



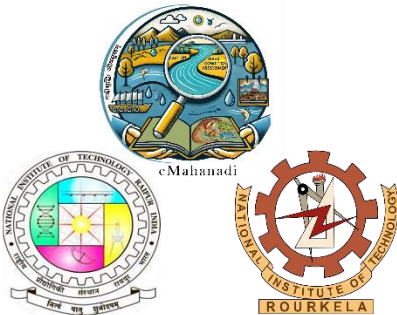
**National River Conservation Directorate**  
Ministry of Jal Shakti,  
Department of Water Resources,  
River Development & Ganga Rejuvenation  
Government of India

सत्यमेव जयते

# Climate Change Assessment Mahanadi River Basin



December 2025



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

## Disclaimer

This report is a preliminary version prepared as part of the ongoing Condition Assessment and Management Plan (CAMP) project. The analyses, interpretations and data presented in the report are subject to further validation and revision. Certain datasets or assessments may contain provisional or incomplete information, which will be updated and refined in the final version of the report after comprehensive review and verification.

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## Preface

In an era of unprecedented environmental change, understanding our rivers and their ecosystems has never been more critical. This report aims to provide a comprehensive overview of our rivers, highlighting their importance, current health, and the challenges they face. As we explore the various facets of river systems, we aim to equip readers with the knowledge necessary to appreciate and protect these vital waterways.

Throughout the following pages, you will find an in-depth analysis of the principles and practices that support healthy river ecosystems. Our team of experts has meticulously compiled data, case studies, and testimonials to illustrate the significant impact of rivers on both natural environments and human communities. By sharing these insights, we hope to inspire and empower our readers to engage in river conservation efforts.

This report is not merely a collection of statistics and theories; it is a call to action. We urge all stakeholders to recognize the value of our rivers and to take proactive steps to ensure their preservation. Whether you are an environmental professional, a policy maker, or simply someone who cares about our planet, this guide is designed to support you in your efforts to protect our rivers.

We extend our heartfelt gratitude to the numerous contributors who have generously shared their stories and expertise. Their invaluable input has enriched this report, making it a beacon of knowledge and a practical resource for all who read it. We hope that this report will catalyze positive environmental action, fostering a culture of stewardship that benefits both current and future generations.

As you delve into this overview of our rivers, we invite you to embrace the opportunities and challenges that lie ahead. Together, we can ensure that our rivers continue to thrive and sustain life for generations to come.

Centre for Mahanadi River Basin  
Management Studies (cMahanadi)  
NIT Raipur & NIT Rourkela

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## Abbreviations

cMahanadi	Centre for Mahanadi River Basin Management and Studies
cGanga	Centre for Ganga River Basin Management and Studies
CWC	Central Water Commission
CV	Coefficient of Variation
DoWR	Department of Water Resources
EC-Earth3	Earth System Model (EC-Earth Version 3)
GRBMP	Ganga River Basin Management Plan
IIT	Indian Institute of Technology
IPCC	Intergovernmental Panel on Climate Change
JJAS	June–July–August–September (Southwest Monsoon Season)
MCM	Million Cubic Metres
MRB	Mahanadi River Basin
MoWR	Ministry of Water Resources
NIT	National Institute of Technology
NMCG	National Mission for Clean Ganga
NRCD	National River Conservation Directorate
NRCP	National River Conservation Plan
OND	October–November–December (Non-Monsoon Season)
SD	Standard Deviation
SWM	Surface Water Management
WRIS	Water Resources Information System

## Executive Summary

Climate change is increasingly reshaping hydrological systems, agricultural productivity, and water security across river basins in India. Recognizing these growing challenges, the present Climate Change Assessment for the Mahanadi River Basin has been developed to provide a comprehensive, evidence-based understanding of evolving climatic patterns and their implications for water resources, ecosystems, and socio-economic sustainability. The report serves as a strategic knowledge base to support informed decision-making, long-term planning, and climate-resilient development within the basin.

The primary purpose of this assessment is to evaluate historical climatic trends, assess present vulnerabilities, and project future climate-driven changes in water availability across the Mahanadi River Basin. By integrating observed data, trend analysis, and future climate projections, the report aims to identify emerging risks and opportunities for adaptive water management. The study adopts a basin-wide perspective while maintaining district-level resolution, ensuring that regional heterogeneity and localized challenges are adequately captured.

A key finding of the report is the strong dependence of the basin on a narrow monsoon window. Rainfall analysis reveals that a substantial proportion of annual precipitation is concentrated within the southwest monsoon months, making the basin highly sensitive to shifts in monsoon timing, intensity, and variability. While overall long-term rainfall trends remain statistically stable across much of the basin, several districts exhibit significant upward or downward tendencies, indicating increasing spatial unevenness in rainfall distribution. This emerging variability poses risks to rain-fed agriculture, groundwater recharge, and surface water storage reliability. However, temperature analysis highlights a consistent warming trend across the basin, with increases in both maximum and minimum temperatures. The rise in maximum temperatures is more pronounced, suggesting intensifying heat stress, longer dry spells, and elevated evapotranspiration losses. These changes directly affect crop water requirements, reservoir evaporation, and soil moisture retention, thereby compounding existing water stress during non-monsoon periods. The report underscores that warming trends, even in the absence of large rainfall declines, can significantly alter basin-scale water balances.

Future climate projections indicate a general wetting tendency across the basin, particularly toward the mid- and far-future periods. However, this increase in projected precipitation is not uniform. Several interior and upstream districts are expected to experience substantial rises in rainfall, potentially increasing flood risks, sediment loads, and pressure on reservoir safety. In contrast, some coastal and deltaic districts display non-linear patterns, with near-term declines followed by long-term increases, suggesting possible shifts in monsoon dynamics and intra-seasonal variability. These findings emphasize that future climate impacts will be complex and spatially differentiated rather than uniformly beneficial.

Groundwater assessment reveals that, at the basin scale, aquifer conditions remain broadly within safe limits; however, district-level analysis identifies emerging stress hotspots. Intensive agricultural practices, expanding irrigation demand, and industrial withdrawals are driving

localized over-extraction, particularly in districts with limited recharge buffers. The report highlights that rainfall-dependent recharge and seasonal abstraction patterns increase vulnerability to climate variability, especially under projected temperature rise and changing rainfall characteristics. Coastal districts, while benefiting from high recharge, face quality constraints such as salinity intrusion, reducing effective groundwater availability.

The report also evaluates existing water management policies and institutional arrangements, identifying gaps between policy intent and on-ground implementation. Current strategies have historically prioritized supply-side interventions, such as expanding irrigation infrastructure, while demand-side measures and economic instruments remain underutilized. Overlapping institutional roles, fragmented governance structures, and limited technical capacity at local levels further constrain effective climate-responsive water management. These institutional challenges are likely to intensify under future climate stress if not addressed proactively. One of the most significant contributions of this assessment lies in its forward-looking recommendations. The report emphasizes the urgent need for climate-resilient water infrastructure, improved reservoir operation strategies, and district-specific adaptation planning. It advocates for the integration of long-term climate projections into agricultural planning, irrigation scheduling, groundwater regulation, and flood management frameworks. Technological innovations, including data-driven monitoring systems and decision-support tools, are identified as critical enablers of adaptive governance.

Capacity building and stakeholder engagement emerge as central themes throughout the report. Strengthening the technical and institutional capabilities of local bodies, water user associations, and grassroots institutions is essential for translating scientific insights into effective action. Public awareness and participatory governance are highlighted as key mechanisms for fostering shared responsibility, improving compliance, and enhancing resilience at the community level. Therefore, this report provides a scientifically robust and policy-relevant evaluation of climatic risks and water resource challenges in the Mahanadi River Basin. The findings underscore that climate change impacts are already visible and are likely to intensify in the coming decades, affecting water availability, agricultural stability, and ecosystem health. By combining empirical analysis with strategic recommendations, the report offers a practical roadmap for climate-informed water management. Its importance lies not only in diagnosing current and future challenges but also in guiding adaptive actions that can safeguard water security, livelihoods, and environmental sustainability for present and future generations.

## **1. Introduction**

Climate change has become one of the most significant drivers of environmental transformation, with far-reaching implications for water resources, agriculture, ecosystems, and socio-economic stability. Rising global temperatures, altered precipitation regimes, and increasing frequency of extreme climatic events are reshaping hydrological cycles and intensifying pressures on river basins worldwide. In monsoon-dominated regions such as India, these changes are particularly consequential, as rainfall variability directly governs surface water availability, groundwater recharge, agricultural productivity, and flood-drought dynamics.

Understanding climate-induced changes at the river basin scale is therefore critical for sustainable water resource planning and long-term development.

River basins function as integrated socio-hydrological systems, where climatic processes interact with land use, population growth, infrastructure development, and governance structures. Climate change alters not only the magnitude of precipitation and temperature but also their temporal distribution, seasonality, and spatial coherence. These changes can disrupt long-established hydrological patterns, affecting river flows, soil moisture, evapotranspiration, and groundwater systems. In large basins supporting diverse livelihoods, such disruptions may translate into heightened water insecurity, agricultural stress, ecological degradation, and increased disaster risk (Central Water Commission [CWC], 2013).

The Mahanadi River Basin represents one of the most important and complex river systems in eastern and central India. Spanning multiple agro-climatic zones across Chhattisgarh and Odisha, the basin supports extensive agricultural activity, industrial development, hydropower generation, and urban water supply. Historically, the basin has been characterized by high monsoonal rainfall, fertile alluvial plains, and substantial surface water storage infrastructure. However, these advantages are increasingly offset by growing water demand, land-use change, and emerging climate variability, placing the basin under mounting stress (Ministry of Water Resources, 2014).

Recent climatic assessments indicate a clear warming trend across the Mahanadi Basin, with increases observed in both maximum and minimum temperatures. Rising temperatures have implications for evapotranspiration rates, crop water demand, and soil moisture dynamics, while also intensifying heat stress across urban and agricultural landscapes. Temperature increases are not spatially uniform; interior plains and industrial corridors tend to experience stronger warming than forested or coastal regions. Such spatial heterogeneity complicates basin-scale planning and underscores the need for region-specific climate adaptation strategies (Directorate of Economics and Statistics, Government of Chhattisgarh, 2015).

Changes in precipitation patterns present an equally complex challenge. While total annual rainfall in parts of the basin may show modest increases, rainfall distribution has become increasingly uneven, with higher inter-annual and intra-seasonal variability. Concentration of rainfall within shorter periods elevates flood risks during the monsoon while reducing effective water availability during non-monsoon months. Conversely, prolonged dry spells and delayed monsoon onset heighten drought vulnerability, particularly in rain-dependent agricultural areas. Such variability erodes the reliability of traditional water management practices that are based on historical rainfall norms (CWC, 2012).

The hydrological consequences of these climatic shifts are already evident in altered runoff generation, groundwater recharge patterns, and streamflow regimes. Studies within the basin indicate that increased rainfall does not necessarily translate into proportional increases in surface runoff, as enhanced infiltration and reduced evapotranspiration can modify surface-subsurface water exchanges. In some districts, declining runoff and baseflow threaten dry-season water availability, while in others, intensified rainfall raises concerns regarding reservoir

safety and downstream flooding (Department of Water Resources, Government of Odisha, 2015).

Groundwater systems, which serve as a critical buffer against climate variability, are also under increasing strain. Expanding irrigation, urban demand, and industrial withdrawals have accelerated groundwater extraction in several parts of the basin. Climate change further complicates groundwater sustainability by influencing recharge processes through changes in rainfall intensity, soil moisture retention, and evapotranspiration. District-level assessments reveal widening disparities in groundwater availability, with some regions approaching semi-critical extraction thresholds while others remain relatively resilient. These emerging imbalances highlight the urgency of integrating climate projections into groundwater governance frameworks (Kumar, 2007).

Agriculture remains the dominant water-using sector within the Mahanadi Basin, providing livelihoods for a large proportion of the population. Rainfed rice cultivation occupies a substantial share of the cropped area, making agricultural productivity highly sensitive to rainfall timing and variability. Even in irrigated zones, climate-induced changes in water availability, temperature regimes, and evapotranspiration can significantly affect crop yields and water use efficiency. Rising temperatures during critical growth stages, combined with uncertain water supply, increase production risks and threaten food security at both regional and national scales (Directorate of Economics and Statistics, Government of Chhattisgarh, 2015).

Climate change also amplifies the frequency and severity of hydro-climatic extremes, including floods and droughts. Flooding in the Mahanadi delta has historically caused extensive damage to crop, infrastructure, and settlements, and climate projections suggest that extreme rainfall events may become more intense in the future. At the same time, droughts though less frequent pose serious risks in interior districts where rainfall variability is high and irrigation coverage remains uneven. The coexistence of floods and droughts within the same basin reflects the paradox of water abundance and scarcity under changing climatic conditions (Department of Water Resources, Government of Odisha, 2014).

Beyond physical impacts, climate change interacts with socio-economic drivers such as population growth, urbanization, and industrial expansion to intensify water stress. Rising domestic and industrial water demand places additional pressure on surface reservoirs and river systems, often at the expense of ecological flows and rural water security. Current allocation and pricing mechanisms frequently fail to reflect the true scarcity value of water, leading to inefficient use and sectoral imbalances. Climate change further exposes these governance shortcomings by reducing the margin of error available for water management decisions (Kumar, 2000).

In this context, basin-scale climate change assessments play a critical role in informing policy and planning. By combining long-term observational data with climate projections and hydrological modeling, such assessments provide insights into future water availability, sectoral demand, and vulnerability hotspots. They enable decision-makers to evaluate trade-offs, design

adaptive infrastructure, and prioritize interventions that enhance resilience under uncertain climatic futures. Importantly, basin-level analysis allows for the recognition of upstream–downstream linkages, ensuring that adaptation strategies do not shift risks across regions or sectors.

The present assessment of climate change impacts in the Mahanadi River Basin seeks to address these challenges by systematically evaluating trends in temperature, rainfall, hydrology, and water demand across Chhattisgarh and Odisha. By integrating climatic analysis with water balance assessments and sectoral demand projections, the study provides a comprehensive understanding of how climate change may reshape water security in the basin over the coming decades. Such evidence is essential for transitioning from reactive responses to proactive, climate-resilient water governance. Hence, climate change is redefining the hydrological and socio-economic landscape of the Mahanadi River Basin. Rising temperatures, increasing rainfall variability, and intensifying extremes pose interconnected risks to agriculture, water supply, ecosystems, and livelihoods. Addressing these challenges requires a holistic, basin-scale perspective that recognizes climatic uncertainty, spatial heterogeneity, and institutional complexity. The insights generated through climate change assessments form a critical foundation for sustainable river basin management and long-term resilience in the face of a changing climate.

## **2. Water Resource Availability and Climatic Variability**

### **2.1 Trends in Rainfall and Temperature Patterns**

#### **2.1.1 Annual and Seasonal Rainfall for Chhattisgarh**

Chhattisgarh is naturally endowed with favorable climatic conditions compared to many of its neighboring states, particularly in terms of temperature, humidity, and rainfall distribution. The state receives an average annual rainfall of around 1190 mm, with nearly 88% of the total precipitation occurring during the southwest monsoon season (mid-June to September). Located within the rice-dominant agro-climatic zone of the Mahanadi River Basin, rainfall serves as the primary source of irrigation for agriculture. However, fluctuations in both seasonal and annual rainfall substantially influence crop yields, particularly in rainfed areas. Rainfall analyses have therefore been conducted using the most reliable datasets available to understand these variations.

The mean annual and seasonal rainfall patterns across the 22 districts of the Chhattisgarh region within the Mahanadi River Basin reveal notable spatial variability. The overall mean annual rainfall of the state is 1190 mm with a coefficient of variation (CV) of 26%, signifying moderate variability. Among the three major agro-climatic zones, the Bastar Plateau zone records the highest average annual rainfall ( $\approx 1348$  mm), followed by the Northern Hills zone ( $\approx 1253$  mm), while the Chhattisgarh Plains receive comparatively lower rainfall ( $\approx 1127$  mm). These regional differences highlight the uneven rainfall distribution even within the same river basin system.

Rainfall variability poses a key challenge for agricultural stability in the basin area. High inter-annual variability indicates significant rainfall uncertainty, leading to potential risks in rainfed rice cultivation. Such variability underscores the vulnerability of local farming systems to monsoon fluctuations, resulting in inconsistent crop yields and water stress during critical growth periods. The southwest monsoon season exhibits the greatest rainfall concentration, while the northeast monsoon contributes a smaller yet more variable portion across districts.

Further examination of seasonal patterns reveals that certain parts of the basin experience greater fluctuations during the southwest monsoon, while others show high inconsistency during the northeast monsoon, particularly in the eastern and central regions. Across the three agro-climatic zones, monsoon rainfall accounts for nearly 88% of the total annual precipitation, confirming its dominant role in the hydrological cycle. The Chhattisgarh Plains show a relatively higher contribution from the northeast monsoon, whereas winter rainfall remains uniformly distributed across all zones.

### **2.1.2 Annual and Seasonal Rainfall for Odisha**

The Odisha part of the Mahanadi River Basin is characterized by a humid tropical climate with pronounced monsoonal influence, making it one of the most hydrologically significant regions in eastern India. The basin experiences warm temperatures, high humidity, and a well-defined rainfall regime dominated by the southwest monsoon. The average annual rainfall over the Odisha Mahanadi basin ranges between approximately 1400 and 1600 mm, substantially higher than the upstream Chhattisgarh region, owing to its proximity to the Bay of Bengal and frequent monsoon depressions. Nearly 85–90% of the annual rainfall occurs during the southwest monsoon season (June to September), which governs surface water availability, groundwater recharge, and agricultural productivity across the basin.

Rainfall serves as the primary source of water for agriculture in the Odisha Mahanadi basin, particularly for paddy cultivation, which dominates the deltaic and coastal plains. Despite relatively high total rainfall, the basin remains highly vulnerable to rainfall variability and temporal concentration. Seasonal and inter-annual fluctuations in monsoon rainfall exert strong control over crop yields, flood occurrence, and drought frequency, especially in rainfed and tail-end command areas. Consequently, rainfall analyses based on long-term, high-quality observational datasets are essential to understand spatial and temporal variability within the basin.

Analysis of mean annual and seasonal rainfall across the districts of the Odisha Mahanadi basin reveals considerable spatial heterogeneity. The upper and middle reaches, covering western Odisha districts such as Bargarh, Sambalpur, and Jharsuguda, receive comparatively lower rainfall, whereas the lower basin and deltaic regions, including Cuttack, Jagatsinghpur, Kendrapara, and Puri, experience significantly higher rainfall. This gradient reflects the combined influence of monsoon dynamics, topography, and coastal proximity. The coefficient of variation of annual rainfall generally ranges from 20–30%, indicating moderate to high variability across the basin.

Rainfall variability poses a persistent challenge to agricultural and water-resource stability in the Odisha Mahanadi basin. High inter-annual variability leads to alternating episodes of floods and droughts, often within short temporal spans. Excess monsoon rainfall frequently results in widespread flooding in the deltaic plains, while deficient rainfall years cause agricultural stress in the western and central parts of the basin. Such variability highlights the sensitivity of the basin's socio-hydrological systems to monsoon behavior and underscores the limitations of relying predominantly on rainfall-driven agriculture.

Seasonal analysis indicates that the southwest monsoon contributes the dominant share of annual precipitation, while the northeast monsoon (October–December) provides a smaller but regionally significant contribution, particularly in the coastal and deltaic districts. The northeast monsoon rainfall exhibits higher variability and plays a critical role in post-monsoon crop stages and soil moisture replenishment. Winter and pre-monsoon rainfall contribute marginally to the annual total and remain relatively uniform across the basin.

Overall, the Odisha part of the Mahanadi basin demonstrates a paradox of high rainfall coupled with high vulnerability, driven by strong seasonal concentration and spatial imbalance. These characteristics emphasize the need for integrated basin-scale rainfall assessment, improved storage and drainage infrastructure, and adaptive agricultural planning to mitigate the impacts of rainfall variability and extreme hydro-climatic events.

### **2.1.3 Distribution of Monthly Rainfall for Chhattisgarh**

Rainfall distribution is particularly critical for planning the sowing schedule and selecting crop varieties with durations that align with the available moisture regime. Ensuring that planting coincides with the commencement of effective rainfall minimizes the risk of water stress during sensitive growth stages such as flowering and grain filling. Given that a large portion of Chhattisgarh's agricultural land depends on monsoon-fed irrigation, understanding this temporal pattern of rainfall is essential for maximizing productivity. In the context of the Mahanadi Basin, where Chhattisgarh's farmlands contribute significantly to both surface runoff and groundwater recharge, this growing season alignment supports sustainable water resource utilization while enhancing crop resilience under variable climatic conditions. The rainfall pattern across the districts of Chhattisgarh shows distinct temporal and spatial variability, strongly influenced by the southwest monsoon. The mean monthly rainfall indicates that most of the precipitation occurs between June and September, with July (360.9 mm) and August (333.8 mm) being the peak monsoon months. The lower coefficient of variation (CV) values during these months (<15%) reflect a relatively consistent and dependable rainfall regime across the basin. In contrast, the pre-monsoon (March–May) and post-monsoon (October–December) months display higher variability (CV > 45%), highlighting the irregular and sporadic nature of rainfall outside the monsoon period.

Within the Mahanadi River Basin, rainfall distribution demonstrates notable spatial coherence due to similar climatic influences and topographic conditions. Districts such as Raipur, Durg, Mahasamund, Bilaspur, Raigarh, Korba, Janjgir-Champa, and Baloda Bazar experience moderate to high rainfall during the monsoon season, supporting the region's predominantly agrarian

economy. The onset of monsoon around early June results in a sharp increase in rainfall, which sustains until late September before declining rapidly in October. This consistent monsoonal pattern is vital for crop cultivation, groundwater recharge, and surface water availability across the basin. The pre-monsoon showers, though limited, serve as an important precursor for soil moisture replenishment necessary for agricultural activities.

The seasonal variability observed in rainfall across the basin also carries implications for water resource management and climate adaptation. The higher variability during non-monsoon months emphasizes the need for improved irrigation infrastructure and water storage systems to mitigate agricultural stress during dry spells. Moreover, inter-annual fluctuations in monsoon intensity and duration can significantly affect crop yield and hydrological balance, necessitating integrated watershed management and climate-resilient agricultural practices. Understanding the temporal distribution and variability of rainfall across these districts is, therefore, essential for ensuring sustainable agricultural productivity and effective management of the Mahanadi River Basin's water resources (Table 1).

Table 1 presents the district-wise agricultural adaptation indicators across 21 districts of Chhattisgarh, highlighting spatial variability in adaptive measures and performance. The data indicate a wide range of responses, with coefficients of variation (CV) spanning from 15% to 98%, signifying substantial heterogeneity in adaptation efforts. Lower CV values for indicators 23–26 (15–35%) suggest consistent implementation patterns, potentially corresponding to broader adaptation initiatives such as irrigation improvements or soil conservation practices. In contrast, higher variability among indicators 1–22 reflects differing socio-economic, infrastructural, and environmental capacities among districts.

Districts such as Raipur, Raigarh, and Sarguja consistently exhibit higher indicator values, reflecting enhanced agricultural resilience and better infrastructural or institutional support. On the other hand, Durg, Koriya, and Bemetara display moderate performance levels, implying a need for strategic interventions and localized adaptation planning. Overall, the analysis emphasizes that adaptation capacity is unevenly distributed, underscoring the necessity of district-specific approaches to strengthen resilience against climate-induced agricultural stressors.

**Table 1.** Monthly Average Rainfall (mm) for Districts of Mahanadi River Basin, Chhattisgarh.

S. No	Districts	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Balod	7	6.1	3.7	3	5.1	145.9	361.8	329.9	194.7	42.7	10	2.7
2	Baloda Bazar	6.6	9.4	14.8	9.1	9.5	172.3	324.1	269.1	165.3	39	8.6	4.4
3	Bemetara	10.4	5	6.1	5	8.1	173.1	351.9	297.4	178.7	44.2	5.1	6.7
4	Bilaspur	27.1	19.5	30.2	21.4	31.4	172.5	306.2	323.6	198.3	55.7	15.6	6.9
5	Dhamtari	12.9	7.6	7.9	14.5	17.5	183.6	306.9	307.7	190.1	43.9	11	6
6	Durg	5.2	1	2.6	1.1	6.7	163.4	397.8	326.2	170.3	35.5	8.4	5
7	Gariyaband	4.9	8.8	6.6	8.2	8.9	198.1	350.4	341.8	192.3	38.4	5	3
8	Janjgir-Champa	15.3	13.9	10.6	8.4	8.8	154.5	366.4	372.5	208.2	44.2	11.2	8.1
9	Jashpur	14	10.8	10.5	10.7	19.4	201.4	409.7	361.7	223.9	56.1	10.7	7.4

10	Kanker	9.6	4.4	4.9	5.9	15.9	170.5	330.7	357.5	182.1	54.8	5.8	2.6
11	Kawardha	12.9	19.5	18.6	8.2	10.6	128.4	265.1	285	169.7	55.5	12.2	3.8
12	Kondagaon	15.5	23.1	8.9	9.4	31.9	168.2	312.1	331.7	156.6	36.6	8.6	13.2
13	Korba	8.4	6.4	9.2	6.7	9.6	185.1	386.8	337.2	174.5	32.9	8.6	5.1
14	Koriya	12.8	18	10.7	5.6	5.5	170.2	395.3	350.6	206.6	43.9	13.7	8
15	Mahasamund	10.1	7.1	10.8	12.2	9.4	174.4	374.6	341.5	206.5	47.7	6	5.7
16	Mungeli	14.2	14.9	11.6	9.8	10.2	143.9	318.5	283.3	172	47.7	14.7	7.7
17	Narayanpur	7.4	8.5	16.9	18.9	30.8	221	389.7	431	188.8	60.9	9.3	1.2
18	Raigarh	16.5	18.5	22.9	24	25	185.6	339.3	286.1	191.1	59.7	16.4	14.8
19	Raipur	20.5	20	21.5	18	23.2	174.5	335.2	284.3	152.9	41.5	18.9	16.2
20	Rajnandgaon	9.6	8.9	11.8	4.2	7.9	172.9	355	323.9	167.4	45.2	8.1	7.4
21	Surguja	25.2	22.7	19.1	14.2	19.3	200	396.8	342.7	218.6	58.1	16.9	11.9
22	Surajpur	14	6.7	4.7	2.3	26.5	208.9	422	314.2	179.7	43.9	3.3	2.3
	<b>MEAN</b>	<b>12.1</b>	<b>11.1</b>	<b>13.1</b>	<b>11.3</b>	<b>17.8</b>	<b>175.5</b>	<b>360.9</b>	<b>333.8</b>	<b>192.7</b>	<b>50.5</b>	<b>10.4</b>	<b>6.7</b>
	<b>SD</b>	<b>6.2</b>	<b>6.5</b>	<b>10.1</b>	<b>7.9</b>	<b>12.4</b>	<b>24.4</b>	<b>41.9</b>	<b>41.9</b>	<b>24</b>	<b>12.1</b>	<b>4.7</b>	<b>4</b>
	<b>CV (%)</b>	<b>50.9</b>	<b>58.9</b>	<b>77.4</b>	<b>69.7</b>	<b>69.6</b>	<b>13.9</b>	<b>11.6</b>	<b>12.6</b>	<b>12.4</b>	<b>23.8</b>	<b>45.6</b>	<b>60.2</b>

(CS Change - Raipur: action for the climate today, 2019)

#### 2.1.4 Distribution of Monthly Rainfall for Odisha

Rainfall distribution across the districts of the Mahanadi River Basin in Odisha governs agricultural productivity, hydrological processes, and water resource sustainability. The basin is overwhelmingly monsoon-driven, and any mismatch between rainfall timing and crop water demand directly translates into yield instability and hydrological stress. Therefore, understanding both the temporal concentration and spatial variability of rainfall is essential for effective agricultural and water-management planning.

The mean monthly rainfall pattern (Table 2) clearly demonstrates a strong southwest monsoon dominance, with rainfall intensifying sharply from June and persisting through September. On average, June receives 956.1 mm of rainfall, marking the effective onset of monsoon conditions across the basin. Peak rainfall occurs during July (1715.7 mm) and August (1731.5 mm), followed by a gradual decline in September (1110.7 mm). Collectively, these four months account for most of the annual precipitation, underscoring the basin's high dependence on a narrow seasonal rainfall window.

In contrast, the pre-monsoon period (January–May) receives relatively limited rainfall. Although mean rainfall increases from 55.8 mm in January to 239.4 mm in May, this contribution remains insufficient for rainfed crop sustenance and primarily supports soil moisture replenishment and land preparation. The post-monsoon period (October–December) exhibits a rapid reduction in rainfall, with October (470.3 mm) being the only month contributing meaningfully due to retreating monsoon systems, while November and December receive minimal precipitation.

Spatially, rainfall exhibits considerable heterogeneity across the basin, reflecting variations in topography, distance from the coast, and orographic influences. Western and central districts such as Sambalpur, Balangir, Bargarh, Kalahandi, and Subarnapur record exceptionally high monsoonal rainfall, particularly during July and August, highlighting their dominant role in surface runoff generation and inflows to the Mahanadi River system.

Eastern and coastal districts including Cuttack, Jagatsinghpur, Kendrapada, Puri, and Khordha receive substantial rainfall during both the monsoon and retreating monsoon phases, supporting intensive agriculture while also increasing susceptibility to flooding and waterlogging. Interior upland and forested districts such as Kandhamal, Sundargarh, and Deogarh show comparatively moderate rainfall totals, yet their hydrological significance remains high due to enhanced infiltration and sustained baseflow contributions.

The variability analysis provides critical insights into rainfall reliability across seasons. Coefficient variation (CV) values range from 65% to 75% during most months, indicating moderate to high spatial variability across districts. The highest variability is observed during April (75.3%) and November (81.4%), reflecting the erratic and localized nature of rainfall during transitional seasons.

Notably, the monsoon months (June–September) exhibit relatively stable CV values ( $\approx 65\text{--}70\%$ ), suggesting that although rainfall magnitudes are large, their spatial distribution remains reasonably consistent across the basin. This stability is crucial for the success of monsoon-dependent cropping systems, particularly rice cultivation, which dominates the agricultural landscape of Odisha.

The increasing standard deviation during peak monsoon months is primarily a function of higher rainfall volumes rather than increased uncertainty, a distinction that is critical for correct interpretation. Misreading this as instability would be analytically incorrect. The pronounced concentration of rainfall within a short monsoon window creates a dual challenge for the Mahanadi Basin. While dependable monsoon rainfall supports agricultural production and groundwater recharge, it also elevates risks of runoff losses, soil erosion, and flooding if not managed through appropriate storage and drainage infrastructure.

The high variability during non-monsoon months highlights the vulnerability of rainfed agriculture outside the kharif season and reinforces the need for supplemental irrigation, rainwater harvesting, and conjunctive use of surface and groundwater resources. Moreover, inter-district differences in rainfall magnitude and variability necessitate location-specific adaptation strategies rather than uniform basin-wide interventions.

Overall, the rainfall regime of the Mahanadi River Basin in Odisha emphasizes the need for integrated watershed management, climate-resilient agricultural planning, and optimized reservoir operations to ensure sustainable use of water resources under increasing climatic variability.

**Table 2.** Monthly Average Rainfall (mm) for the period of 1901 - 2023 for the Districts of the Mahanadi River Basin, Odisha.

S. No	Districts	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Anugul	40.6	76.8	71.2	98.9	203.0	677.1	1134.1	1109.5	750.6	341.6	76.8	18.5
2	Balangir	108.0	158.2	165.8	208.4	354.3	2042.6	3766.5	3797.5	2272.2	667.2	130.2	54.0
3	Baragarh	116.0	175.8	151.3	140.7	232.5	1847.6	3731.7	3720.8	2029.7	479.6	87.9	53.1
4	Cuttack	82.9	187.9	171.4	231.1	626.0	1565.6	2482.8	2593.7	1935.2	1200.4	323.8	47.5
5	Deogarh	18.3	26.7	20.3	25.4	57.8	251.8	477.8	460.8	253.4	75.2	14.5	7.6
6	Dhenkanal	12.1	28.5	24.2	33.6	86.1	235.4	365.2	384.1	276.4	147.8	38.3	5.7
7	Ganjam	13.0	27.8	26.5	38.1	75.3	217.8	362.0	344.3	254.4	141.4	36.6	6.0
8	Jagatsinghpur	24.0	48.3	46.5	57.2	189.4	427.6	673.4	722.6	582.9	413.3	133.1	24.8
9	Jajpr	12.5	27.9	28.7	39.5	105.4	224.4	342.1	368.3	295.5	207.7	60.4	9.8
10	Jharsuguda	31.6	46.5	38.4	32.0	60.3	465.6	939.3	962.9	506.0	124.0	21.0	13.5
11	Kalahandi	94.6	132.7	181.0	272.8	436.0	2103.4	3638.7	3819.0	2384.2	801.9	162.7	57.4
12	Kandhamal	100.0	192.4	213.9	341.9	603.9	1670.8	2776.6	2782.1	2112.8	1158.1	339.1	67.7
13	Kendrapada	12.5	27.9	28.7	39.5	105.4	224.4	342.1	368.3	295.5	207.7	60.4	9.8
14	Khordha	47.2	90.8	73.4	97.2	315.5	830.9	1385.5	1448.8	1095.4	751.8	221.1	28.5
15	Nabrangpur	24.7	32.3	45.0	83.6	121.5	653.0	1097.7	1126.7	730.0	211.2	40.4	14.4
16	Nayagarh	71.5	150.8	135.0	183.4	426.1	1243.6	2080.2	2053.7	1533.5	929.4	255.8	34.4
17	Nuapada	41.2	58.0	60.8	83.0	125.8	859.4	1568.0	1552.7	952.9	263.5	50.5	21.0
18	Puri	39.7	67.9	47.3	58.5	220.7	577.4	983.2	1026.1	830.7	610.2	204.3	30.9
19	Sambalpur	131.0	195.2	152.3	160.8	348.3	1955.3	3797.9	3754.5	2037.8	571.8	105.7	57.7
20	Subarnpur	60.3	86.1	76.6	78.4	148.9	920.9	1892.9	1863.3	1055.1	283.9	56.7	25.0
21	Sundargarh	91.5	131.4	97.0	94.9	201.2	1152.3	2262.4	2215.6	1208.9	351.5	62.5	33.3
22	Boudh	54.3	93.8	89.8	115.7	224.1	887.2	1646.2	1618.4	1041.7	408.5	96.7	25.1
	Mean	55.8	93.8	88.4	114.3	239.4	956.1	1715.7	1731.5	1110.7	470.3	117.2	29.4
	SD%	37.8	61.0	60.3	86.1	166.0	646.9	1205.6	1213.7	726.1	329.7	95.4	19.1
	CV%	67.7	65.0	68.3	75.3	69.4	67.7	70.3	70.1	65.4	70.1	81.4	65.1

### 2.1.5 District-wise mean annual and seasonal rainfall variations Chhattisgarh

The rainfall characteristics presented in Table 3 indicate that the Mahanadi River Basin districts in Chhattisgarh experience significant spatial and seasonal variability in precipitation patterns. The annual mean rainfall ranges between 47 mm in Durg and 68 mm in Surguja, with corresponding coefficients of variation (CV%) suggesting moderate consistency across most districts. The relatively high standard deviations in Mungeli and Dhamtari reflect greater year-to-year fluctuations, likely influenced by topographic and climatic factors. These findings suggest that the central and northern basin districts receive a more evenly distributed annual rainfall compared to their southern counterparts, where variability tends to be higher.

During the winter and summer seasons, rainfall levels remain minimal, averaging less than 3 mm across all districts. The coefficient of variation during these dry months is exceptionally high, exceeding 100% in areas like Bemetara and Korba, highlighting the unpredictability of pre-

monsoon and post-monsoon showers. Such variability can severely affect groundwater recharge and crop planning, making irrigation support crucial during non-monsoon periods. Conversely, the south-west monsoon accounts for most of the annual rainfall, with means ranging from 43 mm in Raipur to 54 mm in Surguja. Despite being the primary rainfall season, fluctuations persist, as reflected by the 20–33% CV in districts like Mungeli and Korba, which may influence the timing and adequacy of water availability for agriculture and hydropower generation.

The north-east monsoon contributes marginally to total rainfall but demonstrates high inter-annual variability, particularly in Kawardha and Raipur (CV% > 70). This irregularity underscores the vulnerability of rainfed farming systems in these regions, where supplemental irrigation is limited. The data highlight the need for improved water management strategies, such as rainwater harvesting, groundwater recharge, and the promotion of short-duration crops that can adapt to shifting rainfall patterns. Overall, Table 2 illustrates that while the Mahanadi Basin enjoys relatively adequate annual rainfall, uneven seasonal distribution and high variability pose challenges to sustainable agricultural planning and water resource management across districts.

**Table 3.** Seasonal Mean, Standard Deviation (SD), and Coefficient of Variation (CV%) of Rainfall across Districts in the Mahanadi River Basin, Chhattisgarh.

