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HYDROLOGICAL IMPACTS OF LARGE RESERVOIRS ON ALTERATIONS IN THE RIVER FLOW REGIMES

by

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HYDROLOGICAL IMPACTS OF LARGE RESERVOIRS ON ALTERATIONS IN THE RIVER FLOW REGIMES

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **Hydrological Impacts of Large Reservoirs on Alterations in the River Flow Regimes** in the partial fulfilment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY** and submitted in the **DEPARTMENT OF CIVIL ENGINEERING, Indian Institute of Technology Indore**, is an authentic record of my own work carried out during the time period from May 2024 to May 2025 under the supervision of **Dr. Priyank J. Sharma**, Assistant Professor, Department of Civil Engineering, IIT Indore.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

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This is to certify that the above statement made by the candidate is correct to the best of my/our knowledge.

01/06/2025

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ABSTRACT

This study evaluated the cascading impacts of large dams Rani Avanti Bai Sagar (RABS), Indira Sagar (IS), Omkareshwar, and Sardar Sarovar (SS) on the water flow regimes of the Narmada River Basin in central India. The construction of these dams has significantly altered hydrological patterns, especially affecting downstream ecosystems. To assess dam-specific impacts, the basin was divided into six units—two for each dam: RABS (Manot+Mohgaon+Bamni and Barmanghat-Patan-Belkhedi), IS (Handia and Mandleshwar-Kogaon), and SS (Mandleshwar and Garudeshwar)—representing upstream and downstream flows. Streamflows were adjusted for tributary contributions by adding at upstream stations (Burnher and Bamni) and excluding at downstream stations (Hiran, Sher, and Kundi) to accurately quantify dam impacts. Critical change points were identified with dam commissioning: RABS (1988), IS (2006), and SS at two stages—SS1 (2006, 121.92 m) and SS2 (2017, 138.68 m), as well as using satellite imagery. Streamflow variability was analysed for pre- and post-dam periods using Indices of Hydrological Alteration (IHA) to evaluate changes in magnitude, duration, timing, frequency, and rate of extreme flows. The Range of Variability Approach (RVA) results and Flow Duration Curves (FDCs) showed significant reductions in downstream mean streamflow, especially during the post-monsoon period (November–May), with substantial declines in cumulative minimum flow affecting water availability. The overall alteration in streamflow was high for RABS (68.5%), moderate for IS and Omkareshwar (≈58%), and for SS, moderate at SS1 (≈60%) and high at SS2 (≈70%). These changes, driven by reservoir operations such as water regulation and diversion, highlight the need for balanced management strategies to optimise reservoir function, preserve natural flow regimes, and enhance flood control in the Narmada Basin.

Keywords: Streamflow Variability, Indices of Hydrological Alteration (IHA), Range of Variability Approach (RVA), Cascading Impact, Narmada River Basin.

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Chapter – 1
INTRODUCTION

1.1 Background of Study

Dams built around the globe have significant environmental, economic and social effects on both ecosystems and human communities. Although controlled water releases from these reservoirs play essential roles, such as providing municipal and industrial water, supporting irrigation, generating power, managing floods, enabling recreational activities, and facilitating navigation, they also greatly change the dynamics of rivers downstream. The impact of streamflow change on flood dynamics is among its most important effects. Even though dams are frequently built to reduce flooding, their activities may unintentionally worsen flooding downstream. Flash floods can occur downstream when reservoirs are filled, for example, due to abrupt, intense rainfall that causes massive amounts of water to be released. Flow regimes, geomorphological traits, water quality, sediment transport methods, and the general health of the ecosystem are just a few of the ways these changes show up (Huang et al., 2015). Vatiations in the amount, timing, length, and frequency of low and high flows are the main ways reservoirs impact stream hydrology, producing hydrologic regimes significantly different from those before the dam construction (Magilligan and Nislow, 2005).

The substantial effects of large reservoirs on floodplain habitats, channel shape, and water availability are documented in the literature. Large reservoirs can result in significant changes in sedimentation patterns (Polo et al., 2016), a reduction in peak discharge and annual runoff downstream (Graf, 2006; Batalla et al., 2004; Huang et al., 2012), and a significant change in the timing and regimes of low and high streamflow (Yang et al., 2017; Pyron and Neumann, 2008). Particularly in areas where people depend on steady and regular water supplies for everyday life and agriculture, such changes have a cascading socio-economic impact on riverine ecosystems. The hydrological effects of small and medium-sized reservoirs, which also have a significant impact on river systems, have been the subject of more recent studies.

Problems like decreasing dry-weather flows, increasing salinity downstream, and conflicting patterns in extremely high and low streamflows have been brought to light by these studies (Gain and Giupponi, 2014; Zhang et al., 2016; Lu et al., 2018). Additionally, there have been significant alterations in the annual trend of daily average water temperatures (Maheu et al., 2016), shorter and smaller spring floods, and longer and more frequent droughts (Marcinkowski and Grygoruk, 2017).

1.2 Motivation and Importance of Study

The Narmada River basin presents a compelling case for research due to its unique hydrological, topographical, and anthropogenic characteristics, revealing significant gaps in understanding the impacts of large-scale reservoir systems. It is one of India's most heavily regulated river systems, with 36 small, medium, and large dams, including the Indira Sagar Project (ISP)—India's largest water storage—and the Sardar Sarovar Project (SSP), with the highest volume of concrete used. According to the CWC (2014), large dams in the basin (storage >1000 MCM) collectively hold about 34,500 MCM, a substantial portion of the basin's annual runoff of 45.64 BCM, which could affect the natural flow regimes. While globally, reservoirs are known to modify streamflow (Lehner et al., 2011), the narrow, elongated topography and steep gradients of the Narmada basin, coupled with intense monsoon-driven hydrology, make it one of India's most flood-prone rivers (Mahanta, 2006). These features amplify the effects of reservoir operations on flooding and sediment transport. The cascading arrangement of dams introduces complex, poorly documented interactions in water release and storage (Mondal and Patel, 2022), potentially impacting aquatic biodiversity and downstream riparian communities. Thus, a deeper understanding of cascading reservoirs in the Narmada basin is essential to address critical hydrological, ecological, and socio-economic research gaps in this river system.

1.3 Objectives of Study

The present study aims to address the following objectives:

(i) To analyse the annual and mean monthly variations in streamflow magnitude due to large reservoirs in the Narmada River basin.

(ii) To evaluate the changes in the magnitude, duration, timing, frequency, and rate of change of mean and extreme flow conditions for the post-dam versus pre-dam scenario due to the presence of large reservoirs in the Narmada River basin.

(iii) To quantify the degree of alteration due to the cascading effects of the Rani Avanti Bai Sagar (Bargi) dam, Indira Sagar dam, and Sardar Sarovar dam on Narmada River flow regimes.

1.4 Organisation of Study

The present study is systematically structured across five chapters, each meticulously designed to comprehensively explore the research topic. Chapter 1 introduces the study, delineating its background, motivation, and objectives, establishing the investigation's foundation. Chapter 2 elucidates the materials and methods, encompassing a thorough literature review of prior studies, identifying existing research gaps that justify the current work, and a detailed exposition of the methodologies employed. Chapter 3 focuses on the case study domain, specifically the selected dams in the Narmada River basin, providing an in-depth description of the datasets utilised, their sources, and pertinent details critical to the study's context. Chapter 4 presents the results and analysis, leveraging the methodologies outlined in Chapter 3 to evaluate the hydrological alterations instigated by the three dams under investigation. Finally, Chapter 5 synthesises the study's findings, offering a concise summary, key conclusions, and insights into the future scope of research.

Chapter – 2

MATERIALS AND METHODS

2.1 General

In this chapter, a detailed review of existing literature relevant to this study is presented, highlighting key findings and thematic areas explored by previous researchers. While numerous studies have examined the localized impacts of individual dams on streamflow and hydrological regimes, understanding the cascading impacts of multiple large dams on the entire river basin is less explored. Most existing studies fail to comprehensively address how sequential dam operations collectively influence downstream hydrology at a basin-wide scale. In addition, the specific methodology adopted to carry out the present analysis is also presented here.

2.2 Literature Review

2.2.1 Water Resources Development in the Narmada River Basin

Bhattacharya and Loganathan (1989) critically examined the Narmada Valley Project, which proposed the construction of over 3000 dams to optimise the Narmada River for hydropower, irrigation, and flood mitigation. Their analysis highlighted growing concerns over the project's environmental and socio-economic implications, including forest loss, wildlife threats, seismic risks, and displacement of communities. The study outlined opposing viewpoints from proponents and opponents, focusing on issues such as water supply, public health, power output, and rehabilitation challenges. They emphasized the need for a comprehensive reassessment, arguing that the cumulative costs of the project may ultimately surpass its intended benefits.

Chitale (1997) objectively assessed the Sardar Sarovar Project to divert water from the resource-abundant Narmada basin to drought-prone regions like the Sabarmati and Banas basins. The basin development strategy included plans for 30 major, 135 medium, and around 3000 minor water resource projects, with an estimated cost of Rs 100 billion and a targeted completion by 2010. The study examined a broad range of environmental and social impacts, such as deforestation, wildlife conservation, public health risks, sedimentation, land rehabilitation, and the involvement of nongovernmental organisations. It emphasised the importance of balancing development with ecological and community considerations.

Gupta (2001) explored the complexities of river basin management in the context of intra- and inter-basin water transfers, highlighting their necessity due to regional water disparities and recurring droughts in India. Using the Narmada River Valley Development as a case study, the study adopted a multi-objective framework to examine competing priorities in water resource planning. It emphasised that socioeconomic demands often take precedence over other considerations in inter-state water distribution, even accommodating non-riparian states. Focusing on the Sardar Sarovar Project, the study addressed key issues of rehabilitation, environmental sustainability, and social impact, ultimately portraying the project as a vital resource for water-scarce regions in western India.

Routledge (2003) critically examined the conflict over mega-dam construction in the river valley, focusing on the Narmada Bachao Andolan (NBA) as the central force of resistance. The study explored how the NBA challenged economic, ecological, cultural, and political displacement through both material protests and discursive strategies, including academic critiques, slogans, and peasant testimonies. Drawing on Warren's concept of testimonios, the study argued that the movement's collective identity often masks internal contradictions and differences. It concluded by emphasising the role of academics in revealing these ambiguities through reflective engagement with social movements.

Gupta and Chakrapani (2005) comprehensively analysed the spatial and temporal variations in water discharge and sediment load in the river and its tributaries. Using 22 years of daily discharge data from 19 sites and sediment concentration data from 14 sites, the study identified monsoon-driven rainfall as the dominant factor controlling both water flow and sediment transport. Approximately 85–98% of annual sediment load is delivered during monsoon season, accounting for 85–95% of annual rainfall in the basin. At Garudeshwar, the average annual sediment flux to the Arabian Sea was estimated at 34.29×10^6 T year^{-1}, with a water discharge of 23.57 km^3 year^{-1}. The study emphasised that sediment yield is shaped by rainfall intensity, catchment geology, and dam presence, with the Sardar Sarovar Dam alone trapping 60–80% of the sediment load before river outflow.

Pandey et al. (2008) carried out a series of crop field trials between 2004 and 2006 at the Agronomy Farm in Anand to collect detailed crop-specific data for improving the accuracy of models within the DSSAT 3.5 system. Their study focused on chickpea (Dahod Yellow), pearl millet (MH-179), wheat (GW-496), and two maize varieties (GM-3 and Ganga Safed-2). After validating the models using the field-collected data, they ran simulations across 11 locations in the Narmada canal command area, using average weather data and local soil conditions from each site. The simulation results showed that Ganga Safed-2 maize produced yields between 3595 and 4825 kg/ha, while GM-3 ranged from 3519 to 4717 kg/ha. Chickpea yields were estimated between 1100 and 1800 kg/ha, and wheat showed the highest simulated yield at Vijapur, reaching 5807 kg/ha. The study also explored the link between crop yield and water use, finding that a simple linear model explained this relationship better than more complex ones like exponential or logarithmic curves. This suggests that crop yield tends to increase steadily with water use, offering useful insights for improving irrigation planning and water-use efficiency in agriculture.

2.2.2 Hydrologic Alterations in Streamflow Regimes

Richter et al. (1997) introduced the Range of Variability Approach (RVA) as a method to set streamflow-based ecosystem management objectives. This approach underscores hydrological variability's role in sustaining aquatic ecosystems and uses historical or synthesised streamflow data to define flow targets across 32 hydrological parameters. These targets guide reservoir operations and restoration strategies, enabling adaptive management to protect aquatic biodiversity and ensure ecosystem integrity.

Zhao et al. (2012) examined the spatio-temporal dynamics of hydrological alteration in the Lancang River Basin (1957–2000), focusing on the combined effects of dam construction and precipitation variability. Using linear regression, RVA, and non-parametric trend test, they found that damming and precipitation shifts significantly modified monthly runoff patterns and extreme flow events. Notably, hydrologic alterations were more pronounced downstream, while upstream areas showed relatively lower disturbance due to the absence of dams. The study also revealed that precipitation variability partially mitigated dam-induced impacts, underscoring its role in shaping flow regimes across regulated and unregulated river sections.

Zhang et al. (2016) investigated the hydrologic impacts of small and medium cascade dams in the Jiulong River Watershed, a coastal basin in Southeast China, using 44 years of daily streamflow data. By applying flow duration curves, Indicators of Hydrologic Alteration (IHA), and RVA, the study revealed that dam construction altered flow regimes significantly, reducing high flows and increasing low flows across both reaches. Seasonal patterns shifted, with streamflow rising from July to January and declining from February to May. Extreme events also changed, with earlier low flows and delayed high flows. Notably, the North River saw a sharp increase in low pulse count (+101.8%) and a drop in duration (−62.1%), while the West River exhibited a 37.1% reduction in high pulse count. Rise rates declined and flow reversals increased in both reaches. These findings underscore pronounced and spatially variable impacts of smaller dams and highlight the need for tailored environmental flow strategies.

Sharma et al. (2019) examined the hydrologic impacts of the Hathnur reservoir on the middle Tapi River by analysing 23 flow indices representing magnitude, duration, timing, frequency, and rate of change. Results showed a 21.4% reduction in mean annual runoff and significant deviations in low flow conditions during the post-dam period. High flow regimes were minimally affected, while low flows exhibited early drying and increased low pulse events. A moderate hydrologic alteration (62%) was observed, and the correlation analysis confirmed that changes in streamflow were primarily due to reservoir operations, with minimal influence from climate variability.

Zheng et al. (2019) analyzed the impact of dam construction on riparian wetlands by linking changes in wetland areas to 33 hydrological indicators using hydro-statistical and stepwise multiple regression methods. Dam operations reduced peak discharge, flood frequency, and magnitude, causing a 44% decline in wetland area. The findings suggest optimizing dam operations to restore and conserve downstream wetlands.

Gopikrishna and Mohapatra (2022) evaluated the hydrological health of the Narmada River by comparing pre- and post-dam flow conditions, specifically focusing on the impact of the Indira Sagar Dam. The study analyzed daily and monthly discharge data to calculate relevant river health indices. Results showed an apparent decline in river health during the post-impact period, with reduced flow variability and altered seasonal discharge patterns. The study highlights the significant hydrological disruption caused by dam construction and emphasizes the need for flow-based assessments in river management.

Guo et al. (2022) provided a quantitative assessment of hydrological changes in the Jialing River Basin, focusing on disentangling the influences of climate factors and human activities on streamflow variations. The study employed the Indicators of Hydrologic Alteration with the Range of Variability Approach (IHA-RVA) and Budyko-based hydroclimatic models to analyze the drivers of runoff dynamics. The attribution analysis revealed that changes in precipitation accounted for 61% of the observed runoff variations, while potential evapotranspiration contributed negatively by -16%. Human activities, including land use changes and water resource utilisation, were responsible for 55% of the streamflow alterations. These findings offer a scientific basis for tailored ecohydrological restoration strategies and support the formulation of sustainable water management policies in the Yangtze River Basin.

Ruhi et al. (2022) investigated how dam placement, features, and river network structure influence cumulative flow changes in the Colorado River Basin, analysing 84 dams responsible for over 83% of storage. A spatial Markov network model and regression analysis found that flow alterations accumulate downstream, especially in the main stem, and are influenced by dam characteristics (e.g., storage capacity) and network-level factors (e.g., cumulative upstream storage). High-impact dams often coincide with critical fish biodiversity and imperilled areas, emphasising the potential for ecosystem restoration through regulated flow releases.

Javaid et al. (2023) employed the IHA method to assess the impact of dam construction on the flow regime of the upper and middle reaches of the Narmada River. By analysing 33 hydrological parameters, the study quantified the extent of alteration in river flow patterns before and after dam development. The hydrological alteration (HA) index was found to be significantly higher at Mandleshwar in the middle Narmada (0.86) compared to Burmanghat in the upper Narmada (0.57), indicating greater disturbance downstream. The study observed a decline in the frequency and duration of extreme water events - both floods and low flows - following dam construction. These findings underscore the substantial modification of the natural hydrological regime and highlight the importance of informed water resource management to mitigate cumulative anthropogenic impacts on river systems and aquatic ecosystems.

Mohanty and Tare (2024) evaluated the hydro-morphological impacts of barrage construction on the Yamuna River over 25 years using the River Flow Health Index (RFHI). This methodology assesses flow alterations and develops an index (0-1), revealing moderate flow regime changes (RFHI: 0.379 and 0.328 for different periods). Geomorphological analysis showed reduced sinuosity, narrowing channel width, decreasing channel area, and declining bar density over time. Construction phases increased fluvial bars but reduced channel area and width, with post-barrage operations leaving channels dry during lean seasons. The findings highlight the need for integrated river basin management to balance development with ecological preservation.

Prajapati et al. (2025) employed a multi-method approach to assess the hydrological and sedimentological effects of the Indira Sagar Dam on the Narmada River Basin. The study integrated Monte Carlo simulations, change detection analysis, GAMLSS (Generalised Additive Model for Location, Scale and Shape), and Taylor uncertainty estimates to analyse pre- and post-dam conditions. While no significant change in water discharge was observed at upstream or downstream sites, a marked decline in suspended sediment load was recorded downstream. Specifically, during the monsoon season, sediment transport decreased by approximately 211% between 2005 and 2019. These findings highlight the dam's substantial impact on sediment dynamics, emphasising the need for targeted sediment and flood management strategies in the affected region.

2.3 Research Gap

While numerous studies (Gopikrishna and Mohapatra, 2022; Variam, 2024; Vengadesan et al., 2025; Prejapati et al., 2025) have examined the hydrological impacts of individual reservoirs globally and within the Narmada River basin, there remains a significant gap in the literature regarding the cumulative and cascading effects of multiple large dams across a river. In the case of the Narmada River, where natural flow is heavily regulated, comprehensive assessments are limited. Existing studies often focus on isolated structures rather than the integrated influence of key multipurpose dams such as Rani Avanti Bai Sagar, Indira Sagar, Omkareshwar, and Sardar Sarovar. Through their interconnected operations, these reservoirs significantly alter downstream flow regimes, with wide-ranging implications for irrigation, hydropower, and ecological systems. For instance, the Sardar Sarovar Dam regulates water for power generation and an extensive canal network, directly influencing agricultural productivity and energy usage patterns. This study aims to address this gap by evaluating the combined hydrological alterations resulting from the cascading operation of these major reservoirs in the entire Narmada basin.

