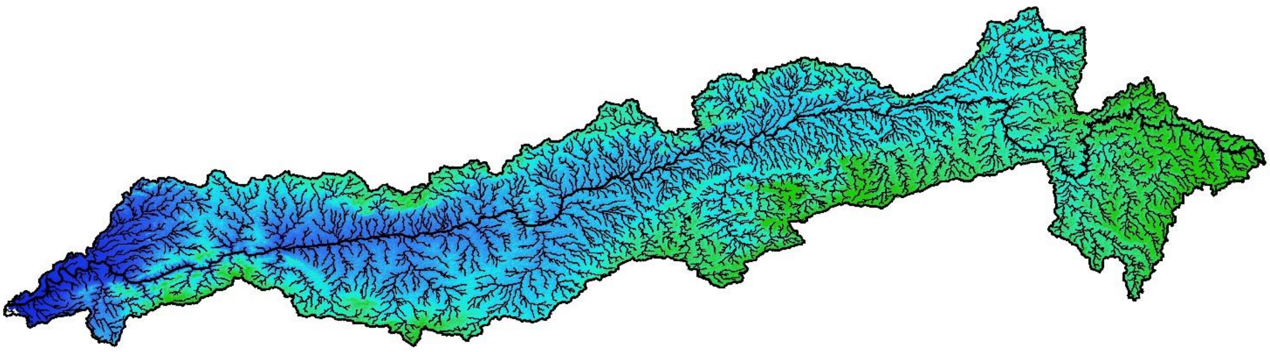
National River Conservation Directorate
Ministry of Jal Shakti,
Department of Water Resources,
River Development & Ganga Rejuvenation
Government of India

Geological Profile

Of Narmada River Basin



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National River Conservation Directorate (NRCD)

The National River Conservation Directorate, functioning under the Department of Water Resources, River Development & Ganga Rejuvenation, and Ministry of Jal Shakti providing financial assistance to the State Government for conservation of rivers under the Centrally Sponsored Schemes of ‘National River Conservation Plan (NRCP)’. National River Conservation Plan to the State Governments/ local bodies to set up infrastructure for pollution abatement of rivers in identified polluted river stretches based on proposals received from the State Governments/ local bodies.

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Centres for Narmada River Basin Management Studies (cNarmada)

The Center for Narmada River Basin Management Studies (cNarmada) is a Brain Trust dedicated to River Science and River Basin Management. Established in 2024 by IIT Gandhinagar and IIT Indore, under the supervision of cGanga at IIT Kanpur, the center serves as a knowledge wing of the National River Conservation Directorate (NRCD). cNarmada is committed to restoring and conserving the Narmada River and its resources through the collation of information and knowledge, research and development, planning, monitoring, education, advocacy, and stakeholder engagement.

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cGanga is a think tank formed under the aegis of NMCG, and one of its stated objectives is to make India a world leader in river and water science. The Centre is headquartered at IIT Kanpur and has representation from most leading science and technological institutes of the country. cGanga’s mandate is to serve as think-tank in implementation and dynamic evolution of Ganga River Basin Management Plan (GRBMP) prepared by the Consortium of 7 IITs. In addition to this, it is also responsible for introducing new technologies, innovations, and solutions into India.

www.cganga.org

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Team Members

Vikrant Jain, cNarmada, IIT Gandhinagar
Karamveer Jadeja, cNarmada, IIT Gandhinagar
Sunny Kumar Jha, cNarmada, IIT Gandhinagar

Preface

The geological profile of the Narmada River Basin is fundamental to understanding its complex geological evolution, structural framework, and dynamic fluvial processes. Characterized by a variety of rock types, including granite gneisses, metamorphic rocks, and the extensive Deccan Traps, the basin's geology influences its hydrological behavior and ecological diversity. The basin's intricate geological history, shaped by both tectonic activity and sedimentary deposition, has resulted in its unique geomorphological features and varied terrain.

However, the basin's geological stability is increasingly challenged by anthropogenic activities and natural geological hazards, which has led to fragmented studies and the necessity for a cohesive understanding of the geological factors influencing the basin. This report seeks to consolidate current knowledge and provide a comprehensive analysis of the Narmada River Basin's geological profile, emphasizing the interplay between its geological framework, anthropogenic impacts, and natural hazards.

Drawing upon existing research, geological surveys, and spatial data, the report examines the key geological and anthropogenic factors that shape the basin. It addresses the challenges and opportunities in studying the basin's geology and highlights the importance of integrating geological information into sustainable management practices and hazard mitigation strategies. Each section of the report builds on essential aspects, from the basin's seismicity and landslide potential to the impacts of deforestation and riverbed mining, to provide a holistic view of its dynamic geological environment.

By presenting an integrated geological profile, this report aims to serve as a valuable resource for decision-makers, researchers, and stakeholders involved in the Narmada River Basin. It advocates for continued interdisciplinary research, improved data collection and monitoring efforts, and the implementation of informed policies to promote the basin's long-term ecological health and sustainable development.

cNarmada and cGanga

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Abbreviations and Acronyms

CGM	Commissionerate of Geology and Mining, Gujarat
DGM	Directorate of Geology and Mining, Madhya Pradesh
FSI	Forest Survey of India
GLOFs	Glacial Lake Outburst Floods
GMDC	Gujarat Mineral Development Corporation Limited
GSI	Geological Survey of India
IPCC	Intergovernmental Panel on Climate Change
ISC	International Seismological Centre
MDF	Moderate Dense Forest
MPSMPCL	Madhya Pradesh State Mining Corporation Limited
MW	Megawatt
Mw	Moment Magnitude
NRZ	Narmada Rift Zone
NSF	Narmada-Son Fault
OF	Open Forest
RBM	River bed mining
RIS	Reservoir-induced Seismicity
SMM	Seismic Moment Magnitude
VDF	Very Dense Forest

1. Introduction

The Narmada Basin, one of the most geologically significant river basins in the Indian subcontinent, exhibits a complex lithological and structural framework that has evolved over millions of years. The Narmada River originates from the Amarkantak plateau in the Satpura Ranges at an elevation of about 1,057 meters and flows westward for approximately 1,284 kilometres across central India before emptying into the Arabian Sea near Baroda, Gujarat.

The basin's geology is characterized by a variety of rock types, including unclassified granite gneisses and metamorphic rocks from the Archaean basement. Above these lie sedimentary sequences from the Bijawar and Jobat formations of Precambrian age, the Vindhyan Group of Paleozoic age, the Nimar and Bagh groups of Cretaceous age, the infratrappeans and the Lameta Group, the Deccan Traps, lower and upper Tertiary sediments, laterite, and recent alluvium (Babu, 1984), which contribute to its unique tectonic and sedimentary history.

Anthropogenic activities have increasingly influenced the geological stability of the Narmada Basin, leading to significant alterations in its natural geomorphological processes. Large-scale excavations, mining operations, riverbed extraction, deforestation, and modifications to hill slopes have accelerated soil erosion, increased sedimentation in river channels, and contributed to slope destabilization (Sharma & Patel, 2020). Mining, particularly in regions rich in bauxite, limestone, and other minerals, has resulted in extensive land degradation and groundwater depletion (Singh et al., 2018). Riverbed mining, driven by high demand for sand and gravel, has disrupted the natural sediment transport processes, leading to channel deepening, bank erosion, and changes in flow regimes (Sinha, 2025). Deforestation, often linked to agricultural expansion and urbanization, has further exacerbated soil erosion and altered local hydrological cycles, making the basin more susceptible to landslides and flooding (Chakraborty et al., 2021). Additionally, infrastructure development projects involving controlled explosions for road and dam construction have introduced mechanical disturbances, triggering microseismicity and weakening geological structures over time (Rai et al., 2017).

Apart from human-induced alterations, the Narmada Basin is also prone to natural geological hazards, primarily earthquakes and landslides. The Narmada-Son Lineament, a major tectonic feature running across central India, makes the region seismically active, with historical records of moderate to strong earthquakes (Kumar et al., 2015). Seismic events along this lineament have been associated with crustal faulting and lithospheric flexure, which continue to influence the basin's stability (Gupta, 2012). Landslides, particularly in the hilly regions of Madhya Pradesh and Maharashtra, are triggered by heavy monsoonal rainfall, deforestation, and anthropogenic modifications to slopes, posing risks to both natural ecosystems and human settlements (Joshi et al., 2020). The combination of these natural and human-induced factors underscores the need for comprehensive geological assessments and sustainable resource management strategies.

