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

Assessment of Gross Agricultural Structure

Mahanadi River Basin

December 2025

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Assessment of Gross Agricultural Structure

Mahanadi River Basin

National River Conservation Directorate (NRCD)

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

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Centres for Mahanadi River Basin Management Studies (cMahanadi)

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

www.cmahanadi.org

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

www.cganga.org

Acknowledgment

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.

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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. It is our hope that this report will serve as a catalyst for 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.

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

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Abbreviations and Acronyms

cMahanadi	Centre for Mahanadi River Basin Management and Studies
MRB	Mahanadi River Basin
NIT	National Institute of Technology
IIT	Indian Institute of Technology
LGP	Length of Growing Period
GPM	Gaurela-Pendra-Marwahi
KCG	Khairagarh-Chhuikhadaan-Gandai
MCB	Manendragarh-Chirmiri-Bharatpur
MMAC	Mohla-Manpur-Ambagarh Chouki
SB	Sarangarh-Bilaigarh

1. Introduction

1.1 Background and Rationale

The Mahanadi River Basin (MRB) spans approximately 1,41,589 km² across Chhattisgarh, Odisha, Jharkhand, and Maharashtra, and functions as one of peninsular India's most agriculturally intensive river systems. Nearly two-thirds of its total area is under cultivation, and agriculture remains the primary livelihood for the majority of the basin's population a dependence that the workforce, income, and landholding data examined in subsequent sections demonstrate in spatial and structural detail.

This report is driven by growing pressures or factors that make traditional agricultural management increasingly unsustainable. Land fragmentation has deepened consistently over the past three decades; the agrarian structure is overwhelmingly composed of marginal and small farmers with limited ability to absorb investment, risk, or climatic shock. The basin's precipitation regime is intensely seasonal, concentrating nearly 86% of annual rainfall into a four-month monsoon window and leaving non-monsoon cultivation structurally dependent on stored water and groundwater. Recurrent flooding in the lower delta and persistent moisture deficits in the upper basin represent opposing but simultaneous climatic stresses. Across the basin, land degradation dominated by water-driven sheet erosion affects more than a quarter of the total area, progressively diminishing the productive capacity of the very land base on which millions of farming households depend.

These are not discrete problems but structurally interconnected ones. Fragmented holdings limit investment in irrigation and soil conservation; degraded soils reduce water retention, amplifying drought stress; deforestation and land-use change in headwater areas intensify downstream flood peaks; and low and volatile agricultural incomes constrain households' ability to manage risk or diversify livelihoods. Understanding these interlinkages rather than treating each constraint in isolation is the analytical purpose of this report.

1.2 Linkage with Agricultural Profile Report

The Gross Agricultural Structure of MRB report complements the MRB Agricultural Profile report. The Profile Report characterises what the basin's agriculture looks like in terms of crop patterns, land use, irrigation infrastructure, and production trends, while this report examines why outcomes differ across the basin and what structural conditions enable or constrain agricultural performance.

The structural analysis here is built directly on the empirical foundation laid by the Profile Report. Irrigation infrastructure mapped in the Profile Report is here interrogated through the irrigation–intensity typology framework (Section 3), which distinguishes districts that effectively convert water access into multi-season cropping from those where substantial infrastructure remains underutilised. Crop production trends from the Profile Report are given explanatory depth by the workforce composition, income, and landholding analyses in Section 2, which identify the human and economic conditions shaping farmer behaviour and investment capacity. The climatic risk assessments in Section 4 flood exposure and drought stress provide the hazard context within which the productivity patterns documented in the Profile Report must be interpreted.

Together, the two reports form the evidentiary basis for the strategic interventions in Section 6 and the planning framework in Section 7. The Profile Report establishes the baseline; this report identifies the structural leverage points.

2. Agricultural Resources and Workforce

2.1 Operational Landholdings

Operational holding means the size of a farm that was operated for agricultural purposes. It is majorly categorised into five types, namely marginal (less than 1 ha), small (1-2 ha), semi-medium (2-4 ha), medium (4-10 ha), and large land holding (more than 10 ha). This acts as an indirect indicator to measure the intensity and productivity of agriculture in any particular area. The more the smaller and fragmented agricultural farms, the less will be the productivity in the area.

Odisha

As shown in Fig. 5, during the period 1995–96 to 2015–16, the proportion of marginal holdings (<1 ha) showed a steady increase, indicating a continued fragmentation of agricultural landholdings over the years. In 1995–96, marginal holdings accounted for 54 % of the total operational holdings, which further rose to around 74% in 2015–16. On the contrary, the share of small (1–2 ha) and semi-medium (2–4 ha) holdings declined gradually during this period. The proportion of medium (4–10 ha) and large (>10 ha) holdings remained very low and showed a declining trend. This pattern indicates the dominance of small and marginal farmers in the agricultural structure, suggesting increasing subdivision of land due to population pressure and inheritance, leading to reduced average holding size and limited land availability for cultivation.

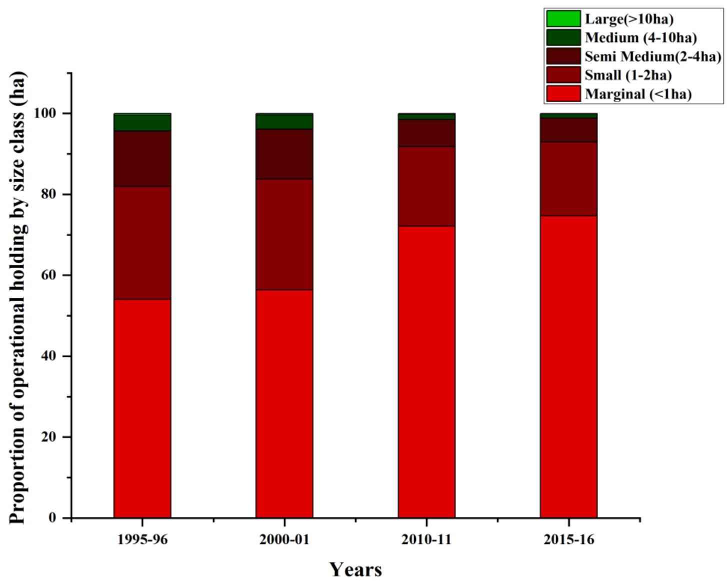
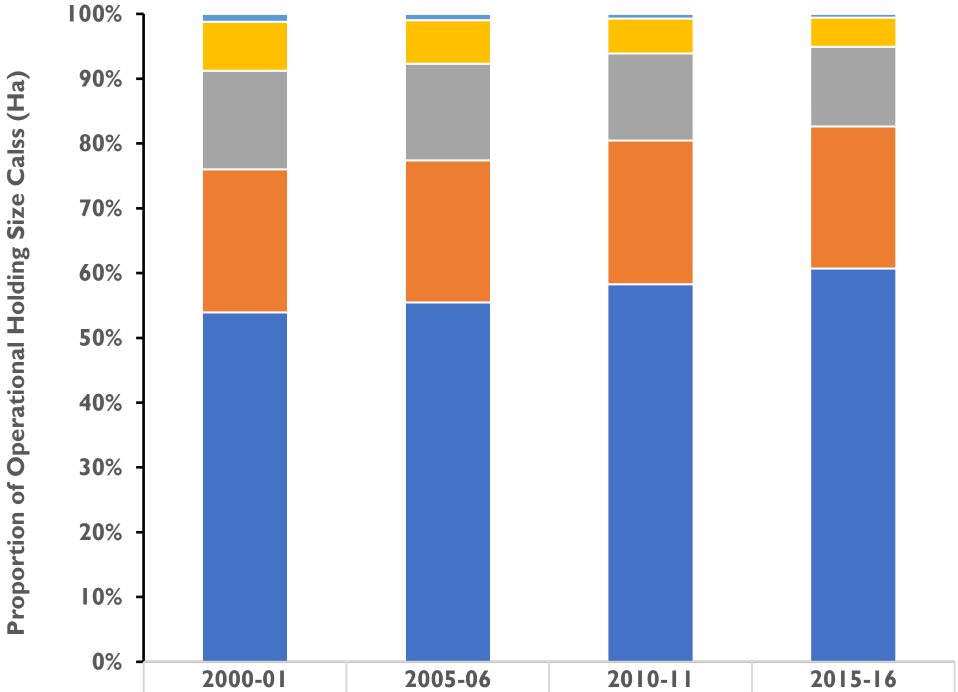


Figure 1: Proportion of operational holdings (%) by size class (ha) of agricultural land, Odisha, 1995-96 to 2015-16. Data taken from the Odisha Agricultural Statistics Report (1995-96;2000-01;2010-11;2015-16).

Chhattisgarh

The distribution of agricultural operational holdings in Chhattisgarh between 2000-01 and 2015-16 shows a clear and progressive dominance of marginal farms below 1 ha. Their share increases steadily from 53.67 percent in 2000-01 to 60.69 percent in 2015-16, while the proportion of small holdings (1–2 ha) remains almost unchanged at around 22 percent, indicating that the rising share of marginal holdings is largely associated with fragmentation of existing landholdings rather than a parallel increase in the area held by farmers.

As, Over the same period, the shares of semi-medium (2–4 ha), medium (4–10 ha) and large (>10 ha) holdings decline consistently, from 15.16 to 12.29 percent, 7.53 to 4.51 percent and 1.20 to 0.58 percent respectively, reflecting continued fragmentation and subdivision of larger agricultural holdings into smaller units. This pattern points towards increasing land pressure, greater prevalence of marginal farming households and a gradual erosion of medium and large farm categories in the state's agrarian structure.



	2000-01	2005-06	2010-11	2015-16
Large (> 10 Ha)	1.20	0.99	0.74	0.58
Medium (4-10 Ha)	7.53	6.68	5.39	4.51
Semi Medium (2-4 Ha)	15.16	14.94	13.43	12.29
Small (1-2 Ha)	22.00	21.95	22.18	21.93
Marginal (< 1.0 Ha)	53.67	55.44	58.26	60.69

Figure 2: Proportion of operational holdings (%) by size class (ha) of Agricultural Land in Chhattisgarh, 2000-01 to 2015-16.

[Source: Agriculture Census [2005-06, 2010-11, and 2015-16], Dept. of Agriculture & Farmers Welfare, Govt. of India]

2.1.1 District - wise proportion of operational holdings (in number)

Odisha

This section presents the trend in the proportion of operational holdings (in number) across the districts of Odisha from 1995–96 to 2015–16 (Fig 3).

Districts like Puri, Angul, Cuttack, Dhenkanal, Jagatsinghpur and Kendrapada recorded a very high proportion of marginal holdings, ranging between 80–85%. In contrast, relatively lower shares of marginal holdings are observed in Khordha, Bargarh, and Rayagada, where they constitute around 60–70%, suggesting a comparatively more balanced distribution of operational land sizes. The proportion of small holdings (1–2 ha) remains moderate, contributing about 10–20% in most districts, with higher concentrations in Angul, Cuttack, Khordha, Ganjam, Kendrapara, and Jagatsinghpur.

Districts such as Deogarh, Boudh, Sonepur, Sambalpur, and Nuapada (around 18–25 %) possess the highest share of small holdings. The semi-medium holdings (2–4 ha) form a small fraction, ranging between 5 and 10%, and are more prominent in Sundargarh, Jharsuguda, Sambalpur, Bargarh, and Kalahandi. The medium holdings (4–10 ha) category appears marginal, accounting for around 2–4% of total operational holdings in Nabarangpur, Bolangir, Sundargarh, Jharsuguda, Sambalpur, and Bargarh, while in the rest of the districts, their share remains between 0.1-2%. The large holdings (>10 ha) are nearly absent across the state, contributing less than 1% in most districts. Overall, the pattern reveals a predominance of marginal and small farmers in Odisha, with larger holdings confined mainly to the western and industrial districts, reflecting both the physiographic and socio-economic diversity of the state.

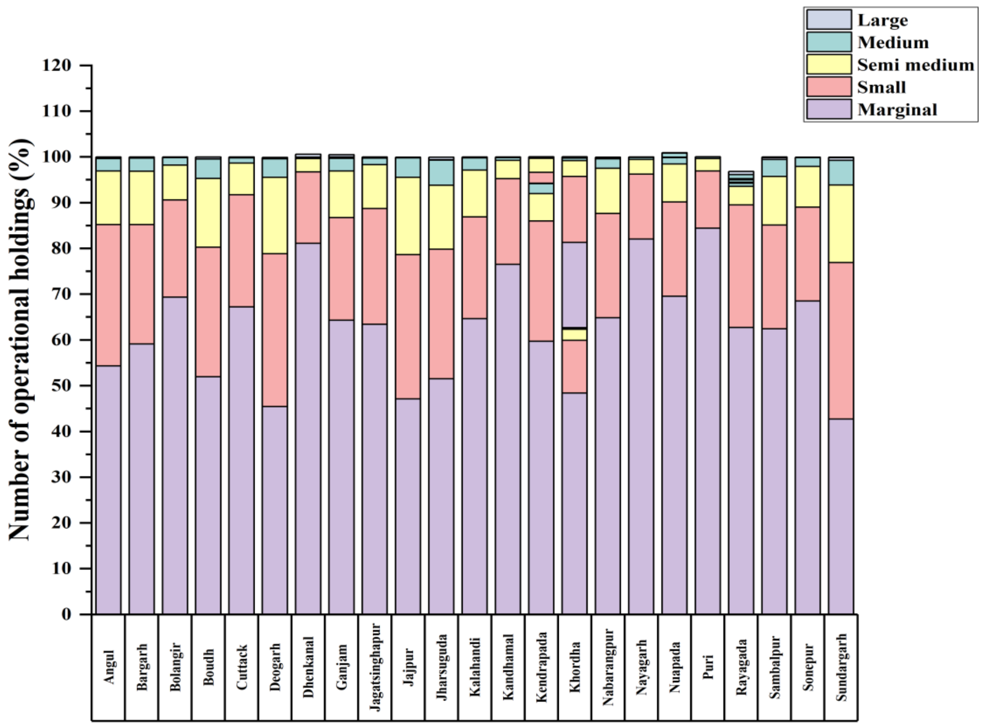


Figure 3: Proportion of operational holdings (%) by size class (ha) of agricultural land across districts of Odisha, 1995-96 to 2015-16. Data taken from the Odisha Agricultural Statistics Report (1995-96;2000-01;2010-11;2015-16).

Chhattisgarh

Across the Chhattisgarh portion of the Mahanadi River Basin, district-wise data show marked spatial differentiation within the overall dominance of marginal holdings. Districts such as Janjgir-Champa, Bilaspur, Balodabazar, Mungeli, Raipur and Dhamtari report marginal holdings in excess of 65–75 percent, coupled with very low proportions of medium and large farms, reflecting a highly fragmented landholding structure and a predominance of small, household-operated farms. This pattern is typically associated in the literature with intensive cultivation in irrigated or high-pressure agricultural belts, repeated subdivision of land through inheritance, and limited scope for consolidation of operational holdings.

In contrast, districts including Kanker, Kondagaon, Korea and Jashpur have comparatively lower shares of marginal holdings (about 39–48 percent) and higher combined shares of semi-medium and medium holdings (up to about 33 percent in Kanker and Kondagaon, and 33 percent medium alone in Jashpur), indicating relatively larger average operational sizes in these parts of the basin. Reported explanations for such patterns in plateau and forest-fringe districts include the presence of more extensive land parcels, lower population density, and a higher incidence of community, forest-fringe or estate-type cultivation, which together allow farms to remain above the marginal threshold despite gradual fragmentation pressures.

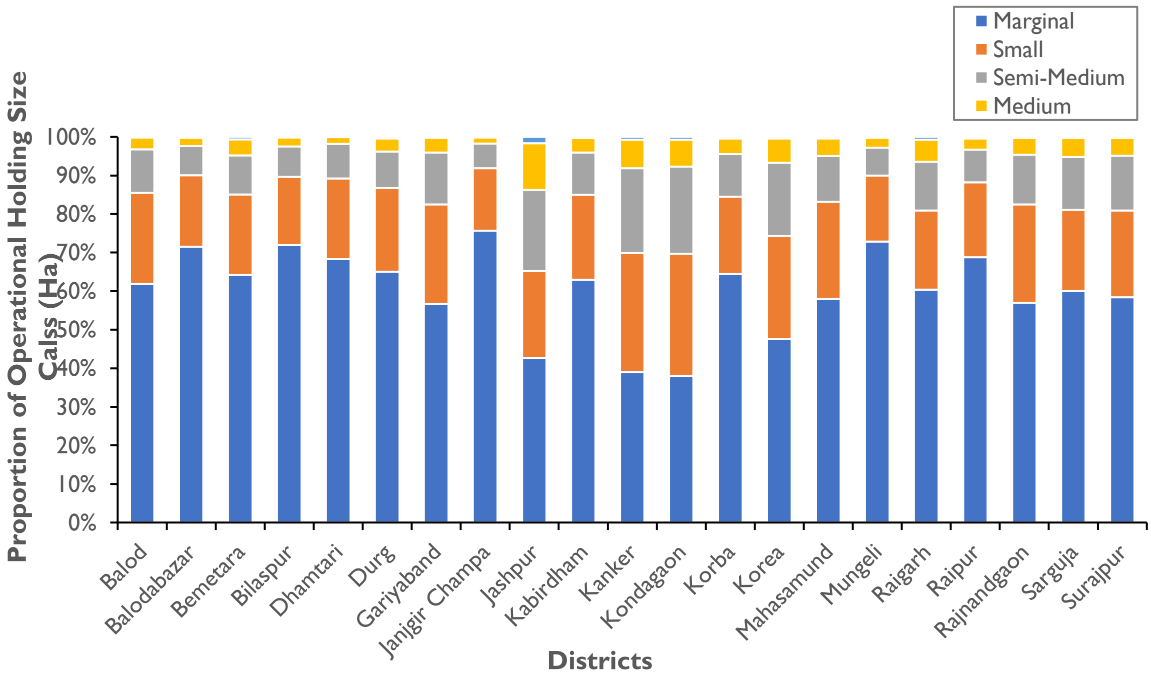


Figure 4: Proportion of operational holdings (%) by size class (ha) of agricultural land across districts of MRB (CG Portion).

[Source: Agriculture Census [2015-16], Dept. of Agriculture & Farmers Welfare, Govt. of India]

2.1.2 Area of operational holdings

Odisha

Across the districts, marginal and small holdings (1–2 ha) together occupy a major portion of the total operational area, although their individual landholdings remain small. The semi-medium (2–4 ha) and medium (4–10 ha) categories, on the other hand, contribute significantly to the total area in several districts, reflecting relatively better land availability per holding.

Districts such as Bolangir, Bargarh, Sambalpur, Kalahandi, and Boudh show a higher proportion of area under medium and semi-medium holdings, indicating relatively larger farm sizes in these regions. In contrast, Ganjam, Nabarangpur, Rayagada, and Kandhamal possess a dominant share of area under marginal holdings, typical of hilly and tribal-dominated regions where land fragmentation is high. Districts in the coastal plain, such as Puri, Cuttack, Kendrapara, and Jagatsinghpur, display a balanced distribution across marginal, small, and semi-medium categories. The large holdings (>10 ha) occupy only a minor fraction of the area in almost all districts, though they are relatively more visible in Bolangir, Sambalpur, and Deogarh (Fig 5).

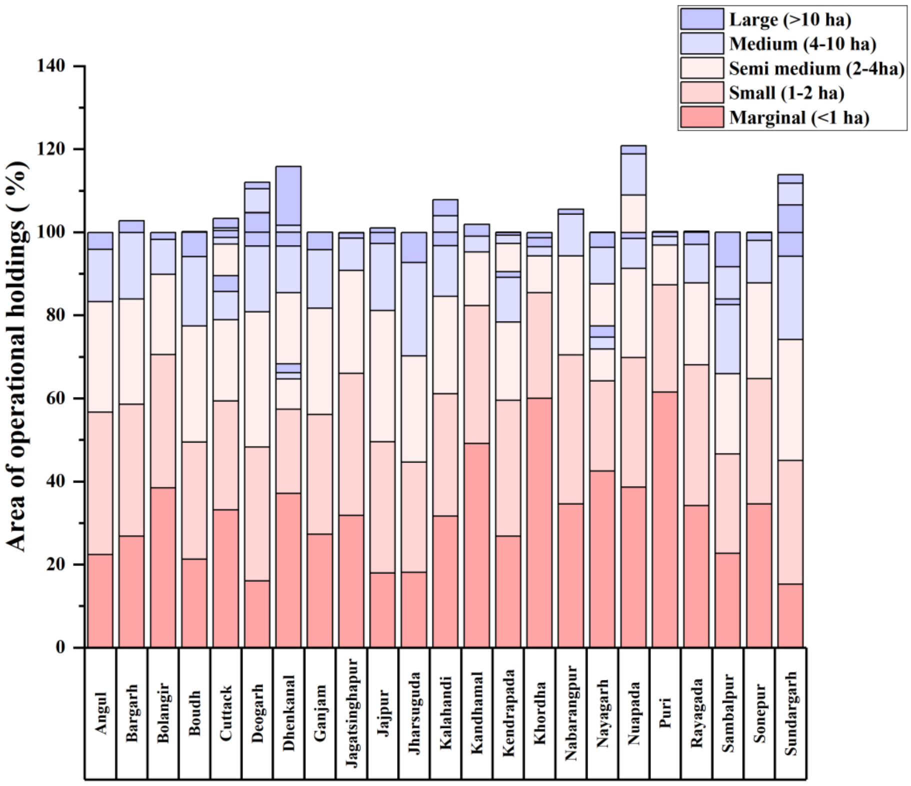


Figure 5: Area of operational holdings (%) by size class (ha) of agricultural land across districts of Odisha, 1995-96 to 2015-16. Data taken from the Odisha Agricultural Statistics Report (1995-96;2000-01;2010-11;2015-16).

Chhattisgarh

Across the Chhattisgarh portion of the Mahanadi River Basin (MRB), the area under operational holdings is dominated by small to semi-medium farm sizes, reflecting a largely smallholder agrarian structure. At the basin scale, **semi-medium holdings account for the largest area (≈1.32 million ha)**, followed closely by **small (≈1.24 million ha)** and **marginal holdings (≈1.04 million ha)**, while **medium holdings (≈1.03 million ha)** contribute a comparable share. In contrast, **large holdings occupy the smallest area (≈0.37 million ha)**, underscoring their limited presence in the region. This pattern highlights the predominance of fragmented landholdings and the central role of small and semi-medium farmers in MRB agriculture.

District-wise, higher concentrations of area under medium to large holdings are observed in agriculturally productive districts such as **Jashpur, Raigarh, Rajnandgaon, Mahasamund, and Kanker**, indicating relatively larger farm sizes and more commercialized agriculture in these pockets. Meanwhile, districts like **Balod, Dhamtari, Gariyaband, and Kondagaon** show stronger dominance of marginal and small holdings, typical of rainfed and tribal-dominated landscapes. Overall, the distribution points to a heterogeneous agrarian structure across the basin, with implications for farm mechanization, productivity enhancement, and targeted policy support for smallholders.