2.4 Methods

2.4.1 Indices of Hydrological Alteration (IHA)

Table 2.1 presents the hydrologic indices utilized in this study, derived from the framework established by Richter et al. (1997). These indices provide a systematic approach to understanding changes in streamflow patterns over time. To examine the variability of streamflows in the upstream and downstream of each reservoir, the coefficient of variation (C_v) is employed. The C_v measures the degree of variation or inequality in streamflow distribution, capturing both the temporal fluctuations and the magnitude of streamflow events (Huang et al., 2012). By focusing on C_v, we aimed to quantify the consistency and predictability of streamflow in the system, offering insights into how reservoir operations may alter natural hydrological variability.

To better understand the impact of each reservoir, it is divided into two distinct periods, pre-dam and post-dam, based on their year(s) of commissioning or any major operational change. The pre-dam period represents the natural or unaltered flow regime, while the post-dam period accounts for the altered or regulated flow regime. For instance, for the Rani Avanti Bai Sagar (RABS) reservoir, the pre- and post-dam periods were 1978–1987 and 1988–2023, respectively. For the Indira Sagar reservoir, the pre- and post-dam periods were 1978–2005 and 2006–2023, respectively. Interestingly, the Sardar Sarovar dam had two change points, i.e., 1996 and 2017, reflecting flow patterns influenced by the reservoir's construction and operation. Hence, the pre-dam period for the Sardar Sarovar reservoir was 1978–2005, while the post-dam 1 and post-dam 2 periods were 2006–2016 and 2017–2023, respectively. Hydrologic indices were calculated separately for each of these periods for each reservoir, allowing for a comparative evaluation of changes.The degree of hydrologic modification was then assessed by contrasting its values in the pre-dam period (representing unregulated, natural flow) with those in the post-dam period (representing regulated, altered flow). This approach provides a direct measure of the impact of both reservoirs on the streamflow characteristics.

Table 2.1 Definition of hydrologic indices used in the present analysis (Richter et al., 1997)

Group	Regime Features	Hydrologic Indices	Notation and Units
I: Magnitude of mean flow conditions	Magnitude, timing	• Mean annual runoff • Mean monthly streamflow for each month	QA_{mean} [10^6 m^3] Q_{month} [m^3/s]
II: Magnitude and duration of annual extreme conditions	Magnitude, duration	• 1-day annual maximum flow • 3-day annual maximum flow • 5-day annual maximum flow • 10-day annual maximum flow • 30-day annual maximum flow • 1-day annual minimum flow • 3-day annual minimum flow • 5-day annual minimum flow • 10-day annual minimum flow • 30-day annual minimum flow	$Q_{1\text{-}D\ Max}$ [m^3/s] $Q_{3\text{-}D\ Max}$ [m^3/s] $Q_{5\text{-}D\ Max}$ [m^3/s] $Q_{10\text{-}D\ Max}$ [m^3/s] $Q_{30\text{-}D\ Max}$ [m^3/s] $Q_{1\text{-}D\ Min}$ [m^3/s] $Q_{3\text{-}D\ Min}$ [m^3/s] $Q_{5\text{-}D\ Min}$ [m^3/s] $Q_{10\text{-}D\ Min}$ [m^3/s] $Q_{30\text{-}D\ Min}$ [m^3/s]
III: Occurrence of annual extreme timing conditions	Timing	• Julian date of 1-day annual maximum flow • Julian date of 1-day annual minimum flow	$Q_{J\text{-}Max}$ [Day] $Q_{J\text{-}Min}$ [Day]
IV: Frequency and duration of high and low pulses	Magnitude, Frequency, Duration	• No. of high pulses in each year • No. of low pulses in each year	HighP [No.] LowP [No.]
V: Rate and frequency of water condition changes	Frequency, Rate of change	• Means of all positive differences between consecutive daily values (Rise rate) • Means of all negative differences between consecutive daily values (Fall rate) • No. of reversals	RiseR [m^3/s] FallR [m^3/s] Rev [No.]

2.4.2 Range of Variability Approach (RVA)

In order to statistically evaluate changes in streamflow regimes based on different hydrologic indices, Richter et al. (1997) created the range of variability approach (RVA). Many researchers have used the RVA approach extensively to assess how reservoir construction and operation affect downstream streamflow regimes (Gain and Giupponi, 2014; Zhang et al., 2016; Xue et al., 2017). For a given hydrologic index, the RVA goal range is established either parametrically (based on standard deviation) or non-parametrically (based on percentiles), which reflects the natural flow regime. The range between the 25th and 75th percentile values of a particular hydrologic index, which corresponds to circumstances anticipated to occur 50% of the time in any specific year, is known as the RVA target range. As explained by Richter et al. (1998) and further utilized by Xue et al. (2017), the degree of hydrologic alteration (D) for each hydrologic index is computed to reflect the extent to which the RVA goal range is not reached. The degree of hydrologic alteration (D) is computed as:

$$D_i = \left|\frac{OF - EF}{EF}\right| \times 100 \qquad \text{.........(1)}$$

where, EF is the expected frequency, expressed as $p \times N$, where p is the percentage of pre-dam years where the hydrologic index fell within the RVA target range and N is the total number of post-dam years. OF stands for the observed frequency or the number of post-dam years in which the value of a specific hydrologic index falls within the RVA target range.

According to Richter et al. (1998), the degree of hydrologic modification (D) can be divided into four categories: (i) no alteration: $D = 0\%$; (ii) low alteration: $D < 33\%$; (iii) moderate alteration: $33\% \leq D \leq 67\%$; and (iv) high alteration: $D > 67\%$. Considering that the degree of flow regime fluctuation may vary among hydrologic indices, an overall degree (OD) of hydrologic alteration across all thirty indices can also be computed as:

$$OD = \sqrt{\frac{\sum_{i=1}^{30} {D_i}^2}{30}} \qquad \text{.........(2)}$$

2.5 Research Methodology

To illustrate the methodology employed in this study, Figure 2.1 depicts the adopted systematic approach, beginning with the collection of daily streamflow data(CWC Data) from ten stream-gauging stations - Manot (Man), Mohgaon (Moh), Bamni (B), Patan (P), Belkhedi (Bel), Barmanghat (Bar), Handia (H), Mandleshwar (M), Kogaon (K), and Garudeshwar (G) - located upstream and downstream of the Rani Avanti Bai Sagar RABS, Indira Sagar (IS), and Sardar Sarovar (SS) dams on the Narmada River (refer to Table 3.2). These stations were selected for their proximity to the dams and consistent data availability (from 1978 to 2023). The data were analysed to derive the reconstructed streamflow series to estimate the total contribution into and out of the reservoir.

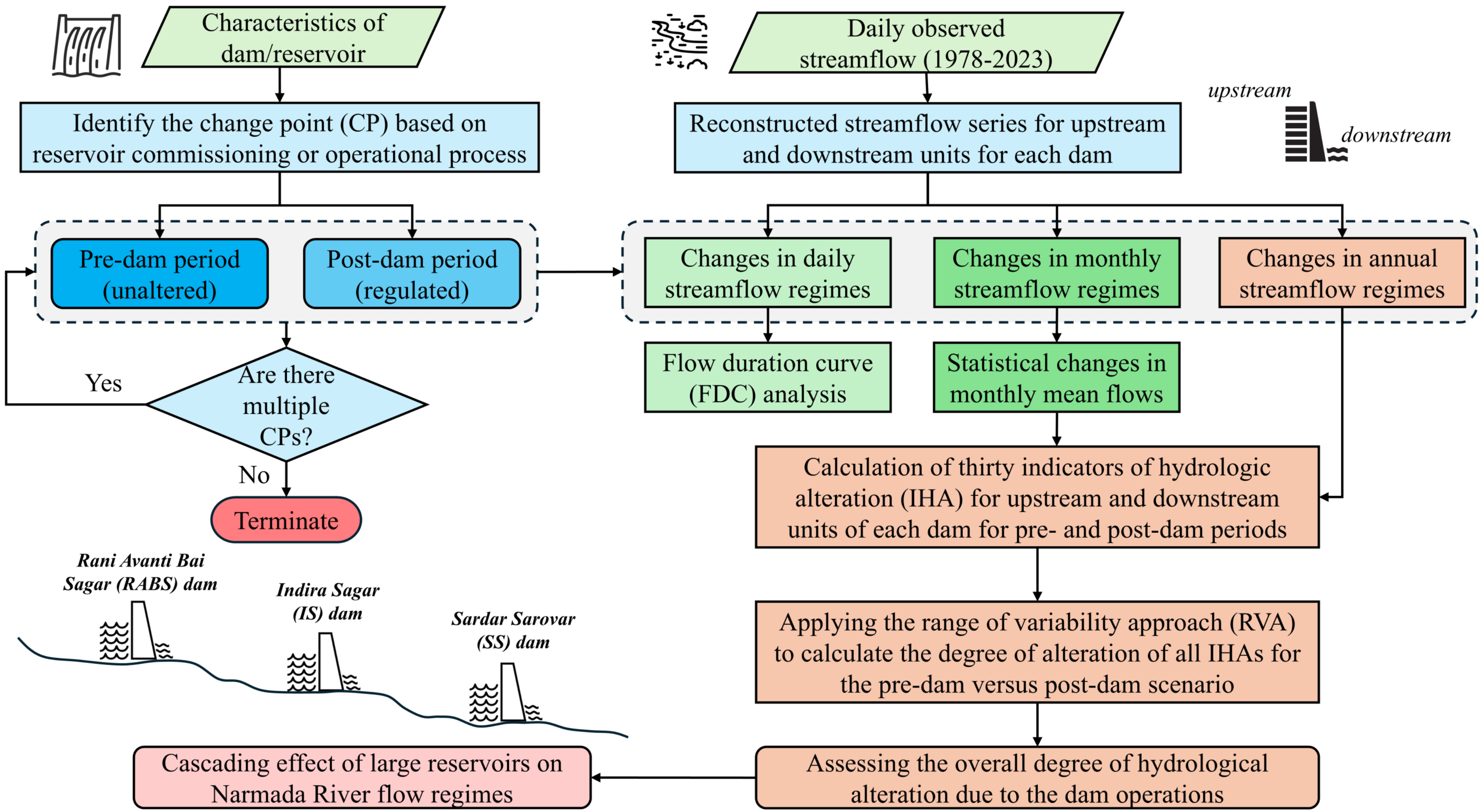

Figure 2.1 Methodology used for this study

For instance, the inflow into the RABS is accounted for by $Q(Man + Moh + B)$, and the outflow from the RABS is $Q(Bar - P - Bel)$. Similarly, the inflow into the IS is taken as $Q(H)$, while the outflow from the IS is estimated as $Q(M - K)$. Lastly, the inflow and outflow of SS are accounted as $Q(M)$ and $Q(G)$, respectively. Therafter, thirty IHA are computed for the reconstructed streamflows for each reservoir, separately for the pre-dam and post-dam period, and the RVA approach is performed to derive the overall degree of alteration.

2.6 Closure

This chapter integrated existing literature, delineated its scope, and identified critical research gaps. It further elucidated the methods for analyzing hydrological alteration and described the specific methodology adopted for this study. Building upon this foundation, the subsequent chapter will provide a comprehensive overview of the study area for the analysis.

Chapter – 3

STUDY AREA

3.1 General

This chapter provides a comprehensive overview of the study domain, including its key physical characteristics and essential attributes. This discussion encompasses the details of the dam and its associated catchment area, including their hydrological characteristics. Additionally, the pre-processing of streamflow data is explained, alongside a thorough description of the data sources utilized, ensuring a robust foundation for the hydrological alteration analysis presented in this study.

3.2 Case Study Domain

The Narmada River, originating from Amarkantak in west-central India, is the largest (≈1312 km) westward-flowing and the fifth-largest river in India. Narmada River drains 98,796 km^2 area over Madhya Pradesh, Maharashtra, and Gujarat, out of which 87% of its drainage area falls in Madhya Pradesh. Narmada River has 41 tributaries, while the major tributaries include Burhner, Banjar, Hiran, Tawa, Chhota Tawa, Shakkar, Orsang, and Kundi. The upper hilly areas in the Narmada basin receive over 1400 mm annual rainfall, while the lower plains receive less than 1000 mm annual rainfall, dropping to below 650 mm around Barwani. The construction of several dams across the Narmada River and its tributaries is critical for flood management, irrigation, water supply, and hydropower generation. The Rani Avanti Bai Sagar (RABS) or Bargi dam is the first major dam on the Narmada River, located at approximately 22°56'27" latitude and 79°55'23" E longitude. As one of the earlier structures on the river, the RABS dam is important for fulfilling the water demand for agriculture and generating hydropower as well. The RABS dam covers a catchment area of 14556 km^2, while receiving an average annual rainfall of 1275 mm.

The Indira Sagar (IS) dam, located downstream of the RABS dam at approximately 22°17'01" N latitude and 76°28'16" E longitude, is the largest dam in the Narmada River basin. Immediately downstream of the IS dam, the Omkareshwar dam is constructed to augment the hydropower generation capacity; however, the capacity of the Omkareshwar dam is nearly one-tenth that of the IS dam. It complies with statutory water release requirements outlined in inter-state water-sharing agreements between Madhya Pradesh and Gujarat, balancing flood control, water supply, and hydropower generation. The IS dam receives inflow from a catchment area of 61642 km^2, and receives an average annual rainfall of 1253 mm.

The Sardar Sarovar (SS) dam is the terminal storage structure on the Narmada River, after which the Narmada River meets the Arabian Sea. The SS dam, draining an area of 88000 km^2, is located in Gujarat at approximately 21°49'49" N latitude and 73°44'50" E longitude. The SS reservoir receives regulated discharges from major upstream reservoirs, including Indira Sagar and Omkareshwar. It plays a key role in downstream flood attenuation, irrigation distribution, municipal and industrial water supply, and hydropower production. The reservoir is operated under the governance of the Narmada Water Disputes Tribunal (NWDT), which prescribes inter-state water allocation protocols and reservoir operation rules. The SS dam catchment experiences a mean annual rainfall of approximately 1087 mm, shaping seasonal storage patterns and downstream release behaviour.

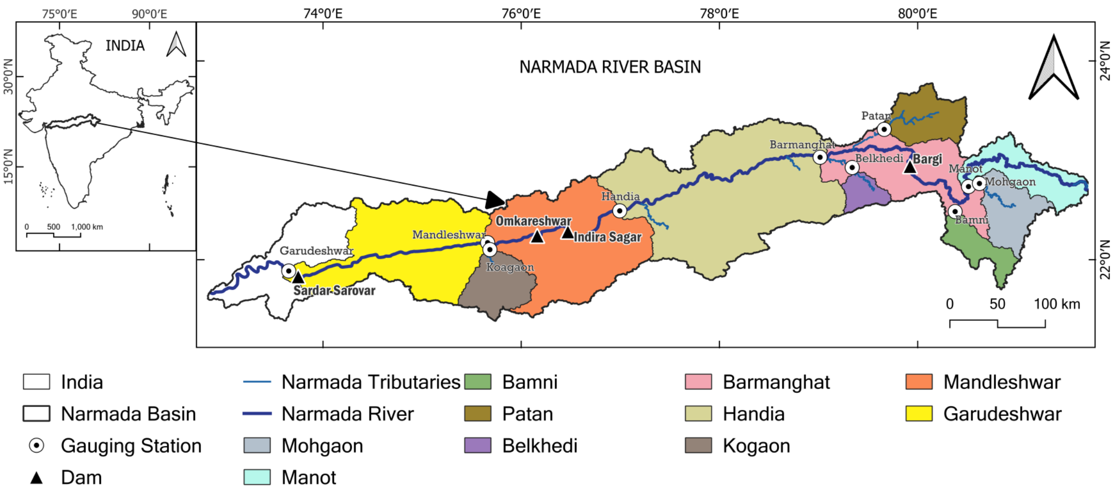

Figure 3.1 Index map showing the location of major reservoirs and stream gauging stations in the Narmada River basin

3.3 Dam and Catchment Attributes

A set of spatially distinct upstream and downstream units is delineated to assess the influence of the RABS, IS, and SS dams on streamflow dynamics within the Narmada

River system (refer to Figure 3.1). For the RABS dam, the upstream unit is designated as Man+Moh+B, which includes the gauging stations at Manot (Man) on the Narmada River, Mohgaon (Moh) on the Burhner River, and Bamni (B) on the Banjar River, all contributing to inflow into the RABS dam. The $\boldsymbol{Q(Man+Moh+B)}$ characterises natural, unregulated flow conditions unaffected by dam operations. In contrast, the downstream, $\boldsymbol{Q(Bar-P-Bel)}$, represents the outflow from the RABS dam at Barmanghat (Bar) on the Narmada River. To solely represent the regulatory impact of the RABS dam, streamflow at the Patan (P) and Belkhedi (Bel) stations due to the Hiran and Sher Rivers is subtracted from the Barmanghat (Bar) streamflow.

For the IS Dam, the upstream unit is defined by the Handia (H) station on the Narmada River, capturing pre-regulation inflow into the reservoir. The downstream unit, Mandleshwar–Kogaon (M-K), reflects regulated outflows from the IS reservoir, as observed at Mandleshwar on the Narmada River. In this case, the streamflow from Kogaon station (across the Kundir River) is subtracted from the Mandleshwar flows to represent outflows solely from the IS dam. The IS dam has the highest storage capacity of 12.22 billion cubic meters (BCM) in India, while the Omkareshwar dam has a nominal storage of 0.987 BCM compared to the IS dam.

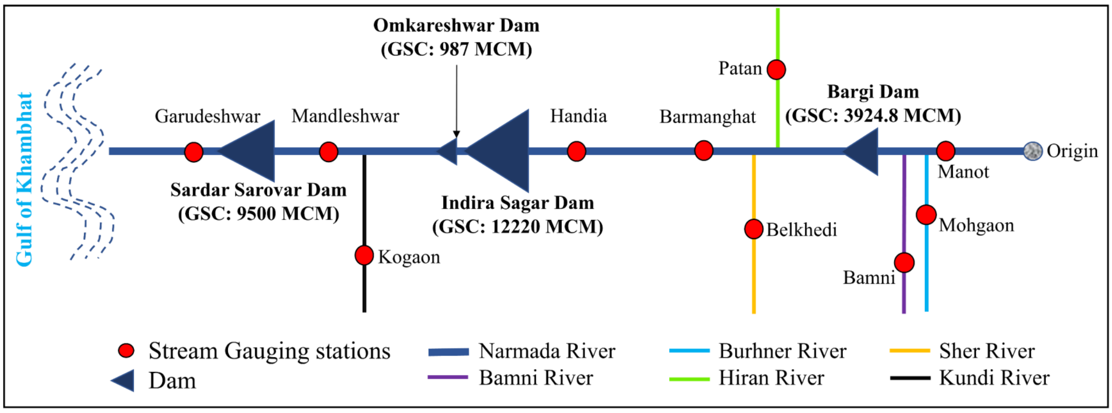

Figure 3.2 Line diagram of the Narmada River basin. *Here, GSC indicates the gross storage capacity of the dam in million cubic meters (MCM).*

Regarding the Sardar Sarovar (SS) dam, Mandleshwar (M) is used to represent upstream flow conditions, while Garudeshwar (G) serves as the downstream control point. Between these two stations, no major gauged tributaries contribute to the Narmada River, nor are there any gauge stations with consistent daily streamflow records for the entire study period (i.e., 1978–2023). This approach enhances the precision of comparative analyses between pre- and post-regulation conditions, enabling a clearer understanding of dam-induced alterations in streamflow patterns. The spillway capacity of the SS dam is 87000 m^3/s, which makes it the third-highest spillway capacity in the world (https://ssnnl.gujarat.gov.in/dam-reservoir.aspx).