This report aims to present a comprehensive geological profile of the Narmada Basin, analysing both anthropogenic and natural factors influencing its geology. By understanding these aspects, this study seeks to contribute to sustainable resource management and hazard mitigation strategies in the region.

2. Natural Geological Disasters

Natural geological disasters such as earthquakes, volcanic eruptions, landslides, and glacial lake outburst floods (GLOFs) play a significant role in shaping river basins. These disasters disrupt hydrological cycles, sediment transport, and fluvial morphology, often leading to devastating socio-economic and environmental consequences (Gupta & Sah, 2008). River basins, being dynamic systems, are particularly sensitive to geological disturbances, which can cause long-term changes in river courses, water quality, and biodiversity (Kale, 2014).

Seismic activity profoundly affects river basins by inducing ground shaking, triggering landslides, altering drainage patterns, and even creating new water bodies through subsidence or uplift. One of the most significant ways earthquakes impact rivers is through river avulsion, where a river suddenly shifts its course due to changes in topography (Kale, 2014). Historical evidence suggests that earthquakes have repeatedly reshaped major river systems worldwide. For instance, the 2008 Wenchuan earthquake in China triggered over 15,000 landslides, leading to the formation of several temporary dammed lakes that posed flood risks upon their failure (Xu et al., 2009). Similarly, the 1897 Assam earthquake in India caused massive upheavals, altering the Brahmaputra River's course and increasing sedimentation, which affected the region's hydrology for decades (Oldham, 1899).

Another consequence of earthquakes is the modification of groundwater and surface water interactions. Seismic activity can increase permeability in fault zones, leading to the emergence of new springs or the drying up of existing water sources (Montgomery & Manga, 2003). This phenomenon can have cascading effects on river flow regimes, particularly in arid and semi-arid regions where groundwater contribution is crucial for sustaining river discharge during dry periods.

Volcanic eruptions have both immediate and long-term consequences for river basins, primarily through the deposition of volcanic ash, lava flows, and the formation of lahars—high-speed mudflows generated by the mixing of volcanic debris with water (Pierson et al., 1990). The 1985 Nevado del Ruiz eruption in Colombia serves as a striking example of the catastrophic impact of lahars on river systems. The eruption melted the volcano's ice cap, producing massive lahars that traveled downriver and buried the town of Armero, killing over 20,000 people (Pierson et al., 1990). Such events demonstrate how volcanic hazards extend far beyond the eruption site, affecting entire river basins.

Long-term volcanic effects include increased sedimentation and changes in river morphology. Volcanic ash and tephra deposits can alter riverbed compositions, reducing water infiltration and increasing surface runoff, which may intensify flood hazards (Manville et al., 2009). Additionally, lava flows can create natural dams, redirecting river courses and leading to the formation of new lakes, which may later breach and cause catastrophic flooding (Major et al., 2000). The 2010 Eyjafjallajökull eruption in Iceland, for example, resulted in extensive glacial melting that caused flash floods in downstream rivers, emphasizing the complex interactions between volcanic activity and river basin dynamics (Roberts et al., 2011).

Landslides, whether triggered by earthquakes, volcanic activity, or heavy rainfall, significantly impact river basins by altering sediment transport, blocking river channels, and creating landslide dams (Sidle & Ochiai, 2006). When these natural dams fail, they release enormous volumes of water downstream, often leading to catastrophic floods. The 2013 Kedarnath disaster in India, which resulted from a combination of landslides and glacial outburst flooding, demonstrated how landslide-generated blockages in river basins can amplify flood hazards (Bhambri et al., 2016).

Additionally, landslides contribute to increased sedimentation in rivers, leading to aggradation—a process where riverbeds rise due to excessive sediment deposition (Korup et al., 2010). This can cause rivers to become shallower and more prone to flooding, affecting both agricultural productivity and infrastructure. For example, landslide-induced sedimentation in the Mekong River Basin has been linked to increased flood risks and reduced water storage capacity in reservoirs (Kondolf et al., 2018).

GLOFs are a growing concern in mountainous river basins, especially in regions like the Himalayas and the Andes, where climate change is accelerating glacial melt (Richardson & Reynolds, 2000). These floods occur when the natural or moraine-dammed lakes formed by melting glaciers suddenly release large volumes of water, leading to devastating downstream floods (Bhambri et al., 2016).

The 2013 Uttarakhand floods in India, triggered by a GLOF from the Chorabari Tal glacial lake, exemplify the severe impacts of such events on river basins. The floodwaters carried enormous amounts of debris, washed away settlements, and altered the morphology of the Mandakini and Alaknanda rivers (Bhambri et al., 2016). As global temperatures continue to rise, the frequency and intensity of GLOFs are expected to increase, posing a significant threat to downstream communities and ecosystems.

2.1 Historical Flood Events and Geological Disaster Interactions in Indian River Basins

The interplay between geological disasters and river flooding has been evident in historical events. India has witnessed several devastating flood events that were influenced by geological disasters such as earthquakes, landslides, and glacial lake outburst floods (GLOFs). The country's diverse topography, ranging from the Himalayan Mountain range to the vast alluvial plains of the Ganges-Brahmaputra basin, makes its river systems highly susceptible to natural geological hazards. These events have repeatedly altered river courses, increased sedimentation, and caused widespread damage to human settlements and infrastructure.

One of the earliest recorded instances of earthquake-induced river flooding in India occurred during the 1897 Assam earthquake, a magnitude 8.1 event that significantly impacted the Brahmaputra River Basin. The seismic event caused extensive liquefaction, leading to the subsidence of riverbanks and the formation of numerous landslide dams along tributaries of the Brahmaputra (Oldham, 1899). These blockages temporarily stored large volumes of water, which were later released as sudden floods, intensifying the flood risk in the downstream Assam plains. Additionally, the earthquake led to a rise in the riverbed due to tectonic uplift, increasing sediment deposition and altering the river's hydrodynamics.

Another significant seismic event affecting Indian river systems was the 1950 Assam earthquake (magnitude 8.6), which drastically altered the Brahmaputra River and its tributaries (Gupta, 2002). The earthquake triggered massive landslides in the Eastern Himalayas, leading to the deposition of large amounts of sediment into the Brahmaputra, raising its riverbed and making it more prone to flooding (Kale, 2014). In the years following the earthquake, the river experienced higher flood frequencies due to the reduced water-carrying capacity caused by sedimentation. This event illustrates how earthquakes can have long-term geomorphological consequences on river basins.

One of the most catastrophic geological disaster-induced floods in India occurred in June 2013, when a combination of heavy rainfall, landslides, and a glacial lake outburst flood (GLOF) resulted in massive devastation along the Mandakini, Alaknanda, and Bhagirathi rivers in Uttarakhand (Bhambri et al., 2016). The Chorabari Tal glacial lake burst after intense rainfall, releasing a sudden surge of water and debris, which exacerbated landslides along the steep river valleys. This flood event caused widespread destruction in Kedarnath, one of India's most important pilgrimage sites, and led to the loss of thousands of lives. The rapid sediment transport and riverbank erosion also altered the course of the Mandakini River, highlighting how GLOFs and landslides can drastically reshape river basins in mountainous regions (Dobhal et al., 2013).

The Kosi River, often referred to as the "Sorrow of Bihar," has a history of frequent and devastating floods, largely due to geological and geomorphological factors. In August 2008, a major breach occurred in the river's embankments near Kusaha in Nepal, leading to the worst flood in Bihar in decades. The breach was primarily caused by excessive sedimentation, which had raised the riverbed over the years, making the embankments vulnerable to collapse (Sinha, 2009). The Kosi, known for its high sediment load originating from landslides in the Himalayas, frequently changes its course, leading to massive displacement of communities and farmland loss. The 2008 flood was particularly devastating as the river abruptly shifted its course eastward, inundating over 3,000 square kilometers of land and affecting more than 3 million people (Mishra, 2010).

In September 2014, unprecedented rainfall in the Kashmir Valley triggered severe flooding along the Jhelum River, affecting both India and Pakistan-administered Kashmir. The floods were exacerbated by landslides in the surrounding mountainous regions, which blocked river channels and created temporary reservoirs that later burst, releasing floodwaters into densely populated areas (Romshoo et al., 2018). Geologists suggest that the region's history of tectonic activity and past earthquakes may have contributed to the increased instability of slopes, making them more susceptible to landslides during heavy rains. The floods caused extensive damage to infrastructure in Srinagar and surrounding districts, highlighting the interaction between geological processes and hydrological extremes in the Himalayan River basins.