District	Annual (Mean / SD / CV%)	Winter (Mean / SD / CV%)	Summer (Mean / SD / CV%)	South-West Monsoon (Mean / SD / CV%)	North-East Monsoon (Mean / SD / CV%)
Balod	52 / 12 / 23	1 / 0 / 56	1/1/1962	44 / 3 / 7	3 / 0 / 14
Balodabazar	51 / 10 / 20	1 / 0 / 14	2 / 0 / 10	44 / 0 / 0	3 / 0 / 10
Bemetara	49 / 14 / 28	1 / 2 / 174	1 / 2 / 173	44 / 13 / 29	3 / 3 / 104
Dhamtari	53 / 17 / 31	1 / 0 / 11	3 / 0 / 7	45 / 2 / 4	4 / 0 / 9
Durg	47 / 9 / 19	0 / 0 / 28	1 / 0 / 14	43 / 1 / 2	3 / 0 / 7
Gariyaband	54 / 10 / 18	1 / 0 / 60	2/1/1934	48 / 3 / 5	3/1/2023
Janjgir-Champa	55 / 9 / 16	2 / 0 / 15	2/1/1935	47 / 1 / 2	4 / 0 / 9
Kanker	53 / 13 / 24	1 / 0 / 13	2/1/1932	46 / 1 / 2	4 / 0 / 1
Kawardha	56 / 11 / 19	2 / 3 / 127	3 / 3 / 102	46 / 9 / 20	4/4/1981
Korba	56 / 15 / 26	1 / 2 / 174	2 / 3 / 135	50 / 14 / 29	3 / 3 / 107
Mahasamund	57 / 9 / 15	1/1/1964	2 / 2 / 112	50 / 4 / 8	4 / 0 / 13
Mungeli	61 / 18 / 29	2 / 3 / 121	2 / 3 / 105	52 / 17 / 33	5/3/1976
Raigarh	61 / 14 / 22	2/1/1965	4/2/1950	50 / 9 / 19	5/2/1933
Raipur	56 / 8 / 15	2 / 3 / 116	4 / 4 / 110	43 / 5 / 12	4/3/1972
Rajnandgaon	53 / 11 / 20	1/1/1947	2/1/1960	46 / 3 / 7	3/1/2026
Surguja	68 / 10 / 15	4/3/1968	5/4/1971	54 / 9 / 16	6/4/1968

(CS Change - Raipur: action for the climate today, 2019)

### 2.1.6 District-wise mean annual and seasonal rainfall variations Odisha

The rainfall characteristics presented in Table 4 indicate that the districts of the Mahanadi River Basin in Odisha exhibit pronounced spatial and seasonal variability in precipitation. Annual mean rainfall shows a wide range across districts, with comparatively lower values in interior districts such as Deogarh, Dhenkanal, and Ganjam, and substantially higher totals in western and central districts including Kalahandi, Balangir, Sambalpur, and Kandhamal. The annual coefficient of variation (CV%), which often exceeds 100% in many districts, points to considerable inter-annual variability, particularly in western Odisha, highlighting the basin’s susceptibility to both drought and excess rainfall conditions.

Rainfall during the winter and summer seasons remains relatively low across the basin but is characterized by very high variability, with CV values frequently exceeding 50% and, in several cases, surpassing 100%. Districts such as Anugul, Jharsuguda, and Subarnpur exhibit especially erratic winter and summer rainfall, reflecting the sporadic nature of convective and western disturbance-related precipitation. Such high variability reduces the reliability of non-monsoon rainfall for agriculture and limits its contribution to groundwater recharge, thereby increasing dependence on irrigation during these periods.

In contrast, the South-West Monsoon (SWM) dominates the rainfall regime of the basin, contributing most of the annual precipitation across all districts. Mean SWM rainfall is particularly high in Kalahandi, Balangir, Sambalpur, and Bargarh, while coastal and central districts such as Cuttack, Puri, and Khordha receive comparatively moderate monsoonal rainfall. The CV during SWM is notably lower (generally between 20% and 36%) than in other seasons, indicating relatively greater seasonal stability; however, the remaining variability is still sufficient to influence agricultural productivity, flood occurrence, and reservoir inflows.

The North-East Monsoon (NEM) contributes a smaller share of total rainfall but exhibits extreme inter-annual variability, with CV values exceeding 100% in most districts. This erratic behavior is particularly evident in districts such as Anugul, Kalahandi, and Sundargarh, underscoring the unreliability of post-monsoon rainfall for crop planning. Overall, the results demonstrate that while the Mahanadi Basin districts in Odisha receive substantial annual rainfall, the strong dependence on the South-West Monsoon and the high variability of non-monsoon rainfall pose significant challenges for sustainable water resources management, rainfed agriculture, and climate-resilient planning.

**Table 4.** Seasonal Mean, Standard Deviation (SD), and Coefficient of Variation (CV%) of Rainfall across Districts in the Mahanadi River Basin, Odisha for the period of 1901 – 2023.

District	Annual (Mean/SD/CV )	Winter (Mean/SD/CV)	Summer (Mean/SD/CV)	South-West Monsoon (Mean/SD/CV )	North-East Monsoon (Mean/SD/CV )
Anugul	383.2 / 422.5 / 110.2	58.7 / 25.6 / 43.6	124.4 / 69.5 / 55.9	917.8 / 237.6 / 25.9	145.6 / 172.2 / 118.2
Balangir	1143.7 / 1444.2 / 126.3	133.1 / 35.5 / 26.7	242.8 / 98.9 / 40.7	2969.7 / 942.7 / 31.7	283.8 / 334.2 / 117.8

Baragarh	1063.9 / 1417.5 / 133.2	145.9 / 42.3 / 29.0	174.8 / 50.2 / 28.7	2832.4 / 1034.8 / 36.5	206.9 / 236.8 / 114.5
Cuttack	954.0 / 964.4 / 101.1	135.4 / 74.2 / 54.8	342.8 / 247.0 / 72.1	2144.3 / 481.4 / 22.4	523.9 / 601.9 / 114.9
Deogarh	140.8 / 176.3 / 125.2	22.5 / 5.9 / 26.4	34.5 / 20.3 / 59.0	361.0 / 125.3 / 34.7	32.4 / 37.2 / 114.7
Dhenkanal	136.4 / 142.3 / 104.3	20.3 / 11.6 / 57.1	48.0 / 33.4 / 69.5	315.3 / 71.0 / 22.5	63.9 / 74.4 / 116.4
Ganjam	128.6 / 132.6 / 103.1	20.4 / 10.5 / 51.3	46.6 / 25.5 / 54.7	294.6 / 69.6 / 23.6	61.3 / 71.0 / 115.8
Jagatsinghpur	278.6 / 269.7 / 96.8	36.1 / 17.2 / 47.5	97.7 / 79.6 / 81.5	601.6 / 129.6 / 21.5	190.4 / 200.5 / 105.3
Jajpr	143.5 / 136.3 / 95.0	20.2 / 10.9 / 53.9	57.9 / 41.5 / 71.7	307.6 / 63.1 / 20.5	92.6 / 102.8 / 111.0
Jharsuguda	270.1 / 360.8 / 133.6	39.0 / 10.5 / 27.0	43.6 / 14.8 / 34.1	718.5 / 269.3 / 37.5	52.8 / 61.7 / 116.9
Kalahandi	1173.7 / 1427.0 / 121.6	113.6 / 26.9 / 23.7	296.6 / 129.2 / 43.5	2986.3 / 868.1 / 29.1	340.7 / 402.9 / 118.3
Kandhamal	1029.9 / 1044.9 / 101.5	146.2 / 65.3 / 44.7	386.6 / 198.8 / 51.4	2335.6 / 543.3 / 23.3	521.6 / 567.7 / 108.8
Kendrapada	143.5 / 136.3 / 95.0	20.2 / 10.9 / 53.9	57.9 / 41.5 / 71.7	307.6 / 63.1 / 20.5	92.6 / 102.8 / 111.0
Khordha	532.2 / 543.6 / 102.1	69.0 / 30.8 / 44.7	162.0 / 133.4 / 82.4	1190.2 / 284.7 / 23.9	333.8 / 374.6 / 112.2
Nabrangpur	348.4 / 431.6 / 123.9	28.5 / 5.4 / 18.9	83.4 / 38.3 / 45.9	901.9 / 245.2 / 27.2	88.7 / 106.9 / 120.6
Nayagarh	758.1 / 782.6 / 103.2	111.2 / 56.1 / 50.4	248.2 / 156.0 / 62.9	1727.8 / 409.3 / 23.7	406.5 / 466.2 / 114.7
Nuapada	469.7 / 600.9 / 127.9	49.6 / 11.9 / 24.0	89.9 / 33.0 / 36.8	1233.2 / 379.7 / 30.8	111.7 / 132.3 / 118.5
Puri	391.4 / 390.8 / 99.9	53.8 / 19.9 / 37.1	108.8 / 97.0 / 89.2	854.3 / 202.8 / 23.7	281.8 / 297.3 / 105.5
Sambalpur	1105.7 / 1426.8 / 129.0	163.1 / 45.4 / 27.8	220.5 / 110.8 / 50.3	2886.4 / 1028.2 / 35.6	245.1 / 284.0 / 115.9
Subarnpur	545.7 / 711.8 / 130.4	73.2 / 18.2 / 24.9	101.3 / 41.2 / 40.7	1433.1 / 517.0 / 36.1	121.9 / 141.2 / 115.9
Sundargarh	658.5 / 843.5 / 128.1	111.5 / 28.2 / 25.3	131.0 / 60.8 / 46.4	1709.8 / 611.8 / 35.8	149.1 / 175.9 / 118.0
Boudh	525.1 / 614.4 / 117.0	74.0 / 27.9 / 37.7	143.2 / 71.2 / 49.8	1298.4 / 390.9 / 30.1	176.8 / 203.9 / 115.3

## 2.1.7 Trend Analysis of Annual Rainfall in the Mahanadi Basin, Chhattisgarh

The rainfall trend analysis presented in Table 5 reveals varying degrees of change across districts within the Mahanadi Basin of Chhattisgarh. Out of the twenty-two districts analyzed, only a few displays statistically significant shifts in annual rainfall patterns. Bemetara, Mahasamund, Korba, Raigarh, Raipur, and Surguja exhibit notable positive trends, indicating a possible increase in precipitation over time. These upward trends, though modest, suggest that certain pockets of the basin may experience slightly higher rainfall in the coming decades. On the other hand, most districts show non-significant or stable trends, implying minimal long-term change in annual rainfall amounts.

**Table 5.** District-wise Trend and Significance Levels of Annual Rainfall in the Mahanadi Basin Region of Chhattisgarh.

District	Annual RF (mm)	Significance Level	SWM RF (mm)	Significance Level
Balod	0.576	NS	0.142	NS
Baloda Bazar	-0.431	NS	-0.883	NS
Bemetara	2.76	<i>S (0.01)</i>	3.312	<i>S (0.01)</i>
Bilaspur	0.637	NS	-0.335	NS
Dhamtari	-0.951	NS	0.7	NS
Durg	-0.951	NS	-1.056	NS
Gariyaband	-0.597	NS	-0.475	NS
Janjgir-Champa	-0.742	NS	-1.421	NS
Jashpur	-0.318	NS	-0.431	NS
Kanker	1.25	NS	1.079	NS
Kawardha	0.621	NS	0.008	NS
Kondagaon	-1.03	NS	-1.195	NS
Korba	1.823	<i>S (0.1)</i>	1.647	<i>S (0.1)</i>
Koriya	0.065	NS	-0.152	NS
Mahasamund	3.014	<i>S (0.01)</i>	-0.152	NS
Mungeli	-1.264	NS	-1.639	NS
Narayanpur	0.802	NS	0.13	NS
Raigarh	0.035	NS	2.396	<b><i>S (0.05)</i></b>
Raipur	0.233	NS	3.456	<i>S (0.01)</i>
Rajnandgaon	-0.701	NS	-0.403	NS
Surguja	1.75	<i>S (0.1)</i>	-1.136	NS
Surajpur	-0.507	NS	0.245	NS

**Note:** *S* = Significant; *NS* = Not Significant.

(CS Change - Raipur: action for the climate today, 2019)

Districts such as Raipur, Raigarh, and Bemetara show statistically significant positive trends during the monsoon season, implying increasing monsoon intensity or duration in recent years. However, districts like Durg, Janjgir-Champa, and Kondagaon demonstrate weak negative trends, which could indicate localized reductions in rainfall or delayed monsoon onset. The predominance of non-significant results across most districts suggests that monsoon variability in Chhattisgarh remains relatively stable overall, although regional microclimatic factors continue to influence temporal rainfall behavior.

The northern districts, such as Surguja and Korba, exhibit marginally increasing rainfall trends at a 10% significance level. This gradual increase might be linked to changing moisture dynamics due to forest cover, altitude, and prevailing wind patterns. Meanwhile, central districts like Durg, Baloda Bazar, and Rajnandgaon show negative but statistically insignificant rainfall anomalies, which may still hold hydrological implications for groundwater recharge and agricultural productivity if these minor declines persist over extended periods. These variations underscore the importance of localized watershed management and adaptive cropping systems to address uneven water distribution.

Overall, the analysis highlights that while Chhattisgarh's Mahanadi Basin districts are not undergoing drastic rainfall declines, subtle upward or downward shifts exist regionally. The findings reinforce the need for continuous long-term climate monitoring, especially in districts with increasing rainfall variability. Incorporating these insights into agricultural planning, irrigation scheduling, and water resource management will help ensure resilience against both potential droughts and excessive rainfall events in the future.

## **2.2 Variability and Trends in Annual Maximum and Minimum Temperatures of Chhattisgarh Region, Mahanadi River Basin**

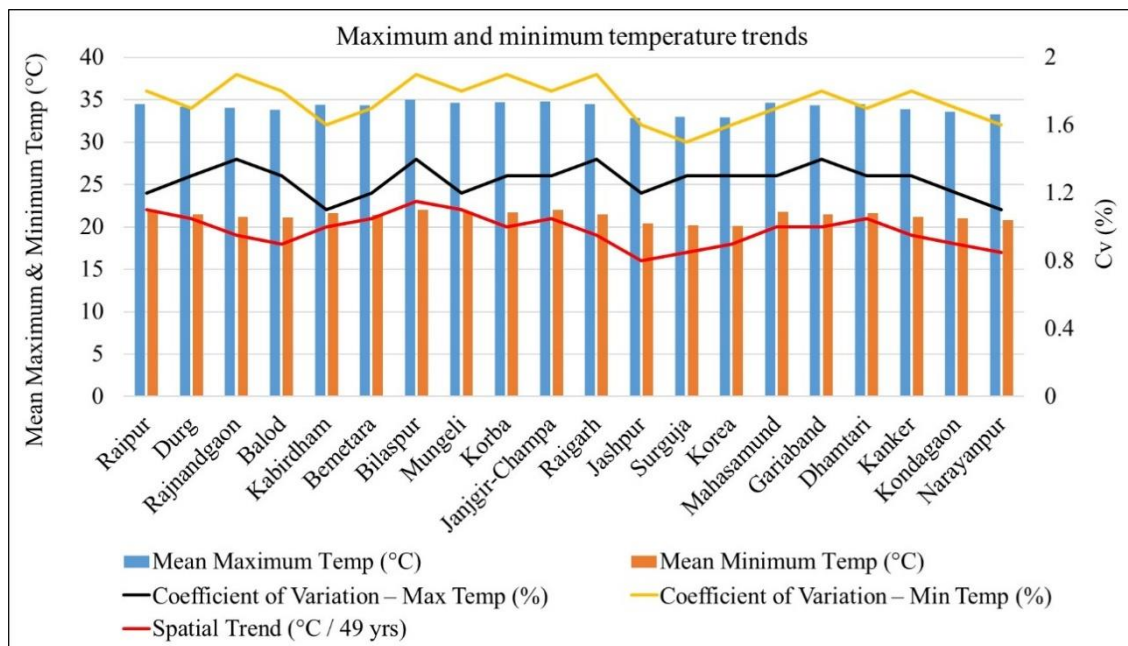
The long-term climatic assessment of Chhattisgarh between 1969 and 2017 reveals a consistent and spatially diverse pattern of temperature rises across most districts of the state (Figure 1). The mean maximum temperature generally ranges between 32.8°C and 35°C, while the mean minimum temperature falls between 20°C and 22°C, suggesting an overall warming trend in both daytime and night-time conditions. The spatial trend in temperature increase varies from +0.80°C to +1.15°C across different districts. Notably, the rise in maximum temperatures is more pronounced than the increase in minimum temperatures, indicating an intensification of summer heat waves and reduced nighttime cooling.

In the central region, districts such as Raipur, Durg, and Rajnandgaon exhibit some of the highest warming intensities in the state. Raipur shows a rise of around +1.10°C, reflecting strong urban heat island effects and increased anthropogenic emissions due to rapid urbanization. Durg follows closely with a similar warming magnitude, largely influenced by its industrial expansion and dense population zones. Rajnandgaon and Balod show slightly lower warming of about +0.90–0.95°C, maintaining moderate variability in temperature across the observation period. These districts are witnessing growing heat stress during the pre-monsoon season, which may directly affect agricultural productivity and local hydrological balance.

Moving towards the northern plains and transitional districts, including Kabirdham, Bemetara, and Bilaspur, a persistent upward shift in both maximum and minimum temperatures is evident. Bilaspur, with the highest recorded mean maximum temperature of around 35°C, demonstrates the strongest warming trend (+1.15°C) in the state. This can be attributed to industrial and mining activities, urban expansion, and the reduction of natural vegetation cover. Neighboring districts such as Kabirdham and Bemetara show moderate warming (+1.00–1.05°C), with limited temperature variability, reflecting stable but gradually intensifying heat patterns. These findings underline the need for sustainable land-use policies and improved urban ventilation mechanisms in the central belt of Chhattisgarh.

The eastern corridor of the state, covering Korba, Janjgir-Champa, and Raigarh, portrays a distinct industrial-influenced warming pattern. Korba, being one of India's major thermal power hubs, exhibits a steady increase in temperature (+1.00°C) with slightly higher variability, suggesting an accumulation of local heat due to energy production and industrial emissions. Janjgir-Champa shows a rising maximum temperature trend (+1.05°C), possibly influenced by irrigation development and surface heat absorption. Raigarh presents a moderate but consistent warming (+0.95°C), where deforestation and coal mining might have contributed to localized

heat accumulation. Collectively, this region reflects the implications of industrialization on regional climate stability.



**Figure 1.** Maximum and minimum temperature trends across the Chhattisgarh region or the Mahanadi River basin (1969–2017).

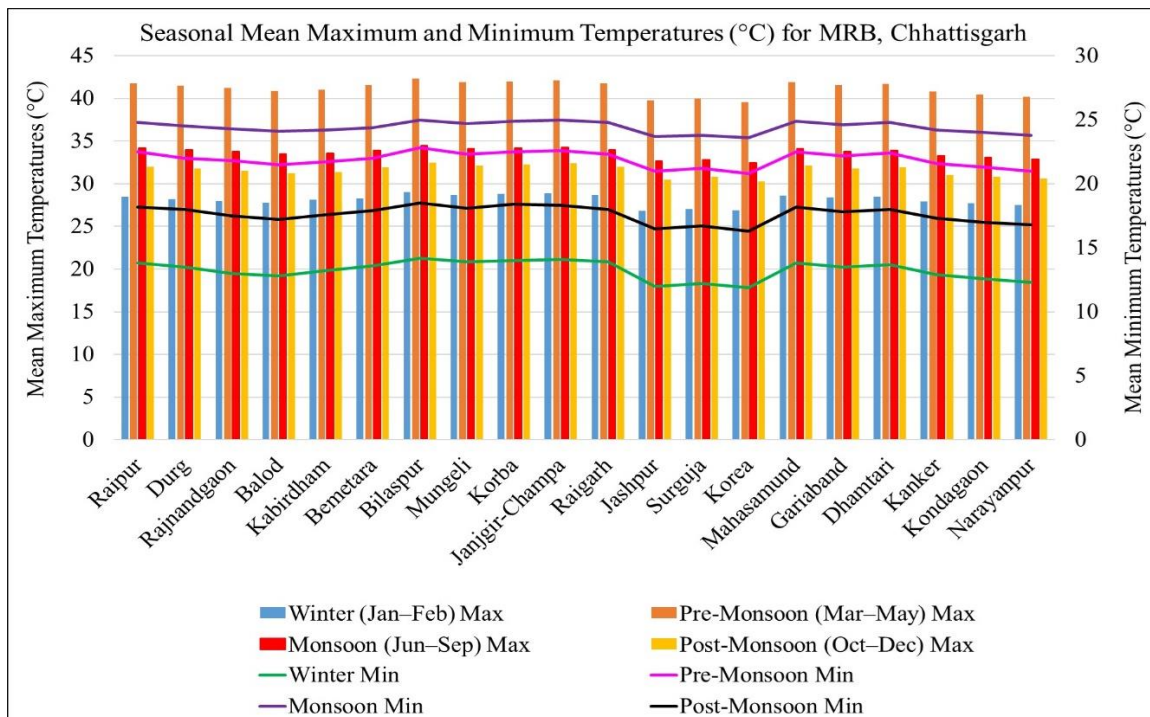
The northern highland districts Jashpur, Surguja, and Korea display relatively cooler climatic profiles with mean maximum temperatures ranging from 32.8°C to 33°C and mean minimum temperatures near 20°C. Their spatial warming trends are modest, varying between +0.80°C and +0.90°C, highlighting the buffering effect of higher elevation, dense forests, and natural vegetation cover. However, even these traditionally cooler areas have begun to experience gradual temperature increases in recent decades, which may alter their ecological dynamics and biodiversity balance. The lower coefficients of variation (around 1.5–1.6%) suggest relatively stable temperature patterns compared to the central plains, though continued deforestation could amplify warming in the future.

In the southern transitional and forested zones, including Mahasamund, Gariaband, Dhamtari, Kanker, Kondagaon, and Narayanpur, the observed warming trend remains steady and uniform, generally around +0.90°C to +1.00°C. These districts, while less industrialized, are witnessing climatic changes linked to agricultural expansion and reduced canopy cover. Mahasamund and Gariaband show a noticeable rise in both maximum and minimum temperatures, reflecting the sensitivity of these regions to land-use change. Kanker and Kondagaon maintain relatively balanced temperature ranges with minimal fluctuations, indicating moderate resilience due to their forest cover. Narayanpur, located in the southern fringe, remains one of the least affected districts, with a limited warming of +0.85°C, representing a comparatively stable microclimate.

### 2.2.1 Seasonal Variation of Maximum and Minimum Temperatures in Chhattisgarh Region, Mahanadi River Basin

The long-term analysis of seasonal temperature variation in the Chhattisgarh region, Mahanadi River basin, between 1969 and 2017 highlights a distinct warming pattern across all seasons, with varying intensities among the districts (Figure 2). The mean maximum temperature remains highest during the pre-monsoon months (March–May), reaching above 42°C in central and eastern districts. Conversely, the mean minimum temperatures are lowest in winter (January–February), typically ranging from 11°C to 14°C. The study reveals a clear upward shift in both maximum and minimum temperatures, suggesting a narrowing diurnal temperature range and a transition toward a warmer climate regime across the state.

In the central districts, Raipur, Durg, Rajnandgaon, and Balod, the warming trend is substantial, especially in the pre-monsoon and post-monsoon seasons. Raipur records the highest increase in mean maximum temperature, peaking at 41.8°C during the pre-monsoon season, accompanied by warmer minimum temperatures of around 22.5°C. Durg and Rajnandgaon exhibit similar thermal patterns with slightly lower variability, indicating a consistent upward trend over the decades. The extended dry season and urban heat accumulation have intensified heat stress in these regions, reflecting the growing effects of rapid urbanization and reduced vegetation cover.



**Figure 2.** District-Wise Seasonal Mean Maximum and Minimum Temperatures (°C) for the MRB, Chhattisgarh (1969–2017).

The northern and north-central districts, including Kabirdham, Bemetara, Bilaspur, and Mungeli, show a prominent increase in both maximum and minimum temperatures. Bilaspur emerges as the hottest district, with pre-monsoon highs of 42.3°C, while winter and post-

monsoon minima have also increased by nearly 1°C since the 1970s. Mungeli and Bemetara demonstrate a similar trend with rising average night-time temperatures, suggesting an overall warming of the regional atmosphere. This region experiences prolonged dry spells and higher evapotranspiration rates, which could influence agricultural productivity and local water balance.

In the eastern industrial belt, comprising Korba, Janjgir-Champa, and Raigarh, the warming is accentuated by industrial and mining activities. Korba and Janjgir-Champa record sustained high temperatures across all seasons, exceeding 42°C during summer and maintaining elevated night temperatures near 25°C during the monsoon months. These findings underline the role of anthropogenic heat emissions, coal combustion, and reduced forest density in accelerating local climatic shifts. Raigarh shows comparable warming but retains slightly more seasonal variability, influenced by its mix of industrial and semi-rural landscapes.

The northern highland districts, namely Jashpur, Surguja, and Korea, remain the coolest parts of the state but are not immune to warming. Their maximum temperatures during the pre-monsoon period reach around 39–40°C, and the minimum temperatures rise to 21°C, marking a noticeable increase over previous decades. Korea maintains the lowest mean temperature profile, reflecting its altitude and forested terrain. However, the gradual rise in both day and night temperatures may impact local biodiversity, water availability, and ecosystem stability, as these regions have historically acted as temperature buffers for the state.

In the southern transitional and forested districts, Mahasamund, Gariaband, Dhamtari, Kanker, Kondagaon, and Narayanpur, the thermal pattern indicates a balanced but steady warming. Mahasamund and Dhamtari show a strong rise during the pre-monsoon and post-monsoon seasons, highlighting the increasing persistence of warmer conditions. Kanker and Kondagaon record moderate increases with stable variability, suggesting gradual but continuous climatic shifts. Narayanpur remains the least affected district, with a cooler microclimate and minimal seasonal fluctuation due to dense forest cover and limited anthropogenic influence.

Overall, the seasonal warming trend across Chhattisgarh demonstrates that while all districts are experiencing temperature increases, the central and eastern regions exhibit the most significant rises, primarily due to human-induced activities. The northern and southern forested districts, although comparatively cooler, show signs of incremental warming, which could have long-term implications for agriculture, water resources, and forest ecosystems. These findings emphasize the need for district-level climate resilience planning, including afforestation, sustainable land management, and the adoption of adaptive agricultural practices to mitigate the evolving impacts of climate change.

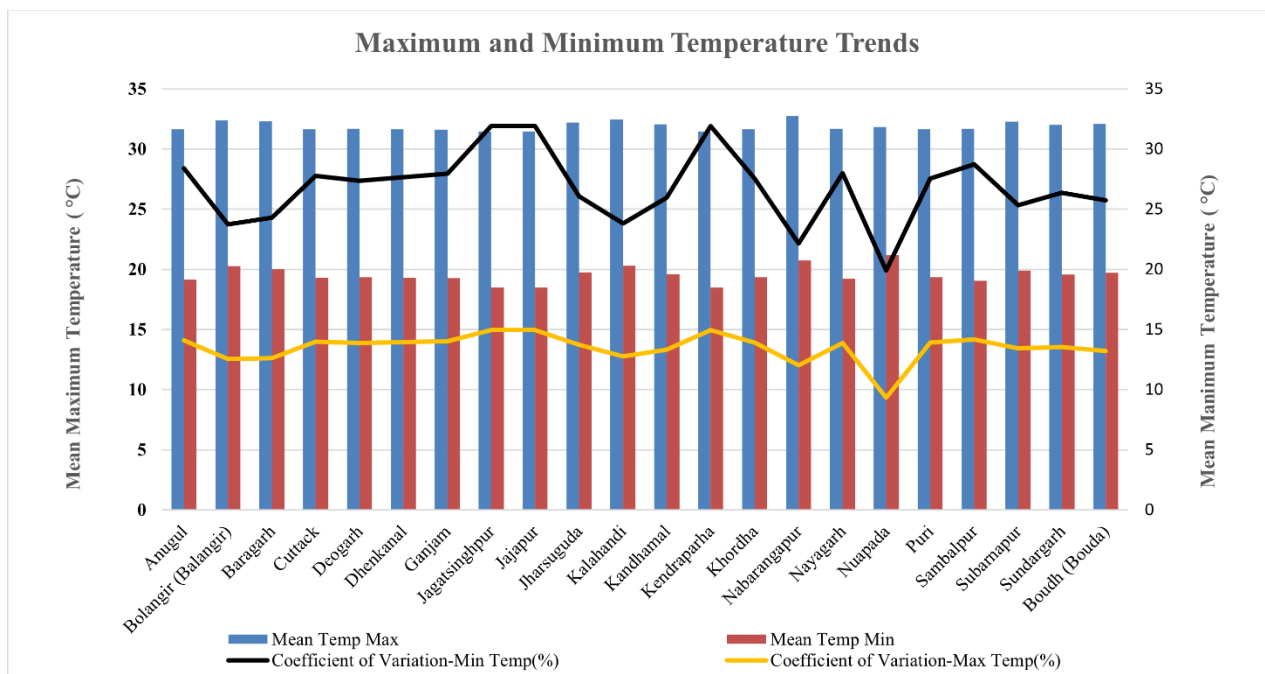
### **2.3 Variability and Trends in Annual Maximum and Minimum Temperatures of Odisha Region, Mahanadi River Basin**

The long-term climatic assessment of the Odisha region of the Mahanadi River basin between 1951 and 2014 reveals a diverse thermal profile, characterized by distinct spatial variations across the state's districts. The mean maximum temperature generally ranges between 31.4°C and

32.8°C, while the mean minimum temperature fluctuates between 18.5°C and 21.2°C (Figure 3). This data indicates a significant thermal gradient from the coastal plains to the western highlands. While coastal districts maintain a moderated climate, the interior and western districts exhibit higher thermal baselines, suggesting a susceptibility to extreme heat conditions and distinctive regional microclimates.

In the western and southern highlands, districts such as Nabarangapur, Kalahandi, and Balangir record some of the highest temperatures in the basin. Nabarangapur exhibits the highest mean maximum temperature of approximately 32.74°C, followed closely by Kalahandi (32.45°C) and Balangir (32.38°C). Nuapada stands out with the highest recorded mean minimum temperature of 21.19°C, indicating reduced nighttime cooling compared to the rest of the state. This elevated thermal profile in the western belt reflects the region's continental climate and susceptibility to heatwaves, which has implications for local agriculture and water resource management in these drought-prone zones.

Moving towards the northern and industrial corridors, districts like Jharsuguda and Sundargarh display elevated maximum temperatures of 32.22°C and 32.00°C, respectively. This pattern aligns with the intense industrial and mining activities prevalent in these regions, which likely contribute to localized heat accumulation like the trends observed in Chhattisgarh's industrial hubs. Sambalpur and Subarnapur also show high maximums (31.69°C and 32.28°C), further reinforcing the trend of higher daytime heat stress in the northwestern interior compared to the coastal districts.



**Figure 3.** Average Annual Maximum and Minimum Temperature across the Odisha region of the Mahanadi River basin (1951–2023).

The eastern coastal and deltaic districts, including Jagatsinghpur, Kendraparha, Jajapur, and Puri, present a contrasting climatic picture with relatively lower thermal averages.

Jagatsinghpur, Jajapur, and Kendraparha share identical and the lowest observed mean statistics, with a maximum of 31.44°C and a minimum of 18.50°C. Cuttack and Puri follow a similar pattern with maximums hovering around 31.6°C. These lower values highlight the moderating influence of the Bay of Bengal, which buffers these districts against the extreme temperature spikes seen in the interior, though they remain vulnerable to humidity-driven thermal discomfort.

### **2.3.1. Seasonal Variation of Maximum and Minimum Temperatures in Odisha Region, Mahanadi River Basin**

The long-term seasonal temperature characteristics across the Mahanadi River Basin (MRB) districts of Odisha reveal a strongly organized thermal regime governed by monsoonal seasonality, inland–coastal gradients, and physiographic controls (Figure 4). Across all districts, mean maximum temperatures peak during the pre-monsoon season (March–May), while mean minimum temperatures are lowest during the winter months (January–February). The pre-monsoon mean maximum temperature varies from about 34–36 °C in coastal and eastern districts to above 40 °C in western interior districts, clearly identifying the western MRB as the principal heat-prone zone. Conversely, winter minimum temperatures range between ~14–16 °C in elevated and forested districts and ~18–20 °C along the coastal belt, reflecting the combined influence of elevation, continentality, and maritime moderation.

Western and interior districts such as Nuapada, Bolangir, Sambalpur, Subarnapur, Jharsuguda, Nabarangapur, and Rayagada exhibit the highest thermal extremes across seasons. Pre-monsoon mean maximum temperatures in these districts frequently exceed 38–40 °C, with Nuapada recording the highest value (~40.1 °C). Even during the southwest monsoon season (June–September), maximum temperatures remain relatively elevated (~35–36 °C), indicating limited cooling due to lower cloud persistence and higher sensible heat fluxes. Minimum temperatures in these districts also remain comparatively high during the monsoon (~27–28 °C), suggesting enhanced atmospheric moisture retention and reduced nocturnal cooling. These characteristics point to a continental heat-dominated regime, with implications for evapotranspiration stress, crop water demand, and heat-wave susceptibility.

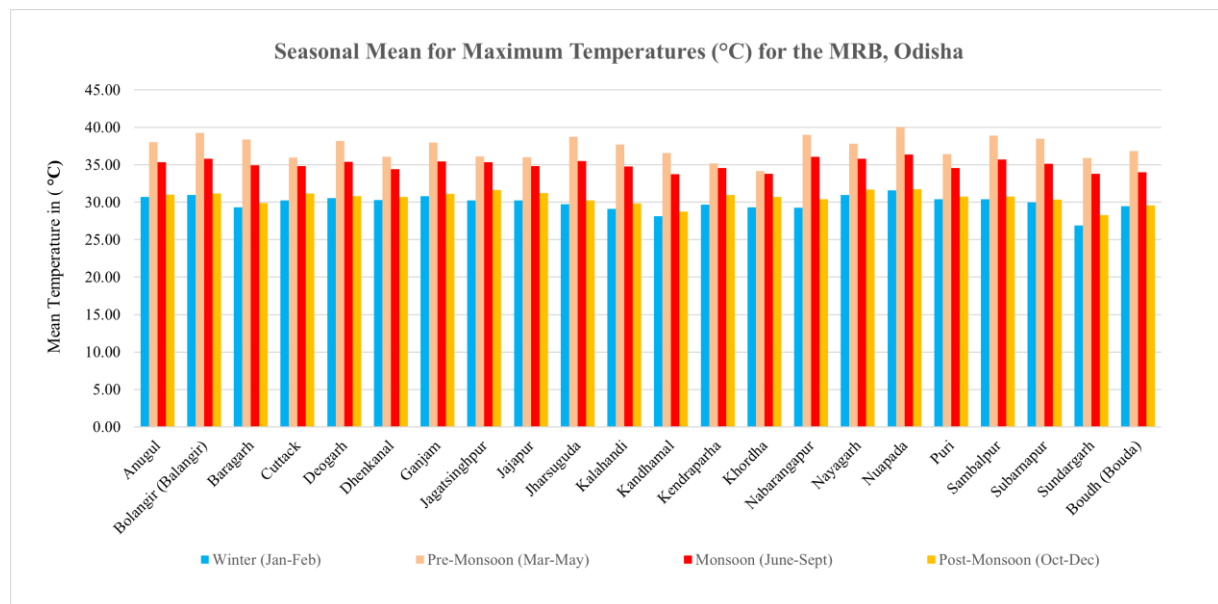
The central MRB districts, including Angul, Dhenkanal, Deogarh, Boudh, Nayagarh, and Jajpur, display a moderate but consistent seasonal thermal pattern. Pre-monsoon maximum temperatures generally range between 36–38 °C, while winter maxima remain near 30–31 °C, indicating less extreme seasonal amplitude compared to the western districts. Minimum temperatures increase sharply from winter (~17–18 °C) to the monsoon season (~26–27 °C), reflecting monsoon-induced humidity and cloud cover. These districts act as a thermal transition zone between the hot western interiors and the relatively cooler coastal belt, making them particularly sensitive to incremental warming and land-use changes.