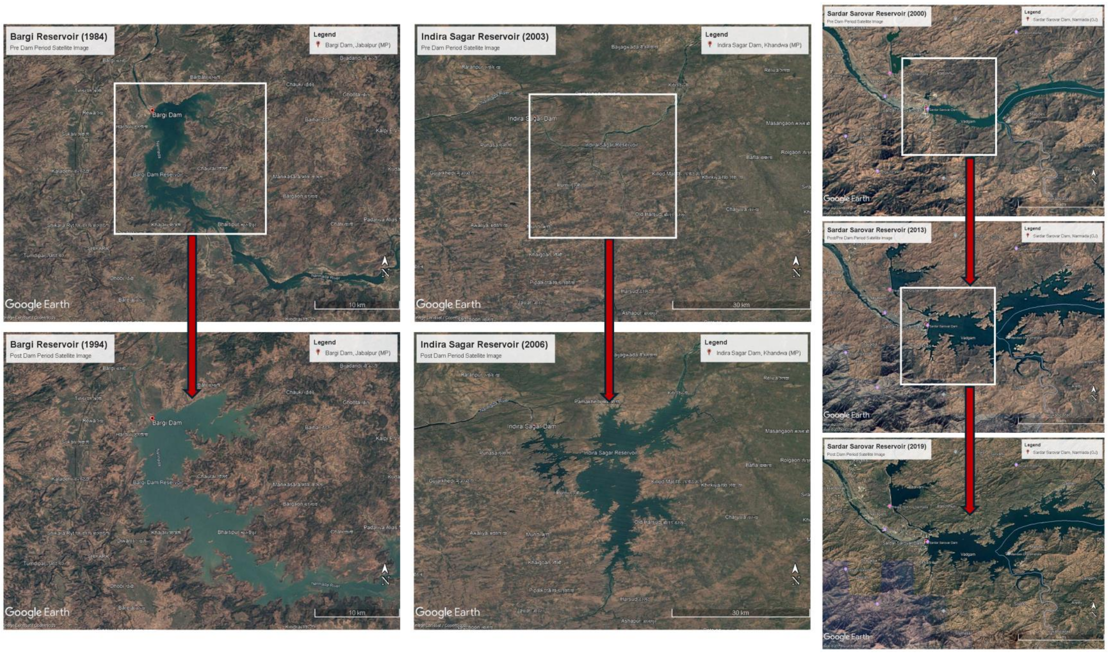

Figure 3.3 Satellite imagery of the RABS, IS, and SS dams (left to right) for pre- and post-dam period showing water inundation

A detailed overview of the key features of all three dams, RABS, IS, and SS, is presented in Table 3.1. The satellite imagery clipped for the case study domain using Google Earth (refer to Figure 3.3) further illustrates the extent of surface water inundation, providing visual confirmation of hydrological changes across the pre- and post-dam periods for the RABS, IS, and SS dams to validate change point considered for this study. The Narmada River basin has witnessed several notable flood events over the years. Significant floods have occurred at the Indira Sagar (IS) dam in 2013, 2022, and 2023, and at RABS in 1999, 2013, and 2020 (Pathak et al., 2021). Among these, the 2013 flood at the IS dam stands out for recording the highest water levels in over three decades, while the 2023 event was the most substantial in the past ten years (NHDC, 2024). Further downstream, the Garudeshwar station has also experienced frequent flooding due to excessive releases from the SS dam, with major events recorded in 1973, 1984, 1990, 1994, and most recently in 2023, the highest recorded event (Mangukiya et al., 2022). During the 2023 floods, continuous release of water from the Sardar Sarovar dam flooded downstream regions in Narmada and Bharuch districts (www.thehindu.com dated 18/09/2023).

Table 3.1 Salient characteristics of RABS, IS, and SS reservoirs

Characteristics	Unit	RABS dam	IS dam	SS dam
Gross Storage Capacity (GSC)	10^9 m^3 (BCM)	3.92	12.220	9.46
Live Storage Capacity (LSC)	10^9 m^3 (BCM)	3.18	9.750	5.76
Dead Storage Capacity (DSC)	10^9 m^3 (BCM)	0.74	2.470	3.7
Total Catchment Area (A)	km^2	14556	61642	88000
Spillway Capacity	m^3/s	45296	83000	87000
Full Reservoir Level (FRL)	m	422.76	262.13	138.68
Highest Flood Level (HFL)	m	425.70	263.35	140.21
Spillway Crest Level	m	407.50	245.13	121.92
Dead Storage Level (DSL)	m	403.55	243.23	110.64
Water Spread Area at FRL*	km^2	267.97	824.92	375.33
Standard Project Flood (SPF)	m^3/s	45005	65670	87000

** Source: (CWPRS, 2023)*

3.4 Data Used and Their Sources

To illustrate the methodological framework adopted in this study, Figure 2.1 presents a systematic workflow beginning with the compilation of daily streamflow data from ten Central Water Commission (CWC) gauging stations - Manot (Man), Mohgaon (Moh), Bamni (B), Patan (P), Belkhedi (Bel), Barmanghat (Bar), Handia (H), Mandleshwar (M), Kogaon (K), and Garudeshwar (G) – which are located upstream and downstream of the Rani Avanti Bai Sagar, Indira Sagar, and Sardar Sarovar dams along the Narmada River (refer to Table 3.2). The daily observed streamflow and water level for these stream gauging stations were collected from the Central Water Commission (CWC) offices at Bhopal and Surat as well as from the India-WRIS web portal (https://indiawris.gov.in/wris/#/Reservoirs). These stations were selected based on their spatial relevance (refer to Figure 3.2) to the study objectives and the availability of consistent daily discharge records over 46 years (1978–2023). An exception was Bamni (B), for which observed flow data were available only from 2005 to 2023. To address this gap, historical streamflow for the Bamni site during 1980-2004 was reconstructed using an LSTM (Long Short-Term Memory) model, derived from the CAMELS-India dataset (https://zenodo.org/records/14999580) (Mangukiya et al., 2025). This hybrid dataset ensured temporal continuity for long-term trend and impact assessments. The consolidated data from these stations were subsequently processed to reconstruct composite catchment-wise streamflow series for six delineated spatial units: Man+Moh+B, Bar-P-Bel, H, M-K, M, and G. These represent hydrologically distinct upstream and downstream regimes associated with each of the three major dams, enabling robust analysis of their regulatory impacts on downstream flow dynamics.

Table 3.2 Details of stream gauging station data used in this study

Dam	Location	Stream Gauging Station	River	Drainage Area (km^2)	Mean Annual Runoff (10^6 m^3)
Rani Avanti Bai Sagar	Upstream	Manot (Man)	Narmada	4467	2879.1
		Mohgaon (Moh)	Burhner	4090	2319.7
		Bamni (B)	Bamni	1864	909.7
	Downstream	Barmanghat (Bar)	Narmada	26453	11635.0
		Patan (P)	Hiran	3950	1556.0
		Belkhedi (Bel)	Sher	1508	797.8
Indira Sagar	Upstream	Handia (H)	Narmada	54027	24094.2
	Downstream	Kogaon (K)	Kundi	3919	1085.9
		Mandleshwar (M)	Narmada	72809	31056.6
Sardar Sarovar	Upstream	Mandleshwar (M)	Narmada	72809	31056.6
	Downstream	Garudeshwar (G)	Narmada	87892	23830.6

3.5 Closure

This chapter establishes a clear understanding of the study domain, dam characteristics, and the rationale behind data preparation. The collected streamflow data is pre-processed to ensure its quality and can be further utilised for hydrologic alteration analysis.

Chapter – 4

RESULTS AND ANALYSIS

4.1 General

This chapter presents the results and discussion derived from the datasets and methodology outlined in the previous chapter, with a focused application to the Narmada River basin. Specifically, the chapter investigates the hydrological impacts associated with the RABS, IS, and SS dams. A comprehensive analysis is conducted to assess changes in streamflow patterns through three key approaches: streamflow change analysis, inter-annual streamflow variability, and hydrological alteration assessment. These analyses are carried out for both upstream and downstream stations of each dam, comparing conditions during the pre- and post-dam periods. This integrated approach aims to quantify hydrological modifications induced by dam construction and operation at mainly downstream.

4.2 Streamflow Change Analysis

4.2.1 Rani Avanti Bai Sagar or Bargi Dam

The streamflow change analysis is based on the premise of considering change point due to the commissioning of the dam or any major operational modification (such as lowering the gates to increase the impoundment or increasing the dam height). Based on the change point, pre- and post-dam conditions are analysed. For the Manot+Mohgaon unit, the mean monthly streamflow curves for both the pre-dam and post-dam periods exhibit a high degree of overlap (see Figure 4.1 (a)), suggesting that upstream conditions have remained largely unchanged over entire period (1978–2023). This indicates that the upstream hydrological dynamics have been relatively unaffected by the dam's operation, with no significant alterations in flow patterns across the annual cycle. The intra-annual streamflow variations reveal significant shifts in flow patterns before and after dam construction (see Figure 4.1 (b)). For Barman-Patan-Belkhedi unit, the mean monthly streamflow during the pre-dam period (1978–1987) exhibited a peak of 1,500 m^3/s in August. However, during the post-dam period (1988–2023), peak flow noticeably reduced, while the low flows were augmented, reflecting the regulatory influence of the reservoir. Specifically, the streamflow in August decreased by approximately 400 m³/s in the post-dam period compared to the pre-dam period. In contrast, streamflows from November to May increased by around 100 m³/s during the post-dam period, indicating altered flow patterns due to reservoir regulation.

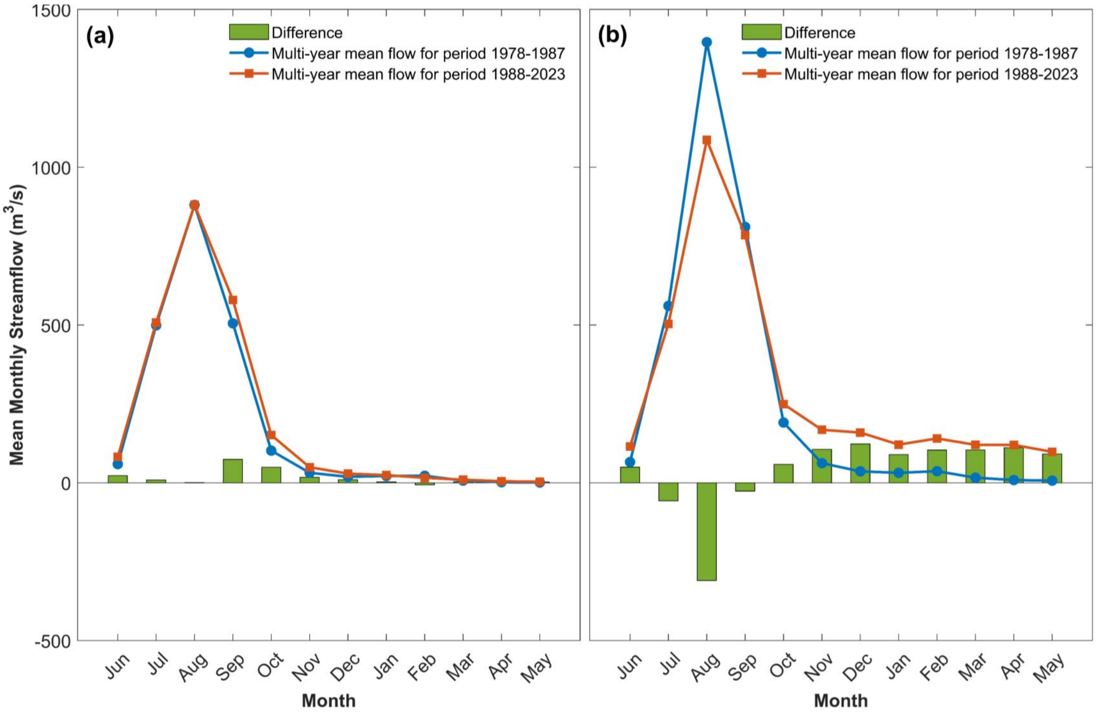

Figure 4.1 Mean monthly streamflow variations at (a) upstream (Manot+Mohgaon+Bamni) and (b) downstream (Barmanghat-Patan-Belkhedi) of RABS dam.

The flow duration curves (FDCs) of daily streamflow are constructed for the pre- and post-dam periods. As shown in Figure 4.2 (a), the FDCs for the upstream unit exhibit minimal differences between the pre- and post-dam periods, indicating that the dam has had little impact on upstream flow conditions. In contrast, Figure 4.2 (b) displays the FDCs for the downstream location, where a clear shift is observed. The post-dam curve lies above the pre-dam curve for flows greater than 20% dependability level onward, indicating an increase in low flows. Conversely, in the high-flow range (up to approximately 20% dependability), the post-dam curve falls below the pre-dam curve, suggesting that peak flows have been attenuated. This pattern reflects the dam's influence in enhancing low flows while suppressing high flows in the downstream. In the downstream, low flows (exceeding 75% of the time) have increased, highlighting the role of reservoir operations in sustaining minimum discharge to help maintain environmental flows to support the ecological status of the river. In addition, the moderate flows (between 20-75% dependability) have also increased in the downstream.

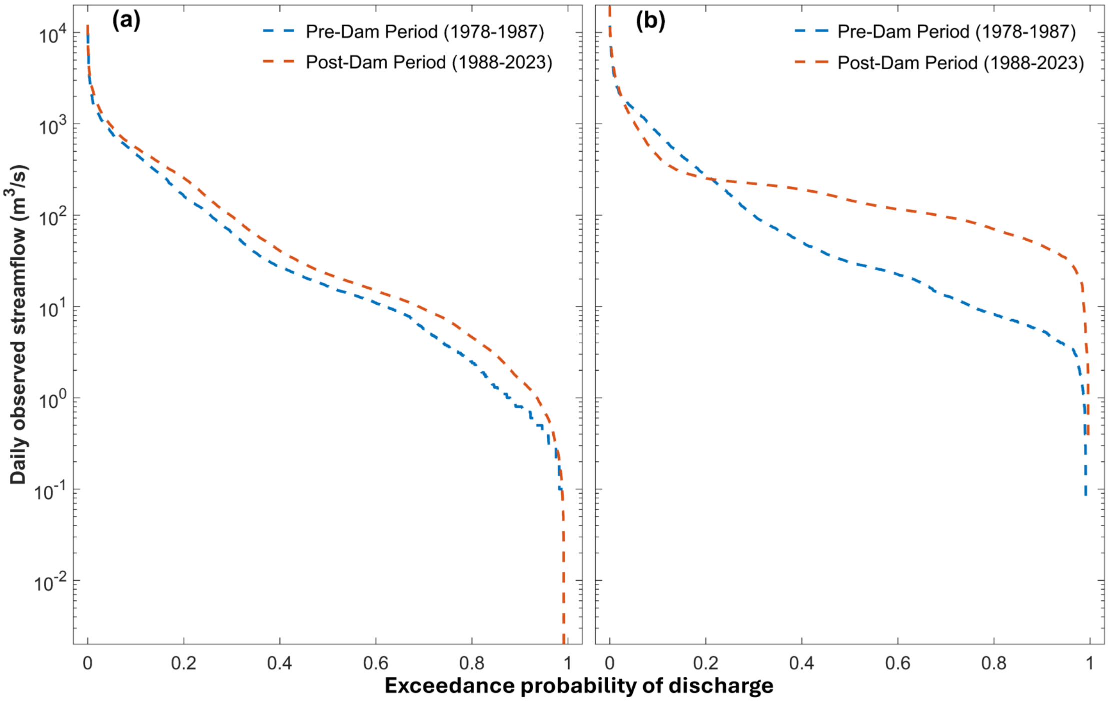

Figure 4.2 Flow duration curves of daily observed streamflow at (a) upstream (Manot+Mohgaon+Bamni) and (b) downstream (Barmanghat-Patan-Belkhedi) of RABS dam.

4.2.2 Indira Sagar Dam

In comparing intra-annual streamflow variability between the Handia (H) and Mandleshwar-Kogaon (M-K), these catchments revealed notable changes following the construction of the Indira Sagar reservoir. As shown in Figures 4.3 (a) and (b), the mean streamflow for August, which typically corresponds to the peak flood period, has significantly decreased at both upstream (H) and downstream (M-K) of IS dam. However, the difference is more pronounced in the downstream. This reduction underscores the reservoir's effectiveness in flood control, as it regulates and moderates the flow resulting from heavy rainfall during the monsoon season. It is noteworthy that the IS dam has almost four times the capacity of the RABS dam, thus, it can regulate higher flow volumes. However, the decrease in streamflow is more pronounced at M-K, where the flow during the flood season has reduced twice as compared to the reduction observed at Handia. This indicates that the reservoir has a stronger influence on the downstream, reflecting its pivotal role in moderating flood impacts. A different trend emerges during the non-monsoon from November to May, as shown in Figure 4.3(b). The upstream of IS dam hardly shows any variation in the lean period flows for post-dam vis-à-vis pre-dam, but the variation is more pronounced in the downstream. The flows during November to May have increased twofold in the post-dam period at M-K unit (see Figure 4. (b)). This shift highlights the reservoir's role in enhancing water availability during the dry months, likely through regulated releases aimed at meeting downstream water demands. In contrast, the post-dam data displays a substantial increase in mean streamflow during the same period, with a notable peak observed in March (refer to Figure 4.3 (b)). This shift highlights the reservoir's role in enhancing water availability during the dry months, likely through regulated releases aimed at meeting downstream water demands.

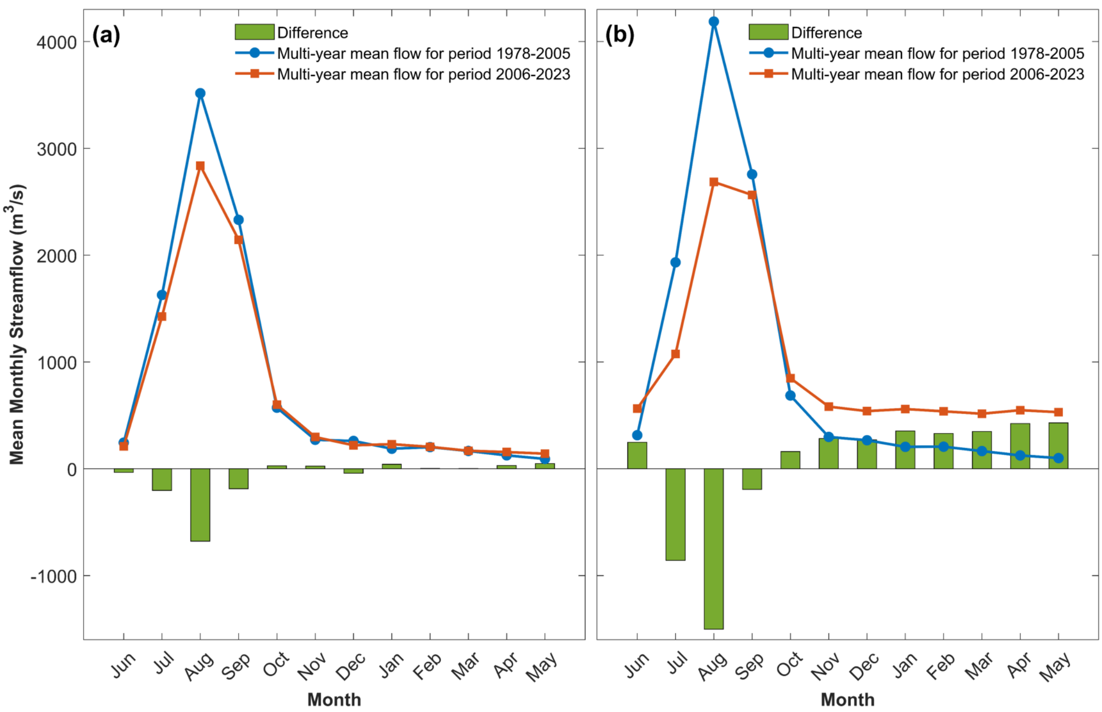

Figure 4.3 Mean monthly streamflow variations at (a) upstream (Handia) and (b) downstream (Mandleshwar-Kogaon) of IS dam.

