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Spatiotemporal Dynamics of Forest Cover in the Narmada River Basin: Insights from Enhanced Vegetation Index (1991–2021)

Arkadeep Dutta[*], Naziya Sultana, Riya Mandal, Rupsa Panja, Roni Dey, Saptarshi Mondal, Rakesh Samanta, Manua Banerjee, Ratnadeep Ray

Department of Earth Sciences and Remote Sensing, JIS University, Agarpara, Kolkata-700109, India

E-mail: me.addutta@gmail.com

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Abstract

This study investigates the spatiotemporal changes in forest cover within the Narmada River Basin from 1991 to 2021, utilizing satellite imagery and the Enhanced Vegetation Index (EVI) to assess forest dynamics over the past three decades. The analysis reveals a significant decline in forest cover, with a 17% reduction in forested area, attributed to anthropogenic pressures such as agricultural expansion, urbanization, and infrastructure development, compounded by potential climate change effects. The study identifies key hotspots of deforestation and highlights the absence of substantial forest regeneration, suggesting that current conservation efforts may be inadequate. Given the basin's critical role in providing ecosystem services such as water regulation, carbon sequestration, and biodiversity conservation, the study calls for urgent intervention in forest management. It emphasizes the importance of using remote sensing and geospatial technologies for continuous monitoring and advocates for scaling up afforestation and reforestation initiatives to restore forest health. The findings offer valuable insights for policymakers, providing a foundation for developing sustainable land-use practices and long-term conservation strategies to protect the Narmada River Basin's ecosystems.

Keywords: Deforestation, EVI, Forest health, Geospatial technologies, Narmada River Basin, Remote sensing

I. Introduction

The Narmada River Basin is among the most ecologically significant and geographically expansive river systems in central India, covering a vast area across Madhya Pradesh, Maharashtra, and Gujarat. It is characterized by its diverse landscapes and unique forest ecosystems, ranging from tropical dry deciduous forests to moist deciduous forests. These forests are not merely natural assets but crucial providers of essential ecological services such as water regulation, carbon sequestration, and biodiversity conservation. Furthermore, the basin plays a pivotal role in the regional hydrology and climate, contributing to agricultural productivity, sustaining wildlife habitats, and supporting millions of people who depend on the river and its resources for their livelihoods.

In recent decades, however, the Narmada River Basin has witnessed significant transformations in its forest cover, driven by both anthropogenic and natural factors. Between 1991 and 2021, rapid socio-economic development has brought about profound changes in land use and land cover. Urbanization, agricultural expansion, infrastructure development, and industrial activities have exerted immense pressure on the basin’s forest ecosystems. Simultaneously, natural factors such as climate variability and riverine erosion have further influenced these dynamics. These forces have led to varied patterns of deforestation, degradation, and afforestation, with some areas experiencing substantial forest loss and others showing signs of regeneration.

This study focuses on analyzing the spatiotemporal changes in forest cover within the Narmada River Basin over a 30-year period, aiming to provide a comprehensive understanding of the patterns, drivers, and implications of these changes. By utilizing satellite imagery, remote sensing technologies, and secondary data sources, the research seeks to document deforestation, afforestation, and land-use changes while identifying the underlying causes. The study also explores the ecological consequences of these changes, particularly their impact on biodiversity, carbon storage, water cycles, and the overall health of the basin.

Understanding these changes is crucial not only for academic and scientific purposes but also for formulating effective conservation strategies and policy interventions. The Narmada River, central to this basin, is an essential lifeline for millions, providing water for drinking, irrigation, and industrial use. The health of its forest ecosystems directly influences the river's water quality, flow dynamics, and resilience to climatic fluctuations. Therefore, monitoring and managing forest resources within the basin are vital for ensuring long-term ecological and economic sustainability.

This research also aims to provide actionable insights for policymakers, enabling them to design and implement sustainable management practices for forest and water resources. Furthermore, it establishes a robust baseline dataset that can serve as a foundation for future research and long-term monitoring efforts. By documenting the temporal changes in forest cover and their far-reaching implications, this study contributes to the broader understanding of landscape dynamics and offers pathways for restoring and protecting the fragile yet essential ecosystems of the Narmada River Basin.