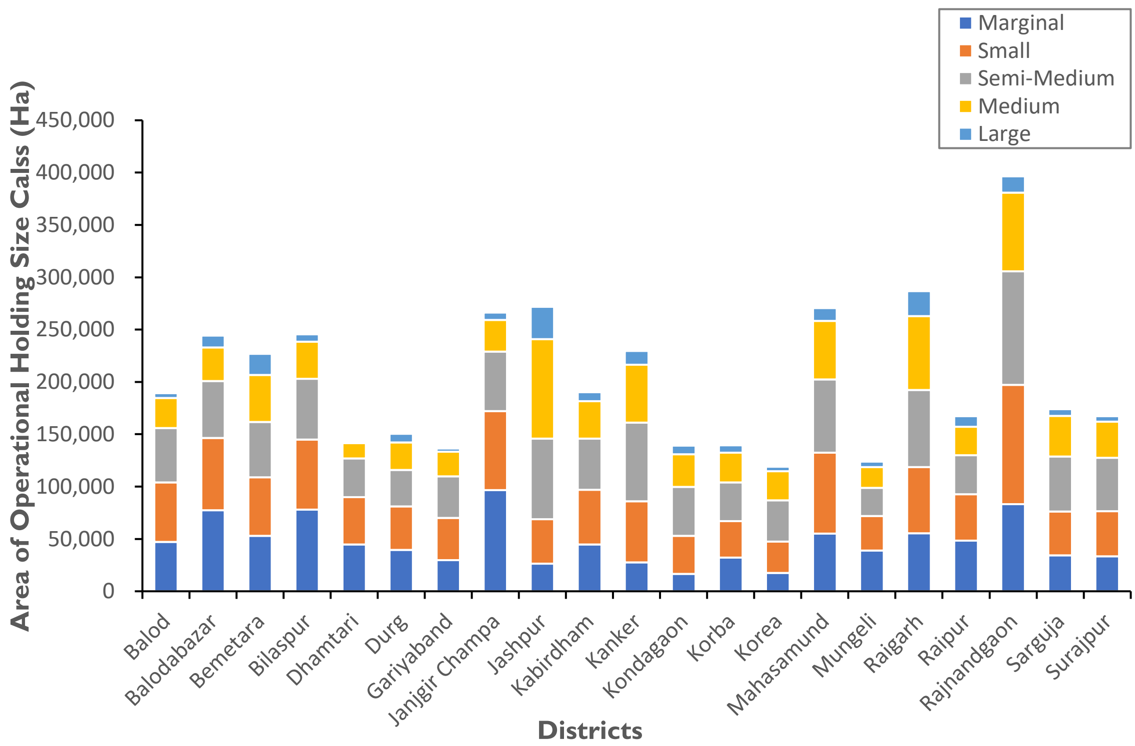


Figure 6: Area of operational holdings (%) by size class (ha) of agricultural land across districts of MRB (CG Portion).

[Source: Agriculture Census [2015-16], Dept. of Agriculture & Farmers Welfare, Govt. of India]

2.2 Workforce Dependence

2.2.1 Agricultural Manpower/Workforce

Odisha

The distribution of agricultural manpower across Odisha shows substantial inter-district variation. Ganjam exhibits the highest agricultural manpower, rising sharply above 8.5 lakh, indicating its large agrarian population. This is followed by Sundargarh and Kendrapara, each with manpower levels above 7.5-8 lakh, marking them as major agricultural labour hubs.

Districts like Sundargarh, Nabarangpur, Kalahandi, Bolangir, and Bargarh also maintain moderately high values, generally between 4–6.5 lakh, reflecting strong agricultural engagement. In contrast, Deogarh, Boudh, Angul, and Nayagarh register the lowest manpower, mostly below 1.5–2 lakh, suggesting smaller agricultural bases or higher dependence on non-agricultural work. Mid-range districts such as Dhenkanal, Jagatsinghpur, Jajpur, Puri, Rayagada, Sambalpur, Khordha, Cuttack, Kendrapara, Nuapada, and Sonepur fall between 2–3.5 lakh, indicating balanced but moderate agricultural workforce participation.

Overall, the pattern highlights a strong concentration of manpower in the coastal and densely populated districts, while interior and western districts show relatively lower agricultural labour availability.

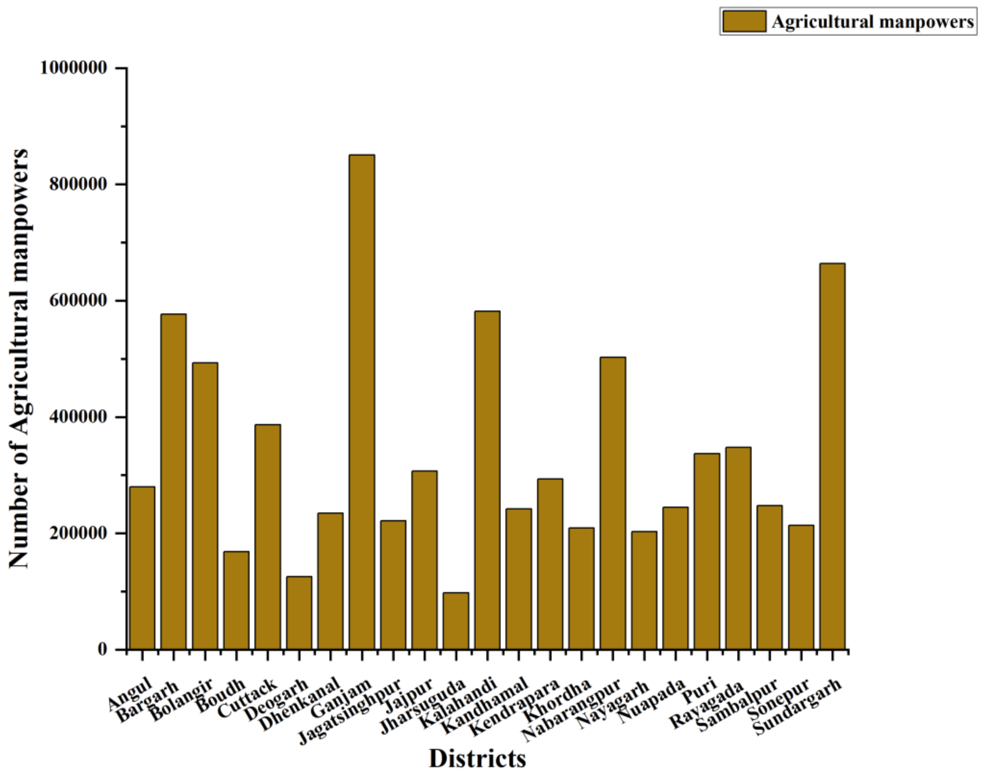


Figure 7: Agricultural manpower across districts of Odisha according to the 2011 census.

Chhattisgarh

The agricultural manpower in MRB (Chhattisgarh Portion), comprising cultivators and agricultural labourers as per the **Census of India 2011**, underscores the state's strong agrarian base, with a total of **about 9.10 million** people engaged in agriculture. Within the Mahanadi River Basin (CG portion), **Raipur** stands out with the highest agricultural workforce (~**1.09 million**), reflecting its extensive rural hinterland and intensive agricultural activity. This is followed by **Surguja (~0.99 million)** and **Durg (~0.95 million)**, indicating major concentrations of agrarian livelihoods in both central plains and northern uplands of the basin.

Other important contributors include **Bilaspur (~0.85 million)**, **Janjgir–Champa (~0.68 million)**, and **Rajnandgaon (~0.63 million)**, which together form key agricultural belts of the basin. In contrast, relatively lower agricultural manpower is observed in **Koriya (~0.21 million)**, **Korba (~0.33 million)**, **Kabeerdham (~0.35 million)**, and **Uttar Bastar Kanker (~0.32 million)**, reflecting a mix of forested terrain, mining–industrial influence, and lower population density. Overall, the distribution highlights the spatial heterogeneity of agrarian dependence across the basin and reinforces the central role of agriculture as a livelihood source in the MRB districts of Chhattisgarh.

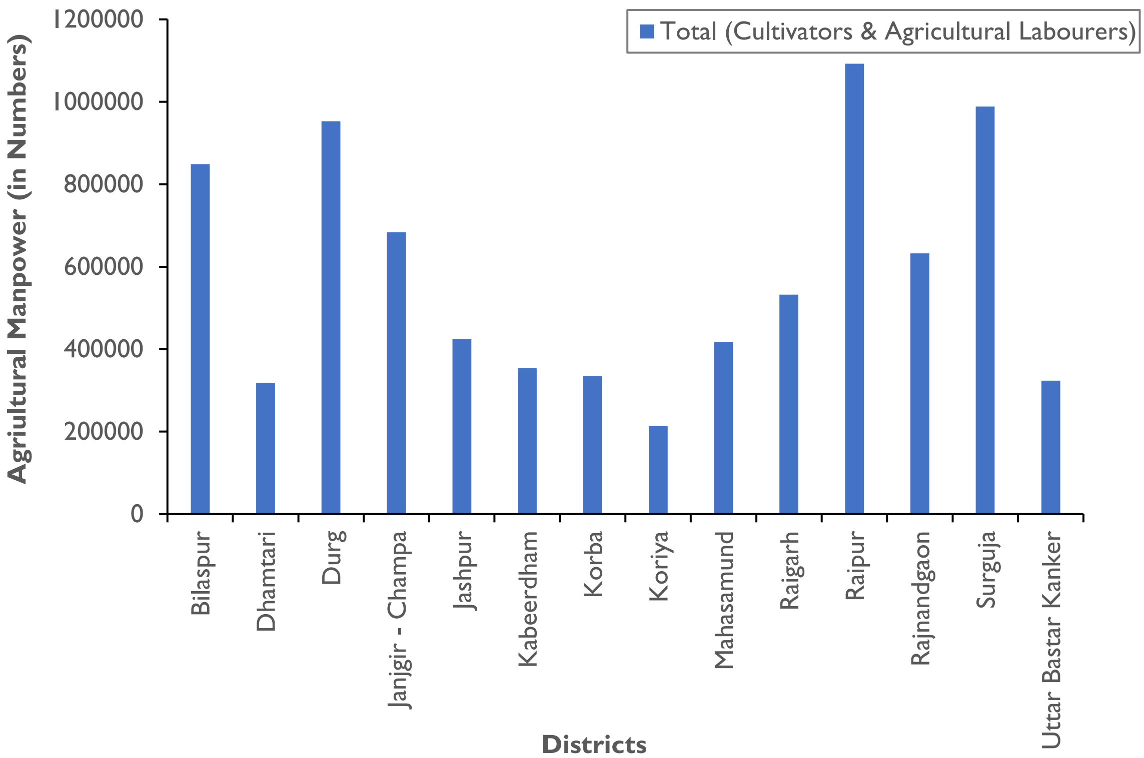


Figure 8: Agricultural manpower across districts of Chhattisgarh according to the 2011 census.

[Source: Population Census 2011]

2.2.2 Gender-wise Composition and Participation of the Agricultural Workforce

Odisha

The gender-wise composition of the agricultural workforce in the Odisha portion of the Mahanadi River Basin reveals a distinctly male-dominated structure across most districts, though women continue to play a substantial and indispensable role in sustaining agrarian livelihoods. Districts such as Dhenkanal, Kendrapara, Nayagarh, and Jagatsinghpur exhibit particularly high proportions of male cultivators and agricultural labourers, reflecting patterns of land ownership, mechanisation uptake, and male engagement in market-oriented agriculture, irrigation management, and allied activities such as fisheries and input procurement. These districts are characterised by relatively better irrigation infrastructure and higher cropping intensity, which often correlates with increased male participation in decision-making and farm management.

At the same time, several districts, including Ganjam, Rayagada, Sambalpur, and parts of coastal Odisha such as Puri, demonstrate comparatively higher female participation, highlighting the feminisation of agricultural labour in regions where male out-migration to urban and industrial centres is common. In tribal and upland districts like Rayagada, women's involvement is especially pronounced due to their central role in subsistence farming, minor millet cultivation, shifting agriculture interfaces, and collection of non-timber forest products. Women in these areas are heavily engaged in labour-intensive operations such as paddy transplantation, manual weeding, harvesting, threshing, and post-harvest processing, often contributing significantly to household food security despite limited access to land titles and formal credit.

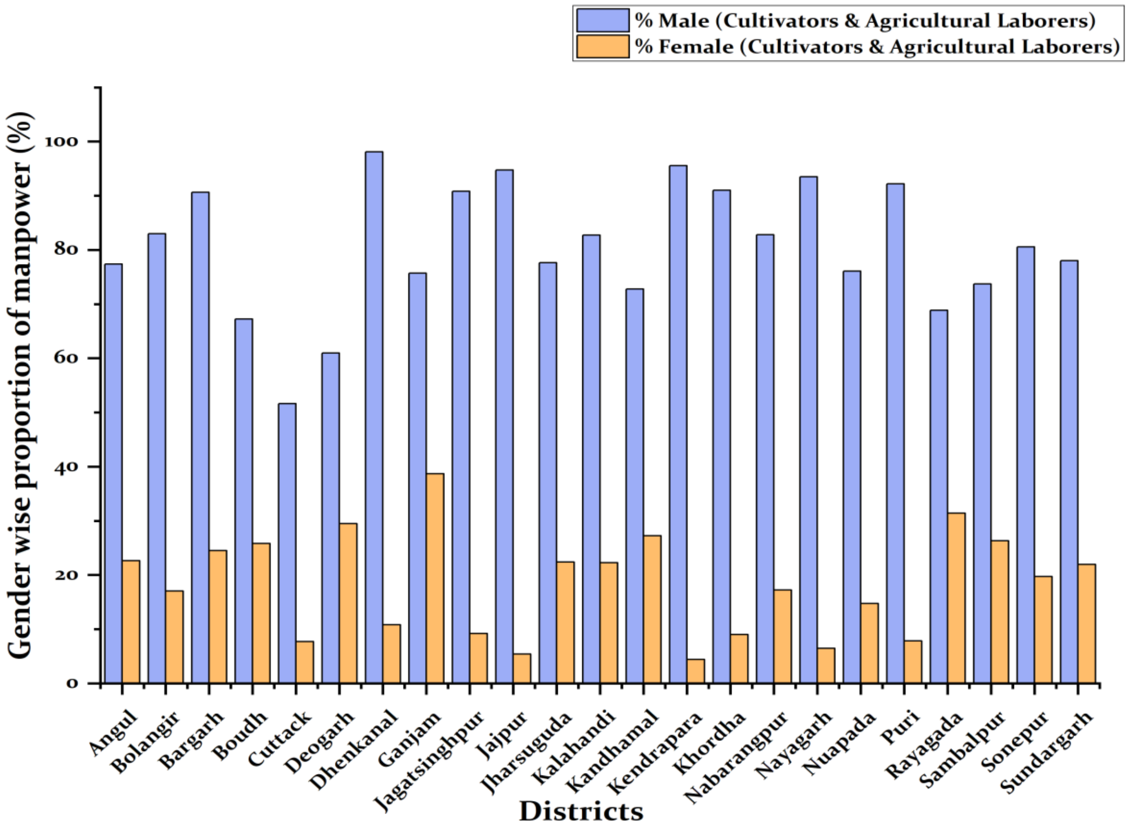


Figure 9: Gender-wise Composition of the Agricultural Workforce in the Mahanadi River Basin

[Source: Population Census 2011]

The observed spatial variation also reflects agro-ecological gradients across the basin from deltaic rice systems in coastal districts to rainfed and forest-fringe agriculture in interior regions, each shaping gendered labour dynamics differently. In many districts, the relatively lower female share in agricultural workforce statistics may mask substantial unpaid and informal contributions by women, including seed selection, livestock care, water management at the household level, and participation in self-help group–based agricultural enterprises.

Overall, the Odisha segment of the basin illustrates a complex interplay between male dominance in formal agricultural roles and strong female participation in operational and subsistence activities. These patterns highlight the need for gender-responsive interventions, including recognition of women as farmers, improved access to extension services, climate-resilient technologies tailored for women workers, mechanisation suited to smallholders, and strengthening of women's producer groups. Integrating gender considerations into basin-level planning will be critical for enhancing productivity, resilience to climate variability, and equitable rural development in the Mahanadi River Basin.

Chhattisgarh

The gender-wise composition of the agricultural workforce in the Mahanadi River Basin (Chhattisgarh part) reveal a near-balanced participation of men and women, with a slight overall dominance of male workers across most districts. In districts such as Raigarh (57.3%), Mahasamund (55.1%), and Korba (54.2%), male participation is relatively higher, indicating a greater concentration of male cultivators and agricultural labourers. These districts are characterised by a mix of irrigated agriculture, forest–agriculture interfaces, and higher male engagement in both farm operations and allied activities.

At the same time, female participation is notably high and nearly at par with males in several districts, highlighting the critical role of women in basin agriculture. Rajnandgaon stands out with a female majority (51.3%), while Durg, Kabeerdham, and Dhamtari show an almost equal gender composition, each with female shares close to 49 percent. This balanced workforce structure reflects the labour-intensive nature of agriculture in the basin, especially in paddy cultivation, transplanting, weeding, and post-harvest operations where women's participation is substantial. Overall, the data underline that agriculture in the Mahanadi River Basin is strongly supported by women's labour, making gender-sensitive agricultural policies, skill development, and mechanisation strategies essential for sustainable rural livelihoods.

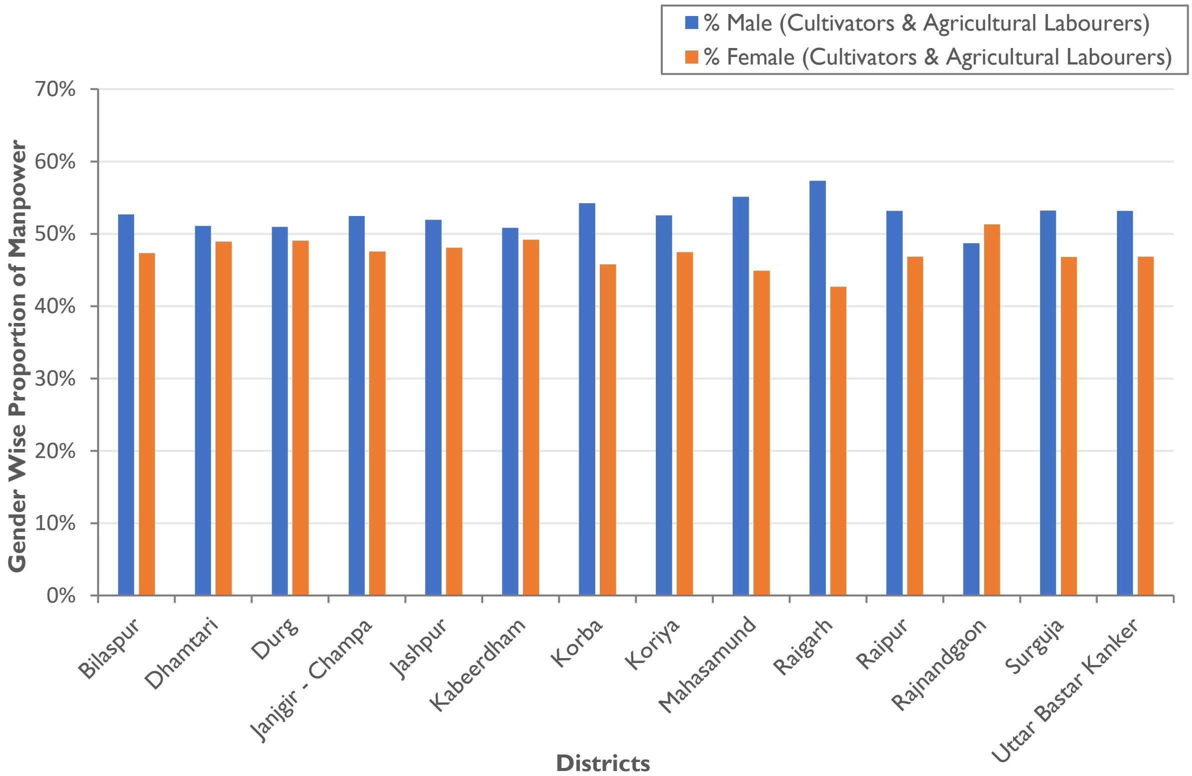


Figure 10: Gender-wise Composition of the Agricultural Workforce in the Mahanadi River Basin

[Source: Population Census 2011]

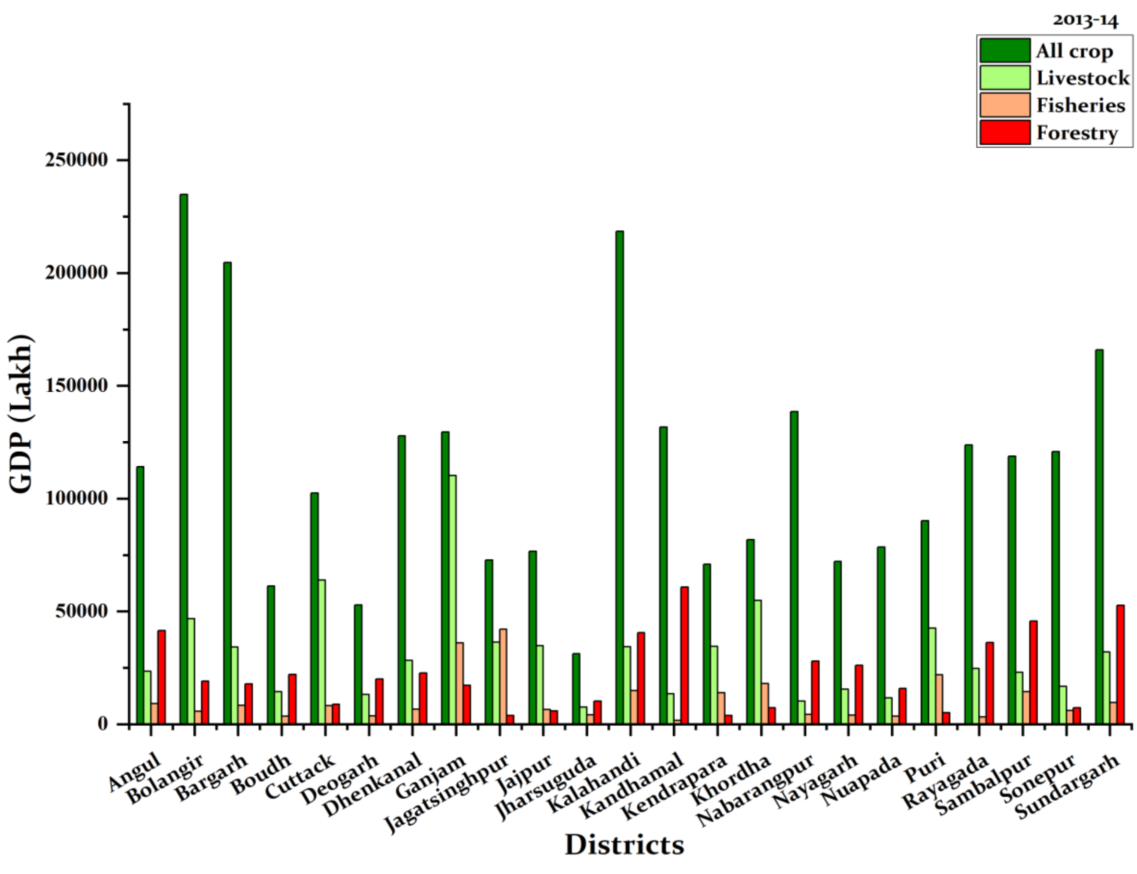
2.3 Economic Structure and Livelihood Dependence on Agriculture and Allied Activities

2.3.1 Sector-wise Contribution to District GDP (At Constant Prices)

Odisha

The sector-wise contribution of agriculture and allied activities to district GDP (in lakh ₹) in the Odisha portion of the Mahanadi River Basin (MRB) reflects gradual structural change between 2011–12, 2013–14, and 2015–16. Although total agricultural GDP increased in absolute terms across the basin, its internal composition reveals emerging diversification. Crops continue to dominate agricultural output in most districts, particularly in Bolangir, Bargarh, Ganjam, Kalahandi, and Sundargarh, with canal-irrigated regions such as Bargarh maintaining consistently high crop values. At the same time, livestock and fisheries have gained relative importance in several districts, indicating a shift from purely crop-centric growth toward a more diversified primary sector.

Spatial variation remains pronounced. Livestock contributions are stronger in districts such as Cuttack, Khordha, and Ganjam, while fisheries are significant in coastal and deltaic districts, including Jagatsinghpur, Kendrapara, and Puri. Forestry continues to play a notable role in tribal-dominated districts such as Kandhamal, Rayagada, and Sundargarh. Overall, the Odisha segment of the MRB exhibits a gradual and uneven transformation, where agriculture remains central to district economies but increasingly reflects intra-sectoral diversification rather than a sharp structural decline.