The FDC analysis provides valuable insights into the changes in streamflow characteristics at both the Handia and Mandleshwar-Kogaon units due to dam construction and operations. At the upstream (Handia) unit, the FDCs of pre-dam (1978–2005) and post-dam (2006–2023) periods reveal no significant changes in the daily streamflow patterns. This stability suggests that upstream hydrological regimes at Handia remain largely unaffected by the Indira Sagar dam, as it represents natural flow conditions unaffected by the dam's influence (see Figure 4.4 (a)). In stark contrast, the FDC for the M-K station displays a clear shift, with the post-dam FDC consistently lying above the pre-dam FDC, especially for streamflows below 1000 m^3/s (see Figure 4.4 (b)). This upward shift highlights a substantial increase in moderate and low flows during the post-dam period, demonstrating the dam's role in effectively routing the incoming flows. The continuous release of water from the dam, dictated by requirements for hydropower generation and maintaining environmental flows downstream, is a likely driver of an increase in moderate and low flows.

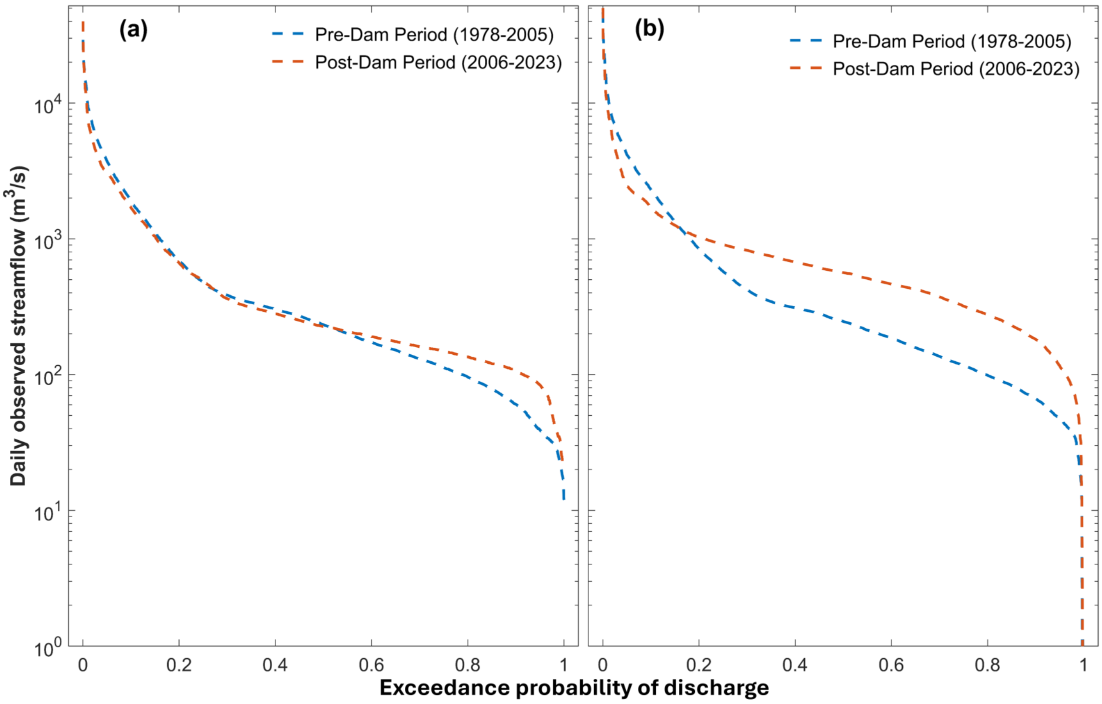

Figure 4.4 Flow duration curves of daily observed streamflow at (a) upstream (Handia) and (b) downstream (Mandleshwar-Kogaon) of IS dam.

4.2.3 Sardar Sarovar Dam

The SS dam construction started in 1988, and thereafter it underwent a consistent rise in its height in a stagewise manner owing to consistent legal scrutiny and political interventions. The dam height was raised to the crest level (121.92 m) in 2006 and then to its FRL (138.68 m) owing to the closure of gates in 2017. Thus, two change points (CPs) are considered for SS dam. In examining mean monthly streamflow variability upstream and downstream of SS dam, significant hydrological alterations are evident following its operationalisation in 2006 (CP1). As illustrated in Figures 4.5(a) and (b), the upstream catchment of the SS dam—already influenced by regulated flows from the IS dam—exhibits substantial shifts in mean monthly streamflow. A marked reduction in monsoonal flows is observed, indicating the cascading effect of upstream IS reservoir.

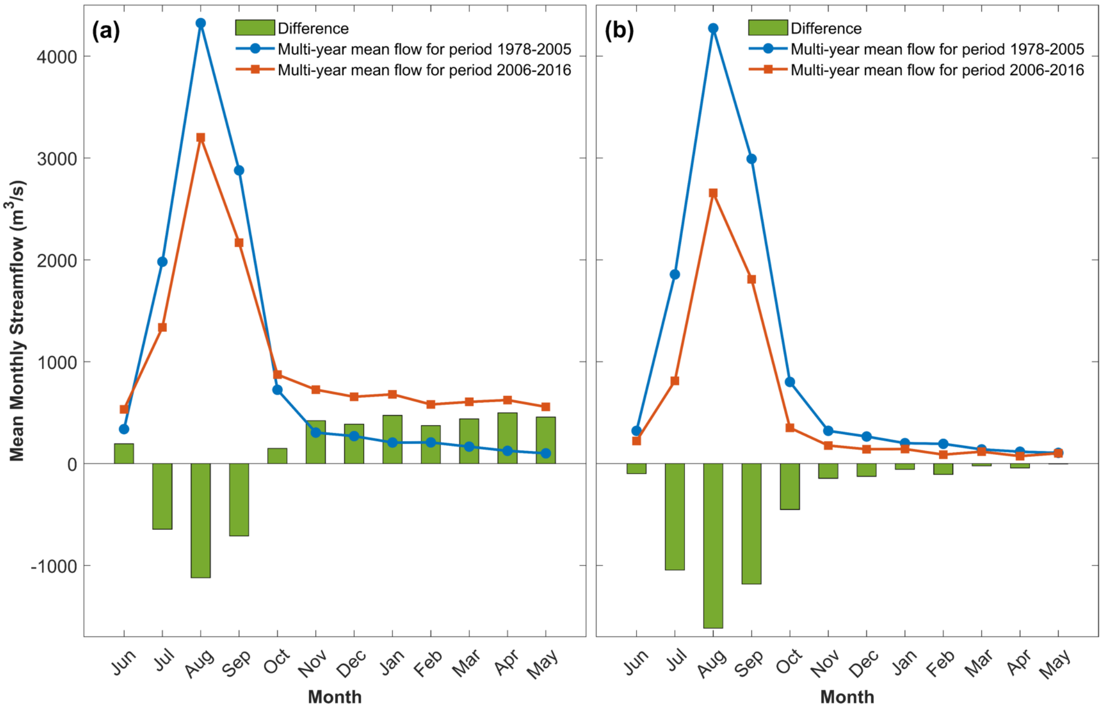

Figure 4.5 Mean monthly streamflow variations at (a) upstream (Mandleshwar) and (b) downstream (Garudeshwar) of SS dam for the change point 1.

Simultaneously, a noticeable increase in streamflow during the dry season months (November to May) reflects enhanced flow stabilisation and effective water release, likely aimed at supporting downstream water demand and maintaining ecological balance. The downstream reach of the SS dam also shows a stark decline in monsoonal flow volumes. However, it is of higher magnitude as compared to the upstream, as depicted in Figure 4.5(b). This pronounced reduction highlights the dam's critical role in attenuating peak flood discharges, thereby contributing to effective flood risk mitigation in the lower reaches of the Narmada River.

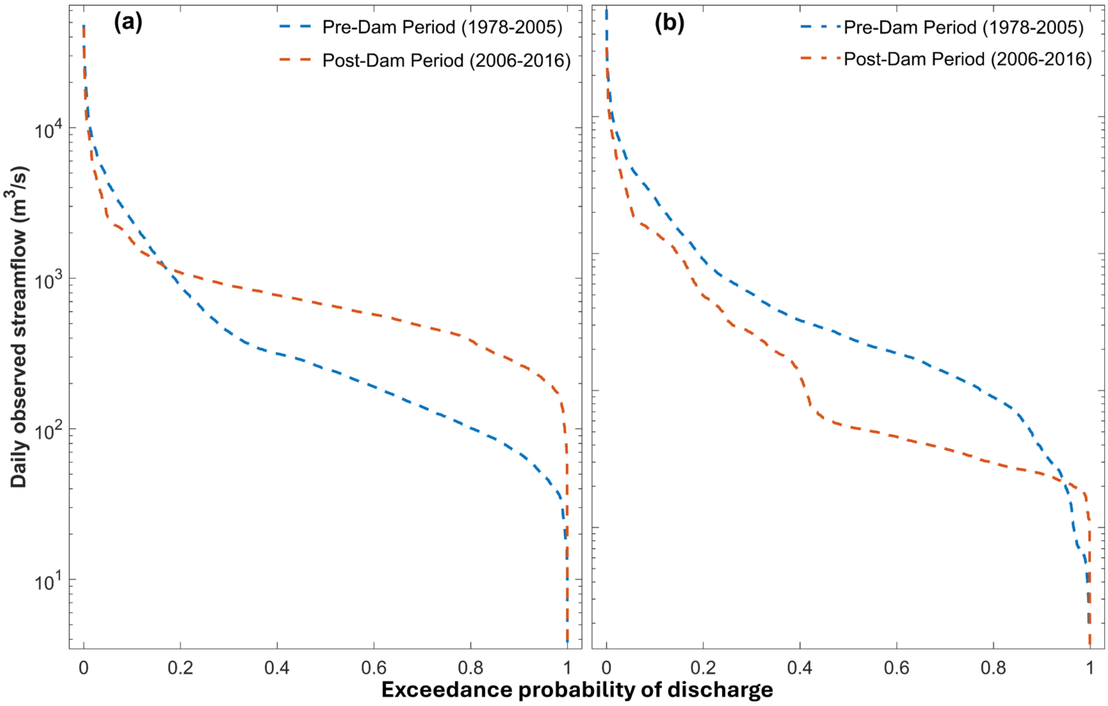

Figure 4.6 Flow duration curves of daily observed streamflow at (a) upstream (Mandleshwar) and (b) downstream (Garudeshwar) of SS dam for change point 1.

After the legal clearance, the gates of SS dam were closed in 2017, thus enabling it to achieve its full storage capacity by impounding water till FRL. Thus, 2017 is taken as change point 2 (CP2) for the SS dam. Considering CP2 (year 2017), the upstream region of the SS dam exhibits a general decline in mean monthly streamflow in the post-dam period relative to the pre-dam, indicating a consistent reduction in flow across most months. However, a notable exception is observed in September, where the mean streamflow demonstrates a significant increase of approximately 1500 m^3/s during the post-dam period (refer to Figure 4.7 (a)). This surge may be attributed to regulated releases from the IS dam in response to peak inflow management. On the downstream of the SS dam, the mean streamflow for the post-dam period shows a notable decline in the monsoon months of July and August. However, the streamflow during June and

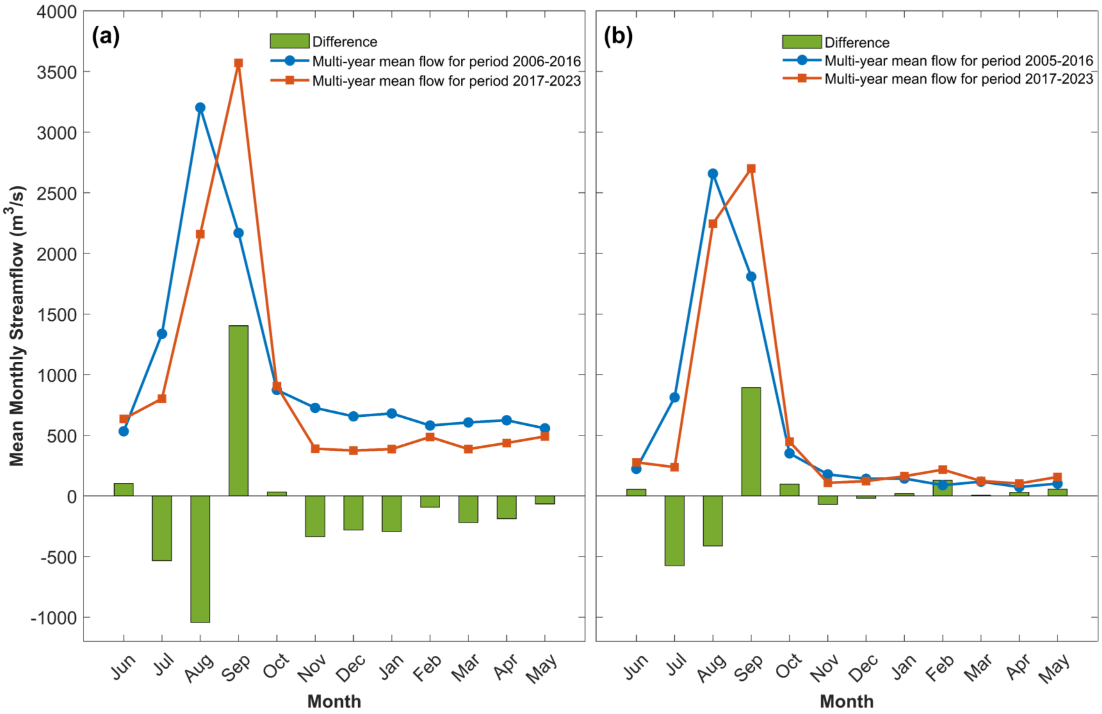

Figure 4.7 Mean monthly streamflow variations at (a) upstream (Mandleshwar) and (b) downstream (Garudeshwar) of SS dam for the change point 2.

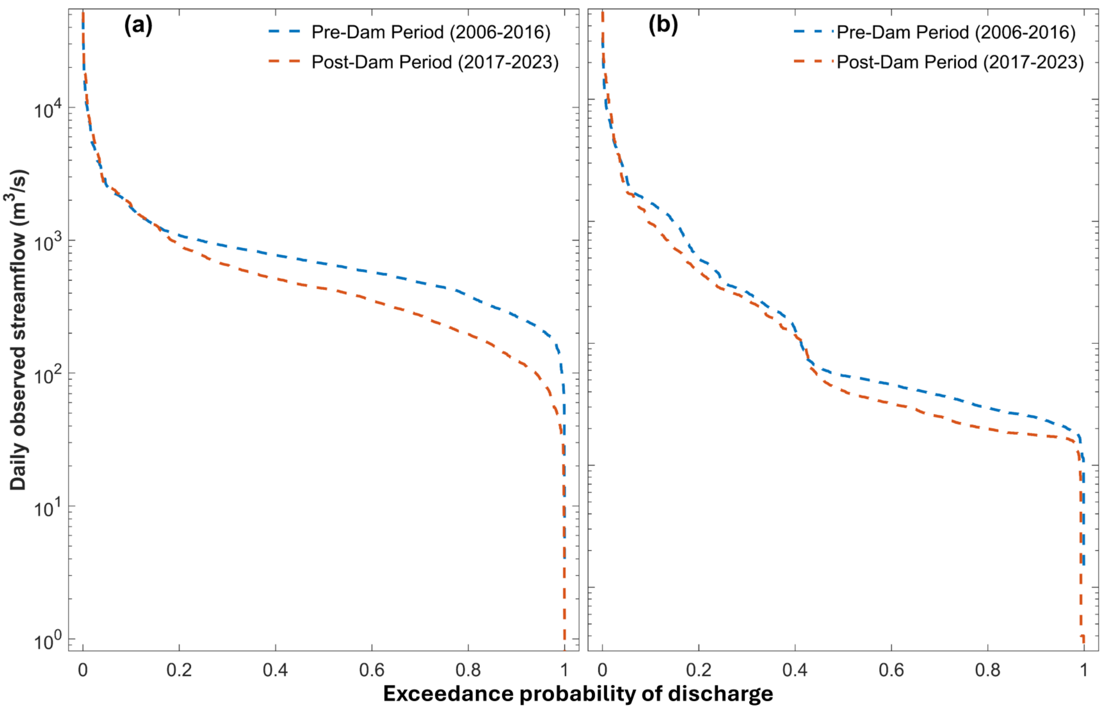

Figure 4.8 Flow duration curves of daily observed streamflow at (a) upstream (Mandleshwar) and (b) downstream (Garudeshwar) of SS dam for change point 2.

September has increased; a prominent increase is noted in the September flows (refer to Figure 4.7 (b)). This clearly reflects the SS dam's role in attenuating high flows during the flood season, effectively reducing the intensity of discharge conveyed downstream while maintaining necessary flow regulation upstream. On the contrary, the low flows at downstream of the SS dam remain largely unaltered, which indicates judicious release of water during lean period to avoid overflows into the Arabian Sea.

4.3 Inter-annual Streamflow Variability

The inter-annual streamflow variability assesses the long-term changes in the annual flow characteristics before and after the change point(s).

4.3.1 Rani Avanti Bai Sagar or Bargi Dam

In comparison to the pre-dam period, the post-dam mean annual runoff was higher in the downstream of the RABS dam, while no appreciable change was observed in the upstream for both periods (see Figure 4.9). This shift is particularly evident at the Barman-Patan-Belkhedi unit, where the post-dam annual runoff curve exhibits greater variability, suggesting an increase in water availability downstream.

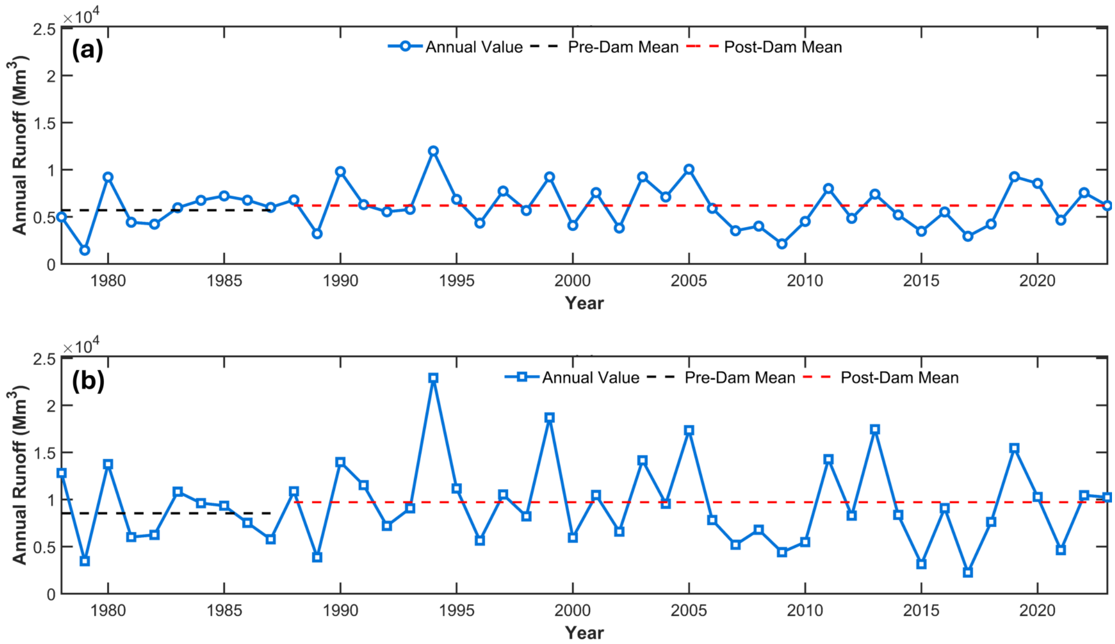

Figure 4.9 Variability of annual runoff at (a) upstream (Manot+Mohgaon+Bamni) and (b) downstream (Barmanghat-Patan-Belkhedi) of RABS dam.

