, Nepal; [b]Central Department of Hydrology and Meteorology, Tribhuvan University, Kirtipur, Nepal; [c]Earth and Environmental Systems Institute, The Pennsylvania State University, University Park, Pennsylvania, USA; [d]IIHR-Hydroscience and Engineering, The University of Iowa, Iowa City, Iowa, USA

ABSTRACT
River flow exhibits morphological changes over time. The shifting of river channels is a common natural phenomenon which often poses risk to life and property. Channel shifting is mostly associated with weak geology, extreme floods, and land cover alterations. Here we assess the changing morphology of the largest depositional landform in Nepal, called the Karnali Megafan, over the period of 1977–2013. We applied geographic information system (GIS) and remote sensing techniques to analyse the spatiotemporal changes in the Karnali Megafan. We obtained historical channel information from Landsat Operational Land Imager (OLI) and the Thermal InfraRed Sensor (TRIS) satellite image, Landsat Enhanced Thematic Mapper Plus (ETM+), Thematic Mapper (TM) and Multispectral Scanner (MSS) for years 1977, 1990, 2000, 2010 and 2013. The channel shifting depicts a generally increasing trend in the right branch while the trend is less prominent in the left branch. We find that the extreme rainfall and flooding contribute to channel shifting in the Karnali Megafan. This study identifies the channel shifting spatiotemporal trends along the Karnali Megafan and are of practical use in developing and implementing appropriate river management strategies.

ARTICLE HISTORY
Received 16 September 2020
Accepted 27 December 2020

KEYWORDS
Karnali Megafan; channel shifting; remote sensing; geographic information system

1. Introduction

River flow is dynamic and exhibits morphological changes over time. Bank erosion, down cutting, and bank accretion within the floodplains are common phenomena that could lead to a significant shift of channel position along the river course (Yao et al. 2013; Dabojani, Mithun, and Kanti 2014). These shifts are generally associated with local variations in geology, hydrology, and other natural and human-induced factors, including geomorphic setup, soil composition, natural bank geometry, distribution of riparian vegetation, land use patterns and flood dynamics. River channel shifting poses a significant risk to life and property within the floodplain. The strategies to manage these risks rely on a sound understanding of spatiotemporal shifts in river channels.

Development of modelling tools (e.g., Langendoen, Simon, and Thomas 2001; Jia, Wang, and Xu 2002; Gibson et al. 2006; Ghimire, DeVantier, and Sharma 2020) and availability of temporal satellite imageries have made it possible to study long-term spatiotemporal changes in river channels. Unlike ground observations, remote sensing provides wider coverage of rivers and other waterbodies (Sichangi, Wang, and Hu 2018). The availability of remote sensing data at temporal scale provides the option to select the satellite image of a specific time to compare the ground features and detect the changes using GIS. Remote sensing and GIS are some advanced techniques that are widely used for environmentally deterministic research studies (e.g., Graf 2000; Pal and Pani, 2019; Sinha 2014; Saleem et al. 2020). The ability of these tools to process higher resolution satellite images as well as geo-reference, visualize, overlay and extract channel banks information in geometric formats enables efficient analysis of channel shifting at larger spatiotemporal scales.

The objective of this study is to identify the long-term trends of channel shifts and delineate the historical channel migration zones. We specifically focus on one of the largest depositional landforms in Nepal called the Karnali Megafan (Leier, DeCelles, and Pelletier 2005; MacClune et al. 2014) (Figure 1). River channel shifting is a critical issue in the Karnali Megafan. We selected Karnali Megafan because it has experienced several catastrophic flood damages in recent decades (MacClune et al. 2014). Every year people lose their property and fertile agricultural land as a result of river morphologic changes. Sound understanding of channel shifting patterns is important to identify the vulnerable locations

CONTACT Tirtha Raj Adhikari tirtha43@gmail.com Central Department of Hydrology and Meteorology, Tribhuvan University, Kirtipur 44618, Nepal

and implement appropriate risk management strategies across the Karnali Megafan. We applied the GIS and remote sensing techniques to analyse the channel shifting trend in the Karnali Megafan.

2. Study area

The Karnali Megafan extends from 28°26′ N – 28°67′N and 80°97′ E – 81°28′ E with a total area of about 789 km^2 (~522 km^2 in Nepal and ~267 km^2 in India). The Karnali Megafan is a fan-shaped depositional landform consisting of alluvial deposits which formed a piedmont plain and is continuously being reshaped by the denudational process of the Karnali river system (Sinha 2014). Geologically the study area is made of quaternary fluvial deposit called Indo-Gangetic plain sediment (Baral, Ding, and Chamlagain 2017). The Karnali Megafan conforms to the area where the fluvial system changes from meandering to gravelly braided river system (Baral, Ding, and Chamlagain 2017) (Figure 1).

The Karnali Megafan is bound by the Churiya Range (~1200 m above the mean sea level (amsl)) in the north, the plains of Bardiya National Park in the east and the Mohana watershed in the west (see Figure 1). The fan-shaped landscape begins from the narrow valley of the Churiya at an elevation of ~260 m amsl and sprawls to the Ghagra Dam (~40 m amsl) in the Indian territory. The lowest elevation of the Karnali Megafan in Nepal is ~139 m amsl along the Indo-Nepal border. The gradient of the landmass (0-3-degree slope) has developed idyllic conditions for the Karnali River to create braided channel patterns forming two branches to flow in the south and southwesterly direction. The Karnali River, therefore, has an upstream width of ~6.5 km between the banks below the Chisapani Bazar. After divergence, the right branch gradually trends into a straight to meandering pattern as it flows to the south while the left branch remains braided throughout the reach (up to 30 km) before taking a sharp bend downstream towards the west. Braidening has caused the fluvial landforms of the Karnali Megafan to continuously be reshaped. Unstable river islands, changing the position of sandbars and river-banks curvature are common phenomena in the Karnali Megafan (Sinha 2014). There are additional two rivers between the two branches of the Karnali River called the Maila Khola and the Budhi Khola that transport significant landmass to the Megafan. The Jamara