The northeastern region of India, particularly Arunachal Pradesh, is highly vulnerable to landslide-induced river blockages due to its rugged terrain and seismic activity. In July 2017, heavy monsoon rains triggered a series of landslides that blocked the Siang River, a major tributary of the Brahmaputra (Ghosh et al., 2018). This led to a temporary accumulation of water upstream, creating a dam-like situation. When the water overtopped the landslide debris, it resulted in sudden downstream flooding, affecting several villages in Arunachal Pradesh and Assam. Such events demonstrate how landslides, often linked to tectonic activity and extreme weather, can create secondary flood hazards in Himalayan River basins.

India's river basins have been repeatedly shaped and reshaped by geological disasters, with earthquakes, landslides, and glacial lake outburst floods playing a crucial role in altering hydrological and geomorphological dynamics. These disasters not only cause immediate devastation but also leave long-term impacts by increasing sedimentation, shifting river courses, and reducing floodplain stability. Understanding these interactions is essential for effective disaster mitigation, flood control, and sustainable river basin management in India. The following chapter provides a detailed account of natural geological disasters in the Narmada River Basin.

2.2 Earthquakes

The Narmada River Basin, located in central India, is a geologically significant region influenced by active tectonics associated with the Narmada-Son Fault (NSF) system. The Narmada Rift Zone (NRZ) is a tectonically active intraplate region, primarily governed by reactivation of pre-existing faults. The NSF is a major structural discontinuity that extends across central India, acting as a zone of crustal weakness (Kaila et al., 1981). This basin has experienced multiple seismic events, including the 1997 Jabalpur earthquake (Mw 6.0), which was attributed to deep-seated faulting along the NSF (Singh et al., 1999) leading to geomorphological, hydrological, and infrastructural consequences. Seismic hazard assessments indicate that strain accumulation along these faults can lead to periodic seismic activity, necessitating long-term monitoring (Gupta, 2002). Figure 1 illustrates the distribution of earthquakes by magnitude within the Narmada Basin. Table 1 presents a record of earthquakes in the Narmada Basin, as documented by the International Seismological Centre (ISC) and Seismic Moment Magnitude (SMM), including their date, location, magnitude, and depth.

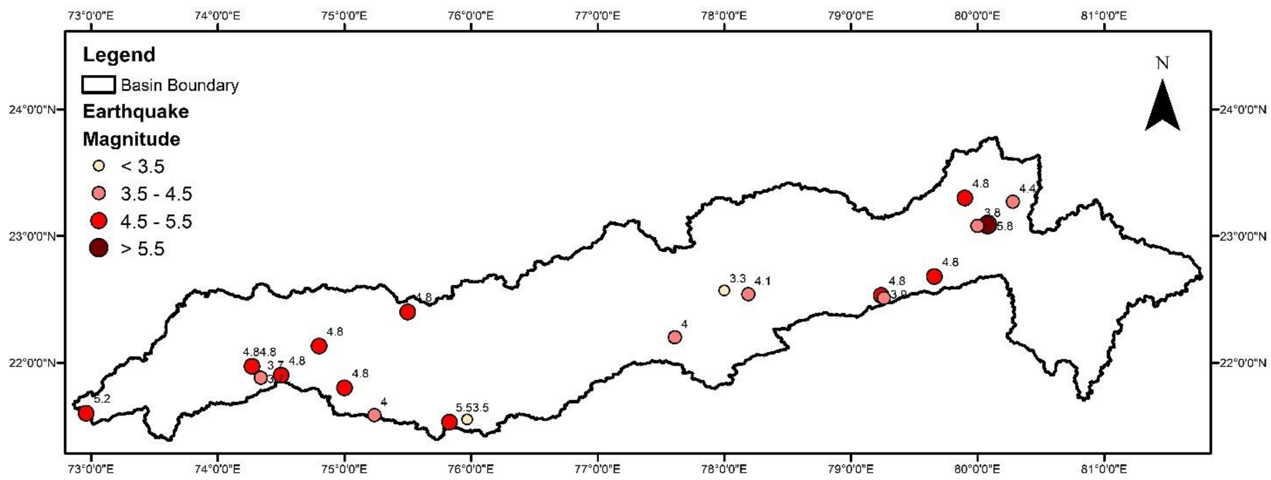

Fig. 1 Distribution of Earthquakes by Magnitude within the Basin (Data Source: ISC, Data downloaded from https://bhukosh.gsi.gov.in/Bhukosh/Public)

Seismic activity can significantly alter river dynamics by influencing channel morphology, sediment transport, and groundwater flow. Earthquakes have been documented to cause uplift, subsidence, and lateral shifts in river courses globally (Wells & Coppersmith, 1994). In the

Narmada Basin, seismic events have triggered localized channel avulsions, changes in sediment deposition, and bank instability (Kumar et al., 2013).

Additionally, groundwater systems within the basin are affected by seismic shaking, which can lead to enhanced permeability in faulted aquifers or the sealing of fractures due to compaction (Shukla & Patel, 2017). The impact of earthquakes on groundwater recharge remains an area requiring further empirical investigation, as regional hydrogeological responses to seismicity remain poorly constrained.

The Narmada Basin is home to major hydraulic structures, including the Sardar Sarovar Dam, which is located in a zone of moderate seismic hazard (Bapat, 2010). While no catastrophic structural failures have been recorded, concerns regarding reservoir-induced seismicity (RIS) due to impoundment effects have been raised (Gupta, 2002). Studies suggest that fluctuations in reservoir levels can trigger seismic activity by altering stress distributions in the underlying crust, as observed in other dam-induced seismicity cases worldwide (Simpson et al., 1988).

Furthermore, seismic shaking poses a risk to bridges, canals, and embankments across the basin, necessitating seismic retrofitting and stringent engineering standards in future developments. Seismic risk assessment models incorporating probabilistic hazard analyses can aid in designing resilient infrastructure (Kumar & Kumar, 2016).

Table 1: ISC and SMM Recorded Earthquakes in the Narmada Basin

Source	Date	Latitude	Longitude	Magnitude	Depth (in kms)
SMM	14th Mar 1938	21.53000100000	75.83000200000	5.50000000000	40.00000000000
ISC	22nd Nov 2003	21.54999900000	75.97000100000	3.50000000000	11.00000000000
ISC	4th Jan 2009	21.58500000000	75.23630000000	4.00000000000	8.40000000000
ISC	10th Jul 2000	21.79999900000	75.00000000000	4.80000000000	20.00000000000
ISC	27th Jul 2003	21.87999900000	74.33999600000	3.70000000000	20.00000000000
ISC	14th Apr 2000	21.90000000000	74.50000000000	4.80000000000	10.00000000000
ISC	6th Jan 1967	21.96999900000	74.26999700000	4.80000000000	0.00000000000
ISC	24th Jul 2000	22.12999900000	74.80000300000	4.80000000000	15.00000000000
ISC	10th Jan 1996	22.20000100000	77.61000100000	4.00000000000	10.00000000000
ISC	13th Sept 1998	22.40000000000	75.50000000000	4.80000000000	15.00000000000
ISC	9th Mar 1998	22.54000100000	78.19000200000	4.10000000000	21.00000000000
ISC	19th Jul 1998	22.57000000000	78.00000000000	3.30000000000	33.00000000000
ISC	16th Oct 2000	23.27000000000	80.27999900000	4.40000000000	29.00000000000
ISC	21st May 1997	23.09000000000	80.08000200000	5.80000000000	39.00000000000
ISC	4th Jun 1997	23.08000000000	80.00000000000	3.80000000000	31.00000000000
ISC	23rd Jan 2001	23.29999900000	79.90000200000	4.80000000000	13.00000000000
ISC	17th Apr 2002	22.68000000000	79.66000400000	4.80000000000	15.00000000000
ISC	29th Mar 1998	22.51000000000	79.26000200000	3.90000000000	33.00000000000
ISC	18th Apr 1987	22.53000100000	79.23999800000	4.80000000000	20.00000000000
ISC	23rd Mar 1970	21.60000000000	72.95999900000	5.20000000000	8.00000000000

The Narmada River Basin, influenced by the NSF, remains vulnerable to moderate seismic activity that can impact its geomorphology, hydrology, and infrastructure. While significant research has been conducted on regional seismicity, further studies are needed to quantify long-term hydrogeomorphic responses and assess infrastructure vulnerability. Given the presence of critical water management structures, continued seismic monitoring and integration of hazard mitigation strategies into development planning are essential for reducing seismic risks in the basin.

