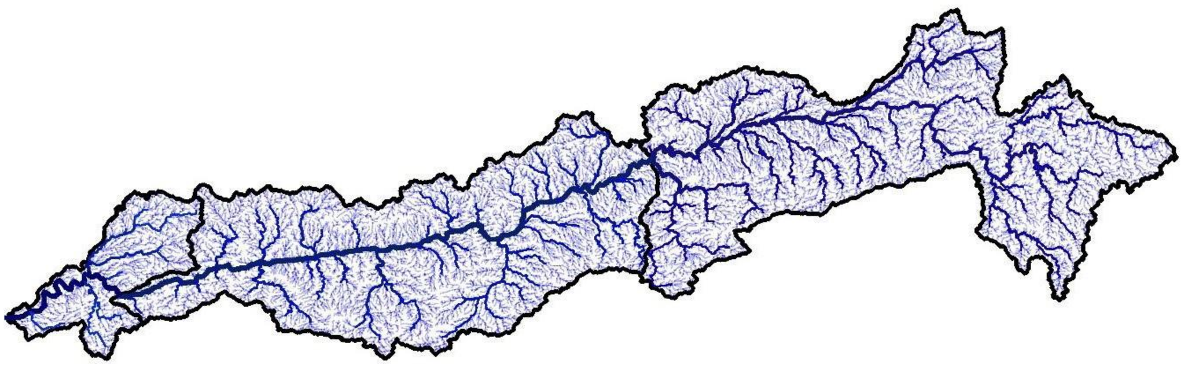
National River Conservation Directorate
Ministry of Jal Shakti,
Department of Water Resources,
River Development & Ganga Rejuvenation
Government of India

Flood Hazard Model of Narmada River Basin



June 2025

cNarmada

cGanga

Flood Hazard Model of Narmada River Basin

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.

www.nrcd.nic.in

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.

www.cnarmada.org

Centre for Ganga River Basin Management and Studies (cGanga)

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

Acknowledgment

This report is a comprehensive outcome of the project jointly executed by IIT Gandhinagar (Lead Institute) and IIT Indore (Fellow Institute) under the supervision of cGanga at IIT Kanpur. It was submitted to the National River Conservation Directorate (NRCD) in 2024. We gratefully acknowledge the individuals who provided information and photographs for this report.

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PREFACE

The Narmada River, the lifeline of central India, is also the source of an intense and irregular flood regime. The increasing frequency and complexity of major flood events pose a growing threat to the region's communities and infrastructure, making a comprehensive understanding of this hazard more critical than ever.

This report, "Flood Hazard Modeling of the Narmada River Basin: Past Flood Scenarios and Identification of Flood Risk," addresses this challenge by consolidating the basin's fragmented flood data. Its primary purpose is to synthesize historical records, scientific modeling, and government reports into a single, cohesive framework to provide a clear understanding of the evolving flood risk.

The report provides an in-depth analysis of past flood scenarios, documenting the basin's shift to a "human-modulated" system where dam operations are now a critical factor. By synthesizing historical case studies and scientific research, it identifies the key drivers of flooding and delineates the most vulnerable geographic zones and communities.

The findings and recommendations herein are intended as a foundational resource for policymakers, basin authorities, and disaster management agencies. This consolidated assessment aims to inform more integrated and proactive flood risk management strategies, fostering collaborative action toward the long-term safety and sustainability of the Narmada basin.

We are deeply grateful to all the individuals and institutions who contributed to this comprehensive study. This report is a collaborative outcome of the dedicated efforts at the Centre for Narmada River Basin Management and Studies (cNarmada), established jointly by IIT Gandhinagar and IIT Indore.

Centre for Narmada River Basin
Management and Studies (cNarmada)
IIT Gandhinagar, IIT Indore

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ABBREVIATIONS AND ACRONYMS

ALOS PALSAR	Advanced Land Observing Satellite Phased Array type L-band Synthetic Aperture Radar
AMO	Atlantic multidecadal Oscillation
ASF DAAC	Alaska Satellite Facility Distributed Active Archive Centre
CAMELS-India	Catchment Attributes and Meteorology for Large-Sample Studies in India
cGanga	Centres for Ganga River Basin Management and Studies
CGWB	Central Ground Water Board
cNarmada	Centres for Narmada River Basin Management and Studies
CWC	Central Water Commission
DEM	Digital Elevation Model
FFA	Flood Frequency Analysis
FRL	Full Reservoir Level
FVI	Flood Vulnerability Index
GAMLSS	Generalized Additive Models for Location, Scale, and Shape
GSI	Geological Survey of India
HEC-RAS	Hydrologic Engineering Centre’s River Analysis System
HFL	Highest Flood Level
IHA	Indicators of Hydrologic Alteration
IMD	India Meteorological Department
IOD	Indian Ocean Dipole
IoT	Internet of Things

LULC	Land Use/Land Cover
MMK	Modified Mann-Kendall (Test)
NCA	Narmada Control Authority
NDMA	National Disaster Management Authority
NDRF	National Disaster Response Force
NHDC	Narmada Hydro Development Corporation
NMCG	National Mission for Clean Ganga
NRCD	National River Conservation Directorate
NRCP	National River Conservation Plan
OSL	Optically Stimulated Luminescence
PCA	Principal Component Analysis
RCP	Representative Concentration Pathway
RVA	Range of Variability Approach
SANDRP	South Asia Network on Dams, Rivers and People
SDMA	State Disaster Management Authority
SRTM	Shuttle Radar Topography Mission
SSD	Sardar Sarovar Dam
SSNNL	Sardar Sarovar Narmada Nigam Limited
SWAT	Soil and Water Assessment Tool
VIC	Variable Infiltration Capacity (Model)
WRIS	Water Resources Information SystEM

Chapter 1: Introduction

1.1 BASIN BACKGROUND: GEOGRAPHIC PROFILE

1.1.1 Geographic Location and River System

India's vibrant and diverse landscapes are intricately linked to its remarkable river systems, which span from the towering Himalayas to the coastal ranges of the Western and Eastern Ghats. These rivers are vital, providing life-sustaining water for agriculture, drinking, and energy production while shaping the country's terrain and supporting its ecosystems. They also hold immense cultural and spiritual importance, making them central to India's traditions and economy. Among these, the Narmada River stands out as a westward-flowing marvel and the fifth longest river in the country. Flowing primarily through Madhya Pradesh and Gujarat, it is often referred to as the "Lifeline" of these states for its crucial contributions to irrigation, drinking water, and hydropower. The river is revered in Hindu mythology, with numerous temples and sacred sites along its banks, underscoring its spiritual significance.

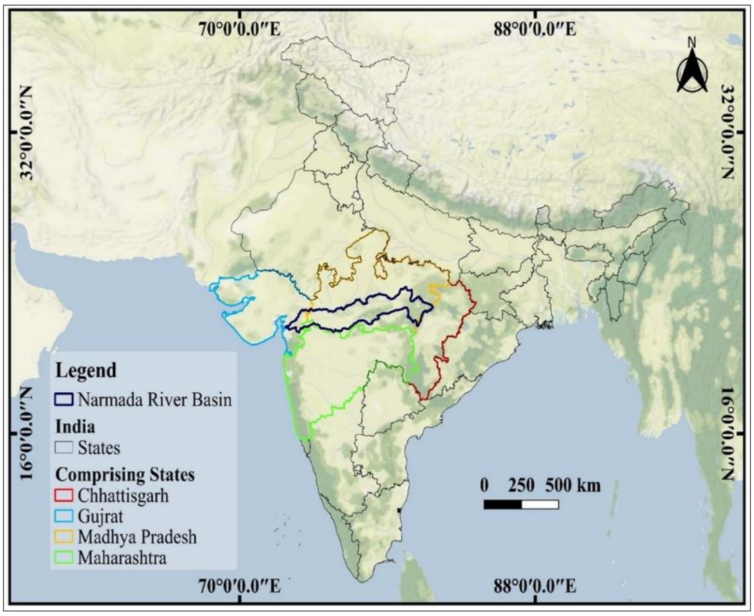

Figure 1: Geographical Location of the Narmada River Basin

Originating from the Amarkantak Plateau in Madhya Pradesh, this westward-flowing river stretches about 1,312 kilometres before it flows into the Arabian Sea. Its vast basin covers 95,959.7 square kilometres, traversing the states of Madhya Pradesh, Gujarat, Maharashtra, and Chhattisgarh, as shown in Figure 1 (Geographical Location of the Narmada River Basin).

The river's physiography is defined by its unique location within the Narmada Rift Valley, a tectonic feature flanked by the Vindhya Range to the north and the Satpura Range to the south. This geological setting gives the basin an elongated shape and heavily influences the river's flow, sediment movement, and discharge patterns.

1.1.2 Basin Physiography, Infrastructure, and Tributaries

Originating from the Amarkantak Plateau in Madhya Pradesh, the Narmada River flows westward for 1,312 km before emptying into the Arabian Sea through the Gulf of Khambhat. Its basin extends from 21° 40' 12" to 23° 41' 24" N latitudes and 72° 48' 36" to 81° 45' 36" E longitudes, covering 95,959.70 sq. km approximately 3% of India’s total geographical area. The basin’s elongated shape spans 915.65 km from east to west and 236 km from north to south. The river’s physiography is defined by three distinct zones: the upper, middle, and lower reaches. These segments Upper, Middle, and Lower are depicted in Figure 2 (Drainage area of the Narmada River with its three segments) and each possesses unique characteristics and critical water infrastructure that influence flood dynamics.

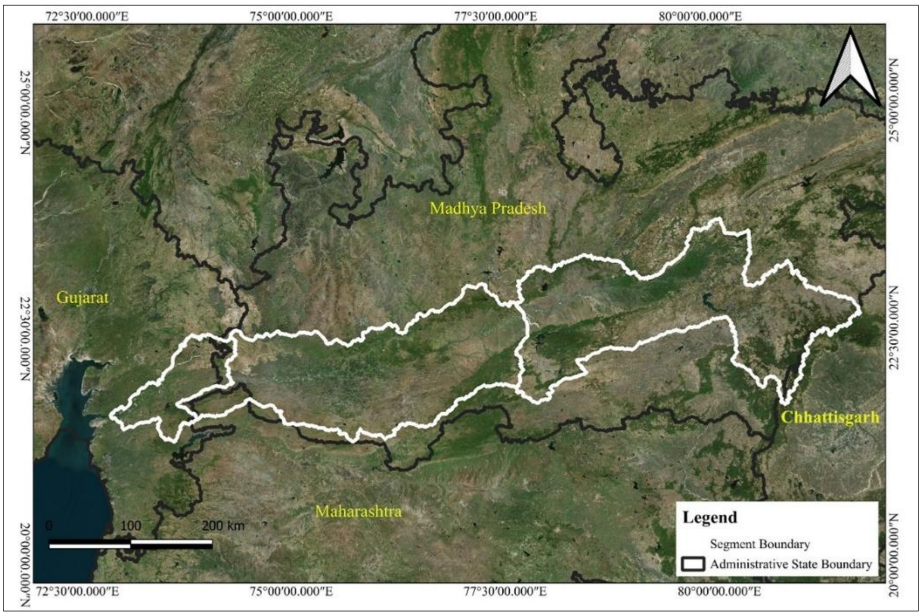

Figure 2: Drainage area of the Narmada River with its three segments

The upper Narmada flows through rugged and forested terrain, characterized by steep slopes and narrow valleys. Notable topographical features include the Kapildhara Falls near the river’s origin and the Marble Rocks gorge at Bhedaghat near Jabalpur. The middle Narmada is marked by wider valleys and fertile plains, with prominent basaltic formations from ancient volcanic activity. This region is ideal for agriculture and supports several large irrigation projects. The lower Narmada basin transitions into the Gujarat plains, featuring alluvial deposits and a gentler gradient as it approaches the Arabian Sea.