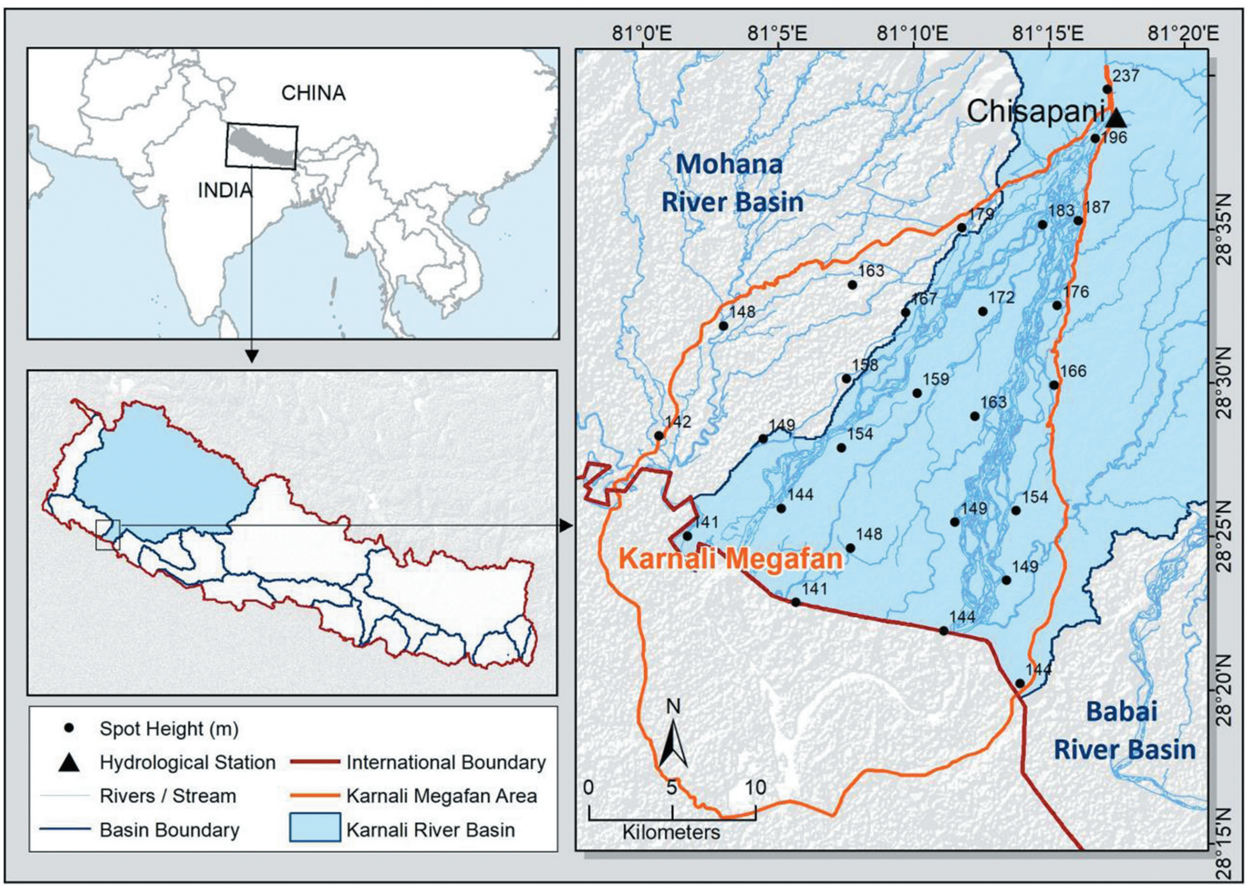

Figure 1. Location map of Karnali Megafan in Nepal.

Nadi, the Kahra Khola and the Pathari Nadi along with the Mohana River join the right branch of the Karnali River in the west near the Indo-Nepal border.

Here we select the downstream section of the Karnali River reach to analyse the shift in the position of the river banks (Figure 1). The selected section extends from Chisapani Bazar in the north to the National border of Nepal in the south. We analyse the 37 km and 33 km stretch of the right branch and left branch of the Karnali Megafan, respectively (Figure 1).

3. Data and methods

In this study, we used space-based moderate-resolution land remote sensing data such as optical Landsat imageries from the United States Geological Survey (USGS) (Landsat 2020). We acquired a series of decadal historic Landsat imageries on the Karnali River course for the past 36 years (1977–2013). We used the 60 m resolution Multispectral Scanner (MSS) for the year 1977 and the 30 m resolution Landsat Operational Land Imager (OLI) and the Thermal InfraRed Sensor (TRIS) satellite image, and Landsat Enhanced Thematic Mapper Plus (ETM+) for years 1990, 2000, 2010 and 2013 (see Figure A1).

Quantifying spatiotemporal changes in channel shift consists of three phases. The first phase involves acquiring remotely sensed moderate resolution historic decadal Landsat satellite images. We used the Earth Resources Data Analysis System-ERDAS Imagine software to stack the individual band layers from these images, and further enhanced and executed radiometric correction to make the images free of anomalies and easily interpretable. To extract the information of river features, we performed visual interpretation of images and generated the layers of information in shapefile format by performing on-screen digitization in ArcGIS. The key river features include river polygons, sandbars, river islands, river bank lines, and river centerlines. We used river bank lines for quantification of planimetric channel shifts. In addition to Landsat images, we extracted the present status of landforms, the imprint of old rivers and the oxbow lakes from Google Earth at high resolution to obtain current information on the spatial distribution of land cover types in the Karnali Megafan. The landform type is based on Carson, Shah, and Maharjan (1986).

In the second phase, we generated the quantitative data of bank position using the bank lines in plane form. We applied the theory of displacement for the measurement of channel shifting. Theory of displacement interprets distance as a one-dimensional quantity representing the separation between two defined points along a straight line. Thus, an imaginary straight line was drawn approximately along the river centre line for the base year 1977, which we bisected later at every 2000 m by a perpendicular line crossing the banks of the river for every decadal image. We used available editing tools to split lines at every 2000 m to develop a new vertex from where horizontal lines are generated to bisect the vertical straight line perpendicularly. In order to maintain the unique identity of each bisecting line, we attributed them with unique codes and branch names. We used ArcMap editor tool to digitize the river bank lines on the satellite images. ArcMap can read the georeferenced satellite images, create shapefiles and generate geometric features through on-screen digitization. Separate vector layers of the river bank lines of 1977, 1990, 2000, and 2013 were generated from visual image interpretation and digitization process.

Next, we overlaid the layers of river bank lines upon the horizontal straight lines and applied geoprocessing tools to intersect bank lines with horizontal lines to obtain the vertices of intersection, which correspond to the position of river banks. We converted the intersected lines later into points and computed the coordinates (i.e. easting and northing) of these points in the attribute table. The attribute table of intersected point shapefile is exported to obtain the easting and northing of the river bank position in a dbase file format that is readable in an excel spreadsheet.

Finally, in the third phase, we used eastings to determine the temporal displacements of river banks. Eastings are the longitudinal values and we reported them in the metric system to compute any change in river bank position towards right or left of the river centre line. The eastings corresponding to the river bank were identified with reference to the unique code and name of the branch. We filtered the compiled data and arranged them in spreadsheets for computing differences. We computed the shift of bank positions using 1977 as the base year and calculated the displacement at different timescales. Figure 2 summarizes the procedure in this study to estimate the channel shifts in the Karnali Megafan area.