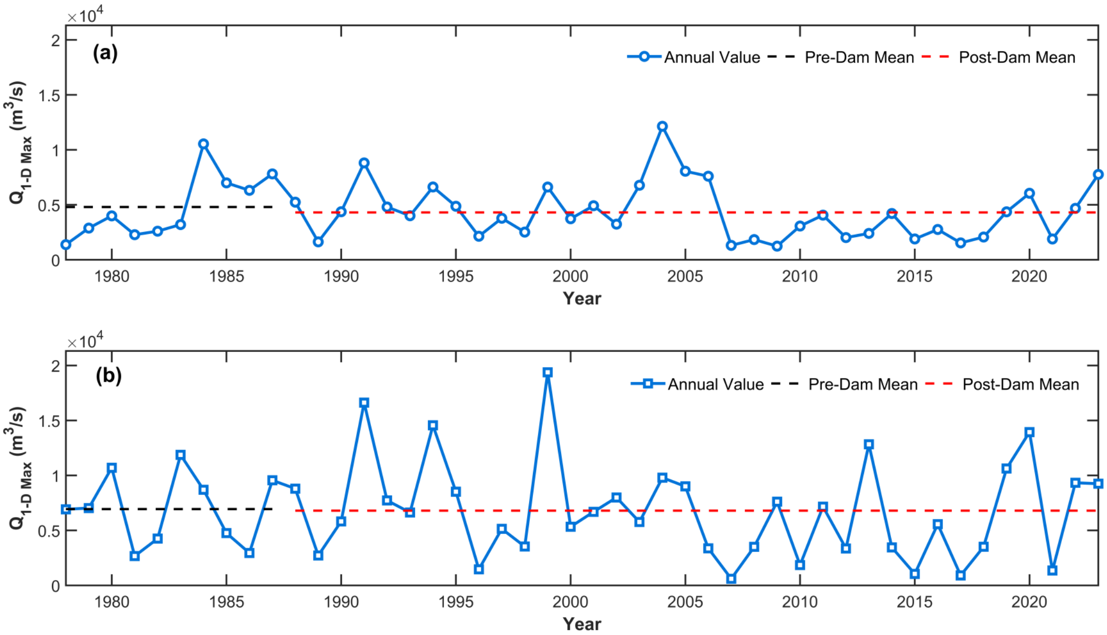

Figure 4.10 Variability of 1-day maximum streamflow at (a) upstream (Manot+Mohgaon+Bamni) and (b) downstream (Barmanghat-Patan-Belkhedi) of RABS dam.

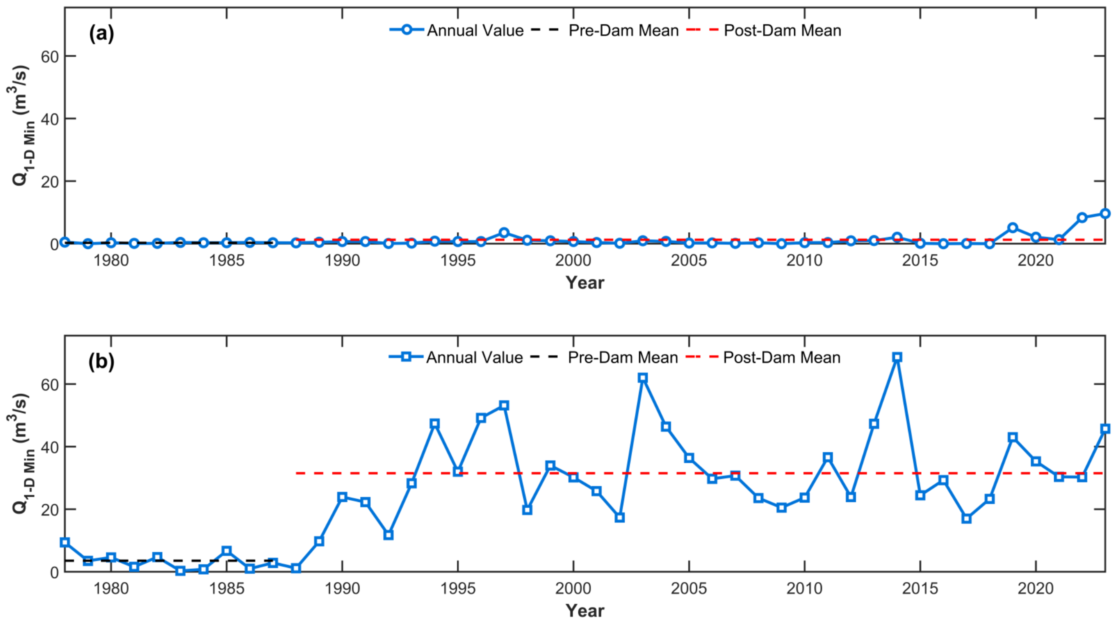

Figure 4.11 Variability of 1-day minimum streamflow at (a) upstream (Manot+Mohgaon+Bamni) and (b) downstream (Barmanghat-Patan-Belkhedi) of RABS dam.

The one-day maximum flow analysis indicates that the mean one-day maximum flow during the post-dam period remains unchanged compared to the pre-dam period, both upstream and downstream of the RABS dam. However, post-dam, these extreme flow values have increased, indicating higher flood risk in downstream regions. The mean one-day maximum flow remains unaltered both at upstream and downstream in the post-dam period (see Figure 4.10 (a) and (b)).

In contrast, one-day minimum flow shows a significant rise in its mean value for the post-dam period than pre-dam period, indicating that regulated flow releases ensure the ecological stability downstream. Upstream conditions, however, remain unchanged, with minimum flow values continuing to hover around zero, as in the pre-dam period.

4.3.2 Indira Sagar Dam

The comparative analysis of extreme and mean annual streamflow variability between the pre-dam period (1978–2005) and the post-dam period (2006–2023) reveals a clear transformation in the hydrological patterns of the Handia (H) and Mandleshwar-Kogaon (M-K) units.

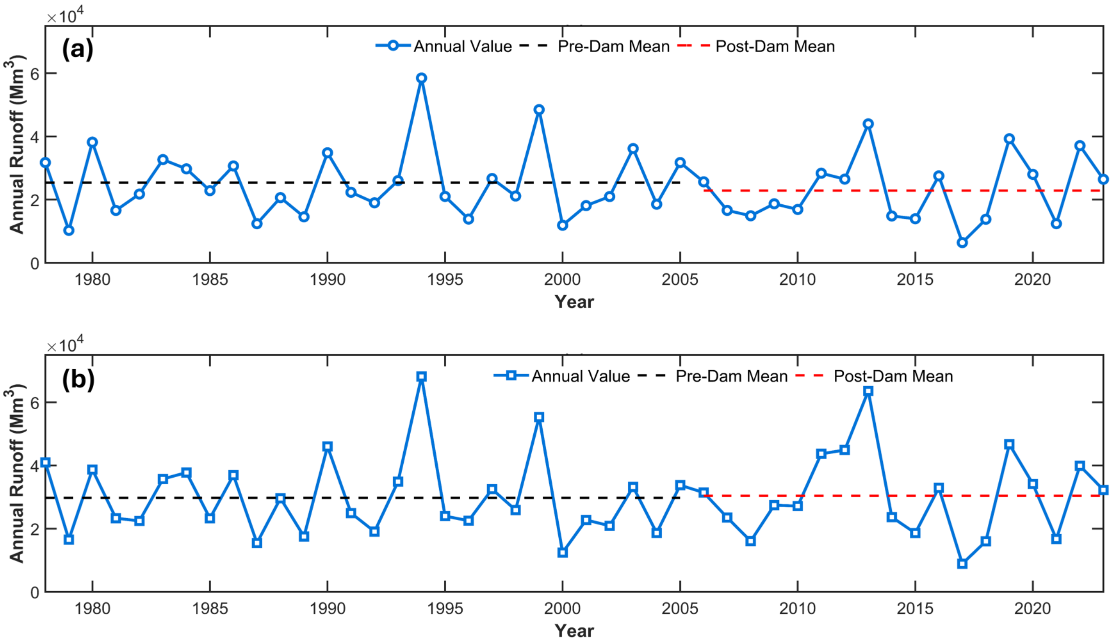

Figure 4.12 Variability of annual runoff at (a) upstream (Handia) and (b) downstream (Mandleshwar-Kogaon) of IS dam.

After the construction of the IS Dam, some noticeable changes were observed in the flow patterns. Upstream of the dam, the mean annual runoff slightly decreased in the post-dam period (Figure 4.12(a)), possibly due to reduced inflows or catchment changes. In contrast, the downstream runoff remained almost the same as before (Figure 4.12(b)), indicating that the dam is maintaining consistent flow further downstream.

The analysis of one-day maximum flows shows a reduction both upstream and downstream, with the decrease being more pronounced downstream (Figures 4.13(a) and 4.13(b)). This suggests that the dam is effective in controlling peak flows.

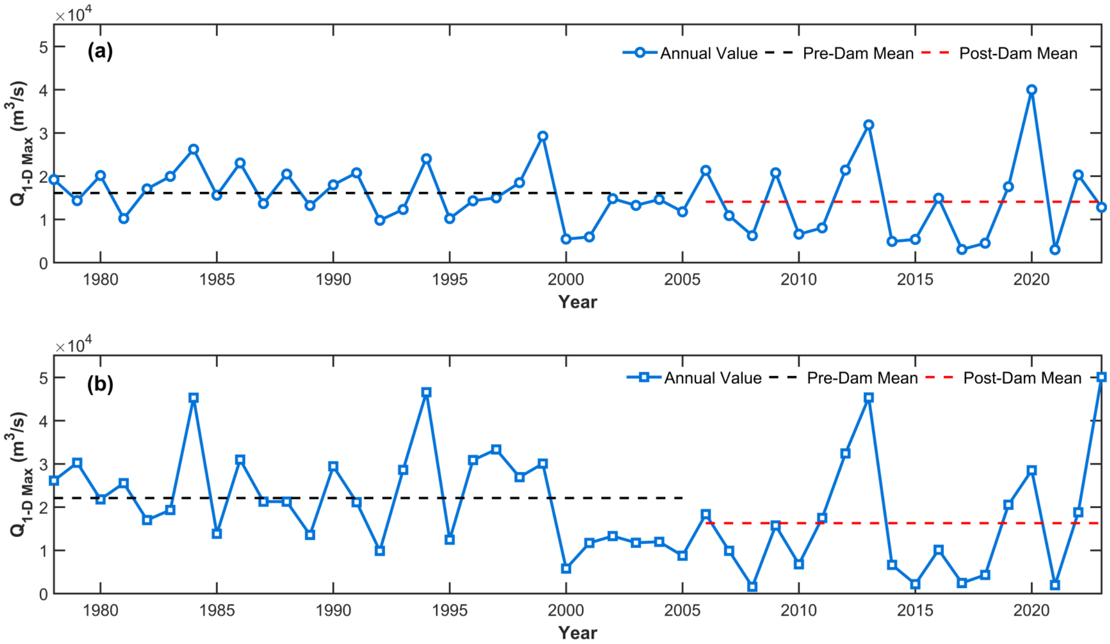

Figure 4.13 Variability of 1-day maximum streamflow at (a) upstream (Handia) and (b) downstream (Mandleshwar-Kogaon) of IS dam.

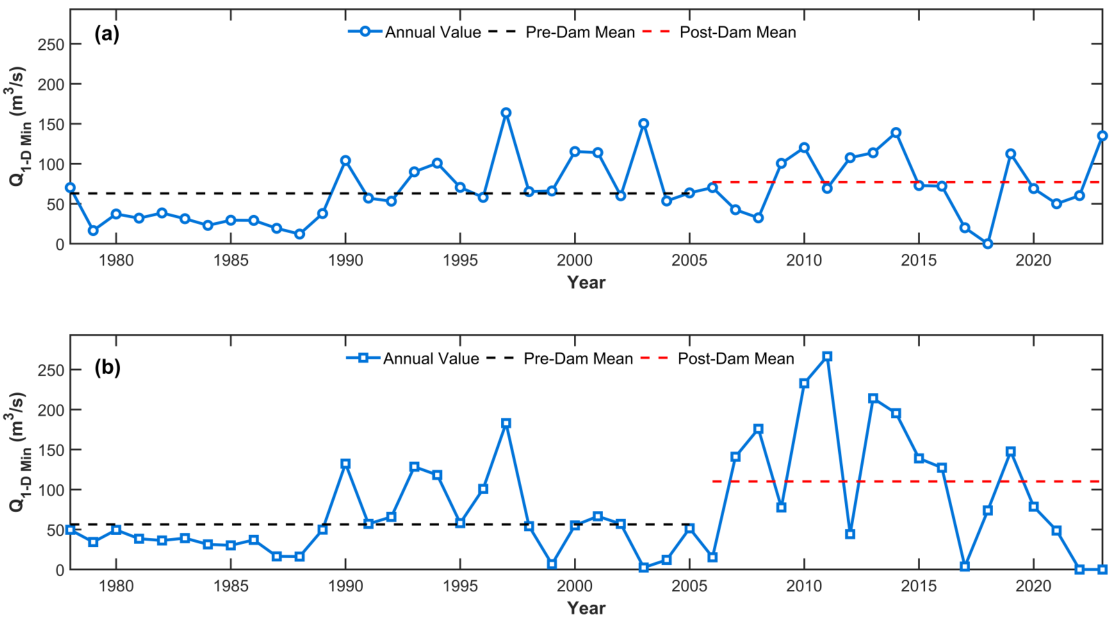

Figure 4.14 Variability of 1-day minimum streamflow at (a) upstream (Handia) and (b) downstream (Mandleshwar-Kogaon) of IS dam.

Remarkably, one-day minimum flows increased in both locations. Upstream flows saw a clear rise (Figure 4.14(a)), while downstream, the increase was even more significant, almost 200% higher than in the pre-dam period (Figure 4.14(b)). This points to the dam playing an important role in keeping a steady flow of water downstream throughout the year.

4.3.3 Sardar Sarovar Dam

The SS Dam for CP1 shows more noticeable changes in the flow regime. Upstream, the mean annual runoff increased (Figure 4.15(a)), which could be due to changes in water retention or inflows. However, downstream, there was a sharp decrease in annual runoff (Figure 4.15(b)), likely due to regulated water releases. One-day maximum flows have decreased on both sides of the dam, with the drop being more significant downstream (Figures 4.16(a) and 4.16(b)). This highlights the dam's role in reducing sudden high-flow events.

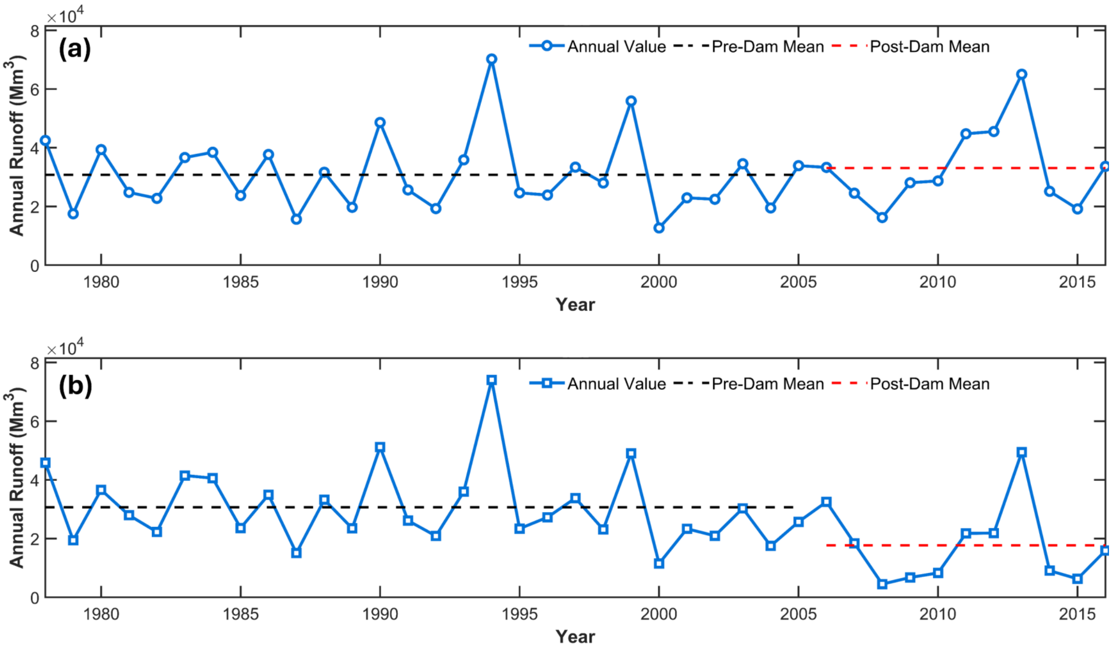

Figure 4.15 Variability of annual runoff at (a) upstream (Mandleshwar) and (b) downstream (Garudeshwar) of SS dam for the change point 1.

For one-day minimum flows, the upstream side experienced a stark increase, up to 300% more than in the pre-dam period (Figure 4.17(a)). On the other hand, the downstream side saw a decrease in minimum flow (Figure 4.17(b)), indicating that dam operations might be limiting the flow further downstream. Overall, while the dam improves water availability upstream, it seems to reduce flow consistency downstream.

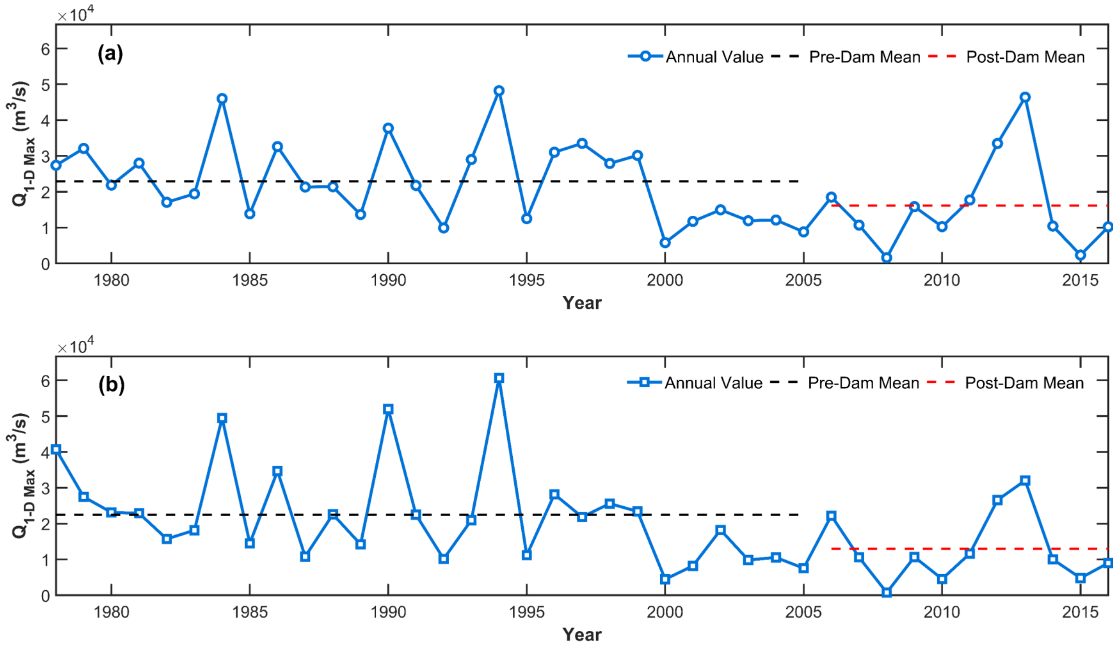

Figure 4.16 Variability of 1-day maximum streamflow at (a) upstream (Mandleshwar) and (b) downstream (Garudeshwar) of SS dam for the change point 1.