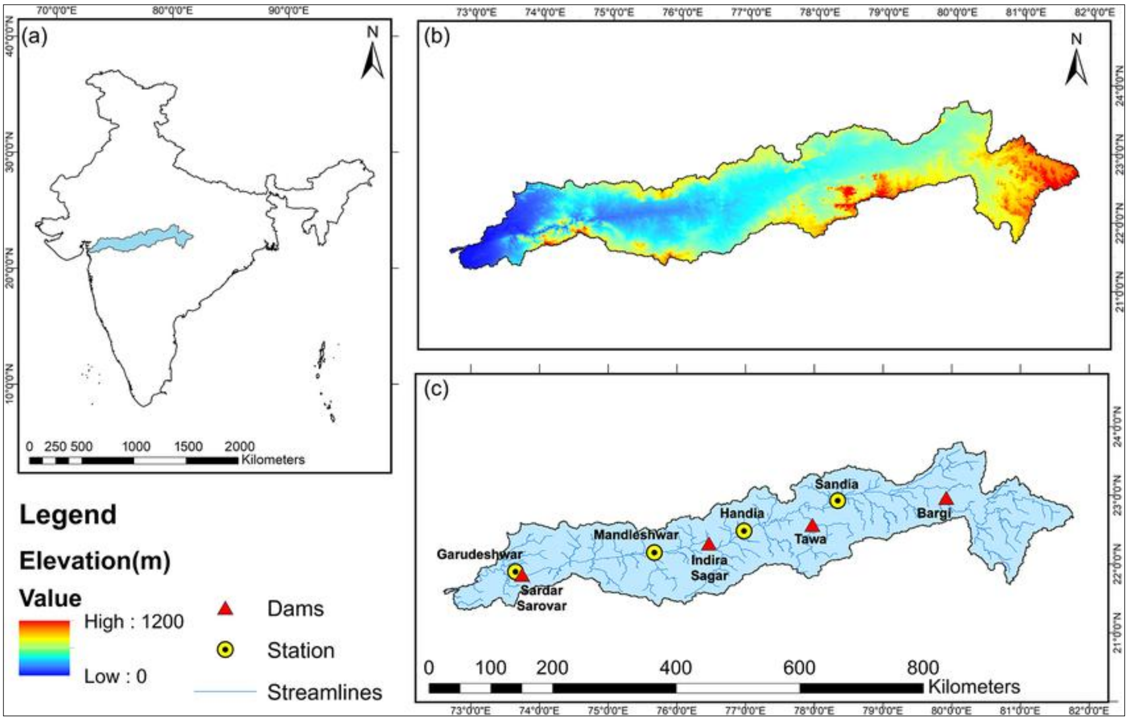

Figure 3: Basic information about (a) location in India, (b) topography, (c) streamlines, location of streamflow gauge stations and reservoirs. (Vegad and Mishra 2022)

- **Upper Narmada Sub-Basin:** Extending from Amarkantak to Hoshangabad (about 720 km), this region features rugged, forested terrain with steep gradients. This topography is ideal for hydropower, and it is where the Bargi Dam, one of the basin's first major projects, is located. Completed in 1988, this large gravity structure has a height of 69.8 meters and a length of over 5.3 kilometres. While its primary purpose is irrigation and power generation, its massive reservoir capacity plays a significant role in regulating monsoon runoff, which has direct implications for flood moderation downstream. The hydrology of this reach is also defined by major tributaries that originate in the surrounding highlands, with the most significant being the Banjar and Shakkar rivers, as illustrated in Figure 4 (Tributaries of Upper Narmada River segment).

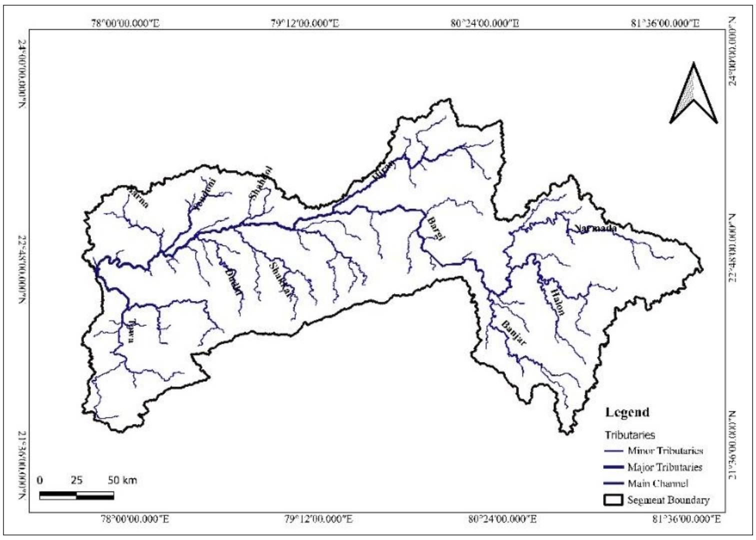

Figure 4: Tributaries of Upper Narmada River segment

Middle Narmada Sub-Basin: This segment runs from Hoshangabad to Navagam (about 485 km) and is marked by wider valleys and fertile plains. Its hydrology is dominated by two of India's most significant dams: the Indira Sagar Dam, with the largest reservoir in India by water volume, and the downstream Omkareshwar Dam, which is explicitly designed for purposes including flood control. The coordinated operation of these dams is critical for managing the immense water volumes in the middle basin. This challenge is compounded by inflows from some of the river's largest tributaries, such as the Tawa and Kolar rivers, whose extensive networks are detailed in Figure 5(Tributaries of the Middle Narmada River segment). The confluence of these large tributaries with regulated dam releases makes flood management in this sub-basin exceptionally complex.

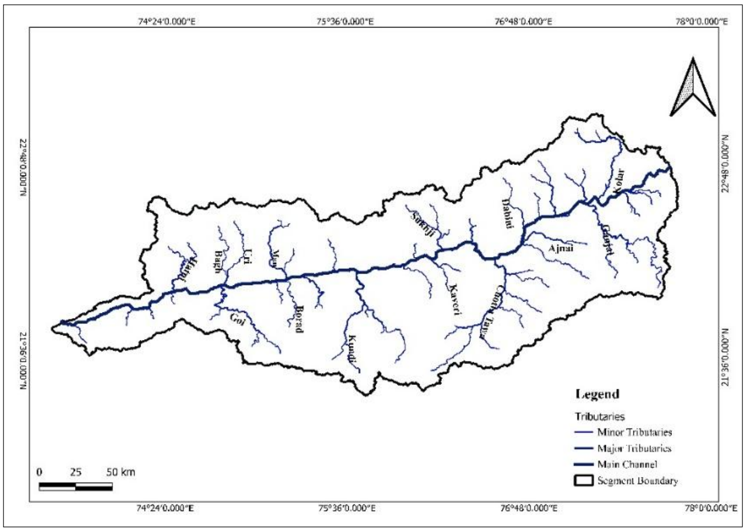

Figure 5: Tributaries of the Middle Narmada River segment

- **Lower Narmada Sub-Basin:** Covering the final stretch from Navagam to the Gulf of Khambhat (about 145 km), the lower basin transitions into flat, low-lying alluvial plains, a landscape inherently vulnerable to flooding. The primary hydrological control here is the monumental Sardar Sarovar Dam. As the terminal dam on the river, its operations are the single most important factor in flood management for the plains of Gujarat. The potential for large, sudden releases during extreme monsoon events poses a significant flood risk to downstream population centers. In this final stretch, the main channel is also fed by important tributaries such as the Karjan and Orsang rivers, as shown in (Tributaries of Lower Narmada River segment).

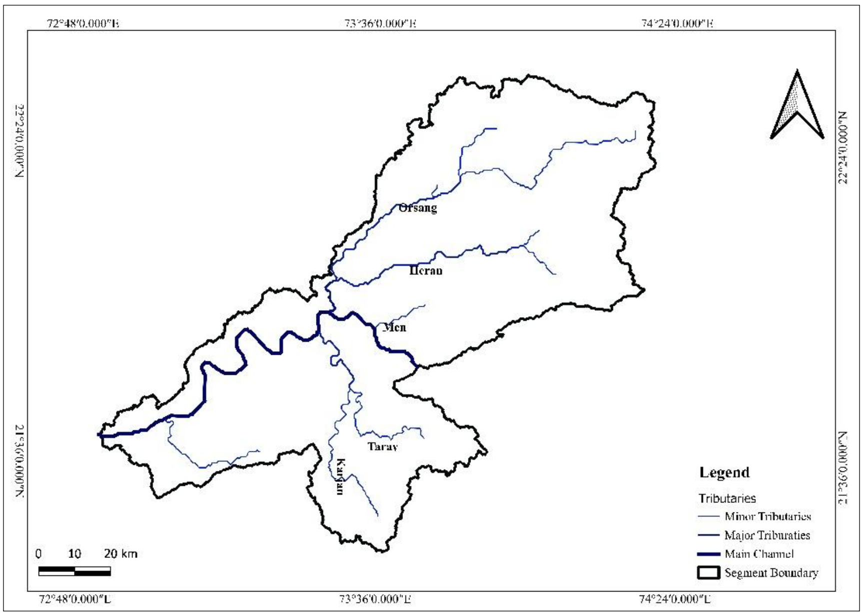

Figure 6: Tributaries of Lower Narmada River segment

1.2 OBJECTIVES

The Narmada River Basin faces "mounting challenges from anthropogenic pressures and environmental changes", which are compounded by climatic variability, leading to an increased risk of flooding. While various agencies and researchers have collected extensive data, this information often exists in separate reports and specialized studies. To manage flood risk effectively, a "holistic perspective on the river's functioning" is required.

Therefore, the primary rationale for this report is to consolidate these disparate sources of information into a single, comprehensive framework. By synthesizing historical data, scientific literature, and existing assessments, this report aims to provide a clear and accessible understanding of flood hazards across the basin. Such a consolidated assessment is essential to "serve as a cornerstone for future initiatives" and to foster collaborative, "informed decision-making" among all stakeholders involved in the sustainable management of the Narmada River.

To achieve this, the report will focus on the following primary objectives:

1. **To Consolidate Historical Flood Information:** This objective involves a detailed investigation and compilation of data from past flood events in the Narmada basin. The goal is to create a comprehensive record of hydro-meteorological drivers, spatial inundation patterns, and documented socio-economic impacts to better understand the frequency, magnitude, and characteristics of historical floods.
2. **To Synthesize Existing Scientific Knowledge:** The report will conduct a thorough review of existing scientific literature, government reports, and previous flood modeling studies. This synthesis aims to leverage prior research, understand the various methodologies that have been applied to the basin, and identify both consensus findings and critical gaps in the current understanding of flood risk.
3. **To Identify and Delineate High-Risk Areas:** A core objective is to use the consolidated historical and scientific evidence to identify and map flood-prone zones. This involves creating an inventory of vulnerable elements within these zones, including key population centers, agricultural lands, and critical infrastructure such as roads, bridges, and dams.
4. **To Inform Sustainable Flood Management Strategies:** Ultimately, this report aims to provide actionable findings that can "inform climate-resilient strategies, enhance water resource planning, and support the development of policies that balance ecological preservation with socioeconomic progress". The goal is to provide a foundation for collaborative efforts toward the long-term safety and sustainability of the Narmada basin.

1.3 SCOPE OF THE REPORT

The scope of this report is to provide a comprehensive flood hazard assessment based on the review and synthesis of existing information. The study's boundaries are defined as follows:

In Scope:

- The geographical focus of this report is the entire Narmada River Basin, encompassing its upper, middle, and lower sub-basins and their respective tributary systems.
- Thematic coverage includes the consolidation of available historical flood data, a review of existing scientific literature and government reports, and an analysis of the primary natural and anthropogenic factors influencing flood risk in the basin.
- The key outputs of this assessment are the identification and delineation of flood-prone zones and a qualitative summary of key vulnerabilities based on the consolidated evidence.

Out of Scope:

- This report does not involve the development or execution of new numerical flood models (e.g., 1D/2D hydraulic models). The assessment is based entirely on existing data and studies.
- The collection of new primary field data, such as topographical surveys, geotechnical investigations, or hydrological measurements, is outside the scope of this study.
- The report provides strategic recommendations for flood management but does not include detailed engineering designs for specific mitigation structures.

Chapter 2: Methodology and Assessment Framework

This chapter details the systematic methodology used to conduct this flood hazard assessment for the Narmada River Basin. A credible assessment requires a comprehensive review that integrates information from diverse, authoritative sources. The framework for this report is therefore built upon consolidating and synthesizing findings from four principal categories of data: official hydrological and meteorological records; geospatial datasets; historical archives and government reports; and a broad range of published scientific literature. This chapter describes these specific data sources and outlines the methodological framework used to integrate their findings, ensuring a holistic analysis of flood risk in the basin.

2.1 THE CHALLENGE OF FLOOD RISK ASSESSMENT IN THE NARMADA BASIN

Floods are among India's most frequently occurring natural disasters, causing significant economic, social, and environmental impacts. The Narmada River Basin, in particular, is frequently affected by flood-like conditions during the summer monsoon. Historical records indicate that large floods are common hydrologic events on the Narmada, making its flood regime one of the most "intense and irregular" in the seasonal tropics. These floods are often a direct result of intense tropical cyclones embedded within the summer monsoon circulation, with recent decades showing an anomalous increase in both the magnitude and frequency of large flood events.

Assessing flood risk in the Narmada basin is a complex task. The challenges are compounded by factors such as climate change, which has impacted rainfall patterns and created non-stationarity in hydrological data. This non-stationarity means that traditional flood frequency analysis methods, which assume that flood characteristics remain the same over time, are often not sufficient to capture the true flood dynamics in the basin. Furthermore, while there have been numerous studies on specific aspects of Narmada floods, there has been a noted "dearth of flood vulnerability assessments for the Narmada river basin of India, considering its relatively large size". This highlights the need for a comprehensive framework that can integrate the various factors contributing to flood risk.

2.2 REVIEW OF METHODOLOGICAL APPROACHES IN NARMADA FLOOD STUDIES

The scientific literature concerning flood risk in the Narmada Basin employs a wide array of methodologies, ranging from statistical analysis to advanced computational modeling. This assessment reviews these diverse approaches to understand the current state of knowledge and identify a suitable framework for a consolidated analysis.

A significant portion of the research focuses on Flood Frequency Analysis (FFA) to estimate the probability and magnitude of peak flood events. Traditional statistical distributions such as Gumbel's EV-I and Log-Pearson Type-III are commonly used to predict flood peaks for various return periods. More recent studies have utilized advanced techniques like the Generalized Additive Models for Location, Scale, and Shape (GAMLSS) to account for non-stationarity in flood data, which may be influenced by climate change or other factors. Other regional FFA approaches, such as the Index Flood Procedure using L-Moments, have also been applied to the basin.