The coastal and eastern districts notably Cuttack, Kendrapara, Jagatsinghpur, Khordha, Puri, and Ganjam exhibit a comparatively moderated temperature regime throughout the year. Pre-monsoon maximum temperatures are generally lower (~34–36 °C) than in inland districts, and winter minimum temperatures remain relatively high (~18–20 °C), reflecting the influence of

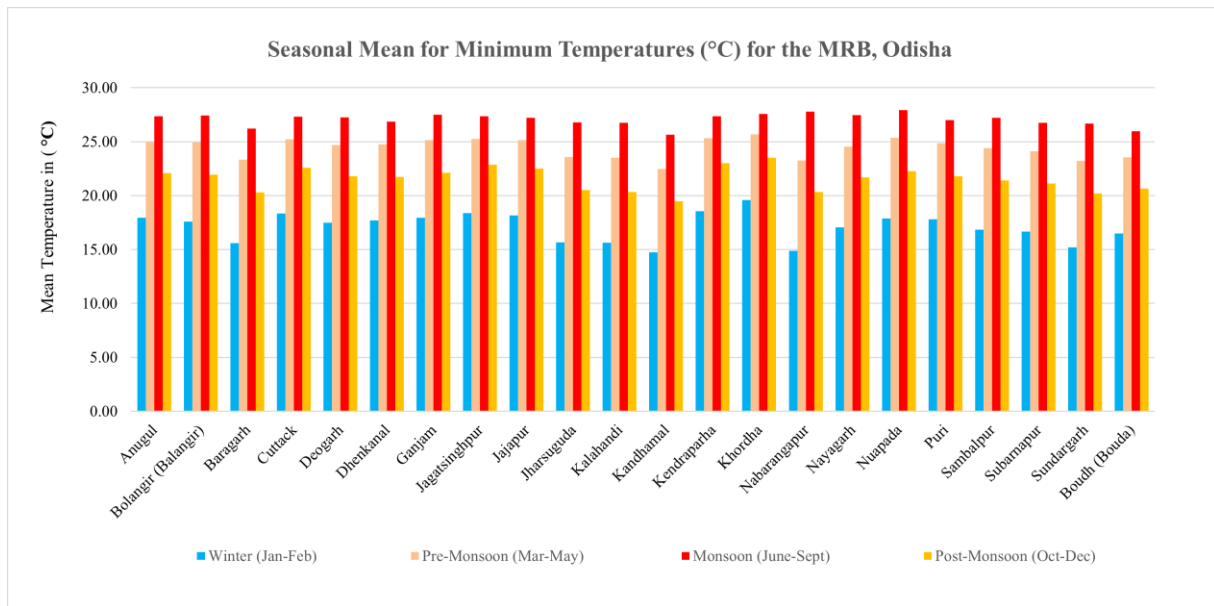
the Bay of Bengal. During the monsoon season, minimum temperatures peak (~27–28 °C), (Figure 5) especially in Khordha and Kendrapara, indicating warm and humid nighttime conditions. While these districts are less exposed to extreme daytime heat, persistently high minimum temperatures may increase thermal discomfort and energy demand, particularly in urban and peri-urban zones.

The upland and forested districts, such as Kandhamal and Sundargarh, remain the coolest regions within the MRB. Kandhamal records the lowest winter minimum temperature (~14.7 °C) and among the lowest post-monsoon maxima (~28.8 °C), underscoring the role of elevation, dense forest cover, and lower anthropogenic activity in regulating local climate. However, even these districts show elevated monsoon minimum temperatures (~25–26 °C), suggesting a basin-wide warming signal that transcends physiographic advantages. These areas, traditionally acting as thermal buffers, may face future stress on forest ecosystems and hydrological processes if warming trends persist.

Overall, the seasonal temperature distribution across the Mahanadi River Basin of Odisha highlights pronounced spatial contrasts and strong monsoonal control, with the western interior districts experiencing the most severe thermal conditions and the coastal belt showing moderated but humid regimes. The combination of high pre-monsoon maximum temperatures and elevated monsoon minimum temperatures indicates increasing thermal stress and reduced diurnal cooling, particularly in inland and industrializing districts. These findings underscore the necessity for district-specific climate adaptation strategies, including heat-resilient agricultural planning, improved water management, urban heat mitigation, and forest conservation, to address the evolving thermal dynamics of the MRB.



**Figure 4.** District-Wise Seasonal Mean for Maximum Temperatures (°C) for the MRB, Odisha (1951–2023).



**Figure 5.** District-Wise Seasonal Mean for Minimum Temperatures (°C) for the MRB, Odisha (1951–2023).

### 2.3 Projected Changes in mean annual precipitation and temperature in the Chhattisgarh region MRB

The district-level analysis between 1969–2017 and projected mid- to end-century scenarios highlight a significant warming tendency across Chhattisgarh. The mean maximum temperature is projected to rise between +2°C and +4.5°C, while the mean minimum temperature shows a comparable increase, indicating a narrowing gap between daytime and nighttime temperatures. This warming pattern is particularly pronounced in central and eastern districts, where industrial and urban activities dominate, while northern and southern forested districts exhibit relatively moderate changes.

In central Chhattisgarh, including Raipur, Durg, Bemetara, and Rajnandgaon, the projections indicate a strong warming of 2.0–4.0°C by the end of the century, with a parallel decline in precipitation by 10–20% (Table 6). These districts already experience frequent heatwaves, and the continued temperature rise will likely exacerbate evapotranspiration and reduce groundwater recharge. The decline in annual rainfall could also alter cropping patterns and reduce soil moisture availability during critical agricultural seasons.

The northern plateau region, comprising Surguja, Jashpur, and Korea, demonstrates a distinct thermal moderation due to dense forests and higher elevations. While their mean maximum temperature increase is limited to +3.0–3.4°C, the minimum temperature is also rising steadily, suggesting warmer nights and longer dry spells. Interestingly, precipitation here remains steady or even slightly increasing, reflecting a possible enhancement in orographic rainfall caused by changing monsoon dynamics. However, despite this resilience, the ecosystems may face stress from altered seasonality and reduced cold spells.

**Table 6.** District-wise Observed (1969–2017) and Projected Changes in Climate Parameters for the Chhattisgarh region MRB.

District	Observed Mean Annual Precipitation (mm, 1969–2017)	Projected Change in Precipitation (%)	Observed Mean Max Temp (°C, 1969–2017)	Projected Increase in Max Temp (°C)	Observed Mean Min Temp (°C, 1969–2017)	Projected Increase in Min Temp (°C)	Key Observation
Raipur	1240	-10 to -20	33.8	+2.2 (mid) → +4.0 (end)	21.5	+2.0 (mid) → +3.8 (end)	Rapid warming, declining rainfall trend
Durg	1185	-10 to -20	33.5	+2.1 → +3.9	21.2	+1.8 → +3.6	Urban heat is intensifying the local climate
Rajnandgaon	1150	-10 to -15	33.3	+2.0 → +3.8	20.9	+1.7 → +3.5	Moderately warmer with drier monsoons
Balod	1170	-10 to -20	33.1	+2.0 → +3.9	21.0	+1.8 → +3.7	Noticeable warming in pre-monsoon months
Kabirdham	1160	-5 to -15	33.4	+2.1 → +3.7	20.8	+1.7 → +3.4	Stable precipitation, gradual thermal rise
Bemetara	1188	-10 to -20	33.6	+2.2 → +3.9	21.1	+1.9 → +3.6	Declining rainfall, warmer nights
Bilaspur	1320	-5 to -10	34.0	+2.3 → +4.1	21.7	+2.0 → +3.8	Strong summer warming, reduced rainfall
Mungeli	1275	-5 to -15	33.8	+2.1 → +3.9	21.5	+1.9 → +3.7	Increasing temperature across all seasons
Korba	1305	-10 to -15	34.2	+2.4 → +4.3	22.0	+2.2 → +4.0	Warming amplified by industrial emissions
Janjgir-Champa	1258	-10 to -20	33.9	+2.3 → +4.0	21.8	+2.1 → +3.9	Decreasing rainfall, strong diurnal rise
Raigarh	1290	-10 to -20	34.1	+2.3 → +4.2	21.9	+2.2 → +4.0	High heat exposure; wet season decline
Jashpur	1420	+5 to +10	32.6	+1.8 → +3.3	19.8	+1.6 → +3.1	Cooler region: rainfall slightly increases

Surguja	1395	0 to +5	32.8	+1.9 → +3.4	20.0	+1.7 → +3.2	Minor warming; precipitation steady
Korea	1375	0 to +5	32.4	+1.8 → +3.2	19.7	+1.6 → +3.0	Forest influence maintains humidity
Mahasamund	1255	-10 to -20	33.9	+2.2 → +4.0	21.5	+2.0 → +3.8	Heatwave frequency expected to rise
Gariaband	1260	-10 to -15	33.7	+2.0 → +3.8	21.3	+1.9 → +3.6	Decreasing rainfall, warm post-monsoon
Dhamtari	1280	-10 to -20	33.8	+2.1 → +3.9	21.4	+1.9 → +3.7	Progressive rise in minimum temperatures
Kanker	1340	-5 to +5	33.3	+2.0 → +3.7	20.9	+1.8 → +3.5	Modest warming, rainfall mostly stable
Kondagaon	1325	-5 to 0	33.0	+1.9 → +3.6	20.7	+1.7 → +3.4	Mild increase in heat, near-normal rains
Narayanpur	1360	-5 to 0	32.8	+1.8 → +3.5	20.5	+1.6 → +3.3	Least affected, forest-driven stability

Baseline period (1969-2017), Mid-century (2021-2050), and End century (2071-2098)

(CS Change - Raipur: action for the climate today, 2019)

The eastern industrial corridor, covering Korba, Raigarh, and Janjgir-Champa, shows one of the sharpest thermal increases across the state. The mean maximum temperature is projected to rise to +4.3°C, accompanied by a significant 10–20% decline in precipitation. These trends suggest intensified urban heat island effects and air pollution-driven radiative forcing, which can amplify surface warming. The resulting changes may also affect hydropower potential and water quality in these districts, emphasizing the need for emission control and sustainable industrial operations.

The southern and transitional districts, Kanker, Kondagaon, Narayanpur, and Gariaband, exhibit moderate warming trends, with projected temperature increases between +1.8°C and +3.6°C and minor precipitation fluctuations. These districts are shielded to some extent by dense forest canopies that help regulate local microclimates. However, reduced winter coolness and increasing pre-monsoon temperatures could lead to shifts in vegetation composition and wildlife habitats. Narayanpur remains the most climate-resilient district, showing limited temperature escalation and near-stable rainfall patterns.

The northeastern districts, Bilaspur, Mungeli, and Mahasamund, record a mixed climatic response. Bilaspur, already a heat-prone region, is projected to experience a 4.1°C rise in maximum temperature and a 10–15% decline in annual rainfall, indicating greater exposure to extreme heat and agricultural stress. Mahasamund mirrors this trend, with an increased likelihood of summer heatwaves and prolonged dry conditions. The combination of temperature elevation and reduced rainfall could threaten water availability for both irrigation and domestic use.

Overall, Chhattisgarh's climate outlook portrays a clear warming trajectory and a moderate to high risk of rainfall decline, especially toward the central and eastern parts of the state. The intensification of heatwaves, warmer nights, and reduced rainfall will have direct implications on agriculture, forest health, and water security. Immediate adaptation strategies, such as improved water harvesting, heat-tolerant crop varieties, afforestation, and green urban planning, will be essential to mitigate the adverse impacts and ensure long-term sustainability.

#### **2.4 Projected Changes in mean annual precipitation and temperature in the Odisha region MRB**

The below table presents a coherent but spatially uneven intensification of precipitation across the Odisha portion of the Mahanadi River Basin (MRB) when comparing long-term observed conditions with projected changes across near-, mid-, and far-future periods. Observed mean annual precipitation during the baseline period (1901–2023) ranges from ~1247 mm in Nabarangpur and ~1275 mm in Nuapada to more than 1600 mm in coastal and deltaic districts such as Jajpur, Kendrapara, Jagatsinghpur, and Dhenkanal, highlighting the strong inland-coastal rainfall gradient that already exists in the basin. Future projections indicate that most districts experience a progressive increase in annual precipitation, with the magnitude of change strengthening toward the far-future period (2071–2100), pointing to a basin-wide wetting tendency under changing climate conditions.

The western and interior districts including Sambalpur, Jharsuguda, Bargarh, Subarnapur, Kalahandi, Nuapada, and Balangir show some of the largest absolute increases in precipitation, despite having moderate baseline rainfall. Sambalpur emerges as a hotspot of future intensification, with projected mean annual precipitation rising from ~1489 mm in the observed period to over 2170 mm in the far future, representing one of the strongest increases in the basin (Table 7). Similar robust increases are evident in Bargarh, Subarnapur, Jharsuguda, and Sundargarh, where far-future precipitation exceeds 2100 mm, suggesting heightened flood potential and increased variability in runoff generation in these upstream catchments.

In the central MRB districts such as Anugul, Deogarh, Dhenkanal, Boudh, and Nayagarh, the projections indicate a steady and sustained increase across all future periods, with Deogarh and Dhenkanal showing particularly strong long-term intensification. These districts transition from moderately high baseline rainfall to substantially wetter future regimes, implying greater pressure on reservoir operations, soil saturation, and erosion processes. Kalahandi exhibits a distinct pattern, with near-future rainfall remaining almost stable relative to the observed period, followed by a sharp rise in mid- and far-future projections, indicating a delayed but pronounced climate response.

The coastal and deltaic districts including Cuttack, Jagatsinghpur, Kendrapara, Khordha, and Puri display a more complex signal. While mid- and far-future periods generally show increasing precipitation, several districts (Khordha, Puri, Jajpur, and Kendrapara) experience a near-future decline relative to the observed baseline, followed by partial recovery and subsequent increase. This non-monotonic behavior suggests possible shifts in monsoon timing, intra-seasonal variability, or model sensitivity to coastal processes rather than a simple linear increase. Nevertheless, by the far future, even these districts show higher rainfall than present-day conditions, with Jagatsinghpur and Cuttack exceeding ~2000 mm, indicating an enhanced risk of urban flooding and waterlogging in low-lying coastal zones.

Overall, the projected precipitation changes for the Odisha MRB indicate a dominant wetting trend with increasing spatial contrast, where already wet districts become wetter and relatively drier interior districts experience substantial absolute gains. The combination of increasing precipitation totals, particularly in the far future, and the presence of near-term declines in some coastal districts underscores the importance of adaptive, district-specific water resource planning. These findings imply heightened challenges related to flood management, sediment transport, reservoir safety, and agricultural water management, reinforcing the need to integrate long-term climate projections into basin-scale hydrological and infrastructural decision-making rather than relying solely on historical rainfall patterns.

**Table 7.** District-wise Observed (1901–2023) and Projected Changes in Precipitation for the Odisha region MRB From EC-Earth3.

District	Observed Mean Annual Precipitation (1901–2023)	Projected Precipitation Near Future	Projected Precipitation Mid Future	Projected Precipitation Far Future	Key Observation
	mm				
Anugul	1394.41	1511.18	1632.82	1950.33	Steady increase with strong long-term intensification.
Balangir	1389.24	1446.54	1629.66	1941.03	Gradual rise accelerating toward the far future.
Bargarh	1423.97	1584.30	1749.01	2118.68	Consistent and substantial increase across all periods.
Cuttack	1546.63	1589.75	1691.75	1957.97	Moderate increase, more pronounced in the far future.
Deogarh	1535.99	1659.34	1825.51	2154.25	Strong continuous increase in all future periods.
Dhenkanal	1595.30	1650.30	1738.27	2043.01	Mild near-term rise, sharper far-future increase.
Ganjam	1308.21	1321.98	1430.49	1505.73	Progressive increase indicating a future wetting trend.
Jagatsinghpur	1595.32	1613.04	1739.97	2107.18	Minor near-term change, strong mid- to long-term rise.
Jajapr	1623.84	1601.38	1721.46	1917.90	Slight near-future decline followed by later increase.
Jharsuguda	1445.24	1592.53	1746.58	2134.53	Strong and sustained increase throughout.
Kalahandi	1461.49	1466.70	1676.04	2057.98	Near-stable initially, sharp rise in later periods.
Kandhamal	1421.23	1434.37	1564.63	1811.46	Mild but consistent increase over time.

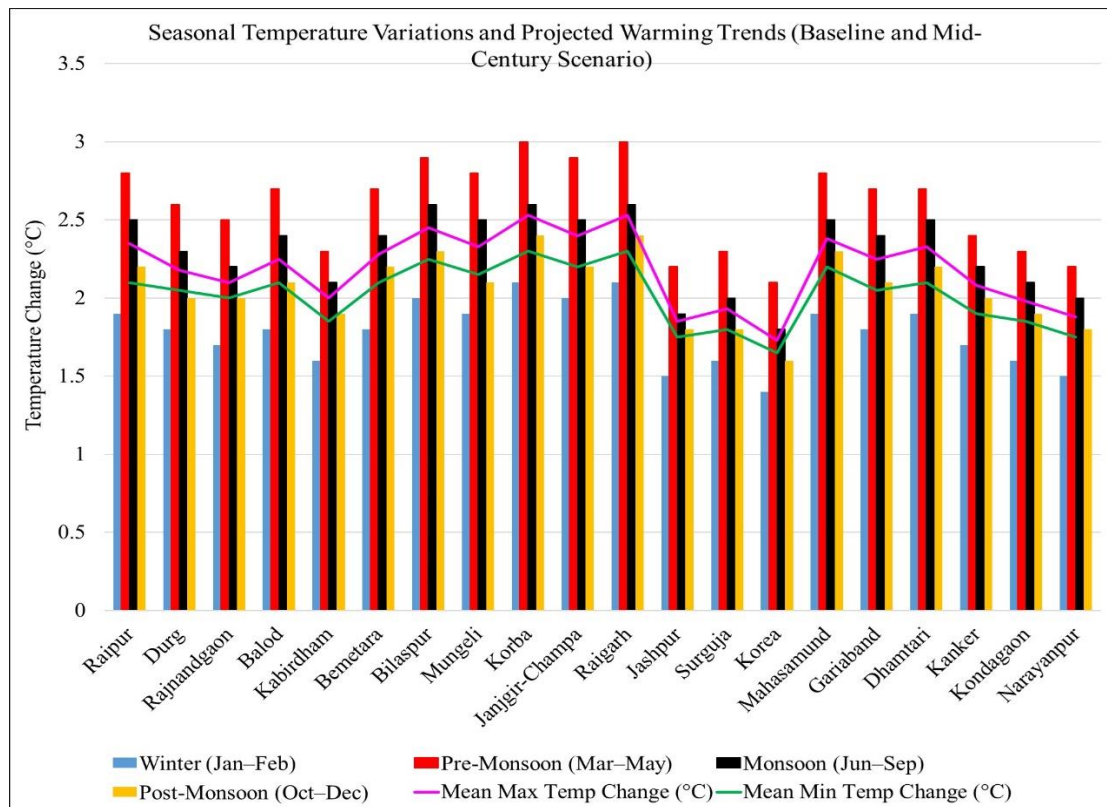
Kendrapara	1623.84	1601.38	1721.46	1917.90	Initial decline followed by recovery and increase.
Khordha	1526.02	1396.37	1498.64	1734.79	Noticeable near-term decrease with partial recovery later.
Nabarangpur	1246.57	1296.53	1454.22	1732.77	Gradual increase, remaining relatively low overall.
Nayagarh	1412.01	1475.13	1570.32	1811.76	Stable moderate increase across future periods.
Nuapada	1274.69	1311.34	1468.67	1749.25	Slow but consistent wetting trend.
Puri	1434.65	1385.88	1471.97	1501.52	Near-term decrease with weak long-term recovery.
Sambalpur	1489.23	1642.75	1810.98	2173.03	One of the strongest increases toward the far future.
Subarnapur	1501.43	1581.70	1757.11	2116.09	Steady and robust increase across periods.
Sundargarh	1387.53	1556.71	1696.39	2049.75	Significant increase, especially in the far future.
Boudh	1410.07	1479.93	1612.03	1911.50	Moderate increase strengthening over time.

Note: Baseline period (1901–2023), Mid-Future (2026–2040), Mid-Future (2041–2070) and Far Future (2071–2100).

### 2.3.1 District-wise Seasonal Temperature Variations and Projected Warming Trends for Chhattisgarh Region MRB

The analysis of projected seasonal temperature changes for Chhattisgarh suggests an overall warming pattern across all districts for both mean maximum and mean minimum temperatures. The seasonal rise is most significant during the pre-monsoon (March–May) and monsoon (June–September) periods, indicating increased heat stress before and during the core agricultural months. Across most districts, the mean maximum temperature is expected to increase by 2.0°C to 3.0°C, while the minimum temperature shows a slightly lower increase, ranging from 1.8°C to 2.5°C. This suggests both day and night temperatures are likely to remain elevated in the coming decades (Figure 6).

In the central belt of Chhattisgarh, including Raipur, Durg, Balod, and Bemetara, the projected temperature rise is relatively higher than the state average. These regions show pre-monsoon warming up to 2.8–3.0°C, attributed to urbanization, reduced vegetation cover, and increased anthropogenic heat. The simultaneous rise in nighttime temperatures suggests a reduction in diurnal temperature range, which can adversely affect crop productivity and human comfort levels. This region may experience more frequent hot days and warm nights, thereby intensifying the overall heat stress.



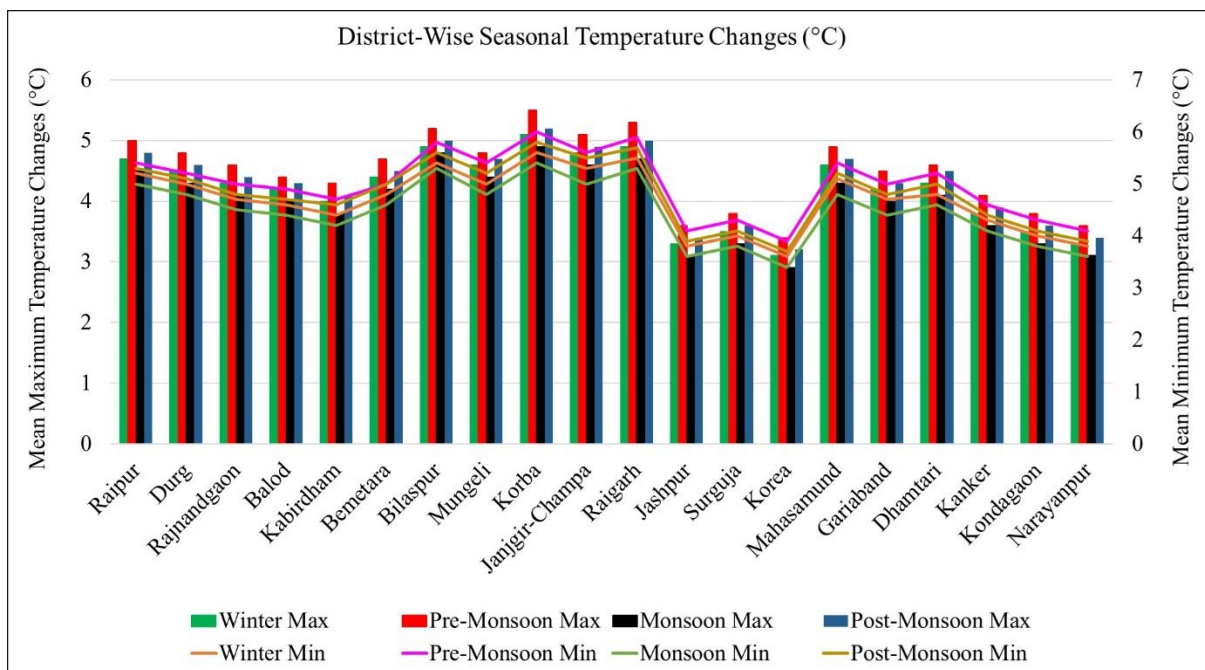
**Figure 6.** Seasonal Temperature Variations and Projected Warming Trends (Baseline and Mid-Century Scenario).

The northern hill districts, namely Korea, Surguja, and Jashpur, exhibit relatively moderate

warming compared to the plains. The seasonal temperature rise remains within 1.5–2.3°C for both maximum and minimum temperatures. Dense forest cover, higher elevation, and less industrial interference contribute to this moderation. However, even a small temperature rise in these ecosystems can shift species composition, alter forest dynamics, and affect water retention capacity. Jashpur, being a cooler region, is projected to experience the least heat amplification among all districts analyzed.

The eastern industrial districts, particularly Korba, Janjgir-Champa, and Raigarh, are expected to face the highest thermal intensification, with a mean maximum temperature increase of 2.5–3.0°C. Industrial emissions, extensive mining activities, and reduced vegetation density are major contributors to these patterns. Such increases can amplify urban heat island effects and deteriorate air quality, while also leading to increased surface evaporation and a decline in water availability. These factors highlight the urgent need for emission mitigation and greening interventions in these districts.

In southern and transitional districts such as Kanker, Kondagaon, and Narayanpur, the projected temperature increase remains relatively mild, ranging from 1.8°C to 2.3°C. These districts, dominated by forests and rural settlements, have lower anthropogenic pressure. Nevertheless, rising temperatures may gradually impact forest health, soil moisture retention, and local biodiversity. Narayanpur stands out as the least affected district, with the most stable thermal regime due to dense vegetation and limited industrial exposure.



**Figure 7.** District-Wise Seasonal Mean Maximum and Minimum Temperature Changes (°C) for End-Century Relative to Baseline in Chhattisgarh, MRB.

(CS Change - Raipur: action for the climate today, 2019)

Overall, the seasonal projection reveals that pre-monsoon and monsoon months will experience

the most pronounced warming, posing challenges for agriculture, water management, and ecosystem balance. The increasing trend in minimum temperatures across all districts suggests warmer nights, fewer cooling periods, and potential health impacts. These changes collectively call for adaptive measures such as heat-resilient crop varieties, afforestation, green urban infrastructure, and efficient water resource management. Strengthening local climate governance and community awareness will be crucial to mitigate these mid-century climatic risks.

The analysis of seasonal projections for the end-century period reveals a consistent and significant increase in both maximum and minimum temperatures across Chhattisgarh. On average, maximum temperature rise varies between 3°C and 6°C, while minimum temperatures rise slightly more, between 3.5°C and 6.5°C, suggesting warmer nights and reduced diurnal variation. This long-term warming aligns with regional climate model projections and indicates intensifying heat stress, extended summer duration, and a potential shift in monsoon onset and retreat patterns.

During winter, most districts exhibit warming in the range of 3°C–5.5°C for maximum temperature and 3.5°C–6°C for minimum temperature (Figure 7). The central plains Raipur, Durg, and Bilaspur, show the strongest anomalies, with Raipur reaching up to 5°C in daytime highs. Northern districts like Korea and Jashpur remain relatively cooler, though they still warm considerably compared to the historical baseline. Elevated winter minimums imply milder winters, possibly impacting Rabi crops and reducing the chilling hours required for certain crops.

The pre-monsoon period records the highest warming rates across the state, with daytime temperatures exceeding 5°C in Korba and Bilaspur, and nighttime temperatures reaching up to 6.3°C in the same zones. This season is critical because of its link to agricultural sowing and water stress. Such intense warming, especially before monsoon rainfall begins, will increase evapotranspiration, amplify drought intensity, and challenge groundwater sustainability, particularly in industrial belts like Raigarh and Janjgir-Champa.

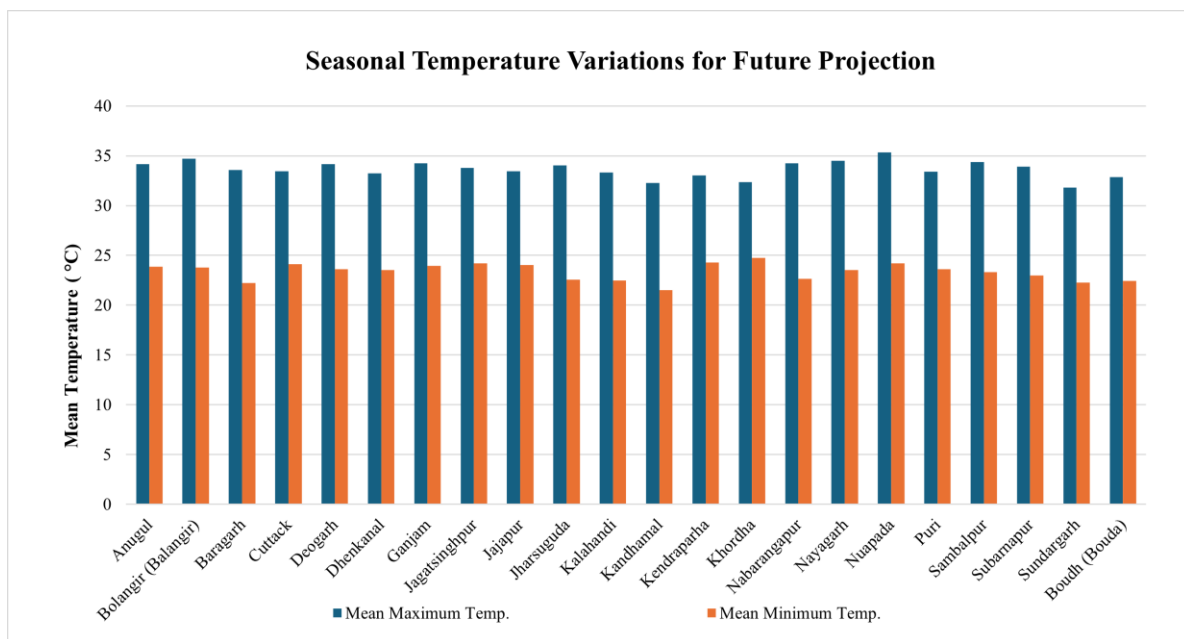
The monsoon season shows a surprisingly high warming trend, with average maximum temperature increases of 4.5–6°C and minimums up to 6.5°C. Central and eastern districts, notably Korba and Bilaspur, display the most pronounced changes. These shifts may alter rainfall intensity and reduce rainfall efficiency due to increased atmospheric heat content. Nighttime warming during monsoon months also affects soil moisture retention and crop yield patterns, stressing both water and energy resources.

Post-monsoon trends remain like winter, with warming rates between 3.5°C and 5.5°C across districts. The persistence of elevated temperatures after the monsoon season points to delayed cooling and prolonged heat retention in the atmosphere. Such patterns may reduce groundwater recharge efficiency and increase evapotranspiration during post-harvest periods. The rise in minimum temperatures during this phase also indicates a transition towards a consistently warm climate state throughout the year.

Spatially, the central (Raipur, Durg) and eastern (Korba, Bilaspur, Raigarh) regions experience the most pronounced warming, while northern hill districts (Korea, Jashpur, Surguja) and southern forested regions (Kanker, Kondagaon, Narayanpur) exhibit moderated increases. The widespread warming in both maximum and minimum temperatures imply persistent heat stress, reduced cold-season relief, and altered hydrological cycles. Adaptive interventions such as enhancing green cover, adopting heat-resilient crops, improving irrigation efficiency, and integrating temperature projections into regional planning will be essential for long-term sustainability.

### 2.3.2 District-wise Seasonal Temperature Variations and Projected Warming Trends for Odisha Region MRB

The district-wise analysis reveals a clear thermal gradient across Odisha, with mean maximum temperatures ranging from 31.8 °C in Sundargarh to 35.35 °C in Nuapada (Figure 8), confirming the dominance of interior and western districts as thermal hotspots. Coastal districts such as Khordha, Puri, Jagatsinghpur, and Kendrapara consistently record lower maximum temperatures ( $\approx 32\text{--}33$  °C) but higher minimum temperatures ( $\approx 24\text{--}25$  °C), reflecting strong maritime moderation and reduced nocturnal cooling. In contrast, southern and western districts notably Nabarangapur, Kandhamal, Kalahandi, and Sundargarh - exhibit lower minimum temperatures ( $\approx 21\text{--}22$  °C), indicative of continental influence and greater diurnal range.

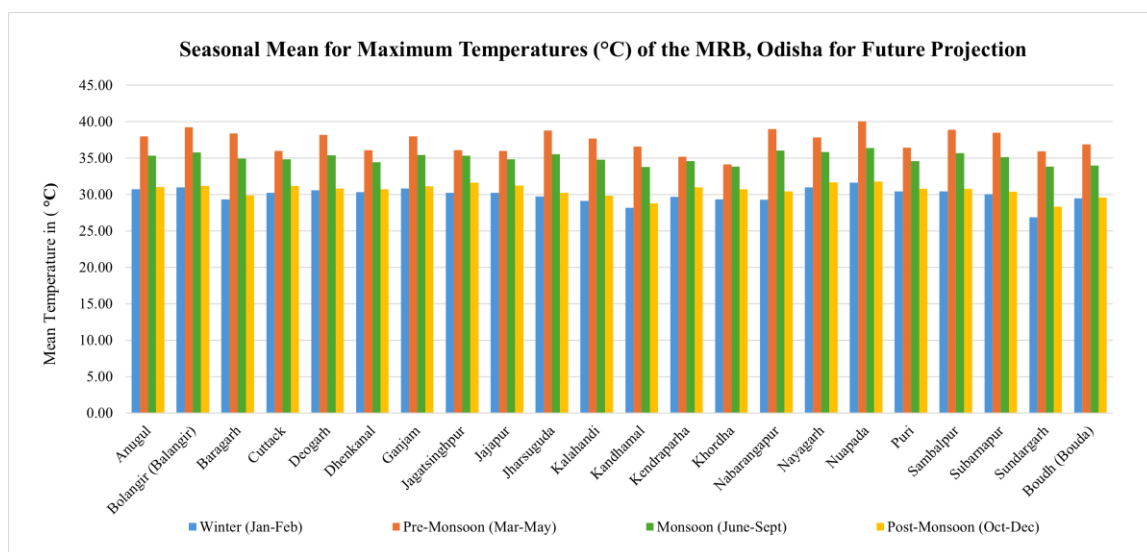


**Figure 8.** Seasonal temperature variation across the Odisha region or the Mahanadi River basin for Future Projection (2026-2100).

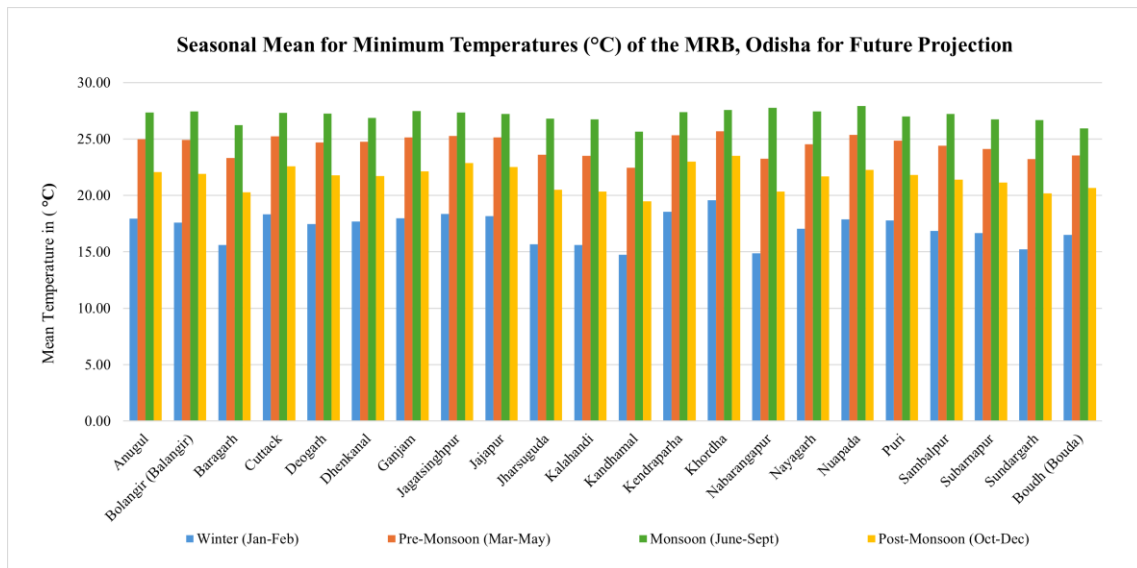
The coefficient of variation (CV) exposes a pattern you cannot ignore temperature variability is systematically higher in interior districts. Maximum temperature CV peaks in Nabarangapur (23.15 %), Sundargarh (21.10 %), and Kandhamal (20.72 %), signalling greater interannual instability and higher climate sensitivity. Minimum temperature variability follows the same spatial logic, with CVs exceeding 14 % in several western and southern districts, while coastal

districts remain relatively stable ( $CV < 9\%$ ). This asymmetry confirms that climate variability - and therefore climate risk - is not evenly distributed, with interior Odisha facing both higher extremes and higher uncertainty, a point that must be explicitly acknowledged in any climate impact or adaptation assessment.

The seasonal temperature structure across the Mahanadi River Basin (MRB), Odisha, exhibits a clear and internally consistent thermal regime marked by strong pre-monsoon heating, moderated monsoon conditions, and relatively mild winters. District-wise winter (January–February) maximum temperatures are spatially constrained, generally ranging between  $\sim 27\text{--}31.6\text{ }^{\circ}\text{C}$ , with the lowest values observed in Sundargarh ( $26.88\text{ }^{\circ}\text{C}$ ) and the highest in Nuapada ( $31.61\text{ }^{\circ}\text{C}$ ) (Figure 9), indicating limited winter-time thermal contrast across the basin. In contrast, the pre-monsoon season (March–May) shows pronounced heating and spatial variability, with maximum temperatures frequently exceeding  $38\text{ }^{\circ}\text{C}$  in interior western districts such as Nuapada ( $40.06\text{ }^{\circ}\text{C}$ ), Bolangir ( $39.24\text{ }^{\circ}\text{C}$ ), Nabarangapur ( $39.00\text{ }^{\circ}\text{C}$ ), Sambalpur ( $38.90\text{ }^{\circ}\text{C}$ ), and Rayagada ( $38.89\text{ }^{\circ}\text{C}$ ), clearly identifying this season as the dominant thermal stress period in the MRB. Monsoon (June–September) maximum temperatures decline modestly to  $\sim 33.8\text{--}36.4\text{ }^{\circ}\text{C}$ , reflecting cloud cover and rainfall moderation, yet interior districts like Nuapada, Rayagada, and Nabarangapur still retain elevated thermal levels, indicating persistent continental influence. Post-monsoon (October–December) maxima further reduce to  $\sim 28.3\text{--}31.8\text{ }^{\circ}\text{C}$ , with coastal and deltaic districts such as Puri, Jagatsinghpur, Khordha, and Kendrapara exhibiting relatively higher retained warmth due to maritime moderation. Minimum temperatures follow a parallel seasonal progression: winter minima range from  $\sim 14.7\text{--}19.6\text{ }^{\circ}\text{C}$ , with the lowest values in upland and forested districts like Kandhamal and Nabarangapur, while pre-monsoon and monsoon minima rise sharply to  $\sim 22\text{--}28\text{ }^{\circ}\text{C}$ , peaking during the monsoon season, particularly in humid coastal districts (Khordha, Kendrapara, Puri). Overall, the dataset clearly delineates a west–interior heat dominance during pre-monsoon, monsoon thermal moderation without full relief, and coastal buffering of minimum temperatures, underscoring strong physiographic and seasonal controls on temperature variability across the MRB.