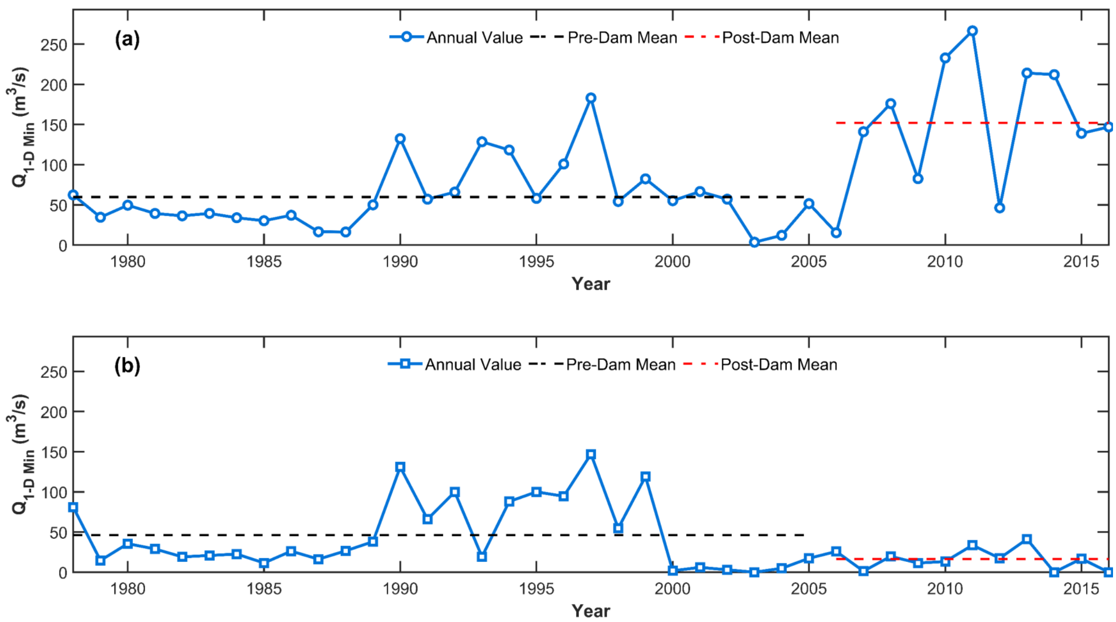

Figure 4.17 Variability of 1-day minimum streamflow at (a) upstream (Mandleshwar) and (b) downstream (Garudeshwar) of SS dam for the change point 1.

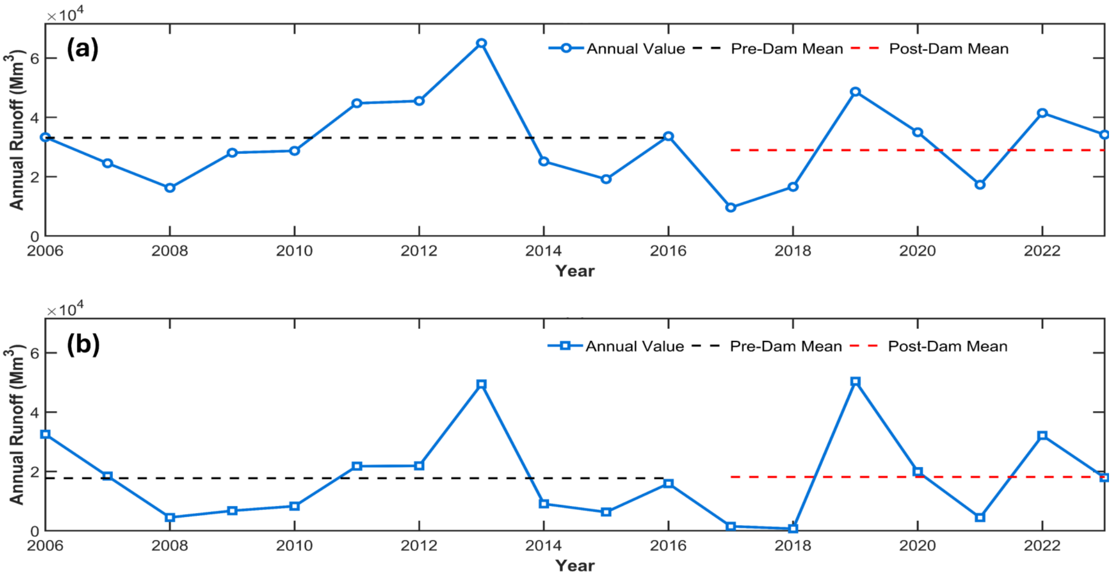

Figure 4.18 Variability of annual runoff at (a) upstream (Mandleshwar) and (b) downstream (Garudeshwar) of SS dam for the change point 2.

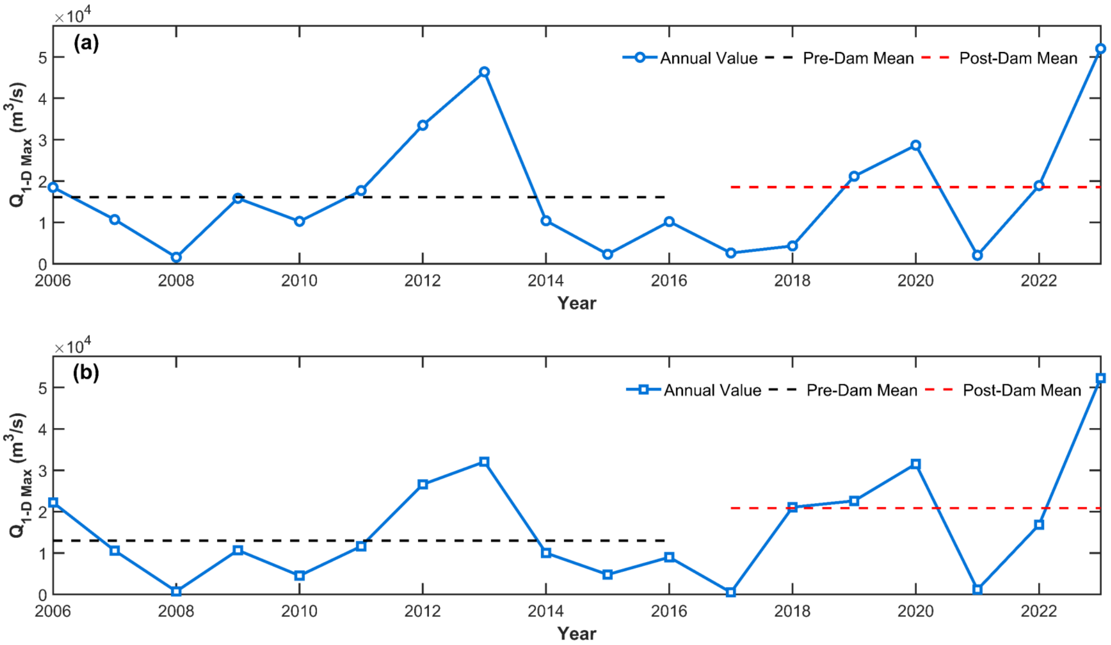

Figure 4.19 Variability of 1-day maximum streamflow at (a) upstream (Mandleshwar) and (b) downstream (Garudeshwar) of SS dam for the change point 2.

In case of CP2 for the SS Dam, the flow patterns show a different trend. The mean annual runoff upstream decreased after the dam was built (Figure 4.18(a)), but downstream values remained mostly unchanged (Figure 4.18(b)). This points to good regulation of water releases to maintain flow downstream. The one-day maximum flow increased slightly upstream and showed a more visible rise downstream (Figures

4.19(a) and 4.19(b)), which could be due to operational releases or more variable rainfall events. The one-day minimum flow upstream dropped significantly (Figure 4.20(a)), suggesting less consistent streamflow in that area. However, downstream, the minimum flow remained stable (Figure 4.20(b)), which shows that the dam is helping to maintain low-flow conditions, supporting a more balanced and reliable water supply in the downstream reach.

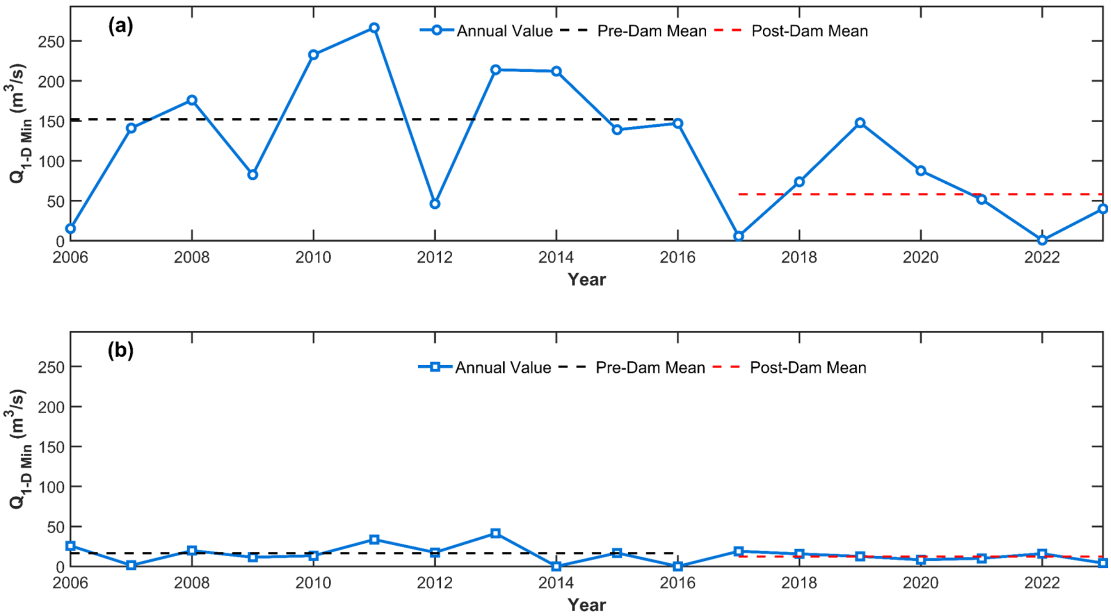

Figure 4.20 Variability of 1-day minimum streamflow for at (a) upstream (Mandleshwar) and (b) downstream (Garudeshwar) of SS dam for the change point 2.

4.4 Hydrological Alteration Analysis

The hydrologic alteration analysis involves evaluating thirty IHAs for the pre- and post-dam conditions for each reservoir and quantifying the degree of alteration and its inherent interpretation. These thirty IHAs are clubbed into five distinct groups (as discussed in Table 2.1).

4.4.1 Rani Avanti Bai Sagar or Bargi Dam

For the Manot+Mohgaon+Bamni unit, in Group I, only the mean streamflows for April and May exhibit a moderate degree of alteration, while the remaining parameters in Group I show low levels of alteration. These findings highlight changes in seasonal flow patterns during the critical pre-monsoon period, a time when the rivers nearly run dry. In Groups II and III, the 3-day and 5-day minimum flows have experienced high alterations, reflecting significant changes in short-term low-flow events. Furthermore, in Groups IV and V, the number of low pulses has shifted notably, suggesting an increase in the number of zero-flow days. These changes indicate a modification of the natural recession patterns of streamflow (see Figure 4.21 (a)).

At the Barmanghat-Patan-Belkhedi (Bar-P-Bel) unit, the analysis reveals significant alterations in streamflow parameters, primarily driven by anthropogenic factors and dam operations. In Group I, the post-monsoon mean streamflow from November to May shows high alterations, highlighting substantial changes in seasonal flow patterns. In Groups II and III, the most altered parameters include the minimum flows ranging from 1- to 30-days. These increases in flow over extended periods reflect a significant shift in low-flow dynamics. Significant changes are observed in the number of low pulses and reversals in Groups IV and V. Alterations in low-flow pulses indicate fewer short-duration low-flow events, while the increase in flow reversals signals greater instability in streamflow patterns. Out of the 30 IHA parameters analysed, 15 exhibit high alterations, underscoring the considerable impact of the dam on the natural flow regime of the river (see Figure 4.21 (b)).

4.4.2 Indira Sagar Dam

At the Handia unit (upstream of IS dam), most streamflow parameters exhibit low levels of alteration, with only July, August, January, and March showing moderate alteration in Group I, while all other months and the mean annual runoff remain largely unaltered. These moderate changes point to minor adjustments in seasonal flow patterns during both monsoon and winter months. In Groups II and III, the 1-, 10-, and 30-day maximum flows are moderately altered due to decreased peak flows, while 5- and 10-day minimum flows show a moderate increase, indicating slight improvements in low-flow conditions. Timing for both minimum and maximum flows is moderately altered. In Groups IV and V, no significant change is observed in the number of low pulses, while high pulses and flow reversals show low to moderate alteration, suggesting limited disturbance in short-duration flow variability. Overall, 14 out of 30 IHA parameters show moderate alteration, indicating relatively low hydrological disruption at the upstream site (see Figure 4.22 (a)).

Conversely, the M-K unit (downstream of IS dam) exhibits substantial hydrological alterations, particularly in the non-monsoon months. Group I parameters show high alterations during January, February, April, and May, and moderate changes in August, November, December, and March, reflecting regulated lean-period releases to sustain downstream flows. In Groups II and III, significant changes are observed in minimum flows from 1 to 30 days, with all durations showing increased flow—indicative of managed flow releases to maintain ecological flows. Flow timing remains minimally altered. Groups IV and V display high alterations in high pulses and reversals, with flow regulation via dam gates introducing abrupt fluctuations. With 11 parameters highly altered and 9 moderately altered out of 30, the analysis underscores considerable impact from dam operations on the downstream flow regime (see Figure 4.22 (b)).

4.4.3 Sardar Sarovar Sagar Dam

For CP1, at the Mandleshwar unit (upstream of the SS dam), notable hydrological alterations are observed despite the upstream location, likely due to cascading effects from the IS dam. In Group I, high alterations occur consistently from November to May, indicating modified dry-season flows. Minimal alterations are seen from June to October. In Groups II and III, minimum flows from 1 to 30 days are highly altered, with increased flow levels, suggesting an artificial augmentation of baseflow. The timing of extreme flows shows low alteration. However, Groups IV and V reveal substantial disruptions: both low and high pulses, as well as reversals, are highly altered, indicating frequent and abrupt changes in flow conditions. With 15 parameters showing high alteration, the upstream site reflects a significant anthropogenic footprint, primarily due to upstream dam operations (see Figure 4.23 (a)).

Downstream at the Garudeshwar unit, substantial alterations persist. In Group I, high alterations in monthly flows from November to March, and a decrease in annual runoff, reflect modified seasonal and annual flow regimes. Moderate alterations from June to August, October, and May point to an altered monsoon and transition-season flow pattern. Group II and III parameters show moderate alterations in 1-, 3-, 10-, and 30-day maximum flows (all decreased) and 10-day minimum flows (increased), suggesting subdued flood peaks and maintained baseflows. The timing of minimum flows is moderately altered, while the timing of maximum flows shows low alteration. In Groups IV and V, moderate alterations in both low and high pulses, along with high alterations in reversals and fall rates, reflect unstable flow conditions driven by downstream regulation. Out of 30 IHA parameters, 8 are highly and 14 are moderately altered, highlighting the dam's role in reshaping flow dynamics downstream (see Figure 4.23 (b)).

For CP2, Upstream of the SS dam at the Mandleshwar unit, Group I shows high alterations in select months—June, July, September, November, and January—pointing to modified monsoon and dry-season flows. December and May are moderately altered, while other months and the mean annual runoff remain stable. Group II parameters reveal high alterations in 1- to 10-day maximum flows and moderate increases in 3- to 5-day minimum flows, highlighting shifts in peak and low-flow magnitudes. Group III shows low timing alteration. In Groups IV and V, moderate alteration in low pulses and high alteration in reversals suggest both seasonal and event-based flow variability. With 12 parameters highly altered and 6 moderately altered, this upstream site reflects a pronounced cascading impact from IS dam operations (see Figure 4.24 (a)).

At the Garudeshwar unit (downstream of SS dam), significant modifications are evident. Group I shows high alterations for September, December, February, April, and May, with moderate changes across multiple other months, indicating controlled releases during both monsoon and dry periods. Annual runoff is also highly altered. Group II parameters show high alteration in 1- to 30-day maximum flows and 10- to 30-day minimum flows, indicating suppression of flood peaks and artificial maintenance of low flows. In Group III, minimum flow timing is highly altered, while maximum flow timing is moderately altered. Groups IV and V reveal moderate changes in pulses and high alterations in reversals, suggesting intensified instability due to operational practices. With 14 highly and 13 moderately altered parameters out of 30, the downstream environment experiences substantial disruption, especially due to the dam height increase to 138.68 m in 2017 (see Figure 4.24 (b)).

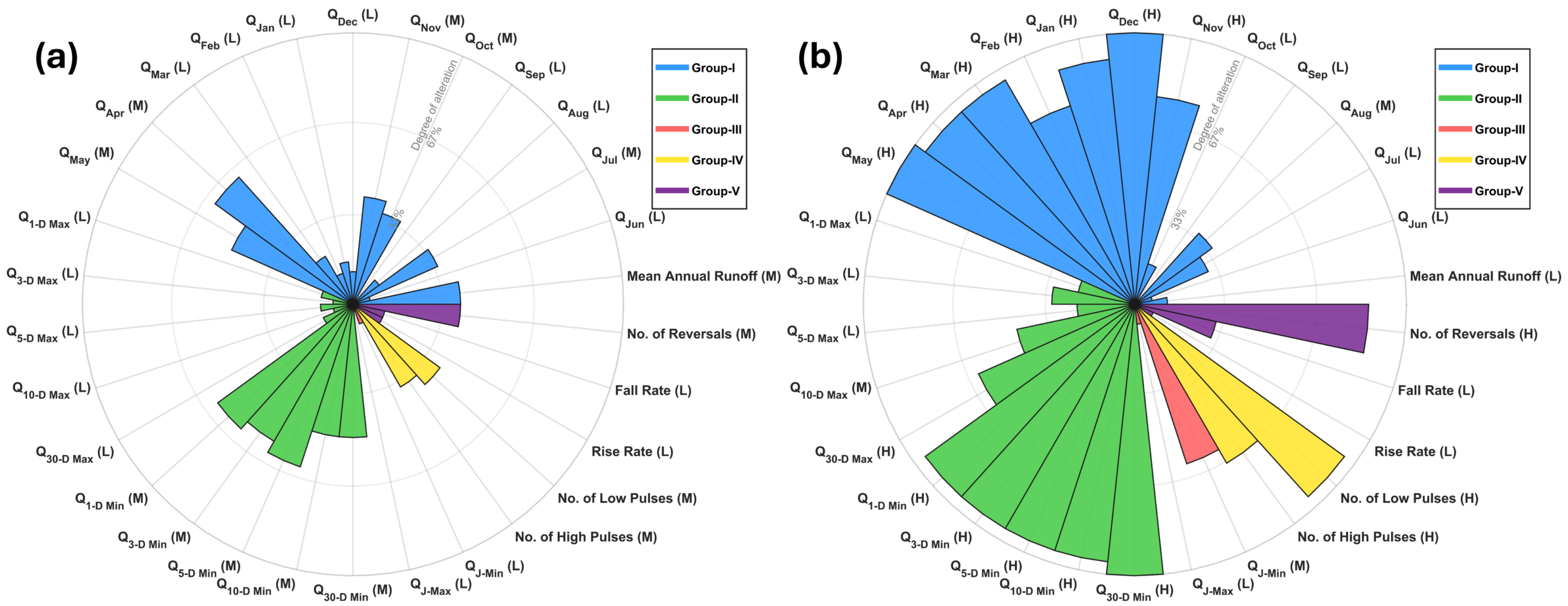

Figure 4.21 Degree of hydrological alteration at (a) upstream (Manot+Mohgaon+Bamni) and (b) downstream (Barmanghat-Patan-Belkhedi) of RABS dam.