Hydrodynamic modeling is another cornerstone of flood studies in the region, used to simulate the physical processes of floods. The Hydrologic Engineering Centre's River Analysis System (HEC-RAS) is the most frequently mentioned tool, with researchers using both its 1-D and 2-D capabilities to create flood inundation maps and determine water depth and velocity for different flood scenarios. These hydraulic models are often driven by outputs from hydrological models like the Soil and Water Assessment Tool (SWAT) or HEC-HMS, which simulate rainfall-runoff processes in the basin.

To assess the broader impacts on society, researchers have developed vulnerability and risk assessment frameworks. These often integrate multiple factors using Geographic Information Systems (GIS) and Multi-Criteria Decision Analysis (MCDA) techniques. Specific methods applied to the Narmada districts include Data Envelopment Analysis (DEA) to create a Flood Vulnerability Index (FVI) and machine learning algorithms like Random Forest to predict flood risk zones. Some studies also propose forward-looking solutions, including the potential use of Internet of Things (IoT)-based sensors for real-time flood alert systems.

2.3 RATIONALE FOR A CONSOLIDATED ASSESSMENT FRAMEWORK

As established in the preceding sections, flood risk in the Narmada Basin is a complex issue, and the scientific community has employed a diverse range of methodologies to study it. While these individual studies provide critical, in-depth knowledge on specific aspects such as flood frequency at a particular gauging station or the vulnerability of certain districts their findings often remain specialized. There is a recognized "dearth of flood vulnerability assessments for the Narmada River basin of India, considering its relatively large size", and research is often focused on smaller sub-regions rather than the basin as a whole.

This creates a need for a consolidated framework that can synthesize these disparate sources of information. A holistic, basin-wide perspective is essential for effective and integrated flood management. Therefore, the primary rationale for this report's methodology is to review and consolidate the findings from the broad spectrum of existing studies and data sources. By integrating historical records, hydro-meteorological data, and the results from various scientific analyses, this report aims to provide a comprehensive and accessible overview of flood hazards, which can serve as a foundational resource for planners and policymakers.

2.4 THE ADOPTED FRAMEWORK FOR THIS REPORT

This report adopts a framework of systematic review and synthesis. The approach is designed to consolidate the vast and diverse information available for the Narmada basin into a cohesive assessment of flood hazards. The framework consists of defining the key data sources and the process used to integrate them.

2.4.1 Data Sources for This Assessment

The foundation of this hazard assessment is the consolidation of data from four key categories. These sources provide the necessary information on the basin's physical characteristics, its hydro-meteorological behavior, historical flood events, and the findings from previous scientific work.

2.4.1.1 Hydrological and Meteorological Data

Critical data on the river's behaviour, such as time-series streamflow, water levels, and climatic variables, form the backbone of any flood assessment. For this review, the primary sources for such data are official government platforms and widely used global datasets.

Time-series data for rainfall are sourced from the daily gridded rainfall product provided by the India Meteorological Department (IMD), which has been extensively used for hydrological studies in the basin. This is supplemented by other precipitation datasets such as the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS).

- The Central Water Commission (CWC): Provides essential discharge and water level data from its extensive network of monitoring stations across the Narmada River Basin. The spatial distribution of these key data collection sites is shown in Figure 7 (Key Data Collection Sites in the Narmada Basin).
- Sardar Sarovar Narmada Nigam Limited (SSNNL): As the body managing the Sardar Sarovar Project, SSNNL provides crucial operational data, including reservoir levels and water release information, which is vital for understanding flood dynamics in the lower basin.
- India Water Resources Information System (India-WRIS): This platform, developed by the Ministry of Jal Shakti, serves as a comprehensive repository for hydrological data, dam and canal information, and basin-wide attributes.

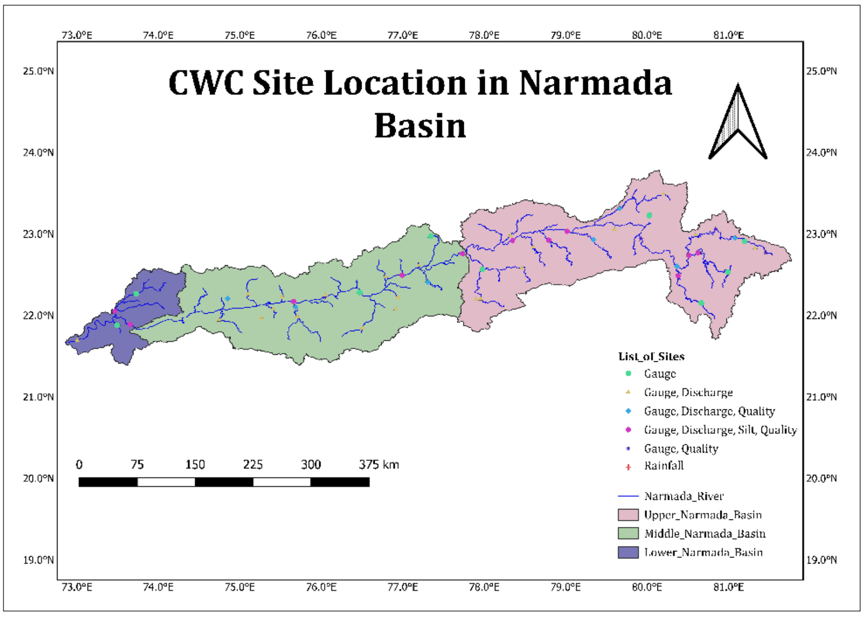

Figure 7: CWC Monitoring Site Locations in the Narmada Basin

- Hydrometeorological Datasets: Resources like the CAMELS-India dataset contribute to the understanding of long-term climatic trends impacting the basin.

This assessment is built upon the four categories of data sources that were identified and reviewed in the scientific literature for the Narmada Basin.

2.4.1.2 Historical Archives and Reports

To reconstruct the socio-economic impacts and physical extent of past floods, this assessment relies on documented historical records from a variety of sources. This includes post-flood reports, damage assessments, and official memorandums from government bodies. Studies on the Narmada Basin frequently draw upon reports from the State Disaster Management Authority (SDMA), M.P. , and the Relief & Revenue Dept (M.P.) to gather data on the number of affected villages and the scale of damage.

Furthermore, this review considers information from global disaster databases such as the Emergency Events Database (EM-DAT) and the Dartmouth Flood Observatory (DFO), which provide invaluable data on flood event occurrences and impacts. These archival sources are crucial for understanding the real-world consequences of flooding, including damage to infrastructure, impacts on agriculture, and human displacement—details often absent in raw hydrological data.

2.4.1.3 Geospatial Datasets

Geospatial data provides the essential physical context for any flood hazard assessment by defining the terrain, land use, and geomorphology of the basin. The various studies on the Narmada basin draw upon several key geospatial datasets:

- **Digital Elevation Models (DEM):** A high-resolution DEM is the most critical geospatial dataset, offering a digital representation of the terrain's elevation as shown in **Error! Reference source not found.** (ALOS PALSAR 12.5m DEM of the N armada River Basin). The literature on the Narmada basin utilizes various DEM sources, including the Shuttle Radar Topography Mission (SRTM) at 30m or 90m resolution and the ASTER GDEM at 30m resolution. This topographic data is crucial for delineating watersheds and deriving key flood conditioning factors like slope, elevation, drainage density, and flow accumulation.

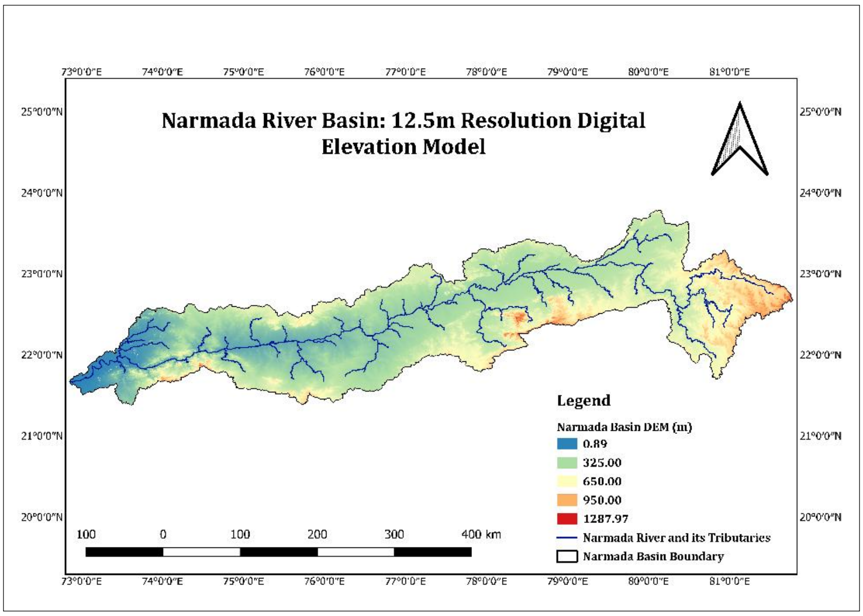

Figure 8: Narmada River Basin: 12.5m Resolution Digital Elevation Model

- **Land Use/Land Cover (LULC):** LULC maps are vital for understanding how different land surfaces (e.g., urban areas, forests, agricultural land) influence rainfall runoff and contribute to flood dynamics. These datasets, often sourced from the National Remote Sensing Centre (NRSC) or from global products like MODIS, are also used to assign surface roughness values (Manning's n) in hydraulic models.
- **Other Datasets:** Additional geospatial information includes geomorphology maps from the Geological Survey of India (GSI), which provide spatial information on landforms such as active and older floodplains. Visual interpretation using high-resolution imagery from platforms like Google Earth is also a common practice to supplement and verify other datasets.

2.4.1.4 Published Scientific Literature

A critical component of this assessment is a comprehensive review of the published, peer-reviewed scientific literature. The Narmada basin, due to its significant flood risk, has been the subject of numerous scientific investigations employing a wide array of methodologies. This body of work provides the foundation for understanding the basin's complex flood dynamics.

A primary theme in the literature is Flood Frequency Analysis (FFA), used to estimate the magnitude and probability of flood events. Many studies have utilized traditional statistical distributions like Gumbel's Extreme Value Type-I (EV-I) and Log-Pearson Type-III (LP-III) to predict peak flood discharges for various return periods (Pawar et al., 2020; Mangukiya et al., 2022). Recognizing that factors like climate change and reservoir construction can introduce non-stationarity into flood records, researchers have also applied more advanced techniques. These include the use of Generalized Additive Models for Location, Scale, and Shape (GAMLSS) which can incorporate covariates and better model the complex, non-linear nature of flood data (Chandel et al., 2025). Furthermore, regional approaches like the Index Flood Procedure, often utilizing L-Moments, have been employed to develop flood frequency relationships for the basin's many ungauged tributaries (Dubey, 2019).

Another major area of research is hydrodynamic and hydrological modeling. These studies use computational models to simulate river flow and flood inundation. The most commonly used hydraulic model for the Narmada is the Hydrologic Engineering Centre's River Analysis System (HEC-RAS), which has been applied in both 1-D and 2-D configurations to map flood extent, depth, and velocity under different scenarios (Bhargav et al., 2024; Chowdhury and Choudhary, 2024). These hydraulic simulations are often driven by runoff data generated from hydrological models like the Soil and Water Assessment Tool (SWAT), which simulates the entire water cycle of the basin (Goswami and Kar, 2015). A key aspect of these modeling studies is the calibration of parameters like Manning's roughness coefficient to ensure the accuracy of the model outputs (Bhargav et al., 2024).

Beyond the physical processes, a growing body of literature focuses on vulnerability and risk assessment. These studies integrate physical flood hazards with socio-economic data to create a more holistic picture of risk. Methodologies applied to the Narmada districts include the use of Data Envelopment Analysis (DEA) to construct a composite Flood Vulnerability Index (FVI) (Pathak and Kulshrestha, 2022). More recently, machine learning algorithms, such as Random Forest, have been used to identify flood-prone zones by analyzing the relationships between various hazard factors (e.g., elevation, rainfall) and observed flood events (Mangukiya and Sharma, 2022). These studies highlight that factors like elevation, land use, and distance from the river are major contributors to flood risk in the basin.

Finally, to provide a long-term perspective that extends beyond the instrumental record, some studies have focused on paleoflood and geomorphic analysis. This research examines sedimentary deposits and slackwater flood deposits to reconstruct high-stage flood events from the Holocene epoch, providing invaluable insights into the long-term variability and frequency of large-magnitude floods in the Narmada system (Sridhar et al., 2022; Sukumaran et al., 2021).

2.4.2 Framework for Synthesis and Risk Identification

The assessment process follows a multi-stage framework to move from data collection to a consolidated understanding of flood hazards.

1. **Data Consolidation:** The process begins by aggregating all relevant information from the sources listed above into a unified knowledge base for the Narmada basin.
2. **Cross-Verification and Synthesis:** In this stage, information from different sources is compared and integrated. For example, peak discharge data from the CWC for a specific year is correlated with historical accounts of inundation from SDMA reports or newspapers for the same period. This allows for a more robust and holistic understanding of each major flood event.
3. **Hazard and Vulnerability Identification:** The synthesized information is then used to identify patterns. Areas that are repeatedly mentioned in historical records and identified as high-risk in previous scientific studies are delineated as flood-prone zones. Critical infrastructure and population centers within these zones are then documented to assess their vulnerability.
4. **Formulation of Recommendations:** The final step involves using the consolidated findings to develop strategic recommendations for sustainable flood management, policy adjustments, and future research priorities.