**Figure 9.** District-Wise Seasonal Mean Maximum Temperatures ( $^{\circ}\text{C}$ ) for future projection the MRB, Odisha (2026-2100).



**Figure 10.** District-Wise Seasonal Minimum Temperatures (°C) for future projection the MRB, Odisha (2026-2100).

The district-wise comparison of observed (1951–2023) and projected temperature changes across the Mahanadi River Basin (MRB), Odisha, reveals a clear and non-uniform warming signal, with minimum temperatures increasing more rapidly than maximum temperatures in most districts, indicating a systematic intensification of night-time warming. Observed mean maximum temperatures during the historical period range from approximately 31.4 to 32.7 °C, while projected maximum temperatures rise to ~32.3–35.4 °C, with the most pronounced increases in Nuapada (35.35 °C), Balangir (34.70 °C), Nayagarh (34.48 °C), Sambalpur (34.39 °C), and Nabrangpur (34.25 °C), highlighting strong future heat intensification in the western and interior districts (Figure 10). In contrast, districts such as Kandhamal and Sundargarh exhibit comparatively muted increases in projected maximum temperature, reflecting the moderating influence of elevation, forest cover, and physiographic controls. Observed mean minimum temperatures, which historically range between ~18.5 and 21.2 °C, show a substantial projected rise to ~22.3–24.8 °C, with Khordha (24.75 °C), Kendrapada (24.30 °C), Jagatsinghpur (24.21 °C), Nuapada (24.20 °C), and Jajpur (24.02 °C) (Table 8) experiencing the strongest increases. The consistently larger rise in minimum temperature relative to maximum temperature across coastal and deltaic districts such as Cuttack, Khordha, Puri, and Kendrapada points to enhanced humidity, urbanization effects, and reduced nocturnal cooling, whereas interior districts such as Jharsuguda and Nabrangpur retain a stronger maximum-temperature signal. Overall, the data indicate a basin-wide transition toward warmer days and disproportionately warmer nights, with spatial contrasts driven by topography, land–atmosphere interactions, and proximity to the coast, underscoring heightened risks related to heat stress, reduced thermal comfort, and altered agro-climatic conditions across the MRB under future climate scenarios.

**Table 8.** District-wise Observed (1951–2023) and Projected Changes in Temperature for the Odisha region MRB.

District	Observed Mean Max Temp (°C, 1951–2014)	Projected Max Temp (°C, 2026–2100)	Observed Mean Min Temp (°C, 1951–2014)	Projected Min Temp (°C, 2026–2100)	Key Observation
Anugul	31.65	34.16	19.16	23.87	Strong increase in both maximum and minimum temperatures, with higher warming in minimum temperature.
Balangir	32.38	34.70	20.25	23.79	Significant rise in maximum temperature accompanied by substantial minimum temperature warming.
Baragarh	32.32	33.59	20.02	22.25	Moderate increase in maximum temperature with relatively lower rise in minimum temperature.
Cuttack	31.63	33.43	19.30	24.10	Clear warning signal, with stronger increase in minimum temperature than maximum.
Deogarh	31.68	34.15	19.35	23.61	Pronounced warming in both maximum and minimum temperatures.
Dhenkanal	31.64	33.23	19.31	23.52	Moderate maximum temperature rises with strong minimum temperature increase.
Ganjam	31.60	34.24	19.28	23.97	Strong warming trend, particularly evident in minimum temperature.
Jagatsinghpur	31.44	33.76	18.50	24.21	Substantial increase in minimum temperature, indicating warmer nights.
Jajapr	31.44	33.46	18.50	24.02	Consistent warming, with minimum temperature increasing faster than maximum.
Jharsuguda	32.22	34.05	19.76	22.57	Strong maximum temperature rises but comparatively lower minimum temperature increase.
Kalahandi	32.45	33.33	20.30	22.48	Moderate increase in both maximum and minimum temperatures.

Kandhamal	32.04	32.28	19.60	21.50	Least warming among districts, especially in maximum temperature.
Kendrapada	31.44	33.01	18.50	24.30	Strong minimum temperature increase, suggesting enhanced nighttime warming.
Khordha	31.66	32.37	19.33	24.75	Exceptional rise in minimum temperature, indicating pronounced night-time warming.
Nabrangpur	32.74	34.25	20.75	22.64	Strong warming signal, with higher increase in maximum temperature.
Nayagarh	31.68	34.48	19.22	23.55	Significant increase in both maximum and minimum temperatures.
Nuapada	31.83	35.35	21.19	24.20	Highest projected increase in maximum temperature among districts.
Puri	31.66	33.39	19.33	23.63	Moderate warming with stronger rise in minimum temperature.
Sambalpur	31.69	34.39	19.06	23.34	Strong and consistent increase in both temperature extremes.
Subarnpur	32.28	33.92	19.89	23.00	Moderate increase, with balanced warming of max and min temperatures.
Sundargarh	32.00	31.81	19.56	22.28	Lowest projected increase in maximum temperature but notable rise in minimum temperature.
Boudh (Bouda)	32.10	32.86	19.72	22.45	Moderate warming in both maximum and minimum temperatures.

## 2.4 Surface Water and Groundwater Resources

Chhattisgarh is predominantly an agrarian state, with more than four-fifths of its population earning their livelihood from farming. Forests occupy nearly 44% of its geographical area, and the Scheduled Tribe community constitutes about 32% of the total population. By 2011, the state had developed an irrigation potential of nearly 18.09 lakh hectares; however, only around 11.62 lakh hectares were irrigated. The total cultivated area in Chhattisgarh is approximately 56.83 lakh hectares. Consequently, the share of irrigated land stands at about 31.83%, which remains significantly below the national average of 48.90%.

Currently, the state has completed 7 major, 33 medium, and 2,335 minor irrigation schemes. In addition, 4 major, 6 medium, and 412 minor irrigation projects are still in progress. Some of the key ongoing projects include Minimata Bango, Rajiv Samoda Phase-II, Sondhur, Kelo, Kosarteda, and Karranalla Barrage. The principal river systems supporting these developments are the Mahanadi, Shivanth, Hasdeo, and Indravati rivers. Given the crucial role of agriculture in the state's economy, the efficient development and management of water resources remain central to Chhattisgarh's long-term growth.

Odisha's economy within the Mahanadi River Basin is predominantly agrarian, with a substantial proportion of the population directly dependent on agriculture and allied activities for livelihood. The basin encompasses some of the state's most agriculturally productive districts, particularly in the coastal plains and deltaic regions, while the upper and middle reaches are characterized by rain-fed farming systems and significant forest cover. Forests account for a considerable share of land use in the basin, especially in districts such as Kandhamal, Deogarh, Sundargarh, and Rayagada, and Scheduled Tribe communities form a major component of the population in these upland and interior regions. Irrigation development in the Odisha part of the Mahanadi basin has expanded over time through a network of major, medium, and minor irrigation projects; however, a large portion of cultivated land continues to depend on monsoon rainfall, making agricultural production highly sensitive to inter-annual and seasonal rainfall variability. The basin is supported by several major irrigation systems, including the Hirakud, Rengali, and Upper Indravati projects, along with numerous medium and minor schemes that utilize both surface and groundwater resources. Despite these developments, spatial disparities in irrigation coverage persist, with relatively higher irrigation intensity in the deltaic districts and limited assured irrigation in the western and southern parts of the basin. The Mahanadi and its tributaries such as the Brahmani, Baitarani, Tel, and Ong rivers form the backbone of the basin's water resources, supporting agriculture, hydropower generation, and domestic water supply. Given the increasing pressures from population growth, agricultural intensification, and climate-induced variability in rainfall and temperature, the sustainable and integrated management of water resources in the Odisha part of the Mahanadi basin remains critical for ensuring long-term agricultural productivity, livelihood security, and regional development.

### 2.4.1 Projected Water Availability, Allocation, and Regeneration Scenario for Chhattisgarh

The assessment of Chhattisgarh’s water resources for the year 2040 shows that the state begins with an estimated 62,844 MCM of water, derived from both surface and groundwater sources (Table 9). Surface water contributes a major share, while groundwater acts as an important supplementary source that enhances overall resilience. This initial estimate forms the benchmark for planning future allocations and ensuring that the state can sustain its growing demands.

A forward-looking allocation plan distributes the available water among domestic, agricultural, and industrial needs. Agriculture remains the largest consumer, accounting for 50% of the total available water due to the ambitious plan to irrigate 40 lakh hectares by 2040. Domestic requirements are projected to take up 20%, ensuring adequate provisions for drinking, household use, and community water systems. The industrial sector, though smaller in proportion, is allocated 5%, reflecting expected growth in manufacturing and allied activities.

**Table 9.** Projected Water Availability, Allocation, and Regeneration in Chhattisgarh.

S. No.	Component	Descriptions	Quantity (MCM)
1	Primary Water Availability	Surface Water	48,296
		Groundwater	14,548
		<b>Total Initial Availability</b>	<b>62,844</b>
2	Proposed Water Allocation (2040)	Domestic Use (20%)	12,569
		Agricultural Use (50%)	31,422
		Industrial Use (5%)	3,142
		<b>Total Allocated Quantity</b>	<b>47,133</b>
3	Balance Water Before Regeneration	Remaining Quantity	<b>15,711</b>
4	Regenerated Water	From Domestic Use (50%)	6,285
		From Agriculture (10%)	3,142
		From Industries (50%)	1,571
		<b>Total Regenerated Water</b>	<b>10,998</b>
5	Final Water Availability (2040)	Balance + Regenerated Water	<b>26,709</b>

(CS Change - Raipur: action for the climate today, 2019)

After allocating 47,133 MCM, the state is left with 15,711 MCM of unutilized water, which forms a crucial buffer. However, the real strength of the water system emerges through regeneration. Treated domestic wastewater, partial return flows from irrigation, and industrial recycling together add 10,998 MCM back into the system. This regenerated water significantly enhances the overall sustainability of water resources by reducing the pressure on primary sources. By

combining the unutilized water with regenerated flows, Chhattisgarh is projected to have 26,709 MCM of water available for contingency, ecological maintenance, and future developmental needs. This represents a substantial reserve that can help the state address uncertainties related to climate variability, uneven monsoons, or unexpected surges in demand.

Overall, the projections indicate that with strategic allocation and efficient regeneration, Chhattisgarh can maintain a strong water security position by 2040. The calculated reserve ensures that not only immediate needs are met, but long-term sustainability is also safeguarded through prudent resource management and recycling initiatives.

#### **2.4.2 District-Wise Groundwater Recharge, Extraction, and Availability Status in Chhattisgarh, MRB**

The groundwater assessment across the districts of Chhattisgarh highlights considerable variation in recharge, extraction pressure, and future availability, as presented in Appendix I. Districts with strong monsoonal recharge and well-managed extraction practices exhibit healthier aquifer conditions, while others are under mounting stress due to intensive irrigation demands. Statistically, recharge contributions from rainfall dominate the total annual groundwater potential, accounting for more than 78% of the total recharge volume across districts. The statewide mean stage of extraction stands at 47.32%, placing Chhattisgarh in the “safe” category, yet several districts individually exceed safe thresholds and require strategic interventions.

Balod demonstrates a moderately stressed groundwater regime with a stage of extraction of 73.98%, signaling a rising pressure on available resources. Despite substantial recharge from rainfall and other sources, extraction for irrigation remains the dominant driver of depletion. Baloda Bazar, by contrast, has a relatively lower extraction stage of 43.02%, indicating better groundwater sustainability. The district benefits from a higher recharge volume and comparatively moderate industrial and domestic withdrawals. Key observations suggest that while Balod requires stricter control measures, Baloda Bazar should focus on maintaining its current water-efficient practices.

Bemetara records one of the highest extraction levels in the state, at 92.81%, which places it in a critical category according to standard groundwater norms. The intensive agricultural footprint significantly contributes to this stress. Bilaspur, however, remains in a semi-critical state with a stage of extraction of 60.11%, backed by strong recharge inputs from monsoon and non-monsoon sources. Statistical review indicates that Bilaspur’s domestic extraction accounts for roughly 14% of its total withdrawals, suggesting that agricultural demand remains the primary driver of groundwater pressure.

Dhamtari exhibits a stressed aquifer condition with an extraction stage of 73.09%, influenced heavily by large irrigation withdrawals during the non-monsoon season. Despite strong rainfall-based recharge, demand continues to exceed sustainable limits. Durg also shows elevated stress with an extraction stage of 75.21%, reflecting intense agricultural dependency and industrial requirements. Both districts show a distinct statistical pattern: irrigation represents over 80%

of total groundwater extraction, indicating the need for micro-irrigation and crop diversification strategies.

Gariaband records a moderate extraction level of 63.41%, benefiting from balanced recharge across monsoon and non-monsoon periods (Appendix I). While irrigation remains the dominant user, domestic withdrawal contributes nearly 6–7% of total extraction. Gorela-Pendra-Marwahi exhibits a safer extraction stage of 39.43%, suggesting minimal stress on groundwater systems. The district's relatively low industrial footprint and moderate irrigation withdrawals account for its stable groundwater status. Key statistical insights show that rainfall recharge forms over 70% of its annual groundwater input.

Janjgir-Champa records a relatively low extraction stage of 25.47%, indicating a healthy groundwater regime supported by strong annual recharge totals. The district's substantial rainfall-based recharge plays a crucial role in maintaining aquifer stability throughout the year. Jashpur, with an extraction stage of 48.29%, also remains within the safe limit, though irrigation continues to be the dominant user. Statistical evidence shows that domestic extraction in Jashpur constitutes nearly 10% of total usage, which is higher than the state average and warrants improved urban supply management.

Kabirdham shows considerable stress with an extraction stage of 59.04%, driven by high irrigation withdrawals during peak agricultural months (Appendix I). Monsoonal recharge remains high, yet storage depletion continues to accelerate, indicating the need for artificial recharge measures. Kanker, on the other hand, demonstrates a safer extraction level of 37.71%, supported by robust groundwater recharge exceeding 55,000 hams annually. Key observations suggest that while Kabirdham requires substantial groundwater governance improvements, Kanker demonstrates resilience due to its extensive forest cover and lower agricultural extraction intensity.

Khairagarh-Chhuikhadan-Gandai reports a moderate extraction stage of 62.84%, driven largely by irrigation demand and lower non-monsoon recharge volume. Kondagaon shows a slightly safer extraction level of 43.16%, primarily due to its balanced recharge regime and relatively moderate industrial withdrawal. Statistical review highlights that these districts collectively contribute nearly 6% of the state's total annual recharge, demonstrating their importance in the regional groundwater budget.

The remaining districts display a wide range of extraction stages, from as low as 7.33% in Narayanpur to a high of 75% in Rajnandgaon (Appendix I). Districts such as Korea (49.25%), Surguja (47.56%), and Sakti (47.69%) fall within the safe-use classification yet display signs of increasing agricultural pressure. Raipur and Mahasamund exhibit higher extraction levels above 59%, reflecting rapidly growing irrigation and domestic demands. Statistically, these districts together contribute nearly 45% of the total groundwater extraction in the state. Key observations suggest that while some districts remain in safe zones, others are edging toward semi-critical categories, underscoring the urgent need for targeted groundwater conservation programs and demand-side regulation.

### 2.4.3 Projected Changes in Water Balance Components for the Chhattisgarh Part of the Mahanadi River Basin in Monsoon Season

The SWAT model projections for the Chhattisgarh segment of the Mahanadi River Basin under the IPCC AR5 RCP 4.5 climate scenario (2041–2060 vs. 1981–2010) reveal spatially variable but hydrologically coherent trends across the basin's districts. The analysis indicates a moderate rise in monsoonal precipitation of approximately 1–5%, equivalent to around 27 mm increase in total rainfall. This enhancement is primarily observed in Raipur, Mahasamund, Janjgir-Champa, and Baloda Bazar, reflecting improved water availability potential during the June–September season. However, despite this modest rainfall increase, downstream hydrological responses show mixed behavior, highlighting the influence of other controlling factors such as infiltration and evapotranspiration dynamics.

A substantial reduction in surface runoff (–30% to –50%) is projected for several districts, particularly Bemetara, Dhamtari, and Baloda Bazar. These areas, located within the central Chhattisgarh Plains, may experience decreased streamflow and lower flood peaks despite higher rainfall totals. The reduced runoff may be attributed to enhanced infiltration and soil moisture storage, potentially altering surface drainage and sediment transport patterns within the basin. Such changes could impact reservoir inflows and irrigation water availability, necessitating careful management of monsoonal water surpluses.

Evapotranspiration (ET) displays a widespread decline of 30–50%, most notably across the northern and eastern parts of the basin encompassing Bilaspur, Raigarh, and Jashpur. Lower ET rates suggest increased soil moisture retention and potentially cooler microclimatic conditions. This reduction could benefit crop water use efficiency but may also influence local convection processes, possibly modifying monsoonal rainfall distribution patterns across the basin.

The projections for baseflow (BF) and groundwater recharge (GW) exhibit contrasting yet complementary trends. Baseflow changes remain marginal (–10% to +10%), implying a near-stable subsurface contribution to river discharge. Meanwhile, groundwater recharge shows a notable improvement (+10% to +30%) in Korba, Raigarh, and Janjgir-Champa, reflecting favorable infiltration conditions under projected climatic shifts (Table 10). This could enhance the basin's long-term water storage capacity, particularly in regions already dependent on shallow aquifers for irrigation.

Overall, the net water balance is projected to show a slight positive gain (~3%), suggesting that the Chhattisgarh portion of the Mahanadi Basin may remain hydrologically resilient under moderate climate change. However, the uneven spatial distribution of gains and losses highlights the need for localized adaptation strategies, including improved rainwater harvesting, soil conservation, and aquifer recharge initiatives. Strategic water resource management will be essential to leverage the modest rainfall increase while mitigating reductions in surface runoff and evapotranspiration, ensuring sustainable water security for the mid-century horizon.

**Table 10.** Changes water balance components for the Chhattisgarh part of the Mahanadi River Basin during the monsoon season (JJAS).

Water Balance Component	Trend / Spatial Pattern	Change Category (%)	Dominant Affected Zone (Mahanadi Basin Districts)
Precipitation (PCP)	Moderate increase across most districts	+1% to +5%	Raipur, Baloda Bazar, Janjgir-Champa, Mahasamund
Surface Runoff (SR)	Significant decrease in the central plains and northern districts	-30% to -50%	Bemetara, Dhamtari, Baloda Bazar, Raipur
Baseflow (BF)	Slight decrease to moderate increase; spatially mixed	-10% to +10%	Korba, Kanker, Mahasamund, Durg
Evapotranspiration (ET)	Substantial decline in the northern and eastern basin	-30% to -50%	Bilaspur, Raigarh, Jashpur, Korba
Groundwater Recharge (GW)	Minor to moderate increase in eastern districts	+10% to +30%	Korba, Janjgir-Champa, Raigarh
Net Water Balance	Slight positive change due to rainfall rise	≈ +3% (≈ +27 mm)	Central and eastern plains of the Mahanadi Basin

(CS Change - Raipur: action for the climate today, 2019)

#### 2.4.4 Projected Changes in Water Balance Components for the Chhattisgarh Part of the Mahanadi River Basin in Non-Monsoon Season

The SWAT model projections for the Chhattisgarh segment of the Mahanadi River Basin under the IPCC AR5 RCP 4.5 climate scenario (2041–2060) compared to the baseline period (1981–2010) highlight distinctive changes in water balance components during the October–December (OND) season. The projections indicate a 7% (~9 mm) (Table 11) increase in total rainfall, suggesting a moderate intensification of post-monsoon precipitation over central and eastern districts such as Raipur, Mahasamund, and Janjgir-Champa. This rainfall increase may support late-season agricultural activities but could also alter the recharge dynamics of shallow aquifers.

Despite the modest rainfall rise, surface runoff is projected to decline sharply by 30–50%, particularly across Baloda Bazar, Dhamtari, and Raipur. This decline implies a potential reduction in direct overland flow and a consequent decrease in flood peaks. The projected runoff reduction suggests a shift towards enhanced infiltration and groundwater recharge, modifying the surface–subsurface water interactions. These changes may also affect streamflow timing and reservoir inflows within the Mahanadi Basin, with possible implications for water resource planning and irrigation management.

The evapotranspiration (ET) component shows a significant decline ( $-30\%$  to  $-50\%$ ) across northern and eastern Chhattisgarh, including Bilaspur, Korba, and Raigarh. This reduction could be associated with cooler or less humid post-monsoon conditions, resulting in improved soil moisture retention. Lower ET rates may enhance agricultural water use efficiency; however, they could also influence atmospheric feedback mechanisms, potentially affecting regional rainfall recycling and land-atmosphere coupling processes.

Baseflow (BF) demonstrates spatial variability, ranging from slight decreases to moderate increases ( $-20\%$  to  $+10\%$ ) across the basin. This variation is largely governed by geological and soil permeability differences. Districts such as Korba, Kanker, and Raigarh may experience improved baseflow conditions due to higher infiltration, while others may see a decline due to reduced groundwater contribution to streamflow. On the other hand, groundwater recharge (GW) shows a positive trend ( $+10\%$  to  $+30\%$ ) in eastern districts such as Janjgir-Champa and Raigarh, reflecting enhanced percolation from increased soil moisture and decreased evapotranspiration.

**Table 11.** Changes in water balance components for the Chhattisgarh part of the Mahanadi River Basin during the non-monsoon (OND) season.

Water Balance Component	Change Category (%)	Dominant Affected Zone (Mahanadi Basin)	Remarks
Precipitation (PCP)	+5% to +10%	Raipur, Baloda Bazar, Mahasamund, Janjgir-Champa	Moderate rise in post-monsoon rainfall
Surface Runoff (SR)	-30% to -50%	Dhamtari, Bemetara, Baloda Bazar, Raipur	Reduction in runoff indicates reduced flood potential
Base flow (BF)	-20% to +10%	Korba, Kanker, Mahasamund, Raigarh	Spatially heterogeneous response linked to soil and geology
Evapotranspiration (ET)	-30% to -50%	Bilaspur, Raigarh, Korba, Jashpur	Major reduction in ET rates over northern and eastern basin
Groundwater Recharge (GW)	+10% to +30%	Janjgir-Champa, Korba, Raigarh	Enhanced infiltration potential in eastern basin districts
Net Water Balance	$\approx +7\%$ ( $\sim 9$ mm)	Central and Eastern Plains	Overall improvement in basin-scale water availability

(CS Change - Raipur: action for the climate today, 2019)

Overall, the net water balance indicates a positive gain (~7%) for the Chhattisgarh portion of the Mahanadi Basin, implying a favorable hydro-climatic outlook under moderate climate change. However, the uneven spatial distribution of hydrological responses underscores the need for localized adaptation measures. The combination of decreased surface runoff and evapotranspiration but increased groundwater recharge suggests that future water management strategies should prioritize aquifer recharge enhancement, soil-water conservation, and optimized irrigation scheduling to sustain basin hydrology and agricultural productivity during the mid-century period.

#### 2.4.5 Projected Water Availability, Allocation, and Regeneration Scenario for Odisha

The projected water availability framework for Odisha indicates a total initial resource base of 65,901 MCM, largely dominated by surface water systems, which makes the state highly sensitive to monsoon variability and inter-annual climate fluctuations (Table 12). By 2050, approximately 42,000 MCM is expected to be allocated to various sectors, with agriculture alone consuming nearly 75% of the total demand, reflecting the continued reliance on irrigation-intensive practices and limited shifts toward water-efficient cropping systems.

**Table 12.** Projected Water Availability, Allocation, and Regeneration in Odisha.

S. No.	Component	Descriptions	Quantity (MCM)
1	Primary Water Availability	Surface Water (Average Annual Yield)	51,788
		Groundwater (Replenishable)	14,113
		<b>Total Initial Availability</b>	<b>65,901</b>
2	Proposed Water Allocation (2050)	Domestic Use (~10%)	4,200
		Agricultural Use (~75%)	31,500
		Industrial Use (~15%)	6,300
		<b>Total Allocated Quantity</b>	<b>42,000</b>
3	Balance Water Before Regeneration	Remaining Quantity	<b>23,901</b>
4	Regenerated Water	From Domestic Use (50%)	2,100
		From Agriculture (10%)	3,150
		From Industries (50%)	3,150
		<b>Total Regenerated Water</b>	<b>8,400</b>
5	Final Water Availability (2050)	Balance + Regenerated Water	<b>32,301</b>

*Note: The data presented in the table is sourced from the Vision 2050 document published by the ICAR-Indian Institute of Water Management (IIWM).*

Domestic and industrial sectors together account for about 25% of the total allocation, driven by population growth, urbanization, and industrial expansion. After sectoral allocation, the remaining balance of 23,901 MCM does not imply excess water availability, as a substantial portion is constrained by ecological flow requirements, storage and conveyance losses, spatial-temporal mismatches between supply and demand, and limited accessibility during non-monsoon periods. In this context, regenerated water plays a critical role in augmenting effective availability, with an estimated 8,400 MCM recoverable through wastewater treatment, industrial recycling, and agricultural return flows; however, these recovery assumptions are contingent upon robust infrastructure, regulatory enforcement, and consistent operational efficiency. Consequently, the final effective water availability of 32,301 MCM represents a managed water balance rather than a natural surplus, emphasizing that Odisha's future water security will depend less on absolute resource endowment and more on improvements in water-use efficiency, reuse potential, demand-side management, and institutional capacity, particularly within the agricultural sector where even marginal efficiency gains could yield substantial system-wide benefits.

#### **2.4.6 District-Wise Groundwater Recharge, Extraction, and Availability Status in Odisha, MRB**

The groundwater assessment across the Odisha portion of the Mahanadi River Basin reveals pronounced spatial variability in recharge potential, extraction intensity, and long-term aquifer sustainability, as detailed in Appendix I. Districts located in the upper and middle reaches of the basin, characterized by favourable lithology and higher monsoonal rainfall, generally exhibit stronger recharge conditions, whereas downstream and agriculturally intensive districts face increasing groundwater stress. Statistically, rainfall recharge remains the dominant contributor, accounting for more than 80% of the total annual groundwater recharge across most districts of the basin. At the basin scale, the mean stage of groundwater extraction remains within the "safe" category; however, several districts display extraction levels approaching or exceeding sustainability thresholds, indicating emerging localized stress.

Anugul demonstrates a moderately stressed groundwater regime, with extraction primarily driven by irrigation demand and supplementary industrial use associated with mining and thermal power activities. Despite substantial monsoonal recharge, the growing dependence on groundwater during the non-monsoon period elevates seasonal stress levels. Boudh, by contrast, maintains a relatively lower stage of extraction, supported by balanced recharge and limited industrial withdrawals. The district benefits from comparatively low population density and restrained irrigation intensity, contributing to stable aquifer conditions.

Balangir emerges as one of the more vulnerable districts within the Odisha segment of the Mahanadi Basin, exhibiting high extraction pressure due to intensive agricultural practices and recurrent drought conditions. Groundwater abstraction for irrigation dominates total withdrawals, while recharge remains highly rainfall-dependent and temporally concentrated. Cuttack, despite high domestic and urban demand, remains within a manageable extraction range due to substantial recharge from canal seepage and surface water-groundwater interaction, highlighting the buffering role of conjunctive use in deltaic and floodplain settings.

Dhenkanal presents a semi-stressed groundwater scenario, where expanding irrigation and moderate industrial withdrawals increasingly offset monsoonal recharge gains. The district shows a clear statistical pattern in which agricultural extraction exceeds 75% of total groundwater use, underscoring the sensitivity of aquifer conditions to cropping intensity and irrigation efficiency. Deogarh, on the other hand, retains relatively safe groundwater conditions due to lower abstraction rates and a strong contribution from forest-mediated recharge processes.

Jharsuguda records elevated groundwater stress driven by industrial demand, particularly from power and manufacturing sectors, in addition to irrigation withdrawals. Although rainfall recharge remains substantial, localized over-extraction around industrial clusters poses a growing risk to aquifer sustainability. In contrast, Kendujhar benefits from high recharge associated with hilly terrain and forest cover, which offsets moderate irrigation demand and supports a comparatively stable groundwater regime.

Nayagarh and Subarnapur exhibit moderate extraction stages, with groundwater use dominated by agriculture and limited industrial influence. Recharge remains largely monsoon-controlled, rendering these districts vulnerable to inter-annual rainfall variability. Sambalpur reflects a mixed groundwater condition, where strong recharge from rainfall and canal systems is counterbalanced by rising irrigation withdrawals and urban demand, keeping the district near the upper limit of the safe extraction category.

The lower basin districts, including Jagatsinghpur and Kendrapara, generally display lower stages of groundwater extraction due to greater reliance on surface water irrigation and high natural recharge from alluvial aquifers. However, these districts face quality-related concerns, particularly salinity ingress in coastal and deltaic zones, which constrains effective groundwater availability despite favorable recharge volumes.

Overall, statistical synthesis indicates that a small number of agriculturally intensive and industrially developing districts account for a disproportionately large share of groundwater extraction within the Odisha portion of the Mahanadi Basin. While basin-wide groundwater conditions remain broadly safe at present, the district-level analysis clearly demonstrates emerging stress hotspots driven by irrigation dominance, seasonal abstraction, and uneven recharge distribution. These findings emphasize the urgent need for district-specific groundwater management strategies, including micro-irrigation adoption, artificial recharge interventions, conjunctive use planning, and stricter regulation of industrial abstraction to ensure long-term aquifer sustainability across the basin.

#### **2.4.7 Projected Changes in Water Balance Components for the Odisha Part of the Mahanadi River Basin in Monsoon Season**

The analysis of monsoon-season (JJAS) water-balance components for the Odisha portion of the Mahanadi River Basin reveals a fundamental reorganization of hydrological processes driven by changing rainfall characteristics, rising thermal stress, and intensified land- and water-use pressures. Precipitation across the basin exhibits a spatially heterogeneous but overall declining trend, with total seasonal rainfall reducing by approximately 2–5%. This decline is not uniform; western districts such as Bolangir, Nuapada, and Sambalpur already located in the rain-shadow zone experience more frequent rainfall deficits, while coastal districts like Kendrapara show

increased intra-seasonal variability. Importantly, this reduction in total rainfall is accompanied by an increase in high-intensity precipitation events and a reduction in the number of rainy days, indicating a shift toward short-duration, high-magnitude rainfall that limits effective soil moisture replenishment and groundwater recharge.

Surface runoff responses strongly reflect this altered rainfall regime. Despite a reduction of nearly 10% in total runoff volume, peak runoff intensities increase by 5–12%, particularly in the lower basin and deltaic districts such as Cuttack, Puri, Jagatsinghpur, and Jajpur. This pattern signifies a growing dominance of flash-flood processes, where rapid overland flow generated by intense rainfall overwhelms drainage systems and floodplains. The increased runoff peaks reduce the residence time of water within the basin, thereby diminishing opportunities for infiltration and storage while simultaneously heightening flood risk in densely populated and agriculturally productive delta regions.

Baseflow contributions to river discharge exhibit a consistent declining trend across the Odisha basin, decreasing by approximately 10–15% during the monsoon season. Mid-basin districts including Angul, Dhenkanal, and Nayagarh show the most pronounced reductions, reflecting diminished groundwater–surface water interactions. The decline in baseflow is directly linked to reduced infiltration efficiency caused by rapid runoff generation, soil compaction, and land-use changes, as well as increased abstraction of groundwater during and after the monsoon. This weakening of baseflow has critical implications for sustaining river flows during post-monsoon and dry seasons, increasing the vulnerability of downstream water users.

Evapotranspiration demonstrates one of the most significant changes among all water-balance components, increasing by approximately 10–18% across large parts of the basin. This rise is driven by increasing surface temperatures, extended warm periods, and enhanced atmospheric demand for moisture. Industrial clusters in Jharsuguda, Angul, and the Talcher region exhibit particularly high evapotranspiration rates due to thermal emissions, altered land cover, and extensive surface exposure, while agriculturally dominant districts such as Bargarh also contribute substantially through crop water use. Elevated evapotranspiration effectively removes a larger fraction of monsoonal precipitation from the basin before it can contribute to runoff or recharge, intensifying water stress even during the wet season.

Groundwater recharge across the Odisha portion of the basin shows a moderate but spatially significant decline of approximately 5–12%. Interior districts such as Boudh and Sonepur experience reduced recharge due to accelerated runoff and limited soil infiltration, while coastal districts including Kendrapara and Jagatsinghpur face additional constraints from salinity ingress and shallow water tables, which restrict freshwater recharge potential. The reduction in recharge during JJAS is particularly concerning because the monsoon season constitutes the primary replenishment period for groundwater systems in the basin; any deficit during this window propagates into long-term aquifer stress.

The cumulative impact of these changes results in a negative net monsoon water balance of approximately 4% (around –35 mm) across the Odisha part of the Mahanadi Basin (Table 13). Western districts, already characterized by climatic marginality, and coastal districts, constrained by salinity and hydrodynamic complexity, emerge as dominant deficit zones. This negative balance indicates that, despite the monsoon remaining the primary source of water input,

increasing losses through runoff peaks and evapotranspiration, coupled with declining recharge and baseflow, are causing demand to outpace effective water availability. The findings underscore that future water security in the Odisha portion of the Mahanadi Basin will depend not only on rainfall magnitude but increasingly on rainfall distribution, land-surface processes, and integrated basin-scale water management interventions.

**Table 13.** Changes water balance components for the Odisha part of the Mahanadi River Basin during the monsoon season (JJAS).

Water Balance Component	Trend / Spatial Pattern	Change Category (%)	Dominant Affected Zone (Odisha Basin Districts)
Precipitation (PCP)	Spatially Mixed / Slight Decrease (High intensity events increase, but total rainy days decrease)	-2% to -5%	<b>Bolangir, Sambalpur</b> (Rain shadow areas), <b>Nuapada, Kendrapara</b> (Coastal variability)
Surface Runoff (SR)	High Variability / Flash Floods (Increase in peak flood intensity despite lower total rainfall)	+5% to +12% (Peak Flow)	<b>Cuttack, Jagatsinghpur</b> (Deltaic flood plains), <b>Puri, Jajpur</b>
Baseflow (BF)	Moderate Decrease (Due to lower infiltration and faster runoff)	-10% to -15%	<b>Angul, Nayagarh</b> (Mid-basin regions), <b>Dhenkanal</b>
Evapotranspiration (ET)	Significant Increase (Driven by rising surface temperatures and industrial heat)	+10% to +18%	<b>Jharsuguda, Talcher, Bargarh</b> (Industrial belt), <b>Angul</b>
Groundwater Recharge (GW)	Moderate Decline (Restricted by rapid runoff and salinity ingress in coast)	-5% to -12%	<b>Kendrapara, Jagatsinghpur, Boudh, Sonepur</b> (Salinity)
Net Water Balance	Negative / Deficit Trend (Demand outstripping recharge rates)	≈ -4% (≈ -35 mm)	<b>Western and Coastal Odisha</b>

*Note: Based on hydro-climatic studies of the Lower Mahanadi Basin (specifically SWAT model analyses and CWC trend reports from Lilhare & Mishra, 2014; Panda et al., 2013)*

#### 2.4.8 Projected Changes in Water Balance Components for the Odisha Part of the Mahanadi River Basin in Non-Monsoon Season

The non-monsoon (OND) season water-balance assessment for the Odisha portion of the Mahanadi River Basin indicates a pronounced shift toward hydrological deficit conditions driven by declining inflows, weakened subsurface support, and rising atmospheric losses. Precipitation

during OND exhibits high inter-annual variability, ranging from a 5% decline to a 15% increase, with positive anomalies largely confined to coastal districts such as Puri, Jagatsinghpur, Kendrapara, and Cuttack due to the increased frequency of October cyclonic systems. Outside these episodic events, however, the basin experiences a predominantly dry post-monsoon regime, offering limited and unreliable contribution to basin-wide water availability. Surface runoff shows a substantial decline of 20–40% across middle and upper-basin districts including Sambalpur, Bargarh, Sonepur, and Boudh, primarily due to reduced upstream releases and regulated storage at Hirakud Reservoir, which significantly constrains downstream flow continuity during the rabi season.