2.3 Landslides

A landslide is a geomorphic process characterized by the downward and outward movement of soil, rock, and debris under the influence of gravity. Landslides occur due to natural and anthropogenic factors, often triggered by heavy rainfall, earthquakes, volcanic activity, deforestation, and human-induced land modifications (Highland & Bobrowsky, 2008). Landslides within the Narmada River basin have not been extensively documented in the available literature. However, related studies on land degradation, flood events, and seismic activities provide insights into the region's susceptibility to such hazards.

A study by Ely et al. (1996) analyzed late Holocene monsoon floods on the Narmada River, revealing an increase in the magnitude and frequency of severe floods over recent decades. These findings suggest a heightened vulnerability to flood-related erosion and potential landslide occurrences in the basin. Additionally, research by Khare et al. (2015) examined the impact of land use and land cover changes on runoff within a Narmada River catchment. The study highlighted those alterations in land use significantly influence runoff patterns, which can exacerbate soil erosion—a precursor to landslides.

Land degradation assessments indicate that approximately 43.16% of the upper Narmada basin is highly susceptible to erosion, further predisposing the region to landslide activity (Rawat et al., 2023). The degradation is exacerbated by anthropogenic activities such as mining, infrastructure development, and unsustainable agricultural practices. These activities contribute to slope destabilization, increasing the likelihood of landslides, especially during monsoon seasons.

Although direct studies on landslides in the Narmada River basin are scarce, the interplay of geological, hydrological, and anthropogenic factors suggests a significant potential for landslide occurrences. Further research integrating remote sensing, GIS-based susceptibility mapping, and field investigations is necessary to enhance our understanding of landslide hazards in the basin and to develop effective mitigation strategies.

2.4 Other Natural Geological Disasters

Natural hazards such as avalanches, tsunamis, and sinkholes are significant geological and hydrological phenomena that occur under specific environmental conditions. Avalanches refer to the rapid downward movement of snow, ice, and debris along steep slopes, commonly triggered by weather changes, seismic activity, or human disturbances (McClung & Schaerer, 2006). They are predominantly found in high-altitude mountainous regions with heavy snowfall, such as the Himalayas (Singh et al., 2012). Since the Narmada River basin lies within a tropical and subtropical climatic zone, it lacks the necessary snowfall and glacial cover required for avalanche formation. Furthermore, the basin's elevation is relatively low compared to the Himalayas, making it unsuitable for avalanche occurrences.

Tsunamis are large sea waves caused by underwater seismic activity, volcanic eruptions, or landslides (Satake, 2014). These events primarily impact coastal regions and open ocean environments, such as those surrounding the Pacific and Indian Ocean basins. The Narmada River is an inland river system that does not connect to the ocean, eliminating any direct exposure to tsunami risks. Additionally, there are no significant water bodies within the basin large enough to generate inland tsunami-like waves due to seismic activity. Therefore, tsunamis are not a plausible threat to the Narmada region.

Sinkholes occur when soluble rock formations, such as limestone, dissolve over time due to groundwater infiltration, leading to sudden ground collapses (Waltham et al., 2005). These formations are most common in karst landscapes, where extensive underground drainage and dissolution processes shape the terrain. While some regions of India, such as parts of Madhya Pradesh and Rajasthan, exhibit karst topography, the Narmada River basin is largely composed of basaltic and sedimentary formations, which are less prone to dissolution-induced sinkholes (Kale, 2014). As a result, sinkholes are rare and unlikely to occur in this region.

The absence of high-altitude snow-covered mountains, coastal exposure, and karst topography in the Narmada River basin makes avalanches, tsunamis, and sinkholes highly improbable. Future studies on the region’s geological evolution may provide further insights into potential localized risks, but current evidence strongly supports their improbability.

3. Anthropogenic Activities affecting the Basin

Anthropogenic activities have significantly altered river basins worldwide, impacting their hydrological, ecological, and geomorphological characteristics. Human-induced modifications such as deforestation, mining, urbanization, infrastructure development, and intensive agriculture have disrupted the natural balance of river ecosystems, leading to severe environmental consequences. The increasing demands for land and water resources have accelerated these impacts, threatening the sustainability of river basins and the communities that depend on them.

Deforestation within river basins has led to increased soil erosion, sedimentation, and changes in runoff patterns, thereby exacerbating flood risks and reducing groundwater recharge (Allan, 2004). The removal of vegetation destabilizes soil structures, making slopes prone to landslides and increasing sediment load in rivers. This process not only disrupts aquatic habitats but also affects water quality by introducing excess sediments, which can alter the physical and chemical composition of river systems (Bruijnzeel, 2004).

Mining and industrial operations contribute to heavy metal contamination and sediment disruption, which degrade water quality and aquatic ecosystems. Open-pit mining and riverbed extraction disturb the natural sediment balance, leading to increased turbidity and loss of aquatic biodiversity (Rinaldi et al., 2005). Additionally, industrial waste discharge introduces hazardous chemicals into river systems, affecting both human populations and aquatic life (Meybeck, 2003). These pollutants accumulate over time, leading to long-term ecological damage and rendering water sources unsafe for consumption and irrigation.

Urbanization has further exacerbated the degradation of river basins. The construction of impervious surfaces such as roads, buildings, and pavements alters natural drainage patterns, reducing infiltration and increasing surface runoff. This process leads to higher peak flows during rainfall events, increasing the risk of flash floods and erosion (Walsh et al., 2005). Furthermore, the expansion of cities has resulted in the encroachment of floodplains, reducing the river's ability to absorb excess water and increasing flood vulnerability in densely populated areas.

Infrastructure developments, including dam construction, disrupt sediment transport and aquatic habitats, leading to riverbank erosion and loss of biodiversity (Graf, 2006). Dams and reservoirs alter the natural flow regime of rivers, trapping sediments that would otherwise replenish downstream ecosystems. This sediment starvation contributes to the erosion of riverbanks, deltas, and coastal areas, affecting both ecological and human settlements (Kondolf et al., 2014). Additionally, the fragmentation of river habitats due to damming has severe consequences for migratory fish species and other aquatic organisms dependent on free-flowing rivers.

Intensive agriculture further depletes river water through excessive irrigation and contaminates water bodies with chemical runoff, causing eutrophication and aquatic life degradation. The overuse of fertilizers and pesticides leads to nutrient pollution, resulting in algal blooms and oxygen depletion in water bodies (Carpenter et al., 1998). These conditions create dead zones where aquatic life cannot survive, disrupting the food chain and reducing biodiversity.

Furthermore, the diversion of river water for irrigation reduces downstream flow, affecting the availability of water for ecosystems and communities reliant on the river for sustenance.

Climate change, driven by anthropogenic factors, has intensified these impacts by altering precipitation patterns and increasing drought and flood occurrences. Rising global temperatures influence hydrological cycles, leading to irregular rainfall distribution, prolonged dry periods, and intensified storm events (IPCC, 2014). These changes further stress river basins already weakened by human activities, compounding the risks of water scarcity, habitat loss, and extreme weather events.

The combined effects of these anthropogenic activities have resulted in water scarcity, biodiversity loss, increased flood risks, and ecosystem degradation. To mitigate these impacts, sustainable management strategies such as afforestation, stringent industrial regulations, sustainable agriculture, and integrated water resource management must be implemented (Poff et al., 1997). Restoration of degraded riverbanks, reforestation of watershed areas, and enforcement of pollution control measures are essential steps in preserving river basin integrity. Additionally, coordinated efforts from policymakers, scientists, and local communities are necessary to implement conservation initiatives and promote sustainable practices for the protection of riverine ecosystems. Addressing these challenges requires a holistic approach that balances economic development with environmental stewardship to ensure the long-term resilience of river basins.

3.1 Excavation, Explosions and Mining Activities

Excavation activities, such as dredging and channelization, are often undertaken for navigation, flood control, and resource extraction. While these activities may serve specific human needs, they can have profound impacts on river basins.