Chapter 3: Analysis of Historical Flood Events

A thorough review of past events is the essential starting point for any comprehensive flood hazard assessment. Understanding the causes, magnitudes, and impacts of historical floods provides the foundational context needed to evaluate current and future risks. The Narmada River Basin has a well-documented history of significant flooding, with historical records indicating that "large floods are relatively common hydrologic events". The basin is considered not only highly susceptible to floods but also possesses one of the most "intense and irregular flood regime in the seasonal tropics". This chapter delves into this history by providing a detailed analysis of major floods. It begins by establishing a chronology of significant events from the twentieth and twenty-first centuries. This is followed by in-depth case studies of the most impactful floods to understand their hydro-meteorological drivers, the scale of peak discharges, and their documented regional consequences.

3.1 CHRONOLOGY OF MAJOR RECORDED FLOODS IN THE BASIN

The Narmada River's history is deeply intertwined with a long and powerful record of flooding. To fully understand the basin's modern flood dynamics, it is essential to first establish a historical context that extends beyond recent memory. Geological archives provide a crucial long-term perspective, with palaeo flood studies revealing that the Narmada experienced a sequence of less frequent but more extreme flood events between 400 and 1000 AD. This ancient record underscores the fact that high-magnitude flooding is an intrinsic characteristic of the river system, driven by long-term climatic cycles.

The instrumental and documented record of the 20th century begins to paint a more detailed picture of a basin prone to recurrent and severe inundation. The early part of the century saw several major events, with the years 1923 and 1926 being classified in geomorphic studies as "Mega flood years" for the entire basin. A high flood level was also recorded at Bharuch in 1944, noted as one of the largest historical floods at that location prior to the era of major dam construction.

The mid-century was marked by a series of powerful floods that would serve as critical benchmarks for all subsequent engineering and disaster management planning. A major flood was recorded in the middle basin at Hoshangabad in 1961. This was followed by the "unprecedented high floods" of August 1968 in both the Narmada and its major tributary, the Orsang, which caused extensive destruction to riverside villages in the Vadodara district of Gujarat, with significant loss of homes, crops, and cattle. However, the flood of 1970 is consistently cited as the definitive benchmark event for the basin. It was a catastrophic, widespread flood that caused severe inundation in South Gujarat, particularly in Bharuch. This was followed by another major event in 1973, which established a Highest Flood Level (HFL) record at the Mandleshwar gauging station that would stand for 50 years.

The latter part of the 20th century, a period that marks the transition to a more regulated river system, continued to see severe flooding. The years 1978, 1984, and 1990 are all documented as having severe floods in the lower Narmada. The decade of the 1990s was particularly active, with 1991 being classified as another "Mega flood year" and 1994 being considered a severe and widespread event that caused significant backwater effects from the partially constructed Sardar Sarovar Dam. A high flood was also recorded in the upper basin at the Barmanghat gauging station in 1999.

The 21st century has seen this trend of frequent and intense flooding continue, increasingly characterized by the complex interplay between heavy rainfall and dam operations. Notable floods occurred in the lower basin in 2003, 2006 (when the Sardar Sarovar Dam overflowed), and 2012. The event of September 2013 was particularly widespread and destructive, termed a "man-made calamity" due to the perception of sudden, large-scale water releases from the Sardar Sarovar Dam. The period from 2019 onward has been marked by a succession of high-intensity events impacting the basin nearly every year, including in 2020, 2022, and the hydrologically extreme flood of September 2023, which set new all-time flood records at 13 different monitoring sites across the basin.

3.2 CASE STUDY 1: THE BENCHMARK FLOOD OF 1970

To accurately model flood hazards, it is essential to first establish a baseline of the river's natural, unregulated behavior. The flood events that occurred prior to the commissioning of the major dam cascade provide this critical historical context, and none is more significant than the flood of 1970. This event stands as one of the most powerful floods ever recorded on the Narmada River and is recognized as a record-breaking hydrological event on a global scale. It remains a critical benchmark for understanding the river's maximum natural flood potential and is frequently referenced in palaeoflood and hydrological studies.

3.2.1 Hydro-meteorological Context and Drivers

The catastrophic flood of September 6, 1970, was triggered by severe meteorological conditions associated with a cyclonic weather system that brought widespread and exceptionally heavy rainfall over Central India. This powerful tropical depression originated in the Bay of Bengal before moving inland, unleashing torrential rain across the Narmada's catchment. This intense precipitation, falling on a monsoon-saturated landscape, generated massive runoff that channeled into the river system, creating an unprecedented flood wave.

3.2.2 Recorded Peak Discharge and Regional Impact

The hydrological response to this extreme rainfall was immense. On September 6, 1970, the river produced a peak discharge estimated at a staggering 69,400 m^3/s at the Garudeshwar gauging station. This was the highest flood recorded on the Narmada in 107 years and established a world record for a catchment of its size. The Highest Flood Levels (HFLs) established by the Central Water Commission (CWC) during this event 41.645 meters at Garudeshwar and 12.645 meters at Bharuch remain the official standards against which all subsequent floods are measured.

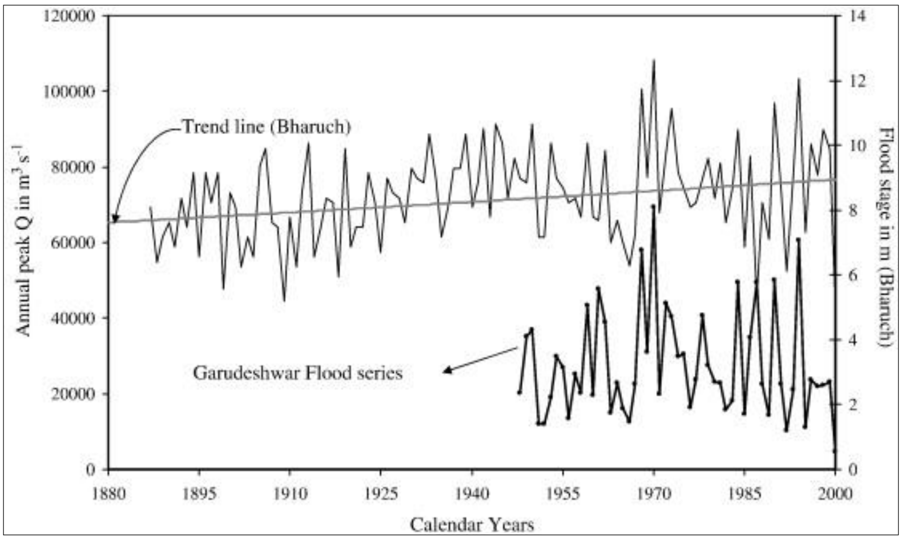

Figure 9: Annual peak discharge for the Narmada River at Garudeshwar and corresponding flood stage at Bharuch (c. 1880–2000).(Kale 2008)

The impacts of this unregulated flood were devastating across the basin. In the Upper Basin, the village of Pichhodi in Madhya Pradesh was reportedly washed away entirely, forcing the community to relocate. In the Lower Basin, the floodwaters caused severe inundation in South Gujarat. The towns of Bharuch and Surat were submerged as the Narmada and Tapi rivers overflowed their banks, severing critical rail and road communications with Mumbai for nearly a month. The event is still recalled by long-time residents as a time when a "menacing Narmada had unleashed havoc as there was no dam then," underscoring its severity in the pre-regulation era.

3.3 CASE STUDY: THE 1994 FLOOD – AN EVENT OF EXTREME DISCHARGE

The 1994 monsoon season produced one of the most significant high-discharge floods of the 20th century in the Narmada Basin, an event that highlighted the river's immense power while also demonstrating the emerging and complex impacts of dam construction .

3.3.1 Hydro-meteorological Context and Hydrological Response

The flood was driven by widespread and torrential monsoon rains that affected multiple states across western and northern India . Hydrological data captured the event's extreme magnitude. At the Garudeshwar gauging station in the lower basin, the peak discharge on September 7, 1994, was recorded at an immense 53,749 m^3/s . Furthermore, the total annual water flow at Garudeshwar for the 1994-1995 water year was 73.46 km^3, the highest volume recorded in the entire 1978–2000 dataset . The event's reach was extensive, with tributaries such as the Banjar River recording a new Highest Flood Level (HFL) at the Mukki CWC site on September 1, 1994 .

3.3.2 Regional Impacts and Early Backwater Effects

The flood had severe consequences throughout the basin. By late July, the monsoon had already claimed 117 lives in Gujarat . The floodwaters in September were so severe that the village of Chandod, located downstream of the Sardar Sarovar Dam site, was inundated to a level not seen again until the extreme flood of 2023 .

Crucially, this flood demonstrated for the first time the significant impact of the dam infrastructure, even while under construction. The partially built Sardar Sarovar Dam caused significant backwater effects, leading to periodic flooding in upstream villages in both Madhya Pradesh and Maharashtra . This event served as a physical manifestation and precursor to the large-scale submergence and displacement issues that would come to define the Narmada dam controversy for decades . The 1994 flood occurred in the same year that the World Bank, under intense international pressure, withdrew its funding for the Sardar Sarovar Project, crystallizing the conflict between the project's development objectives and its profound social and environmental costs .

3.4 CASE STUDY: THE 2006 FLOOD AND UPSTREAM SUBMERGENCE

The flood of August 2006 is a significant example of how dam infrastructure interacts with intense catchment-wide rainfall, leading to major upstream impacts. Unlike events primarily characterized by downstream releases, the 2006 flood was defined by the Sardar Sarovar Dam overflowing.

The event was caused by "incessant rains in the catchment area," which generated massive inflows into the Sardar Sarovar reservoir, exceeding its capacity at the time. The primary consequence of the dam overflowing was not in the lower basin, but rather "widespread submergence in the upstream valley". This backwater effect caused significant flooding that affected villages in both Maharashtra and Madhya Pradesh, demonstrating another dimension of dam-related flood risk. This event underscores that in a regulated system, flood risk is not only a downstream phenomenon but can also manifest as extensive upstream inundation when a reservoir's storage capacity is overwhelmed by extreme rainfall.

3.5 CASE STUDY 2: THE 2013 FLOOD – A MULTI-STATE CASCADE OF DISASTER

The August 2013 flood was a textbook example of a cascading disaster, where extreme rainfall in the upper and middle catchments was translated into a devastating flood wave that traveled the length of the basin, its impacts amplified by dam operations. The event highlighted the interconnectedness of the basin's hydrology and the profound downstream consequences of upstream events and infrastructure management.

3.5.1 Hydro-meteorological Context and Drivers

The flood was initiated by intense and sustained heavy rainfall in Madhya Pradesh around August 23, 2013. This meteorological trigger caused the Narmada River and its major tributaries, such as the Betwa, to swell rapidly and flow well above their established danger levels. This massive volume of runoff from the upper and middle catchments began to cascade downstream, overwhelming the series of major reservoirs in its path.

3.5.2 Recorded Peak Discharge and Regional Impact

The impacts in the upper and middle basin in Madhya Pradesh were severe. At least 12 districts were affected, with Hoshangabad, Vidisha, and Dewas being the worst-hit. Over 100 villages were inundated, affecting 40,000 people and destroying an estimated 24,000 homes. The disaster resulted in at least 30 fatalities in the state and necessitated large-scale rescue operations by the Indian Army and Air Force.

The massive inflow from the catchments overwhelmed the major reservoirs. The Indira Sagar Dam was forced to release high discharges, on the order of 20,000–35,000 m^3/s, for a prolonged period. This enormous volume of water then flowed into the Sardar Sarovar Dam (SSD) reservoir, where operators released a massive discharge downstream at a reported maximum rate of approximately 45,870 m^3/s (16.2 lakh cusecs).

This sudden, large-scale release from the Sardar Sarovar Dam caused catastrophic flooding in the lower basin. The Narmada River at the Golden Bridge in Bharuch surged to a level of 32–33.5 feet, far exceeding the danger mark of 24 feet. Low-lying areas of Bharuch city, Ankleshwar, and Jhagadia were flooded, forcing authorities to evacuate over 7,000 people from more than 30 villages. The event caused immense physical damage, including extensive bank erosion for about 10 km downstream of Bharuch and agricultural losses estimated at Rs. 140 crore. Due to the perception that the sudden dam releases were a primary cause of the downstream devastation, the event was termed a "man-made calamity”.

3.6 CASE STUDY: THE 2020 FLOOD AND THE ROLE OF DAM OPERATIONS

The flood of late August and early September 2020 serves as a critical case study of how reservoir operations can create a downstream disaster, turning a high-rainfall event into what one analysis called an "entirely avoidable" catastrophe .

3.6.1 Hydro-meteorological Context and Upstream Impact

From August 27-31, 2020, torrential monsoon rains lashed Madhya Pradesh. The city of Hoshangabad recorded over 400 mm of rain in a 24-hour period, causing the Narmada River to rise 2.1 meters above its danger mark, reaching a level described as "very close to the historic floods of 1972" . The flooding in Madhya Pradesh was widespread and severe, affecting an estimated 33,000 people in nearly 2,000 villages across 28 districts . The disaster resulted in at least 24 deaths, required the rescue of 11,000 people, and damaged over 11,000 homes .