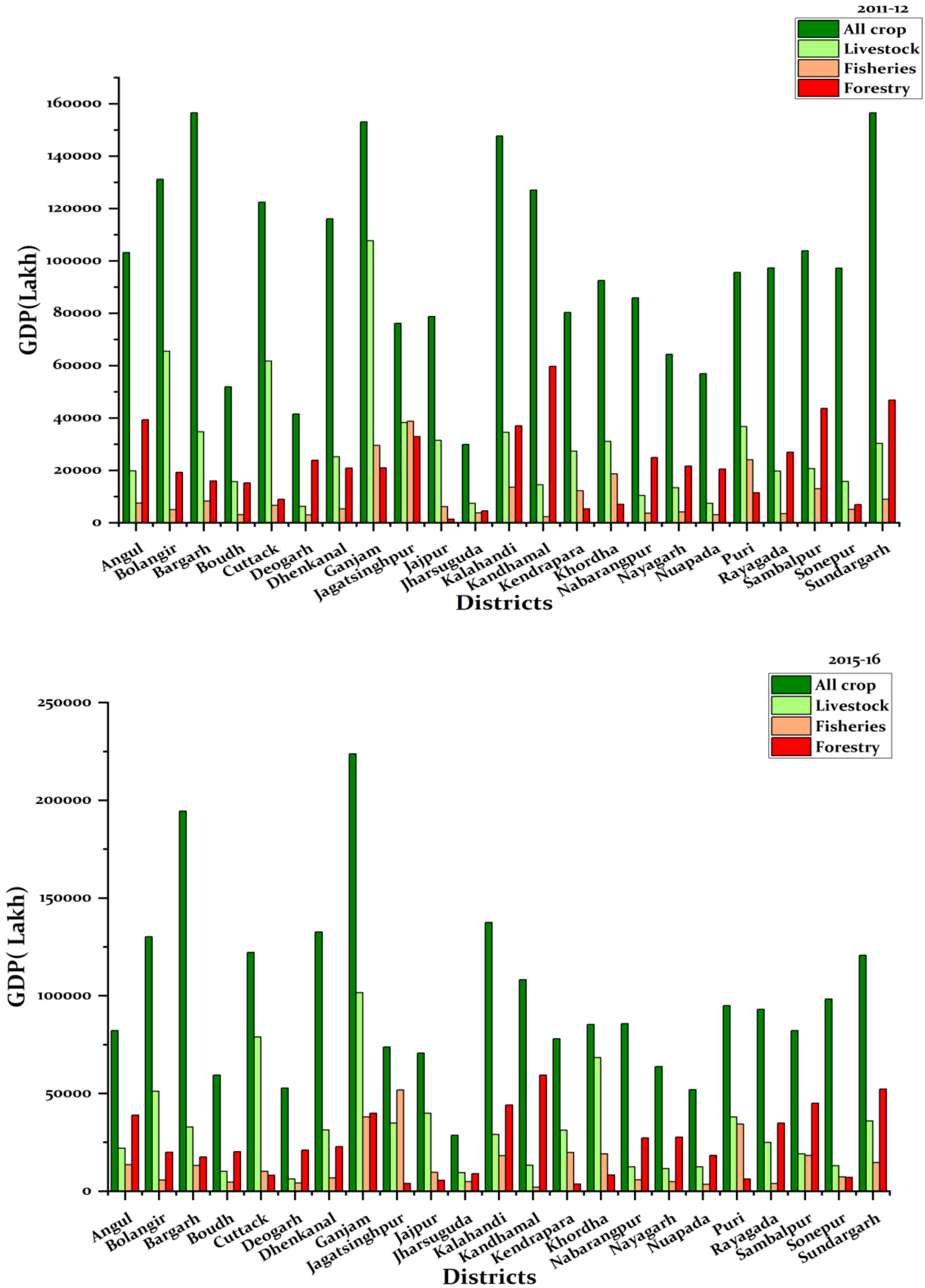


Figure 11: Agriculture and Allied Sector Contribution to District GDP(lakh), MRB (OD part).
[Source: Directorate of Economics & Statistics, Govt. of Odisha.]

Chhattisgarh

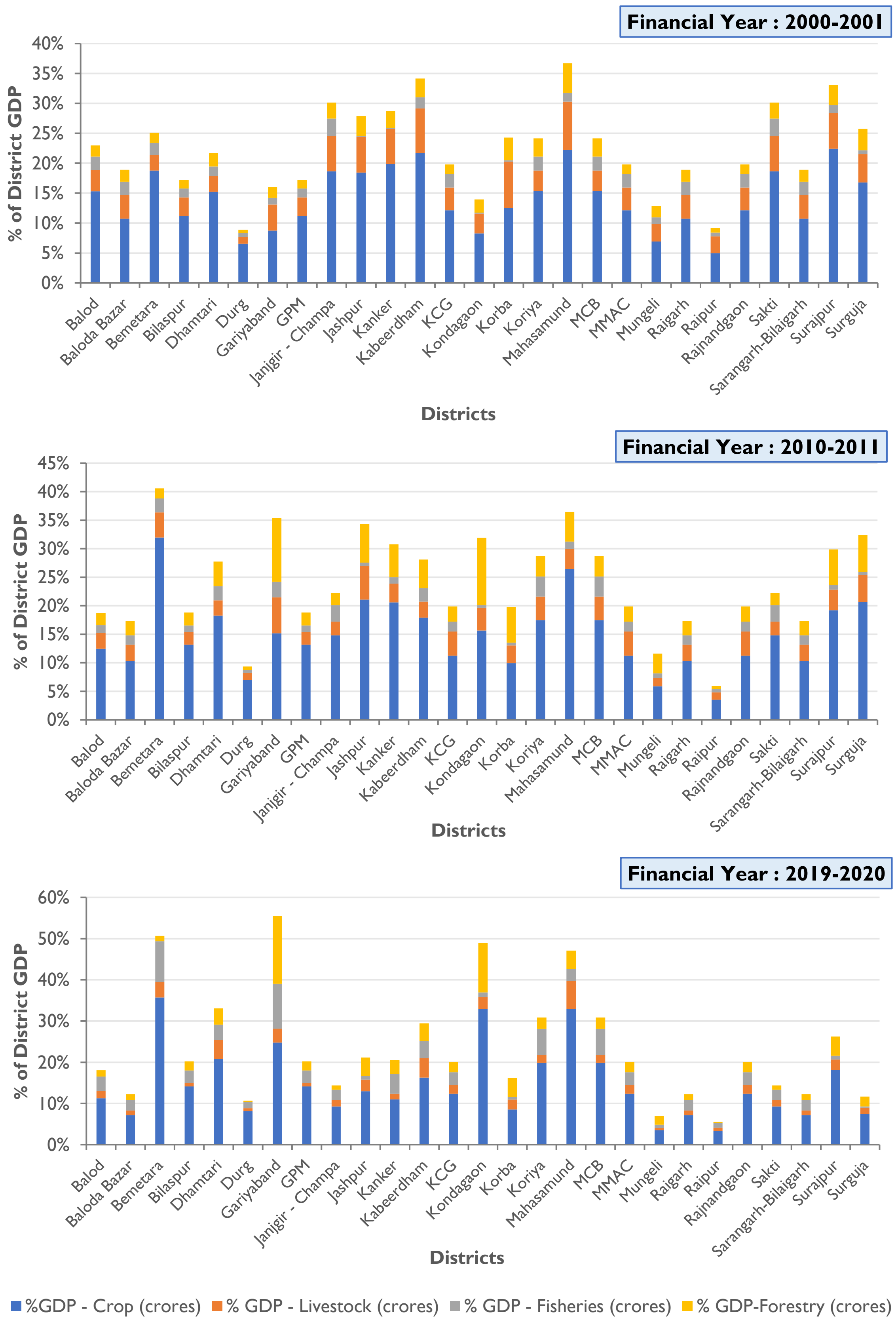


Figure 11: Agriculture and Allied Sector Contribution to District GDP, MRB (CG Portion).
[Source: Directorate of Economics & Statistics, Govt. of C.G.]

The sector-wise contribution of agriculture and allied activities to district GDP in the Chhattisgarh part of the Mahanadi River Basin (MRB) reveals a clear long-term structural transition between 2000–01, 2010–11, and 2019–20. At the basin scale, agriculture and allied sectors contributed 18% of total GDP in 2000–01, declining marginally to 17% in 2010–11 and further to 15% in 2019–20, even as the total basin GDP expanded sharply from ₹20,330 crore to ₹63,600 crore and then to ₹1,77,974 crore. Within this aggregate trend, the crop sector's share declined from 12% to 9%, while livestock remained relatively stable at around 2–4%, and fisheries and forestry together consistently accounted for 3–4%, highlighting gradual diversification away from crop-centric growth at the basin level.

At the district scale, however, substantial heterogeneity persists. In 2000–01, agriculture and allied activities accounted for over 30% of district GDP in predominantly agrarian districts such as Mahasamund (37%), Kabeerdham (34%), Janjgir–Champa (30%), Jashpur (28%), and Surguja (26%), indicating strong agricultural economic dominance. In contrast, more urban–industrial districts like Raipur (9%) and Durg (9%) already exhibited low agricultural dependence despite having much larger total GDPs. By 2010–11, while total GDP increased across all districts, agriculture's relative contribution strengthened in some rural districts Bemetara (41%), Mahasamund (36%), Gariyaband (35%), and Surguja (32%) even as it declined further in districts such as Raipur (6%), Durg (9%), and Mungeli (12%), reinforcing a spatially uneven transformation process.

By 2019–20, the contrast between agriculture-dominant and diversified economies became sharper. Districts such as Gariyaband (56%), Bemetara (51%), Kondagaon (49%), and Mahasamund (47%) showed very high dependence on agriculture and allied sectors, despite relatively modest total GDP sizes. Conversely, districts like Raipur (5%), Mungeli (7%), Durg (11%), Raigarh (12%), and Bilaspur (20%) exhibited low agricultural shares alongside very large GDP bases, reflecting deepening industrialisation, mining, trade, and service-sector expansion. These patterns underline that while basin-level figures suggest gradual diversification, several districts remain structurally agrarian.

2.3.2 Degree of Agricultural Economic Dominance vs. Diversification

Odisha

The Odisha segment of the Mahanadi River Basin (MRB) exhibits a predominantly agrarian economic structure, though the pace and depth of diversification vary considerably across districts. Agriculture and allied activities continue to account for a significant share of district GDP (in lakh ₹), particularly in western and tribal-dominated districts where crop cultivation, livestock rearing, and forestry remain central to livelihoods and local production systems. Despite sustained growth in total GDP, many of these districts remain structurally dependent on primary-sector activities, making them more vulnerable to climatic variability, irrigation limitations, and natural resource stress.

A group of transitional districts such as Sambalpur, Dhenkanal, Khordha, and Cuttack reflects a more diversified economic profile, where agriculture is increasingly complemented by livestock, fisheries, trade, and service-sector expansion. In contrast, districts like Jharsuguda and Angul, along with parts of coastal Odisha, display a broader economic base driven by industry, mining, energy production, and urban-led services, with agriculture playing a relatively secondary role. This spatial gradient from agriculture-dominant interior districts to industrial–urban growth centres highlights the need for differentiated development strategies that integrate productivity enhancement and irrigation strengthening in agrarian regions with diversification, value addition, and resource sustainability in rapidly transforming districts of Odisha's MRB.

Chhattisgarh

Overall, the MRB in Chhattisgarh demonstrates a dual economic structure. At the basin level, declining agricultural shares alongside rapidly rising total GDP indicate steady diversification. However, this aggregate masks strong district-level agricultural dominance, particularly in eastern and central basin districts where livelihoods, land use, and income remain closely tied to crops, livestock, and forests. These districts are more vulnerable to rainfall variability, irrigation constraints, and groundwater stress, making agricultural sustainability a core economic concern.

A second group of districts such as Dhamtari, Kabeerdham, Janjgir–Champa, Rajnandgaon, and Surguja, represent transitional economies, where agriculture still contributes 20–33% of GDP, but allied activities and non-farm sectors are gaining importance. These districts show potential for balanced growth through value-chain development, agro-processing, and diversification into fisheries and livestock.

In contrast, highly diversified districts like Raipur, Durg, Raigarh, and Korba reflect advanced structural transformation, with agriculture playing a stabilising but secondary role in overall economic output. From a basin management and planning perspective, this gradient from agriculture-dominant to diversified economies highlights the need for differentiated development strategies, combining water- and productivity-focused interventions in agrarian districts with livelihood diversification and resilience-building in rapidly transforming urban–industrial regions of the Mahanadi River Basin.

2.3.3 Employment Dependence on Agriculture and Allied Sectors

Odisha

I. Total Employment (Population)

This graph illustrates the district-wise change in total employed population across Odisha between 2008–09 and 2023–24, revealing a clear upward trend in employment across most districts alongside notable variation. Overall, the state demonstrates a broad expansion in employment opportunities over the period, reflecting population growth, gradual economic diversification, expansion of rural livelihood programmes, and increasing engagement in both farm and non-farm sectors.

At the aggregate level, most districts recorded substantial increases in total employment, with particularly strong growth observed in major population and economic centres. Cuttack shows a notable rise from about 0.79 million in 2008–09 to 0.94 million in 2023–24, while Khordha increased from approximately 0.58 million to 0.79 million, reflecting rapid urban expansion, service-sector growth, and administrative concentration around the capital region. Sundargarh also recorded a significant increase from about 0.73 million to 0.87 million, likely driven by mining, industrial activity, and associated labour demand. Similarly, Bargarh (0.59 to 0.76 million), Kalahandi (0.62 to 0.75 million), and Bolangir (0.55 to 0.72 million) demonstrate strong gains, indicating sustained growth in both agricultural and rural non-farm employment.

Several districts exhibit moderate but steady increases, including Ganjam (1.31 to 1.50 million), which remains the largest employment base in the state, as well as Jajpur, Kendrapara, Nayagarh, Sambalpur, and Puri, where employment growth reflects a combination of agriculture, fisheries, small industries, and service activities. Coastal districts, in particular, show diversified livelihood structures supported by trade, tourism, and port-related activities.

In contrast, a few districts, such as Jharsuguda, show relatively modest growth (0.18 to 0.24 million), possibly reflecting their smaller population base despite strong industrial presence. Western districts like Nuapada and Boudh also record increases but remain comparatively lower in absolute employment, indicating continued structural constraints and limited economic diversification.

Overall, the pattern depicted in Figure 11 highlights a widening gradient between rapidly growing urban–industrial districts and slower-growing interior regions. The steady rise in employment across Odisha underscores expanding livelihood opportunities but also signals increasing demand for natural resources, infrastructure, and sustainable job creation. These trends emphasise the need for balanced regional development strategies that promote inclusive growth, strengthen rural non-farm sectors, and enhance resilience in economically lagging districts.

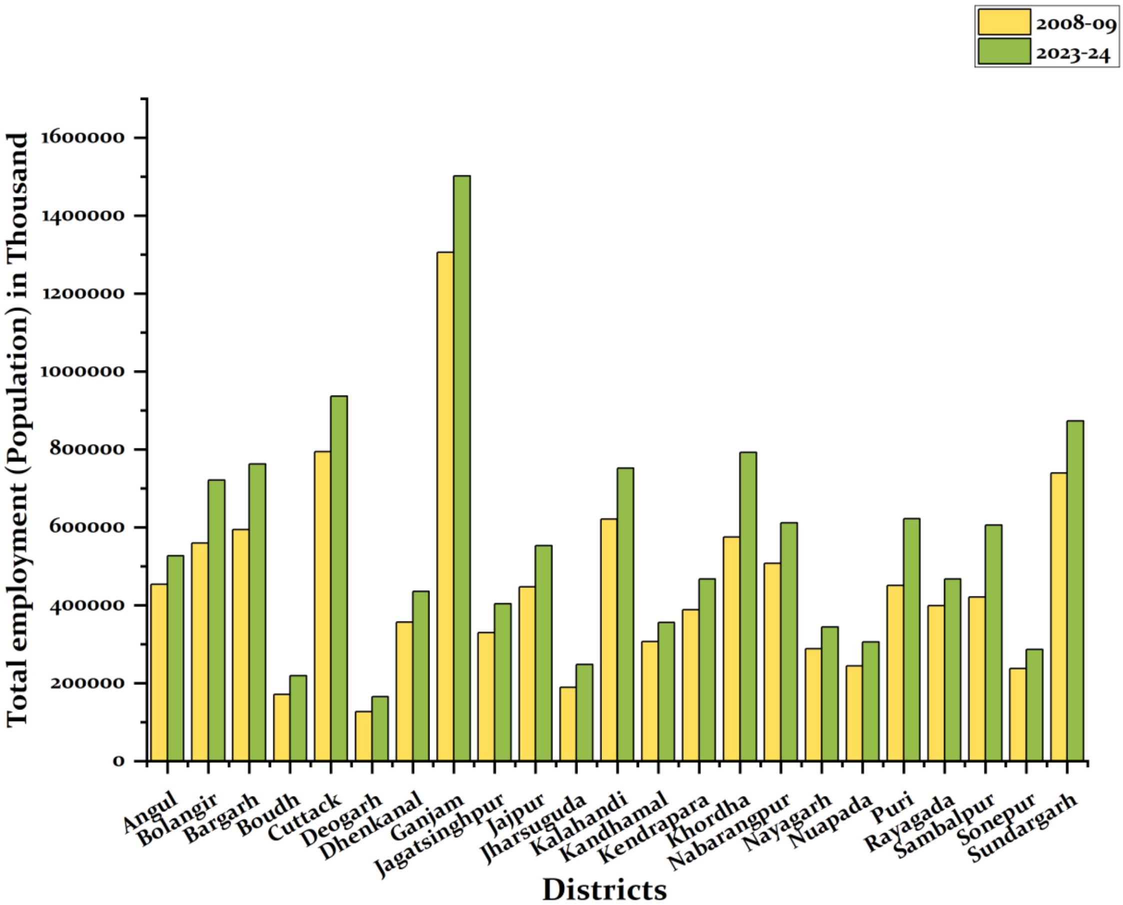


Figure 13: Total Employment (Population) under the MRB (Odisha Portion).
[Source: Population Census 2001 & 2011 & Odisha Agriculture Statistics report (2008-09;2023-24]

II. % Employment under Agriculture & Allied Sector

Across Odisha, the share of the workforce engaged in agriculture and allied activities exhibits substantial spatial variability, highlighting the uneven pace of livelihood diversification across districts. The highest dependence on agriculture is observed in western districts such as Nuapada (80.06%), Boudh (76.71%), Deogarh (75.65%), Bargarh (75.72%), Sonepur (74.45%), Rayagada (74.38%), and Kalahandi (77.36%), reflecting their predominantly rural economies, limited industrial base, and strong reliance on rainfed farming systems. Similarly, Bolangir (68.41%) and Kandhamal (68.15%) show elevated agricultural engagement, indicative of constrained non-farm employment opportunities and persistent agrarian livelihoods.

In contrast, districts with stronger urbanisation and industrial presence demonstrate lower agricultural workforce shares. Khordha (26.37%), which includes the state capital region, records the lowest dependence, followed by Angul (34.79%), suggesting greater participation in services, industry, and mining-related activities. Jharsuguda (39.43%), Cuttack (41.33%), Sambalpur (40.87%), and Sundargarh (50.11%) also reflect relatively diversified employment structures shaped by industrial corridors, transport connectivity, and urban growth.

Several districts fall within a moderate range, including Ganjam (56.63%), Jajpur (55.57%), Jagatsinghpur (54.91%), Nayagarh (53.30%), Dhenkanal (53.93%), Kendrapara (62.78%), and Puri (54.16%), where agriculture remains an important livelihood source alongside fisheries, trade, small industries, and public sector employment. Overall, the pattern underscores a clear west–coast and rural–urban gradient in employment structure, with agriculture dominating in interior districts while coastal and industrial belts display increasing economic diversification.

These spatial contrasts highlight the need for region-specific development strategies that simultaneously enhance agricultural productivity, promote value addition, and expand rural non-farm opportunities to support inclusive and resilient livelihoods across Odisha.

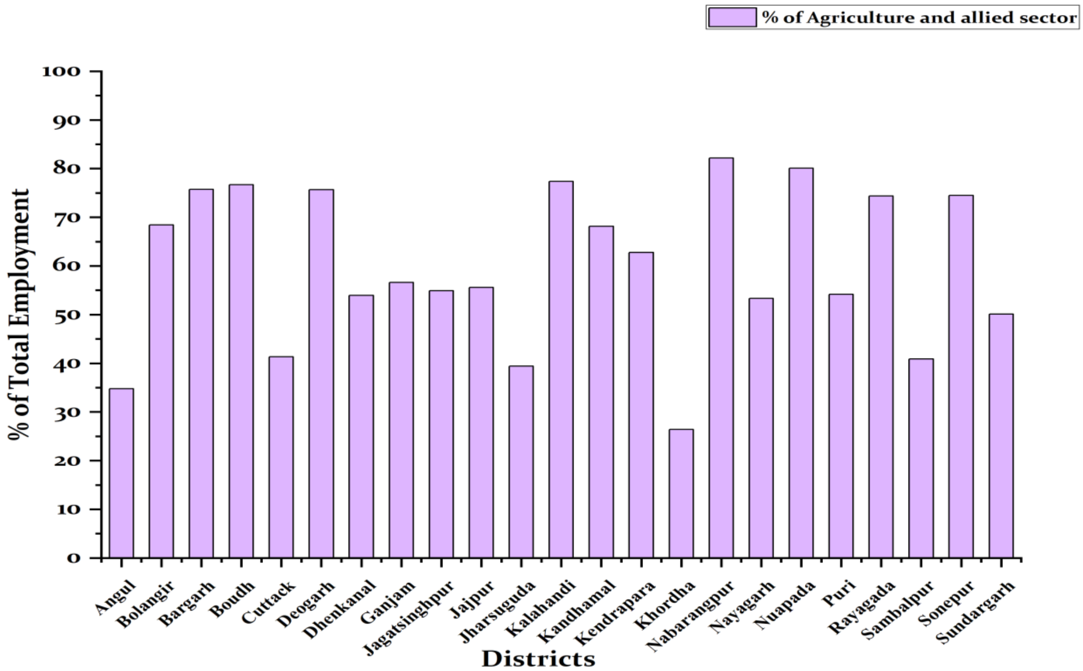


Figure 14: % Employment (Agriculture & Allied Sector) under the MRB (Odisha Portion). [Source: Odisha Agriculture Statistic Report, 2018-19]

Chhattisgarh

I. Total Employment (Population)

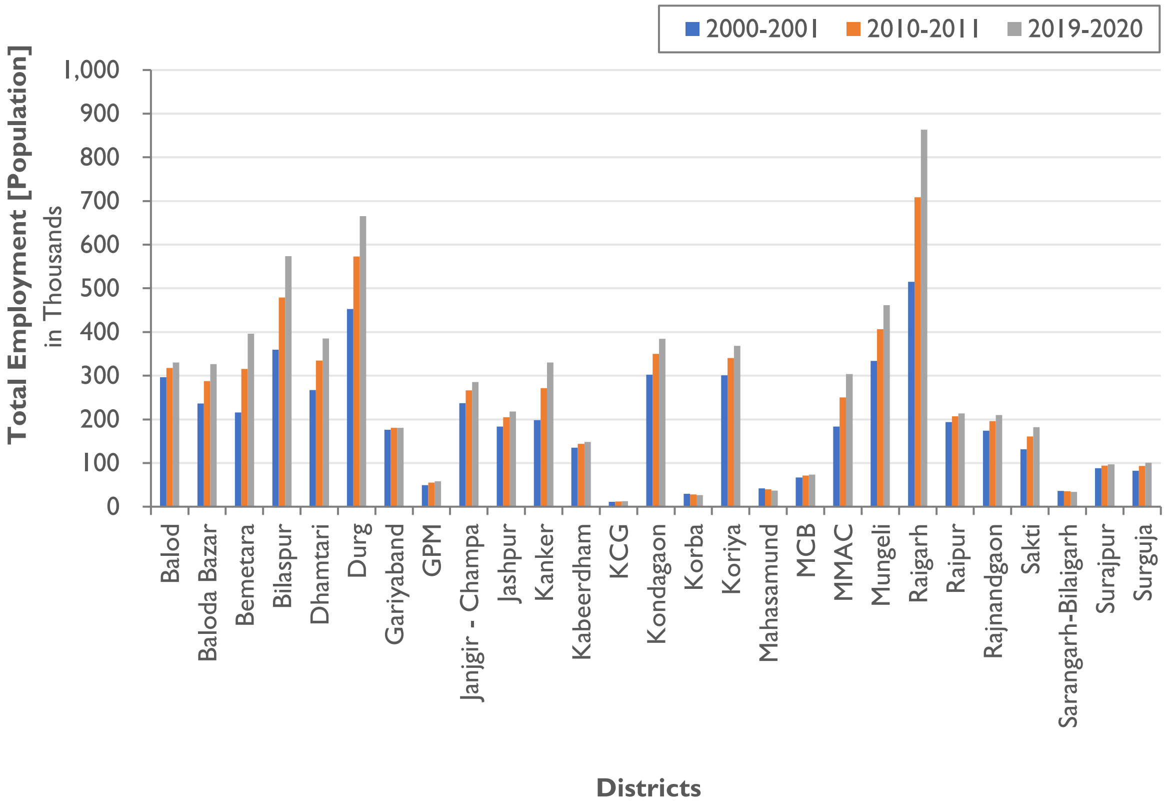


Figure 12: Total Employment (Population) under the MRB (CG Portion).
[Source: Population Census 2001 & 2011 & National Commission On Population, Ministry Of Health & Family Welfare, GoI]

The total employed population has shown a steady and substantial increase over the past two decades. At the basin level, total employment rose from 5.30 million in 2000–01 to 6.42 million in 2010–11, and further to 7.27 million in 2019–20, reflecting an overall growth of nearly 37% during the study period. This expansion closely mirrors population growth combined with rising participation in both agricultural and non-agricultural livelihoods, indicating increasing pressure on land, water, and employment-generating sectors across the basin.