Excavation can alter river flow regimes, leading to changes in water velocity, depth, and sediment transport (Kondolf, 1997). Channelization, for instance, often results in straightened channels with increased flow velocity, which can exacerbate erosion downstream and reduce habitat complexity (Brookes, 1988). The removal of substrate and vegetation during excavation directly destroys aquatic and riparian habitats (Newcombe & Jensen, 1996). This can lead to a decline in biodiversity, affecting fish spawning grounds, invertebrate communities, and riparian vegetation (Allan & Castillo, 2007). Excavation can increase sediment suspension, leading to turbidity and reduced light penetration, which can negatively impact primary productivity and aquatic organisms (Bilotta & Brazier, 2008). Furthermore, the disturbance of sediments may release pollutants, such as heavy metals and nutrients, into the water column (Förstner & Wittmann, 1981).

Explosions in or near river basins, often associated with construction, mining, or demolition, can have immediate and severe impacts. Underwater explosions generate shockwaves that can cause direct physical harm to aquatic organisms, including fish, marine mammals, and invertebrates (Keevin & Hempenius, 1997). The destruction of habitat can be extensive, particularly in confined areas (Wright, 1982). Explosions can resuspend bottom sediments, leading to increased turbidity and the release of contaminants (Nedwell et al., 2007). This can have long-term effects on water quality and aquatic ecosystems. Explosions, particularly those related to dam removal or breaching, can cause sudden and drastic changes in river flow, leading to flooding and erosion downstream (Poff et al., 1997).

Mining activities, including surface and subsurface extraction, are major sources of pollution and degradation in river basins. The exposure of sulfide minerals during mining can lead to the formation of sulfuric acid when these minerals react with water and oxygen (Akcil & Koldas, 2006). AMD can lower the pH of water bodies, making them toxic to aquatic life and mobilizing heavy metals (Lottermoser, 2010). Mining can release a variety of heavy metals, such as mercury, arsenic, and lead, into river systems (Nriagu & Pacyna, 1988). These metals can accumulate in sediments and biota, posing risks to human health through the consumption of contaminated fish and water (Mason et al., 2000). Mining operations often involve the removal of vegetation and topsoil, leading to increased erosion and sedimentation in rivers (Walling & Fang, 2003). This can smother aquatic habitats, alter channel morphology, and reduce water quality (Richards et al., 1992).

3.2 River Bed Mining

River bed mining (RBM), the extraction of sand, gravel, and other materials from riverbeds and banks, has been extensively studied for its detrimental impacts on river basin ecosystems. Research consistently demonstrates that RBM directly alters the physical structure of rivers, leading to habitat destruction and a consequent reduction in biodiversity, evidenced by declines in fish populations, altered macroinvertebrate communities, and loss of riparian vegetation (Kondolf, 1994; Padmalal et al., 2008; Sharma et al., 2010). Hydrological regimes are also significantly affected, with RBM causing changes in river morphology, channel instability, altered flow patterns, and increased turbidity and sedimentation downstream (Kondolf, 1997; Rinaldi et al., 2008). These hydrological alterations can exacerbate flood risks, reduce base flows leading to water scarcity, and negatively impact water quality (Evans et al., 2006; Walling, 2005). Beyond environmental concerns, RBM poses considerable socio-economic challenges, potentially diminishing access to water resources, damaging infrastructure, negatively affecting traditional livelihoods like fishing and agriculture, and contributing to social conflicts and governance issues, particularly when extraction is unregulated (Evans et al., 2006; Alam & Dutta, 2012; Guptha, 2017). The magnitude of these impacts is context-specific, varying based on the scale and intensity of mining, geological characteristics, flow regimes, and existing ecological conditions, as highlighted in studies from various regions globally (Bravard et al., 1996; Singh et al., 2017).

Note: Currently, the data collection for *excavation, explosions, & mining activities* and *river bed mining* is ongoing. To gather the necessary information regarding the impact of these activities on the river basin the following agencies have been contacted:

- Geological Survey of India (GSI)

- Commissionerate of Geology and Mining (CGM), Gujarat
- Gujarat Mineral Development Corporation Limited (GMDC)
- Directorate of Geology and Mining, Madhya Pradesh
- Madhya Pradesh State Mining Corporation Limited

As of the current date, the requested data has not yet been received from these agencies. We are actively following up on our requests and anticipate receiving the information for this report.

3.3 Tunnels in the Basin

The Narmada River Basin is primarily characterized by surface water management structures such as dams and canals. However, limited information is available on tunnel infrastructure, which, where documented, is mainly associated with hydropower generation and inter-basin water transfer schemes.

The Sardar Sarovar Dam, a major infrastructure project on the Narmada River, includes a significant underground powerhouse with a capacity of 1200 MW (Narmada Control Authority, n.d.). This necessitates the presence of tunnels for water conveyance and discharge. Specifically, the powerhouse utilizes draft tube and exit tunnels to manage the flow of water after it passes through the turbines. These tunnels, excavated through the prevalent dolerite rock formations in the region, are critical for the efficient operation of the hydropower facility (Central Board of Irrigation and Power, 1995). Additionally, the Kaplan turbines at the Canal Head Power House are situated at a considerable depth below sea level, requiring a kilometer-long access tunnel (8m x 9m) for operational and maintenance purposes (Sardar Sarovar Narmada Nigam Limited, n.d.). These tunnels, while integral to the hydropower infrastructure, primarily manage controlled water flow and are less likely to cause widespread hydrological alterations compared to long diversion tunnels.

Inter-basin water transfer projects aim to redistribute water resources from surplus to deficit areas. Within the Narmada Basin, the Bargi Diversion Project is designed to transfer water to the Son-Tones basin. A key component of this project is a substantial 12 km long tunnel with a 10-meter diameter, known as the Sleemanabad Tunnel (National Water Development Agency, n.d.). Such long tunnels, designed to convey significant volumes of water across hydrological divides, can have notable impacts on groundwater regimes and potentially alter surface water flow patterns in both the donor and recipient basins (Ghasemi et al., 2013).

The proposed Par-Tapi-Narmada Link Project further highlights the use of tunnels in inter-basin water transfer within the region. This project envisions the construction of two tunnels (5.0 km and 0.5 km) to transfer surplus water from the Par and Tapi river basins to the Narmada canal command area (National Water Development Agency, n.d.). These tunnels, while shorter than the Sleemanabad Tunnel, still represent a significant engineering intervention that requires assessment of potential impacts on local hydrology and geology.

These tunnels, while serving essential engineering functions, have the potential to interact with the basin's hydrology and geological framework, necessitating careful consideration of their design, construction, and operational impacts.

3.4 Fracking Zones in the Basin

A fracking zone refers to an area where hydraulic fracturing, commonly known as fracking, is actively being conducted to extract natural gas and oil from underground rock formations, particularly shale. This process involves injecting a high-pressure mixture of water, sand, and chemicals into wellbores to create fractures in the rock, allowing the trapped hydrocarbons to flow more freely to the surface. Based on current scientific understanding and available geological data, there is a lack of evidence to support the existence of active or planned hydraulic fracturing (fracking) zones within the Narmada River basin. This conclusion is primarily attributed to the basin's geological characteristics and the current focus of hydrocarbon exploration activities.

The dominant lithological unit within the Narmada River basin is characterized by the Deccan Traps, the extensive basaltic lava flows that constitute a significant portion of the basin's geological framework. These igneous rocks are generally not considered prospective formations for unconventional hydrocarbon extraction via hydraulic fracturing due to their low porosity and permeability. While sedimentary rocks of Precambrian, Mesozoic, and Cenozoic ages are present, the available literature does not indicate the widespread presence of shale formations with the requisite organic matter content and maturation levels necessary for economic shale gas or tight oil extraction. Hydraulic fracturing is primarily targeted at organic-rich shale formations with low permeability.

Apart from this comprehensive geological surveys and resource assessments, as documented in scientific literature and energy resource databases, have not identified the Narmada River basin as a major shale gas or tight oil play comparable to other regions globally where fracking is prevalent (e.g., Permian Basin, Marcellus Shale). Historical hydrocarbon exploration within the Narmada basin, particularly in its lower reaches and proximity to the Cambay Basin, has primarily focused on conventional oil and gas reservoirs trapped within structural and stratigraphic traps in formations like sandstones and carbonates. While the adjacent Cambay Basin does possess shale gas potential and has witnessed some fracking activities, these operations are geographically distinct and do not extend into the Narmada River basin proper.