**Table 14.** Changes in water balance components for the Odisha part of the Mahanadi River Basin during the non-monsoon (OND) season.

Water Balance Component	Change Category (%)	Dominant Affected Zone (Odisha Basin Districts)	Remarks
Precipitation (PCP)	-5% to +15%	Puri, Jagatsinghpur, Kendrapara, Cuttack	Highly volatile due to increased frequency of <b>October cyclones</b> ; otherwise, dry trend.
Surface Runoff (SR)	-20% to -40%	Sambalpur, Bargarh, Sonepur, Boudh	Significant reduction in inflows from upstream (Hirakud) affects middle-basin availability.
Base flow (BF)	-15% to -25%	Angul, Dhenkanal, Nayagarh	Critical decline in river regeneration affects ecological flow and rabi irrigation.
Evapotranspiration (ET)	+10% to +20%	Jharsuguda, Angul, Talcher, Sambalpur	Unlike Chhattisgarh, ET <b>increases</b> here due to higher industrial heat islands and coastal humidity.
Groundwater Recharge (GW)	-5% to -10%	Bolangir, Nuapada, Kalahandi	Delayed monsoon withdrawal helps slightly, but overall recharge is limited by hard rock geology.
Net Water Balance	Negative Trend (Deficit)	Western & Central Uplands	Widening gap between post-monsoon demand and available storage.

*Note: Based on SWAT hydrological modeling (N.K. Mishra et al., 2023; Panda et al., 2013)*

Baseflow contributions decline sharply by 15–25% (Table 14) in mid-basin districts such as Angul, Dhenkanal, and Nayagarh, reflecting reduced groundwater–surface water interactions following monsoon recession and sustained groundwater abstraction. This decline critically affects river regeneration, ecological flow maintenance, and the reliability of rabi irrigation, particularly in canal-fed command areas dependent on sustained baseflow support. Evapotranspiration

increases by 10–20% across industrial and urbanizing districts including Jharsuguda, Angul, Talcher, and Sambalpur, driven by elevated post-monsoon temperatures, industrial heat-island effects, and higher coastal humidity marking a distinct contrast to upstream Chhattisgarh where cooler post-monsoon conditions moderate ET losses. Groundwater recharge during OND declines by 5–10% in western districts such as Bolangir, Nuapada, and Kalahandi; although delayed monsoon withdrawal occasionally prolongs soil moisture availability, overall recharge remains constrained by hard-rock geology, limited infiltration capacity, and rapid depletion during early rabi abstraction.

Collectively, these changes result in a persistent negative net water balance across the western and central uplands of the Odisha Mahanadi Basin during the non-monsoon season, reflecting a widening gap between post-monsoon water demand and available surface and subsurface storage. The OND season thus emerges as a critical stress period, where hydrological regulation, reservoir operation, and groundwater dependence increasingly determine water security rather than climatic inputs alone.

### **3. Sectoral Water Demand Assessment**

#### **3.1 Agricultural Water Demand in the Mahanadi River Basin**

In both Chhattisgarh and Odisha, agriculture remains the primary source of livelihood for most of the population. In both states, rainfed rice dominates cultivation, accounting for about 70–75% of the gross cropped area. In irrigated regions, rice covers over 90% of the sown area.

The overview of the agricultural landscape and the allocation and use of water for agriculture across the Mahanadi Basin. It examines key aspects such as changes in the total cropped area, cropping patterns, and irrigation trends over the past two decades to project possible future water-use scenarios in this sector. The analysis is primarily based on secondary data from government sources, particularly from the Directorate of Economics and Statistics, Ministry of Agriculture, Government of India. Later sections of the report incorporate field observations to validate and refine these trends derived from secondary data.

The findings indicate a notable acceleration in agricultural development in Chhattisgarh. This progress has been supported by the expansion of Kharif season surface irrigation in the plains of Dhamtari, Durg, Raipur, and Janjgir-Champa districts, while groundwater irrigation has played a key role in the agricultural growth of western Chhattisgarh, including Bilaspur, Kawardha, and Durg. Although Rabi irrigation is gradually increasing in Chhattisgarh, it remains less widespread than in Odisha.

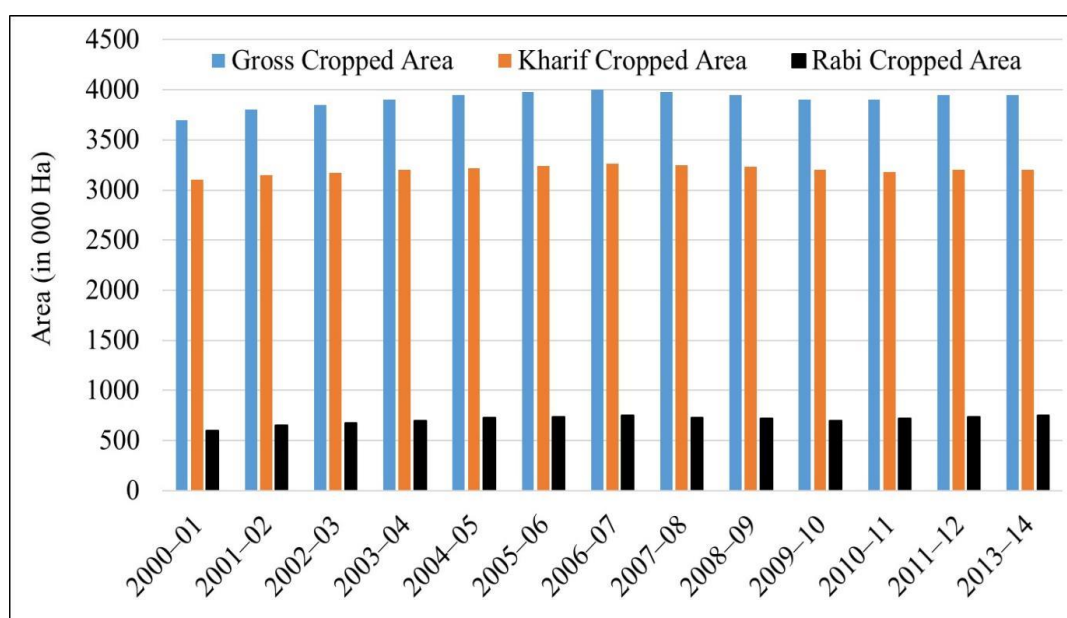
In contrast, Odisha's agriculture appears to be declining, as reflected by a reduction in the gross cropped area over the last two decades. The increase in culturable wastelands and fallow lands largely explains this change, according to available land-use statistics. Irrigation facilities are concentrated in the delta regions and western Odisha, where the irrigated area has expanded significantly over time. Chhattisgarh also shows signs of agricultural diversification, with the proportion of land under rice cultivation decreasing in favor of pulses and oilseeds, which are

mainly Rabi crops. In Odisha, the share of land under rice has remained relatively stable, while the area under pulses has increased, and that under oilseeds has declined.

### 3.1.1 Seasonal Variations in Cropping

#### Chhattisgarh

According to the statistics published by the Directorate of Economics & Statistics, Ministry of Agriculture, Government of India (2013–14), the total gross cropped area across the 15 districts of Chhattisgarh within the Mahanadi Basin is approximately 4,010 thousand hectares. Out of this, the Kharif cropped area accounts for about 3,296 thousand hectares, while the Rabi cropped area covers around 693 thousand hectares. This reflects a cropping intensity of roughly 121% in the Chhattisgarh portion of the Mahanadi Basin. Notably, the Kharif-cropped area has shown a consistent increase of nearly 200 thousand hectares since the formation of the state, whereas the Rabi cropped area reached its peak in 2005–06 and has shown a gradual decline thereafter.



**Figure 11.** Temporal variation in Gross, Kharif, and Rabi Cropped Areas of the Mahanadi Basin.

(Source: Directorate of Economics and Statistics, Ministry of Agriculture, Government of India, District-wise, Season-wise Cropped Area, Chhattisgarh)

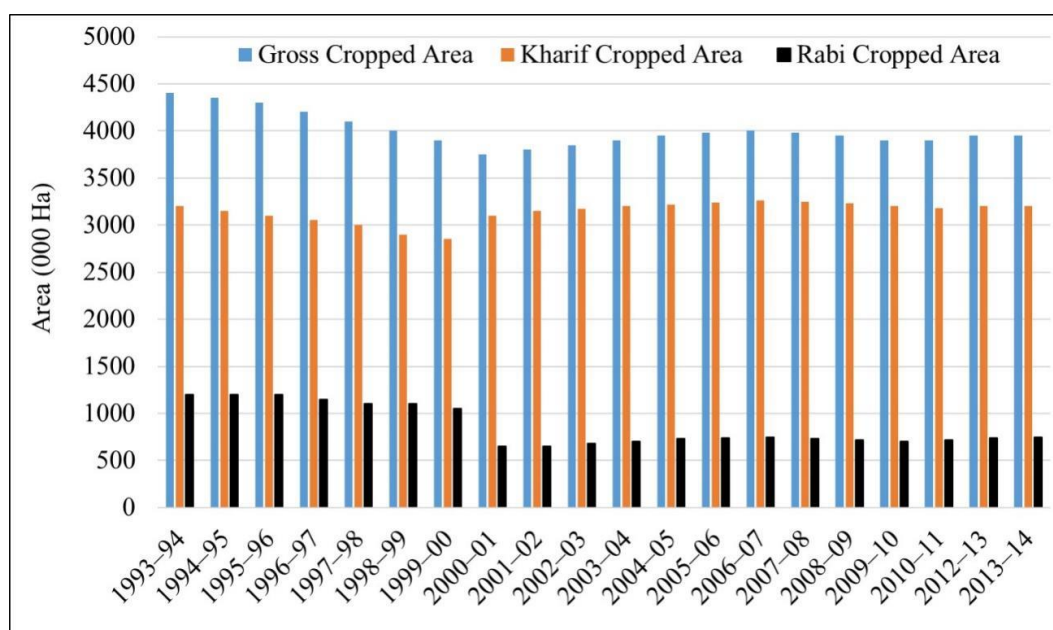
As illustrated in Figure 11, the gross cropped area (GCA) in the Mahanadi Basin exhibits a steady trend between 2000–01 and 2013–14, fluctuating around 3700–4000 thousand hectares. The Kharif cropped area consistently accounts for the majority share, representing approximately 80–85% of the total cropped area. This dominance indicates the heavy reliance of the basin’s agricultural system on monsoon rainfall.

Meanwhile, the Rabi cropped area shows a gradual increase over the study period, rising from around 600 to 750 thousand hectares, suggesting a modest but consistent improvement in

irrigation infrastructure and water availability during the dry season. The stabilization of both Kharif and Rabi cropped areas after 2007–08 may reflect saturation in cultivated land expansion and a shift toward productivity-based improvements rather than area expansion. Overall, the data suggest that while the Mahanadi Basin’s agriculture remains predominantly monsoon-dependent, efforts toward enhancing Rabi season cultivation have contributed to a more balanced annual cropping pattern (Figure 11).

## Odisha

In comparison, the Mahanadi districts of Odisha have experienced a decline in the gross cropped area from 4,506 thousand hectares to 4,122 thousand hectares in 2013–14, representing a reduction of approximately 8.5 percent. According to land use data, this decrease can be attributed to a shift toward fallow lands and culturable wastelands. The total cropped area during the Kharif season stands at about 2,712 thousand hectares, while the Rabi season covers around 1,396 thousand hectares, reflecting a high cropping intensity of nearly 151 percent. Over time, the Kharif cropped area has decreased considerably from 3,066 thousand hectares to 2,712 thousand hectares, whereas the Rabi cropped area has shown a recovery, increasing again to 1,396 thousand hectares after a notable decline in the late 1990s.



**Figure 12.** Temporal variation in Gross, Kharif, and Rabi Cropped Areas of the Mahanadi Basin.

(Source: Statistics Cell, Ministry of Agriculture, Government of Odisha, District-wise, Season-wise Cropped Area, Odisha)

As illustrated in Figure 12, the gross cropped area (GCA) of the Mahanadi Basin demonstrates a declining trend from 1993–94 to 1999–00, followed by stabilization and slight recovery after 2000–01. The Kharif cropped area remained dominant throughout the period, accounting for approximately 75–80% of the total cropped area, emphasizing the region’s heavy dependence on monsoon-based agriculture.

The Rabi cropped area, though comparatively smaller, exhibits a noticeable fluctuation during the early years and a gradual increase after 2000–01, rising from about 650 to 750 thousand hectares. This increase reflects improved irrigation facilities and better water resource management, likely driven by the development of canal systems and groundwater utilization during the dry season. The overall stabilization of the GCA after 2000–01 suggests that while land expansion reached its limit, productivity and cropping intensity improved through more efficient water use and diversification of Rabi crops. Therefore, the figure signifies a transition from purely rainfed to semi-irrigated agricultural systems within the basin (Figure 12).

### **3.1.2 Geographical Variations in Cropping**

#### **Kharif Season**

In the plains of Chhattisgarh, more than 50 percent of the geographical area is cultivated during the Kharif season, with Durg, Mahasamund, and Janjgir-Champa having the highest sown areas. Notably, Durg and Raipur districts together contribute nearly one-third of the total Kharif cropped area in the state. These regions benefit from extensive surface irrigation systems, primarily fed by the Mahanadi River, including the major Mahanadi Reservoir Project.

In contrast, the upland districts located in the northern and southern parts of Chhattisgarh, such as Koriya, Surguja, Kanker, and Bastar, are predominantly forested. The western highland districts, including Bilaspur, Kawardha, and Rajnandgaon, have 40 percent or less of their geographical area under cultivation. These areas lack large-scale surface irrigation infrastructure, although groundwater irrigation is gradually expanding.

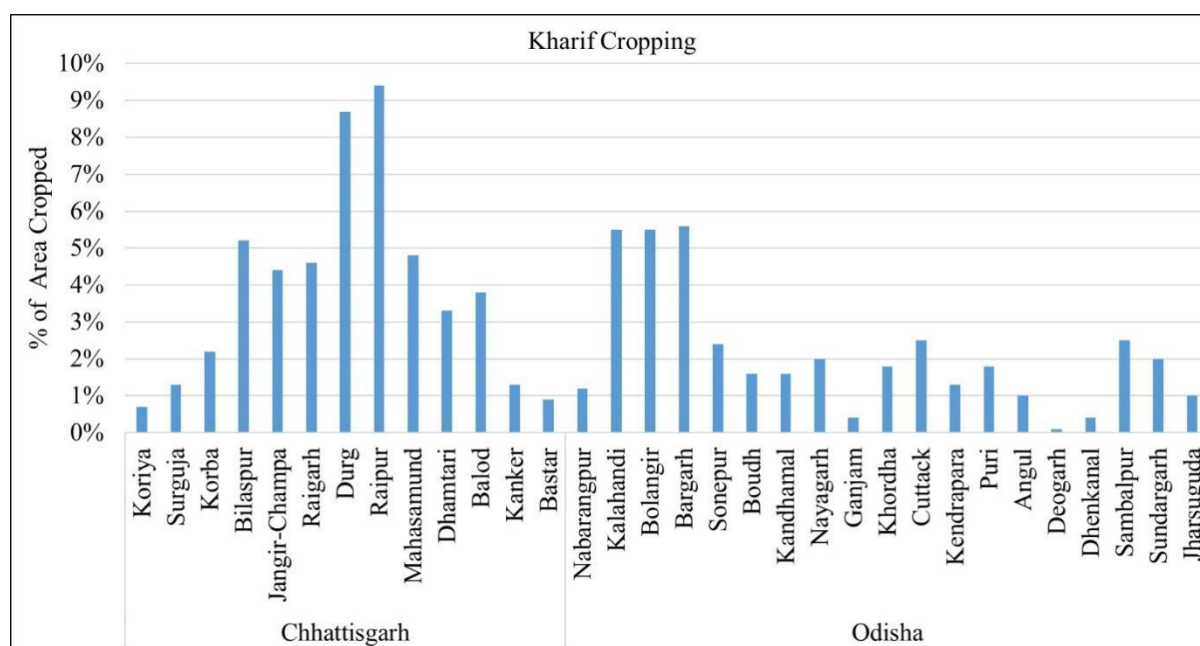
In Odisha, the western plains districts of Balangir, Bargarh, Nuapada, Kalahandi, and Subarnapur, along with the coastal district of Kendrapara, record the highest share of Kharif cropping. On average, around 60 percent of their geographical area is sown during the Kharif season. Balangir, Bargarh, and Kalahandi alone account for about 38 percent of Odisha's total Kharif cropped area. While much of this land is rainfed, it also benefits from major surface irrigation projects such as Hirakud, Indravati, and the Mahanadi Delta Project.

Districts like Jharsuguda and Sambalpur, located along the Mahanadi River, and the central districts of Boudh, Kandhamal, Nayagarh, and Angul have higher forest cover and limited irrigation potential. In other coastal districts, Cuttack, Jagatsinghpur, and Puri, approximately 40 percent of the geographical area is sown during the Kharif season. However, Kharif cropping in the deltaic region remains highly vulnerable to flooding, making its agricultural pattern distinct from other parts of the state.

As shown in Figure 13, the spatial distribution of Kharif cropping intensity in the Mahanadi Basin during 2013–14 reveals significant regional variation between the upper, middle, and lower basin districts. The central basin areas of Chhattisgarh, particularly Raipur (9.4%), Durg (8.7%), and the Bargarh–Kalahandi–Balangir belt (5–6%), exhibit the highest Kharif cropping intensity, primarily due to better irrigation infrastructure, fertile alluvial soils, and higher rainfall.

In contrast, southern districts (e.g., Bastar, Nabarangpur) and eastern coastal districts (e.g., Puri, Kendrapara, Ganjam) show relatively low Kharif cropping intensity (below 2%), likely reflecting rainfed cultivation, lower irrigation access, and land-use competition with urban and forested areas.

The northern upland areas (Koriya, Surguja, Korba) also display low intensities (<2%) because of their topography and forest cover. Overall, the pattern signifies that Kharif cultivation is concentrated in the middle basin, where agricultural activities are supported by favorable hydrological and soil conditions, while peripheral areas remain less intensively cropped (Figure 13).



**Figure 13.** Distribution of Kharif Cropping Intensity (% of Area Cropped) in the Mahanadi Basin.

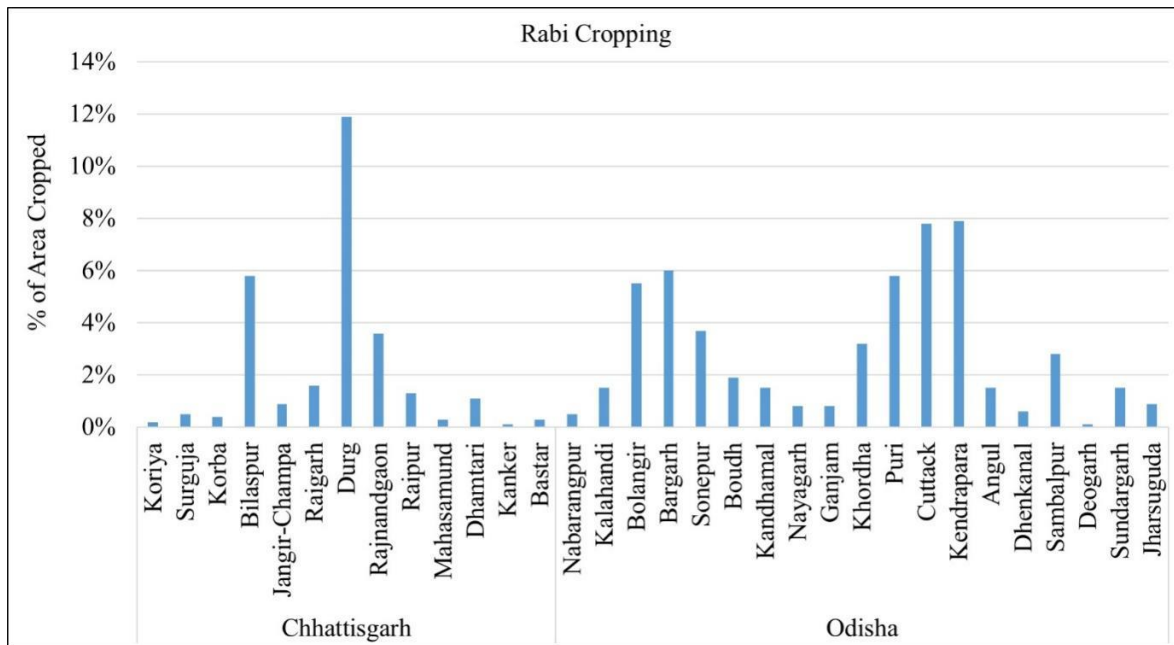
(Source: Directorate of Economics and Statistics, Ministry of Agriculture, Government of India, 2014, and Statistics Cell, Ministry of Agriculture, Government of Odisha, District-wise, Season-wise Cropped Area, Chhattisgarh & Odisha)

### Rabi Season

In Chhattisgarh, the western districts of Durg, Kawardha, and Bilaspur have the highest proportion of land cultivated during the Rabi season, accounting for approximately 29%, 19%, and 16% of their total geographical area, respectively. In contrast, the plains districts such as Raipur, Mahasamund, and Janjgir-Champa, which are extensively irrigated during the Kharif season, receive much less irrigation in Rabi. Consequently, less than 5% of their area is under Rabi cultivation. Notably, Durg and Bilaspur districts together contribute nearly 53% of Chhattisgarh’s total Rabi-cropped area.

In Odisha, the low-lying coastal districts of Cuttack, Jagatsinghpur, and Puri record the highest share of their geographical area under Rabi cultivation, with more than 40% of their land sown during this season. Much of this cultivation is supported by irrigation from the Mahanadi Delta

Project. In contrast, Rabi cropping in western Odisha districts such as Bargarh, Sonepur, Sambalpur, and Kalahandi depends primarily on surface irrigation, mainly provided by the Hirakud Project. Here, the Rabi sown area ranges between 20% and 25% of the total geographical area, compared to about 60% during the Kharif season. Overall, the districts of Cuttack and Kalahandi are the most significant contributors, together accounting for around 25% of Odisha's total Rabi cropped area.



**Figure 14.** Distribution of Rabi Cropping Intensity (% of Area Cropped) in the Mahanadi Basin.

(Source: Directorate of Economics and Statistics, Ministry of Agriculture, Government of India, 2014, and Statistics Cell, Ministry of Agriculture, Government of Odisha, District-wise, Season-wise Cropped Area, Chhattisgarh & Odisha)

As illustrated in Figure 14, the Rabi cropping intensity in the Mahanadi Basin during 2013–14 shows strong spatial disparities between districts. The western and central basin areas, particularly Durg (11.9%), Bargarh (6.0%), Bolangir (5.5%), and Bilaspur (5.8%), record the highest Rabi cropping intensity, reflecting better irrigation access from canal networks, groundwater exploitation, and residual soil moisture from the preceding Kharif season.

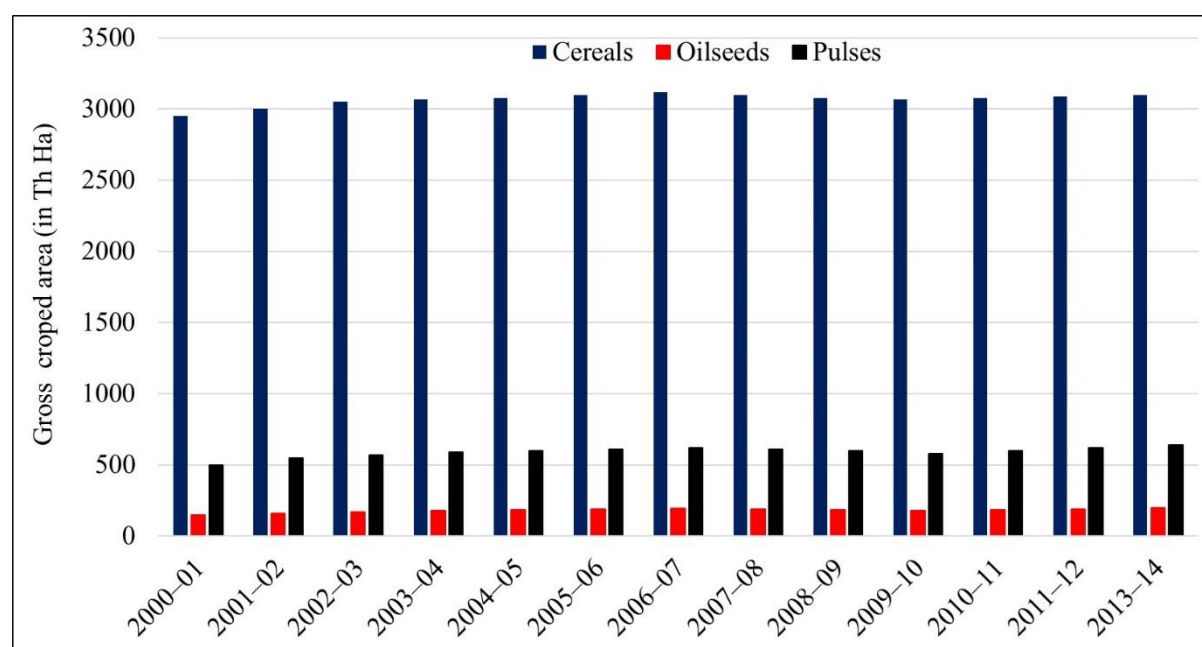
The coastal Odisha districts, such as Cuttack (7.8%), Kendrapara (7.9%), and Puri (5.8%), also demonstrate significant Rabi cropping due to proximity to the deltaic irrigation systems of the lower Mahanadi and favorable climatic conditions. Conversely, upland and forest-dominated districts in the northern and southern basin, such as Kanker, Bastar, Deogarh, and Nabarangpur, show very low Rabi intensity (<1%), indicating dependence on rainfed Kharif crops and limited irrigation facilities. Overall, the spatial pattern reveals that Rabi cropping is highly concentrated in the irrigated command areas, while large portions of the basin remain single-cropped and rain-dependent (Figure 14).

### 3.1.3 Cropping Patterns

#### Chhattisgarh

Since 2000–01, Chhattisgarh has witnessed an overall increase in its total gross cropped area from 3,620 thousand hectares (Th Ha) to 4,010 Th Ha. The gross cropped area under cereals has shown only a modest rise, from 2,942 Th Ha (81%) to 3,090 Th Ha (77%), while the area under pulses has grown significantly, from 508 Th Ha (14%) to around 692 Th Ha (17%).

During the Kharif season, cereals dominate the cropping pattern, covering about 3,015 Th Ha (91%) of the total 3,296 Th Ha sown area. Among cereals, rice alone accounts for 2,932 Th Ha (89%) of the total Kharif sown area. Oilseeds and pulses occupy approximately 5% and 4% of the Kharif area, respectively. Notably, the Kharif area under cereals has expanded since 2000–01, when cereals were grown on 2,888 Th Ha (93%) of the Kharif sown area. Meanwhile, the share of oilseeds in the Kharif season has increased from 2% to 5% over the same period.



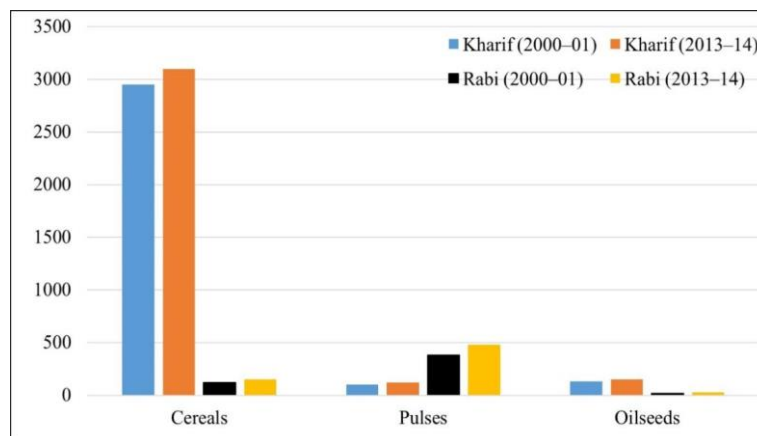
**Figure 15.** Temporal variation in Gross Cropped Area under major crop groups in the Mahanadi Basin.

(Source: Directorate of Economics and Statistics, Ministry of Agriculture, Government of India, District-wise, Year-wise, Crop-wise, Cropped Area, Chhattisgarh)

In the Rabi season, pulses, mainly gram and khesari, constitute the largest crop group, covering about 573.5 Th Ha (83%) of the sown area. Cereals and oilseeds account for 11% and 6%, respectively. The rise in Rabi cultivation is primarily due to the expansion of pulses, which occupied only 366 Th Ha (74%) in 2000–01. In contrast, the share of oilseeds has declined sharply from 15% in 2000–01 to the current 6%. Among the districts, Raipur and Durg together contribute the largest share of cereal cultivation, accounting for 34% of the total sown area. Durg also leads in pulse cultivation, representing about 33% of the total pulse area, followed by Bilaspur, which accounts for around 16% (Figure 15).

As depicted in Figure 15, cereals dominate the gross cropped area of the Mahanadi Basin throughout the study period (2000–01 to 2013–14), consistently accounting for around 80–85% of the total cultivated land. This predominance is largely due to the extensive cultivation of paddy (rice) as the principal Kharif crop, which thrives under the basin’s monsoon-dependent irrigation system. The pulses occupy the second-largest share, showing a gradual increase from about 500 to 640 thousand hectares, reflecting growing diversification and improved awareness of soil fertility management through legume cultivation. Oilseeds, on the other hand, represent the smallest proportion of the cropped area (about 150–200 thousand hectares) with only a modest increase over time, indicating limited expansion due to climatic and soil constraints. Overall, the temporal stability of cereal dominance coupled with a slight rise in pulses suggests a gradual shift towards crop diversification without major alteration in the region’s traditional rice-based cropping pattern (Figure 15).

As illustrated in Figure 15, cereals continue to dominate the agricultural landscape of the Mahanadi Basin, with the Kharif season accounting for most of the cropped area, approximately 90–95% of total cereal cultivation in both 2000–01 and 2013–14. This dominance reflects the rainfed nature of agriculture in the basin, where monsoon-dependent paddy (rice) is the principal crop. The Rabi cereals area shows a marginal increase, indicating a slight expansion of irrigated cropping during the dry season, possibly due to improved irrigation infrastructure and water availability. Pulses, on the other hand, have shown a notable increase in Rabi cultivation (from ~380 to 480 thousand hectares), highlighting their growing role as a winter-season crop that supports soil fertility improvement through nitrogen fixation. Kharif pulses show only a minor increase, suggesting limited adaptability to heavy monsoon conditions.



**Figure 16.** Comparison of gross cropped area under major crop groups during Kharif and Rabi seasons in the Mahanadi Basin

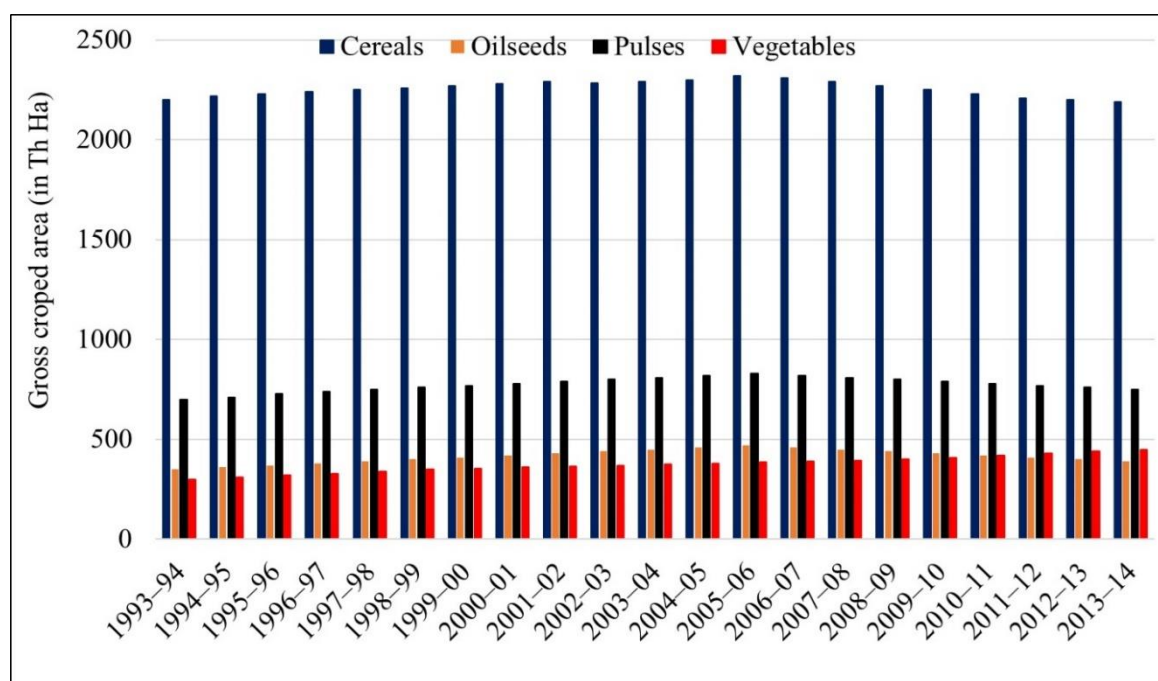
(Source: Directorate of Economics and Statistics, Ministry of Agriculture, Government of India, District-wise, Season-wise, Crop-wise, Cropped Area, Chhattisgarh)

Oilseeds maintain a relatively small share of the total cropped area across both seasons, though a marginal increase is observed by 2013–14, potentially reflecting diversification efforts and market-driven cultivation incentives. Overall, the data emphasize that while cereals remain the staple and dominant crop, there is a gradual trend toward diversification and enhanced Rabi season utilization in the basin (Figure 16).

## Odisha

The gross cropped area in Odisha has declined from 4,414 thousand hectares (Th Ha) to 4,122 Th Ha over the study period (Figure 17). Like Chhattisgarh, the agricultural system in Odisha is predominantly rice-based, with paddy being cultivated across three main growing seasons Autumn, Winter, and Rabi.

The gross cropped area under cereals recorded a marginal decrease from 2,304 Th Ha (52%) in 1993-94 to 2,167 Th Ha (53%) in 2013-14. In contrast, the area under pulses showed a slight increase from 1,076 Th Ha (24%) to 1,163 Th Ha (28%) during the same period (Figure 17). Comparatively, the area under cereals in Odisha is smaller than in Chhattisgarh, whereas the area under pulses is significantly larger. The Kharif (Autumn + Winter) area under rice declined from 2,011 Th Ha to 1,833 Th Ha (67%) between 1993-94 and 2013-14, representing a portion of the total Kharif cereal area of 1,938 Th Ha (71%). Other key Kharif crops include pulses (396 Th Ha), oilseeds (120 Th Ha), and vegetables (124 Th Ha), contributing to a total Kharif cropped area of 2,712 Th Ha. Among all crop groups, pulses and fibres have shown an increase in area since 1993-94, whereas oilseeds, vegetables, and other crops have experienced a decline.



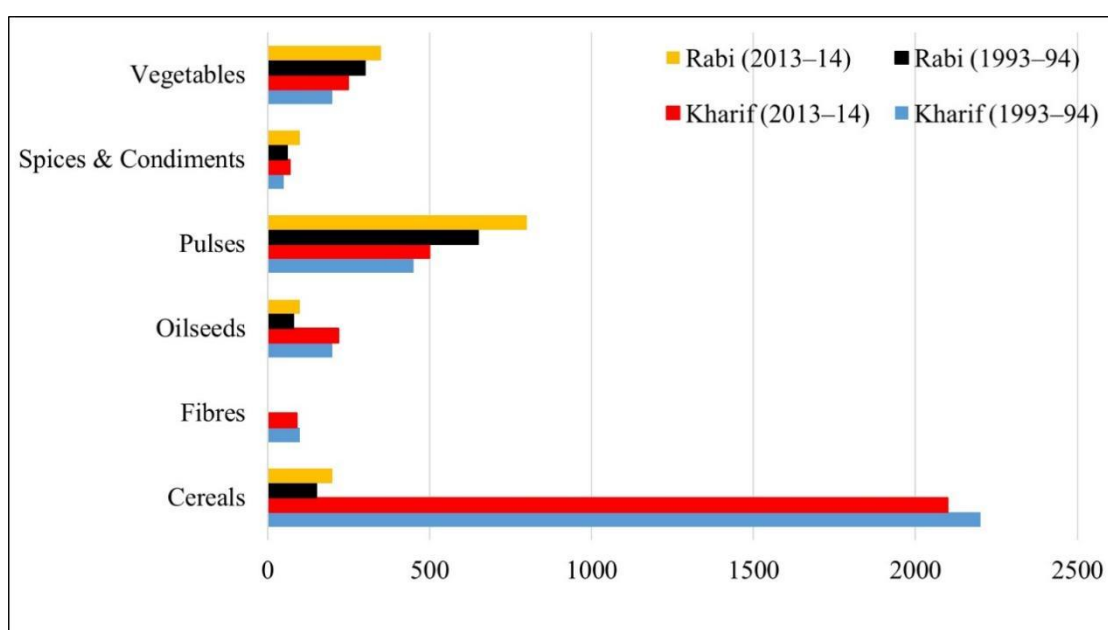
**Figure 17.** Change in gross cropped area and crop distribution in Odisha.