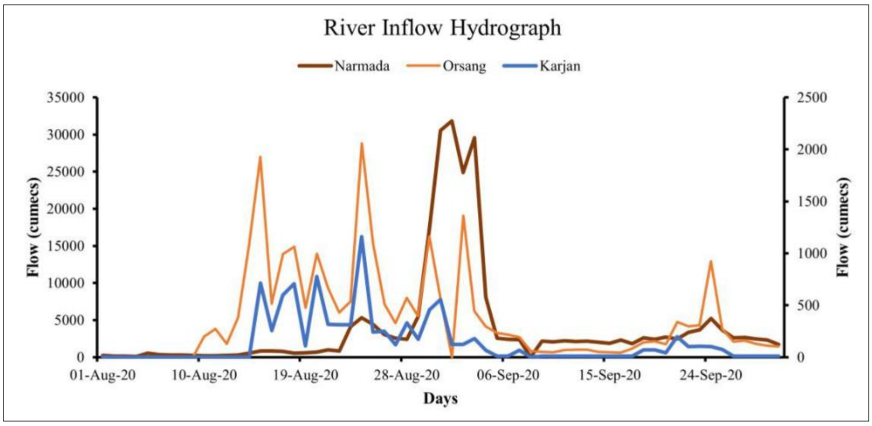

Figure 10: River inflow hydrograph for the Narmada, Orsang, and Karjan rivers during the August-September 2020 flood event (Bhargav et al. 2025)

3.6.2 Dam Operations and Downstream Impact

Despite clear warnings from the CWC and IMD about the heavy upstream rain, operators of the Sardar Sarovar Dam kept downstream outflows minimal until August 29. As the reservoir filled rapidly from the upstream floodwaters, authorities were forced to begin sudden, massive releases, discharging up to 10.70 lakh cusecs (approximately 30,300 m^3/s) of water .

This created a powerful, man-made flood wave that inundated the lower basin in Gujarat from August 29 to September 2 . The event was described as one of the worst floods in a decade for the city of Bharuch . Low-lying villages in the Bharuch, Narmada, and Vadodara districts were flooded, forcing the evacuation of over 9,700 people from 49 villages . An analysis by the South Asia Network on Dams, Rivers and People (SANDRP) concluded that the disaster resulted from the dam operators violating their own flood memorandum by failing to make pre-emptive releases to create a flood cushion in the reservoir .

3.7 CASE STUDY: THE 2023 FLOOD – UNPRECEDENTED HYDROLOGICAL EXTREMES

The flood of September 2023 was hydrologically one of the most extreme events in the basin's recent history, defined by record-breaking water levels at numerous locations and renewed scrutiny of dam management practices during periods of intense rainfall .

3.7.1 Hydro-meteorological Context and Hydrological Impact

The event was triggered by a spell of very heavy rainfall (over 100 mm) in the Madhya Pradesh catchment area between September 14 and 16, 2023 . This intense precipitation resulted in an unprecedented flood wave that breached the all-time Highest Flood Levels (HFLs) at 13 different CWC gauging sites within the Narmada Basin. This included the Mandleshwar site in the middle basin, where the flood level surpassed the previous record which had stood for exactly 50 years, since the great flood of 1973 .

3.7.2 Dam Operations and Regional Impacts

In response to the massive inflows, the Sardar Sarovar Dam reached its Full Reservoir Level (FRL) of 138.68 meters . Authorities subsequently opened 23 of the dam's gates, releasing a peak discharge of approximately 1.8 million cusecs (over 50,000 m^3/s) . This action sparked significant controversy, with activists and political opposition alleging that the massive releases were deliberately delayed to ensure the reservoir would be full for a ceremony on September 17, turning a manageable high-flow event into an avoidable, catastrophic flood .

The consequences of the massive release were severe in both downstream and upstream areas.

- **Downstream Impact (Gujarat):** The release caused the Narmada at Bharuch's Golden Bridge to rise to 37 feet, nine feet above the danger mark. This led to severe flooding and the relocation of around 10,000 people in the Bharuch, Narmada, and Vadodara districts .

The table below details the new Highest Flood Levels (HFLs) established during this extreme event.

Table 1: Highest Flood Level (HFL) Breaches during the September 2023 Flood

CWC Site	River/ Tributary	District/State	Old HFL (m) & Date	New HFL (m) & Date	Rise over HFL (m)
Abna at Khandwa	Narmada	Khandwa/MP	301.27 (18.07.2022)	302.95 (16.09.2023)	1.68
Hathed at Misrod	Narmada	Hoshangabad/MP	297.35 (18.07.2022)	297.80 (16.09.2023)	0.45
Kalimachak at Charuwa	Narmada	Harda/MP	286.20 (18.07.2022)	287.00 (16.09.2023)	0.8
Datuni at Dudwas	Narmada	Dewas/MP	252.06 (01.09.2020)	252.16 (16.09.2023)	0.1
Kaner at Mendhikheda	Narmada	Khargone/MP	214.81 (14.07.2022)	217.70 (16.09.2023)	2.89
Charol at Barwah	Narmada	Khargone/MP	173.90 (13.09.2019)	175.40 (16.09.2023)	1.5
Mandleshwar	Narmada	Khargone/MP	157.29 (31.08.1973)	158.40 (16.09.2023)	1.11
Karam at Dahiwar	Narmada	Dhar/MP	166.925 (22.08.2020)	169.66 (16.09.2023)	2.73
Bhamgarh	Chota Tawa	Khandwa/MP	270.68 (01.09.2019)	275.25 (16.09.2023)	4.57
Beda at Satwadi	Beda	Khargone/MP	205.52 (13.07.2022)	205.70 (16.09.2023)	0.18
Maan at Gopalpura	Man	Dhar/MP	195.90 (10.08.2019)	196.30 (17.09.2023)	0.4
Deb at Khajuri	Deb	Barwani/MP	180.10 (01.09.2022)	181.38 (16.09.2023)	1.28
Barod at Thikri	Barod	Barwani/MP	165.55 (07.08.2019)	168.33 (16.09.2023)	2.78

Source: Adapted from SANDRP analysis of CWC data

- **Upstream Impact (Madhya Pradesh):** The dam's backwaters caused severe flooding in upstream villages like Ekalbara in Dhar district, with water levels reportedly reaching 142 meters . The flooding destroyed homes and damaged crops, reigniting debates over the adequacy of rehabilitation for communities in the submergence zone .

3.8 SYNTHESIS OF FLOOD CHARACTERISTICS AND PATTERNS

The chronological and case-study analysis of flood events in the Narmada River Basin reveals a clear and concerning evolution in the region's flood risk profile. The historical data demonstrates three interconnected trends that define the modern flood regime of the Narmada.

First, there is a clear pattern of increased frequency and intensity of extreme events. The period since 2018, in particular, has been marked by a succession of frequent, high-intensity floods, including major events in 2019, 2020, 2022, and 2023 . Many of these recent events have resulted in the breaching of all-time Highest Flood Levels (HFLs) at multiple locations, with the 2023 flood setting new records at 13 different CWC sites, some of which had stood for half a century . This points towards a hydrological system under increasing stress, likely influenced by changing climate patterns that favor short-duration, high-intensity rainfall events .

Second, there has been a definitive shift in the primary driver of flood disasters in the basin. While heavy rainfall initiates the potential for flooding, the analysis of the 2013, 2020, and 2023 events demonstrates conclusively that the timing, magnitude, and duration of downstream inundation are now critically controlled by the release strategies of the major reservoirs, especially the Sardar Sarovar Dam . The practice of maintaining high reservoir levels for water storage and power generation has created a system where sudden, large-volume releases in response to high inflows are a recurrent cause of "man-made" or "avoidable" flood disasters .

Finally, the cumulative effect of extensive dam construction and evolving operational protocols has introduced significant non-stationarity into the basin's flood series . The statistical relationship between rainfall and runoff is no longer constant. As a result, flood frequency analyses based on the traditional assumption of stationarity—that the statistical properties of floods do not change over time—are now considered fundamentally flawed for the Narmada and will likely underestimate the true flood risk, posing a significant danger for infrastructure design and flood management planning .

Chapter 4: Synthesis of Scientific Knowledge on Flood Risk.

4.1 THE NARMADA'S FLOOD REGIME: NATURAL VS. HUMAN-MODULATED

The scientific literature defines the flood regime of the Narmada River through two distinct but interconnected lenses: its inherent nature as a high-energy, monsoon-fed river, and the fundamental transformation it has undergone in the modern era of dam regulation. Understanding both of these aspects is critical to fully appreciating the basin's contemporary flood risk.

Naturally, the Narmada River is characterized by extreme hydrological variability and is described as a system inherently dominated by high-magnitude flood processes(Kale 2008). Its flood regime is considered one of the most "intense and irregular" in the seasonal tropics(Kale et al. 1994). This natural intensity is a direct result of its geography and climate; the basin's flood patterns are governed by the powerful forces of the Indian Summer Monsoon, which delivers concentrated rainfall, and the passage of embedded tropical cyclones that can trigger extreme precipitation events(Thomas et al. 2015). Geological archives confirm that this is not a new phenomenon. Palaeoflood studies have revealed that episodic, high-magnitude flooding is a recurring and intrinsic characteristic of the river system, long predating modern human intervention(Ely et al. 1996).

However, a central thesis emerging from the contemporary research is that while the Narmada has always been a flood-prone river, its flood regime has undergone a "fundamental transformation over the past five decades". The analysis of flood events, particularly since the year 2000, reveals that the basin's flood dynamics are now "inextricably linked to, and are now significantly modulated by, the operational management of an extensive cascade of large dams"(Javaid et al. 2023). This network of major structures—including the Bargi, Tawa, Indira Sagar, Omkareshwar, and the terminal Sardar Sarovar Project (SSP) dam—has created a significant anthropogenic overlay on the natural hydrological cycle. This shift to a "human-modulated flood regime" has introduced significant non-stationarity into the flood series, meaning the statistical properties of flood events like frequency and magnitude are changing over time(Varma and Patel 2025). Consequently, traditional flood risk assessment methods that assume a stationary climate and landscape are no longer considered adequate for accurately assessing flood hazards in the modern, regulated Narmada Basin.

4.2 INSIGHTS FROM PALAEOFLOOD AND GEOLOGICAL ARCHIVES

To fully comprehend the nature and scale of flooding in the Narmada basin, it is essential to look beyond the limited instrumental record of the last century. Scientific analysis of the basin's geological archives provides a crucial long-term perspective, revealing that extreme flood events are an intrinsic characteristic of the river system that have shaped its landscape for millennia(Ely et al. 1996). Palaeoflood hydrology, which reconstructs past flood events by analyzing geological evidence such as slackwater deposits (SWDs)—accumulations of fine-grained sand and silt that settle out of suspension in protected, low-velocity areas during major floods—has been instrumental in this effort. The Narmada's passage through entrenched bedrock canyons, particularly the Punasa Gorge, creates ideal conditions for the formation and long-term preservation of these sedimentary archives, allowing for the reconstruction of a detailed flood history spanning the last 2,000 years(Ely et al. 1996).

This research has yielded critical insights into the river's long-term behavior. The paleoflood record shows a clear and anomalous increase in both the magnitude and frequency of large floods in the past few decades when compared to the longer record(Ely et al. 1996). Sand deposits from recent, post-1950 floods consistently blanket the older, finer-grained paleoflood deposits at numerous sites, indicating that the recent floods were of a greater magnitude(Ely et al. 1996). Further evidence from an undisturbed surface archaeological site suggests that no floods significantly larger than the recent megafloods have occurred in at least the past 3000 years(Ely et al. 1996). This long-term context demonstrates that while high-magnitude flooding is a natural feature of the basin, the current period of frequent and intense flooding represents a significant deviation from the historical pattern.

4.3 REVIEW OF FLOOD HAZARD MODELING AND MAPPING STUDIES

While geological archives provide long-term context, a significant body of contemporary scientific literature focuses on using computational models to simulate flood events and map the resulting hazards(Bhargav et al. 2024; Mangukiya and Sharma 2022). These studies are critical for translating abstract hydrological data, such as a peak discharge for a given return period, into tangible spatial information like flood depth and inundation extent, which is invaluable for risk assessment, infrastructure planning, and land-use management . The following sections summarize the key methodologies used and the major findings that have emerged from this body of work.

4.3.1 Summary of Methodologies and Models Used

The research on the Narmada basin employs a diverse toolkit of computational models that can be broadly categorized as hydrological, hydraulic, statistical, and machine learning models . Key approaches include:

- **Hydrological Models:** These models are essential for simulating the rainfall-runoff process. Commonly used models for the Narmada include the Soil and Water Assessment Tool (SWAT) for simulating water cycle components (Goswami and Kar,2015) and the Variable Infiltration Capacity (VIC) model for simulating streamflow while accounting for reservoir operations(Vegad and Mishra 2022).
- **Hydraulic Models:** For simulating flood wave propagation and creating detailed inundation maps, the Hydrologic Engineering Center's River Analysis System (HEC-RAS) is the most predominantly used tool. It has been applied in both 1-D and 2-D configurations to model flood dynamics in the basin(Bhargav et al. 2024; Chowdhury and Choudhary 2024; Mangukiya and Sharma 2022).
- **Statistical Models:** Flood Frequency Analysis (FFA) is used to estimate the probability of flood events. Studies on the Narmada have frequently used traditional distributions like Gumbel's EV-I and Log-Pearson Type-III (Dubey 2019; Mangukiya et al. 2022). Other regional approaches like the Index Flood Procedure using L-Moments have also been applied to develop flood frequency relationships for ungauged tributaries in the basin(Dubey 2019).