Table 4.1 Hydrologic alteration analysis results for downstream (Barmanghat-Patan-Belkhedi) of RABS dam

Hydrologic Indices [Unit]	Mean			Coefficient of Variation			Degree of hydrological alteration (%)
	Pre-dam	Post-dam	% Deviation	Pre-dam	Post-dam	% Deviation	
Mean Annual runoff [10^6 m3]	8541.0	9697.1	13.5	0.4	0.5	24.8	12.0
Mean June streamflow [m^3/s]	65.9	117.1	77.7	1.1	0.6	-48.6	6.5
Mean July streamflow [m^3/s]	560.7	502.8	-10.3	0.8	1.2	44.9	29.6
Mean August streamflow [m^3/s]	1396.4	1095.9	-21.5	0.5	0.8	57.6	35.2
Mean September streamflow [m^3/s]	810.8	784.7	-3.2	0.7	0.9	25.7	1.9
Mean October streamflow [m^3/s]	190.9	248.5	30.2	0.6	0.6	-3.3	15.7
Mean November streamflow [m^3/s]	62.2	167.3	168.9	0.5	0.4	-18.6	76.9
Mean December streamflow [m^3/s]	36.2	157.4	334.8	0.7	0.4	-40.2	100.0
Mean January streamflow [m^3/s]	31.6	120.4	281.1	0.5	0.5	4.1	90.7
Mean February streamflow [m^3/s]	36.8	139.4	279.0	0.7	0.7	-1.0	76.9
Mean March streamflow [m^3/s]	16.1	119.1	638.2	0.6	0.5	-20.2	95.4
Mean April streamflow [m^3/s]	8.6	119.8	1286.2	0.7	0.5	-26.0	95.4
Mean May streamflow [m^3/s]	6.8	99.9	1366.9	0.8	0.4	-45.9	100.0
1-Day annual maximum flow [m^3/s]	6943.0	6801.6	-2.0	0.5	0.7	44.2	21.3
3-Day annual maximum flow [m^3/s]	14880.3	14401.7	-3.2	0.4	0.7	58.0	30.6
5-Day annual maximum flow [m^3/s]	19105.2	19062.1	-0.2	0.4	0.7	79.1	21.3
10-Day annual maximum flow [m^3/s]	28268.2	26697.7	-5.6	0.4	0.7	97.7	44.4
30-Day annual maximum flow [m^3/s]	54131.7	45231.2	-16.4	0.3	0.7	125.6	63.0
1-Day annual minimum flow [m^3/s]	3.5	31.5	788.4	0.8	0.5	-44.4	95.4
3-Day annual minimum flow [m3/s]	8.9	91.0	919.1	1.0	0.5	-43.5	95.4
5-Day annual minimum flow [m^3/s]	15.7	172.7	1002.7	0.9	0.5	-46.5	95.4
10-Day annual minimum flow [m^3/s]	41.0	402.7	882.2	1.0	0.5	-55.3	95.4
30-Day annual minimum flow [m^3/s]	199.1	1751.0	779.6	0.8	0.4	-50.4	100.0
Julian Date of 1-Day Annual Max [day]	76.6	83.3	8.8	0.2	0.2	-0.9	7.4
Julian Date of 1-Day Annual Min [day]	346.8	272.4	-21.4	0.1	0.2	305.0	61.8
No. of High Pulses [no.]	91.2	163.6	79.4	0.4	0.5	32.6	67.6
No. of Low Pulses [no.]	91.6	3.5	-96.1	0.5	4.6	791.6	95.4
Rise Rate [m^3/s]	130.3	116.9	-10.3	0.6	0.6	6.0	7.4
Fall Rate [m^3/s]	-80.5	-96.3	19.7	-0.5	-0.6	17.8	30.6
No. of Reversals [no.]	143.9	179.7	24.9	0.1	0.1	-18.2	86.1
Overall Degree of alteration							**68.5**

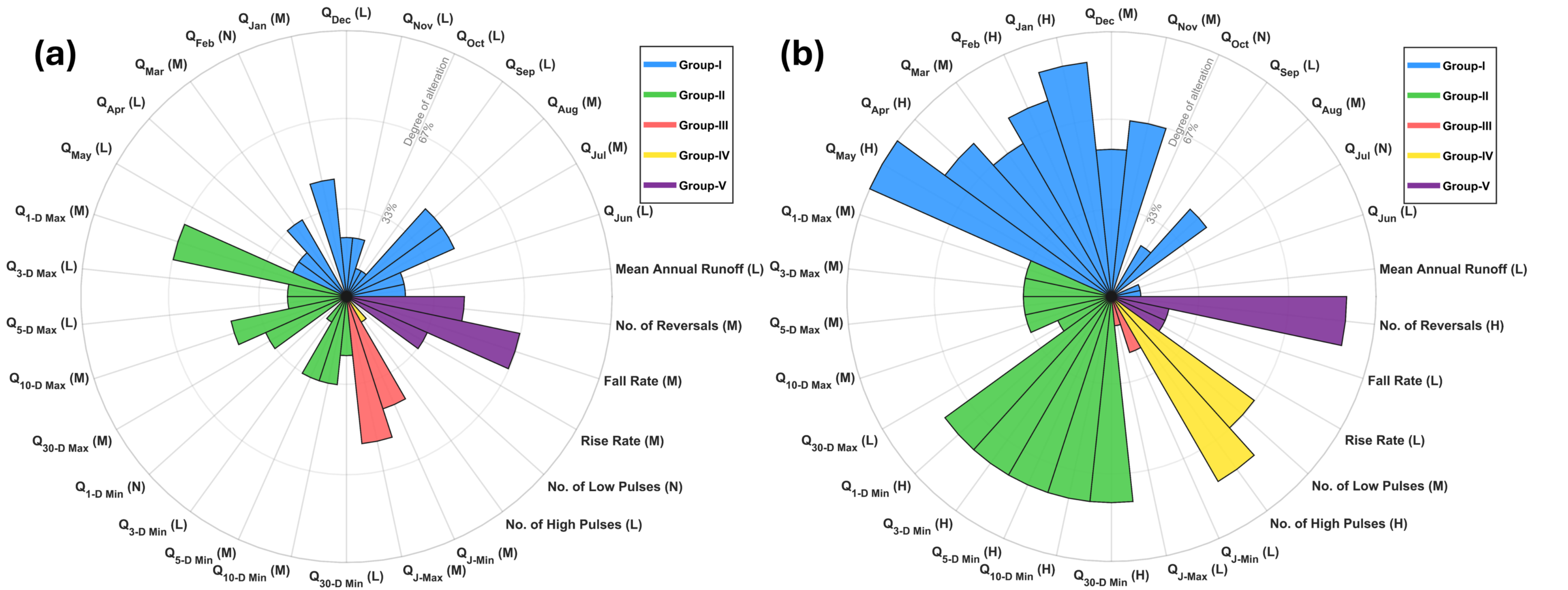

Figure 4.22 Degree of hydrological alteration at (a) upstream (Handia) and (b) downstream (Mandleshwar-Kogaon) of IS dam.

Table 4.2 Hydrologic alteration analysis results for downstream (Mandleshwar-Kogaon) of IS dam.

Hydrologic Indices [Unit]	Mean			Coefficient of Variation			Degree of hydrological alteration (%)
	Pre-dam	Post-dam	% Deviation	Pre-dam	Post-dam	% Deviation	
Mean Annual runoff [10^6 m3]	29771.5	30431.9	2.2	0.4	0.4	6.5	11.1
Mean June streamflow [m^3/s]	314.7	563.5	79.1	0.8	0.6	-30.8	11.1
Mean July streamflow [m^3/s]	1932.9	1075.6	-44.4	0.9	0.9	5.3	0.0
Mean August streamflow [m^3/s]	4187.5	2685.5	-35.9	0.5	1.0	82.2	44.4
Mean September streamflow [m^3/s]	2757.2	2563.8	-7.0	0.8	0.9	10.3	22.2
Mean October streamflow [m^3/s]	686.2	848.2	23.6	0.8	0.5	-38.5	0.0
Mean November streamflow [m^3/s]	298.3	582.2	95.2	0.4	0.4	-6.2	66.7
Mean December streamflow [m^3/s]	267.4	540.1	102.0	0.8	0.4	-49.4	55.6
Mean January streamflow [m^3/s]	205.6	559.6	172.2	0.5	0.4	-22.2	88.9
Mean February streamflow [m^3/s]	207.0	537.9	159.9	0.6	0.4	-33.8	77.8
Mean March streamflow [m^3/s]	166.0	515.7	210.7	0.5	0.5	0.2	66.7
Mean April streamflow [m^3/s]	125.0	548.8	338.9	0.6	0.5	-24.0	77.8
Mean May streamflow [m^3/s]	100.4	530.3	428.2	0.7	0.5	-33.5	100.0
1-Day annual maximum flow [m^3/s]	22111.3	16300.7	-26.3	0.5	0.9	89.8	33.3
3-Day annual maximum flow [m^3/s]	49522.4	35213.0	-28.9	0.5	0.9	85.6	33.3
5-Day annual maximum flow [m^3/s]	64864.7	47509.6	-26.8	0.5	0.8	75.7	33.3
10-Day annual maximum flow [m^3/s]	93614.2	68487.2	-26.8	0.5	0.8	61.3	33.3
30-Day annual maximum flow [m^3/s]	167497.1	122033.5	-27.1	0.4	0.7	65.0	22.2
1-Day annual minimum flow [m^3/s]	56.3	110.1	95.4	0.7	0.8	3.8	77.8
3-Day annual minimum flow [m3/s]	186.0	476.7	156.3	0.7	0.7	8.6	77.8
5-Day annual minimum flow [m^3/s]	336.8	969.3	187.8	0.7	0.7	1.0	77.8
10-Day annual minimum flow [m^3/s]	749.0	2394.6	219.7	0.7	0.6	-16.1	77.8
30-Day annual minimum flow [m^3/s]	2702.7	10180.9	276.7	0.6	0.4	-32.5	77.8
Julian Date of 1-Day Annual Max [day]	76.4	88.8	16.2	0.2	0.2	-6.8	11.1
Julian Date of 1-Day Annual Min [day]	333.7	269.2	-19.3	0.2	0.3	91.6	22.2
No. of High Pulses [no.]	91.3	177.6	94.6	0.3	0.4	26.5	80.6
No. of Low Pulses [no.]	91.3	18.7	-79.5	0.7	1.4	107.4	66.7
Rise Rate [m^3/s]	444.5	344.4	-22.5	0.5	0.6	11.7	22.2
Fall Rate [m^3/s]	-274.1	-316.1	15.3	-0.5	-0.6	16.5	22.2
No. of Reversals [no.]	143.9	198.2	37.8	0.2	0.1	-66.8	88.9
Overall Degree of alteration							**57.8**

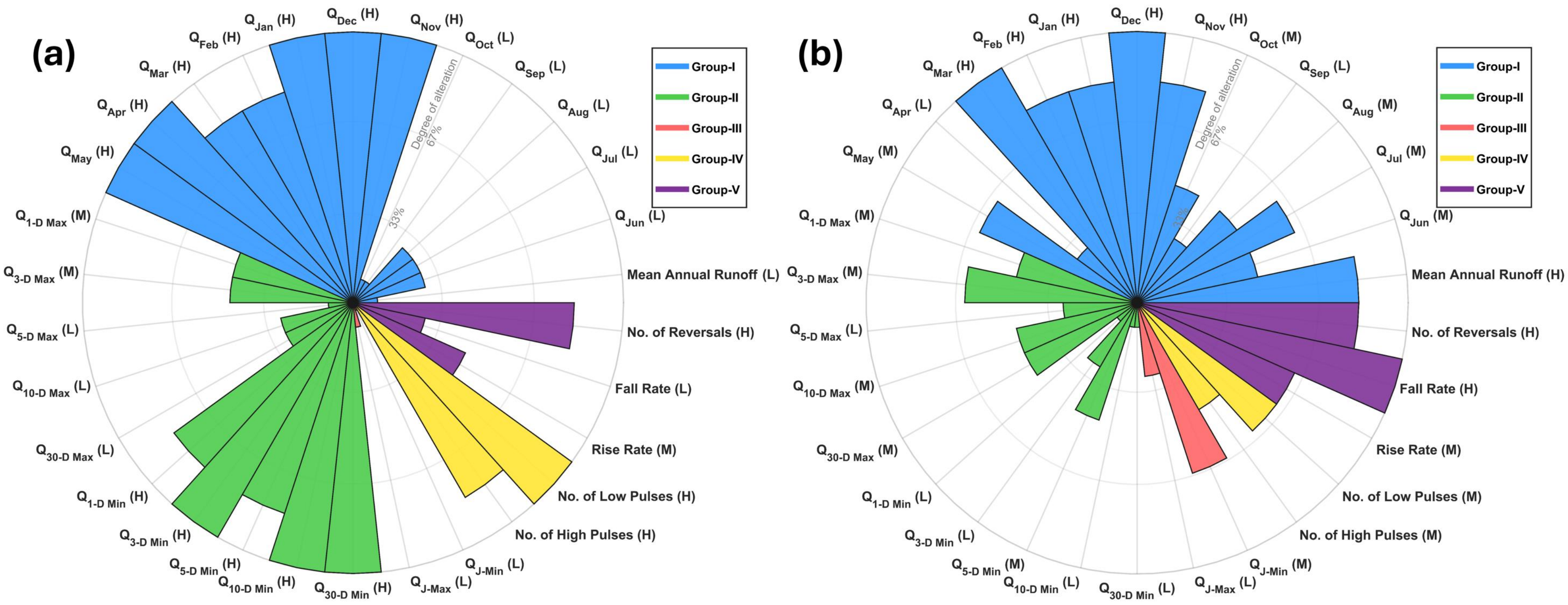

Figure 4.23 Degree of hydrological alteration at (a) upstream (Mandleshwar) and (b) downstream (Garudeshwar) of SS dam for the change point 1.

Table 4.3 Hydrologic alteration analysis results for downstream (Garudeshwar) of SS dam for the change point 1

Hydrologic Indices [Unit]	Mean			Coefficient of Variation			Degree of hydrological alteration (%)
	Pre-dam	Post-dam	% Deviation	Pre-dam	Post-dam	% Deviation	
Mean Annual runoff [10^6 m3]	30663.1	17708.9	-42.2	0.4	0.8	78.9	81.8
Mean June streamflow [m^3/s]	321.4	222.8	-30.7	0.8	0.9	14.3	45.5
Mean July streamflow [m^3/s]	1856.9	812.3	-56.3	0.9	1.4	63.1	63.6
Mean August streamflow [m^3/s]	4273.4	2657.7	-37.8	0.5	1.0	84.4	45.5
Mean September streamflow [m^3/s]	2991.0	1808.5	-39.5	0.7	0.7	-9.8	27.3
Mean October streamflow [m^3/s]	801.6	351.0	-56.2	0.7	0.9	20.4	45.5
Mean November streamflow [m^3/s]	321.7	177.3	-44.9	0.4	1.2	226.4	81.8
Mean December streamflow [m^3/s]	265.8	140.9	-47.0	0.7	1.4	85.4	100.0
Mean January streamflow [m^3/s]	200.5	143.3	-28.5	0.6	0.9	48.9	81.8
Mean February streamflow [m^3/s]	194.0	88.0	-54.6	0.6	1.2	100.0	81.8
Mean March streamflow [m^3/s]	139.5	117.2	-16.0	0.6	1.7	178.6	100.0
Mean April streamflow [m^3/s]	116.8	73.2	-37.4	0.8	0.6	-24.6	27.3
Mean May streamflow [m^3/s]	105.3	101.6	-3.6	0.8	0.7	-15.2	63.6
1-Day annual maximum flow [m^3/s]	22491.3	12989.7	-42.2	0.6	0.8	21.1	45.5
3-Day annual maximum flow [m^3/s]	48659.0	28533.0	-41.4	0.5	0.8	46.8	63.6
5-Day annual maximum flow [m^3/s]	64055.2	38259.2	-40.3	0.5	0.8	58.3	27.3
10-Day annual maximum flow [m^3/s]	94720.8	54645.3	-42.3	0.5	0.8	55.5	45.5
30-Day annual maximum flow [m^3/s]	173310.4	106307.7	-38.7	0.5	0.8	65.8	45.5
1-Day annual minimum flow [m^3/s]	46.2	16.4	-64.5	0.9	0.8	-13.1	9.1
3-Day annual minimum flow [m3/s]	150.0	72.1	-52.0	0.9	0.4	-53.3	27.3
5-Day annual minimum flow [m^3/s]	259.0	134.8	-48.0	0.9	0.4	-55.3	45.5
10-Day annual minimum flow [m^3/s]	564.0	288.9	-48.8	0.9	0.4	-57.6	9.1
30-Day annual minimum flow [m^3/s]	2252.5	1017.4	-54.8	0.8	0.4	-56.0	9.1
Julian Date of 1-Day Annual Max [day]	78.4	75.1	-4.2	0.2	0.3	52.7	27.3
Julian Date of 1-Day Annual Min [day]	324.9	241.0	-25.8	0.2	0.3	52.2	66.1
No. of High Pulses [no.]	91.3	65.2	-28.6	0.3	0.7	138.1	45.5
No. of Low Pulses [no.]	91.3	216.5	137.2	0.7	0.3	-50.2	63.6
Rise Rate [m^3/s]	448.1	213.4	-52.4	0.7	0.8	11.4	63.6
Fall Rate [m^3/s]	-245.4	-183.6	-25.2	-0.6	-0.9	49.7	100.0
No. of Reversals [no.]	139.8	190.0	35.9	0.2	0.1	-35.5	81.8
Overall Degree of alteration							**60.2**

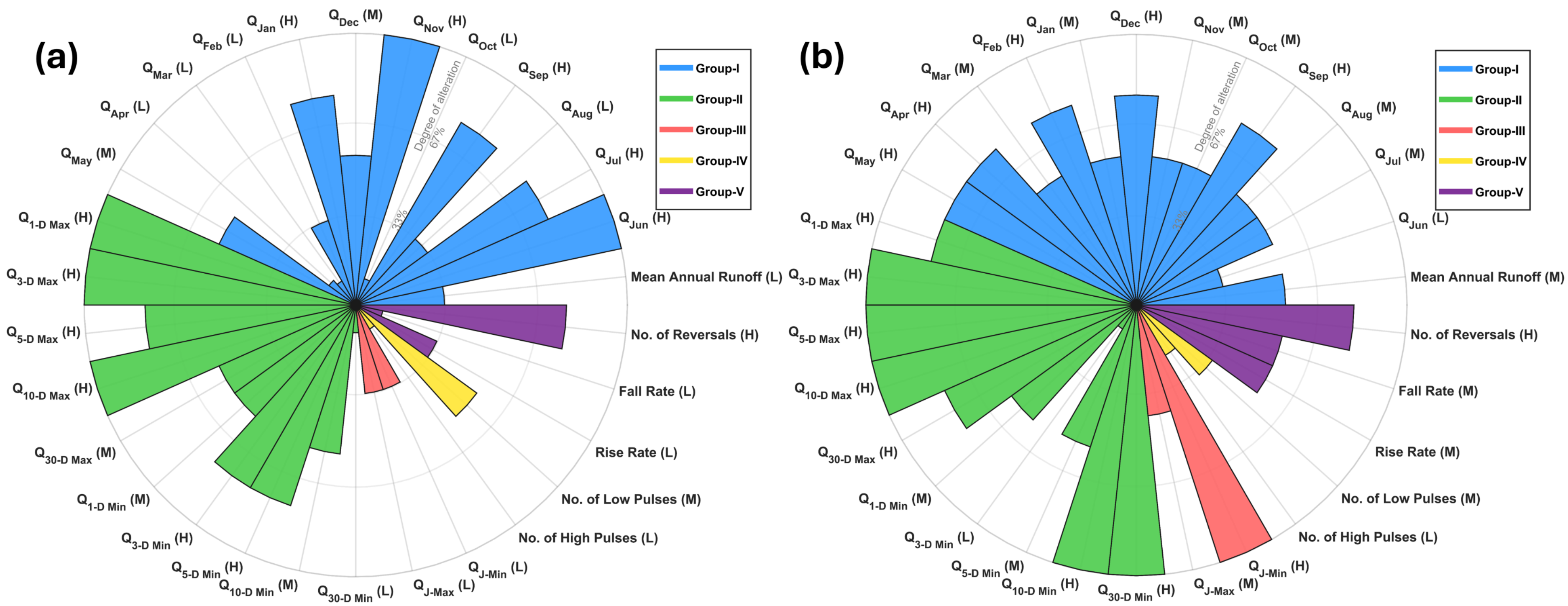

Figure 4.24 Degree of hydrological alteration at (a) upstream (Mandleshwar) and (b) downstream (Garudeshwar) of SS dam for the change point 2.