District-wise trends reveal pronounced spatial variability in employment growth. Major districts such as Raigarh, Durg, Bilaspur, Mungeli, Bemetara, and Kondagaon recorded strong increases, with Raigarh alone expanding from 0.52 million to 0.86 million, reflecting rapid industrialisation, mining activity, and associated service-sector employment. Similarly, Bilaspur and Durg showed sustained growth linked to urban expansion and diversified economic bases. In contrast, districts like Gariyaband, Korba, Mahasamund, and Sarangarh–Bilaigarh exhibited stagnant or marginally declining employment, suggesting limited livelihood diversification and possible out-migration. Overall, the rising employment concentration in select districts alongside slower growth elsewhere underscores emerging intra-basin employment disparities, with important implications for regional planning, infrastructure provision, and sustainable resource management within the Mahanadi River Basin.

II. % Employment under Agriculture & Allied Sector

At the basin scale, about 37.7% of the total workforce was engaged in agriculture and allied sectors, underscoring the predominantly agrarian nature of the region despite growing diversification of livelihoods. Several districts recorded high dependence on agriculture, notably Bemetara (36.4%), MMAC (36.0%), Gariyaband (35.2%), Koriya (33.6%), and Dhamtari (32.5%), reflecting their strong rural character and limited penetration of non-farm employment opportunities.

In contrast, districts with greater urbanisation, industrial presence, or mining activity exhibited lower shares of agricultural employment. Korba (10.6%), KCG (11.5%), Durg (16.4%), Surguja (16.1%), Jashpur (16.7%), and Raigarh (17.0%) fall into this category, indicating a shift towards industry, services, and allied non-agricultural livelihoods. Mid-range districts such as Bilaspur, Janjgir–Champa, Mahasamund, Rajnandgaon, and Raipur show a more balanced employment structure, with agriculture still supporting around one-fourth of the workforce. Overall, the pattern highlights strong spatial contrasts in livelihood dependence within the MRB, with agriculture remaining a dominant employer in rural districts while gradually giving way to diversified economic activities in more urbanised and industrial belts.

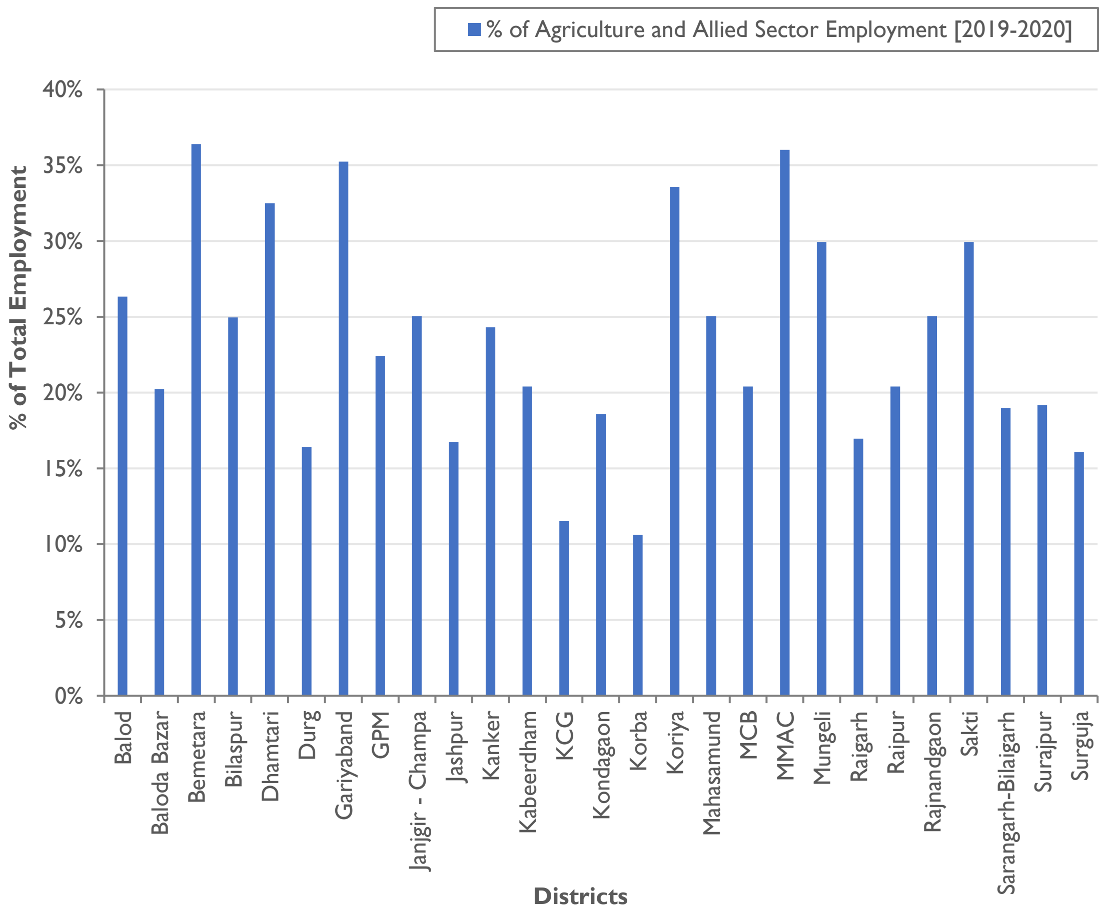


Figure 13: % Employment (Agriculture & Allied Sector) under the MRB (CG Portion).
[Source: National Commission On Population, Ministry Of Health & Family Welfare, GoI]

2.3.4 Agriculture–Income Linkages at Household Level

Odisha

Household income from agricultural activities across the Odisha segment of the Mahanadi River Basin (MRB) in 2013–14 exhibits significant spatial variation, driven by irrigation access, agro-ecological conditions, landholding size, and market connectivity. Higher monthly household incomes are concentrated in Jharsuguda (₹10,726), Deogarh (₹10,524), Dhenkanal (₹9,992), Nabarangpur (₹9,569), and Bolangir (₹8,689), reflecting relatively higher irrigation intensity and more diversified cropping systems. Western districts such as Bargarh (₹6,869) and Sundargarh (₹6,960) also demonstrate comparatively robust agricultural earnings, supported by canal irrigation and higher productivity. Moderate income levels are observed in Sambalpur (₹6,243), Kalahandi (₹5,275), Khordha (₹5,231), Sonepur (₹5,144), and Nuapada (₹4,580), where partial irrigation coverage and rainfall variability constrain farm returns.

In contrast, structurally lower agricultural incomes are evident in Ganjam (₹2,363), Kandhamal (₹2,348), Boudh (₹2,930), Rayagada (₹2,941), Nayagarh (₹2,521), and Puri (₹3,177), largely associated with rainfed systems, small holdings, and limited infrastructural access. Coastal districts such as Kendrapara (₹3,531), Jajpur (₹3,858), and Cuttack (₹4,717) record moderate-to-low farm incomes, where urbanisation and land fragmentation reduce agriculture's relative contribution. Overall, the pattern highlights clear intra-basin disparities, indicating that agricultural income generation in Odisha's MRB remains uneven and largely influenced by the level of irrigation development and the pace of structural transformation across districts.

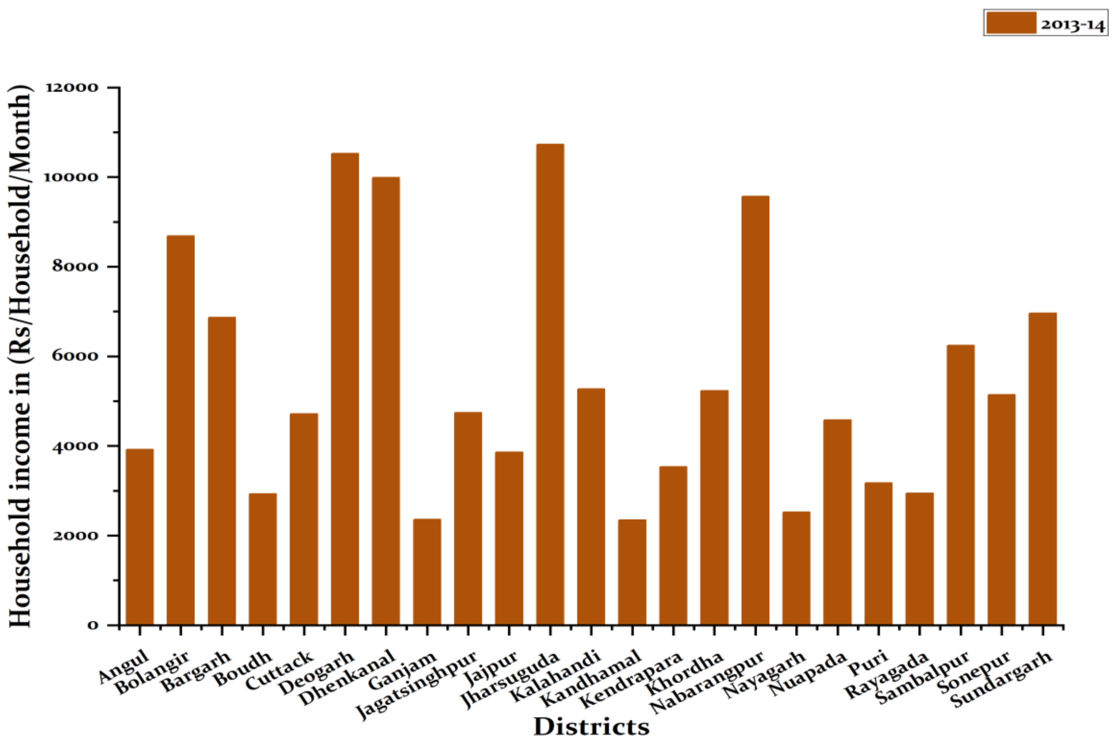


Figure 17: District-wise Composition of Average Monthly Income per Agricultural household from agricultural activities by Source in the Mahanadi River Basin (Odisha Part), Year 2013–14.

[Source: Directorate of Economics & Statistics, Govt. of Odisha]

Chhattisgarh

Household income levels across the Chhattisgarh portion of the Mahanadi River Basin (MRB) in 2019–20 show wide spatial variation, reflecting differences in livelihood structure, access to non-farm employment, and degree of urbanisation. At the basin scale, the average monthly household income aggregates to about ₹27,985, with wages and salaries (₹13,382) forming the largest component, followed by non-farm income (₹11,601). Income from crop cultivation (₹2,581) and livestock (₹421) contributes a relatively smaller share, indicating that while agriculture remains important for employment, household incomes are increasingly supported by wage labour and non-farm activities.

At the district level, MMAC (₹12,195), GPM (₹10,560), Bemetara (₹7,898), Durg (₹7,705), Raigarh (₹7,450), and KCG (₹7,455) record comparatively higher monthly household incomes, largely driven by wages/salaries and non-farm sources, suggesting stronger linkages to industrial, mining, or service-sector activities. In contrast, districts such as Kondagaon (₹2,343), Koriya (₹2,374), Sarangarh–Bilaigarh (₹2,917), Jashpur (₹3,512), and Janjgir–Champa (₹3,720) exhibit lower income levels, with a greater dependence on agriculture and limited diversification. Overall, the income pattern highlights a structural transition in the MRB, where agricultural households increasingly rely on non-agricultural and wage-based livelihoods to sustain monthly incomes, especially in districts with better connectivity and economic diversification.

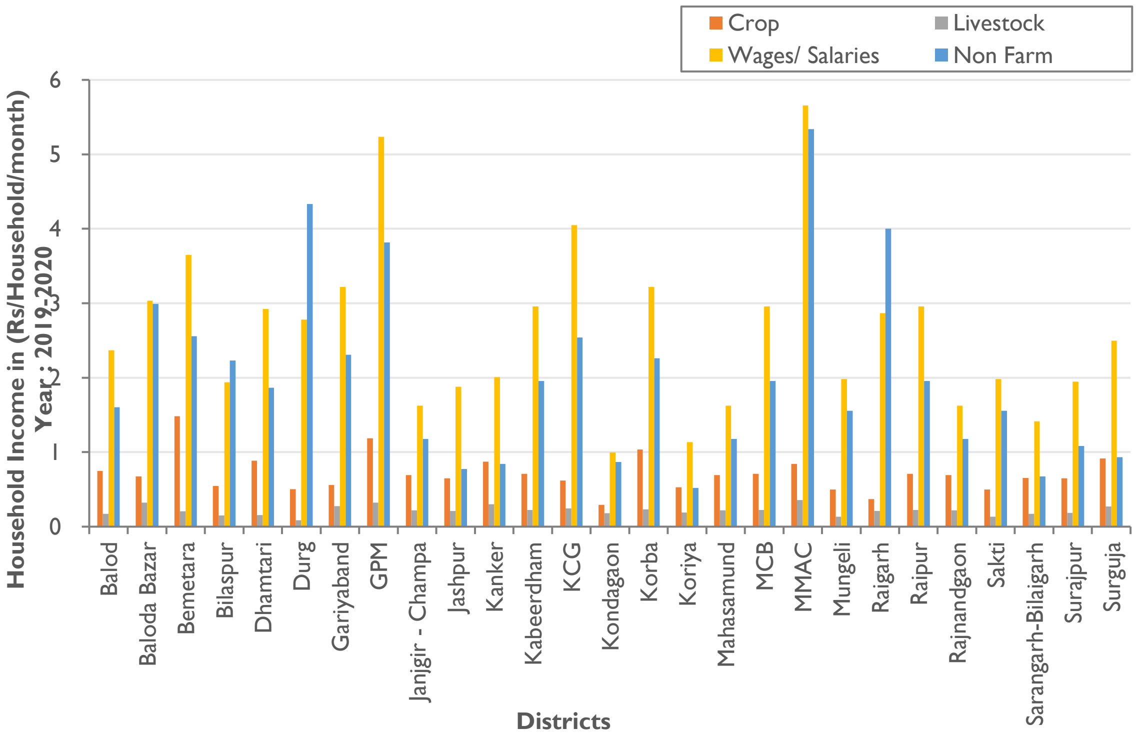


Figure 14: District-wise Composition of Monthly Household Income by Source in the Mahanadi River Basin (Chhattisgarh Part), Year 2019–20.

[Source: Directorate of Economics & Statistics, Govt. of C.G.]

3. Structural Linkages between Irrigation Availability and Cropping Intensity across Districts

Odisha

The district-level analysis of gross irrigated area and cropping intensity in the Odisha portion of the Mahanadi River Basin reveals a non-linear relationship between irrigation expansion and land-use intensification. While deltaic and canal-irrigated districts effectively convert irrigation into higher multi-season cropping, several western and upland districts show limited intensity gains despite substantial irrigation coverage. Conversely, some low-irrigation districts maintain moderate intensity through rainfall-based and adaptive practices.

To better interpret these patterns, districts were classified into irrigation–intensity typologies (High–High, High–Low, Low–High, and Low–Low). This framework helps distinguish efficient irrigation use, underutilised potential, and structurally constrained systems, thereby supporting targeted district-level planning.

Chhattisgarh

The analysis of district-wise gross irrigated area and cropping intensity across the Chhattisgarh portion of the Mahanadi River Basin reveals a complex and non-linear relationship between irrigation expansion and land-use intensification. At the basin scale, total gross irrigated area increased steadily from about 1.62 million ha in 2011–12 to a peak of over 2.11 million ha in 2021–22, before declining in recent years. However, cropping intensity at the basin level remained largely stable within a narrow band of 121–126%, indicating that increases in irrigation availability have not proportionately translated into higher multiple cropping.

To systematically interpret the interaction between irrigation availability and cropping intensity across the Chhattisgarh part of the Mahanadi River Basin districts were classified into irrigation–intensity typologies. This framework enables a clearer distinction between efficiency-driven intensification, underutilized irrigation potential, and structurally constrained production systems, thereby supporting targeted, district-specific planning interventions.

3.1 Criteria for Irrigation–Cropping Intensity Classification

3.1.1 Irrigation Area Availability Classification

Irrigation availability is assessed using Gross Irrigated Area (GIA) trends and relative district performance over the study period (2011–12 to 2023–24)for CG and (2001-01 to 2023–24) for OD [Source: Directorate of Economics & Statistics, Govt. of C.G. and Odisha Agricultural Statistic Report, 2000-01 to 2023-24].

Table 1: Irrigation Area Availability Classification

Category	Criterion	Rationale
High Irrigation	Districts with consistently high or rapidly increasing GIA, typically above the MRB district median, and showing sustained	Indicates presence of functional canal commands, groundwater access, or tank systems capable of supporting multi-season cropping

	post-2017 expansion or stability	
Low Irrigation	Districts with persistently low GIA, marginal growth over time, or high inter-annual variability	Reflects physical constraints, limited storage, tribal/forested terrain, or weak irrigation infrastructure

Note: A district is classified as High Irrigation if its average GIA (2011–12 to 2023–24) for CG and (2001-01 to 2023–24) for OD is ≥ MRB median GIA; otherwise, it is Low Irrigation.

3.1.2 Irrigation Coverage Classification

Irrigation coverage is assessed using Irrigation Coverage % (Irrigated Area / Gross Cropped Area × 100) trends and relative district performance over the study period (2011–12 to 2023–24)for CG and (2001-01 to 2023–24) for OD [Source: Directorate of Economics & Statistics, Govt. of C.G. and Odisha Agricultural Statistic Report, 2000-01 to 2023-24].

Table 2: Irrigation Area Availability Classification

Category	Criterion	Rationale
High Coverage	Districts with consistently high or rapidly increasing Irrigation Coverage %, typically above the MRB district median, and showing sustained post-2017 expansion or stability	Indicates robust irrigation infrastructure relative to cropped area, enabling intensive farming, multi-cropping, and higher productivity
Low Coverage	Districts with persistently low Irrigation Coverage %, marginal growth over time, or high inter-annual variability	Reflects limited irrigation relative to cropped land, due to physical constraints, low storage, tribal/forested terrain, or underdeveloped infrastructure

Note: A district is classified as High Coverage if its average Irrigation Coverage % (2011–12 to 2023–24) for CG and (2001-01 to 2023–24) for OD is ≥ MRB median Irrigation Coverage %; otherwise, it is Low Coverage.

3.1.3 Cropping Intensity Classification

Cropping intensity is measured as Gross Cropped Area / Net Area Sown (%), averaged across recent years to smooth climatic shocks. [Source for the Gross Cropped Area and Net Area Sown data : Directorate of Economics & Statistics, Govt. of C.G. and Odisha Agriculture Statistic Report (2000-01 to 2023-24)].

Table 3: Cropping Intensity Classification

Category	Criterion	Interpretation
High Cropping Intensity	≥ 150%	Indicates effective multiple cropping, rabi utilisation, and irrigation-enabled intensification

Moderate Cropping Intensity	120–149%	Reflects partial intensification; irrigation exists but cropping systems remain kharif-dominant
Low Cropping Intensity	< 120%	Signifies single-crop dominance and strong dependence on monsoon rainfall

3.1.4 Combined Irrigation–Intensity Typology Matrix

Table 4: Combined Irrigation–Intensity Typology Matrix:

Irrigation Availability	Cropping Intensity	Typology	Diagnostic Meaning
High	High (≥150%)	High–High	Efficient irrigation utilisation; smaller yield gaps
High	Low/Moderate (<150%)	High–Low	Latent yield gaps; structural or institutional constraints
Low	High (≥150%)	Low–High	Risk-prone intensification; groundwater stress or rainfall dependence
Low	Low (<120%)	Low–Low	Structural limitations dominate; limited scope for intensification

Following are the Irrigation–Cropping intensity typology of districts under CG an OD Part of MRB.

3.2 Irrigation Area Availability (Ha) Vs Cropping Intensity (%)

Odisha

The Gross Irrigated Area–Cropping Intensity classification for the Odisha portion of the Mahanadi Basin reveals four distinct structural regions of agricultural intensification.

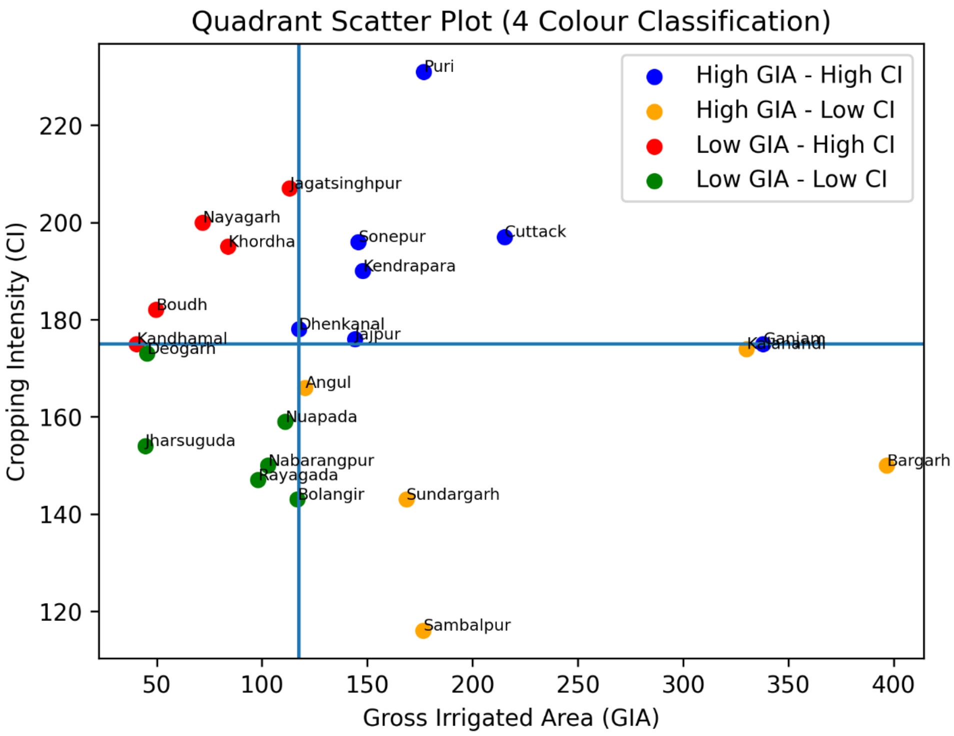
High GIA–High Intensity districts such as Cuttack, Ganjam, Puri, Kendrapara, Jajpur, Sonepur, and Dhenkanal represent mature irrigation-command systems where large irrigated areas are effectively converted into additional crop cycles. Coastal and deltaic districts particularly benefit from assured canal irrigation and fertile soils, enabling stable rabi expansion and multi-cropping.