3.5 Deforestation

To understand deforestation patterns within the Narmada basin, a quantitative analysis was performed to understand temporal variations in forest cover from the data obtained from Forest Survey of India (FSI) for districts in Gujarat and Madhya Pradesh. This involved acquiring FSI data, which categorizes forest cover into Very Dense Forest (VDF), Moderate Dense Forest (MDF), and Open Forest (OF), providing a standardized measure of forest density. The results were visualized through clear graphs and interpreted in the context of deforestation, considering potential drivers such as agricultural expansion, urbanization, and resource extraction.

3.5.1 Temporal Variations in Very Dense Forest

Fig. 02 shows the temporal variation in very dense forest cover across different districts of Gujarat from 2003 to 2023. Surat exhibited the most significant changes, with a rapid increase in forest cover from 2005, peaking around 2010–2015 at approximately 90 square kilometers. However, this was followed by a sharp decline around 2017, stabilizing at a much lower level in subsequent years, indicating possible large-scale deforestation or land-use changes. The Narmada district displayed a steady increase in forest cover until 2009, reaching around 20 square kilometers, and remained stable thereafter. In contrast, the districts of Bharuch, Dahod, Panch Mahals, and Vadodara showed relatively minimal fluctuations, maintaining consistently low forest cover throughout the study period. The overall trend suggests that while some districts experienced an increase in very dense forest cover initially, a significant decline, particularly in Surat, highlights potential anthropogenic or environmental factors influencing forest dynamics in the region.

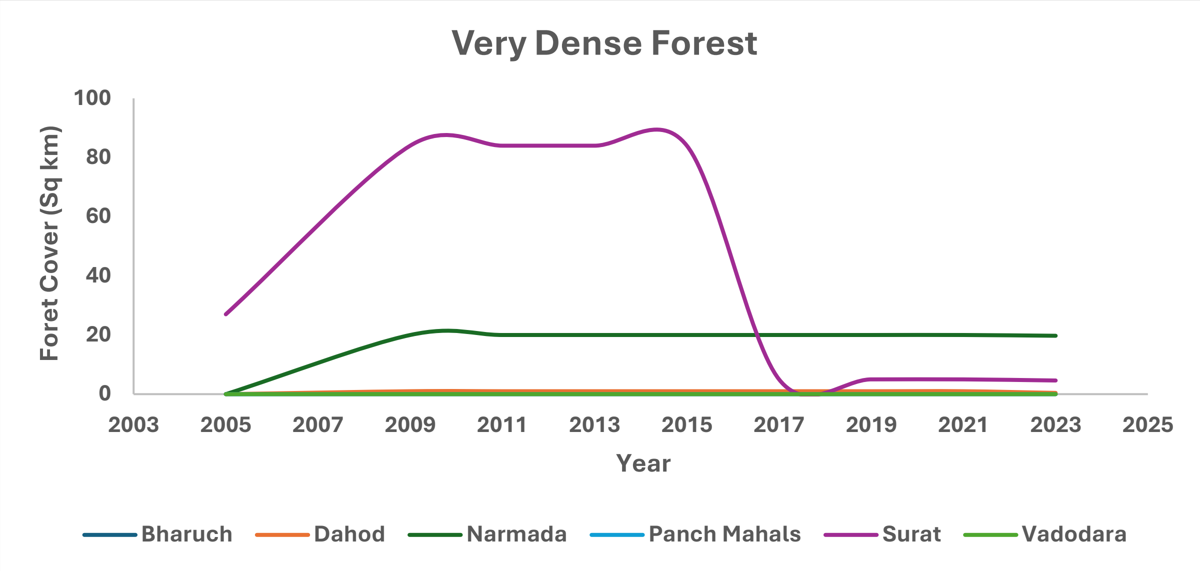

Fig. 02: Temporal Variation in Very Dense Forest Cover Across Gujarat Districts Within the Narmada Basin (2003–2023)

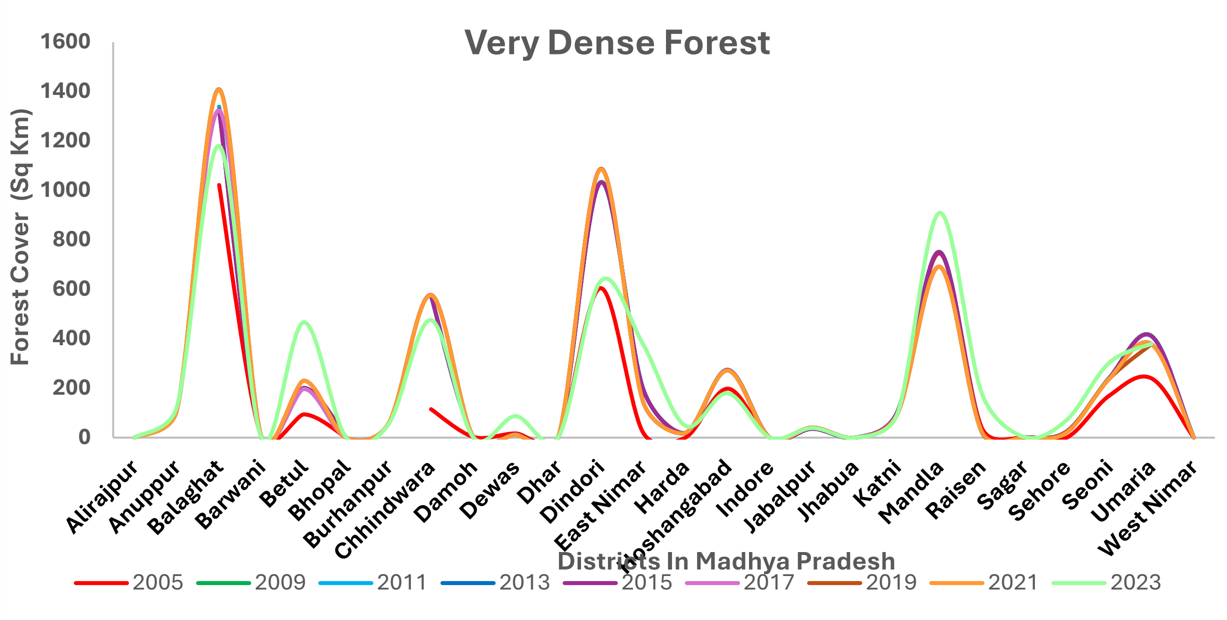

Fig. 03: Temporal Variation in Very Dense Forest Cover Across MP Districts Within the Narmada Basin (2003–2023)

Fig. 03 presents the changes in very dense forest cover (measured in square kilometers) across various districts of Madhya Pradesh, India, from 2005 to 2023. The data reveals significant spatial and temporal heterogeneity in forest cover. Several districts, including Balaghat, Dindori, Harda, Katni, Raisen, and Sehore, exhibit prominent peaks, indicating areas with substantial very dense forest cover. Balaghat, in particular, shows the highest peak, suggesting it consistently maintains a large area of very dense forest. Conversely, districts like Bhopal, Burhanpur, Chhindwara, Dewas, Dhar, East Nimar, Hoshangabad, Indore, Jhabua, Jabalpur, Mandla, Sagar, Seoni, Umaria, and West Nimar display relatively lower levels of very dense forest cover throughout the study period. The temporal trends reveal fluctuations in forest cover across all districts. For instance, some districts show a notable increase in very dense forest cover between 2005 and 2011, followed by a decline or stabilization in subsequent years. The observed variations likely reflect a combination of factors, including deforestation, afforestation efforts, forest management practices, and natural disturbances. The pronounced peaks in certain districts suggest the presence of favorable environmental conditions or effective conservation strategies that support the growth and maintenance of very dense forests.