4. RESULTS

4.1. Planform dynamics

We show in Figures 1 and 3 the sections of the Karnali Megafan that have experienced river channel planform change over the period of 1977–2013. The Karnali Megafan is largely braided in nature (Figures 1 and 3). After flowing 26 km downstream, the river right branch changes its pattern from braided to meandering at section RS13. The left branch, however, remains braided

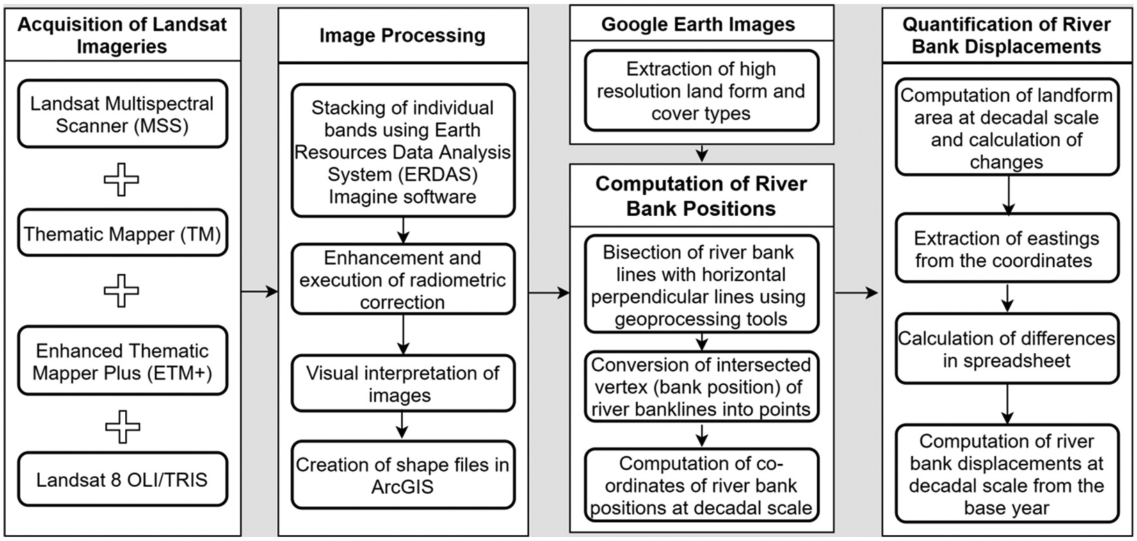

Figure 2. Diagrammatic representation of the method used to estimate channel shifts using remote sensing and GIS.

throughout downstream until it reaches LS16 which is nearly 32 km downstream of Chisapani. The left branch also turns into a narrow channel and takes a meandering bend before joining the right branch in India.

The satellite image reveals that both branches have multiple braided channels that traversed the river island and created sandbars with wide cross-sections (Kleinhans and Berg 2011). We considered the channel width as the distance between the extreme right and left banks of the river branch because bars separating channels at low flow are often submerged at high flow (Leopold, Wolman, and Miller 1964). Therefore, in this study channel width includes all the fluvial landmass and sandbars between the two banks. The temporal variation in the channel width (Figure A3) demonstrates that the river underwent several changes in its planform. The Karnali river has experienced the channel expansion and contraction as well as major changes in its shape. The major changes are observed downstream when the channel pattern changes from braided to sinuous and shifts its positions multiple times.

Across temporal scales, the variation in planform remained largely stable (see Figure A2) in the left branch though it experienced channel width contraction in LS06-LS09 and LS11 between 1977 and 1990. The variation in channel width in the right branch is observed in all 20 locations where the majority of the locations exhibit width expansion. Channel widening, for instance, was prominent during 1990 and 2013, when the channel appeared to encroach onto the floodplains through lateral migration. We also find that channel shape drastically changed in the right branch between RS15 to RS21 (Figure 3) which can be attributed to multiple factors, including extreme flood events, lateral erosion, scouring and shifting of river course.

There are five major geomorphological land units in the Karnali Megafan: present river channel, sand and gravel bars, active alluvial plain (low terrace), active alluvial plain (higher terrace) and recent alluvial plain (Table 1). The land units are differentiated by landscape characteristics (Carson, Shah, and Maharjan 1986). The present river channel is an active river course with alluvium bedload subjected to deep scouring and river bank instability during peak flow. The sand and gravel bars are active depositional landforms composed of clean sands and gravels subjected to frequent severe flooding. The active alluvial plain (low terrace) is an immediate flood plain composed of deposited alluvial materials and is subjected to severe river flooding. The active alluvial plains (higher terrace) are also depositional landform and occasionally flooded. The recent alluvial plains are the lower piedmont (depositional and erosional) floodplains used for cultivation, grazing and often for settlement purpose at higher elevations (Carson, Shah, and Maharjan 1986).

Recent alluvial plain depicts the largest geomorphic type in 2013, covering ~508 km^2; i.e. 64% of the total land area (Table 1). The area of the present river channel is only about 50 km^2, which is the lowest geomorphic coverage in 2013. During the period of 1977 to 2013, we noticed the increase in area of the active alluvial plain (83% and 16% for low terrace and high terrace, respectively). However, the recent alluvial plain, present river channel and sand/gravel bars depict decrease in area by about 6, 8 and 17%, respectively. In other words, there is an apparent transformation from recent alluvial plain to