In contrast, High GIA–Low Intensity districts such as Bargarh, Kalahandi, Sambalpur, Sundargarh, and Angul exhibit underutilised irrigation potential. Despite substantial irrigation coverage, cropping intensity remains moderate, reflecting kharif-dominated paddy systems, delayed rabi diversification, and possible water allocation constraints. These districts indicate significant unrealised intensification potential.

A different adaptive pattern is observed in Low GIA–High Intensity districts such as Boudh, Jagatsinghpur, Khordha, Nayagarh, and Kandhamal, where higher cropping intensity is achieved despite limited irrigation. This reflects effective rainfall utilisation, shorter-duration crops, and diversified farming practices rather than large canal infrastructure.

Finally, Low GIA–Low Intensity districts Bolangir, Deogarh, Jharsuguda, Nabarangpur, Nuapada, and Rayagada remain structurally constrained due to upland terrain, lower irrigation penetration, and socio-economic limitations. Here, decentralised water management and climate-resilient diversification may be more appropriate than large-scale irrigation expansion.

Overall, the Odisha segment demonstrates that irrigation extent alone does not determine intensification; regional agro-ecological and institutional factors shape how effectively water resources translate into cropping intensity gains.



Note: Median Gross Irrigation Area = 117.41 Thousand Ha; Median cropping intensity = 175%

Figure 19: Scatter Plot (Gross Irrigation Area –Cropping Intensity Classification (2023–24))

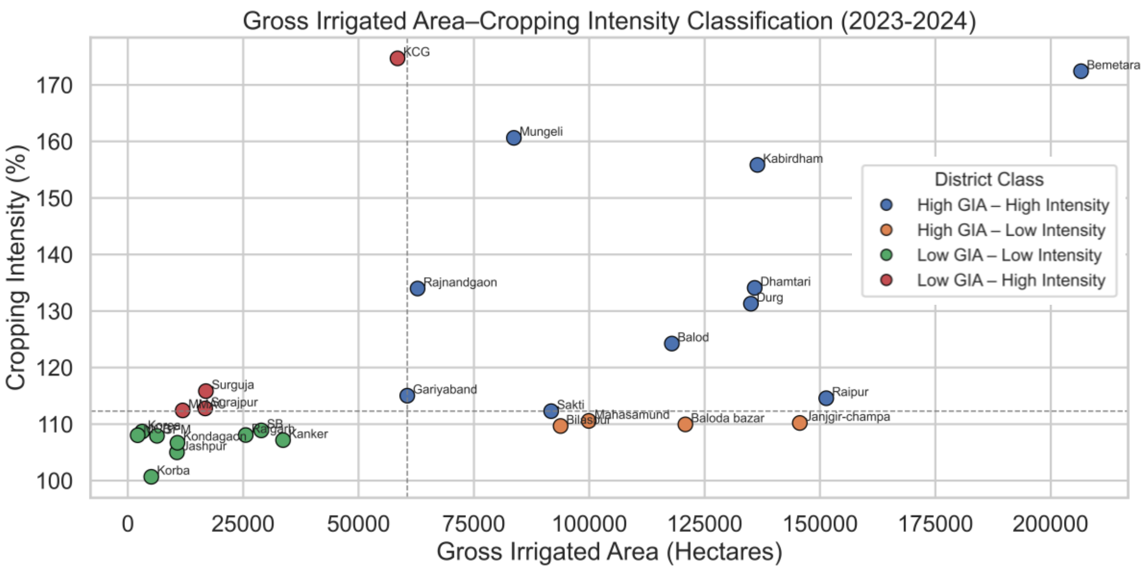
Table 5: Districts under the various Gross Irrigation Area –Cropping Intensity Classification (2023–24)

Typology	Districts
High GIA – High Intensity	Cuttack, Dhenkanal, Ganjam, Jajpur, Kendrapara, Puri and Sonepur
High GIA – Low Intensity	Angul, Bargarh, Kalahandi, Sambalpur and Sundargarh

Low GIA – High Intensity	Boudh, Jagatsinghpur, Kandhamal, Khordha, Nayagarh
Low GIA – Low Intensity	Bolangir, Deogarh, Jharsuguda, Nuapada and Rayagada

Chhattisgarh

The Gross Irrigated Area–Cropping Intensity classification reveals **distinct structural regimes of agricultural intensification across the CG part of the Mahanadi River Basin**. Districts such as **Bemetara, Kabirdham, Mungeli, and Dhamtari** combine large irrigated areas with cropping intensities exceeding 150%, indicating effective conversion of irrigation infrastructure into additional crop cycles. These districts reflect relatively mature irrigation command systems, timely rabi expansion, and lower yield gaps attributable to water availability. However, even within this group, **Raipur exhibits only moderate intensity (≈115%) despite very high GIA**, signalling saturation effects and competing non-agricultural water demands.



Note: Median Gross Irrigation Area = 62,800 Ha; Median cropping intensity = 112.3%

Figure 15: Scatter Plot (Gross Irrigation Area –Cropping Intensity Classification (2023–24))

In contrast, **High GIA–Low Intensity districts** notably **Janjgir–Champa, Baloda Bazar, Mahasamund, and Bilaspur** represent the **largest unrealised yield potential** in the basin. Despite substantial irrigation coverage, cropping intensity remains stagnant around 110%, pointing to rigid kharif-dominated cropping systems, limited rabi diversification, and inefficiencies in canal command utilisation. These districts highlight that irrigation expansion alone is insufficient without parallel cropping system transformation.

A distinct adaptive pattern emerges in **Low GIA–High Intensity districts** such as **KCG, Surguja, Surajpur, and MMAC**, where cropping intensities exceed basin averages despite limited irrigated area. This reflects effective rainfall utilisation, shorter-duration crops, and traditional multiple-cropping practices. While yield gaps persist, they are less irrigation-driven and more sensitive to rainfall variability, underscoring the importance of supplemental irrigation and soil moisture conservation rather than large-scale irrigation expansion.

Finally, **Low GIA–Low Intensity districts**, largely concentrated in tribal, forested, and mining-influenced regions (e.g., **Jashpur, Kondagaon, Kanker, Korba, Korea, and MCB**), remain structurally constrained. Low cropping intensity in these districts reflects terrain limitations, shallow soils, fragmented holdings, and ecological restrictions, where conventional paddy-centric intensification is neither feasible nor desirable.

Table 6: Districts under the various Gross Irrigation Area –Cropping Intensity Classification (2023–24)

Typology	Districts
High GIA – High Intensity	Bemetara, Kabirdham, Mungeli, Dhamtari, Durg, Rajnandgaon, Balod, Gariyaband, Sakti, Raipur
High GIA – Low Intensity	Janjgir–Champa, Baloda Bazar, Mahasamund, Bilaspur
Low GIA – High Intensity	KCG, Surguja, Surajpur, MMAC
Low GIA – Low Intensity	Kanker, Kondagaon, Jashpur, GPM, Korba, Korea, Raigarh, SB, MCB

Overall Interpretation Across Typologies

- Type II districts represent the largest unrealised yield potential in the CG–MRB
- Type I districts are nearing intensification ceilings
- Type IV districts require alternative development pathways, not paddy-centric intensification
- Basin-level stagnation in cropping intensity despite irrigation growth confirms that water availability alone is no longer the binding constraint.

3.3 Irrigation Coverage (%) vs Cropping Intensity (%)

Odisha

The irrigation–cropping intensity typology (2023–24) for the Odisha portion of the Mahanadi River Basin highlights several structural advantages alongside regional disparities.

High Irrigation–High Cropping Intensity districts such as Puri, Cuttack, Jagatsinghpur, Kendrapara, Jajpur, Ganjam, and Sonepur demonstrate Odisha's key strengths, including well-established canal systems in the delta, fertile alluvial soils, relatively dense irrigation networks, and strong rabi expansion. These districts reflect the effective conversion of irrigation potential into multiple cropping and reduced monsoon dependence.

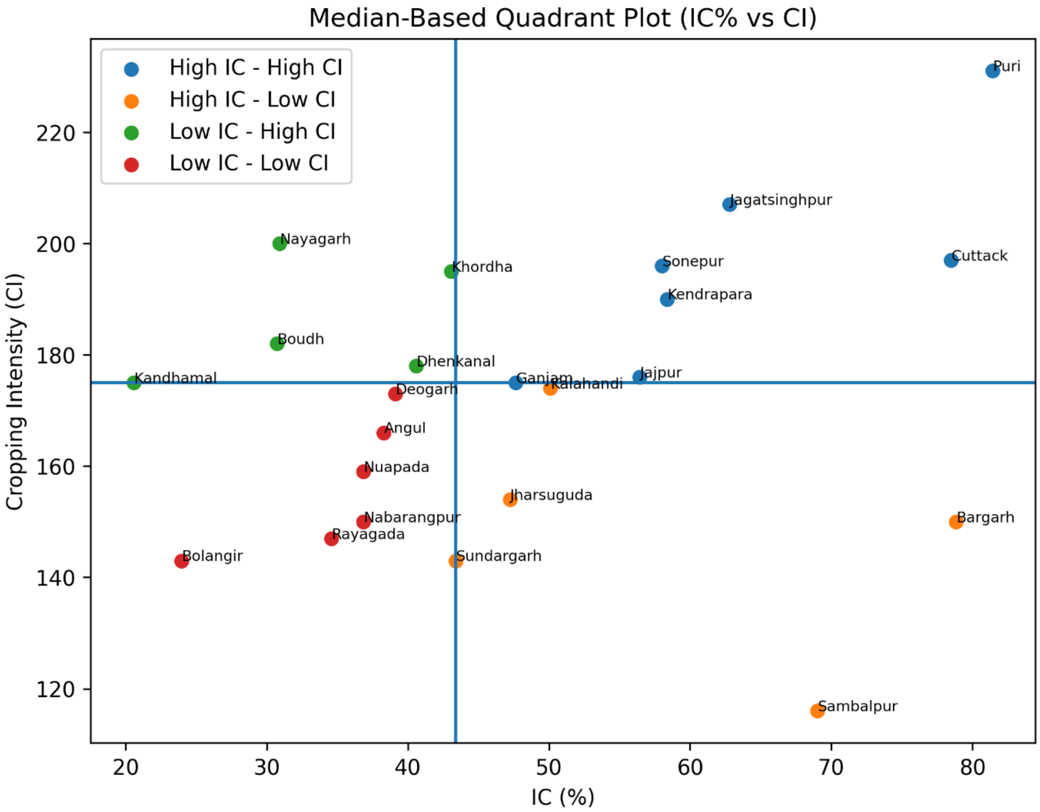
High Irrigation–Low Cropping Intensity districts like Bargarh, Sambalpur, Jharsuguda, Sundargarh, and Kalahandi still benefit from major irrigation projects and reservoir systems.

Although cropping intensity remains moderate, the presence of large-scale irrigation infrastructure provides significant scope for diversification and productivity enhancement.

Low Irrigation–High Cropping Intensity districts, such as Kandhamal, Boudh, Khordha, Nayagarh, and Dhenkanal, illustrate adaptive strengths. Even with limited irrigation coverage, farmers sustain relatively higher cropping intensity through rainfall utilisation, groundwater use, tanks, and short-duration crop varieties, indicating resilience and agronomic adaptability.

Low Irrigation–Low Cropping Intensity districts like Angul, Bolangir, Deogarh, Nabarangpur, Nuapada, and Rayagada face terrain and infrastructural constraints; however, Odisha's advantage lies in the potential for watershed development, minor irrigation expansion, and diversification beyond paddy-based systems.

Overall, Odisha benefits from a strong deltaic irrigation base, established canal infrastructure, favourable agro-climatic conditions, and demonstrated adaptive capacity, providing a solid foundation for further intensification and balanced regional agricultural development.



Note: Median Irrigation Coverage = 43.4%; Median Cropping Intensity = 175%

Figure 20: Scatter Plot (Irrigation Coverage –Cropping Intensity Classification (2023–24)

Table 7: Districts under the various Irrigation Coverage –Cropping Intensity Classification (2023–24)

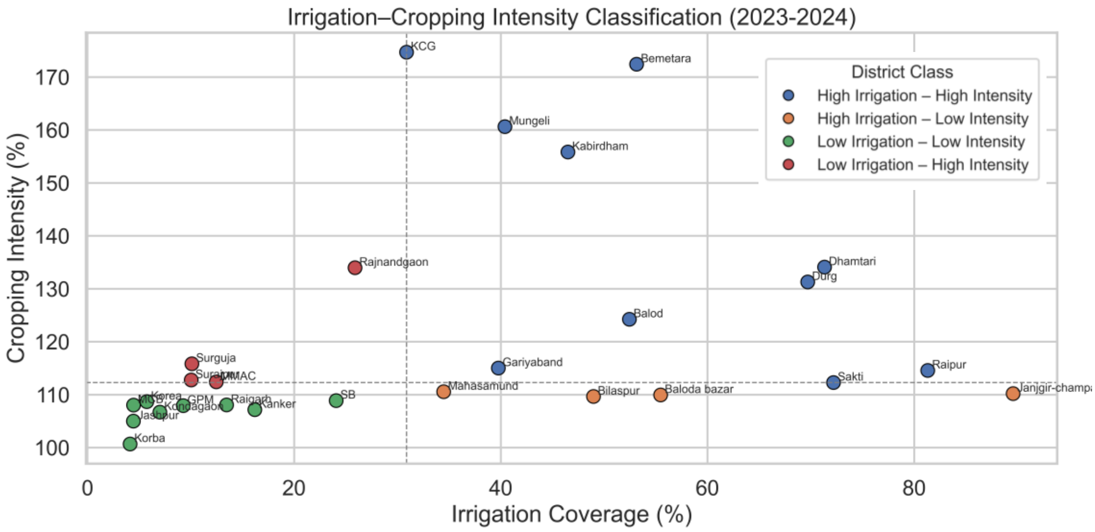
Typology	Districts
Type I: High Irrigation – High Cropping Intensity	Puri, Cuttack, Jagatsinghpur, Kendrapara, Sonepur, Ganjam, Jajpur,

Type II: High Irrigation – Low Cropping Intensity	Bargarh, Sambalpur, Jharsuguda, Sundargarh and Kalahandi
Type III: Low Irrigation – High Cropping Intensity	Kandhamal, Boudh, Khordha, Nayagarh and Dhenkanal
Type IV: Low Irrigation – Low Cropping Intensity	Angul, Bolangir, Deogarh and Nabarangpur

Chhattisgarh

The irrigation–cropping intensity typology for 2023–24 reveals clear structural differentiation across districts of the Chhattisgarh part of the Mahanadi River Basin. Districts classified under **High Irrigation–High Cropping Intensity** represent zones where irrigation availability is effectively translated into multiple cropping. These districts such as **Bemetara, Mungeli, Kabirdham, Dhamtari, Durg, Raipur, and Sakti** exhibit cropping intensities well above the basin median, indicating relatively efficient utilisation of irrigation infrastructure, better rabi season expansion, and reduced dependence on monsoonal variability.

In contrast, **High Irrigation–Low Cropping Intensity** districts including **Baloda Bazar, Bilaspur, Janjgir–Champa, and Mahasamund** highlight a utilisation gap. Despite substantial irrigation coverage, cropping intensity remains close to or below the basin median, suggesting structural constraints such as dominance of long-duration kharif paddy, limited diversification into rabi crops, or operational inefficiencies within canal and groundwater systems.



Note: Median Irrigation Coverage = 30.9%; Median Cropping Intensity = 112.3%

Figure 16: Scatter Plot (Irrigation Coverage –Cropping Intensity Classification (2023–24))

Districts falling under **Low Irrigation–High Cropping Intensity** (e.g., **Rajnandgaon, Surguja, Surajpur, and Mohla–Manpur–Ambagarh Chowki**) demonstrate adaptive intensification under constrained water availability. Here, relatively higher cropping intensity is sustained through rainfall utilisation, short-duration crops, and traditional agronomic practices rather than formal irrigation expansion.

Finally, **Low Irrigation–Low Cropping Intensity** districts largely located in forested and tribal regions such as **Jashpur, Korea, GPM, MCB, Raigarh, and Sarangarh–Bilaigarh** reflect agro-ecological and infrastructural limitations. In these areas, both irrigation development and intensification potential remain structurally constrained, indicating the need for alternative livelihood pathways rather than conventional paddy-led intensification.

3.3.1 Notable District-Level Cases and Emerging Contrasts

Odisha

Several districts in the Odisha part of the Mahanadi River Basin exhibit patterns that challenge a simple linear relationship between irrigation coverage (IC%) and cropping intensity (CI%), revealing structural contrasts and latent yield gaps.

Puri represents one of the strongest high–high cases in the basin. With the highest irrigation coverage (above 80%) and the highest cropping intensity (231%), the district reflects highly effective utilisation of deltaic canal systems. Irrigation is successfully translated into multi-season cultivation, indicating strong rabi expansion and efficient water management.

In contrast, Sambalpur presents a striking paradox. Despite high irrigation coverage (69%), its cropping intensity (116%) remains far below the basin median. This suggests that irrigation is largely reinforcing a mono-cropped kharif system, possibly dominated by long-duration paddy, with limited seasonal diversification. The district illustrates how irrigation expansion alone does not automatically ensure intensification.

Bargarh, another highly irrigated district (nearly 79%), also records relatively low cropping intensity (150%). While irrigation infrastructure is substantial, cropping patterns appear less diversified, indicating scope for improving irrigation scheduling and promoting short-duration or rabi crops.

By contrast, Nayagarh and Boudh demonstrate adaptive intensification under limited irrigation conditions. With irrigation coverage well below the median, they achieve high cropping intensities (200% and 182%, respectively). These districts likely rely on rainfall utilisation, tanks, and shorter crop cycles, highlighting agronomic adaptability rather than infrastructure dependence.

Khordha and Jagatsinghpur stand out as efficient performers. Jagatsinghpur combines moderately high irrigation coverage (63%) with very high cropping intensity (207%), while Khordha achieves high intensity (195%) despite irrigation coverage close to the median. These cases underscore the role of crop planning and local water management in enhancing intensity.

Among low irrigation districts, Kandhamal presents an interesting case. Despite the lowest irrigation coverage (around 21%), it maintains cropping intensity at the basin median (175%), reflecting traditional multi-cropping and rainfall-based resilience. However, further expansion may be constrained by terrain and forest cover.

Finally, districts such as Nabarangpur, Rayagada, Nuapada, and Bolangir reflect structural low–low or near low–low conditions. Here, moderate-to-low irrigation coverage coincides with lower cropping intensity, shaped by upland topography, tribal-dominated regions, rainfall variability, and limited canal penetration. These districts highlight the limits of irrigation-led intensification without broader agro-ecological support.

Overall, the Odisha portion of the Mahanadi Basin shows that cropping intensity is not determined by irrigation coverage alone. Coastal and delta districts efficiently convert irrigation into higher multi-season cropping, while some western districts with substantial irrigation display limited diversification and moderate intensity gains. At the same time, several upland districts sustain reasonable intensity despite low irrigation through rainfall use and adaptive practices. The pattern highlights that crop choice, agro-ecology, and institutional efficiency are as important as irrigation extent in shaping agricultural performance.

Chhattisgarh

Several districts in the Chhattisgarh part of the Mahanadi River Basin exhibit patterns that challenge linear assumptions between irrigation availability and cropping intensity, offering critical insights into the nature of yield gaps and structural constraints.

Janjgir–Champa represents one of the most striking paradoxes in the basin. Despite recording the *highest irrigation coverage* (nearly 90%), its cropping intensity remains only marginally above the basin median. This suggests that irrigation infrastructure is largely reinforcing a mono-cropped, long-duration kharif paddy system rather than enabling rabi expansion or diversification. The district illustrates how irrigation saturation, in the absence of cropping system transition, can lead to stagnation in intensity and persistence of latent yield gaps.

Bemetara and Mungeli, by contrast, demonstrate how moderate-to-high irrigation coverage can translate into exceptionally high cropping intensities (above 160–170%). These districts appear to benefit from shorter crop cycles, better synchronisation of irrigation with rabi cultivation, and relatively flexible land-use decisions. Their performance indicates that institutional and agronomic efficiency not merely irrigation extent plays a decisive role in closing yield gaps.

An equally instructive case is **Rajnandgaon**, which achieves high cropping intensity despite relatively low irrigation coverage. This pattern reflects adaptive intensification under water-limited conditions, likely supported by favourable rainfall distribution, widespread adoption of short-duration varieties, and traditional multiple-cropping practices. However, the sustainability of such intensification remains sensitive to climatic variability, making the district vulnerable in drought years.

Raipur stands out as a high irrigation–high intensity district, yet with cropping intensity only modestly above the basin median despite very high irrigation coverage. This suggests that even in administratively and infrastructurally advantaged districts, cropping intensity gains may be approaching a ceiling due to urbanisation pressures, competing non-agricultural water demand, and declining marginal returns to irrigation expansion.

Among low irrigation districts, **Surguja and Surajpur** present notable cases where cropping intensity exceeds expectations. These districts illustrate the role of rainfall utilisation, crop calendar optimisation, and traditional practices in sustaining intensification in the absence of formal irrigation. At the same time, the limited irrigation base constrains further expansion, indicating that future yield gains will depend more on soil moisture conservation and climate-resilient agronomy than on large-scale irrigation projects.

Finally, districts such as **Jashpur, Korea, and Gaurella–Pendra–Marwahi** reflect structural low–low equilibria. Here, low irrigation coverage coincides with persistently low cropping intensity, shaped by hilly terrain, forest cover, shallow soils, and fragmented holdings. These districts underscore the limits of conventional irrigation-led strategies and point toward the need for alternative development pathways, including horticulture, agroforestry, and livelihood diversification.

Table 8: Districts under the various Irrigation Coverage –Cropping Intensity Classification (2023–24)

Typology	Districts
Type I: High Irrigation – High Cropping Intensity	Balod, Bemetara, Dhamtari, Durg, Kabirdham, Mungeli, Raipur, Sakti
Type II: High Irrigation – Low Cropping Intensity	Baloda Bazar, Bilaspur, Janjgir–Champa, Mahasamund
Type III: Low Irrigation – High Cropping Intensity	Mohla–Manpur–Ambagarh Chowki, Rajnandgaon, Surajpur, Surguja
Type IV: Low Irrigation – Low Cropping Intensity	Gaurella–Pendra–Marwahi, Jashpur, Korea, Manendragarh–Chirimiri–Bharatpur, Raigarh, Sarangarh–Bilaigarh

The district-level contrasts confirm that **cropping intensity is increasingly decoupled from irrigation expansion in the basin**. Where institutions, crop choices, and agronomic practices align, even moderate irrigation can deliver high intensity. Conversely, without structural transition, high irrigation coverage risks locking districts into low-return production systems.

4. Climatic Constraints

Agricultural productivity in the Mahanadi River Basin is shaped by a complex interplay of climatic and environmental stressors that vary significantly across its physiographic regions. These constraints include soil erosion, seasonal waterlogging, salinity intrusion in the coastal delta, recurrent droughts in the upper basin, and most critically monsoon-induced flooding (Singh et al. 2018; Mishra and Rafiq 2020). Collectively, these factors impose both chronic and episodic stresses on the basin's agricultural systems, influencing crop stability, yield variability, and land-use decisions.

Among these, flooding emerges as the most dominant climatic constraint, particularly in the middle and lower reaches of the basin. Historical evidence indicates that the Mahanadi system is prone to significant flood events at a recurrence interval of approximately 2–3 years. The geomorphological characteristics of the lower basin marked by a flat, low-gradient alluvial and deltaic plain intensify both the spatial extent and duration of inundation (Central Water Commission, 2014; National Disaster Management Authority, 2019). Flood dynamics in the basin are further complicated by the interaction of peak monsoonal discharge, regulated releases from the Hirakud reservoir, tidal influences in the deltaic zone, and backwater effects, resulting in highly dynamic and non-linear flood behaviour that cannot be adequately captured through single-source datasets or simplistic thresholds.