- **Machine Learning (ML) Models:** More recent research has leveraged algorithms such as Random Forest to identify flood-prone zones(Mangukiya et al. 2022). Other advanced models like Long Short-Term Memory (LSTM) and Cat Boost have also been used for enhancing the accuracy of streamflow prediction(Jadhav et al. 2024).

4.3.2 Compilation of Findings and Published Hazard Maps

The application of these models has produced several key findings and published hazard maps for the Narmada basin. Studies focusing on the lower Narmada have generated flood inundation maps for various return periods (e.g., 10, 25, 50, and 100 years), with one such study finding that a 100-year return period flood could inundate an area of 231.54 km²(Mangukiya and Sharma 2022). Others have produced detailed flood simulation maps for specific river segments, such as from Dindori to Bargi, Bargi to Indira Sagar, and Indira Sagar to Sardar Sarovar Dam(Chowdhury and Choudhary 2024). These studies also highlight that optimized reservoir release strategies, simulated using fuzzy inference systems, can significantly decrease the inundated area(Chowdhury and Choudhary 2024). Machine learning-based studies have successfully produced flood risk maps by identifying elevation, land use/land cover, and distance from the river as the most important predictors of flood risk(Mangukiya and Sharma 2022).

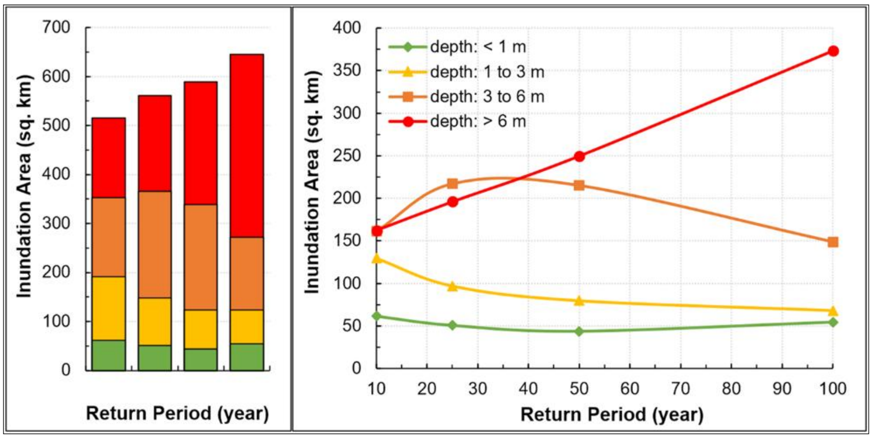

Figure 11: Depth-wise inundation area corresponding to 10-, 25-, 50-, and 100-year return period (Mangukiya and Sharma 2022).

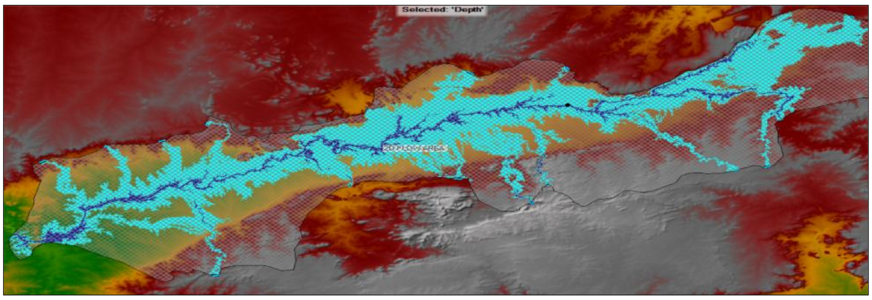

Figure 12: Flood simulation of the Bargi-to-Indra Sagar Project Dam segment (Chowdhury and Choudhary 2024)

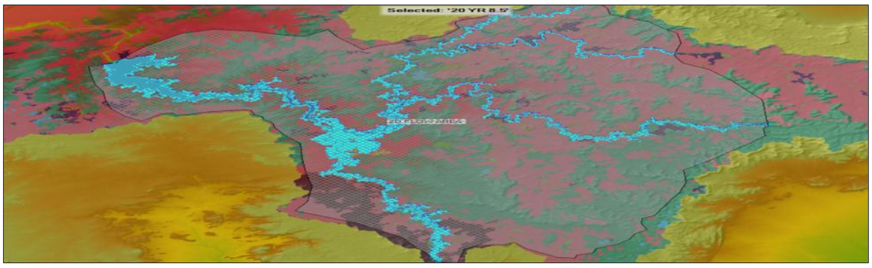

Figure 13: Flood simulation of the Dindori-to-Bargi Dam segment. (Chowdhury and Choudhary 2024)

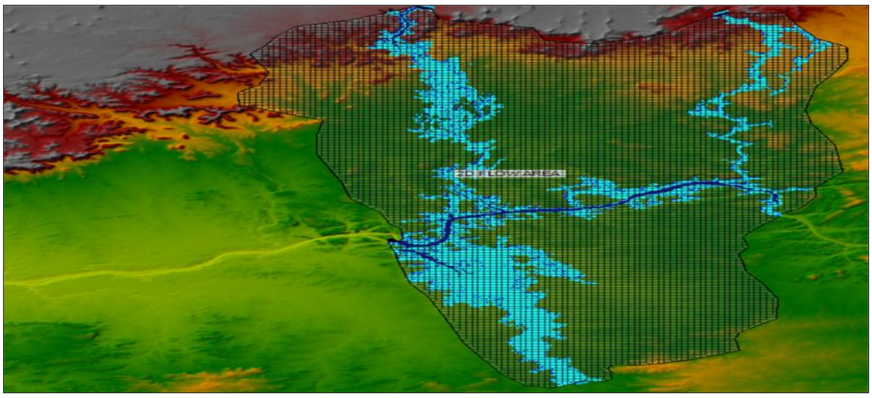

Figure 14: Flood simulation of the Indira Sagar Project Dam-to-Omkareshwar Sagar Project Dam segment. (Chowdhury and Choudhary 2024)

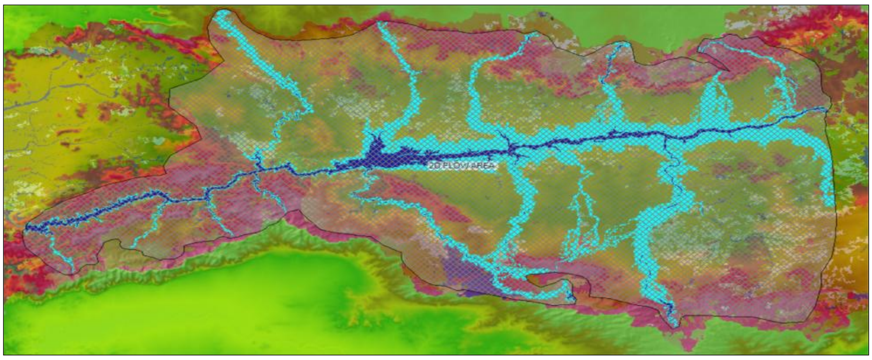

Figure 15: Flood simulation of the Indira Sagar Project Dam-to-Omkareshwar Sagar Project Dam segment. (Chowdhury and Choudhary 2024)

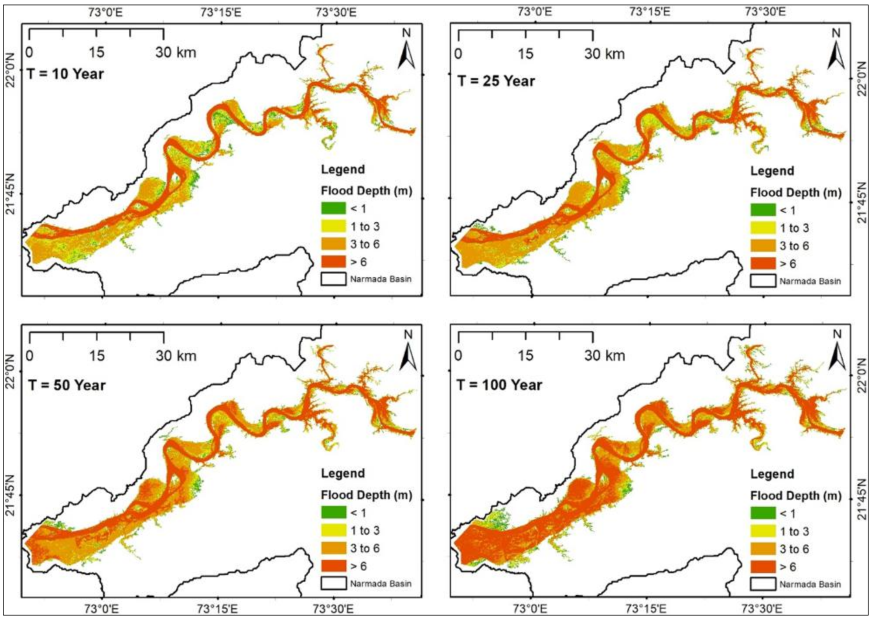

Figure 16: Flood inundation map corresponding to 10-, 25-, 50-, and 100-year return period. (Mangukiya and Sharma 2022).

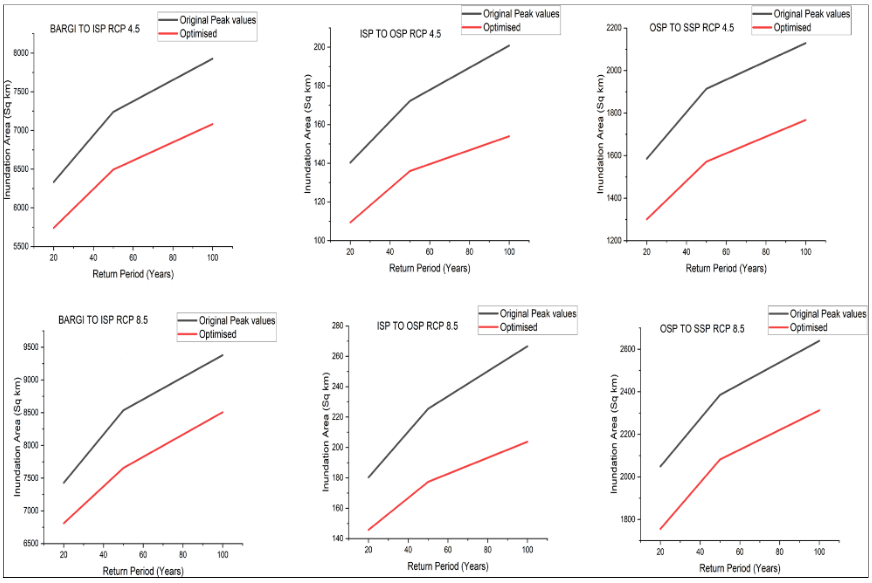

Figure 17: Graphs of inundation area vs. return periods for different stretches. (Chowdhury and Choudhary 2024)

4.4 THE CRITICAL ROLE OF DAM OPERATIONS IN MODERN FLOODS

The extensive research and analysis available on the Narmada Basin conclusively show that the primary driver of flood disasters in the modern era has shifted. While heavy rainfall initiates flood potential, the timing, magnitude, and destructive power of downstream inundation are now critically controlled by the operational management of the basin's extensive cascade of large dams(Pathak and Kulshrestha 2022a). This reality is underscored by the analysis of multiple recent flood events where operational decisions at key reservoirs were a direct and proximate cause of downstream devastation. The following sections explore the underlying operational conflict and the resulting consequences.

4.4.1 The Dam Management Paradox: Conflicting Objectives of Storage and Safety

The literature highlights a dynamic that can be understood as a "dam management paradox". Major dams like Sardar Sarovar and Indira Sagar are multi-purpose projects designed with the dual, and often conflicting, objectives of maximizing water storage for irrigation and hydropower generation while also providing a buffer for flood moderation(Javaid et al. 2023). The strong incentive to keep reservoirs full to meet water and energy demands, especially towards the end of the monsoon season, leaves minimal storage capacity to absorb sudden, high-intensity rainfall events. When such an intense rainfall event occurs, dam operators are often forced into a reactive mode, releasing massive volumes of water suddenly to ensure the structural safety of the dam itself. This action can transform a manageable high-rainfall event into a catastrophic, rapid-onset flood downstream(Chowdhury and Choudhary 2024).

4.4.2 Analysis of Avoidable Disasters and Operational Lapses

This operational paradox has led to several instances of what have been termed "man-made" or "avoidable" disasters by official and non-governmental reports. Reports from state authorities confirm that recent major floods, such as those in 2013 and 2020, were caused not only by heavy downpours but also by the "release of excess flood water from the major dams built on the Narmada River such as Bargi, Tawa and Omkareshwar" (Pathak and Kulshrestha 2022).The 2020 flood is a prime example, where an analysis by the South Asia Network on Dams, Rivers and People (SANDRP) concluded that the disaster was entirely avoidable and resulted from the Sardar Sarovar Narmada Nigam Ltd (SSNNL) violating its own Flood Memorandum by failing to make pre-emptive releases despite clear warnings of heavy upstream rain from the CWC and IMD. Similarly, the 2023 flood, which set new all-time flood level records at 13 locations, was subject to intense scrutiny amid allegations that massive water releases were deliberately delayed to ensure the reservoir reached its Full

Reservoir Level for a ceremony, turning what could have been a managed high-flow event into a catastrophic flood for downstream communities.