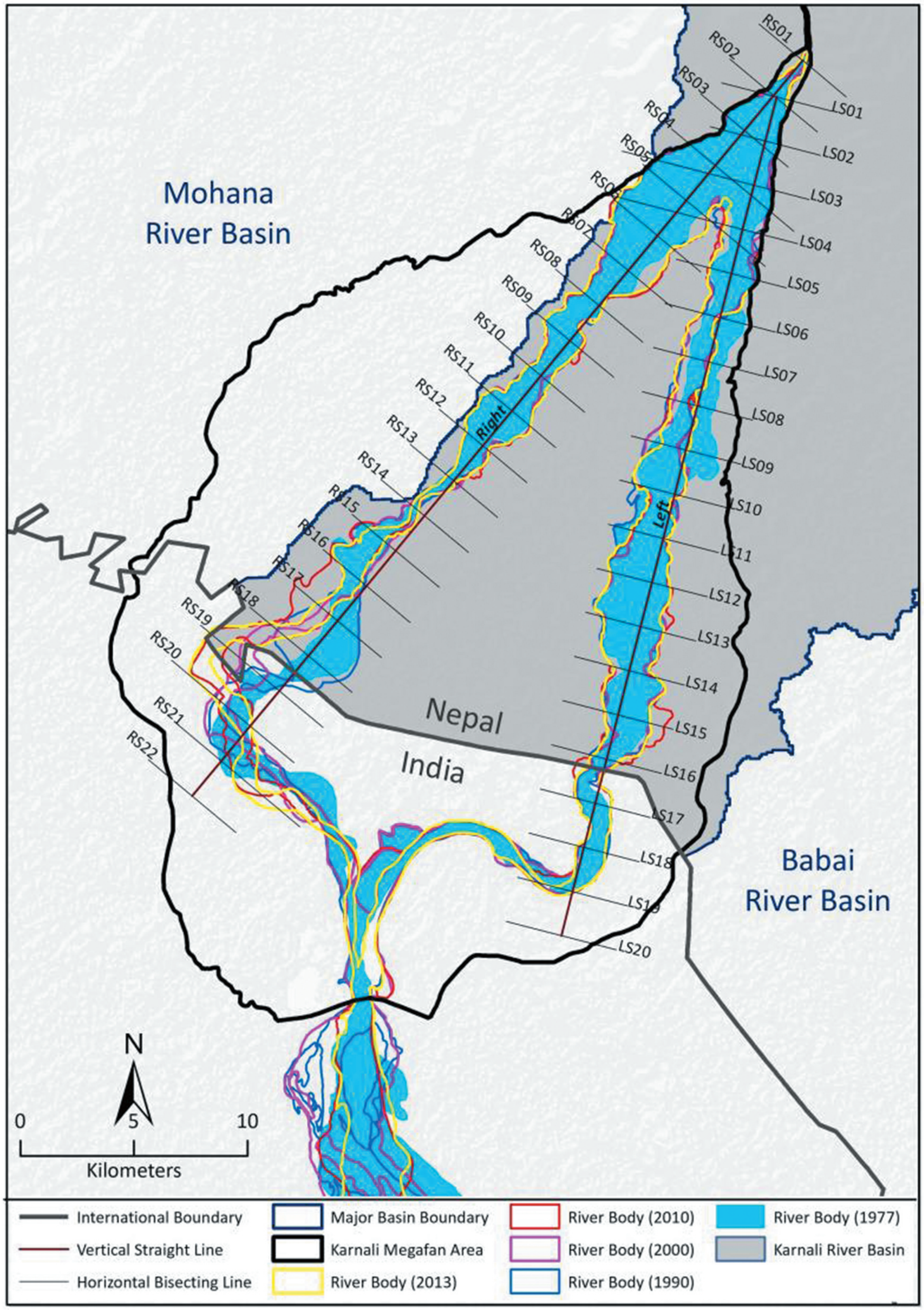

Figure 3. Temporal variation in planimetric width of the Karnali River. The map shows the extent of the river body in different years: 1977, 1990, 2000, 2010 and 2013.

active alluvial plain, active river channel to sand/gravel bars, and vice-versa. We could attribute it to the excessive bank erosion during floods, followed by surface erosion, and shift of the river channel to the opposite-to-opposite bank. Due to lateral shift, the active river channel erodes the sand and gravel bar or the landmass

Table 1. Geomorphic land units in Karnali Megafan due to channel processes.

	1977	1990	2000	2010	2013	
Geomorphic land units/types	Area (km^2)	Area (km^2)	Area (km^2)	Area (km^2)	Area (km^2)	Area increase/decrease from 1977 (%)
Active alluvial plain (low terrace)	48.64	62.67	84.78	79.13	89.15	83.29
Active alluvial plain (high terrace)	76.69	78.58	96.95	86.37	89.45	16.64
Recent alluvial plain	546.17	527.67	519.74	510.63	508.91	−6.82
Present river channel	55.12	56.44	61.33	66.13	50.21	−8.92
Sand and gravel bars	62.59	63.85	26.41	46.96	51.48	−17.74
Total area	789.21	789.21	789.21	789.21	789.21	

on the front and leaves the submerged landmass uncovered with newly formed sand and gravel bars next to the river bank. Note, however, that the geomorphic change of landforms in the Megafan area shows variability across timescales.

4.2. River bank shifting

We estimate the channel shifting at intervals of 2000 metres in both the right- and left-branches. Note that the right-and left-branch refer to the bank positions relative to the flow direction. We estimate both the temporal and spatial variation in the channel width for the period of 1977–2013.

The temporal variation in the channel width is more frequent in the right-branch than the left-branch (Figure 3). Channel shift is maximum in the right branch-left bank, whereas the left branch-right bank depicts the minimum shift (Figure 4). Note that temporal variability of channel shift is more apparent at the downstream end of the Megafan area particularly along the right branch (Figure 3–4). These sections correspond to the most braided and meandered sections before two branches merge into the main stem of the river. The prominent changes at downstream ends of Megafan area could therefore be attributed to changes in channel characteristics, and complex flow and sediment dynamics near the confluence area.

We observe a prominent western shift (towards right bank) at sections RS16 – RS19 (~6 km reach) of the right branch in 2000, 2010 and 2013. Consequently, the largest change in the channel width can be noticed particularly in 2010 along RS16-RS18 (~4 km reach) in the right branch. Left branch underwent a similar prominent shift along LS05-LS09 (~6 km reach) in 2000, 2010 and 2013. It is apparent from Figure 4 that significant changes occurred in channel width between 2010 and 2013 along RS15-RS21 and LS12-LS16. This could be due to two major flooding events during 2010–2013 in the Karnali river (DHM, 2020).

Channel shift in the right branch is as high as 2000 metres relative to the base position of channel in 1977 (Figure 4). Larger channel shift in the right branch could be attributed to multiple factors such as fluctuation in flow (flood) and velocity, bed load gradation, continuous process of scouring and the braided nature of the river. The left branch, however, comprises part of the Bardiya national park, and hence protected and covered with dense forest. The apparent difference in the general topography, lithology and bank elevations between the two banks contribute to the difference in the magnitude of shifts between two banks. For example, the digital elevation data and spot heights depict that the left bank of the Karnali river is generally at higher elevation than that of the right bank making it prone to the extension of flood plain.

The accuracy of temporal displacement of the river bank was estimated to be ±15 m. The average measurement error of the bank position was found ±35 m corresponding to the 1:25,000 topographic maps. The comparison was made between manually digitized river bank of base year and topographic map on the 69 locations of bank positions on the left and right banks in both branches. Since the magnitude of observed channel shifting is substantially higher than the error values, the results of this study can provide important insights on channel shifting characteristics in Karnali Megafan (Saleem, 2020).

In Figure 5, we show the maximum channel shift and annual maximum flow in the Karnali Megafan area for the period of 1977–2013. Overall, the annual maximum flow demonstrates an increasing trend. In addition, the rainfall distribution is relatively higher in the Megafan region (Figure A4). Indeed, the channel shift demonstrates different trends in the left and right branches in the period 1977–2013. A generally increasing trend in channel shift is mostly noticeable in the right branch between the year 1977 and 2000. Channel shifting trend is less prominent in the left bank. The highest channel shift is noticed in the right branch-left bank for the period of 1977–1990. This could be the result of a major flooding event in Karnali river in 1983 (MacClune et al. 2014). Previous studies (e.g.,