Hansen (2008) emphasized the importance of operational landscape monitoring in humid tropical forests to support biodiversity, habitat management, and forest resource conservation. The study introduced a satellite-based method for tracking forest cover changes in the Congo Basin, reporting that less than 1% of the forests were cleared between 1990 and 2000. Ene (2010) analyzed forest dynamics in the Limpedea catchment, focusing on historical landscape changes and highlighting a continuous decline in Subcarpathian forests. Similarly, Blackman (2019) documented urban forest cover changes in St. Peter, MN, over eight decades (1938–2019), showcasing the value of robust methodologies for assessing long-term trends. Huo (2019) presented a semi-automated technique for characterizing high-magnitude forest disturbances (>50% cover loss) across the U.S. (2003–2011) using Landsat-based Global Forest Change and Web-Enabled Landsat Data. Paul and Banerjee (2021) evaluated forest cover and fragmentation in Koraput district over three decades and projected future trends (2017–2027) using logistic regression, noting increased fragmentation and declining forest cover.Chavan (2018) investigated deforestation and fragmentation trends in Telangana's Kinnerasani Wildlife Sanctuary from 2005 to 2015, exposing critical patterns threatening biodiversity. Jayakumar (2009) examined shifts in forest management practices during pre- and post-independence India, highlighting pressures from timber extraction, agriculture, and infrastructure development. DESCLCE (2006) introduced the OB Reflectance Method for detecting forest and land cover changes, utilizing SPOT-HRV imagery over a ten-year period. Nguyen (2018) demonstrated the utility of Landsat time-series data for analyzing forest dynamics across extensive areas over long periods, providing valuable insights into landscape evolution.

II. Study area

The Narmada River Basin, one of the largest and most ecologically significant river basins in India, spans an area of approximately 98,796 square kilometers across the states of Madhya Pradesh, Maharashtra, and Gujarat. The basin is defined by the Narmada River, which originates from the Amarkantak Plateau in Madhya Pradesh at an elevation of about 1,048 meters (near latitude 22.6° N, longitude 81.8° E) and flows westward for 1,312 kilometers before emptying into the Arabian Sea at the Gulf of Khambhat (near latitude 21.7° N, longitude 72.7° E) (Figure1). This westward flow cuts across diverse terrains, encompassing the Satpura Range in the east, the fertile plains of central India, and the coastal regions of Gujarat. The basin's geographical diversity is accompanied by significant ecological and climatic variations, creating a mosaic of landscapes and ecosystems.

The Narmada River Basin features a diverse topography that includes highland plateaus, undulating hills, fertile plains, and expansive forested areas. This varied landscape supports multiple forest ecosystems, such as tropical dry deciduous, tropical moist deciduous, and subtropical forests.

These ecosystems host a rich variety of plant and animal life, including species of significant ecological and economic value. Prominent vegetation includes teak, sal, bamboo, and medicinal plants, while the wildlife ranges from apex predators like tigers and leopards to herbivores and smaller mammals. The forests of the basin play a crucial role in preserving biodiversity, regulating regional climate patterns, maintaining soil health, and improving water quality through natural filtration and watershed management.

The ecological importance of the Narmada River Basin is further enhanced by its network of wildlife sanctuaries and national parks, which act as safe havens for endangered species and biodiversity-rich areas. These forests also provide critical resources to local communities, such as timber, fuelwood, and non-timber forest products, while offering essential ecosystem services like carbon storage and water cycle regulation. The climatic diversity of the basin, ranging from the moist conditions in the upper reaches to the semi-arid zones in the west, adds another layer of complexity to its ecological systems.

With its ecological, economic, and cultural importance, the Narmada River Basin is a key area for addressing broader environmental challenges in central India. Monitoring its forest cover is essential for evaluating ecosystem health, understanding the effects of human activities, and developing strategies for sustainable management. As a critical resource for millions, the basin supports agriculture, supplies drinking water, and drives industrial activities, making its conservation a priority at both local and national levels.

III. Materials and methods

The methodology for this study is designed to analyse forest change dynamics between 1991 and 2021 using the Enhanced Vegetation Index (EVI) and geospatial techniques. EVI was selected due to its ability to minimize atmospheric distortions and reduce soil background noise, making it highly suitable for analysing dense vegetation. The process involved several key steps, beginning with data acquisition and pre-processing.

Satellite imagery for the years 1991 and 2021 was acquired from high-resolution sources, specifically Landsat 5 TM for 1991 and Landsat 8 OLI for 2021. These images were chosen to ensure consistency in spatial resolution and spectral characteristics. Care was taken to select imagery with minimal cloud cover and consistent seasonal conditions to avoid errors arising from phonological variations. Atmospheric corrections were applied to the images using appropriate tools to eliminate distortions caused by haze or aerosols.

The necessary spectral bands, including the Near-Infrared (NIR), Red, and Blue bands, were extracted for EVI calculation, with these bands being crucial for vegetation analysis. To further enhance accuracy, cloud masking algorithms such as Fmask or QA bands were applied to remove the effects of clouds and their shadows.