(Source: Statistics Cell, Ministry of Agriculture, Government of Odisha, 2015 – District-wise, Year-wise, Crop-wise, Cropped Area, Odisha)

In the Rabi season, the total cropped area is approximately 1,395 Th Ha, which is about half of the Kharif cropped area. Pulses dominate this season, occupying 766 Th Ha (55%) of the total area in 2013-14, followed by cereals (16%), oilseeds (14%), and vegetables (13%). Notably, rice covers only 216 Th Ha (15%) of the Rabi cropped area. District-wise, Balangir, Bargarh, and Kalahandi are the major cereal-producing regions, accounting for approximately 35% of the gross

cropped area under cereals. Among these, Kalahandi stands out as the largest producer of oilseeds and pulses in Odisha.

The data (Figure 18) highlights a noticeable shift in the cropping pattern within the Mahanadi Basin between 1993–94 and 2013–14. While cereal cultivation continued to dominate both Kharif and Rabi seasons, the total area under cereals slightly declined from 2,200 Th Ha to 2,100 Th Ha in Kharif. In contrast, pulses and vegetables showed a considerable increase in Rabi cropping from 650 Th Ha to 800 Th Ha for pulses and 300 Th Ha to 350 Th Ha for vegetables, indicating greater diversification and intensified use of land during the dry season. The expansion of oilseeds and spices & condiments also suggests growing interest in high-value crops, possibly due to better irrigation access and market demand. Overall, the trend reflects gradual intensification and diversification of agriculture in the basin, with improved utilization of Rabi season opportunities (Figure 18).



**Figure 18.** Gross cropped area under major crops during Kharif and Rabi seasons in the Mahanadi Basin.

(Source: Statistics Cell, Ministry of Agriculture, Government of Odisha, 2015 – District-wise, Season-wise, Crop-wise, Cropped Area, Odisha)

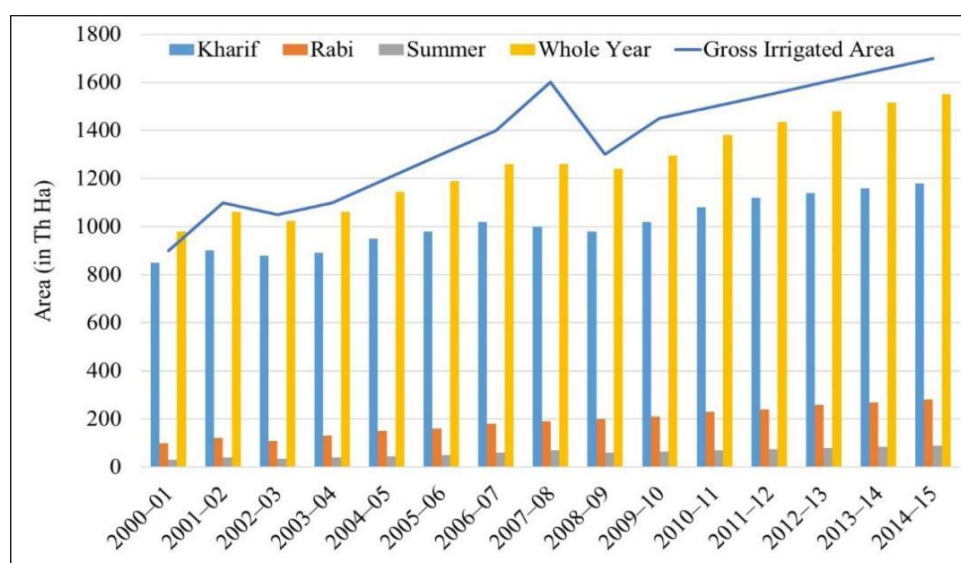
### 3.2 Irrigation Coverage – Seasons and Crops

#### Chhattisgarh

Large tracts of the plains of Chhattisgarh within the Mahanadi Basin are well-equipped with irrigation infrastructure. The state government has made consistent efforts to enhance agricultural productivity by expanding the irrigated area from 950 thousand hectares (Th Ha) in 2000–01 to 1,597 Th Ha in 2013–14. Currently, irrigation in the Kharif season covers about 35% of the total sown area (1,163 Th Ha out of 3,296 Th Ha), while in the Rabi season, it accounts for 27% (190 Th Ha out of 693 Th Ha). Among the districts, Bilaspur, Durg, Dhamtari, Janjgir-

Champa, and Raipur, all located in the plains of Chhattisgarh, are the most extensively irrigated during the Kharif season, with approximately 50% of their sown area under irrigation. Janjgir-Champa stands out with about 75% of its sown area irrigated. In contrast, Kawardha in western Chhattisgarh is highly irrigated during the Rabi season, where around 49% of the sown area receives irrigation. Most of the Rabi irrigation is concentrated in Kawardha and Durg districts (Figure 19).

Rice remains the predominant irrigated crop, occupying nearly 100% of the irrigated area in both the Kharif (1,159 Th Ha) and summer (169 Th Ha) seasons. In the Rabi season, irrigation primarily supports wheat and gram cultivation. Over the years, gram has gained considerable importance. Its share of the Rabi irrigated area increased from about 10% in 2000–01 to 60% in 2013–14, while the share of wheat declined from 68% to 30% during the same period. Additionally, fruits and vegetables account for nearly 70% of the irrigated “whole year” crops. Overall, there has been a noticeable diversification in the irrigated crop pattern. In 2000–01, rice comprised about 91% (868 Th Ha) of the total irrigated area, whereas by 2013–14, its share had declined to 83% (1,330 Th Ha). Meanwhile, pulses (including gram) increased from 1% (7 Th Ha) to 8% (123 Th Ha). The districts of Raipur, Durg, and Janjgir-Champa together account for almost 60% of the irrigated cereals in the state. Notably, Durg district has the largest irrigated area under pulses and vegetables, contributing about 57% of the irrigated pulses in Chhattisgarh.



**Figure 19.** Seasonal and annual irrigated area in the Mahanadi River Basin.

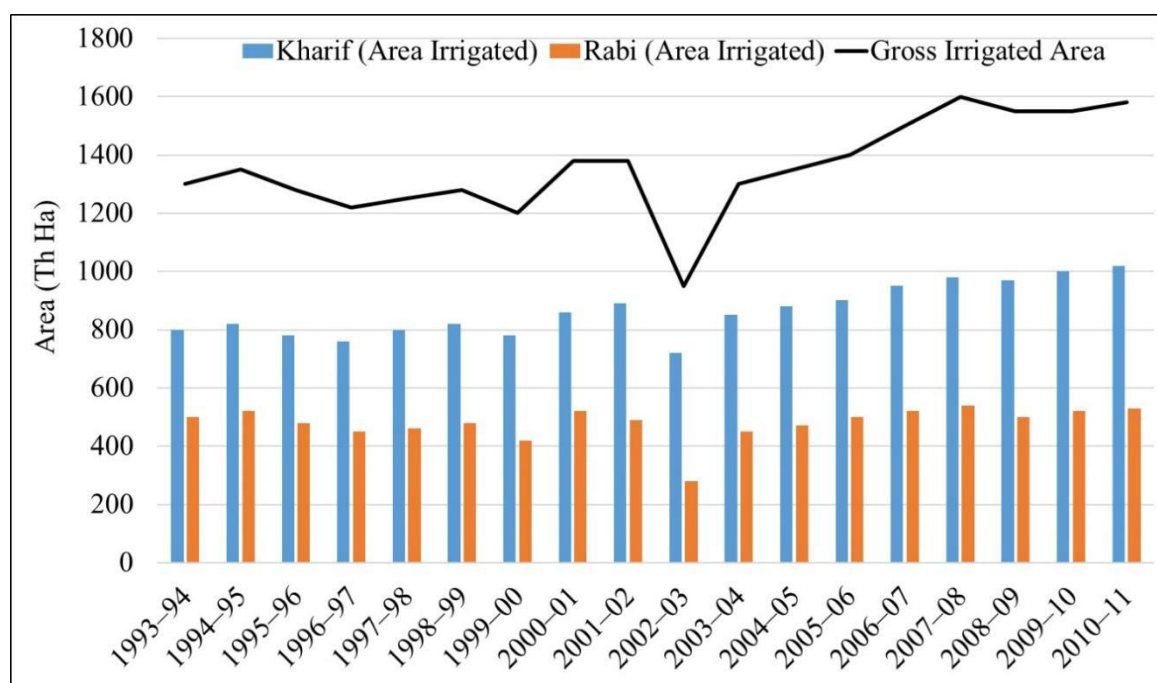
(Source: Directorate of Economics and Statistics, Ministry of Agriculture, Government of India, District-wise, Season-wise, Source-wise, Irrigated Area, Chhattisgarh)

The temporal trend in irrigated area within the Mahanadi Basin (Figure 19) indicates a steady and consistent increase in both seasonal and gross irrigated extents from 2000–01 to 2014–15. The Kharif season maintained the highest share of irrigation throughout, increasing from approximately 850 Th Ha to 1180 Th Ha. Meanwhile, Rabi irrigation more than doubled during this period, reflecting enhanced utilization of stored surface water and groundwater for dry-

season cultivation. The summer irrigation area, though small in magnitude, also exhibited gradual growth, signifying intensified cropping practices and improved water availability. Overall, the gross irrigated area showed a significant rise from around 900 Th Ha to 1700 Th Ha, demonstrating sustained agricultural expansion facilitated by improved irrigation infrastructure and management in the basin (Figure 19).

## Odisha

The Odisha region of the Mahanadi Basin is well irrigated, with a significant improvement in irrigation coverage since 2003-04, following an earlier period of decline. At present, approximately 39% (1,065 Th Ha out of 2,712 Th Ha) of the Kharif sown area and 47% (658 Th Ha out of 1,395 Th Ha) of the Rabi sown area are under irrigation. The deltaic districts of Cuttack, Jagatsinghpur, and Puri record the highest irrigation coverage during the Kharif season, with over 70% of their cultivated land being irrigated, making them the most intensively irrigated zones in the basin (Figure 20).



**Figure 20.** Temporal variation in Kharif and Rabi irrigated areas and gross irrigated areas in the Mahanadi Basin.

(Source: Statistics Cell, Ministry of Agriculture, Government of Odisha, District-wise, Season-wise, Source-wise, Irrigated Area, Odisha)

In contrast, during the Rabi season, the western Odisha districts of Bargarh (79%), Nabarangpur (73%), and Sambalpur (61%) exhibit the highest levels of irrigation. Notably, the districts of Bargarh, Kalahandi, and Cuttack together account for a major share of the Rabi irrigated area within the basin (Figure 15). Rice is the dominant irrigated crop during the Kharif season, occupying about 894 Th Ha (84%) of the total irrigated area. In the Rabi season, both rice and

vegetables are the major irrigated crops, covering 215 Th Ha (32.6%) and 172 Th Ha (26%), respectively.

The temporal variation in irrigated area within the Mahanadi Basin from 1993–94 to 2010–11 reveals a gradual increase in both Kharif and Rabi irrigated areas. The Kharif irrigated area shows a consistent upward trend, rising from approximately 800 Th Ha in 1993–94 to over 1000 Th Ha in 2010–11, indicating improved access to surface and canal irrigation systems during the monsoon period. The Rabi irrigated area, although smaller in magnitude, also increased steadily from about 500 Th Ha to 530 Th Ha, reflecting the expansion of groundwater and storage-based irrigation during the dry season.

The gross irrigated area demonstrates noticeable inter-annual variability, particularly around 2002–03 when a sharp decline occurred due to reduced rainfall and drought conditions. Following this period, irrigation levels recovered steadily, reaching around 1580 Th Ha by 2010–11, which suggests continuous investment in irrigation infrastructure and better water management practices in the basin (Figure 20).

### **3.2.1 Sources of Irrigation**

#### **Chhattisgarh**

As shown in Table 15, most of the surface irrigation in Chhattisgarh is facilitated through 12 major and 29 medium irrigation projects, collectively covering a culturable command area (CCA) of 1,254 thousand hectares (Th Ha), comprising 1,103 Th Ha under major projects and 151 Th Ha under medium projects. The ultimate irrigation potential from these systems stands at 1,237 Th Ha, with 1,076 Th Ha attributed to major projects and 161 Th Ha to medium projects. However, over time, canal irrigation has shown significant progress, expanding to approximately 918 Th Ha in 2013–14, marking a 43% increase since 2000–01. During the same period, well irrigation has nearly tripled, growing from 198 Th Ha to 589 Th Ha, and now contributes about 36% of the total gross irrigated area in the state. In contrast, canal irrigation continues to dominate, accounting for 58% of the total. This clearly indicates a notable shift toward groundwater-based irrigation, which was previously minimal. Dependence on other sources such as tanks (2%) and miscellaneous sources (3%) remains relatively low. However, the distribution of irrigation sources varies significantly across districts. For instance, Raipur, Durg, and Janjgir-Champa together account for nearly 67% of the gross canal-irrigated area in Chhattisgarh, whereas Bilaspur, Durg, and Kawardha collectively contribute around 57% of the gross well-irrigated area.

**Table 15.** Source-wise distribution of irrigation in Chhattisgarh.

Name of the Project	Irrigation Potential Created (Th Ha) (2014–15)	
	Culturable Command Area (Th Ha)	Ultimate Irrigation Potential (Th Ha)
Jonk Diversion	15.5	14.57
Hasdeo–Bango	285	433.5
Kelo (ongoing)	24.39	22.81
Kharang	66.4	56.3
Kodar (ongoing)	21.7	23.47
Mahanadi	301	264.31
Mand	11.1	13.1
Maniyari	64.77	55
Pairi	33.6	42.98
Rajeev Samvardhan Yojana	28	28
Sondur Reservoir Project	12.26	38.47
Tandula	246.3	84
<b>Total</b>	<b>1103</b>	<b>1076</b>

(Source: Central Water Commission, 2016b)

## Odisha

Surface irrigation in Odisha is supported by 11 major irrigation projects (Table 16) and 29 medium irrigation projects, together covering a culturable command area (CCA) of approximately 738 thousand hectares (Th Ha), comprising 611 Th Ha under major projects and 126 Th Ha under medium projects. The ultimate irrigation potential is estimated at 641 Th Ha (Major: 520 Th Ha; Medium: 121 Th Ha).

In Odisha, the irrigation sources are categorized into four types:

1. Major and medium flow projects (canal irrigation),
2. Minor flow projects (canal/tank irrigation),
3. Minor lift projects (well irrigation), and
4. Other sources, including private lift irrigation, shallow tube wells, water harvesting structures (WHCs), creeks, and dug wells.

The first two categories collectively represent surface or canal irrigation, while the third denotes groundwater irrigation. The fourth category is a combination of both surface and groundwater sources; although the exact proportion is unavailable, groundwater is likely to dominate within this group (Ministry of Agriculture, Government of Odisha, 2014).

The gross irrigation potential created in Odisha amounts to 5005 Th Ha, of which the actual irrigated area is about 3521 Th Ha, indicating nearly 70% utilization of the potential. Between

1980–81 and 2013–14, the potential created under major and medium projects nearly doubled from 1110 Th Ha to 2014 Th Ha. However, their share in the state’s total irrigation potential declined from 66% to 40% over the same period.

Simultaneously, the potential under minor flow projects increased from 287 Th Ha to 682 Th Ha, while minor lift projects exhibited the fastest growth from 33 Th Ha to 1059 Th Ha, now contributing around 21% of the state’s total irrigation potential. The “other sources” category also expanded substantially, from 255 Th Ha to 1249 Th Ha (Ministry of Agriculture, Government of Odisha, 2014). Overall, canal irrigation in Odisha remains geographically concentrated, with Bargarh, Kalahandi, Cuttack, and Puri districts accounting for nearly 89% of the state’s major and medium irrigation potential. High groundwater irrigation potential is also observed in several of these canal-irrigated districts, particularly Bargarh, Kalahandi, and Cuttack, along with Balangir and Jagatsinghpur, which possess significant groundwater resources.

**Table 16.** Irrigation Potential and Culturable Command Area of Major Projects in the Mahanadi Basin.

Name of the Project	Irrigation Potential Created (2014–15)	
	Culturable Command Area (CCA)	Ultimate Irrigation Potential
Hirakud	157.8	261.2
Delta Stage I, II	78.3, NA	NA
Lower Indra	29.9	38.8
Lower Suktel	31.8	29.8
Mahanadi Birupa Barrage	NA	NA
Mahanadi Chitrotpola	19.54	25.16
Naraj Barrage	183.2	NA
Salki	19.9	20.1
Sunder	4.6	6.07
Upper Indravati	76.27	125.08
<b>Total</b>	<b>601.3</b>	<b>506.21</b>

(Source: Central Water Commission, 2016b)

### 3.3 Estimated Water Allocations and Use

An estimate of water allocation and utilization is essential to project future trends in water availability across different sectors within the river basin. While data on the number and storage capacity of water resource projects in the basin are available from the National Register of Large Dams (CWC), there is no consolidated secondary source that specifies how water from each project is distributed among various sectors, such as irrigation, domestic, and industrial use. Likewise, comprehensive information on the actual usage of this allocated water is also lacking.

To address this gap, field visits were conducted to some of the major water resource projects within the basin. The data collected from these sites were then extrapolated to develop basin-wide estimates of water allocation and use. Specifically, allocations for irrigation from the four largest projects in the Mahanadi Basin the Mahanadi Reservoir Project, Minimata Bango, Hirakud, and Mahanadi Delta were analyzed to estimate the total irrigation water allocation for the basin. The known allocations for these projects, as obtained from various project reports, are presented in Table 17.

**Table 17.** Design Allocation, Irrigated Area, and Water Allocation per Unit Area for Major Irrigation Projects in the Mahanadi Basin.

Project	Season	Design Allocation to Irrigation (MCM)	Design Area to be Irrigated (Ha)	Design Water Allocated per Unit Area (mm)
Mahanadi Reservoir Project	Kharif	1935	385,410	502
	Rabi	706	130,974	539
Minimata Bango	Kharif	1454	234,600	620
	Rabi	720	127,500	565
	Summer	404	51,000	792
Hirakud	Kharif	1300	153,750	845
	Rabi	1400	76,875	1821
Mahanadi Delta Stage 1	Kharif	965	167,000	578
	Rabi	949	100,960	940
Mahanadi Delta Stage 2	Kharif	786	136,000	578
	Rabi	636	67,622	940

(Source: Government of Chhattisgarh, 2004; Department of Water Resources, Government of Orissa, 2007; Babu, Shrivastava, & Dikshit, 2015)

Table 17 illustrate the average volume of water allocated for irrigation per unit area during the Kharif and Rabi seasons in Chhattisgarh and Odisha (Table 18). Estimates of the actual area irrigated by surface water sources across both seasons were developed in the section “Irrigation Coverage – Seasons and Crops.”

Based on these estimates, the total water allocation was derived by multiplying the actual irrigated area with the corresponding design water allocation per unit area. In Chhattisgarh, the total annual irrigated area is approximately 1,596 thousand hectares (Th Ha). Of this, nearly 983 Th Ha (about 61%) is irrigated using surface water sources including canals, tanks, and half of the irrigation from other minor sources. In the year 2000–01, the gross irrigated area from surface sources alone was estimated at 718 Th Ha.

Seasonal distribution indicates that about 1,163 Th Ha (73%) of the total irrigation occurs during the Kharif season, followed by 191 Th Ha (12%) in the Rabi season, approximately 10.5% in the summer season, and the remaining 74 Th Ha under year-round cultivation (Table 18).

**Table 18.** Comparative changes in area irrigated and sources of irrigation in Chhattisgarh and Odisha within the Mahanadi Basin.

Category	Particulars	Chhattisgarh (2013-14)	Chhattisgarh (2000-01)	Odisha (2013-14)	Odisha (2000-01)	Odisha (1993-94)
Source-wise Irrigated Area	Canal Irrigation / Major Flow	918	641	759	635.5	569
	Well Irrigation / Minor Flow	589	199	206	191	183
	Tank Irrigation / Minor Lift	42	45	353	239.9	179
	Other Sources	46	65	373	339.85	322
	<b>Total</b>	<b>1595</b>	<b>950</b>	<b>1691</b>	<b>1406.95</b>	<b>1254</b>
Season-wise Irrigated Area	Kharif	1163	821	1066	898.95	809
	Rabi	191	41	658	567.65	519
	Summer / Whole Year	169	47	74	41	—
	<b>Total</b>	<b>1597</b>	<b>950</b>	<b>1724</b>	<b>1466</b>	<b>1328</b>

(Source: Directorate of Economics and Statistics, Ministry of Agriculture, Government of India, 2014, and Statistics Cell, Ministry of Agriculture, Government of Odisha, 2015 – District-wise, Season-wise, Source-wise/Project-wise, Year-wise Irrigated Area, Chhattisgarh and Odisha)

If we assume that the proportion of surface irrigation across different sources remains the same 73%, 12%, and 10.5% during both the Kharif and Rabi seasons, the corresponding surface water use for each season in 2013-14 can be estimated (see Table 19). Similarly, for the year 2000-01, the ratio of surface irrigation across the seasons is assumed to be 86%, 4%, and 5%, respectively.

The total estimated annual surface water utilization for irrigation is approximately 5,481 MCM, with the majority being used during the Kharif season. This marks a significant increase from 3,902 MCM recorded in 2000-01. In contrast, Odisha irrigates around 1,724 thousand hectares (Th Ha) annually, of which nearly 1,151 Th Ha (or 66%) is supported by surface water sources including major and minor flow projects, as well as half of other irrigation sources. In 2000-01, the gross irrigated area through surface water was estimated at 996 Th Ha.

Within the gross irrigated area, approximately 1,066 Th Ha (62%) is irrigated during the Kharif season, while 658 Th Ha (38%) occurs in the Rabi season. Assuming a similar seasonal distribution (62:38) applies to surface irrigation, the season-wise surface water use can be estimated accordingly (Table 20). Similarly, in 2000-01, the corresponding seasonal ratio for surface irrigation was approximately 61:39 percent.

**Table 19.** Estimated Surface Water Requirement for Irrigation, Season-wise, in the Mahanadi Basin, Chhattisgarh.

Year	Season	Area Irrigated by Surface Water Sources (Th Ha)	% of Total Irrigated Area	Depth of Irrigation (m)	Surface Water Use for Irrigation (MCM)
2013-14	Kharif	718	73% of 983 Th Ha	0.561	4,028
	Rabi	118	12% of 983 Th Ha	0.539	636
	Summer	103.2	10.5% of 983 Th Ha	0.792	817.3
2000-01	Kharif	617	86% of 718 Th Ha	0.561	3,461
	Rabi	29	4% of 718 Th Ha	0.539	156
	Summer	36	5% of 718 Th Ha	0.792	285

(Source: Derived from Tables 17 and 18)

**Table 20.** Estimated Surface Water Requirement for Irrigation, Season-wise, in the Mahanadi Basin, Odisha.

Year	Season	Total Irrigated Area (Th Ha)	% Area Irrigated by Surface Water	Area Irrigated by Surface Water (Th Ha)	Depth of Irrigation (m)	Surface Water Use (MCM)
2013-14	Kharif	1151	62%	714	0.578	4127
2013-14	Rabi	1151	38%	437	0.94	4107.8
2000-01	Kharif	996	61%	607	0.578	3508
2000-01	Rabi	996	39%	388	0.94	3647.2

(Source: Derived from Tables 15 and 16)

The total estimated annual surface water use for irrigation in Odisha is approximately 8,234 MCM, with nearly equal distribution between the Kharif and Rabi seasons. This represents an increase from 7,155 MCM in 2000-01.

Overall, the surface water use for irrigation in the Mahanadi River Basin amounts to about 13,715 MCM, which constitutes roughly 20 percent of the river's 66.87 BCM annual average flow, of which 50 BCM is considered utilizable surface water. This value has risen from 11,057 MCM in 2000-01, a 24 percent increase over 13 years, equivalent to an annual growth rate of approximately 1.84 percent. If this trend continues, the projected surface water use for irrigation by 2040 will reach around 20,572 MCM.

In terms of crop distribution, rice dominates irrigation in the region. In 2013-14, it accounted for approximately 882 Th Ha (83 percent) of the Kharif irrigated area in Odisha and 1,159 Th Ha (100

percent) in Chhattisgarh. Given that these proportions have remained stable since 2000–01, it can be reasonably assumed that nearly all 4,028 MCM of Kharif surface water use in Chhattisgarh, 817 MCM of summer water use, and 3,425 MCM (83 percent of Kharif surface water use) in Odisha are utilized for rice cultivation during the Kharif season.

Similarly, in the Rabi season, rice covers about 207 Th Ha (32 percent) of the sown area. Assuming the same proportion of water use, approximately 1,314 MCM of surface water is consumed for rice irrigation during this period. Together, these result in a total water requirement of 9,584 MCM for rice irrigation, equivalent to 64 percent of the total surface water used for irrigation (13,715 MCM) in the basin. If rice water demand continues to expand at the same rate as the overall irrigation water use (24 percent since 2000–01), then the rice water requirement would have been around 7,729 MCM in 2000–01 and is projected to rise to 14,376 MCM by 2040.

### 3.4 Industrial Water Demand

The industrial water demand in the Chhattisgarh region has undergone significant temporal fluctuations between 1991 and 2011 (Appendix II). In 1991, the total water requirement across the Mahanadi Basin part of the state stood at approximately 384.21 MCM, which more than doubled by 2001 to 839.81 MCM, reflecting rapid industrialization and the establishment of large-scale thermal power, steel, and cement plants. However, by 2011, the demand marginally declined to 628.99 MCM, suggesting either improved water-use efficiency or stabilization in industrial expansion due to resource and environmental constraints. The observed shift implies that the peak industrial water consumption period likely occurred around the early 2000s, coinciding with the acceleration of industrial growth corridors in central Chhattisgarh.

A district-wise assessment reveals a clear spatial disparity in industrial water consumption. Durg, Korba, Raipur, Raigarh, and Janjgir-Champa districts collectively accounted for the highest share of water demand throughout the three decades. For instance, Durg alone recorded an exceptionally high demand of 346.63 MCM in 2001, largely due to the presence of major steel plants and ancillary industries. Similarly, Korba's industrial water requirement rose dramatically from 0.006 MCM in 1991 to 204.88 MCM in 2011, driven by the rapid growth of thermal power generation and coal-based industries. Raigarh followed a similar trajectory, escalating from 6.42 MCM in 1991 to 231.33 MCM in 2001, before stabilizing at 130.48 MCM in 2011, reflecting industrial consolidation and possibly improved recycling practices.

The Raipur–Baloda Bazar industrial belt also emerged as a major consumer of water due to the expansion of cement, sponge iron, and engineering industries. Raipur's demand rose significantly in 1991 (111 MCM combined from Arang, Tilda, and Dharsiwa blocks) and fluctuated by 2011 with Tilda (51.29 MCM) and Dharsiwa (0.41 MCM) contributing prominently. Similarly, Baloda Bazar exhibited a steady demand growth, particularly in the Baloda and Simga blocks, with values reaching over 1.0 MCM in 2011, emphasizing its growing industrial base. These findings collectively indicate that industrial development in the basin has been concentrated along transportation and energy corridors where access to water and power is most reliable.

Conversely, the southern and northern districts such as Kanker, Mahasamund, Kawardha, and Bemetara maintained low industrial water demand, with most blocks registering less than 0.02 MCM even in 2011. These areas are characterized by limited industrial activity, a predominantly agrarian economy, and dependency on small-scale industries that consume minimal water. The decline in industrial water use in certain districts between 2001 and 2011, such as in Durg and Raigarh, may also suggest enhanced adoption of water recycling, zero-liquid discharge (ZLD) systems, and wastewater recovery technologies, reflecting gradual shifts towards sustainable water management in industrial operations.

From a temporal perspective, the data suggest that 2001 was a turning point in the region's industrial water dynamics. The sharp surge during this period corresponds to the state's economic restructuring and establishment of industrial hubs like Bhilai, Korba, Raigarh, and Champa, which collectively consumed nearly 80% of the basin's total industrial water. By 2011, however, overall water consumption stabilized or slightly declined due to policy-driven efficiency measures, the phasing out of older high-consumption technologies, and stricter regulations under the Chhattisgarh Water Resources Development Authority (CWRDA). This trend highlights the evolving balance between industrial growth and sustainable water management.

Overall, the analysis of industrial water demand indicates a gradual movement toward sustainable industrialization within the Chhattisgarh portion of the Mahanadi River Basin. While the early decades (1990s–2000s) were marked by rapid expansion and soaring water consumption, the subsequent period (post-2010) reflects improved efficiency and water stewardship among industries. Going forward, optimizing water use through integrated industrial water management plans, treated wastewater reuse, and rainwater harvesting within industrial estates will be essential to maintaining both economic growth and ecological balance in the basin. This evolution represents a positive transition from water-intensive development toward a more resource-efficient industrial framework.

## **3.5 Domestic Water Demand**

### **3.5.1 District-wise Urban and Rural Domestic Water Demand**

The analysis of the district-wise domestic water demand (Appendix III) reveals significant spatial and temporal variations in both urban and rural areas across the Mahanadi Basin region of Chhattisgarh. Over the two decades from 1991 to 2011, the total domestic water demand rose steadily due to population growth, urbanization, and improved access to water supply infrastructure. The total demand increased from 1135.50 MLD in 1991 to 1738.33 MLD in 2011, showing a clear upward trend. However, the rise in urban demand was more pronounced than in rural areas, emphasizing the accelerating pace of urbanization across the basin districts.

In the northern and central districts, moderate but steady growth was observed. Districts such as Balod, Baloda Bazar, and Bemetara showed a consistent rise in both urban and rural water needs. For instance, Balod's total demand increased from 8.24 MLD in 1991 to 10.23 MLD in 2011, reflecting balanced growth in both sectors. Similarly, Baloda Bazar's total demand reached 20.12

MLD in 2011, with rural areas contributing significantly due to agricultural-based livelihoods and dispersed settlements. Bemetara also recorded increasing trends across all blocks, pointing to gradual urban expansion and better rural water supply systems.

The Bilaspur and Durg districts emerged as major centers of domestic water demand, driven by dense populations and rapid industrial-urban growth. Bilaspur's Bilha and Takhatpur blocks registered significant rises, Bilha rose from 48.24 MLD in 1991 to 87.40 MLD in 2011, indicating growing urban concentration and service sector development. In Durg district, the Durg block alone accounted for 139.06 MLD in 2011, with nearly 90 percent of the demand being urban. The rising figures in Patan and Dhamdha also reflect peri-urban growth driven by proximity to industrial clusters and expanding residential areas (Appendix III).

In contrast, southern districts such as Gariabandh and Kanker demonstrated relatively lower total water requirements, reflecting their smaller populations and limited urban centers. Blocks like Chhura and Mainpur in Gariabandh showed marginal increases, primarily in rural demand, while Kanker and Narharpur recorded moderate rises due to growing administrative and service-based settlements. These districts, with their large forest cover and dispersed habitation, display lower per capita consumption rates compared to the central plains.

The Korba and Raigarh districts reflected the combined effect of industrial growth and urban expansion on domestic demand. In Korba, urban water demand surged sharply in Katghora and Korba blocks, reaching 27.61 MLD and 31.88 MLD, respectively, in 2011. Similarly, Raigarh's urban areas, especially in Raigarh and Pussore blocks, exhibited rising demands driven by industrial township development and population inflow. This indicates the dual role of industrialization, not only in increasing employment and settlement density but also in intensifying urban water needs.

In eastern and northern tribal districts such as Jashpur, Surajpur, and Koriya, domestic water demand remained relatively low but consistently rising. For instance, Jashpur's Pathalgaon block increased from 10.94 MLD in 1991 to 14.93 MLD in 2011, while Koriya's Baikunthpur block rose to 13.35 MLD in the same period. These trends suggest gradual improvement in household water access even in less urbanized areas, reflecting the impact of state rural water supply programs and infrastructural outreach.

The Raipur district stands out with the highest domestic demand, largely due to its role as the state capital and economic hub. Dharsiwa block's demand rose dramatically from 78.49 MLD in 1991 to 170.71 MLD in 2011, mainly driven by urban consumption. Arang and Abhanpur also witnessed growing demands linked to suburban growth and infrastructural expansion. The figures for Raipur illustrate the spatial shift from rural-dominant consumption toward a predominantly urban-based demand system, characteristic of rapid metropolitan growth.

Overall, the analysis of all districts highlights a clear pattern of rising domestic water demand with time, where urban areas experienced the sharpest increases due to migration, industrialization, and lifestyle shifts. Rural areas, though slower in growth, also showed steady improvement in accessibility and usage. The results underline the urgent need for integrated

water management planning that addresses both urban expansion pressures and equitable rural supply. Continuous monitoring and infrastructure enhancement will be essential to ensure sustainable water security across all districts and blocks in the Mahanadi Basin (Appendix III).

### **3.5.2 Projected Water Demand–Supply and Deficit Scenarios for the Mahanadi River Basin**

#### **Chhattisgarh**

The Chhattisgarh part of the Mahanadi River Basin, which constitutes a significant share of the basin's catchment and water resources, faces evolving challenges in balancing water demand and supply due to rapid development, agricultural intensification, and climatic variability. The scenario-based projections for 2010–2050 illustrate how different socio-economic and climatic pathways will shape the future of water availability and sustainability in this critical region.

In the Base Case scenario, representing a moderate growth pathway with existing management conditions, the water demand in Chhattisgarh is projected to increase from 8,791.9 MCM in 2010 to 14,701.8 MCM by 2050, while the water supply rises only modestly from 7,924.4 MCM to 12,653.9 MCM (Table 21). This results in a deficit of 2,812.1 MCM, indicating mounting stress on surface and groundwater systems if current water-use patterns persist. This baseline projection underscores the growing strain from population growth, urbanization, and industrial expansion in districts such as Raipur, Durg, Bilaspur, and Janjgir-Champa, which are among the most water-demanding regions of the basin.

Under the High Growth scenario, representing an accelerated economic and infrastructural expansion, the challenge intensifies further. By 2050, water demand in the Chhattisgarh basin segment is estimated at 19,125.8 MCM, far exceeding the projected supply of 15,052.3 MCM, creating a substantial deficit of 5,004.8 MCM. This widening gap reveals that without significant interventions, the Chhattisgarh region could face periodic water shortages, particularly during lean monsoon years, directly affecting agriculture and industrial operations. Encouragingly, the End Use Conservation scenario, which assumes implementation of water-efficient irrigation practices, industrial recycling, and public water conservation programs, shows tangible improvement. The projected deficit reduces to 2,773.1 MCM by 2050. This scenario demonstrates the potential benefits of policy-driven conservation strategies and community-level participation, especially in rural and semi-urban areas dependent on basin water for livelihood and irrigation.

The Climate Change scenarios further illuminate the complex relationship between hydrology and changing climate in the Chhattisgarh basin. Under the Climate Change (Trend Analysis) case, a steady warming pattern and minor shifts in rainfall distribution led to a deficit of 2,373.2 MCM by 2050. However, under the Climate Change (IITM Projections) scenario, which reflects higher precipitation and slightly improved surface runoff predicted by the Indian Institute of Tropical Meteorology, the deficit narrows to 1,683.9 MCM (Table 21). These projections suggest that while climate variability may introduce periods of high rainfall and short-term relief, the overall water balance will still be dominated by increasing demand pressures.

From a regional perspective, the Chhattisgarh portion of the Mahanadi Basin, covering major sub-basins such as Seonath, Hasdeo, and Mand, serves as both a water-rich and agriculturally productive area. However, increasing groundwater extraction, changing cropping patterns, and industrialization near Raigarh and Korba are likely to heighten the basin's vulnerability. The spatial and temporal variations in rainfall further complicate management, emphasizing the need for robust water storage and distribution systems.

To ensure long-term sustainability, Chhattisgarh must prioritize Integrated Water Resources Management (IWRM) approaches that balance supply augmentation with demand regulation. Strengthening catchment area treatment, promoting rainwater harvesting, recycling treated wastewater, and introducing smart irrigation technologies such as drip and sprinkler systems are essential steps. Additionally, reservoir operation optimization and inter-sectoral allocation reforms will be critical for equitable water distribution across agriculture, domestic, and industrial sectors. Therefore, the findings clearly demonstrate that the Chhattisgarh segment of the Mahanadi River Basin will transition from a condition of manageable water balance in 2010 to a state of pronounced stress by 2050 under most scenarios. Unless proactive conservation and management policies are adopted, the basin's natural water endowment could be significantly strained. The scenario-based analysis thus provides an important decision-making framework for policymakers, planners, and water resource managers to secure the future water sustainability of the Chhattisgarh region within the larger Mahanadi River Basin system.

**Table 21.** Projected water demand, supply requirements, and supply availability under various developmental and climate change scenarios for the Chhattisgarh part of the Mahanadi River Basin.