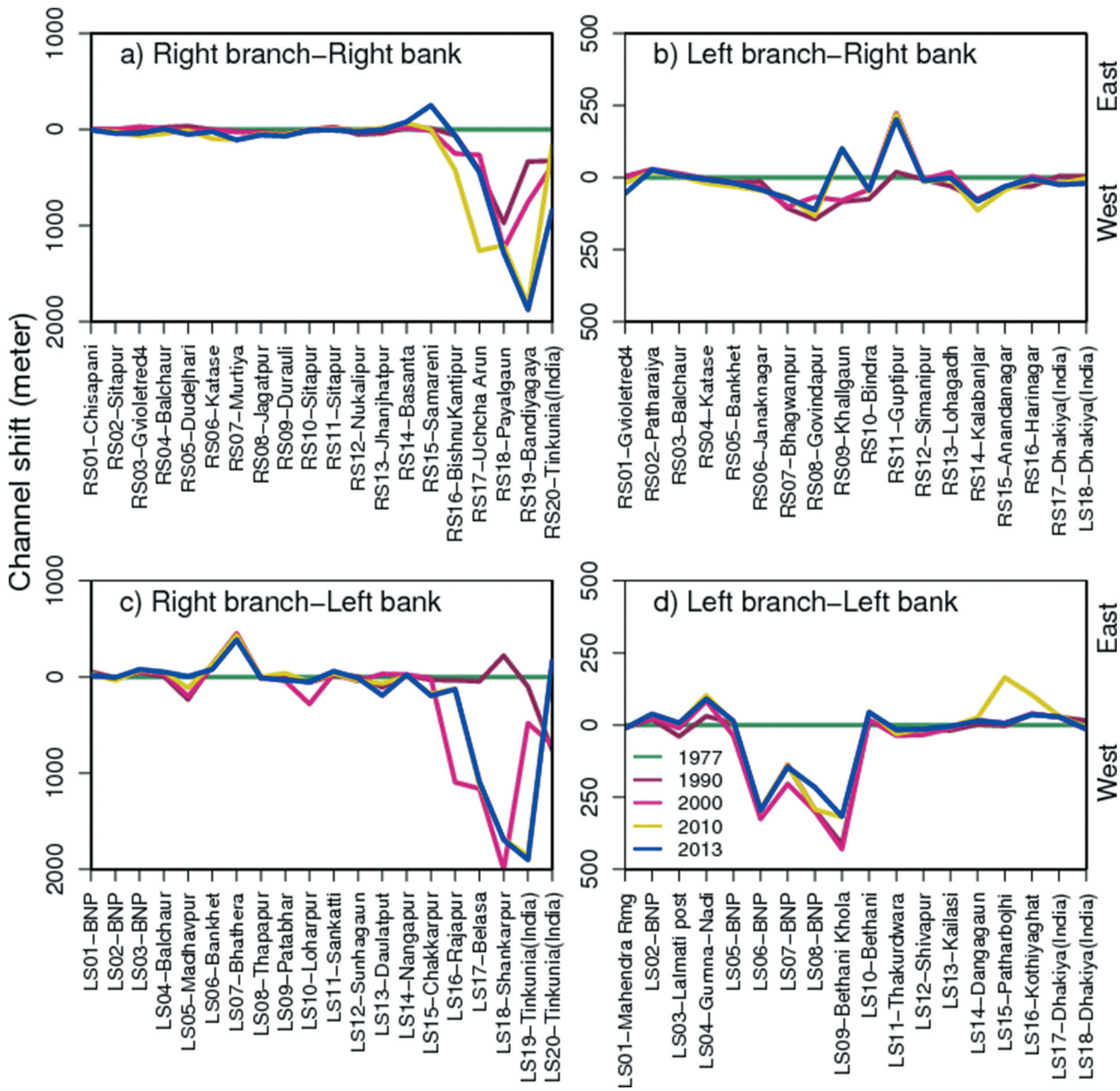

Figure 4. Temporal displacement of the right and left branch of Karnali Megafan in both right and left bank positions. Note that the bank position is relative to the river flow direction. West indicates the right side of the bank and the East indicates left side of the bank.

Khatiwada et al. 2016; Dahal et al. 2020) indicate that the river discharge in the Karnali River basin is sensitive to the change in pre-monsoon temperature. Both precipitation and temperature are projected to increase with future climatic conditions in the Karnali River basin (Dahal et al. 2020). This indicates that in the future, the Karnali River basin is likely to experience major changes in hydrological processes such as higher rate melting of snow and glaciers thereby increasing the river runoff. Since the shifting of river banks is generally associated with river discharge, it can be anticipated that the shifting may get more intense in the future.

Various engineering practices can be implemented to control the channel shifting. Due to the large size of the Karnali River basin, the appropriate management strategy is to approach it from the sub-watershed scale management. Reforestation and mitigation of landslides in the upstream have been some effective solutions to the basins in the central Himalayas. River training works such as marginal embankments, guide banks and spurs are few engineering measures to protect the river bank when implemented systematically on the both banks of the river. For example, several kilometres of embankment and associated spurs were constructed in the

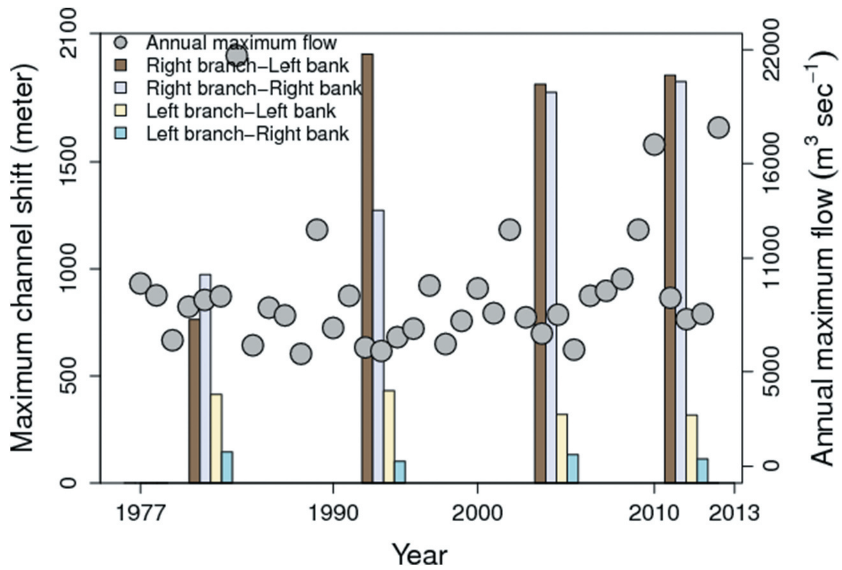

Figure 5. Maximum channel shift during the periods of 1977–1990, 1991–2000, 2001–2010 and 2011–2013. Gray circle denotes the annual maximum streamflow at Chisapani hydrologic station for the period of 1977–2013. Chisapani hydrologic station is located immediately upstream of the Karnali Megafan. Chisapani hydrologic station is monitored by the Department of Hydrology and Meteorology (DHM), Nepal.

central part of the Megafan (e.g., Tikapur region) in 2010 and 2011 which turned out effective to protect the river bank (Zurich 2015). However, the unprotected bank on the other side was washed away by the bounced off floodwater during the 2014 flood resulting in the loss of about 2000 hectares of landmass and about 14,500 houses (Zurich 2015).

5. Conclusions

We examine the channel shift across the Karnali Megafan region over the period of 1977 to 2013. We mostly rely on GIS and Remote Sensing techniques. We find a generally increasing trend in channel shifting across the Karnali Megafan. The channel shifting is higher in the right branch compared to the left branch. We find that the extreme rainfall and flooding contribute to channel shifting in the Karnali Megafan. This study provides scientific evidence of the shifting of bank positions and its trend at key locations along the right and left branch in the Karnali Megafan of Nepal. Future study could assess the relationship between erosion and accretion to the shifting of river banks.

This study considered the planimetric approach to measure the shifting of the river banks using the mid-resolution satellite image. A major challenge with the planimetric approach is to accurately represent the bank line position. Combination of better image processing techniques and high-resolution satellite images could facilitate to achieve the maximum accuracy. The application of pan-sharpened multispectral high-resolution temporal satellite images, orthorectification of temporal images and the object-based image analysis can help better identify and delineate the features better with the highest spatial accuracy. Furthermore, the machine learning algorithms can help improve the accuracy of spatial analysis of the images. For example, with the data on properties in conjunction with field-level inventories, one could use them as training samples for multiple parameters to feed into the machine learning algorithms. Further understanding of shifting patterns requires information on several other factors, including anthropogenic activities, engineering structures, micro-level elevation difference, river cross-section, velocity and bed materials. Correlation analysis of the shifting of river banks with other factors such as geology, hydrology, geomorphic setup, soil composition and land use patterns can further help in deducing the possible reasons for the shifting of river banks. Reconnaissance survey, field-level investigation and data collection could provide further insights on physical controls attributing the shifts in the channel.