EVI was calculated for both 1991 and 2021 using the formula:

$$EVI=G\times \{(RNIR-RRED) / (RNIR+C1\times RRED-C2\times RBLUE+L)\}$$

Where:

RNIR: Reflectance in the near-infrared band*; RREDR:* Reflectance in the red band;

RBLUE: Reflectance in the blue ban*d; L:* Canopy background adjustment value (default: 111)

G: Gain factor (default: 2.5); *C1:* Coefficient for the red band (default: 6)

C2: Coefficient for the blue band (default: 7.57); *Default Values: G=2.5, C1=6, C2=7.5, L=1*

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This formula integrates the blue band to correct for atmospheric conditions while maximizing the sensitivity to dense vegetation. Calculations were performed using Geographic Information System (GIS) platforms such as ArcGIS, QGIS, or Google Earth Engine, ensuring a precise representation of vegetation conditions for both time points.

Forested areas were identified by defining a threshold for EVI values, as dense vegetation typically exhibits higher EVI values. The threshold was determined through iterative validation using reference datasets or high-resolution imagery to ensure accuracy. Once the threshold was applied, non-forested areas were masked out, isolating regions that met the criteria for forest cover.

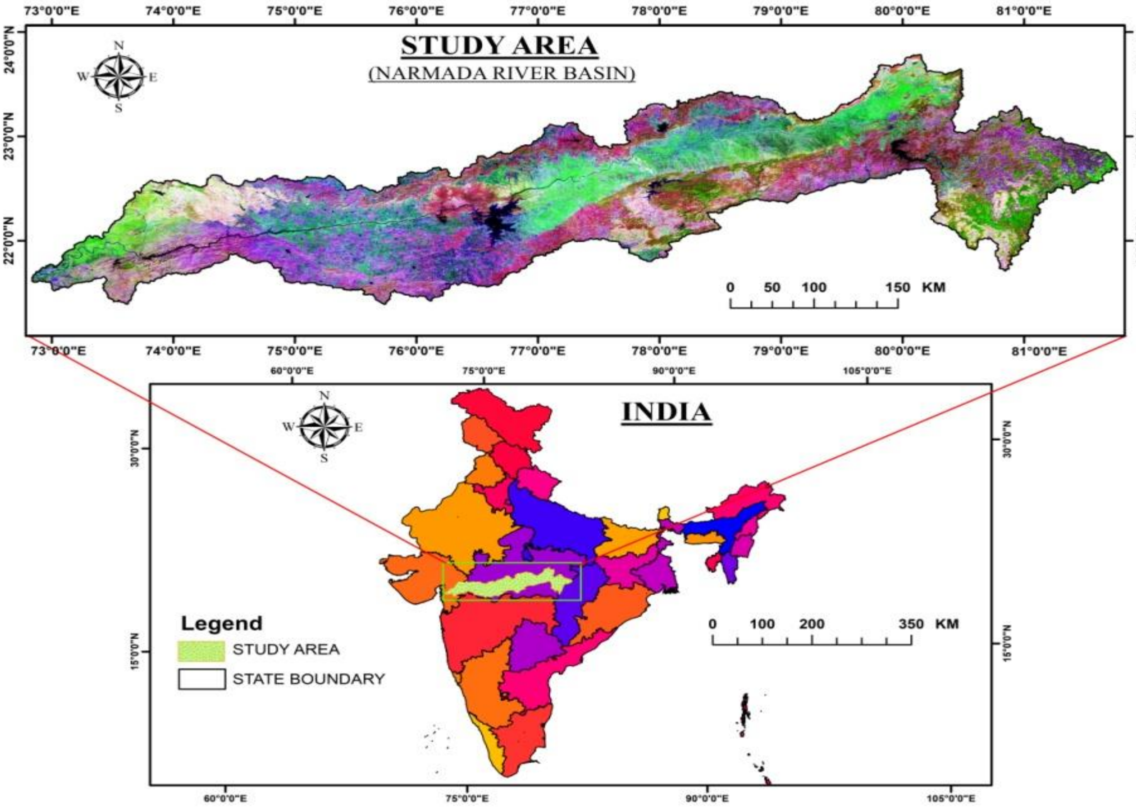

Figure.1: Location map of the study area

The forested regions identified through EVI thresholding were converted from raster to vector format, creating polygon shape files for further analysis. Vector data was used to calculate the total forest area for each year, with results recorded in hectares or square kilometres. GIS tools facilitated these calculations, allowing for detailed examination of forest extent in each timeframe.