This section evaluates these climatic constraints within the framework of the Gross Agricultural Structure.

4.1 Flood-Prone Agricultural Areas

Quantifying the spatial intersection between recurrent flood inundation and active agricultural land is essential for evaluating the resilience of the gross agricultural structure within the Mahanadi River Basin. This sub-section presents a Sentinel-1 SAR-based assessment of flood-prone agricultural areas for the period 2017–2023, leveraging dual-polarisation C-band backscatter to generate cloud-independent flood frequency maps . (Torres et al., 2021; Twele et al., 2016; Cao et al., 2019). The approach enables robust detection of both open water and inundated vegetation conditions during the Kharif season, overcoming limitations of optical datasets under monsoon cloud cover.

4.1.1 SAR Flood Detection Methodology and Parameters

Sentinel-1 GRD imagery in Interferometric Wide (IW) swath mode was accessed through Google Earth Engine (Gorelick et al., 2017). A total of 1,160 scenes covering June–October (Kharif monsoon season) from 2017 to 2023 were processed. Each scene was filtered for dual-polarisation (VV + VH) availability, correcting for both open water and flooded vegetation conditions. The dual-polarisation flood detection logic follows established methodologies for paddy-dominated agricultural systems (Shen et al., 2019; Skakun et al., 2017).

To ensure reliable flood detection, each SAR scene was pre-processed using a 50 m focal mean speckle filter to reduce inherent SAR noise. Flooded pixels were identified using established dual-polarisation thresholds:

- VV < −15.0 dB → detection of open water and bare flooded surfaces
- VH < −22.0 dB → detection of flooded vegetation (e.g., inundated paddy fields)

A pixel was classified as flood-prone if it was detected as flooded in at least 10% of the observed monsoon months over the study period, capturing recurrent rather than isolated flood events. Additional refinements included:

- Permanent water exclusion: Pixels with ≥80% occurrence (JRC Global Surface Water) were removed
- Slope masking: Areas with slope >5° (SRTM) were excluded to avoid terrain-induced errors to further restricts detections to alluvial and low-lying cultivation zones where inundation is agronomically meaningful.
- Parameters

Analysis Period	2017–2023
Flood Source	Sentinel-1 GRD C-band SAR IW mode, VV+VH dual polarisation
VV Threshold	< −15 dB (open water & bare flooded surfaces)
VH Threshold	< −22 dB (flooded vegetation & inundated paddy)
Speckle Filter	Focal mean 50 m kernel (per-image pre-processing)
Flood Threshold	Frequency ≥ 10% of monsoon months (Jun–Oct)
Agriculture Source	MODIS MCD12Q1 Annual LULC (classes 12 & 14) + Sentinel-2 NDVI ≥ 0.20
Platform	Google Earth Engine (geemap) | Scale: 100 m (tiled 3×3 sub-regions)

4.1.2 Agricultural Land Mask

The agricultural land mask was constructed from the MODIS MCD12Q1 Annual Land Use/Land Cover product (Friedl & Sulla-Menashe, 2019), which provides global annual LULC classifications at 500 m resolution. LC_Type1 classes 12 (Croplands) and 14 (Cropland/Natural Vegetation Mosaic) were extracted for 2017–2023, and the temporal mode computed to produce a stable multi-year cropland extent. Class 14 was specifically retained to capture flood-recession and peri-urban cultivation characteristic of the lower Mahanadi delta (Singh et al., 2018).

A secondary Sentinel-2 SR vegetation validation filter was applied (Drusch et al., 2012): pixels with monsoon season (June–October) median NDVI < 0.20 were excluded from the agricultural mask to remove misclassified MODIS pixels. The final mask applied the logic:

Agriculture Mask = (MODIS Class 12 OR Class 14) AND (Sentinel-2 NDVI ≥ 0.20)

4.1.3 Flood Risk within the Agricultural Structure

❖ **Key Statistics**

- Sentinel-1 SAR Based Analysis

1,41,589 km² **Total Basin Area**	**91,735** km² **Agricultural Area**	**3858.61** km² **S1 Flood-Prone Area**	**1331.95** km² **Flood-Prone Agri.**
64.79% of basin **Agriculture Share**	**2.73%** of basin **Flood-Prone Share**	**0.94%** of agri. **At-Risk Agri. Share**	**1160** S1 images **2017–2023 Dataset**

These results indicate that while flood-prone zones occupy a relatively small proportion of the basin, their overlap with agricultural land represents a critical constraint in specific regions.

> **Agricultural Risk:** 1331.95 km² = 1.33 lakh hectares at persistent flood risk | ~2.6 lakh MT Kharif paddy production at risk annually (ICAR, 2020)

The SAR-based flood-prone delineation reveals the following hierarchical structure of agricultural land exposure within the Mahanadi basin's gross agricultural composition:

Table 9: Gross agricultural structure flood risk hierarchy, Mahanadi River Basin (Source: Sentinel-1 SAR | 2017-2023).

Land Category	Area (km²)	% of Basin	Risk Level
Total Basin Area	**141589.00**	100.00%	
Agricultural Area	91735.51	64.79%	Productive Base
Safe Agricultural Area	90403.56	63.85%	Low Risk
Flood-Prone Agricultural Area	**1331.95**	**0.94%**	High Risk
Non-Agricultural Area	49853.49	35.21%	
S1 Flood-Prone Area (Total)	3858.61	2.73%	Flood-Exposed
Flood on Agricultural Land	1331.95	34.52% of flood	Agriculture at Risk
Flood on Non-Agri. Land	2526.66	65.48% of flood	Floodplain/Wetland

Flood exposure is spatially limited (2.73% of the basin), yet 1,331.95 km² of agricultural land (0.94%) falls within high-risk flood-prone zones. Notably, over one-third (34.52%) of total flooding affects agricultural land, reflecting a disproportionate impact on productive areas. Meanwhile, the majority of flooding (65.48%) occurs over non-agricultural landscapes, likely functioning as natural flood buffers. Overall, while the basin remains structurally resilient, targeted interventions are needed in localized flood-prone agricultural zones to reduce risk and sustain productivity.

The concentration of flood-prone agricultural land in the lower Mahanadi delta characterised by near-zero gradients, backswamps, and proximity to tidal influences creates a spatially specific but economically disproportionate vulnerability within the basin's agricultural structure (Singh et al., 2018; Mishra & Rafiq, 2020).

4.1.4 Sub-Basin Wise : Flood Prone Area

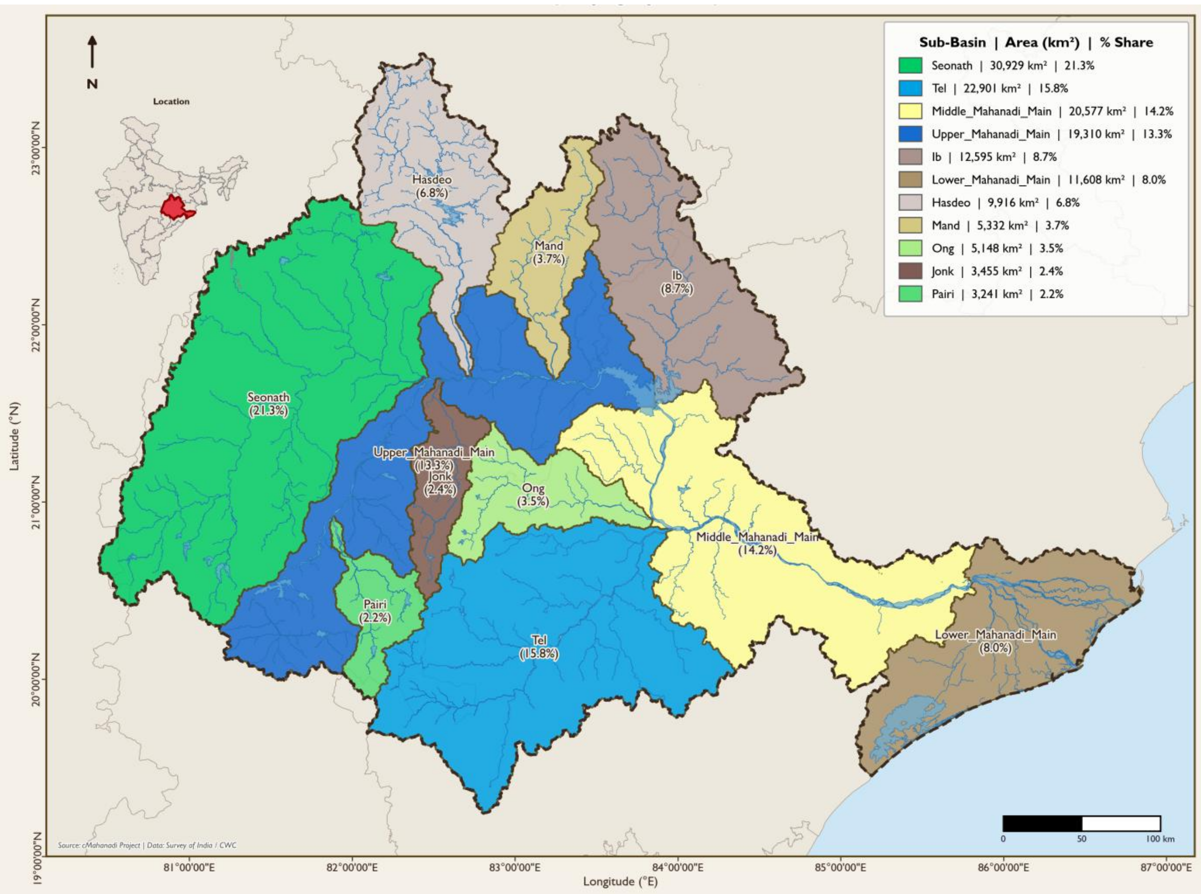


Figure 17: Sub-Basin Boundary with % Area Share under the MRB.

At the Sub-Basin scale, flood-prone agricultural land is unevenly distributed, with a strong concentration in the Lower Mahanadi Main sub-basin, which alone accounts for 808.69 km² of flood-affected agriculture, representing 9.42% of its agricultural land the highest in both absolute and relative terms. This highlights the acute vulnerability of the deltaic region to recurrent monsoon flooding.

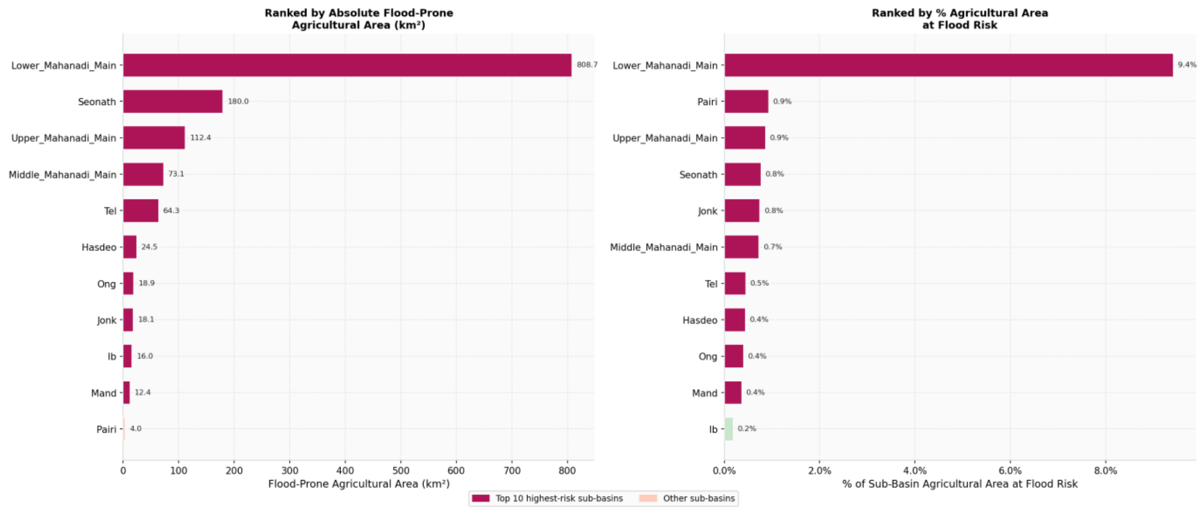


Figure 18: Sub-Basin Wise Flood Prone Agricultural Area Ranking under Mahanadi River Basin (Source: Sentinel-1 SAR | 2017-2023)

The Seonath and Upper Mahanadi Main sub-basins follow, though with significantly lower magnitudes, contributing 179.98 km² and 112.37 km² of flood-prone agricultural area respectively. However, their relative exposure remains below 1%, indicating comparatively lower agricultural risk.

Middle Mahanadi, Tel, and Hasdeo sub-basins exhibit moderate exposure, with flood-prone agricultural shares ranging between 0.44% and 0.73%, suggesting localized flood impacts rather than basin-wide stress.

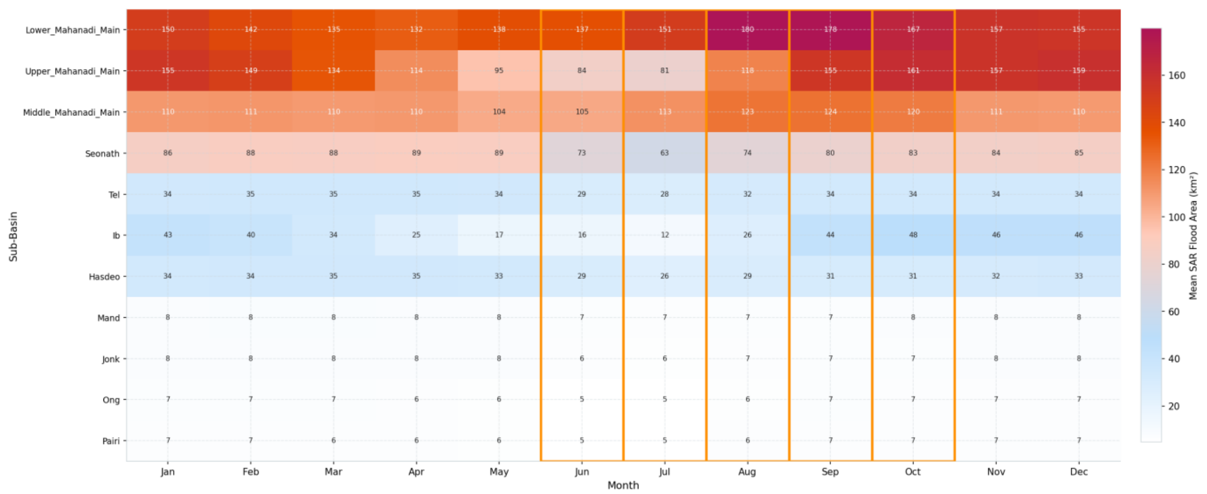


Figure 19: Sub-Basin Wise Monthly SAR Flood Area Heatmap under Mahanadi River Basin (Source: Sentinel-1 SAR | 2017-2023)

Smaller sub-basins such as Ong, Jonk, Mand, and Ib show minimal flood-affected agriculture (<1%), indicating relatively stable agricultural systems. However, Pairi presents a contrasting case: despite a small absolute flooded area (3.96 km²), nearly 0.93% of its agricultural land is affected, making it second in relative vulnerability.

Seasonally, flood extent peaks during the monsoon months (June–October), particularly in August–September, with the Lower Mahanadi Main consistently recording the highest inundation (>170 km²). Upper and Middle Mahanadi sub-basins also show elevated flood extent during these months, while upstream basins like Hasdeo and Ib remain comparatively stable.

Overall, the analysis reveals a clear downstream intensification of flood risk, with deltaic and lower basin regions exhibiting both high exposure and high agricultural vulnerability, while upper basin regions demonstrate resilience due to topographic and hydrological controls.

4.1.5 Analytical Implications for Agricultural Planning

Risk Prioritization

Focus interventions on high-vulnerability sub-basins like Lower Mahanadi (808.69 km^2 at risk, 9.42% of local agriculture) and Pairi (0.93% relative risk), where flat topography amplifies inundation during August–September peaks. Upstream areas like Hasdeo and Ib show minimal risk (<1%), allowing resources to prioritize deltaic zones for cost-effective gains. Nature-based solutions, such as riparian buffers and wetland restoration, can act as flood buffers while preserving biodiversity and soil health in these hotspots.

Crop Adaptation Strategies

Adopt flood-tolerant rice varieties like Swarna-Sub1 and CR Dhan 101, which withstand 14–17 days of submergence and yield 3.5 t/ha even post-flood, enabling "stand-by" cropping in Kharif lowlands. Promote crop diversification (e.g., mixed cropping with vegetables on recession lands) and varietal shifts in lower basin areas, as farmers already use these to counter flood losses. Ex-ante measures like seed banking and stocking foodgrains reduce post-flood dependency on migration or fallowing.

Infrastructure Interventions

Enhance embankment repairs and raised-bed planting in delta backswamps to protect ~1.33 lakh ha at risk, potentially safeguarding 2.6 lakh MT of annual Kharif paddy. Integrate early warning systems with sub-basin-specific forecasts, prioritizing Lower Mahanadi's tidal-influenced zones for timely evacuations and crop salvage. Community-led watershed management, including minor storage ponds, supports equitable water access for recession agriculture without exacerbating upstream droughts.

Policy Recommendations

Develop basin-wide contingency plans incorporating SAR-derived risk maps for insurance subsidies and credit access in flood-prone agri-zones, addressing farmers' top concerns like inadequate government support. Scale climate-smart agriculture via extension services, linking MODIS/Sentinel masks to precision inputs for resilient LULC in 64.79% agricultural share. Monitor via Google Earth Engine for adaptive planning, ensuring interventions balance flood control with ecological buffers like non-agri floodplains (65.48% of inundation).

4.1.6 Data Notes and Limitations

- Area computations are performed at 300 m spatial resolution; fine-scale inundation features below this threshold may be under-represented.

- SAR-based flood mapping is sensitive to wind-induced surface roughness over open water and dense crop canopies, which may introduce marginal classification uncertainty in VH-dominant flooded-vegetation detections.
- The analysis period (2017–2023) captures inter-annual variability in monsoon intensity but does not extend to pre-2017 land-use configurations; decadal trend analysis would require integration with historical Landsat-derived flood records.
- MODIS land-cover (MCD12Q1) at 500 m resolution may conflate small agricultural patches with adjacent land-use classes in heterogeneous landscapes; the supplementary NDVI filter partially mitigates this aggregation error.

4.1.7 Summary

The Sentinel-1 SAR-based assessment of flood-prone agricultural areas in the Mahanadi River Basin (2017–2023) provides the following key insights:

- Agricultural dominance: Nearly two-thirds of the basin (64.79%) is under cultivation, underscoring the importance of agriculture in the basin economy.
- Flood extent: Approximately 2.73% of the basin is subject to recurrent flooding, as detected through SAR-based analysis.
- Agricultural exposure: About 1,331.95 km² (1.42%) of agricultural land is consistently exposed to flood risk, representing localized but significant vulnerability.
- Spatial concentration of risk: Flood-prone agricultural zones are primarily confined to low-lying and hydrologically active regions, particularly along river corridors and deltaic tracts.
- Methodological robustness: The use of SAR data ensures reliable flood detection under monsoon cloud cover, while dual-polarisation enhances detection of both open water and flooded crops.

Overall, although flood-prone agricultural land constitutes a relatively small fraction of the basin, its recurring nature and spatial concentration make it a critical environmental constraint. These areas require targeted management interventions, including flood-resilient cropping strategies, improved drainage, and basin-specific risk zoning to enhance agricultural resilience.

Policy Implication: The 1331.95 km² of SAR-identified flood-prone agricultural area in the Mahanadi River Basin should form the spatial basis for tiered flood risk zoning, targeted flood-tolerant paddy variety deployment, and parametric agricultural insurance scheme design (NDMA, 2019; ICAR, 2020).

4.2 Drought and Moisture Stress Analysis

The drought assessment was conducted for the period 2000–2023 (24 years) using the Composite Weighted Stress Index (CWSI) to evaluate spatio-temporal drought variability across the basin. The analysis covered 11 sub-basins, including three mainstem segments and eight major tributary sub-basins, spanning parts of Chhattisgarh, Odisha, Jharkhand, and Maharashtra. Spatial analysis was performed using a 10 km sampling resolution within the Google Earth Engine (GEE) environment, enabling consistent basin-scale monitoring. The study integrated multiple satellite and climate datasets, including CHIRPS v2.0 precipitation data and MODIS products such as MOD11A2, MOD13A2, and MOD09A1 v061, all processed through Google Earth Engine to derive the drought indicators and composite stress index for the basin.

4.2.1 Data Sources

Table 10: Data Sources, and Normalisation Parameters

Component	Weight	Dataset	Resolution	Normalisation / Notes
Precipitation	35%	CHIRPS v2.0 | UCSB-CHG/CHIRPS/DAILY	0.05° (~5.5 km)	unitScale(500, 2200) mm/yr. Primary drought driver.
Land Surface Temp. (LST)	25%	MODIS MOD11A2 v061 | LST_Day_1km	1 km | 8-day composite	1 – unitScale(20, 46). Inverted: hotter = more stress. K→°C: ×0.02–273.15.
NDVI Vegetation Index	20%	MODIS MOD13A2 v061 | NDVI band	500 m | 16-day composite	unitScale(0.05, 0.75). Scaling ×0.0001. Reflects crop water availability.
LSWI Water Index	20%	MODIS MOD09A1 v061 | NIR (B2) & SWIR (B6)	500 m | 8-day composite	LSWI = (NIR–SWIR)/(NIR+SWIR). unitScale(–0.4, 0.6). Measures liquid water.

4.2.2 CWSI - Composite Weighted Stress Index

The CWSI (Composite Weighted Stress Index) is a multi-source drought and moisture stress index integrating four remote-sensing variables into a single normalised index ranging from 0 (extreme drought) to 1 (no stress). It captures both atmospheric drought (precipitation) and land-surface moisture stress (thermal, spectral, and vegetation). (Svoboda & Fuchs, 2017; AghaKouchak et al., 2015)

$$CWSI = 0.35 \times Preci_{pnorm} + 0.25 \times (1 - LST_{norm}) + 0.20 \times NDVI_{norm} + 0.20 \times LSWI_{norm}$$

Each component normalised to [0, 1]. LST is inverted: higher temperature = greater stress = lower CWSI.

4.2.3 Moisture Stress Index (MSI)

MSI = 1 – CWSI. Measures degree of moisture stress: High MSI (near 1) indicates severe moisture stress; Low MSI (near 0) indicates adequate moisture availability for crop growth. (Svoboda & Fuchs, 2017)

4.2.4 Drought Zone Classification Thresholds

Table 11: CWSI and MSI Drought Zone Classification Thresholds with Agricultural Significance

Drought Zone	CWSI Range	MSI Range	Agricultural Significance
Extreme Drought	< 0.20	> 0.80	Crop failure; severe and irreversible water stress. Irrigation completely ineffective without supplemental supply.
Severe Drought	0.20 – 0.35	0.65 – 0.80	Major yield reductions. Irrigation essential; significant input costs required.
Moderate Drought	0.35 – 0.50	0.50 – 0.65	Moderate stress; irrigation required for viable yields. Rainfed farming risky.
Mild Drought	0.50 – 0.65	0.35 – 0.50	Some moisture stress during dry spells. Rainfed agriculture generally feasible.
No Stress	> 0.65	< 0.35	Optimal moisture conditions. Excellent for all agricultural uses including high-value crops.