Table 4.4 Hydrologic alteration analysis results for downstream (Garudeshwar) of SS dam for the change point 2

Hydrologic Indices [Unit]	Mean			Coefficient of Variation			Degree of hydrological alteration (%)
	Pre-dam	Post-dam	% Deviation	Pre-dam	Post-dam	% Deviation	
Mean Annual runoff [10^6 m3]	8212.1	8708.1	6.0	0.52	0.50	-4.04	55.1
Mean June streamflow [m^3/s]	139.0	100.6	-27.6	0.71	0.42	-40.92	32.7
Mean July streamflow [m^3/s]	374.7	253.9	-32.2	0.78	0.45	-42.70	55.1
Mean August streamflow [m^3/s]	909.1	1109.9	22.1	0.99	0.68	-31.05	55.1
Mean September streamflow [m^3/s]	558.3	941.0	68.5	0.74	0.89	20.52	77.6
Mean October streamflow [m^3/s]	212.1	241.6	13.9	0.62	0.61	-1.92	55.1
Mean November streamflow [m^3/s]	147.3	103.7	-29.6	0.38	0.42	12.08	55.1
Mean December streamflow [m^3/s]	139.5	91.6	-34.4	0.41	0.34	-17.83	77.6
Mean January streamflow [m^3/s]	117.9	90.4	-23.4	0.36	0.19	-46.95	55.1
Mean February streamflow [m^3/s]	127.0	98.3	-22.6	0.30	0.41	35.09	77.6
Mean March streamflow [m^3/s]	123.1	79.4	-35.5	0.34	0.38	11.18	55.1
Mean April streamflow [m^3/s]	145.4	85.8	-41.0	0.35	0.55	54.63	77.6
Mean May streamflow [m^3/s]	116.9	104.4	-10.7	0.31	0.46	46.49	77.6
1-Day annual maximum flow [m^3/s]	4580.9	6991.8	52.6	0.77	0.72	-6.82	77.6
3-Day annual maximum flow [m^3/s]	9796.6	15165.1	54.8	0.82	0.69	-16.39	100.0
5-Day annual maximum flow [m^3/s]	13407.6	20103.2	49.9	0.97	0.64	-34.01	100.0
10-Day annual maximum flow [m^3/s]	18477.4	28342.4	53.4	0.91	0.60	-33.46	100.0
30-Day annual maximum flow [m^3/s]	32968.9	45215.5	37.1	0.81	0.62	-22.84	77.6
1-Day annual minimum flow [m^3/s]	32.6	32.1	-1.4	0.43	0.32	-26.76	57.1
3-Day annual minimum flow [m3/s]	104.4	100.7	-3.5	0.49	0.36	-26.30	10.2
5-Day annual minimum flow [m^3/s]	204.2	180.4	-11.7	0.44	0.35	-20.56	55.1
10-Day annual minimum flow [m^3/s]	482.1	408.7	-15.2	0.44	0.36	-16.50	100.0
30-Day annual minimum flow [m^3/s]	2012.8	1471.9	-26.9	0.35	0.33	-6.28	100.0
Julian Date of 1-Day Annual Max [day]	82.5	84.9	2.9	0.20	0.25	26.72	41.1
Julian Date of 1-Day Annual Min [day]	280.8	227.9	-18.9	0.23	0.22	-3.06	100.0
No. of High Pulses [no.]	147.7	102.0	-31.0	0.49	0.48	-2.46	21.4
No. of Low Pulses [no.]	0.6	0.3	-55.1	2.83	1.71	-39.76	34.7
Rise Rate [m^3/s]	93.0	112.4	20.8	0.61	0.67	11.07	55.1
Fall Rate [m^3/s]	-78.6	-92.5	17.7	-0.57	-0.65	12.55	55.1
No. of Reversals [no.]	182.6	178.4	-2.3	0.08	0.05	-35.11	80.4
Overall Degree of alteration							**69.9**

4.5 Closure

This chapter has presented a detailed analysis of the hydrological impacts of the RABS, IS, and SS dams, focusing on streamflow changes, inter-annual variability, and alterations in hydrological regimes across upstream and downstream stations during the pre- and post-dam periods. The findings offer critical insights into the extent of transformation within the Narmada River basin brought about by dam construction. Building upon these results, the next chapter will synthesize the key takeaways from this comprehensive analysis, drawing meaningful conclusions that highlight the broader implications for river basin management and sustainable water resource planning.

CHAPTER – 5

CONCLUSION AND FUTURE SCOPE

5.1 Key Conclusions

The key conclusions drawn from the study are as:

(i) The range of variability analysis reveals significant hydrological alterations due to the RABS dam, with downstream catchments (Barmanghat–Patan–Belkhedi) experiencing greater changes than upstream (Manot + Mohgaon), especially in intra-annual and annual streamflow variability.

(ii) The post-dam period (1988–2023) for RABS shows increased winter and spring flows, notably a substantial rise in December mean flows and a decline in August, disrupting seasonal flow patterns and reducing extreme flow events. A significant increase in short- and long-duration minimum flows at Barmanghat reflects a major alteration in lean-period flows, contributing to a high alteration rate (~68.5 %) downstream of RABS.

(iii) Indira Sagar dam's post-dam impact (2006–2023) includes a dramatic rise in May mean flows (~428%) and a sharp decrease in July mean flows (~44%), indicating a strong shift in seasonal hydrological dynamics downstream at Mandleshwar. Post-dam period shows pronounced increases in short- and long-duration minimum flows and greater frequency of flow reversals, resulting in a moderate overall alteration (~58%) but significant downstream impact of Indira Sagar dam.

(iv) The effect of Indira Sagar at Mandaleshwar results in significant hydrologic alteration, particularly in low-flow months (November to May), and high alterations in Group II and Group IV parameters.

(v) Garudeshwar, downstream of the Sardar Sarovar (SS) dam, shows less overall alteration but exhibits high changes in Group I (monthly flows from November to March) and Group IV parameters, reflecting active regulation of dry-season discharges. The increase in SS dam height in 2017 led to downstream-dominant alterations. Garudeshwar exhibits high variability and flow reversals across Group I, II, and III parameters, while Mandleshwar shows moderate alteration due to residual upstream regulation and possible backwater effects.

(vi) The overall degree of hydrological alteration induced by the Sardar Sarovar dam at the downstream station, Garudeshwar, is classified as moderate alteration (~60%) for the 2006 change point and increases to a high alteration (~70%) following the 2017, highlighting a substantial intensification in flow regulation over time. Overall, it is noticed that the RABS dam does not exert any cascading effect on the IS dam, while the IS dam has a significant cascading influence on the SS dam.

5.2 Future Scope

Building upon the findings of this study, future research directions can be pursued along two key dimensions. First, although this work offers a robust quantitative assessment of hydrological alterations due to dam operations, it is imperative to complement it with qualitative analyses to capture the full scope of downstream ecological impacts. Specifically, the use of indices of ecological alteration (IEA)—derived from sediment and nutrient data across pre- and post-dam periods—can provide critical insights into the extent to which ecological functions are preserved or disrupted. While regulated flow releases may appear to enhance minimum flows, dams often trap sediments and associated nutrients, potentially leading to ecological deficits downstream. Evaluating IEA would thus enable a more integrated understanding of whether these modified flow regimes sustain essential nutrient transport and ecological health, particularly in a complex and sensitive system like the Narmada River Basin.

Second, while altered flow regimes are evident post-dam construction, it is imperative to account for the influence of climate change in shaping river hydrology. Climate-driven phenomena such as increased variability in precipitation, more frequent extreme rainfall events, prolonged droughts, and temperature fluctuations further complicate the hydrological dynamics. Hence, attributing observed alterations solely to anthropogenic interventions like dam construction may lead to misleading conclusions. Future research must focus on disentangling human-induced impacts from natural climate variability, through comparative and attribution-based modelling approaches, to quantify the relative contribution of each. Such differentiation is critical for accurately assessing the long-term impacts of dams and for informing sustainable water resource and reservoir management strategies under changing climatic conditions.

REFERENCES

Batalla, R. J., Gomez, C. M., and Kondolf, G. M. (2004). Reservoir induced hydrological changes in the Ebro River basin (NE Spain). *Journal of Hydrology*, 290(1), 117–136.

Bhattacharya, B., and Loganathan, M. (1989). Social forces pervading Narmada Valley Development Project. *Journal of Rural Development (Hyderabad)*, 8(5), 485-496.

Chitale, M. A. (1997). The Narmada Project. *International Journal of Water Resources Development*, 13(2), 169-180.

Fenkes, M., Shiels, H. A., Fitzpatrick, J. L., and Nudds, R. L. (2016). The potential impacts of migratory difficulty, including warmer waters and altered flow conditions, on the reproductive success of salmonid fishes. *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology*, 193, 11-21.

Gain, A. K., and Giupponi, C. (2014). Impact of the Farakka Dam on thresholds of the hydrologic flow regime in the Lower Ganges River Basin (Bangladesh). *Water*, 6(8), 2501–2518.

Gopikrishna, B. S., and Mohapatra, P. K. (2022). Effect of Indira Sagar dam on the health assessment of Narmada river. In *Groundwater and Water Quality: Hydraulics, Water Resources and Coastal Engineering* (pp. 105-118).

Graf, W. L. (2006). Downstream hydrologic and geomorphic effects of large dams on American rivers. *Geomorphology*, 79(3–4), 336–360.

Guo, W., Jiao, X., Zhou, H., Zhu, Y., and Wang, H. (2022). Hydrologic regime alteration and influence factors in the Jialing River of the Yangtze River, China. *Scientific Reports*, *12*(1), 11166.

Gupta, H., and Chakrapani, G. J. (2005). Temporal and spatial variations in water flow and sediment load in Narmada River Basin, India: natural and man-made factors. *Environmental Geology*, *48*, 579-589.

Gupta, R. K. (2001). River Basin Management: A Case Study of Narmada Valley Development with Special Reference to the Sardar Sarovar Project in Gujarat, India. *International Journal of Water Resources Development*, *17*(1), 55–78.

Huang, F., Chen, Q., Li, F., Zhang, X., Chen, Y., Xia, Z., and Qiu, L. (2015). Reservoir-induced changes in flow fluctuations at monthly and hourly scales: Case study of the Qingyi River, China. *Journal of Hydrology*, 20(12), 05015008.

Huang, F., Xia, Z., Li, F., Guo, L., and Yang, F. (2012). Hydrological changes of the Irtysh River and the possible causes. *Water Resource Management*, 26(11), 3195–3208.

Javaid, S., Bhat, W. A., Ahmed, R., Rather, A. F., Ahmad, S. T., and Ahmed, P. (2023). Assessing changing flow regime of upper and middle reaches of Narmada river using the indicators of hydrological alterations (IHA) metrics. *ISH Journal of Hydraulic Engineering*, 29(sup1), 315-324.

Lehner, B., Liermann, C. R., Revenga, C., Vörösmarty, C., Fekete, B., Crouzet, P., Döll, P., Endejan, M., Frenken, K., Magome, J., Nilsson, C., Robertson, J. C., Rödel, R., Sindorf, N., and Wisser, D. (2011). High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. *Frontiers in Ecology and the Environment*, *9*(9), 494-502.

Lu, X., Zhuang, Y., Wang, X., and Yang, Q. (2018). Assessment of streamflow change in middle-lower reaches of the Hanjiang River. *Journal of Hydrology*, 23(12), 05018024.

Magilligan, F. J., and Nislow, K. H. (2005). Changes in hydrologic regime by dams. *Geomorphology*, 71(1), 61–78.

Mahanta, C. (2006). Water resources of the Northeast: state of the knowledge base. Background Paper No. 2, 1-25.

Maheu, A., St-Hilaire, A., Caissie, D., and El-Jabi, N. (2016). Understanding the thermal regime of rivers influenced by small and medium size dams in Eastern Canada. *River Research and Applications*, 32(10), 2032–2044.

Mangukiya, N. K., Kumar, K. B., Dey, P., Sharma, S., Bejagam, V., Mujumdar, P. P., and Sharma, A. (2025). CAMELS-IND: hydrometeorological time series and catchment attributes for 228 catchments in Peninsular India. *Earth System Science Data*, 17, 461–491.

Mangukiya, N. K., Mehta, D. J., and Jariwala, R. (2022). Flood frequency analysis and inundation mapping for lower Narmada basin, India. *Water Practice & Technology*, 17(2), 612-622.

Marcinkowski, P., and Grygoruk, M. (2017). Long-term downstream effects of a dam on a lowland river flow regime: Case study of the Upper Narew. *Water*, 9(10), 783.

Mohanty, M., and Tare, V. (2024). Hydromorphological shifts in the Yamuna River: Post-barrage impacts and water management implications. *Water Supply*, 24(6), 2143-2157.

Mondal, S., and Patel, P. P. (2022). Incorporating hydromorphological assessments in the fluvial geomorphology domain for transitioning towards restorative river science—context, concepts and criteria. In *Fluvial Systems in the Anthropocene: Process, response and modelling*, 43-75.

NHDC 2024. Reservoir Regulation Manual – Flood Regulation of ISPS. NHDC Limited, Bhopal.

Pandey, V., Patel, V. J., Vadodaria, R. P., Patel, H. R., and Shekh, A. M. (2008). Irrigation water requirement and production potentials of major crops over Narmada canal command area in Gujarat. *J Agrometeorol*, *10*, 320-41.

Pathak, S. D., Kulshrestha, M., and Kulshreshtha, M. (2021). Flood vulnerability assessment using data envelopment analysis–the case of Narmada river basin districts in central India. *Water Policy*, 23(5), 1089-1106.

Polo, M. J., Rovira, A., García-Contreras, D., Contreras, E., Millares, A., Aguilar, C., and Losada, M. A. (2016). Reservoir impacts downstream in highly regulated river basins: The Ebro delta and the Guadalquivir estuary in Spain. *Proceedings of the International Association of Hydrological Sciences*, 373, 45–49.

Prajapati, P., Meena, G. K., Swarnkar, S., and Jha, S. K. (2025). Impact of Indira Sagar Dam on Water Discharge and Sediment Flow Regimes of the Narmada Basin. *Journal of Hydrologic Engineering*, 30(2), 05025002.

Pyron, M., and Neumann, K. (2008). Hydrologic alterations in the Wabash River watershed, USA. *River Research and Applications*, 24(8), 1175–1184.

Richter, B. D., Baumgartner, J. V., Braun, D. P., and Powell, J. (1998). A spatial assessment of hydrologic alteration within a river network. *Regulated Rivers: Research and Management*, 14(4), 329–340.

Richter, B. D., Baumgartner, J. V., Wigington, R., and Braun, D. P. (1997). How much water does a river need?. *Freshwater Biology*, 37(1), 231–249.

Routledge, P. (2003). Voices of the dammed: discursive resistance amidst erasure in the Narmada Valley, India. Political Geography, 22(3), 243-270.

Ruhi, A., Hwang, J., Devineni, N., Mukhopadhyay, S., Kumar, H., Comte, L., Worland, S., and Sankarasubramanian, A. (2022). How does flow alteration propagate across a large, highly regulated basin? Dam attributes, network context, and implications for biodiversity. *Earth's Future*, 10(6), e2021EF002490.

Sharma, P. J., Patel, P. L., and Jothiprakash, V. (2019). Impact assessment of Hathnur reservoir on hydrological regimes of Tapi River, India. *ISH Journal of Hydraulic Engineering*, 27(sup1), 433–445.

Variam, G. M. P. (2024). Assessment of temporal flow variations due to dam operation–A case study of Bargi dam, Jabalpur district, India. *Current World Environment*, *19*(3), 1559.

Vengadesan, P., Sannasiraj, S. A., and Bhallamudi, S. M. (2025). Impact of a Dam on the Shoreline Evolution in the Downstream Estuarine Region Using a Comprehensive Hybrid Framework. *Estuaries and Coasts*, *48*(3), 69.

Xue, L., Zhang, H., Yang, C., Zhang, L., and Sun, C. (2017). Quantitative assessment of hydrological alteration caused by irrigation projects in the Tarim River basin, China. *Scientific Reports*, 7, 4291.

Yang, Y., Zhang, M., Zhu, L., Liu, W., Han, J., and Yang, Y. (2017). Influence of large reservoir operation on water levels and flows in reaches below dam: Case study of the Three Gorges Reservoir. *Scientific Reports*, 7(1), 15640.

Zhang, Z., Huang, Y., and Huang, J. (2016). Hydrologic alteration associated with dam construction in a medium-sized coastal watershed of southeast China. *Water*, 8(8), 317.

Zhao, Q., Liu, S., Deng, L., Dong, S., Yang, J., and Wang, C. (2012). The effects of dam construction and precipitation variability on hydrologic alteration in the Lancang River Basin of southwest China. *Stochastic Environmental Research and Risk Assessment*, *26*, 993-1011.

Zheng, Y., Zhang, G., Wu, Y., Xu, Y. J., and Dai, C. (2019). Dam effects on downstream riparian wetlands: the Nenjiang River, Northeast China. *Water*, *11*(10), 2038.