3.5.2 Temporal Variations in Moderately Dense Forest

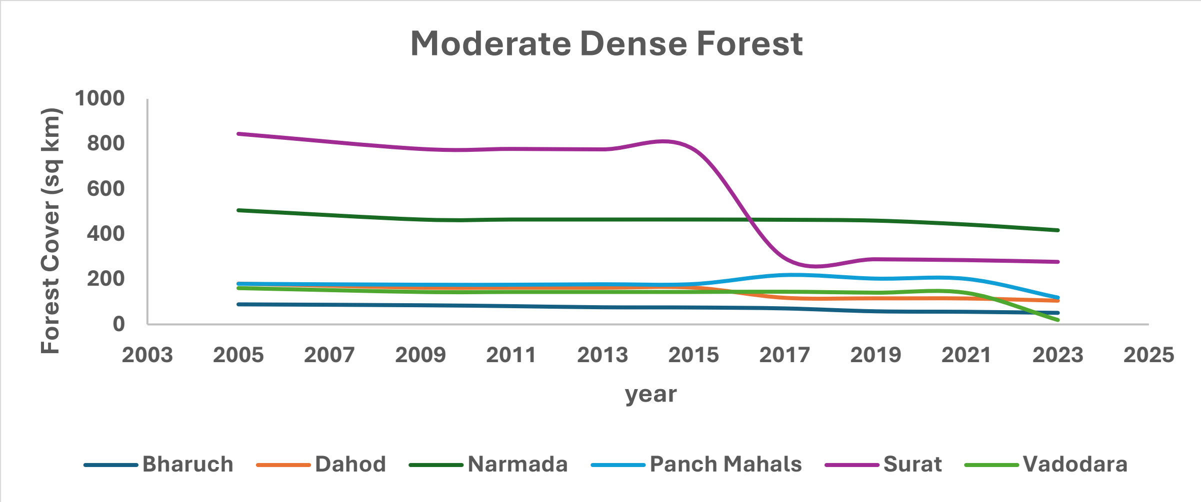

Fig. 04: Temporal Variation in Moderate Dense Forest Cover Across Gujarat Districts Within the Narmada Basin (2003–2023)

Fig. 04 represents the temporal variation in moderately dense forest cover across selected districts of Gujarat within the Narmada Basin from 2003 to 2023. Surat exhibited the highest forest cover at the beginning of the period, with a gradual decline until 2015, followed by a sharp drop around 2017, after which it stabilized at a lower level. The Narmada district maintained relatively stable forest cover throughout the period, with a slight decline in recent years. Vadodara exhibited a consistent but gradual decrease in moderately dense forest cover over time. The districts of Bharuch, Dahod, and Panch Mahals showed minor fluctuations, with Panch Mahals experiencing a slight increase around 2017, followed by a decline. The overall trend indicates a gradual reduction in moderately dense forest cover across most districts, with Surat experiencing the most significant loss, likely due to land-use changes, deforestation, or other anthropogenic activities affecting forest dynamics.

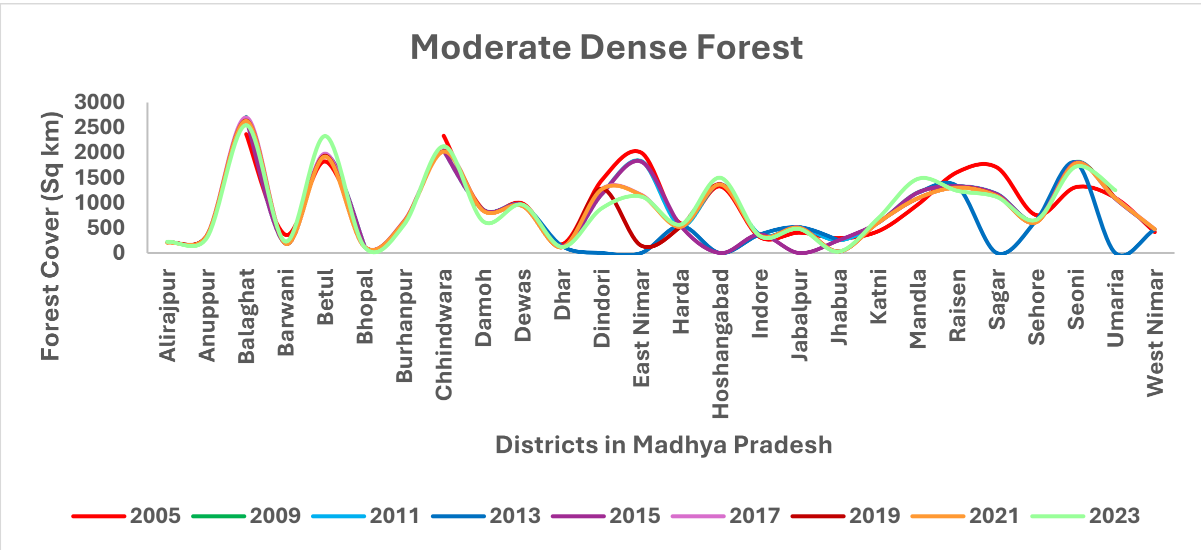

Fig. 05: Temporal Variation in Moderate Dense Forest Cover Across MP Districts Within the Narmada Basin (2003–2023)

Fig. 05 illustrates the temporal variation in moderately dense forest cover across different districts of Madhya Pradesh from 2005 to 2023. Several districts, such as Balaghat, Betul, and Seoni, exhibit the highest forest cover throughout the study period, indicating their significance in maintaining forest resources. The general trend reveals fluctuations in forest cover over the years, with some districts showing an increase while others experience a decline.

Notably, a sharp decline is observed in certain districts around 2017, suggesting possible deforestation, land-use changes, or natural disturbances. Conversely, some districts, such as Mandla and Raisen, show signs of recovery in later years. The variations in forest cover across districts highlight the dynamic nature of forest ecosystems, possibly influenced by conservation efforts, human interventions, and climatic factors. Overall, the trend underscores the need for targeted forest management strategies to maintain and restore moderately dense forests in the region

3.5.2 Temporal Variations in Open Forest

The graph shown in fig. 06 shows the temporal trends in open forest cover (measured in square kilometers) across six districts of Gujarat, India, from 2003 to 2023. Notably, the districts exhibit varied patterns of forest cover change. Bharuch and Narmada show relatively stable open forest cover throughout the period, albeit with minor fluctuations. Surat and Dahod demonstrate a similar stability until around 2016, after which Surat experiences a sharp decline followed by a slight recovery, while Dahod maintains a gradual downward trend. Panch Mahals displays a unique U-shaped pattern, with a decrease in cover until 2016, followed by a substantial increase and a subsequent decline towards 2023. Vadodara, in contrast, shows a gradual increase in open forest cover until approximately 2016, followed by a period of decline and then a more pronounced decrease in the later years.

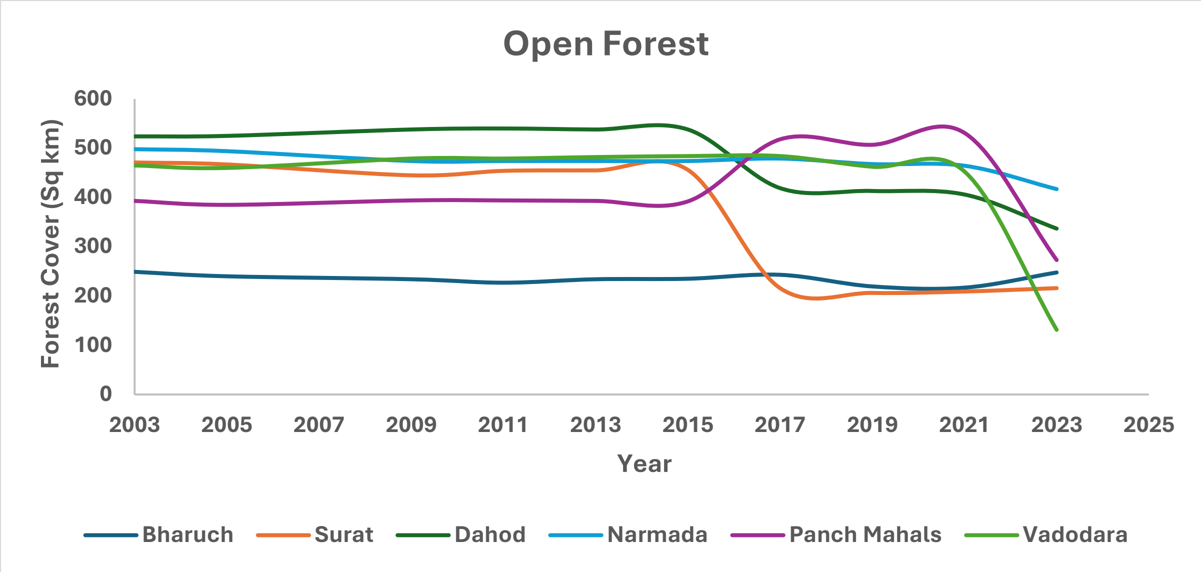

Fig. 06: Temporal Variation in Open Forest Cover Across Gujarat Districts Within the Narmada Basin (2003–2023)