These events, documented in detail by post-flood analyses and reports from disaster management authorities, demonstrate that human decision-making and operational priorities, not just meteorology, are a primary factor in the basin's contemporary flood risk profile

4.5 SYNTHESIS OF FLOOD VULNERABILITY STUDIES

While understanding the physical nature and drivers of floods is critical, a complete hazard assessment must also synthesize research on socio-economic vulnerability to understand who is most at risk and what the tangible impacts of flooding are on the basin's population. A growing body of literature focuses on this human dimension, moving beyond physical hazard mapping to include the socio-economic factors that mediate flood risk(Pathak and Kulshrestha 2022). These studies are crucial for developing targeted and effective mitigation strategies.

4.5.1 Identification of Vulnerable Districts and Populations

The literature indicates a high and widespread degree of vulnerability across the Narmada basin. One key study, using a Data Envelopment Analysis (DEA) framework to create a Flood Vulnerability Index (FVI) for 21 districts in the Madhya Pradesh portion of the basin, concluded that a very high proportion—76% of the districts studied—remain highly vulnerable to floods(Pathak and Kulshrestha 2022). The historical analysis of flood events consistently highlights certain districts as being particularly susceptible. In the middle basin, districts such as Hoshangabad, Harda, Betul, Raisen, Sehore, and Dewas have frequently faced inundation(Pathak and Kulshrestha 2022a). In the lower basin in Gujarat, the districts of Bharuch and Narmada bear the brunt of operational releases from the Sardar Sarovar Dam. Furthermore, reports consistently emphasize that the impacts are often most severe for marginalized groups, with Adivasi and farming communities repeatedly facing the loss of homes, agricultural land, and livelihoods due to both submergence and flooding.

Table 2: Flood Vulnerability Index (FVI) for various districts (Pathak and Kulshrestha 2022a)

Districts	Sensitivity index	Adaptive capacity index	Exposure index	FVI	Normalised FVI on scale of 0-1	Rank for FVI
Alirajpur	0.46	0.15	0.24	0.55	0.49	5
Anuppur	0.31	0.32	0	-0.01	0.09	2
Balaghat	0.39	0.38	1	1.01	0.82	18
Barwani	0.5	0.24	1	1.26	1	21
Betul	0.39	0.38	0.67	0.67	0.58	7
Chhindwara	0.37	0.4	1	0.96	0.78	15
Dewas	0.29	0.5	1	0.79	0.66	12
Dhar	0.41	0.33	0.67	0.75	0.63	10
Dindori	0.47	0.17	0.67	0.97	0.79	16
Harda	0.31	0.53	1	0.78	0.65	11
Hoshangabad	0.27	0.56	1	0.7	0.6	8
Indore	0.46	0.9	0.67	0.23	0.26	3
Jabalpur	0.33	0.62	1	0.7	0.6	9
Katni	0.41	0.33	1	1.07	0.86	20
Khandwa (East Nimar)	0.35	0.37	1	0.98	0.8	17
Khargone (West Nimar)	0.36	0.35	1	1.01	0.82	19
Mandla	0.47	0.26	0.67	0.88	0.73	14
Narsimhapur	0.22	0.4	1	0.82	0.68	13
Raisen	0.34	0.44	0.67	0.57	0.5	6
Sehore	0.32	0.32	0.48	0.48	0.44	4
Seoni	0.33	0.46	0	-0.14	0	1

4.5.2 Socio-Economic Impacts and Livelihood Disruption

The documented socio-economic impacts of floods in the Narmada basin are severe and multi-faceted. The most significant consequence is the direct threat to human life and safety. Major flood events have resulted in significant casualties, such as the 30 fatalities reported in Madhya Pradesh during the 2013 flood and the 24 deaths during the 2020 event. These events necessitate large-scale emergency responses, with tens of thousands of people being evacuated from affected areas, as seen in 2013, 2020, and 2023.

Damage to housing and infrastructure is another major impact. The 2020 flood in Madhya Pradesh alone damaged over 11,000 homes. The economic impacts are further compounded by devastating agricultural losses. The 2013 flood, for example, caused an estimated Rs. 140 crore in agricultural losses in Gujarat . Some events cause long-term land degradation that impacts livelihoods for years. The 2022 Karam Dam breach provides a stark example, where the torrent of water and debris destroyed vast tracts of fertile farmland in 42 villages, burying them under a layer of stones and rendering them unproductive, which devastated the livelihoods of the local tribal farming communities. These recurrent impacts represent a major and ongoing socio-economic dimension of flood risk in the Narmada Basin.

4.6 CONSOLIDATED GAPS IN KNOWLEDGE AND FUTURE RESEARCH DIRECTIONS

While the existing body of research provides a strong foundation for understanding flood risk in the Narmada basin, this comprehensive synthesis also highlights several critical gaps in knowledge. Addressing these gaps is essential for developing more effective and scientifically robust flood management strategies. The following key areas require urgent attention in future research:

- **Integrated, Multi-Reservoir Operational Models:** A primary gap identified in the literature is the need for an integrated, multi-reservoir operational model. Many existing studies use simplified rainfall-runoff models, which are insufficient for a highly regulated system like the Narmada. The research strongly recommends developing a dynamic, coupled model that can simulate the complex, interconnected operational logic of the entire Narmada dam cascade (Bargi, Tawa, Indira Sagar, Omkareshwar, and Sardar Sarovar), as the downstream flood hydrograph is a direct function of upstream releases .

- **Formal Adoption of Non-Stationary Analysis:** The evidence of a changing flood regime means that traditional flood frequency analyses (FFA) based on the assumption of stationarity are now considered fundamentally flawed for the Narmada and will likely underestimate the true flood risk. Future official risk assessments must formally adopt and incorporate advanced statistical techniques like GAMLSS that can account for the influence of dynamic factors such as climate indices and cumulative reservoir storage on flood magnitudes.
- **Development of Scenario-Based Hazard Maps:** Given the significant influence of dam management, a single flood map for a given return period is often described as misleading. A key research gap is the development of scenario-based hazard maps that can show the potential inundation under different, plausible operational scenarios. This should include simulating a "natural/unregulated" scenario, a "current/reactive operations" scenario, and an "optimized/proactive operations" scenario to provide a more nuanced understanding of risk for planners .
- **Enhanced Forecasting and Real-Time Systems:** There is a recognized need to improve hydrological ensemble prediction systems that properly consider the influence of the multiple reservoirs, an effort that has been noted as lacking in India. Future work should focus on improving these systems and exploring the implementation of modern, IoT-based frameworks for real-time flood monitoring and alerts to mitigate flood disasters in the basin.
- **Comprehensive, Basin-Wide Vulnerability Assessment:** While some studies exist, there is a noted "dearth of flood vulnerability assessments for the Narmada river basin of India, considering its relatively large size". There is a need for more comprehensive, basin-wide studies that integrate physical hazards with detailed socio-economic data to create a more complete and actionable picture of risk, particularly for the highly impacted lower basin districts in Gujarat .

Chapter 5: Identification of Flood Risk and Vulnerability

Building on the analysis of historical flood events and the synthesis of scientific literature from the preceding chapters, this chapter consolidates the evidence to identify and delineate the specific areas and elements at risk within the Narmada River Basin. The focus shifts from *why* and *how* floods occur to *where* the impacts are most acute and *what* is most vulnerable. This is achieved by first delineating the primary flood-prone zones based on the consolidated evidence. Subsequently, it analyzes the key natural and anthropogenic factors that contribute to risk within these zones and concludes with a detailed assessment of the most vulnerable population centers, critical infrastructure, and agricultural livelihoods.

5.1 DELINEATION OF FLOOD-PRONE ZONES BASED ON CONSOLIDATED EVIDENCE

The synthesis of historical flood event data and the findings from scientific literature allows for the delineation of specific zones within the Narmada Basin that are consistently and highly susceptible to flooding. These flood-prone zones are not uniform and vary in their characteristics based on their location within the basin's upper, middle, or lower reaches.

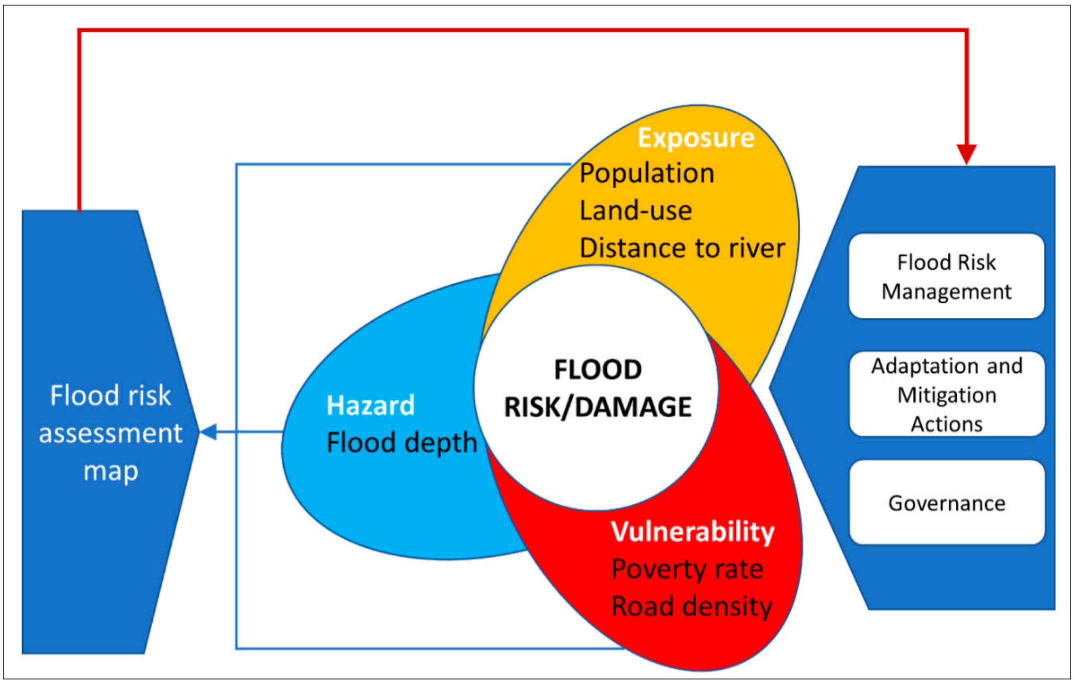

Figure 18: Conceptual Framework of Flood Risk as an Intersection of Hazard, Exposure, and Vulnerability. (Luu et al. 2020)

- **The Lower Narmada Basin:** The consolidated evidence overwhelmingly identifies the lower reaches of the Narmada in Gujarat as the most critically flood-prone zone. This area, particularly downstream of the Sardar Sarovar Dam, is highly susceptible to widespread and prolonged inundation caused by large-scale operational releases from the dam . The districts of Bharuch, Narmada, and Vadodara are repeatedly cited as being severely affected . The city of Bharuch, especially the areas surrounding the Golden Bridge, and the industrial town of Ankleshwar are urban hotspots that have experienced recurrent flooding, notably during the major events of 1970, 2013, 2020, and 2023 .
- **The Middle Narmada Basin:** The middle reaches in Madhya Pradesh face a dual flood risk. They are vulnerable to inundation from heavy monsoon rainfall within their own catchments, as well as from the backwater effects of the downstream Sardar Sarovar Dam . The historical record shows that districts such as Hoshangabad (Narmadapuram), Dhar, Barwani, Raisen, Vidisha, Dewas, and Khargone have been frequently impacted . Hoshangabad, in particular, is a key location where the Narmada frequently crosses its danger level during severe monsoons .
- **The Upper Narmada Basin:** The upper reaches, characterized by steep topography, are naturally prone to rapid-onset or flash floods following intense rainfall events . While active floodplains are more limited in this confined, hilly terrain, key districts like Jabalpur and Mandla have experienced historical flooding . The devastating 1970 flood, for example, reportedly washed away the entire village of Pichhodi in the upper basin .

5.2 KEY FACTORS CONTRIBUTING TO FLOOD RISK

The flood risk in the Narmada Basin is not the result of a single cause but rather the convergence of multiple compounding factors. This synthesis identifies three primary categories of contributing factors: the basin's natural geomorphology, increasing anthropogenic pressures on the landscape, and the profound influence of dam operations.

5.2.1 Natural Factors (Topography, Drainage)

The inherent flood vulnerability of the Narmada Basin is fundamentally rooted in its natural topography and drainage characteristics. The basin exhibits a distinct geomorphological transition from its source to the sea, which dictates its flood behavior .

- The Upper Narmada Basin is defined by steep gradients and a narrow, confined valley . These characteristics promote rapid runoff during intense rainfall, making this reach naturally prone to flash floods .
- The Middle Narmada Basin is where the river's gradient decreases and the valley widens, creating broader floodplains that are naturally susceptible to inundation during high-flow events .
- The Lower Narmada Basin consists of expansive, low-lying alluvial plains with a very gentle gradient . This flat terrain makes the region highly susceptible to widespread and prolonged inundation, as it provides a natural area for floodwaters to spread out and slow down .

Furthermore, the entire basin's drainage network has been shaped by long-term tectonic activity along the Narmada-Son Fault, which controls the river's path and the development of its tributaries.

5.2.2 Anthropogenic Factors (Encroachment, Urbanization)

The natural flood risk in the basin is significantly exacerbated by anthropogenic pressures, particularly land use changes. Increasing urbanization and the encroachment of settlements and agriculture onto natural floodplains have constricted the river's channel . This reduces the river's natural capacity to safely convey floodwaters, forcing flood levels higher and expanding the extent of inundation during high-discharge events . Studies have identified that settlements in flood hazard zones increase the overall flood risk, often due to a lack of information and awareness among the population. Land use characteristics are now considered a key predictor when modeling flood risk in the basin.