Scenario	2010 (MCM)			2020 (MCM)			2030 (MCM)			2050 (MCM)		
	Water Demand	Supply Requirements	Water Supply	Water Demand	Supply Requirements	Water Supply	Water Demand	Supply Requirements	Water Supply	Water Demand	Supply Requirements	Water Supply
Base Case	8791.9	9326.8	7924.4	9931.6	10516.1	9540.3	11267.3	11906.2	10105	14701.8	15466	12653.9
Deficit (MCM)	—	—	—	—	—	975.8	—	—	1801.2	—	—	2812.1
High Growth	8791.9	9326.8	7924.4	10568.8	11182.9	10118.5	12789.6	13494.8	11225.1	19125.8	20057.1	15052.3
Deficit (MCM)	—	—	—	—	—	1064.4	—	—	2269.7	—	—	5004.8
End Use Conservation	8791.9	9326.8	7924.4	9858.6	10436.5	9470.1	11188.1	11819.8	10050.8	14608.4	15364.1	12591
Deficit (MCM)	—	—	—	—	—	966.4	—	—	1769	—	—	2773.1
Climate Change (Trend Analysis)	8791.9	9326.8	7924.4	9931.6	10516.1	9914.5	11267.3	11906.2	10657.7	14701.8	15466	13092.8
Deficit (MCM)	—	—	—	—	—	601.6	—	—	1248.5	—	—	2373.2
Climate Change (IITM Projections)	8791.9	9326.8	7924.4	9931.6	10516.1	9914.5	11267.3	11906.2	11007.9	14701.8	15466	13782.1
Deficit (MCM)	—	—	—	—	—	601.6	—	—	898.3	—	—	1683.9

(CS Change - Raipur: action for the climate today, 2019)

## Odisha

The Odisha reach of the Mahanadi running from the Satkosia Gorge to the Naraj delta head and out to the Bay of Bengal, hosts a large share of the basin's population, command area and industry within districts such as Sambalpur, Bargarh, Subarnapur, Angul, Cuttack, Khordha, Jagatsinghpur, Nayagarh and Jharsuguda. Odisha's own planning baselines put the state's average annual water resources at about 141.41 BCM with 108.15 BCM utilizable (surface + ground), figures that define the physical ceiling for allocations across the Mahanadi sub-basins in the state. Created storage in Odisha was about 17.01 BCM (with additional capacity under construction when assessed), which is the principal cushion against monsoon variability and rising multi-sector demand.

Within the basin infrastructure, live storage already completed across the Mahanadi basin is reported at roughly 12.8–13.0 BCM, and broader assessments cite about 14.47 BCM when including projects under completion capacities in which Odisha's Hirakud system is the dominant component for downstream irrigation, hydropower and flood moderation. Operationally, that storage now serves more purposes than irrigation alone, so seasonal reliability increasingly hinges on how that live capacity is scheduled across kharif and rabi, and on protection of environmental flows through Satkosia and the delta.

Observed demand growth has been rapid. Table 20 document total water requirements of ~55 BCM (2001) rising to ~84 BCM (2005), driven mainly by agriculture ( $\approx 23 \rightarrow \approx 49$  BCM), with domestic use increasing ( $\approx 2.0 \rightarrow \approx 3.0$  BCM) and industry nearly tripling ( $\approx 0.7 \rightarrow \approx 2.0$  BCM) (Table 22). While those are statewide numbers, the bulk of canal irrigation and a large fraction of urban-industrial withdrawals fall inside the Mahanadi corridor, implying that the Odisha segment of the basin bears a disproportionate share of the rising curve. In years with weak or poorly distributed monsoon rain, this shows up as rabi-season shortfalls at canal tails and peri-urban panchayats even when annual totals look comfortable.

Groundwater provides only a partial buffer. The latest Central Ground Water Board assessment places Total Annual Groundwater Recharge for Odisha at ~17.35–17.46 BCM, with Annual Extractable around 15.94 BCM and a stage of extraction  $\approx 46\%$  statewide—figures that mask higher local stress in fast-growing coastal and peri-urban blocks within the Mahanadi delta. As demand rises, conjunctive use helps in the short run, but the assessment cautions against relying on aquifers to permanently bridge seasonal canal deficits. Block-wise management linked to these extraction stages is therefore essential for the basin's Odisha reach.

Looking to 2010–2050, a Base-case (moderate growth with present management extended) implies continued pressure from irrigation expansion in Bargarh–Sambalpur–Subarnapur commands, urban growth around Cuttack–Bhubaneswar, and industrial corridors (Jharsuguda–Angul–Cuttack). Under such a pathway, the system remains volume-adequate in average years but becomes seasonally reliability-limited: pre-monsoon and rabi deficits recur at distributary tails, and groundwater drawdowns increase in the delta unless efficiency measures spread. State annual reports already flag rising consumption from population, lifestyle, industry and agriculture as the structural drivers behind this tightening.

A High-growth variant (accelerated urban-industrial expansion) shifts more of the fixed live storage to non-agricultural withdrawals in lean months, crowding irrigation in dry years and increasing the frequency of local deficits. In contrast, an End-use conservation pathway—lining and volumetric delivery in canals, targeted micro-irrigation on paddy–pulses rotations, and

mandated treated-wastewater reuse for industries-recovers several BCM-equivalent at state scale. Given the sectoral shares above, even 10–15% irrigation efficiency gains combined with industrial recycle targets are enough to erase many rabi-season gaps in vulnerable distributaries and to slow groundwater decline in coastal blocks. These directions are consistent with the state’s policy reviews and scheme guidance.

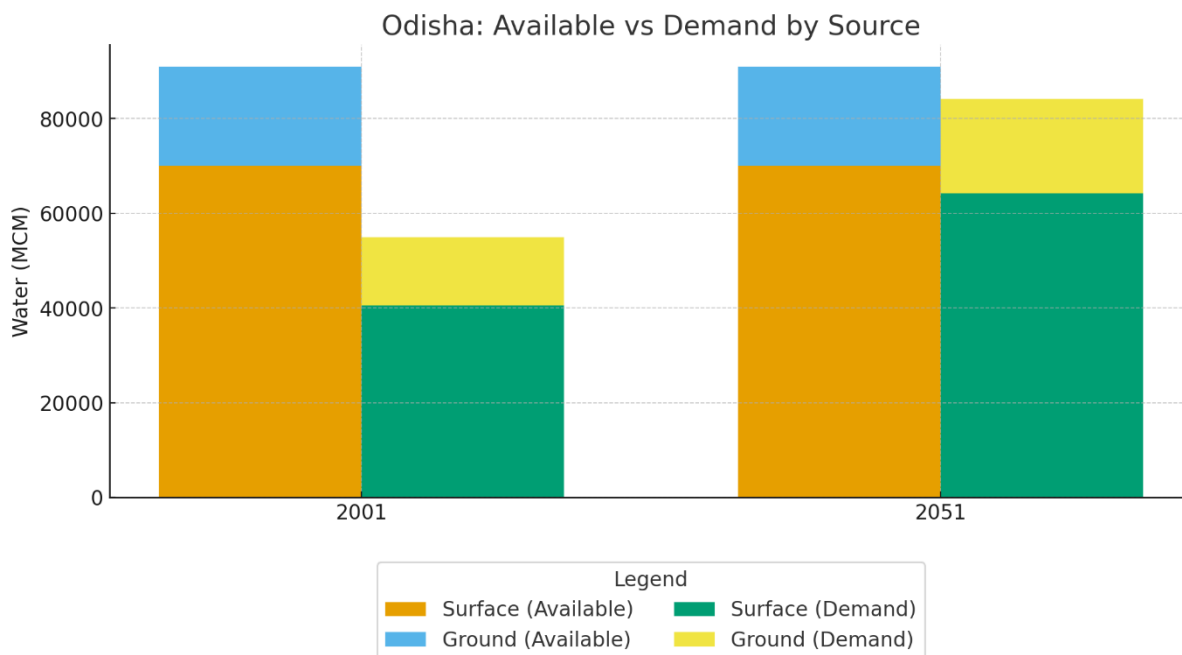
Climate change adds an operational risk more than a simple volume change. Studies for the upper and middle Mahanadi indicate warming with altered rainfall distribution that can increase peak monsoon pulses yet prolong dry spells, complicating Hirakud inflow management and carry-over storage into rabi. The practical effect in Odisha’s reach is a narrower operating window: the same annual quantum may arrive in fewer, bigger bursts, demanding dynamic reservoir rules that hedge across seasons while protecting environmental flows through Satkosia and the deltaic wetlands.

Putting these threads together, the Odisha part of the Mahanadi is best viewed as management-limited rather than volume-limited in many years: annual endowment is sizable, basin live storage is substantial, and yet seasonal reliability is stressed by the timing of inflows, allocation trade-offs, and efficiency gaps. Without a pivot to conservation, reuse and conjunctive governance guided by CGWB stages, rabi shortfalls and local aquifer stress will intensify in the delta and peri-urban belts. With that pivot, the same infrastructure can meet 2050 demands more equitably and with better ecological outcomes.

**Table 22.** Odisha State Water Balance: Sector-wise Surface and Groundwater Demand.

Sector	2001 Demand Surface	2001 Demand Ground	2051 Demand Surface	2051 Demand Ground
Domestic	798	1,198	1,202	1,803
Agriculture	18,000	4,688	40,000	9,408
Industry	606	100	1,750	200
Environment	21,000	8,400	21,000	8,400
Others	100	100	200	200
<b>Total</b>	<b>40,504</b>	<b>14,486</b>	<b>64,152</b>	<b>20,011</b>

Table 22 shows Odisha’s state-wide water balance by source and sector for 2001 and projected 2051. Total demand rises ~53% (54,990→84,163 MCM), led by agriculture (surface 18,000→40,000; groundwater 4,688→9,408 MCM). Domestic and industrial needs also increase with population and growth. Environmental allocations remain large (surface 21,000; groundwater 8,400 MCM), limiting consumptive supply. Available water is assumed constant (surface 70,000; groundwater 21,000 MCM), so by 2051 the tighter margin implies stronger reliance on storage, seasonal regulation, spatial redistribution, and groundwater management to meet peaks. (Government of Odisha’s State Water Plan (2004), State Water Balance).



**Figure 21.** Availability vs. demand for the Odisha state.

(Source: Odisha’s State Water Plan, 2004)

Figure 21 compares Odisha’s total water availability and demand in 2001 and 2051, disaggregated by surface and groundwater. While state-wide availability remains essentially constant at ~91,000 MCM (70,000 MCM surface; 21,000 MCM groundwater) in both years, total demand rises steeply from 54,990 MCM in 2001 to 84,163 MCM in 2051. This compresses the net surplus from about +36,010 MCM to only +6,837 MCM, indicating a system moving toward near closure. The tightening is driven primarily by surface-water demand growth (40,504 → 64,152 MCM) against flat surface availability, while groundwater shifts from a comfortable margin to a small residual surplus (14,486 → 20,011 MCM demand versus 21,000 MCM available). By 2051, even though the annual balance remains slightly positive, the markedly reduced buffer suggests heightened vulnerability to interannual variability, localized deficits, and the need for demand management, conjunctive use, and targeted aquifer protection.

### 3.6 Population Growth within the Mahanadi River Basin

Chhattisgarh's total population was approximately 27.94 million or 29.43 million in 2020, with a projected population of 29.49 million in 2021 (Table 23). In 2011, 16% of the population resided in urban centers, a figure that rose to 23.24% urban and 76.76% rural in 2020. Odisha’s population in 2025 is estimated to reach approximately 46.8 million, showing an 11.4% increase from the 42 million recorded in the 2011 census. Of this, most residents, about 83%, live in rural areas, which equates to roughly 38.4 million people. The urban population is projected to be about 8.4 million, accounting for approximately 17–18% of the state’s total.

Population is an important driver of water demand in many sectors, especially the domestic sector and agriculture. Also, the way population drives water demand depends on where the population growth takes place. Urban population growth will have a much bigger positive impact on demand for water as compared to that of the rural population, for the same level of growth.

Analysis of data on population of urban and rural areas in Chhattisgarh part of Mahanadi River basin for the period from 1971 to 2011 shows that the urban growth rate was very high during the first two decades (1971-81 and 1981-1991) and came down and stabilized at an CAGR of 3.3 per cent during the last decade (2001-11). However, the rural population growth rate has been fluctuating between a lowest of 1.23 per cent per annum and 2.08 per cent per annum. For future projections, an annual growth rate of 3.3 per cent was considered for urban areas and 1.59 per cent for rural areas. The growth rate considered for rural areas is the average of the decadal growth rate for four consecutive decades before 2011.

**Table 23.** Past Growth Trends in Rural and Urban Population and Projected Growth in Population in Chhattisgarh Part of the Mahanadi River Basin.

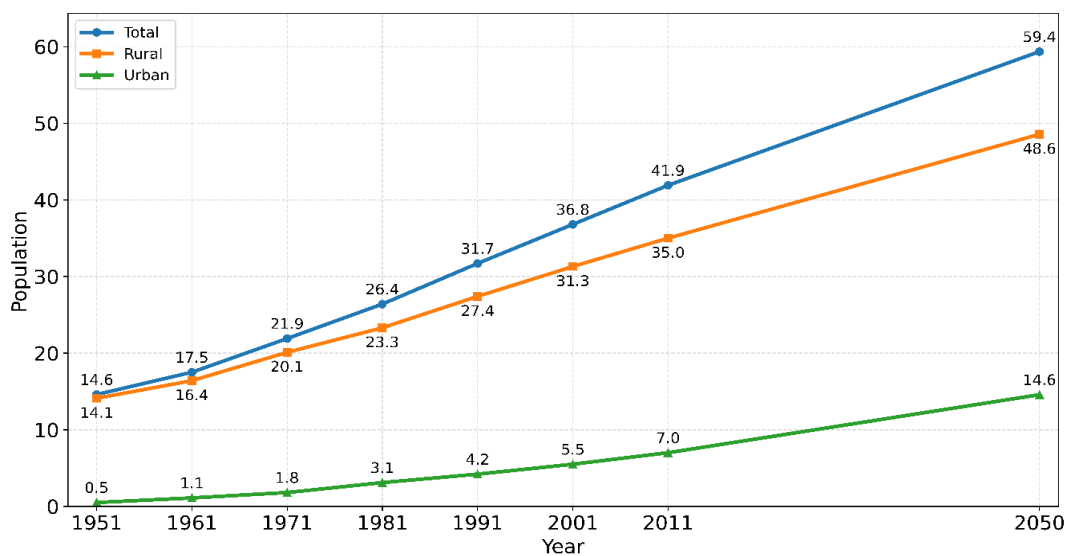
Total Population of the Mahanadi River Basin in Chhattisgarh				Annual Population Growth Rate of the Mahanadi River Basin in Chhattisgarh			
Year	Total	Rural	Urban	Year	Total	Rural	Urban
1971	85,56,927	75,63,825	9,93,102	-	-	-	-
1981	1,02,60,759	85,59,653	17,01,106	1971-81	0.0183	0.0124	0.0553
1991	1,31,27,369	1,05,17,411	26,09,959	1981-91	0.0249	0.0208	0.0437
2001	1,55,12,277	1,18,86,398	36,25,878	1991-01	0.0168	0.0123	0.0334
2011	1,92,65,136	1,42,33,527	50,31,609	2001-11	0.0219	0.0182	0.0333
2050	4,43,85,489	2,63,32,978	1,80,52,511	2011-50	-	0.0155	0.0333

(Source: CWC, 2012 & 2013)

Odisha's water demand is predominantly influenced by its large rural population, which determines both current requirements and future projections for domestic water use. Meanwhile, steady though modest urbanization in districts connected to the Mahanadi River is expected to increase demand pressures for municipal water supplies, even while the population growth remains gradual. The predominance of rural residency and slow urban growth in Odisha means that policy and planning must focus on ensuring reliable water resources for rural households, while also responding to incremental increases in urban demand, especially in the context of the Mahanadi River basin.

The estimated and projected water demand in the Mahanadi Basin (Odisha), indicates a steady rise in total water use from 12.44 BCM in 2018 to 20.76 BCM by 2050, mainly due to growing agricultural and domestic requirements. Despite this increase, the utilizable water remains constant at 29.30 BCM, leading to a declining overall water balance over time.

In the Odisha segment of the Mahanadi basin, domestic water demand exhibits a progressive increase corresponding to demographic expansion and urban development trends. The estimated domestic water use was 0.45 BCM (450 MCM) in the baseline year 2018, projected to rise to 0.55 BCM (550 MCM) by 2030, and further to 0.72 BCM (720 MCM) by 2050 (Figure 22). This incremental growth indicates a sustained escalation in per capita and total domestic water requirements driven by urbanization, improved service coverage, and enhanced living standards. Although the domestic sector accounts for a relatively smaller fraction of the total water use compared to agriculture, its growth rate is notably higher, signifying an increasing stress on available water resources and the necessity for efficient demand management within Odisha’s portion of the Mahanadi basin.



**Figure 22.** Past Growth Trends in Rural and Urban Population and Projected Growth in Population in Odisha Part of the Mahanadi River Basin.

## 4. Implications of Changing Precipitation Patterns

### Chhattisgarh Region

The analysis of long-term rainfall patterns across the Chhattisgarh portion of the Mahanadi River Basin indicates that while mean annual rainfall has remained broadly stable at the basin scale, statistically significant spatial and temporal variability has emerged at the district level. Coefficients of variation ranging around 25–30% highlight moderate to high inter-annual rainfall variability, particularly in districts located in the plains and transitional agro-climatic zones. This increasing unevenness in rainfall distribution has important implications for water availability and management.

Seasonal analysis shows that nearly 85–90% of annual precipitation continues to be concentrated within the southwest monsoon period. However, a growing tendency toward short-duration, high-intensity rainfall events has been observed. These events contribute disproportionately to surface runoff while limiting effective soil moisture recharge. As a result,

despite marginal increases in total rainfall in some districts, groundwater recharge benefits remain uneven, and post-monsoon water availability shows signs of stress.

Statistical trend assessments reveal that several districts exhibit either weakly declining or non-significant trends in monsoon rainfall, combined with increased variability during the non-monsoon season. This pattern has led to a measurable decline in dry season baseflows and reduced reliability of surface water storage systems. The outcome is heightened vulnerability for rainfed agriculture and increased dependence on groundwater abstraction during rabi and summer seasons. These findings imply that traditional monsoon-centric planning approaches are becoming less effective under changing precipitation regimes.

From a flood-risk perspective, districts experiencing upward trends in extreme rainfall days show higher peak flows, increasing pressure on reservoirs and downstream flood protection infrastructure. Conversely, districts with declining or highly variable rainfall face a greater likelihood of seasonal droughts, underscoring a dual risk of floods and water scarcity within the same region. Collectively, these outcomes point toward the need for district-specific adaptation strategies that prioritize rainfall variability management rather than total rainfall volume alone.

### **Odisha Region**

In the Odisha part of the Mahanadi River Basin, precipitation analysis reveals a more pronounced shift in rainfall characteristics, particularly in terms of magnitude and spatial differentiation. Statistical projections indicate that several interior and western districts are likely to experience substantial increases in annual rainfall, in some cases exceeding 10–15% relative to baseline conditions by the end of the century. However, this apparent increase is accompanied by a marked rise in intra-seasonal variability.

Rainfall distribution analysis shows a tendency toward rainfall concentration within fewer monsoon days, resulting in intensified runoff generation and reduced infiltration efficiency. Despite higher projected rainfall totals, non-monsoon season precipitation exhibits limited improvement, with some coastal and deltaic districts showing near-neutral or declining trends. This imbalance has direct implications for water security, as surplus monsoon flows are not effectively translated into sustained water availability during dry periods.

Statistical outcomes further indicate an increase in daily maximum rainfall intensity, which correlates with higher flood peaks and expanded floodplain inundation risks in downstream and delta regions. These changes significantly elevate the exposure of agricultural land, urban settlements, and critical infrastructure to flood-related damage. At the same time, declining post-monsoon flows and reduced baseflow contributions threaten ecological flows and rabi-season irrigation reliability.

The combined effect of increasing rainfall intensity and seasonal imbalance results in a paradoxical situation where water abundance during the monsoon coexists with water scarcity during the non-monsoon months. This outcome challenges existing reservoir operation rules, which are largely based on historical rainfall assumptions. The findings strongly suggest that

without enhanced storage optimization and improved runoff capture mechanisms, the benefits of increased rainfall may remain largely unrealized.

Across both Chhattisgarh and Odisha regions, changing precipitation patterns are reshaping the hydrological behavior of the Mahanadi River Basin in a statistically demonstrable manner. The key outcome is a shift from predictable seasonal rainfall toward a more variable and intensity-driven regime. This transition amplifies flood risks during the monsoon while simultaneously increasing drought vulnerability during the non-monsoon period.

## **4.1 Seasonal and Spatial Variability of Rainfall**

### **Chhattisgarh Region**

Rainfall across the Chhattisgarh portion of the Mahanadi River Basin exhibits strong seasonal concentration and pronounced spatial variability. The region receives an average annual rainfall of approximately 1,190 mm, of which nearly 88% occurs during the southwest monsoon season (June–September). This heavy seasonal dependence underscores the basin’s sensitivity to monsoon timing and intensity.

Spatial analysis reveals notable heterogeneity among agro-climatic zones. The Bastar Plateau records the highest mean annual rainfall, averaging around 1,340–1,350 mm, followed by the Northern Hills zone with approximately 1,250 mm. In contrast, the Chhattisgarh Plains receive comparatively lower rainfall, averaging 1,120–1,130 mm annually. The coefficient of variation (CV) of annual rainfall across districts is about 26%, indicating moderate but meaningful inter-district variability.

Trend analysis shows that long-term annual rainfall remains statistically stable at the basin scale; however, district-level signals indicate divergence. Several eastern and central districts demonstrate marginal increasing trends (1–3%), while parts of the western plains exhibit weak declining or stagnant trends. Seasonal variability is more pronounced during the post-monsoon and winter periods, where rainfall variability often exceeds 35–40%, increasing uncertainty for rabi cropping and groundwater recharge.

### **Odisha Region**

The Odisha region of the Mahanadi River Basin displays higher overall rainfall, but greater spatial contrasts compared to Chhattisgarh. Long-term records (1901–2023) indicate an average annual rainfall ranging between 1,400 and 1,600 mm, with nearly 80–85% received during the monsoon season. Coastal and deltaic districts benefit from higher monsoonal inflows, while interior western districts show greater variability.

Spatially, western Odisha districts such as Sambalpur, Bargarh, Jharsuguda, and Subarnapur exhibit increasing rainfall tendencies, with projected long-term gains exceeding 500–650 mm by the far-future period. In contrast, some coastal districts demonstrate non-linear rainfall behavior, characterized by near-term stagnation or decline followed by recovery in later

decades. The CV of annual rainfall across Odisha districts ranges between 22% and 30%, reflecting moderate to high spatial variability.

Seasonal analysis highlights a critical shift in rainfall distribution rather than magnitude. Monsoon rainfall is increasingly concentrated within shorter, high-intensity events, while non-monsoon rainfall (OND season) shows variability exceeding 40% in several districts. This pattern amplifies flood risk during peak monsoon months while reducing effective water availability during lean periods.

## 5. Floods, Droughts, and Water Security Risks

### 5.1 Assessment of Climate-Induced Flood Flow Changes in the Mahanadi River Basin, Chhattisgarh

The spatial variation in the percentage change in daily maximum flow across Chhattisgarh reveals a distinct hydrological pattern influenced by topography, land use, and climatic variability. Northern districts such as Balrampur, Jashpur, and Surguja exhibit a positive percentage change ranging from 21% to 40%, indicating an increased tendency for higher runoff and flood potential in these regions. This upward shift suggests that future extreme rainfall events could significantly enhance surface flow volumes, thereby elevating flood risks, especially in the upper catchments of the Mahanadi River Basin.

**Table 24.** District-wise percentage change in daily maximum flow with respect to the baseline period across the Mahanadi River basin, Chhattisgarh. [(CS Change - Raipur: action for the climate today, 2019)].

District / Region (Chhattisgarh)	Percentage Change in Daily Maximum Flow (%)	District / Region (Chhattisgarh)	Percentage Change in Daily Maximum Flow (%)
Balrampur	31 - 40	Kanker	-49 - -40
Jashpur	31 - 40	Kondagaon	-49 - -40
Surguja	21 - 30	Narayanpur	-50 or less
Korba	-19 - -10	Balod	-4 - 5
Koriya	-29 - -20	Dhamtari	6 - 10
Janjgir-Champa	-9 - 5	Rajnandgaon	-4 - 5
Raigarh	6 - 10	Bilaspur	-9 - 5
Baloda Bazar	6 - 10		
Bemetara	-4 - 5		
Durg	-4 - 5		
Kawardha	-4 - 5		
Mahasamund	-4 - 5		

Central and eastern districts, including Raigarh, Janjgir-Champa, Baloda Bazar, and Dhamtari show moderate changes in daily maximum flow (ranging from -9% to +10%) (Table 24). This represents a relatively stable hydrological condition, although the potential for local flooding during high-intensity storms cannot be overlooked. The observed moderate increases in flow

can be attributed to seasonal rainfall concentration and altered catchment response due to land cover changes, emphasizing the need for improved water management and controlled urban expansion in flood-prone areas.

In contrast, the southern and southwestern districts, such as Kanker, Kondagaon, Narayanpur, and parts of Mahasamund, depict significant reductions in daily maximum flow, with changes between -50% and -40%. These reductions point to possible decreases in peak discharge and altered drainage patterns, potentially caused by shifts in precipitation distribution or increased infiltration due to vegetation recovery. Such areas may experience reduced flood frequency but could face challenges related to water availability during dry periods. Overall, the results highlight a spatially heterogeneous hydrological response across Chhattisgarh, emphasizing the importance of district-specific adaptation and flood management strategies under changing climate scenarios.

## 5.2 District-wise Drought Frequency and Severity Analysis in Chhattisgarh

**Table 25.** District-wise Drought Frequency and Severity Status Based on Long-term Rainfall Analysis in the Mahanadi River basin Chhattisgarh.

District	No. of Years Analyzed	Normal Years (%)	Moderate Drought (%)	Severe Drought (%)
Balod	52	94	6	0
Balodabazar	56	79	20	2
Bemetara	54	89	7	4
Bilaspur	44	93	2	5
Dhamtari	58	83	12	2
Durg	23	87	13	0
Gariaband	44	77	20	2
Janjgir-Champa	56	89	11	0
Jashpur	44	86	14	0
Kanker	35	86	14	0
Kawardha	53	100	0	0
Kondagaon	17	100	0	0
Korba	56	88	13	0
Koriya	42	81	19	0
Mahasamund	42	91	9	0
Mungeli	44	98	2	0
Narayanpur	42	90	10	0
Raigarh	44	93	7	0
Raipur	58	86	10	0
Rajnandgaon	54	78	22	0
Surajpur	43	91	9	0
Surguja	35	86	14	0

The drought frequency analysis for Chhattisgarh (as shown in Table 25) indicates that most of the districts experience normal rainfall conditions in more than 80–90% of years, reflecting a generally stable climatic regime. However, several regions such as Balodabazar, Gariaband, and Rajnandgaon show relatively higher occurrences of moderate droughts, with 20–22% of the observed years classified under this category. These areas fall within transitional climatic zones that often experience uneven monsoon distribution, making them vulnerable to short-term water stress, especially during the kharif cropping season.

Districts such as Bilaspur and Bemetara exhibit the occurrence of severe droughts in 4–5% of recorded years, suggesting localized rainfall deficiencies that may stem from topographical and hydrological variations. Although these extreme drought events are infrequent, they pose serious threats to agricultural productivity and groundwater recharge. On the other hand, regions like Kawardha and Kondagaon have shown complete drought-free records, highlighting their relatively favorable rainfall regimes and possibly better water retention capacity in local catchments. Overall, the state exhibits a moderate drought vulnerability, where temporary water shortages are more common than prolonged dry periods. The analysis underscores the need for region-specific drought mitigation strategies, particularly in the central and eastern districts. Measures such as improved irrigation coverage, moisture conservation, and drought-tolerant crop varieties are essential to enhance resilience. Strengthening weather monitoring systems and early-warning mechanisms can further minimize the socio-economic impacts of droughts, particularly for small and marginal farmer's dependent on rainfed agriculture.

## **6. Policy and Institutional Framework**

### **6.1 Existing Water Management Policies**

Chhattisgarh's water management strategy has traditionally emphasized increasing water availability, mainly by expanding irrigation infrastructure. Over the years, the state has invested heavily in large, medium, and minor irrigation projects, including reservoir-based systems and diversion structures such as barrages and weirs. These efforts accelerated after the state was formed, resulting in a marked rise in irrigated area, from 23% of the gross sown area (about 1.328 million hectares) in 2000 to nearly 34% by 2015–16. During the same period, irrigation potential from surface water projects increased significantly, growing from 1.45 million hectares to approximately 1.95 million hectares ([www.cgwrdd.in](http://www.cgwrdd.in)).

In addition to expanding surface irrigation, the state also provides free electricity to farmers for operating lift irrigation systems, including groundwater-based installations and small-scale river lift schemes. This has encouraged a rapid rise in groundwater extraction for irrigation over the past decade and a half. Like many other states in India, Chhattisgarh supports the farming sector by offering subsidized or free power. The policy is justified to ease financial pressure on farmers, especially those frequently affected by drought. This assistance plays a key role in sustaining a predominantly paddy-based cropping system by lowering overall production costs.

However, reports such as the CWC assessment and the SAPCC analysis indicate that the state faces several persistent water-related challenges. These include widespread pollution of water

bodies due to industrial discharge, excessive groundwater pumping leading to falling water tables, and the use of naturally contaminated (geo-genic) groundwater for drinking. In many regions, communities struggle with unreliable or poor-quality drinking water supplies, deteriorating irrigation infrastructure, and inefficient water use practices in both agriculture and industry. These problems intensify during the summer months, when scarcity and quality issues become more severe across the state.

The Draft State Water Policy (2012) acknowledges the need to meet water demands across all major sectors, agriculture, industry, and households, while prioritizing environmentally responsible and socially equitable water resource development. The policy also mentions revising water tariffs for different categories of users; however, this revision primarily focuses on cost recovery rather than promoting water-use efficiency. Although the document emphasizes water conservation and quality management, it does not adequately address demand-side measures or promote economic tools such as water pricing or taxation to encourage sustainable usage.

The draft policy also stresses the importance of involving local institutions and Water User Associations (WUAs) in planning, implementing, and managing water projects. It proposes giving WUAs statutory responsibilities such as collecting and retaining a share of water fees, overseeing the quantity of water allocated to them, and maintaining distribution systems within their command areas. In the case of minor irrigation projects, it recommends ensuring that farmers and residents actively participate in the planning process to improve transparency and long-term sustainability.

## **6.2 Institutional Roles and Coordination Mechanisms**

To ensure transparency and accountability in water governance, it is essential to eliminate situations that may create conflicts of interest. At present, several departments perform overlapping roles, for instance, the Water Resources Department handles flood forecasting, the Revenue Department evaluates damage, and the State Pollution Control Board enforces pollution standards. Such arrangements can compromise neutrality. Therefore, the system must provide the right incentives and an enabling environment for each agency to work effectively and without bias.

Another challenge stems from the presence of multiple layers of governance, ranging from the state level to Gram Panchayats. This fragmented structure often leads to coordination gaps and inconsistent decision-making. As a result, restructuring existing water-related institutions has become necessary. Considering the 73rd and 74th Constitutional Amendments, it is crucial to strengthen the technical capabilities of Panchayati Raj Institutions (PRIs) and Urban Local Bodies (ULBs). Building their capacity will enhance local water conservation efforts, prevent contamination, and help monitor groundwater extraction to ensure long-term sustainability.

Improving water governance also requires stronger mechanisms for stakeholder participation. Effective engagement should include farmers, water user groups, communities living around water bodies, panchayats at various levels, local governments, industries, and urban authorities.

Such inclusive collaboration is essential to prevent pollution, improve resource monitoring, and promote shared responsibility for water security.

Institutional restructuring must be guided by a few key principles. First, the roles of water development and water resource management must be clearly separated. Second, agencies responsible for allocating or regulating water use should be distinct from those providing water services, such as the Water Resources Department, Public Health Engineering Department, and environmental agencies. Third, monitoring water quality should not be handled by the same institutions that manage it. Lastly, organizations responsible for investments in water infrastructure and resource management should also enforce water-use regulations.

Although a basin-level authority might seem like a strategic option due to the interconnected nature of water management, creating such an institution may introduce additional bureaucratic complexity without delivering meaningful benefits, particularly because most of Chhattisgarh depends heavily on the Mahanadi basin. Instead of forming a new basin-level body, strengthening institutions within the existing administrative framework is more practical. For multidisciplinary issues, the formation of a high-level, interdepartmental task force under the Water Resources Department can provide coordinated decision-making and better support integrated water management.

### **6.3 Gaps in Governance and Implementation**

### **6.4 Policy Recommendations for Climate-Resilient Water Planning**

Many researchers over the years (Kemper, 2007; Mohanty and Gupta, 2012; Rosegrant and Gazmuri S., 1994; NWC, 2010; Rosegrant and Binswanger, 1994; Saleth, 1996) have emphasized, using strong empirical insights, that introducing clearly defined water-use rights and volumetric entitlements is essential for influencing user behaviour and improving water governance. Such institutional reforms are especially relevant for tackling recurring challenges of water scarcity and drought. Considering the long-term water stress in the Chhattisgarh portion of the Mahanadi Basin, similar reforms should be seriously explored.

The intent behind proposing a water-right system is not to grant permanent ownership of water, but rather to allocate adjustable use rights that may change annually or over longer periods, depending on resource conditions and new users entering the system. To implement such a system, precise quantification of water availability, at various dependability levels, is necessary. This calls for improvements in data collection and resource assessment techniques, including accurate measurement of dry-season flows from smaller catchments (roughly 500–1,000 km<sup>2</sup>). Such information would also enhance estimates of usable groundwater recharge.

Developing a reliable water-right framework further requires robust principles to guide allocation across sectors. These principles should be grounded in equity, sustainability, and efficiency. This will also require competent institutional structures at the basin and sub-basin scales to distribute water among sectors, while line departments, such as the Water Resources Department, Water Supply and Sanitation Department, and the Industrial Development

Corporation, could allocate water to individual users within their respective domains. For irrigation, the Water Resources Department may distribute bulk surface-water volumes to Water User Associations at secondary and tertiary levels, which would then apportion water to farmers.

For groundwater, dedicated institutions will be needed at multiple scales, from the aquifer level to the watershed and village levels, to monitor extraction and uphold water-use rights. This will be challenging, given the fluctuating nature of groundwater availability across seasons and years, and its highly decentralized pattern of use (Kumar, 2000; Kumar, 2007). In the Mahanadi Basin, however, the study placed stronger emphasis on surface-water allocations, as reservoir and diversion systems account for a much larger share of supply than groundwater.

Another key element of institutional reform is designing an appropriate water-pricing structure, including resource fees. Developing fair pricing criteria for different sectors will be complex, particularly when revisiting the current practice of cross-subsidizing agriculture at the expense of industrial and urban users. In the region's evolving socio-economic context, maintaining such subsidies will become increasingly difficult. Prices charged to industries for surface water should reflect the opportunity cost of producing equivalent-quality water independently. Higher industrial tariffs are justified because industries draw large quantities from surface systems, which often forces the domestic sector, particularly rural communities, to rely on poor-quality groundwater containing contaminants like fluoride, nitrates, or high salinity.

To correct this imbalance, the practice of supplying high-quality reservoir water to industries while leaving rural households dependent on inferior groundwater needs urgent reconsideration. Implementing a more realistic pricing strategy for industries can help curb excessive consumption and promote more responsible use of water resources.

## **7. Future Outlook and Recommendations**

The climate outlook for the Mahanadi River Basin indicates a future characterized by rising temperatures, altered rainfall regimes, and increasing hydro-climatic variability. Across both Chhattisgarh and Odisha, projections consistently point toward a warming trend in maximum and minimum temperatures, with the most pronounced increases observed in interior, industrialized, and agriculturally intensive districts. Warmer nights and prolonged heat stress periods are likely to become more frequent, reducing thermal recovery and intensifying pressure on water resources, ecosystems, and crop productivity.

Rainfall projections suggest a complex but coherent shift rather than a uniform decline or increase. While many districts are expected to experience a moderate rise in total annual precipitation, this increase is unevenly distributed across seasons and space. The tendency toward higher rainfall concentration during shorter periods raises the likelihood of floods, soil erosion, and reservoir stress, even as dry-season water availability becomes more uncertain. In contrast, some coastal and transitional districts may experience near-term rainfall declines followed by long-term increases, reflecting changing monsoon dynamics and coastal-atmospheric interactions.

Hydrological modeling outcomes indicate that future water availability will not depend solely on precipitation trends. Reductions in surface runoff and evapotranspiration, combined with moderate gains in groundwater recharge in selected regions, suggest a shift in surface–subsurface water balance. While this may reduce flood peaks in some districts, it could also delay reservoir inflows and complicate irrigation scheduling. Overall, the basin is expected to transition from a relatively manageable water balance toward a more stressed and spatially heterogeneous system by mid- to late-century if current demand trajectories persist.