Finally, the forest area data from 1991 and 2021 was compared to quantify changes over the three decades. This comparison provided insights into deforestation rates, regeneration patterns, and spatial distribution of forest cover changes. Maps were generated to visualize these changes, offering a clear understanding of the dynamics and identifying critical areas of forest loss or gain. This comprehensive methodology integrates remote sensing and GIS-based techniques to yield accurate and actionable results for assessing long-term forest dynamics.

IV. Results and discussion

a. Change Analysis

The analysis of forest cover between 1991 and 2021 reveals a significant decrease in forest area, underscoring notable environmental changes over three decades. Quantifying the forest area for these two years, we observe that in 1991, the total forest cover was 8,771.87 square kilometres, while in

2021, this decreased to 7,282.47 square kilometres. This represents a net loss of 1,489.40 square kilometres of forest cover, a reduction of approximately 17% over 30 years. These results are visualized in Figure 2, which compares the forested area during the two time periods.

The declining trend in forest cover highlights critical environmental challenges. This loss can be attributed to multiple factors, including agricultural expansion, urbanization, logging, infrastructure development, and potentially the adverse effects of climate change. The findings suggest that forest resources in the region have been under pressure, leading to fragmentation and habitat loss, which directly affects biodiversity and ecological balance.

b. Trend Analysis

The trend identified from the data points to ongoing deforestation. This long-term decline has important implications for regional and global environmental health, as forests play a vital role in carbon sequestration, water regulation, and supporting diverse ecosystems. The reduction in forest area over the past 30 years serves as an indicator of unsustainable land-use practices, emphasizing the need for immediate interventions.

Interestingly, while deforestation is evident, the lack of reforestation or significant forest regeneration in the period analysed suggests that conservation measures in the region have either been inadequate or poorly implemented. This calls for an urgent reassessment of land-use policies and conservation strategies to reverse or at least mitigate this downward trend.

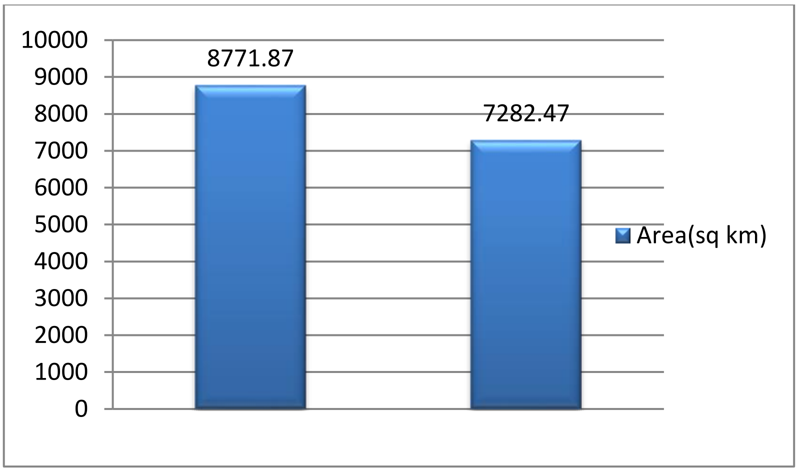

Figure 2: Forest area of 1991 and 2021Conclusions

c. Area Calculations

The calculations for forest cover in 1991 and 2021 were based on geospatial analysis using the Enhanced Vegetation Index (EVI) (Figure 2). This method effectively captured forested regions, allowing for accurate quantification and a clear comparison. The computed forest areas for the two years are summarized below:

1991 Forest Area: 8,771.87 sq km

2021 Forest Area: 7,282.47 sq km

Net Change: −1,489.40 sq km

This significant loss highlights the pressing need to monitor land-use patterns continuously and implement corrective actions to prevent further degradation.

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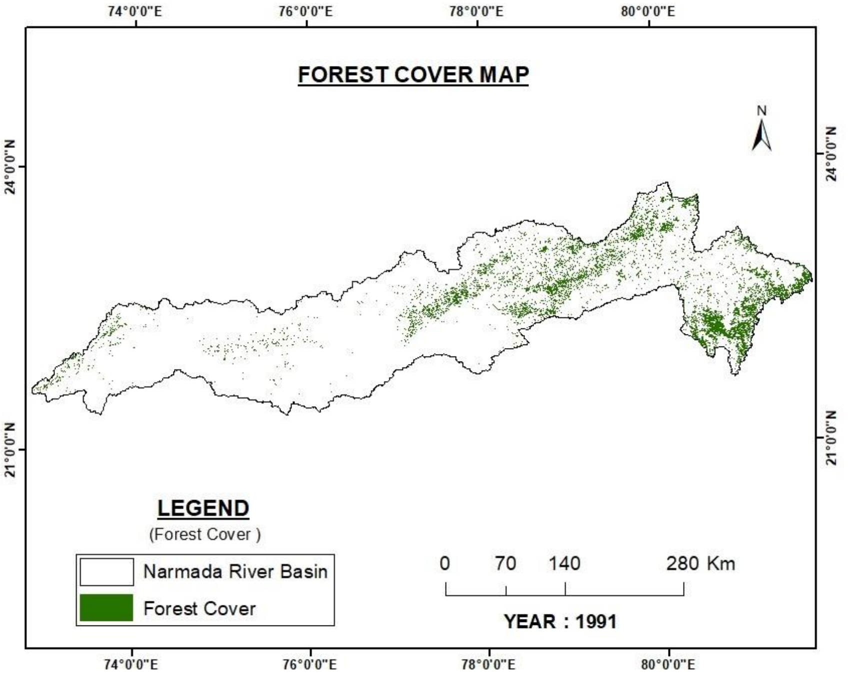