Acknowledgements

The authors greatly acknowledge the Department of Hydrology and Meteorology (DHM), Nepal for providing the streamflow data used for the study. The authors are grateful to the anonymous reviewers for their reviews and constructive comments.

Disclosure statement

The authors declare no competing interests.

Funding

This research received no external funding.

References

Baral, U., L. Ding, and D. Chamlagain. 2017. "Detrital Zircon Ages and Provenance of Neogene Foreland Basin Sediments of the Karnali River Section, Western Nepal Himalaya." *Journal of Asian Earth Sciences* 138: 98–109. doi:10.1016/j.jseaes.2017.02.003.

Carson, B., P. B. Shah, and P. L. Maharjan. 1986. *Land Systems Report: The Soil Landscapes of Nepal*. Kathmandu: Land Resources Mapping Project.

Dabojani, D., D. Mithun, and K. K. Kanti. 2014. "River Change Detection and Bankline Erosion Recognition Using Remote Sensing and GIS." *Forum Geografic. Studii Si Cercetari De Geografie Si Protectia Mediului* 13 (1): 12–17. doi:10.5775/fg.2067-4635.2014.038.i.

Dahal, P., M. L. Shrestha, J. Panthi, and D. Pradhananga. 2020. "Modeling the Future Impacts of Climate Change on Water Availability in the Karnali River Basin of Nepal Himalaya." *Environmental Research* 185: 1094302. doi:10.1016/j.envres.2020.109430.

DHM. 2020. Government of Nepal Ministry of Energy Water Resources and Irrigation; Department of Hydrology and Meteorology (DHM), https://www.dhm.gov.np/, Assessed July 2020.

Ghimire, G. R., B. A. DeVantier, and S. Sharma. 2020. "Site-Specific Sediment Deposition Model for Dredging Planning: Case Study of Olmsted Locks and Dam." *Journal of Waterway, Port, Coastal, and Ocean Engineering* 146 (5): 05020003. doi:10.1061/(ASCE)WW.1943-5460.0000598.

Gibson, S., G. Brunner, S. Piper, and M. Jensen. (2006, April). "Sediment Transport Computations in HEC-RAS." In *Eighth Federal Interagency Sedimentation Conference (8thFISC)*. Reno, NV, USA 57–64.

Graf, W. L. 2000. "Locational Probability for a Dammed, Urbanizing Stream: Salt River, Arizona, USA." *Environmental Management* 25 (3): 321–335. doi:10.1007/s002679910025.

Jia, Y., S. S. Wang, and Y. Xu. 2002. "Validation and Application of a 2D Model to Channels with Complex Geometry." *International Journal of Computational Engineering Science* 3 (1): 57–71. doi:10.1142/S146587630200054X.

Khatiwada, K., J. Panthi, M. Shrestha, and S. Nepal; Khatiwada, K. R., J. Panthi, J.; M. L. Shrestha, S. Nepal. 2016. "Hydro-Climatic Variability in the Karnali River Basin of Nepal Himalaya." *Climate* 4: 17. doi:10.3390/cli4020017.

Kleinhans, M., and J. H. Berg. 2011. "River Channel and Bar Patterns Explained and Predicted by an Empirical and Physics-based Method." *Earth Surface Processes and Landforms* 36: 721–738. doi:10.1002/esp.2090.

Landsat 2020. Landsat Missions. https://www.usgs.gov/land-resources/nli/landsat

Langendoen, E. J., A. Simon, and R. E. Thomas. 2001. "CONCEPTS-a Process-based Modeling Tool to Evaluate Stream-corridor Restoration Designs." *Wetlands Engineering & River Restoration** 2001* 1–11. doi:10.1061/40581(2001)109.

Leier, A. L., P. G. DeCelles, and J. D. Pelletier. 2005. "Mountains, Monsoons, and Megafans." *Geology* 33 (4): 289–292. doi:10.1130/G21228.1.

Leopold, L. B., M. G. Wolman, and J. P. Miller. 1964. Fluvial Processes in Geomorphology WH Freeman and Co. *San Francisco 522pp*.

MacClune, K., S. Yadav, K. Venkateswaran, R. Maharjan, K. M. Dixit, and S. Dugar. 2014. "Urgent Case of Recovery: What We Can Learn from the August 2014 Karnali River Floods in Nepal." http://repo.floodalliance.net/jspui/handle/44111/303

Pal, R., and P. Pani. 2019. "Remote Sensing and GIS-based Analysis of Evolving Planform Morphology of the Middle-lower Part of the Ganga River, India." *The Egyptian Journal of Remote Sensing and Space Science* 22 (1): 1–10. doi:10.1016/j.ejrs.2018.01.007.

Saleem, A., A. Dewan, M. M. Rahman, S. M. Nawfee, R. Karim, and X. X. Lu. 2020. "Spatial and Temporal Variations of Erosion and Accretion: A Case of A Large Tropical River." *Earth Systems and Environment* 4 (1): 167–181. doi:10.1007/s41748-019-00143-8.

Sichangi, A. W., L. Wang, and Z. Hu. 2018. "Estimation of River Discharge Solely from Remote-sensing Derived Data: An Initial Study over the Yangtze River." *Remote Sensing* 10 (9): 1385. doi:10.3390/rs10091385.

Sinha, R. 2014. "The Koshi Megafan: The Best-known Himalayan Megafan." In edited by Kale V.S. *Landscapes and Landforms of India*, 151–156. Dordrecht: Springer. doi:10.1007/978-94-017-8029-2_14.

Yao, Z., J. Xiao, W. Ta, and X. Jia. 2013. "Planform Channel Dynamics along the Ningxia–Inner Mongolia Reaches of the Yellow River from 1958 to 2008: Analysis Using Landsat Images and Topographic Maps." *Environmental Earth Sciences* 70 (1): 97–106. doi:10.1007/s12665-012-2106-0.

Zurich, 2015. "Risk Nexus: Urgent Case for Recovery: What We Can Learn from the Aug 2014 Karnali River Floods in Nepal".