## **7.1 Climate-Resilient Water Infrastructure**

Strengthening climate resilience in the basin will require targeted investments in water infrastructure that reflect future climatic realities rather than historical conditions. Reservoir operation rules should be revisited to accommodate altered inflow timing, higher rainfall intensity, and longer dry spells. Enhancing decentralized storage structures such as check dams, percolation tanks, and farm ponds can help capture excess monsoon runoff while improving groundwater recharge.

Urban drainage systems must be redesigned to manage short-duration high-intensity rainfall events, particularly in low-lying and coastal districts prone to flooding and waterlogging. In parallel, promoting nature-based solutions such as floodplain restoration, wetland conservation, and riparian buffer zones can reduce hydrological extremes while providing ecological co-benefits.

## **7.2 Technological Innovations and Data-Driven Decision Making**

Advances in climate modeling, remote sensing, and hydrological simulation provide an opportunity to shift toward anticipatory water management. Integrating climate projections into basin-scale planning, reservoir operation models, and agricultural advisories can significantly improve preparedness. Early-warning systems for floods, droughts, and heatwaves should be expanded and linked with local governance structures to ensure timely response.

At the agricultural level, precision irrigation, climate-smart agronomy, and digital decision-support tools can enhance water productivity while reducing climate risk. Such technologies must be supported by capacity building and institutional outreach to ensure adoption across small and marginal farming communities.

## **7.3 Capacity Building and Public Awareness**

Long-term climate resilience in the Mahanadi River Basin depends on aligning scientific assessments with policy frameworks and community action. Basin-level coordination across states and sectors is essential to manage shared risks and competing demands. Water pricing and allocation policies should reflect resource scarcity, environmental costs, and social equity considerations.

Capacity building at institutional and community levels is equally important. Training programs for planners, engineers, farmers, and local administrators can facilitate the translation of climate knowledge into practice. Public awareness initiatives should emphasize water conservation, ecosystem stewardship, and climate-adaptive livelihoods to foster a culture of shared responsibility.

## **7.4 Implications for Water Security and Agriculture**

The projected climate trends carry significant implications for water security and agricultural sustainability in the basin. Agriculture, which remains the dominant water-using sector, will face increasing uncertainty due to shifting rainfall timing, higher evaporative demand during warmer periods, and localized groundwater stress. Even districts that currently fall within safe groundwater extraction limits show signs of rising pressure, particularly where irrigation expansion and domestic demand are accelerating.

Increased temperature extremes pose a direct threat to crop productivity, especially during sensitive growth stages. Cropping systems that rely heavily on historical climate norms may become progressively less reliable, necessitating adjustments in crop calendars, varietal selection, and irrigation practices. Rainfed areas are likely to remain the most vulnerable, while irrigated regions may experience rising energy costs and declining water-use efficiency.

Urban and industrial water demand is expected to grow rapidly, intensifying competition across sectors. Without institutional reforms, this imbalance could exacerbate inequities, with rural communities increasingly dependent on lower-quality groundwater sources. These dynamics underscore the urgency of transitioning from supply-oriented planning to integrated demand and risk-based water management.

## **8. Conclusions**

This report provides a comprehensive and statistically grounded understanding of how hydro-climatic dynamics are evolving across the Mahanadi River Basin, with particular emphasis on the Chhattisgarh and Odisha regions. The results clearly demonstrate that the basin is undergoing a systematic climatic transition characterized by rising temperatures, spatially heterogeneous precipitation trends, and marked alterations in hydrological processes. Collectively, these changes signal a shift from historically predictable hydro-climatic conditions toward a more variable and risk-prone future.

Long-term temperature analysis reveals a consistent warming trend across all districts of the basin. Mean maximum temperatures have increased by approximately 1.8–4.3 °C across much of Chhattisgarh by the mid- to end-century horizon, with the strongest warming observed in central and eastern districts such as Korba, Raigarh, Janjgir-Champa, and Bilaspur. Simultaneously, minimum temperatures have risen by 1.6–3.5 °C, indicating warmer nights and reduced thermal relief during winter months. This asymmetric warming pattern is particularly significant, as higher minimum temperatures are known to intensify crop respiration losses, accelerate phenological development, and increase irrigation demand (Directorate of

Economics and Statistics, 2015; IPCC, 2021). The persistence of warming across both agricultural and forested districts suggests that localized land-use effects amplify, rather than replace, broader climate signals.

Precipitation trends across the basin exhibit a more complex but equally consequential pattern. While basin-wide mean annual rainfall shows a modest increase of 1–5% in several districts, the spatial and seasonal distribution of rainfall has become increasingly uneven. Western and interior districts of the Odisha region, including Sambalpur, Bargarh, Jharsuguda, and Subarnapur, are projected to experience substantial long-term rainfall increases exceeding 500–650 mm by the far-future period (2071–2100). In contrast, several coastal and deltaic districts show non-monotonic behavior, with near-term declines followed by recovery and later intensification. This evolving rainfall regime reflects changes in monsoon timing, intensity, and intra-seasonal variability rather than a uniform wetting trend (Central Water Commission [CWC], 2013; Mishra et al., 2023).

Hydrological modeling using SWAT under the IPCC AR5 RCP 4.5 scenario highlights a fundamental reorganization of water balance components within the basin. Despite modest increases in monsoonal precipitation, surface runoff is projected to decline sharply by 30–50% across large parts of the Chhattisgarh plains, including Dhamtari, Bemetara, Baloda Bazar, and Raipur. This counterintuitive result underscores the growing dominance of infiltration and soil moisture retention processes over direct runoff generation. Such a shift reduces flood peaks in certain districts but simultaneously diminishes reservoir inflows, thereby complicating irrigation planning and downstream water availability (CWC, 2012).

Evapotranspiration exhibits one of the most statistically pronounced changes in the assessment. A widespread decline of 30–50% in evapotranspiration is observed across northern and eastern districts such as Bilaspur, Raigarh, Korba, and Jashpur. Lower evapotranspiration rates imply enhanced soil moisture retention and potentially improved short-term water use efficiency for crops. However, this reduction also alters land–atmosphere feedbacks and may affect local convection and rainfall recycling processes, introducing additional uncertainty into future monsoon behavior (Panda et al., 2013).

Groundwater dynamics emerge as a critical outcome of the changing hydro-climatic regime. Groundwater recharge shows a statistically significant improvement of 10–30% in eastern and central districts, notably Korba, Raigarh, and Janjgir-Champa, driven by increased infiltration and reduced evapotranspiration losses. Baseflow contributions to river discharge remain relatively stable, varying within a narrow range of –10% to +10%, indicating that subsurface hydrological systems retain a degree of resilience. However, districts such as Raipur and Mahasamund already exhibit groundwater extraction levels exceeding 59%, collectively accounting for nearly 45% of total groundwater withdrawal in Chhattisgarh. This imbalance suggests that recharge gains alone will not offset unsustainable extraction without targeted demand-side regulation (Department of Water Resources, Government of Chhattisgarh, 2015).

Seasonal analysis further reveals that climate risks are not uniformly distributed throughout the year. During the non-monsoon (OND) season, precipitation variability ranges from –5% to

+15%, while surface runoff declines by 20–40% across large portions of the Odisha basin. Baseflow reductions of up to 25% during this period pose a direct threat to ecological flows and rabi-season irrigation. The widening mismatch between post-monsoon water demand and available storage highlights a growing vulnerability that cannot be addressed through monsoon-centric planning alone (CWC, 2011).

From a water security perspective, scenario-based demand–supply analysis indicates a clear trajectory toward basin-level stress. Under the base-case scenario, water deficits in the Chhattisgarh portion of the basin increase from negligible levels in 2010 to approximately 2,812 MCM by 2050. Under high-growth assumptions, deficits exceed 5,000 MCM, even when climate change impacts are partially moderated through conservation measures. Notably, climate-adjusted scenarios still show deficits of 1,683–2,373 MCM by mid-century, underscoring that climate change acts as a multiplier of existing demand pressures rather than an isolated driver (Ministry of Water Resources, 2014).

The combined evidence from temperature, rainfall, and hydrological indicators leads to a clear and policy-relevant conclusion: the Mahanadi River Basin is transitioning from a state of relative hydrological stability to one characterized by heightened variability, localized surplus-deficit contrasts, and increasing management complexity. While some districts may benefit from enhanced groundwater recharge or reduced flood intensity, others face compounded risks from heat stress, declining runoff, and post-monsoon water scarcity. These outcomes invalidate one-size-fits-all adaptation strategies and reinforce the need for district-specific, seasonally differentiated planning.

In practical terms, the findings emphasize that future resilience will depend less on increasing water supply and more on optimizing allocation, storage, and use efficiency. The statistically significant decline in evapotranspiration and runoff, combined with modest rainfall gains, suggests strong potential for managed aquifer recharge, soil–water conservation, and demand-side interventions. Equally important is institutional reform, including realistic water pricing, sector-specific allocation frameworks, and improved monitoring of groundwater extraction, as highlighted in earlier basin studies (Kumar, 2007). Therefore, this assessment provides robust quantitative evidence that climate change is already reshaping the hydro-climatic foundations of the Mahanadi River Basin. The observed and projected changes demand a paradigm shift from reactive water management to anticipatory, climate-informed governance. Integrating long-term climate projections into basin-scale planning, strengthening institutional capacity, and promoting adaptive agricultural and water-use practices will be essential to safeguard water security, ecosystem integrity, and livelihoods in the decades ahead.

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**Appendix I: District-wise groundwater resources availability, utilization, and stage of extraction**

**Appendix II: District-wise industrial water demand**

**Appendix III: District-wise Total, Urban, and Rural Domestic Water Demand**

## Appendix I: District-wise groundwater resources availability, utilization, and stage of extraction

District	Recharge from Rainfall (Monsoon)	Recharge from Other Sources (Monsoon)	Recharge from Rainfall (Non-Monsoon)	Recharge from Other Sources (Non-Monsoon)	Total Annual GW Recharge	Natural Discharge	Annual Extractable GW Resource	Current Annual GW Extraction				Annual GW Allocation for Domestic Use (2025)	Net GW Availability for Future Use	Stage of Extraction (%)
								Irrigation	Industrial	Domestic	Total Extraction			
Balod	16827.95	15473.6	0	7403.29	39704.84	3839.01	35865.84	24199.76	2259.42	26531.78	2356.22	9598.22	73.98	
Baloda Bazar	25659.93	36010.49	412.24	6557.98	68640.64	6760.17	61880.47	20954.05	1145.11	4522.3	26621.5	5644.19	34581	43.02
Bemetara	18175.02	16782.78	0	12389.23	47347.03	4734.72	42612.31	36869.55	212.3	2465.12	39546.94	2889.52	4366.86	92.81
Bilaspur	21989.71	16860.67	426.62	11914.36	51191.36	4722.24	46469.12	21566.19	664.59	5701.27	27932.02	6529.12	19980.2	60.11
Dhamtari	20986.49	28926.68	0	18274.95	68188.12	6529.57	61658.56	42872.68	2115.66	45067.33	2180.05	16526.84	73.09	
Durg	14510.5	19764.1	0	8830.02	43104.62	4034.8	39069.82	24015.02	408.38	4962.51	29385.91	5135.19	10672.78	75.21
Gariaband	22766.79	8496.39	0	6030.52	37293.7	3524.82	33768.88	19665.59	17.24	1729.48	21412.31	1877.55	12208.5	63.41
GPM (Gourela-Pendra-Marwahi)	11297.19	1275.67	545.15	1242.23	14360.24	1258.33	13101.92	4016.68	1.62	1147.91	5166.22	1324.53	7759.07	39.43
Janjgir-Champa	12350.45	20831.76	153.04	15306.79	48642.04	4522.44	44119.59	8143.85	231.79	2863.32	11238.96	3060.17	32683.76	25.47
Jashpur	27453.62	2804.53	873.11	3715.88	34847.14	2721.18	32125.95	13239.81	29.64	2244.1	15513.57	2320.47	16536.99	48.29
Kabirdham	32690.31	29684.9	1408.77	9245.4	73029.38	7302.94	65726.44	36151.32	75.18	2576.21	38802.73	2837.22	27631.68	59.04
Kanker	55430.65	4915.27	2224.16	8633.41	71203.49	5376.38	65827.11	22734.24	30.55	2057.07	24821.88	2150.07	40912.25	37.71
Khairagarh-Chhuikhadan-Gandai	9010.98	7608.23	98.12	2873.7	19591.03	1753.18	17837.85	10111.42	11.82	1085.67	11208.9	1161.58	6553.04	62.84
Kondagaon	30505.36	2723.03	2064.15	2231.35	37523.89	2500.06	35023.83	13506.65	21.75	1587.46	15115.87	1658.78	20053.25	43.16
Korba	37675.69	4693.11	676.81	5510.46	48556.07	2837.47	45718.6	10260.7	2438.78	3646.02	16345.51	3879.21	29139.9	35.75
Korea	9543.17	3323.71	53.15	1869.95	14789.98	991.72	13798.26	5742.25	390.63	662.96	6795.84	683.63	6981.76	49.25
Mahasamund	47011.09	38521.02	325.68	16779.85	102637.6	8813.26	93824.38	53575.12	124.18	2917.58	56616.87	3077.95	37047.14	60.34

MCB (Manendragarh-Chirmiri-Bharatpur)	47273.19	1891.66	244.3	1709.74	51118.89	4396.4	46722.49	7737.71	720.69	1101.72	9560.12	1136.16	37127.94	20.46
Mohla-Manpur-Ambagarh Chowki	12357.67	1879.34	144.29	2510.11	16891.41	1689.15	15202.26	5107.48	31.5	742.76	5881.72	767.82	9295.49	38.69
Mungeli	9680.27	12373.58	0	4844.83	26898.68	2343.88	24554.8	9315.57	30.68	1919.55	11265.81	2236.98	12971.56	45.88
Narayanpur	25101.06	457.92	772.79	553.46	26885.23	2378.73	24506.5	1393.87	10.65	392.72	1797.25	412.02	22689.96	7.33
Raigarh	35392.31	2788.33	408.53	3429.14	42018.31	3707.28	38311.02	10689.7	2666.41	3144.87	16500.96	3302.28	21652.65	43.07
Raipur	19715.92	23406.18	42.18	7778.94	50943.22	4923.51	46019.71	17943.08	1896.52	7387.33	27226.94	8179.69	19060.3	59.16
Rajnandgaon	20156.4	9704.94	236.55	8541.37	38639.26	3436.43	35202.83	20995.43	228.59	3221.6	24445.65	4080.63	9898.15	69.44
Sakti	9148.9	10717.41	101.69	13030.06	32998.06	3151.13	29846.93	12286.55	8.87	1939.26	14234.66	2086.47	15465.06	47.69
Sarangarh-Bilaigarh	14175.82	6923.33	361.15	3280.46	24740.76	1944.96	22795.8	6980.99	45.46	1848.62	8875.05	2028	13741.37	38.93
Surajpur	28568.63	4629.44	217.28	6415.47	39830.82	2811.19	37019.63	19533.56	955.05	2188.08	22676.75	2298.05	14232.91	61.26
Surguja	34167.83	3443.26	885.79	3916.43	42413.31	3526.12	38887.19	15102.93	1059.23	2330.79	18492.95	2436.01	20303.64	47.56
<b>Total (Ham)</b>	<b>857159.4</b>	<b>342877</b>	<b>15301.12</b>	<b>203016.54</b>	<b>1418354</b>	<b>125620.2</b>	<b>1292733.9</b>	<b>520686.92</b>	<b>13853.01</b>	<b>77216.35</b>	<b>611756.4</b>	<b>84499.02</b>	<b>681919.18</b>	<b>47.32</b>
<b>Total (Bcm)</b>	<b>8.57</b>	<b>3.43</b>	<b>0.15</b>	<b>2.03</b>	<b>14.18</b>	<b>1.26</b>	<b>12.93</b>	<b>5.21</b>	<b>0.14</b>	<b>0.77</b>	<b>6.12</b>	<b>0.84</b>	<b>6.82</b>	<b>47.32</b>

## Appendix II: District-wise industrial water demand

District	Name of the Block	Industrial Water Requirement (MCM)		
		1991	2001	2011
Balod	Balod	0.000276	0.019355	0.059055
	Dondi	7.180000	0.000000	0.000330
	Dondi Luhara	0.000000	0.000000	0.029043
	Gunderdehi	0.000000	0.002640	0.021830
	Gurur	0.009900	0.022143	0.066228
Baloda Bazar	Baloda Bazar	6.580000	0.147620	0.518595
	Bhatapara	0.007887	0.328905	0.281589
	Bilaigarh	0.000000	0.003300	0.023430
	Kasdol	0.001320	0.002475	0.005940
	Palari	1.308780	0.000990	0.061645
	Simga	1.789920	0.009603	1.024980
Bemetara	Bemetara	0.000000	0.000000	0.003600
	Berla	0.000000	0.011900	0.017200
	Nawagarh	0.000000	0.000000	0.002700
	Saja	0.000000	0.000000	0.004200
Bilaspur	Bilha	0.416248	1.022974	5.048100
	Kota	0.002653	0.000000	0.003670
	Masturi	0.030800	93.000000	0.585199
	Takhatpur	0.001500	0.000000	0.001262
Dhamtari	Dhamtari	0.094900	0.047450	0.022630
	Kurud	0.025550	0.043800	0.116300
	Magarlod	0.000000	0.007300	0.007300
	Nagri	0.007300	0.000000	0.023360
Durg	Dhamdha	0.044550	0.000026	0.000669
	Durg	130.809990	346.631848	7.196102
	Patan	0.000000	0.000049	0.000035

Gariabandh	Bindranavagarh (Gariyaband)	0.000000	0.007920	0.003
	Chhura	0.000000	0.000000	0.007
	Deobhog	0.000000	0.000000	0.005280
	Mainpur	0.000000	0.000000	0.003960
	Rajim	0.033000	0.006600	0.104280
Gaurela-Pendra-Marwahi	Marwahi	0.000000	0.000000	0.000
	Pendra	0.000000	0.000000	0.000
	Pendra Road Gorella	0.000000	0.001462	0.022560
Janjgir - Champa	Akaltara	0.000000	2.100000	0.601148
	Baloda	2.160000	10.225000	35.658050
	Champa	0.000000	0.000000	0.000000
	Dabhra	0.000000	21.460000	17.157
	Jaijaipur	0.000000	0.000000	0.000000
	Malkharoda	0.000000	0.000000	0.000135
	Nawagarh	0.000000	0.000000	0.001197
	Pamgarh	0.000000	0.000000	74.674976
	Sakti	0.000000	0.000000	0.0001353
Jashpur	Bagicha	0.000000	0.000000	0.000750
	Duldula	0.000000	0.000000	0.000
	Farsabahar	0.000000	0.000000	0.001200
	Jashpur	0.000000	0.000000	0.000
	Kansabel	0.000000	0.001800	0.001500
	Kunkuri	0.000000	0.000000	1.167150
	Manora	0.000000	0.000000	0.000
	Pathalgaon	0.000000	0.004350	0.034410
Kwrdha	Bodla	0.000000	0.110820	0.004320
	Kawardha	0.000000	0.000000	0.027344
	Pandariya	0.000000	0.000000	0.903580
	Sahaspur Lohara	0.000000	0.000000	0.000000
Kdagaon	Bade Rajpur	0.000000	0.000000	0.000000

	Keskal	0.000000	0.000000	0.000000
	Makdi	0.000000	0.000000	0.000000
Korba	Kartala	0.000000	0.000000	0.001320
	Katghora	116.001825	0.000000	28.750
	Korba	0.006220	37.600099	204.884
	Pali	0.000000	0.000330	0.078730
	Poundi-Uproda	0.000000	0.000000	0.000000
Koriya	Baikunthpur	0.000000	0.000000	0.0016200
	Khadganva	0.000000	0.000000	0.004050
	Manendragarh	0.000000	0.000000	0.000
	Sonhat	0.000000	0.000000	0.000
Mahasamund	Bagbakra	0.000990	0.021285	0.012540
	Basna	0.000000	0.014850	0.007260
	Mahasamund	0.000990	0.067650	1.075355
	Pithora	0.000660	0.004125	0.012210
	Saraipali	0.001980	0.004785	0.005940
Mungeli	Lormi	0.000000	0.000000	0.008180
	Mungeli	0.000000	0.001080	0.010965
	Pathariya	0.000000	0.001620	0.184342
Raigarh	Baramkela	0.000000	0.004320	0.023340
	Gharghoda	0.000000	0.031680	0.043800
	Kharsia	0.000000	0.000000	12.793560
	Lailunga	0.000000	0.000000	0.022620
	Pussore	0.000000	0.691900	45.790260
	Raigarh	6.421000	231.329000	130.484830
	Sarangarh	0.000000	0.000000	0.010455
	Tamnara	0.000000	60.799932	6.983190
Udaipur (Dharamjaigarh)	0.000000	3.668250	0.182180	
Raipur	Abhanpur	0.241910	0.000000	0.050082

	Arang	23.078690	0.000000	0.109940	
	Dharsiwa	0.014090	29.718300	0.410560	
	Tilda	87.759301	0.057300	51.296240	
Rajnandgaon	Ambagarh	0.001500	0.000000	0.000000	
	Chhuikhadan	0.000000	0.000000	0.002100	
	Chhuriya	0.000000	0.000300	0.005000	
	Dongargaon	0.015300	0.025900	0.005709	
	Dongargarh	0.003400	0.005580	0.002868	
	Khairagarh	0.000000	0.000000	0.083990	
	Manpur	0.000000	0.000000	0.000000	
	Mohla	0.000000	0.000000	0.000000	
	Rajnandgaon	0.160254	0.520740	0.130399	
	Oudgi	0.000000	0.000000	0.000000	
	Premnagar	0.000000	0.000000	0.000000	
Ramanujnagar	0.000000	0.000000	0.000000		
Surajpur	Surajpur	0.000000	0.000000	0.000000	
	Ambikapur	0.000000	0.000000	0.000	
	Batouli	0.000000	0.000000	0.00108	
	Lakhanpur	0.000000	0.000000	0.000	
	Lundra	0.000000	0.000000	0.000	
	Mainpat	0.000000	0.000000	0.000	
	Sitapur	0.000000	0.000000	0.000	
	Udaypur	0.000000	0.000000	0.000	
	Antagarh	0.000000	0.000000	0.000	
	Bhanupratappur	0.000000	0.000000	0.000	
Uttar Bastar Kanker	Charama	0.000000	0.008886	0.0013860	
	Durgkondal	0.000000	0.000000	0.000	
	Kanker	0.000000	0.008008	0.0108780	
	Narharpur	0.000000	0.002184	0.0008250	
	<b>Total Mahanadi Basin</b>		<b>384.212684</b>	<b>839.808434</b>	<b>628.985</b>

**Appendix III: District-wise Total, Urban, and Rural Domestic Water Demand**

District	Name of the Block	Demand								
		1991			2001			2011		
		Total Demand (MLD)	Urban Demand (MLD)	Rural Demand (MLD)	Total Demand (MLD)	Urban Demand (MLD)	Rural Demand (MLD)	Total Demand (MLD)	Urban Demand (MLD)	Rural Demand (MLD)
Balod	Balod	8.242845	2.929635	5.31321	9.276075	2.832435	6.44364	10.226125	3.164805	7.06132
	Dondi	5.77381	0	5.77381	13.685005	7.232895	6.45211	13.787055	7.424055	6.363
	Dondi Luhara	17.52702	7.55811	9.96891	11.68853	0	11.68853	14.20925	0.81594	13.39331
	Gunderdehi	10.60878	0	10.60878	12.75806	0	12.75806	15.207865	1.817775	13.39009
	Gurur	7.5523	0	7.5523	9.16524	0	9.16524	10.271125	0.509625	9.7615
Baloda Bazar	Baloda Bazar	12.483665	2.345355	10.13831	11.923075	3.085155	8.83792	20.1275	5.49666	14.63084
	Bhatapara	12.73659	6.13818	6.59841	13.06768	6.76593	6.30175	17.970555	7.767495	10.20306
	Bilaigarh	11.645055	1.166265	10.47879	12.10274	1.11078	10.99196	16.884785	2.148525	14.73626
	Kasdol	10.90635	0	10.90635	11.20651	0	11.20651	16.68649	3.00807	13.67842
	Palari	9.72776	0	9.72776	8.37347	0	8.37347	14.709385	1.156545	13.55284
	Simga	9.934825	1.829385	8.10544	10.426515	1.774305	8.65221	15.79726	2.85741	12.93985
Bemetara	Bemetara	11.091025	2.577555	8.51347	11.889195	3.147525	8.74167	16.94852	3.85236	13.09616
	Berla	8.67573	0	8.67573	9.65643	0	9.65643	13.452045	0.697275	12.75477

	Nawagarh	9.13444	0	9.13444	8.94894	0	8.94894	14.909575	2.313495	12.59608
	Saja	9.84134	0.84186	8.99948	10.512345	0.917865	9.59448	15.239845	3.203415	12.03643
Bilaspur	Bilha	48.24386	33.40386	14.84	65.860535	48.962745	16.89779	87.403015	64.975365	22.42765
	Kota	12.751995	3.991005	8.76099	15.04624	4.70745	10.33879	18.782725	5.810535	12.97219
	Masturi	13.8257	0	13.8257	13.95646	0	13.95646	21.393715	1.148175	20.24554
	Takhatpur	14.026365	1.988955	12.03741	16.39679	2.40057	13.99622	24.045245	6.655635	17.38961
Dhamtari	Dhamtari	18.807805	9.363195	9.44461	22.821815	11.084985	11.73683	26.626315	14.617395	12.00892
	Kurud	11.58246	1.84518	9.73728	14.145495	1.548855	12.59664	16.71736	2.87955	13.83781
	Magarlod	6.16812	0	6.16812	7.32984	0	7.32984	8.9083	0.8478	8.0605
	Nagri	9.91067	0	9.91067	11.17382	0	11.17382	13.342745	1.784835	11.55791
Durg	Dhamdha	15.408815	5.305365	10.10345	19.286895	7.624125	11.66277	23.156735	8.842365	14.31437
	Durg	98.93376	87.47784	11.45592	122.706165	109.780245	12.92592	139.062835	125.014185	14.04865
	Patan	19.51766	7.41123	12.10643	25.884935	12.731445	13.15349	30.121955	15.277545	14.84441
Gariabandh	Bindranavagarh (Gariyaband)	5.4976	1.12806	4.36954	5.79068	0	5.79068	7.338715	1.419795	5.91892
	Chhura	5.82505	0	5.82505	6.98096	0	6.98096	8.539275	0.822825	7.71645
	Deobhog	4.84848	0	4.84848	5.38027	0	5.38027	6.59484	0	6.59484
	Mainpur	6.34956	0	6.34956	7.33852	0	7.33852	8.70688	0	8.70688
	Rajim	8.09592	0	8.09592	10.18591	0	10.18591	13.28551	3.21867	10.06684

Gaurela- Pendra- Marwahi	Marwahi	2.19975	0	2.19975	2.54611	0	2.54611	2.99243	0	2.99243
	Pendra	3.591455	1.066905	2.52455	4.05669	1.13454	2.92215	4.67854	1.29222	3.38632
	Pendra Road Gorella	5.160425	1.280745	3.87968	5.983945	1.370385	4.61356	7.06425	1.6389	5.42535
Janjgir - Champa	Akaltara	9.6093	2.41029	7.19901	11.389435	2.749545	8.63989	13.80188	3.06612	10.73576
	Baloda	5.791355	1.289655	4.5017	6.738105	1.529685	5.20842	8.11128	1.84005	6.27123
	Champa	11.58115	4.06161	7.51954	14.351835	5.123385	9.22845	18.19391	7.08372	11.11019
	Dabhra	8.22332	0	8.22332	9.58783	0	9.58783	12.55064	2.09817	10.45247
	Jaijaipur	7.60543	0	7.60543	8.81195	0	8.81195	12.01392	1.07271	10.94121
	Malkharoda	7.09758	0	7.09758	8.02613	0	8.02613	10.79397	0.98172	9.81225
	Nawagarh	16.94805	4.19202	12.75603	20.88951	5.4837	15.40581	25.49558	7.88211	17.61347
	Pamgarh	8.367055	1.044495	7.32256	10.19496	1.16181	9.03315	12.695265	2.207655	10.48761
	Sakti	10.202555	3.018735	7.18382	11.67615	3.56994	8.10621	14.35201	4.15098	10.20103
Jashpur	Bagicha	6.00936	0	6.00936	6.82213	0	6.82213	8.367045	0.927585	7.43946
	Duldula	1.74902	0	1.74902	1.96749	0	1.96749	2.19954	0	2.19954
	Farsabahar	6.26836	0	6.26836	6.88464	0	6.88464	7.59486	0	7.59486
	Jashpur	0.493185	0.172935	0.32025	0.60499	0.23679	0.3682	0.74388	0.33102	0.41286
	Kansabel	4.32572	0	4.32572	4.8447	0	4.8447	5.37145	0	5.37145
	Kunkuri	5.03209	0	5.03209	5.77185	0	5.77185	7.57099	1.86921	5.70178

	Manora	0.98	0	0.98	1.08955	0	1.08955	1.22381	0	1.22381
	Pathalgaon	10.945775	1.473795	9.47198	12.44251	1.88406	10.55845	14.92934	3.16143	11.76791
Kwrda	Bodla	5.55422	0	5.55422	6.5422	0	6.5422	9.07607	0.51759	8.55848
	Kawardha	10.71453	3.22866	7.48587	13.002825	4.376025	8.6268	19.25471	6.95466	12.30005
	Pandariya	12.03284	1.39725	10.63559	13.50989	1.68129	11.8286	19.38537	3.12255	16.26282
	Sahaspur Lohara	6.90907	0	6.90907	7.59038	0	7.59038	11.112765	0.947295	10.16547
Kdagaon	Bade Rajpur	0.70245	0	0.70245	0.82509	0	0.82509	1.042475	0.205065	0.83741
	Keskal	1.50871	0	1.50871	1.80726	0	1.80726	2.31927	0.48114	1.83813
	Makdi	0.00539	0	0.00539	0.00686	0	0.00686	0.00812	0	0.00812
Korba	Kartala	7.62762	0	7.62762	8.48757	0	8.48757	10.20572	0	10.20572
	Katghora	16.734205	4.993245	11.74096	30.32181	23.72193	6.59988	34.57994	27.61452	6.96542
	Korba	25.20354	16.80669	8.39685	33.622705	25.816725	7.80598	41.200305	31.888485	9.31182
	Pali	8.54392	0	8.54392	11.12986	0	11.12986	14.27063	0.74439	13.52624
	Poundi-Uproda	10.19844	0	10.19844	11.11649	0	11.11649	13.21481	0	13.21481
Koriya	Baikunthpur	9.23662	3.81834	5.41828	11.05941	4.24386	6.81555	13.356275	7.013925	6.34235
	Khadganva	7.72774	2.6946	5.03314	16.18963	10.09746	6.09217	16.667245	9.356445	7.3108
	Manendragarh	11.419485	8.436015	2.98347	7.617435	4.453785	3.16365	8.55641	5.03793	3.51848
	Sonhat	0.76587	0	0.76587	0.86569	0	0.86569	1.05868	0	1.05868

Mahasamund	Bagbahra	11.662405	1.998135	9.66427	12.166895	2.260845	9.90605	14.804515	2.636415	12.1681
	Basna	9.22866	0	9.22866	10.34832	1.19043	9.15789	12.965615	1.396575	11.56904
	Mahasamund	15.76181	5.28876	10.47305	18.31247	6.3585	11.95397	22.505505	8.343945	14.16156
	Pithora	12.15936	1.19232	10.96704	12.67478	1.07109	11.60369	14.87444	1.13778	13.73666
	Saraipali	11.565845	1.872315	9.69353	13.064725	2.305935	10.75879	14.952585	2.705805	12.24678
Mungeli	Lormi	12.946075	1.400625	11.54545	15.473775	1.640655	13.83312	20.22046	2.04552	18.17494
	Mungeli	13.20484	3.5559	9.64894	14.940235	4.267755	10.67248	19.81521	4.92075	14.89446
	Pathariya	7.67368	0	7.67368	7.94766	0	7.94766	13.332545	1.867455	11.46509
Raigarh	Baramkela	8.10936	0	8.10936	9.59147	0	9.59147	11.412185	1.691145	9.72104
	Gharghoda	4.80467	0.9504	3.85427	5.431945	1.093905	4.33804	6.174325	1.276425	4.8979
	Kharsia	8.49307	2.04201	6.45106	10.17121	2.34738	7.82383	11.774925	2.556765	9.21816
	Lailunga	6.8383	0	6.8383	7.94717	0	7.94717	9.67643	1.10808	8.56835
	Pussore	7.28497	0	7.28497	8.6863	0	8.6863	10.09436	0.64044	9.45392
	Raigarh	19.097085	12.185775	6.91131	24.34788	15.64758	8.7003	32.128775	22.021335	10.10744
	Sarangarh	12.616345	1.879605	10.73674	14.441575	1.951965	12.48961	17.04422	2.01879	15.02543
	Tamnar	4.82937	0	4.82937	5.51796	0	5.51796	6.85825	0	6.85825
	Udaipur (Dharamjaigarh)	11.469945	1.484865	9.98508	13.465395	1.835595	11.6298	15.424205	1.937655	13.48655
Raipur	Abhanpur	12.378855	2.835405	9.54345	15.763585	3.454785	12.3088	19.789785	5.905845	13.88394

	Arang	15.150355	1.924695	13.22566	18.095995	2.244915	15.85108	24.08746	4.30623	19.78123
	Dharsiwa	78.491025	62.463825	16.0272	120.0146	101.80998	18.20462	170.710925	155.937285	14.77364
	Tilda	12.75191	2.77803	9.97388	14.179895	3.632715	10.54718	19.65566	6.19893	13.45673
Rajnandgaon	Ambagarh	6.21365	0.90072	5.31293	7.195225	1.149255	6.04597	8.226235	1.335015	6.89122
	Chhuikhadan	7.058945	1.615815	5.44313	7.956855	1.791045	6.16581	9.93056	1.99935	7.93121
	Chhuriya	6.80463	0	6.80463	7.80346	0	7.80346	9.86556	0.46953	9.39603
	Dongargaon	7.011795	1.257795	5.754	8.497045	1.554795	6.94225	10.388805	1.983555	8.40525
	Dongargarh	9.83725	3.33747	6.49978	11.338305	3.653775	7.68453	13.357345	3.964815	9.39253
	Khairagarh	9.76972	1.77201	7.99771	11.53815	1.97937	9.55878	14.434555	2.946645	11.48791
	Manpur	0.00007	0	0.00007	0.00007	0	0.00007	0.00007	0	0.00007
	Mohla	2.40464	0	2.40464	2.77277	0	2.77277	3.17044	0	3.17044
	Rajnandgaon	25.963345	16.925085	9.03826	31.04603	19.40895	11.63708	36.03705	22.02039	14.01666
Surajpur	Oudgi	0	0	0	0	0	0	0	0	0
	Premnagar	2.98088	0	2.98088	3.68186	0	3.68186	4.817405	0.663255	4.15415
	Ramanujnagar	4.16556	0	4.16556	5.07052	0	5.07052	6.02679	0	6.02679
	Surajpur	0.1123	0.0297	0.0826	0.14169	0.03564	0.10605	0.17175	0.05184	0.11991
	Ambikapur	0.03683	0.01674	0.02009	0.05123	0.02862	0.02261	0.06397	0.03807	0.0259
	Batouli	3.24191	0	3.24191	3.90341	0	3.90341	4.47937	0	4.47937

	Lakhanpur	0.00448	0	0.00448	0.00546	0	0.00546	0.006835	0.000675	0.00616
	Lundra	0.44149	0	0.44149	0.53417	0	0.53417	0.63168	0	0.63168
	Mainpat	1.14394	0	1.14394	1.39958	0	1.39958	1.6303	0	1.6303
	Sitapur	5.01011	0	5.01011	5.87622	0	5.87622	7.337635	1.263735	6.0739
	Udaypur	2.40695	0	2.40695	2.99033	0	2.99033	3.31905	0	3.31905
Uttar Bastar Kanker	Antagarh	0.1029	0	0.1029	0.12523	0	0.12523	0.16078	0.02484	0.13594
	Bhanupratappur	1.57122	0	1.57122	1.85066	0	1.85066	2.344325	0.358425	1.9859
	Charama	5.97093	0	5.97093	6.80253	0	6.80253	8.083295	1.310445	6.77285
	Durgkondal	0.01316	0	0.01316	0.0154	0	0.0154	0.01771	0	0.01771
	Kanker	7.70151	2.77344	4.92807	9.54781	4.20471	5.3431	11.004765	5.016195	5.98857
	Narharpur	6.27928	0	6.27928	7.03234	0	7.03234	8.022765	0.608715	7.41405
<b>Total Mahanadi Basin</b>		<b>1135.50658</b>	<b>371.16846</b>	<b>764.33812</b>	<b>1373.101155</b>	<b>511.262415</b>	<b>861.83874</b>	<b>1738.338635</b>	<b>707.744385</b>	<b>1030.59425</b>



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