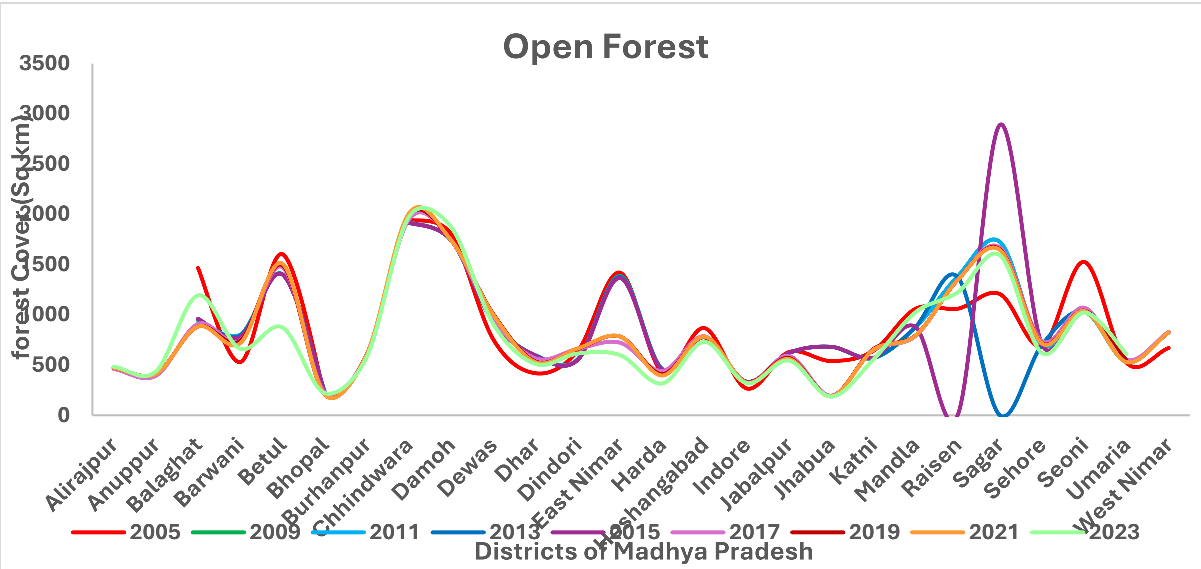

Fig. 07: Temporal Variation in Open Forest Cover Across MP Districts Within the Narmada Basin (2003–2023)

Fig. 07 the changes in open forest cover (measured in square kilometers) across various districts of Madhya Pradesh, India, from 2005 to 2023. The data reveals significant variations in open forest cover both spatially and temporally. Several districts, including Chhindwara, Sehore, and Raisen, show prominent peaks, indicating areas with substantial open forest cover. Chhindwara, in particular, exhibits the highest peak, suggesting it consistently maintains a large area of open forest. Conversely, districts like Alirajpur, Anuppur, Barwani, Betul, Bhopal, Burhanpur, Damoh, Dewas, Dhar, Dindori, East Nimar, Harda, Hoshangabad, Indore, Jhabua, Jabalpur, Katni, Mandla, Sagar, Seoni, Umaria, and West Nimar display relatively lower levels of open forest cover throughout the study period. The temporal trends reveal fluctuations in forest cover across all districts. For instance, some districts show a notable increase in open forest cover between 2005 and 2011, followed by a decline or stabilization in subsequent years.

3.6 Hill Slope Change

Analysis of hillslope dynamics within the Narmada River basin from the available literature reveals a landscape characterized by relative stability, with limited evidence of significant, widespread change. This stability can be attributed to several interacting factors. Firstly, the basin's geological framework, featuring a prevalence of resistant bedrock formations, notably within the Deccan Traps, confers a degree of inherent resilience against rapid erosion. This underlying geology impedes significant hillslope denudation. Secondly, the basin's geomorphological context, marked by broad plateaus and gently sloping terrains in many regions, contributes to reduced erosive forces. Thirdly, while deforestation and land use alterations have occurred, their impact on hillslope processes might be modulated by the basin's climatic regime, where moderate rainfall patterns limit the intensity of erosional events in comparison to regions with extreme precipitation. Furthermore, the basins structural stability, residing in a relatively stable tectonic zone, reduces the influence of dramatic tectonic activities that could generate major hillslope failures. However, it's crucial to acknowledge that localized hillslope modifications, notably along riverbanks and in areas experiencing intensive land use, might occur.

Chapter 4 Applications

The datasets and analysis presented in this report provide a detailed geological profile of the Narmada Basin, offering valuable applications across environmental management, disaster mitigation, resource management, and infrastructure planning. By integrating geological data with the analysis of anthropogenic impacts, this report establishes a framework for informed decision-making within the Narmada River Basin. The practical uses of this report are outlined below:

Sustainable Resource Management: The analysis of anthropogenic activities such as deforestation, mining, and riverbed extraction provides critical insights for developing sustainable resource management strategies. This information can help policymakers and environmental managers to mitigate the negative impacts of these activities and promote long-term ecological balance in the basin.

Hazard Mitigation and Disaster Preparedness: The detailed assessment of natural geological disasters, including earthquakes and landslides, supports improved hazard mitigation and disaster preparedness. This analysis aids in identifying high-risk areas and developing strategies to reduce the vulnerability of communities and infrastructure to geological hazards.

Infrastructure Development: The geological information on seismic activity and slope stability is crucial for the planning and design of infrastructure projects such as dams, tunnels, and transportation networks. Understanding these geological factors helps ensure the safety and longevity of infrastructure while minimizing environmental impacts.

Environmental Conservation and Policy: The report's analysis of deforestation and its impacts on the Narmada Basin supports the development of effective environmental conservation policies. By quantifying the extent and effects of deforestation, the report provides a scientific basis for policies aimed at protecting and restoring forest cover, preserving biodiversity, and maintaining ecosystem services.

Land Use Planning: The data and analysis on land degradation and the impacts of various anthropogenic activities can inform land-use planning decisions. This information helps in identifying suitable areas for different land uses, minimizing environmental degradation, and promoting sustainable development practices.

Climate Change Adaptation: The report's insights into the interplay between geological processes, anthropogenic activities, and environmental changes provide a foundation for climate change adaptation strategies. This information can be used to assess the vulnerability of the Narmada Basin to climate change impacts, such as increased frequency and intensity of extreme weather events, and develop adaptation measures.to identify areas at high risk of climate-related hazards, such as floods and landslides, and implement strategies to enhance community resilience. And to promote sustainable land management practices that enhance carbon sequestration, reduce greenhouse gas emissions, and mitigate the impacts of climate change.

Chapter 5 Conclusion

The geological profile of the Narmada River Basin is critical to understanding the interplay of its geological evolution, tectonic framework, and dynamic geological processes. The basin's diverse geology, shaped by a combination of natural forces and anthropogenic activities, influences its geomorphology, hydrology, and ecological stability. This report has synthesized information on the basin's geological history, seismic activity, landslide potential, and the impact of human-induced alterations such as deforestation and mining.

By detailing the various geological and anthropogenic factors at play within the basin, this study provides a foundation for stakeholders and decision-makers to address the challenges and opportunities facing the region. The insights presented in this report can be applied across several key areas.

The findings of this report offer diverse applications, enabling stakeholders and decision-makers to develop informed strategies. In environmental management, the analysis of deforestation patterns and the impacts of mining activities supports the development of sustainable land-use practices and conservation efforts. The assessment of seismic hazards and landslide susceptibility informs disaster preparedness and mitigation strategies, protecting communities and infrastructure. For infrastructure planning, the geological data and analysis of anthropogenic impacts provide critical information for ensuring the resilience and sustainability of development projects.

Furthermore, the integration of geological data with the analysis of human activities promotes a holistic understanding of the basin's dynamics, which is essential for effective resource management and long-term sustainability. This comprehensive approach enables policymakers, scientists, and local communities to collaborate on strategies that balance economic development with environmental stewardship.

In conclusion, this report serves as a valuable resource for guiding evidence-based decision-making, promoting sustainable practices, and ensuring the Narmada River Basin's resources are managed responsibly for the benefit of current and future generations.

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