5.2.3 Influence of Dam Operations on Downstream Flooding

In the modern era, the single most significant factor influencing the character of major floods in the middle and lower Narmada is the operational management of the extensive cascade of dams . As detailed in the historical analysis, the primary driver of flood disasters has shifted from being purely meteorological to a complex interplay between heavy rainfall and dam operations .

This is most evident in the major flood events of 2013, 2020, and 2023, where sudden, large-volume releases from the Sardar Sarovar and other upstream dams were a direct cause of the catastrophic downstream flooding . The practice of maintaining high reservoir levels for power generation and water storage creates a "dam management paradox," leaving little capacity to absorb sudden flood inflows and forcing reactive, large-scale releases that inundate downstream areas . This operational reality means that human decision-making has become a primary, and at times dominant, factor contributing to flood risk in the basin .

5.3 ASSESSMENT OF VULNERABILITY

Identifying flood-prone zones is the first step in a comprehensive risk assessment. The next critical step is to assess the vulnerability of the population, infrastructure, and economic activities located within these zones. Vulnerability is a function of both the sensitivity of an exposed element to flooding and its capacity to adapt to or recover from the impact. This section provides this assessment by synthesizing the documented evidence to identify the key communities, critical infrastructure, and agricultural livelihoods most at risk from floods in the Narmada Basin.

5.3.1 Vulnerable Population Centers and Communities

The synthesis of flood reports and vulnerability studies reveals that flood risk is not evenly distributed across the basin. Specific population centers and communities are consistently identified as being highly vulnerable due to their geographic location and socio-economic characteristics.

In the Lower Narmada Basin, the primary vulnerability is concentrated in the districts of Bharuch, Narmada, and Vadodara in Gujarat . These areas are susceptible to inundation from large-scale operational releases from the Sardar Sarovar Dam. The city of Bharuch is a major urban hotspot, with low-lying areas frequently flooded when the river level at the Golden Bridge exceeds the danger mark . The nearby industrial town of Ankleshwar is also repeatedly affected . Reports consistently document the evacuation of thousands of people from dozens of villages across these districts during major flood events like those in 2013, 2020, and 2023 .

In the Middle Narmada Basin, key districts in Madhya Pradesh such as Hoshangabad (Narmadapuram), Dhar, Barwani, Raisen, and Khandwa are identified as highly vulnerable to both rainfall-induced floods and the backwater effects of downstream dams . A significant finding from a detailed vulnerability assessment is that a high proportion—76% of the 21 districts studied—are highly vulnerable to flooding. Furthermore, reports highlight that Adivasi and farming communities in the submergence zones of the major dams are particularly vulnerable, facing the loss of homes, agricultural land, and livelihoods from both permanent submergence and periodic backwater flooding . The 2022 Karam Dam breach, for instance, had a devastating impact on the livelihoods of tribal farming communities in the area .

In the Upper Narmada Basin, vulnerability is concentrated in settlements located along the confined river channel, which are at risk from flash floods. The historical record of Pichhodi village being entirely washed away during the 1970 flood serves as a stark reminder of the potential for catastrophic impacts on smaller, riverside communities in this reach.

5.3.2 Critical Infrastructure at Risk (Bridges, Roads, Dams)

Floods in the Narmada Basin pose a significant threat to critical infrastructure that is essential for regional transportation, communication, and economic activity. The historical record provides numerous examples of key infrastructure being damaged or rendered non-operational during major flood events.

Transportation infrastructure is particularly vulnerable. During the 2013 flood, the 1-km-long bridge connecting the districts of Badwani and Dhar was completely submerged, severing a vital transport link. Similarly, the Gora bridge near Kevadia was reported to be submerged during the 2012 flood. The iconic Golden Bridge in Bharuch is a perennial point of concern, with floodwaters frequently surging far above its danger mark, threatening the structure and disrupting traffic on a major arterial route. The most severe disruption documented occurred during the 1970 flood, when both rail and road communications with Mumbai were severed for nearly a month.

Crucially, the basin's hydraulic infrastructure—the dams themselves—are also at risk. The immense force of floodwaters can cause direct structural damage. For instance, the high-volume discharges during the 2013 flood caused significant structural damage to the spillway energy dissipator of the Indira Sagar Dam . An even more severe example is the 2022 Karam Dam breach in Dhar district. This event, attributed to sub-standard construction and negligence, saw a portion of the earthen dam collapse, necessitating the emergency evacuation of 18 downstream villages to avert a more catastrophic failure . This highlights that the dams are not only a factor in flood management but are themselves critical infrastructure at risk of failure, which represents a parallel and significant source of flood hazard .

5.3.3 Impact on Agriculture and Livelihoods

The agricultural sector, which forms the backbone of the rural economy throughout the Narmada Basin, is exceptionally vulnerable to the impacts of flooding. The historical record is replete with instances of devastating impacts on crops, livestock, and long-term agricultural productivity.

During major flood events, the most immediate impact is the widespread destruction of standing crops, leading to significant economic losses for farmers. The 2013 flood in Gujarat, for example, caused agricultural losses estimated at Rs. 140 crores. Historical accounts, such as the report on the 1968 flood, also document the "significant loss of homes, crops, and cattle," highlighting that the impact on agricultural livelihoods extends beyond crop damage to include the loss of valuable livestock.

Furthermore, some flood events can cause long-term land degradation that impacts livelihoods for years. The 2022 Karam Dam breach provides a stark example. The torrent of water and debris released during the breach destroyed vast tracts of fertile farmland in 42 villages, burying them under a layer of stones and rendering them unproductive. This single event had the effect of "devastating the livelihoods of the predominantly tribal farming communities the dam was intended to serve”. These recurrent impacts on agriculture represent a major and ongoing socio-economic dimension of flood risk in the Narmada Basin.

Chapter 6: Conclusions and Recommendations

This concluding chapter synthesizes the primary findings of this report, consolidating the analyses of the Narmada Basin's geographical characteristics, its extensive flood history, and the existing body of scientific research. The chapter distills these detailed reviews into a set of overarching conclusions about the nature of flood risk in the basin. Based on these findings, it then provides a series of concrete recommendations for integrated flood risk management and outlines key directions for future research and detailed studies.

6.1 SUMMARY OF KEY FINDINGS

The comprehensive review of historical flood events, scientific literature, and official reports presented in this document has yielded several key findings regarding the nature of flood risk in the Narmada River Basin.

- **A Fundamentally Altered Flood Regime:** The analysis demonstrates that the primary driver of flood disasters in the Narmada basin has shifted. While historically driven by natural meteorological events, the modern flood regime is now critically controlled by the operational management of the extensive cascade of dams. The timing, magnitude, and duration of major floods, particularly in the middle and lower basins, are now inextricably linked to dam release strategies.
- **The "Dam Management Paradox" as a Primary Risk Factor:** The review highlights a recurring "dam management paradox" where the conflicting objectives of maximizing water storage for power and irrigation clash with the need to maintain a flood cushion for safety. This has led to several instances of "avoidable disasters," where sudden, massive water releases in response to heavy inflows have caused catastrophic downstream flooding.
- **Delineation of High-Vulnerability Zones:** Specific geographic zones face recurrent and severe flood risk. The lower basin districts in Gujarat, particularly Bharuch and Narmada, are highly vulnerable to operational floods from the Sardar Sarovar Dam. The middle basin districts in Madhya Pradesh, such as Hoshangabad and Dhar, face a dual threat from intense rainfall and dam backwater effects. Furthermore, the

analysis identifies critical infrastructure (bridges, roads, and the dams themselves) and agricultural livelihoods as being consistently and severely impacted.

- **The Emergence of Non-Stationarity:** A crucial finding is that the cumulative effect of dam construction and changing rainfall patterns has introduced significant non-stationarity into the basin's flood series. This means the statistical properties of floods are no longer stable over time, rendering traditional risk assessment methods fundamentally inadequate and likely to underestimate true future flood risk.

6.2 RECOMMENDATIONS FOR INTEGRATED FLOOD RISK MANAGEMENT

Based on the key findings of this report, a multi-pronged strategy that combines structural interventions with robust non-structural measures is required to build long-term flood resilience in the Narmada Basin. The following recommendations are proposed for consideration by basin authorities, state governments, and disaster management agencies.

7.2.1. Structural Measures

- **Implement Integrated and Transparent Dam Operations:** There is an urgent need to develop, mandate, and publicly disclose integrated, real-time operational protocols for the entire Narmada dam cascade. These protocols must unambiguously prioritize flood safety above all other objectives, such as power generation or ceremonial water levels, during periods of high inflow. This requires empowering regulatory bodies like the Narmada Control Authority (NCA) and the Central Water Commission (CWC) with a clear, enforceable mandate for public safety.
- **Strengthen Dam Safety and Accountability:** The Dam Safety Act of 2021 must be implemented with the utmost rigor. This includes establishing a framework for regular, independent safety audits of all major and medium dams in the basin to prevent structural failures like the 2022 Karam Dam breach. In the event of failures due to negligence, mechanisms for swift and transparent accountability must be enforced.

7.2.2. Non-Structural Measures

- **Enhance Early Warning Systems:** Investment is needed in modern, technology-driven early warning systems that provide longer, more reliable lead times for downstream communities and disaster management agencies. These systems should integrate real-time data on rainfall from the IMD, reservoir levels from dam authorities, and advanced inflow forecasting models to improve prediction accuracy.

- **Implement and Enforce Floodplain Zoning:** State governments must adopt and rigorously enforce floodplain zoning regulations, as recommended by national bodies like NITI Aayog. Actively discouraging and regulating new construction and encroachment within historical floodplains is a critical non-structural measure to reduce long-term exposure and vulnerability, breaking the cycle of building in harm's way.
- **Invest in Ecological Restoration:** Long-term resilience requires working with, not just against, nature. Promoting large-scale afforestation and watershed management programs in the Narmada's upper catchments can help reduce soil erosion, moderate storm runoff, and improve the basin's natural capacity to absorb rainfall.

6.3 INTENDED APPLICATIONS AND USES OF THIS REPORT

This report has been developed as a foundational resource to serve a wide range of stakeholders involved in the management and safety of the Narmada River Basin. Its primary applications are envisioned as follows:

- **For Policy and Governance Bodies** (e.g., NRCD, NCA, CWC): This consolidated assessment can serve as a key reference document for policy review and formulation. The detailed analysis of past operational lapses and the "dam management paradox" provides a strong evidence base for re-evaluating and strengthening dam operation protocols to prioritize flood safety.
- **For Disaster Management Authorities** (NDMA, SDMAs): The delineation of high-risk zones and the inventory of vulnerable populations and infrastructure provide actionable intelligence for pre-disaster planning, resource allocation, and the strategic deployment of response teams like the NDRF. The findings can help refine evacuation plans and improve the targeting of community awareness programs.
- **For Infrastructure Planners and State Departments** (e.g., Water Resources, Public Works): The report's emphasis on the non-stationarity of the flood regime

and the documentation of historical Highest Flood Levels (HFLs) should inform the design and retrofitting of critical infrastructure. It serves as a caution against relying on outdated flood statistics for the planning of new bridges, roads, and other long-term assets.

- **For the Scientific and Academic Community**: By synthesizing a vast amount of disparate information and explicitly identifying key knowledge gaps, this report provides a launching point for future research. It serves as a comprehensive literature review and highlights the urgent need for integrated, non-stationary risk models, scenario-based hazard mapping, and enhanced forecasting systems.
- **For Civil Society and Community Advocates**: The report offers an accessible, single-source compilation of evidence on the causes and consequences of flooding in the basin. This can empower local communities and advocacy groups to engage in more informed dialogue with authorities regarding dam management, compensation, and the need for more transparent and safety-oriented operational procedures.

6.4 DIRECTIONS FOR FUTURE RESEARCH AND DETAILED STUDIES

The synthesis presented in this report highlights several critical areas where future research and detailed studies are required to build a more resilient Narmada Basin. The following directions are recommended to address the identified knowledge gaps:

- **Develop Integrated, Non-Stationary Risk Models:** Future flood modeling efforts must abandon stationary statistical methods. It is strongly recommended to develop and apply integrated models that explicitly account for the non-stationarity of the flood regime. This should involve using advanced techniques like GAMLSS and incorporating a dynamic, coupled module that simulates the operational logic of the entire Narmada dam cascade.
- **Create Scenario-Based Hazard Maps:** Given the critical influence of dam management, future projects should focus on producing a suite of hazard maps based on distinct, plausible operational scenarios. This should include, at a minimum: a "Natural/Unregulated" scenario to understand the baseline risk, a "Current/Reactive Operations" scenario to map the risk of avoidable disasters, and an "Optimized/Proactive Operations" scenario to identify pathways for mitigation.

- **Enhance Flood Forecasting Systems:** There is a recognized need to develop and improve hydrological ensemble prediction systems that can accurately forecast streamflow while considering the complex influence of the multiple reservoirs. Further research into the application of machine learning and IoT-based frameworks for real-time monitoring and flood alerts should be prioritized.
- **Expand Socio-Economic Vulnerability Assessments:** While detailed vulnerability assessments have been conducted for parts of the basin, there is a need to expand this research to cover all flood-prone regions, particularly the lower basin districts in Gujarat. A comprehensive, basin-wide socio-economic vulnerability assessment is required to better understand who is most at risk and to design more effective, targeted mitigation policies.

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