Figure 3: Forest cover area of the year 1991

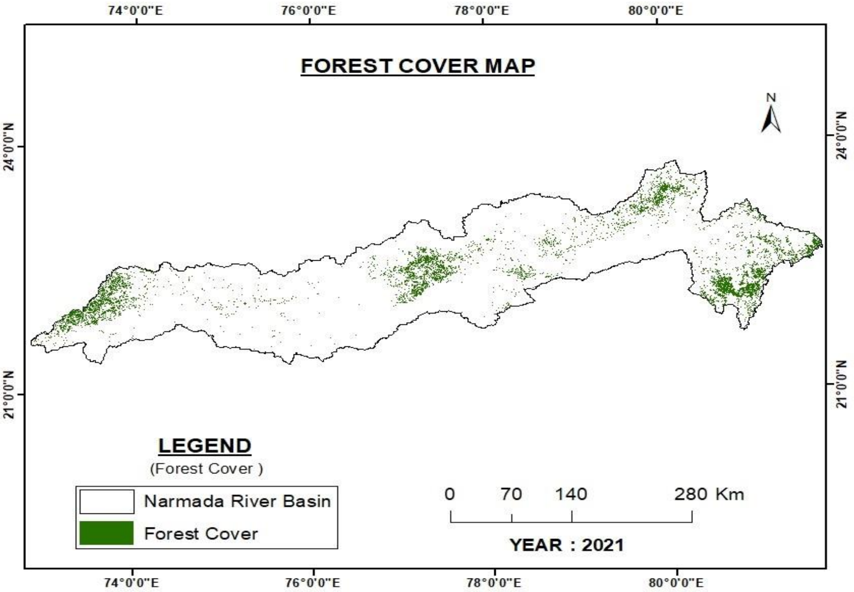

Figure 4: Forest cover area of the year 2021

d. Visualization

Maps generated for 1991 and 2021 provide a spatial representation of forest distribution during these years (Figure3-4). The 1991 map illustrates the extent of forested areas, as identified using EVI thresholds, highlighting dense and contiguous forest regions. In contrast, the 2021 map shows a noticeable reduction in forested regions, with visible fragmentation and encroachment of non-forested areas.

These visualizations offer valuable insights into the spatial dynamics of forest change. Regions that experienced the most significant loss can be identified as hotspots of deforestation, requiring targeted conservation efforts. Furthermore, the maps serve as an effective tool for communicating these changes to policymakers and stakeholders, emphasizing the need for data-driven decision-making in forest management.

e. Implications and Recommendations

The results of this study underscore the urgent need for sustainable forest management practices. Conservation strategies must address the root causes of deforestation, including unregulated agricultural expansion and urbanization. Afforestation and reforestation programs should be prioritized in degraded areas to restore forest cover and improve ecological resilience. Additionally, integrating remote sensing and geospatial technologies into regular forest monitoring can enable timely detection of changes, facilitating swift intervention.

V. Conclusion

This study analyses the spatiotemporal dynamics of forest cover in the Narmada River Basin from 1991 to 2021, revealing a significant 17% decline in forested area, primarily driven by anthropogenic factors such as agricultural expansion, urbanization, and infrastructure development, along with potential climate change impacts. The results highlight critical areas of forest loss that require immediate conservation efforts, while the lack of significant regeneration suggests that current conservation measures may be inadequate. Given the basin's ecological and socio-economic importance, including its role in water regulation, carbon sequestration, and biodiversity support, the study emphasizes the need for integrated forest management practices. It advocates for enhanced monitoring using remote sensing technologies and the scaling up of afforestation and reforestation programs to restore forest health and resilience, providing a foundation for evidence-based policies to ensure the long-term sustainability of the basin's ecosystems.

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