4.2.5 Key Findings at a Glance

The 24-year CWSI analysis (2000–2023) of the Mahanadi River Basin reveals that the dominant moisture condition across the basin is Mild Drought, covering approximately 70.8% of the total area. No zones of Extreme or Severe drought were detected, indicating that the basin generally receives sufficient precipitation to sustain rainfed agriculture, albeit with periodic stress episodes. (Funk et al., 2015; CWC, 2014)

Table 12: Summary of Drought Zone Distribution over Mahanadi River Basin (2000–2023)

Drought Zone	Area (%)	Area (km^2)	CWSI Range	Agricultural Impact
Extreme Drought	0.0%	0	0.00 – 0.20	Crop failure, severe water stress
Severe Drought	0.0%	0	0.20 – 0.35	Major yield reductions
Moderate Drought	25.5%	36,094	0.35 – 0.50	Irrigation essential for viable yields
Mild Drought	70.8%	1,00,281	0.50 – 0.65	Some moisture stress; rainfed feasible
No Stress	3.6%	5,041	0.65 – 1.00	Optimal moisture for agriculture

Key Finding: *70.8% of the Mahanadi Basin (1,00,281 km^2) falls within the Mild Drought zone with a mean CWSI of 0.57. This zone is agriculturally productive under rainfed conditions during the monsoon season, but supplemental irrigation is recommended for kharif crop intensification and rabi cultivation.*

4.2.6 CWSI Drought Zone Statistics Mahanadi River Basin

Table 13: CWSI Drought Zone Statistics with Estimated Precipitation, MSI, and Agricultural Suitability

Zone	Area (%)	Area (km²)	Est. Precip (mm)	CWSI Range	Mean MSI	Agricultural Suitability
Extreme Drought	0.0%	0	490	0.00–0.20	0.18	Very Poor – Unsuitable
Severe Drought	0.0%	0	680	0.20–0.35	0.32	Poor – Very Limited
Moderate Drought	25.5%	36,094	900	0.35–0.50	0.43	Moderate – Irrigation Required
Mild Drought	70.8%	1,00,281	1150	0.50–0.65	0.57	Good – Rainfed Possible
No Stress	3.6%	5,041	1480	0.65–1.00	0.72	Excellent – Optimal
TOTAL BASIN	**100.0%**	**1,41,600**				

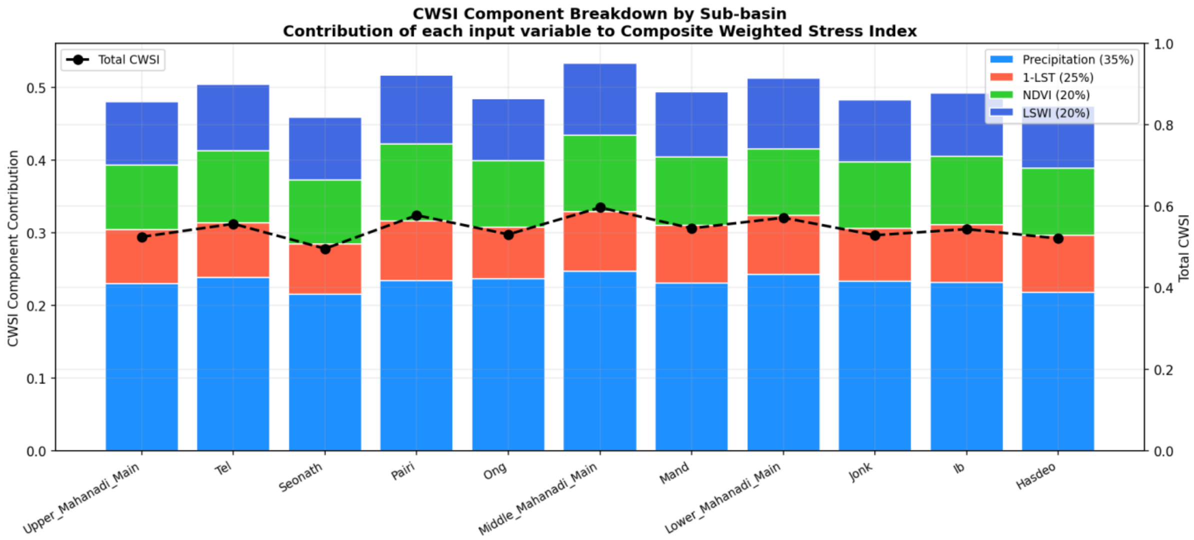


Figure 20: Sub-Basin Wise: CWSI Component Breakdown (Stacked) over MRB

4.2.7 Sub-Basin CWSI & Moisture Stress Analysis

The sub-basin level analysis reveals spatial heterogeneity in drought stress across the Mahanadi Basin. All 11 sub-basins record mean annual precipitation above 1,350 mm, placing them within the Mild Drought to borderline Moderate Drought range. (Funk et al., 2015) The Seonath sub-basin records the lowest CWSI (0.496) and is classified under Moderate Drought, whereas Middle Mahanadi Main records the highest CWSI (0.597), indicating the best moisture conditions within the basin. (McKee et al., 1993; Kogan, 1995)

Table 14: Sub-basin CWSI, Spectral Indices, and Drought Stress Classification - Mahanadi Basin

Sub-basin	Precip (mm)	LST (°C)	NDVI	LSWI	EVI	CWSI	MSI	Stress Zone
Upper Mahanadi Main	1,444.9	32.3	0.443	0.035	0.277	0.525	0.475	**Mild Drought**
Tel	1,496.7	32.2	0.496	0.059	0.313	0.557	0.443	**Mild Drought**
Seonath	1,354.3	33.3	0.442	0.029	0.272	0.496	0.504	**Moderate Drought**
Pairi	1,470.4	30.9	0.531	0.075	0.329	0.578	0.422	**Mild Drought**
Ong	1,487.2	33.0	0.458	0.030	0.294	0.531	0.469	**Mild Drought**
Middle Mahanadi Main	1,552.4	31.0	0.527	0.099	0.333	0.597	0.403	**Mild Drought**
Mand	1,447.9	31.3	0.470	0.050	0.291	0.546	0.454	**Mild Drought**
Lower Mahanadi Main	1,523.6	31.1	0.459	0.087	0.254	0.572	0.428	**Mild Drought**
Jonk	1,464.7	32.6	0.458	0.026	0.293	0.529	0.471	**Mild Drought**
Ib	1,454.7	31.4	0.469	0.039	0.290	0.544	0.456	**Mild Drought**
Hasdeo	1,367.0	31.5	0.461	0.028	0.288	0.521	0.479	**Mild Drought**

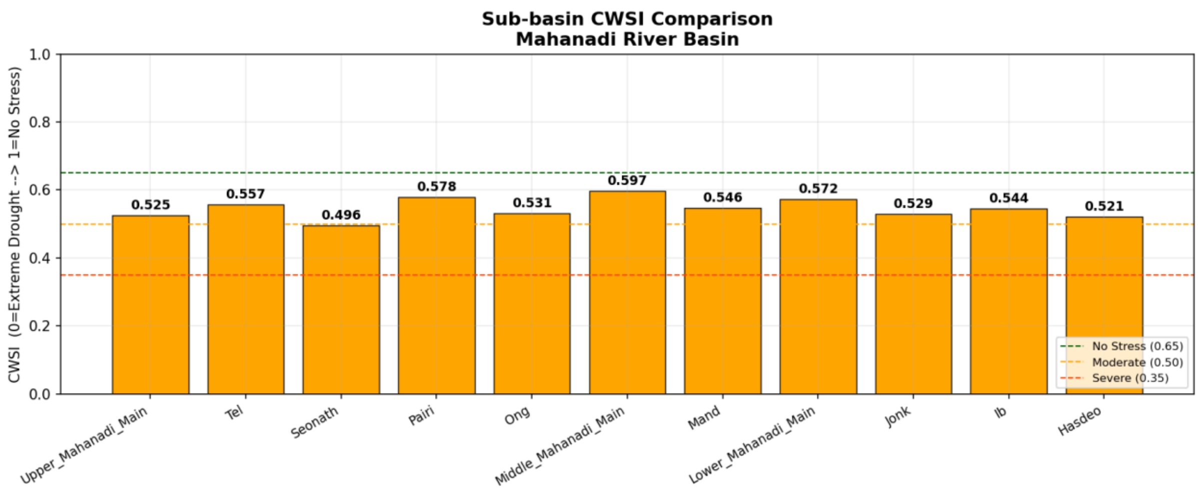


Figure 21: Sub-Basin Wise: CWSI Comparison over MRB

4.2.8 Moisture Stress Analysis LSWI & MSI

➢ **LSWI Moisture Classification**

The Land Surface Water Index (LSWI) provides a direct measure of surface and vegetation liquid water content, complementing the composite CWSI with a single-band spectral moisture indicator. (Xiao et al., 2004)

Table 15: LSWI Moisture Classification Thresholds and Agricultural Implications

LSWI Range	Moisture Status	Typical Condition	Agricultural Impact
> 0.30	**High Moisture**	Dense canopy / wetlands	Excellent for crops; minimal irrigation need
0.10 – 0.30	**Moderate Moisture**	Normal healthy vegetation	Good; minimal stress under normal conditions
−0.05 – 0.10	**Low Moisture**	Sparse / stressed vegetation	Supplemental irrigation advisable
< −0.05	**Moisture Deficit**	Bare / dry soil	Irrigation essential; poor crop establishment risk

➢ **Sub-basin LSWI & MSI Values**

All 11 sub-basins record LSWI values in the range 0.026–0.099, placing them uniformly in the Low Moisture category. (Xiao et al., 2004; Vermote, 2021) This indicates sparse to mildly stressed vegetation canopy and confirms the need for supplemental irrigation, particularly during the pre-monsoon (April–May) and post-monsoon (October–November) growing windows. (CGWB, 2020; ICAR, 2018)

Table 16: Sub-basin LSWI and Moisture Stress Index (MSI) Values Mahanadi Basin

Sub-basin	LSWI	MSI (1 – CWSI)	LSWI Category
Upper Mahanadi Main	0.035	0.475	**Low Moisture**
Tel	0.059	0.443	**Low Moisture**
Seonath	0.029	0.504	**Low Moisture**
Pairi	0.075	0.422	**Low Moisture**
Ong	0.030	0.469	**Low Moisture**
Middle Mahanadi Main	0.099	0.403	**Low Moisture**

Sub-basin	LSWI	MSI (1 – CWSI)	LSWI Category
Mand	0.050	0.454	**Low Moisture**
Lower Mahanadi Main	0.087	0.428	**Low Moisture**
Jonk	0.026	0.471	**Low Moisture**
Ib	0.039	0.456	**Low Moisture**
Hasdeo	0.028	0.479	**Low Moisture**

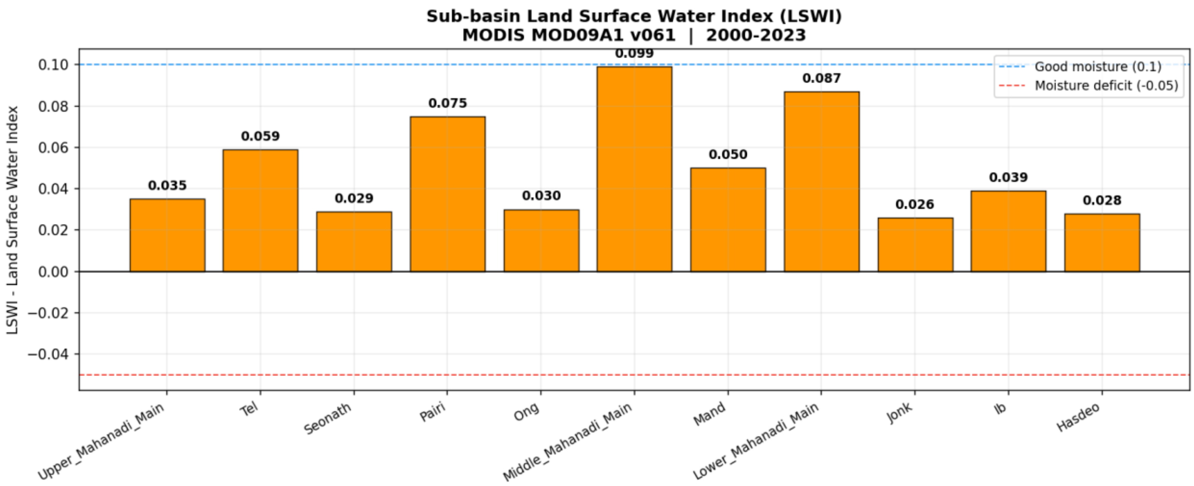


Figure 22: Sub-Basin Wise: Land Surface Water Index (LSWI) over MRB

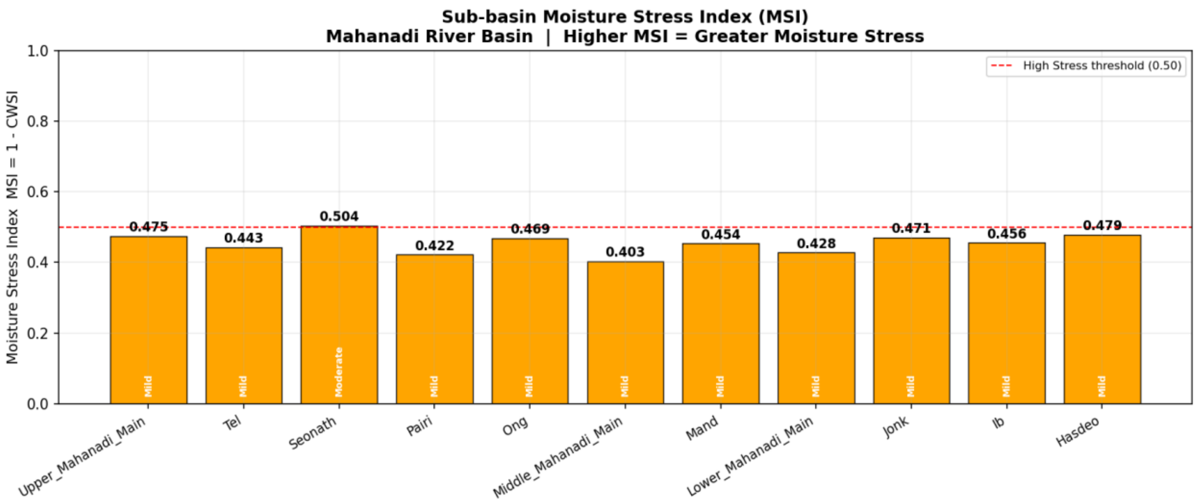


Figure 23: Sub-Basin Wise: Moisture Stress Index (MSI) over MRB

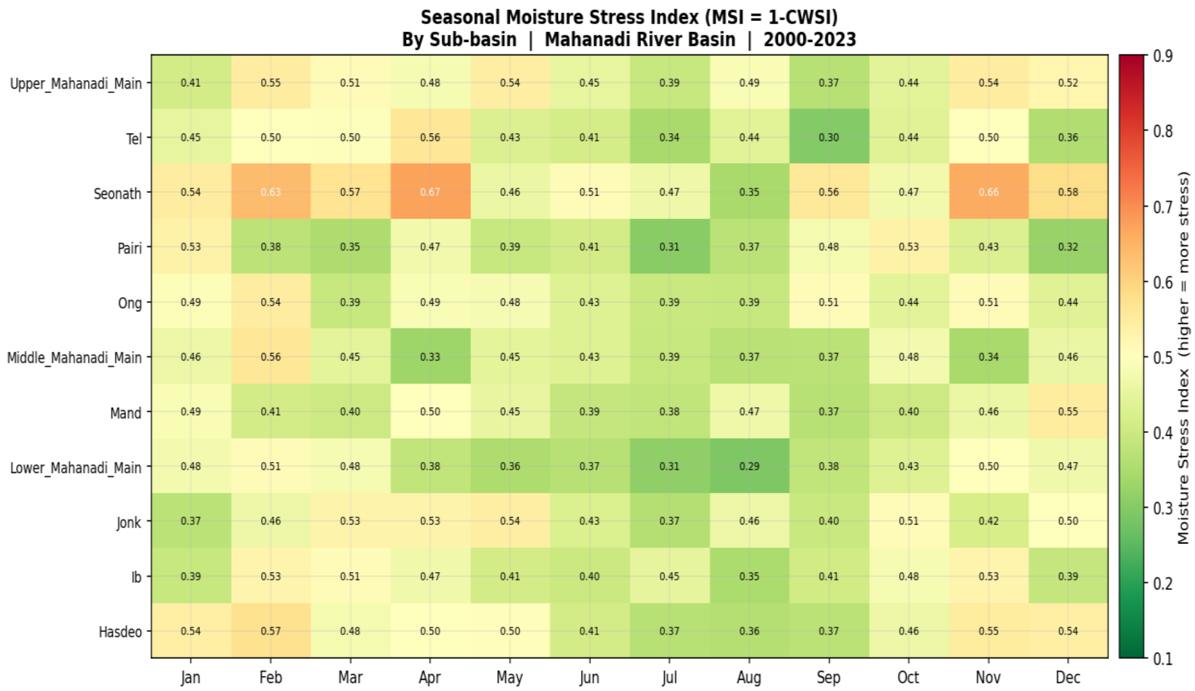


Figure 24: Seasonal Moisture Stress Index (MSI) over MRB

4.2.9 Monthly Precipitation Pattern CHIRPS 2000–2023

The Mahanadi Basin exhibits a strongly monsoonal precipitation regime. (CWC, 2014) The June–September window accounts for approximately 85.7% of the mean annual precipitation of 1,453.2 mm, with peak intensity in July and August. (Funk et al., 2015) The pre-monsoon and rabi (winter) months receive minimal rainfall, critically constraining non-monsoon agricultural cycles. (ICAR, 2018)

Table 17: Mean Monthly Precipitation and Agricultural Season Classification (CHIRPS 2000-2023).

Month	Mean Precip (mm)	% Annual	Season / Agricultural Period
January	14.6	1.0%	Winter / Rabi
February	20.6	1.4%	Winter / Rabi
March	22.8	1.6%	Pre-monsoon
April	21.9	1.5%	Pre-monsoon
May	35.2	2.4%	Pre-monsoon
June	**204.6**	**14.1%**	**Monsoon / Kharif**
July	**390.0**	**26.8%**	**Monsoon / Kharif ◄ Peak**
August	**391.1**	**26.9%**	**Monsoon / Kharif ◄ Peak**

Month	Mean Precip (mm)	% Annual	Season / Agricultural Period
September	**259.4**	**17.9%**	**Monsoon / Kharif**
October	79.7	5.5%	Post-monsoon
November	10.3	0.7%	Winter / Rabi
December	3.0	0.2%	Winter / Rabi

Note: *Green-shaded rows indicate the monsoon (Kharif) season, which delivers 85.7% of annual basin precipitation. Months highlighted in plain white/alternating represent the agriculturally critical Rabi and pre-monsoon windows where moisture deficit is most acute.*

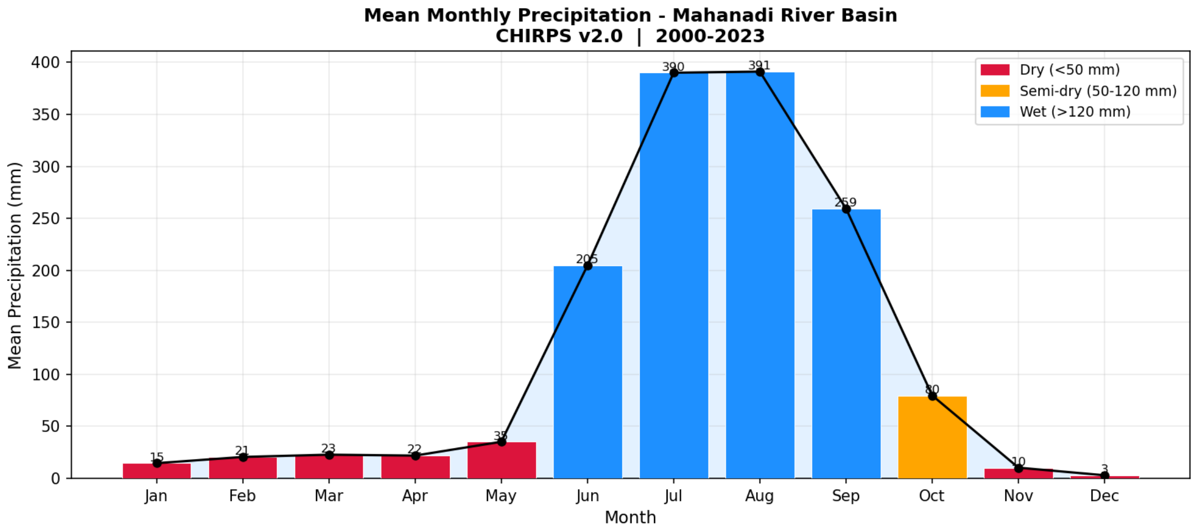


Figure 25: Mean Monthly Precipitation over MRB (Source -CHIRPS v2.0)

4.2.10 Agricultural Implications & Recommendations

➢ Basin-Wide Assessment

The absence of Extreme and Severe Drought zones across the Mahanadi Basin indicates a climatically favourable base for agricultural development. (Svoboda & Fuchs, 2017; McKee et al., 1993) However, the dominant Mild Drought classification (70.8%) and universal Low Moisture LSWI values across all sub-basins underscore the structural dependency on monsoon rainfall and the vulnerability of non-monsoon cropping seasons. (CWC, 2014; Mishra & Singh, 2010)

➢ Sub-basin Specific Observations

Seonath sub-basin (CWSI: 0.496) is the most moisture-stressed tributary, approaching Moderate Drought classification. (McKee et al., 1993) Its higher LST (33.3°C) and lower precipitation (1,354.3 mm) suggest elevated evapotranspiration demand. (Anderson et al., 2011; Wan et al., 2021) In contrast, Middle Mahanadi Main (CWSI: 0.597) and Pairi (CWSI: 0.578) exhibit relatively better moisture conditions. (Funk et al., 2015; Didan, 2021)

- **Irrigation Dependency**

Given that 96.3% of the basin area falls within the Mild to Moderate Drought zones, and all sub-basins record LSWI in the Low Moisture category (0.026–0.099), supplemental irrigation infrastructure is a prerequisite for reliable rabi cultivation and crop intensification. (CGWB, 2020; CWC, 2014) Canal irrigation systems and micro-irrigation adoption are critical agricultural investment priorities for the basin states of Chhattisgarh, Odisha, Jharkhand, and Maharashtra. (ICAR, 2018)

***Summary Recommendation**: The Mahanadi Basin is suitable for broad-based agricultural development under a kharif-primary, irrigation-supplemented rabi system. Priority interventions should target moisture conservation in Seonath and Hasdeo sub-basins, expansion of micro-irrigation in the Mild Drought zone, and investment in post-monsoon water storage to extend agricultural seasons.*

4.3 Land Degradation and Nutrient Stress

Land degradation represents one of the most critical environmental and agricultural constraints facing the Mahanadi River Basin. An analysis of the NRSC Land Degradation Dataset (2015–16) reveals that a significant proportion of the basin's land resources are affected by active degradation processes, with far-reaching implications for agricultural productivity, soil fertility, and long-term food security.