Appendix A

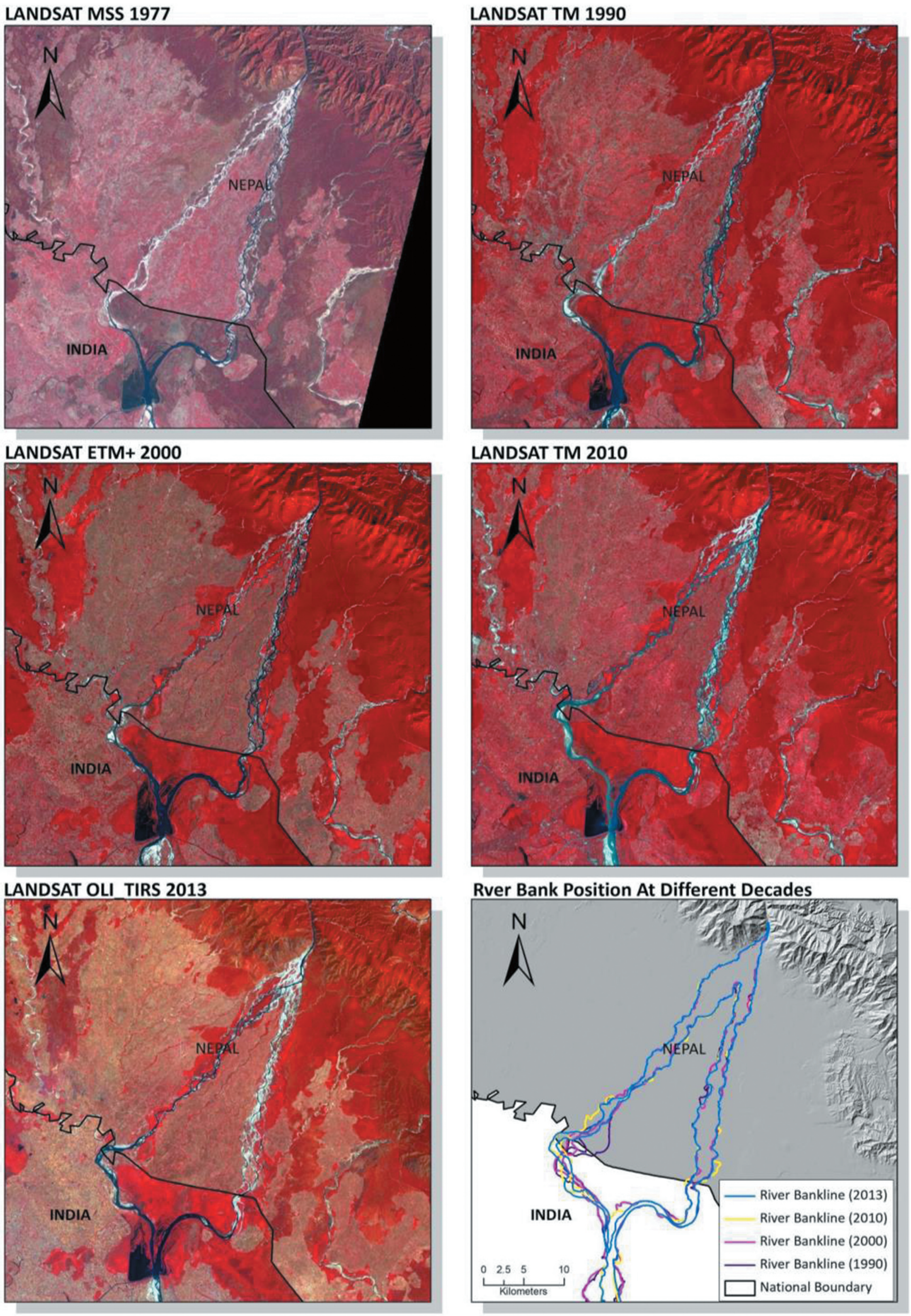

Figure A1: Landsat satellite image of the study area: a) 1977 Landsat Multispectral Scanner (MSS) satellite Image, b) 1990 Landsat Thematic Mapper (TM) satellite image, c) 2000 Enhanced Thematic Mapper Plus (ETM+), d) 2010 Landsat Thematic Mapper (TM), e) 2013 Landsat Operational Land Imager (OLI) and the Thermal InfraRed Sensor (TRIS) satellite image. We also show the digitized river bank line.

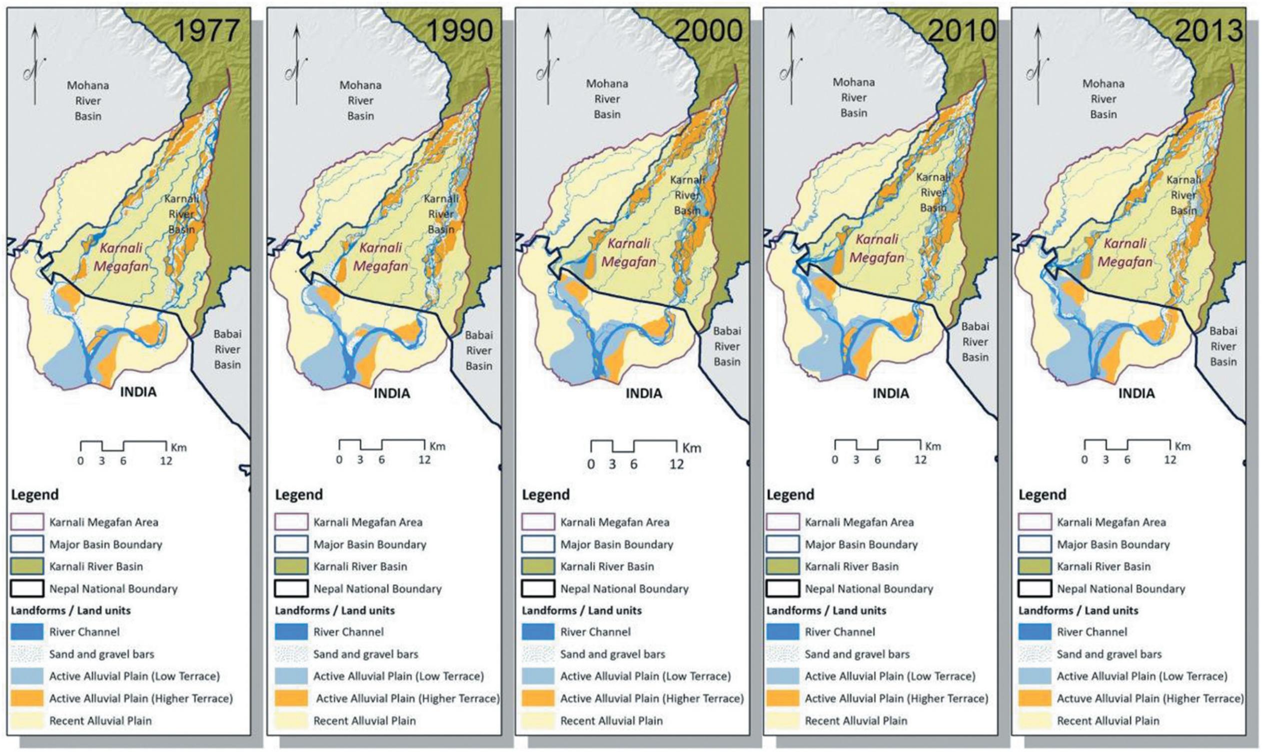

Figure A2: Temporal variation of geomorphic units (landforms/land units) along the Karnali Megafan. The common landforms in the Karnali Megafan are river channel, sand and gravel bars, recent alluvial plain ('lower piedmont' depositional and erosional land form – occasionally flooded), active alluvial plain (low terrace depositional landform-severely flooded), and active alluvial plain (higher terrace-occasionally flooded).

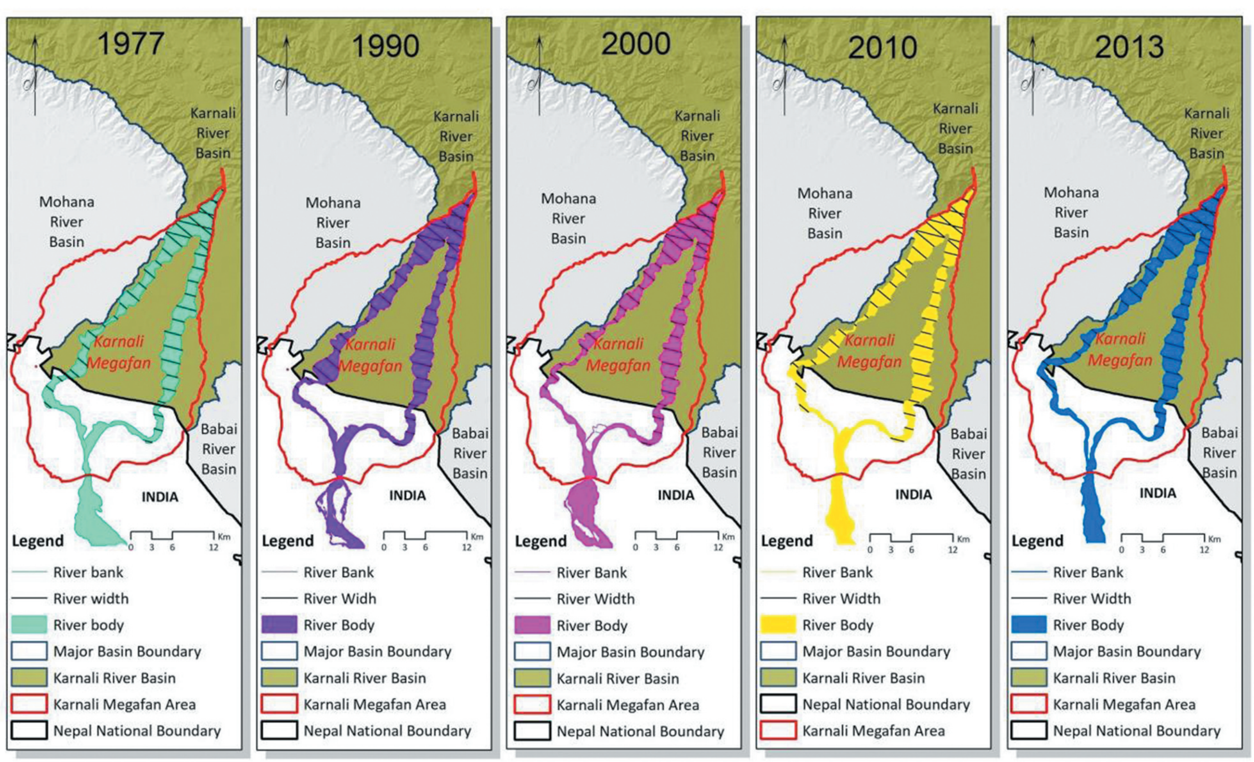

Figure A3: Temporal variation of river width in the Karnali river. The river has two branches that traverse the Karnali megafan area (demarcated in red). The body of the river is filled with distinct colour and the black line on the river body represents the width of the river in each branch.

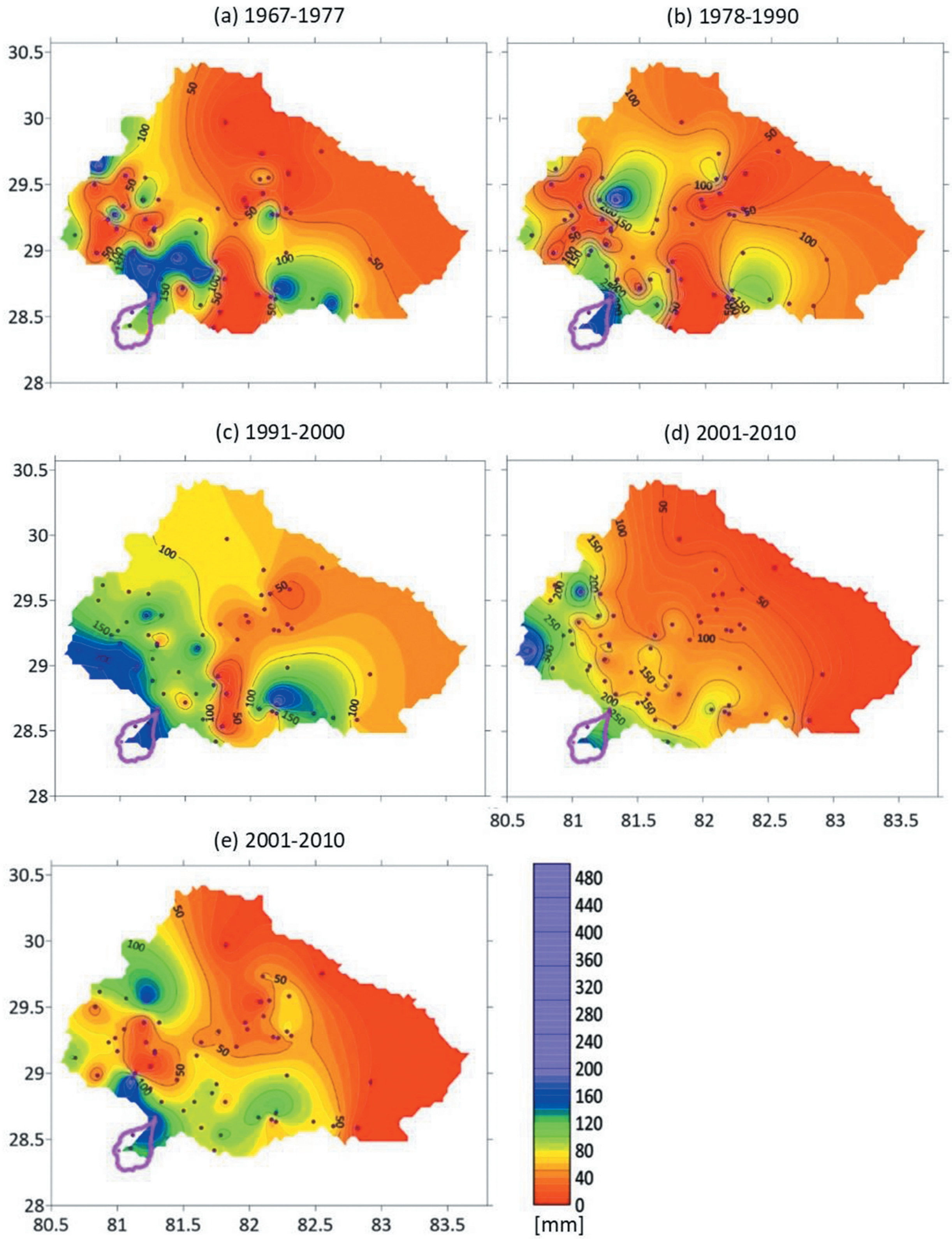

Figure A4: Annual maximum rainfall distribution (inches) in the Karnali Megafan over the periods of a) 1967–1977, b) 1978–1990, c) 1991–2000, d) 2001–2010 and e) 2011–2013. Historical rainfall observation is obtained from the Department of Hydrology and Meteorology (DHM), Nepal.