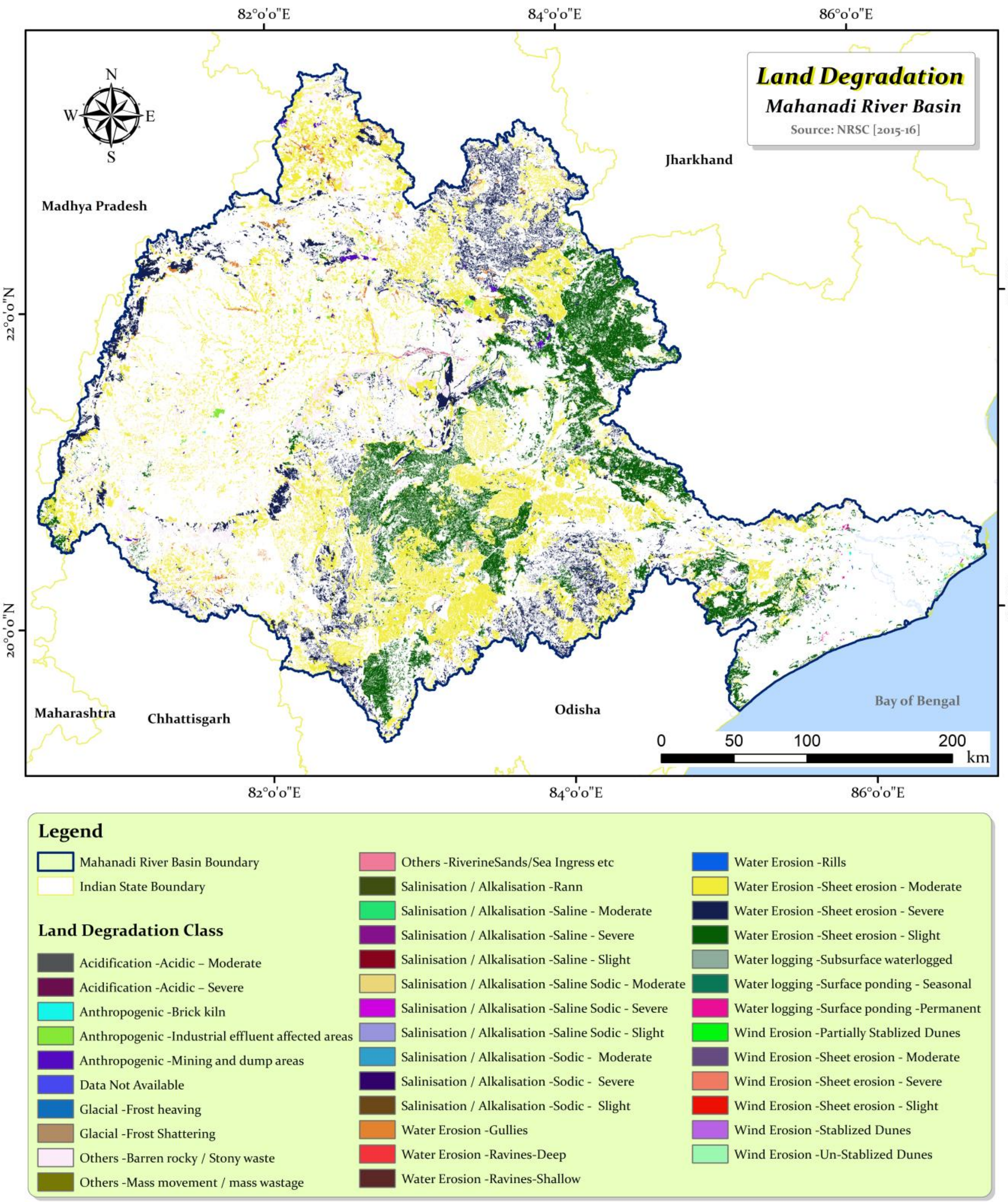


Figure 26: Various Land Degradation class under the Mahanadi River Basin

[Source: NRSC (2015-16)]

Table 18: Key land degradation indicators, Mahanadi River Basin (2015–16)

Basin Area	141,589 km² (14,158,900 ha)
Total Degraded Area	41,512.2 km² (4,151,221.5 ha)
Degradation Intensity	29.32% of basin area
Active Degradation Classes	16

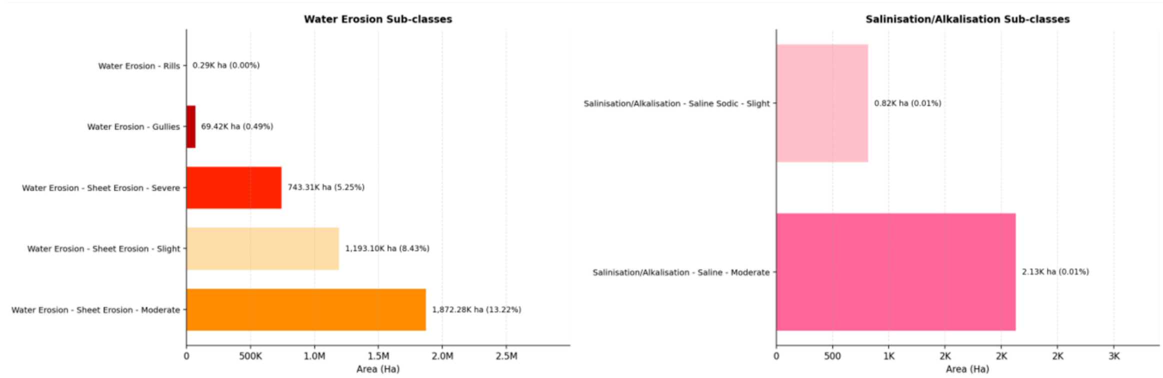
Dominant Process	Water Erosion (93.4% of degraded area)

Source: NRSC Land Degradation Dataset 2015–16

As shown in Table 18, approximately 29.3% of the Mahanadi River Basin, nearly 41,512 km² is under active land degradation. This is a substantial proportion, and highlights the severity of environmental stress on the basin's agricultural and ecological resources. Sixteen distinct degradation classes out of 36 overall classes are active within the basin, reflecting the heterogeneous nature of degradation drivers and processes at work.

4.3.1 Degradation by Process

Land degradation in the Mahanadi Basin is overwhelmingly driven by water-mediated processes. Figure 27 presents the breakdown of degraded area by principal process category.



Source: NRSC Land Degradation Dataset 2015–16

Figure 27: Degraded area by process category, Mahanadi River Basin (2015–16)

Water erosion alone accounts for 3,878,410 ha representing 93.4% of all degraded land within the basin. This dominant role of water-driven degradation is consistent with the basin's monsoonal climate, which delivers inte

nse seasonal rainfall across often unprotected agricultural and wasteland surfaces. The remaining degradation is attributable to a mix of 'other' land types (barren rocky/stony waste, riverine sands), anthropogenic activities, waterlogging, acidification, and salinisation/alkalisation.

4.3.2 Class-wise Degradation Distribution

A more granular view of degradation is provided in Table 19, which disaggregates degraded area into individual NRSC classification categories. This reveals important distinctions in the severity and spatial extent of different degradation sub-types.

Table 19: Class-wise degraded area, Mahanadi River Basin (2015–16)

Degradation Class	Process	Area (Ha)	% Basin
Sheet Erosion – Moderate	Water Erosion	1,872,283.8	13.22%
Sheet Erosion – Slight	Water Erosion	1,193,097.9	8.43%
Sheet Erosion – Severe	Water Erosion	743,313.9	5.25%
Barren Rocky / Stony Waste	Others	198,500.8	1.40%
Gullies	Water Erosion	69,421.6	0.49%
Mining and Dump Areas	Anthropogenic	22,603.8	0.16%
Industrial Effluent Affected	Anthropogenic	17,061.2	0.12%
Riverine Sands / Sea Ingress	Others	14,294.3	0.10%
Acidic – Moderate	Acidification	6,338.3	0.04%
Surface Ponding – Seasonal	Water Logging	6,047.0	0.04%
Surface Ponding – Permanent	Water Logging	2,316.0	0.02%
Saline – Moderate	Salinisation / Alkalisation	2,128.5	0.02%
Subsurface Waterlogged	Water Logging	2,007.5	0.01%
Saline Sodic – Slight	Salinisation / Alkalisation	817.7	0.01%
Brick Kiln	Anthropogenic	696.7	0.005%
Rills	Water Erosion	292.5	0.002%

Source: NRSC Land Degradation Dataset 2015–16

4.3.3 Dominant Degradation Classes

The three most extensive degradation classes are all forms of sheet erosion the gradual removal of the uppermost, nutrient-rich soil layer by surface runoff and together they account for over 3.8 million ha, or approximately 26.8% of the total basin area:

- Sheet Erosion - Moderate (1,872,284 ha; 13.2% of basin): The single largest degradation class. Moderate sheet erosion is widespread across agricultural and degraded land surfaces, progressively stripping the topsoil layer and reducing the soil's capacity to retain nutrients and moisture.
- Sheet Erosion - Slight (1,193,098 ha; 8.4% of basin): Represents areas in early-to-moderate stages of water-driven topsoil loss. While individually less severe, the sheer extent of this class constitutes a major cumulative threat to soil health.
- Sheet Erosion - Severe (743,314 ha; 5.2% of basin): Areas experiencing significant topsoil removal, often rendering land marginally productive or entirely unsuitable for cultivation without major reclamation intervention.

Beyond sheet erosion, gully erosion affects a further 69,422 ha, while barren rocky and stony wastelands largely unproductive surfaces account for 198,501 ha. Anthropogenic degradation from mining and dump areas (22,604 ha) and industrial effluent-affected zones (17,061 ha) presents localised but acute constraints on land quality in affected areas.

4.3.4 Implications for Nutrient Stress and Agricultural Productivity

Land degradation particularly water erosion in its various forms has direct and severe consequences for soil nutrient status, and by extension, for gross agricultural productivity within the basin.

Sheet erosion, which constitutes the overwhelming majority of degradation, selectively removes the fine-textured, organic matter-rich surface horizon of soils. This horizon is precisely where concentrations of essential plant nutrients nitrogen (N), phosphorus (P), potassium (K), as well as secondary nutrients and micro nutrients are highest. Repeated loss of this layer over seasons and years leads to:

- Progressive depletion of soil organic carbon (SOC), which is the primary source of plant-available nitrogen and the foundation of soil biological activity.
- Reduced phosphorus availability, as phosphorus is tightly bound to soil particles and is transported off-site along with eroded sediment.
- Declining cation exchange capacity (CEC), limiting the soil's ability to retain and supply potassium, calcium, magnesium, and other cations to crops.
- Increased soil compaction and reduced water-holding capacity on eroded surfaces, further limiting nutrient uptake by crop roots.
- Greater fertiliser requirements to compensate for nutrient losses, raising input costs for farmers and increasing the risk of nutrient runoff and water quality degradation.

In the context of the Mahanadi Basin, where a large proportion of agricultural land overlaps with moderate to severe erosion zones, these nutrient stress dynamics translate into structurally suppressed crop yields, increased yield variability, and rising dependency on inorganic fertiliser inputs. Gully erosion, though less extensive in area, creates irreversible topographic damage that permanently removes productive agricultural land from use.

Acidification-affected soils (6,338 ha), while limited in extent, represent another nutrient stress pathway, as acidic conditions immobilise key nutrients particularly phosphorus and can elevate concentrations of phytotoxic aluminium and manganese to levels harmful to crops.

Similarly, saline and saline-sodic soils (2,946 ha) create osmotic stress and ion toxicity that impair nutrient uptake even when soil nutrient levels are nominally adequate.

Anthropogenic degradation from mining, industrial effluent zones, and brick kilns, while numerically modest in area, can cause severe and persistent contamination of soils and groundwater in localised areas, with long-term consequences for nutrient cycling and land productivity.

Key Observations and Conclusions

- Nearly 30% of the Mahanadi River Basin is under active land degradation, representing a critical structural constraint on the gross agricultural potential of the basin.
- Water erosion predominantly in the form of sheet erosion is the dominant degradation process, covering 93.4% of all degraded area and driving widespread nutrient depletion across agricultural landscapes.
- The prevalence of moderate and severe sheet erosion indicates that nutrient stress is not a localised or marginal issue, but a basin-wide challenge affecting a significant share of cultivated and cultivable land.
- Degraded lands represent priority areas for reclamation, requiring integrated soil and water conservation measures including contour bunding, check dams, vegetative cover management, and targeted organic matter restoration to arrest further nutrient loss and restore productive capacity.
- The co-occurrence of multiple degradation processes (erosion, waterlogging, acidification, salinity) in different parts of the basin calls for spatially targeted, process-specific interventions rather than blanket approaches.

4.3.5 Land Degradation – Sub-Basin Level Analysis

4.3.5.1 Sub-Basin Degradation

The analysis covers all eleven delineated sub-basins, spanning a total official area of 13,714,071 ha. This spatially disaggregated perspective reveals significant variation in both the intensity and character of degradation across the basin, enabling prioritised targeting of conservation and reclamation interventions.

Table 20 presents the total degraded area and degradation intensity for each sub-basin, ranked by percentage degraded. Colour coding in the final column provides a visual reference to degradation severity: red (>40%), amber (30–40%), blue (20–30%), and green (<20%).

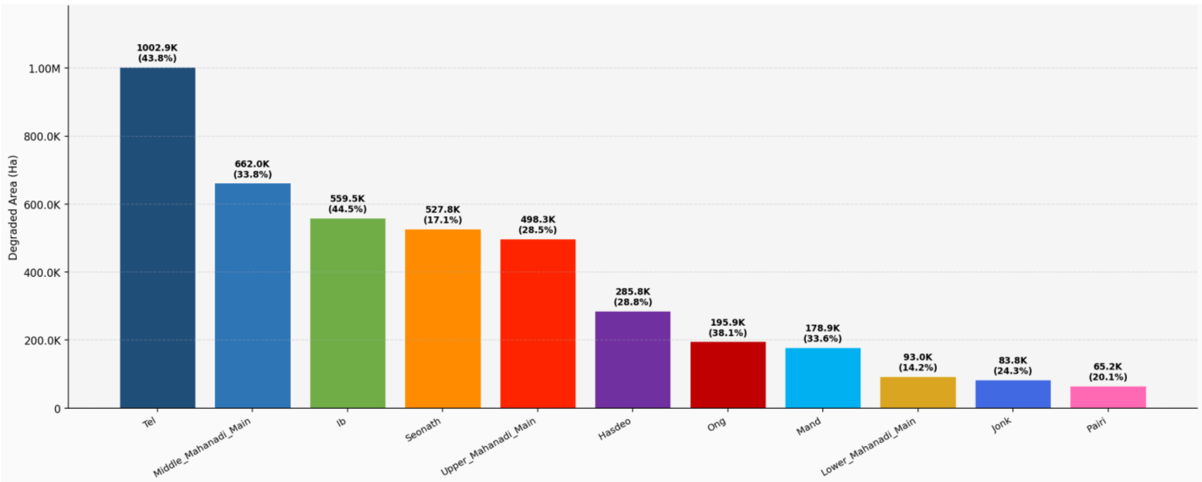
Table 20: Sub-basin degraded area and intensity, Mahanadi River Basin (2015–16) (Sorted by % degraded)

Sub-Basin	Area (Ha)	Degraded Area (Ha)	Degraded (km²)	% Degraded
Tel	22,89,020	10,02,906.60	10,029.10	43.81%
Ib	12,57,500	5,59,458.30	5,594.60	44.49%
Ong	5,14,560	1,95,934.50	1,959.30	38.08%

Middle Mahanadi Main	19,59,660	6,62,044.70	6,620.40	33.78%
Mand	5,32,912	1,78,944.20	1,789.40	33.58%
Upper Mahanadi Main	17,50,020	4,98,339.90	4,983.40	28.48%
Hasdeo	9,91,809	2,85,807.80	2,858.10	28.82%
Jonk	3,45,547	83,826.20	838.3	24.26%
Pairi	3,24,260	65,231.60	652.3	20.12%
Seonath	30,95,000	5,27,805.40	5,278.10	17.05%
Lower Mahanadi Main	6,53,783	93,046.40	930.5	14.23%

Source: NRSC Land Degradation Dataset 2015–16

The data reveal a wide range of degradation intensities, from 14.23% in the Lower Mahanadi Main to 44.49% in the Ib sub-basin. The basin average of 29.32% masks this heterogeneity: five sub-basins exceed the basin-average degradation percentage, with three (Ib, Tel, and Ong) showing degradation rates above 38%. In terms of absolute area, the Middle Mahanadi Main, Tel, and Seonath sub-basins contribute the largest quantities of degraded land, together accounting for over 2.19 million ha more than half of total basin-wide degradation.



Source: NRSC Land Degradation Dataset 2015–16

Figure 28: Degraded Area by Sub-Basin under MRB

4.3.5.2 Degradation by Process – Cross-Sub-Basin Comparison

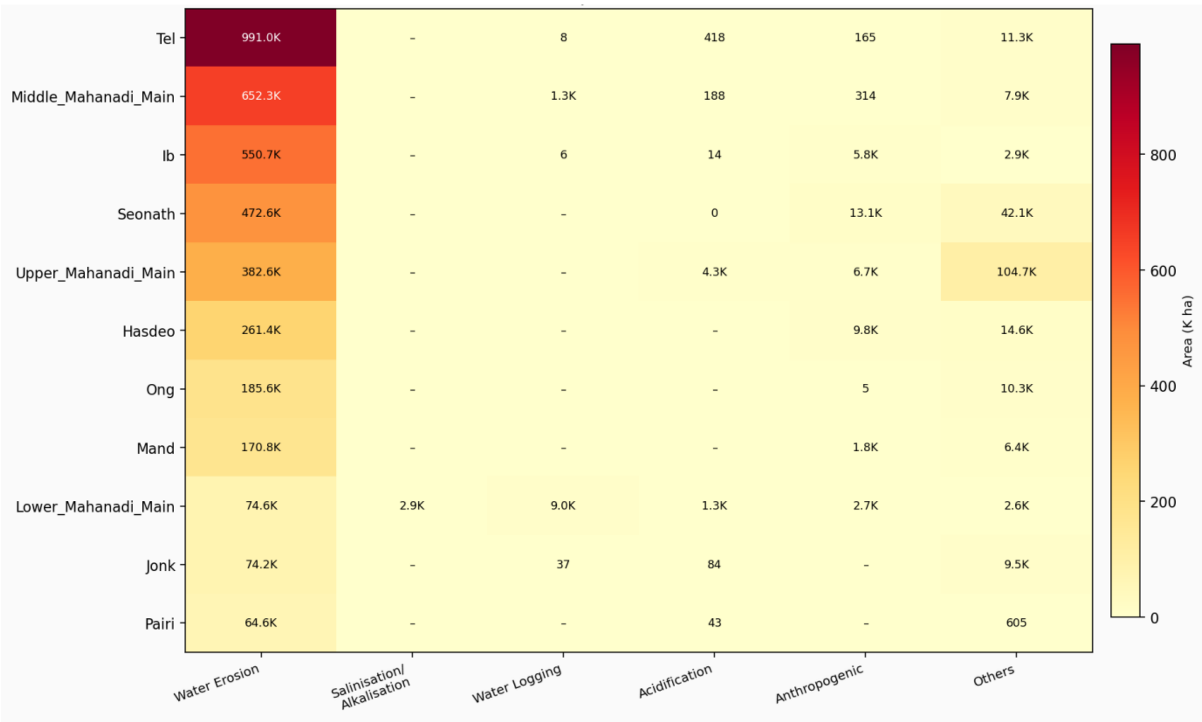
Table 21 & Figure 29 disaggregates degraded area by the principal process operating within each sub-basin. This reveals not only the near-universal dominance of water erosion but also the sub-basins where secondary processes anthropogenic activity, waterlogging, acidification, and salinisation play meaningful roles. Cells with a water erosion share below 85% are highlighted in amber to flag process diversity.

Table 21: Degradation by process per sub-basin (Ha). Amber highlight: Water Erosion share <85% of sub-basin total.

Sub-Basin	Water Erosion (Ha)	% WE	Anthropogenic (Ha)	Water Logging (Ha)	Acidification (Ha)	Others (Ha)
Tel	991,029.6	**98.8%**	164.6	7.8	417.7	11,286.8
Ib	550,716.1	**98.4%**	5,786.9	5.6	14.4	2,935.3
Ong	185,623.0	**94.7%**	5.3	–	–	10,306.2
Middle Mahanadi Main	652,279.8	**98.5%**	313.6	1,337.8	187.5	7,925.9
Mand	170,768.0	**95.4%**	1,814.8	–	–	6,361.4
Upper Mahanadi Main	382,614.6	**76.8%**	6,669.6	–	4,332.7	104,723.0
Hasdeo	261,416.6	**91.5%**	9,756.4	–	–	14,634.8
Jonk	74,249.8	**88.6%**	–	37.0	84.4	9,455.0
Pairi	64,583.4	**99.0%**	–	–	43.0	605.2
Seonath	472,607.7	**89.5%**	13,123.5	–	0.3	42,073.8
Lower Mahanadi Main	74,556.2	**80.1%**	2,741.8	8,984.6	1,260.7	2,556.2

Source: NRSC Land Degradation Dataset 2015–16

Water erosion is the dominant process in every sub-basin without exception. However, its relative share varies from a near-total 99.0% in Pairi to 76.8% in the Upper Mahanadi Main, a sub-basin where a substantial area of barren rocky and stony wasteland ('Others' category: 104,723 ha) contributes 21% of all degradation. Anthropogenic degradation is most concentrated in Seonath, Hasdeo, and Ib, corresponding to coal mining and industrial zones in these sub-basins. The Lower Mahanadi Main stands out as uniquely process-diverse, with significant waterlogging (8,985 ha) and salinisation/alkalisation (2,947 ha) alongside water erosion.



Source: NRSC Land Degradation Dataset 2015–16

Figure 29: Degradation Process Intensity Matrix per sub-basin (Thousand Ha or K Ha)

4.3.5.3 Sub-Basin Profile

The following profiles provide a detailed breakdown for each sub-basin, including the dominant degradation processes, total degraded extent, and key observations on factors driving land quality loss and nutrient stress.

Tel | 43.81% degraded (1,002,906.6 ha)		
Water Erosion	991,029.6 ha	**98.8%**
Others (Barren Rocky / Riverine Sands)	11,286.8 ha	**1.1%**
Acidification	417.7 ha	**0.0%**
Anthropogenic	164.6 ha	**0.0%**
Water Logging	7.8 ha	**0.0%**

The highest-degraded sub-basin by percentage extent after Ib. Nearly all degradation is driven by water erosion (98.8%), with minimal contributions from other processes.

Ib | 44.49% degraded (559,458.3 ha)		
Water Erosion	550,716.1 ha	**98.4%**
Others	2,935.3 ha	**0.5%**
Anthropogenic (Mining / Industrial)	5,786.9 ha	**1.0%**
Acidification	14.4 ha	**0.0026%**
Water Logging	5.6 ha	**0.001%**

The most severely degraded sub-basin at 44.49%. Notable for the highest relative anthropogenic degradation share among smaller sub-basins, reflecting coal mining activity in the Ib valley.

Middle Mahanadi Main | 33.78% degraded (662,044.7 ha)		
Water Erosion	652,279.8 ha	**98.5%**
Others	7,925.9 ha	**1.2%**
Water Logging	1,337.8 ha	**0.2%**
Anthropogenic	313.6 ha	**0.047%**
Acidification	187.5 ha	**0.028%**

The largest contributor of degraded area in absolute terms (662,045 ha). Water erosion is near-total at 98.5%. Some waterlogging presence along the river corridor.

Seonath | 17.05% degraded (527,805.4 ha)		
Water Erosion	472,607.7 ha	**89.5%**
Others (Barren Rocky / Wasteland)	42,073.8 ha	**8.0%**
Anthropogenic	13,123.5 ha	**2.5%**
Acidification	0.3 ha	**0.0001%**

Despite being the basin's largest sub-basin by official area, Seonath has a relatively lower degradation percentage (17.05%). It has one of the higher shares of 'Others' degradation and elevated anthropogenic activity.

Upper Mahanadi Main | 28.48% degraded (498,339.9 ha)		
Water Erosion	382,614.6 ha	**76.8%**

Others (Barren Rocky / Wasteland)	104,723.0 ha	**21.0%**
Anthropogenic	6,669.6 ha	**1.3%**
Acidification	4,332.7 ha	**0.9%**

The most distinctive sub-basin in terms of process mix: only 76.8% of degradation is from water erosion substantially below the basin average. 'Others' (barren rocky/stony waste) accounts for 21% and acidification is the highest absolute figure (4,333 ha) in the basin.

Hasdeo | 28.82% degraded (285,807.8 ha)		
Water Erosion	261,416.6 ha	**91.5%**
Others	14,634.8 ha	**5.1%**
Anthropogenic (Mining / Industrial)	9,756.4 ha	**3.4%**

Significant anthropogenic degradation (3.4%), second only to Seonath in absolute terms, linked to mining activity in the Hasdeo-Arand coalfields. Water erosion remains dominant at 91.5%. More recent data would show higher degaradation oamog other subbasins as the increased mining area

Ong | 38.08% degraded (195,934.5 ha)		
Water Erosion	185,623.0 ha	**94.7%**
Others	10,306.2 ha	**5.3%**
Anthropogenic	5.3 ha	**0.003%**

High degradation intensity (38.08%), among the top three sub-basins. Almost entirely driven by water erosion with negligible anthropogenic presence.

Mand | 33.58% degraded (178,944.2 ha)		
Water Erosion	170,768.0 ha	**95.4%**
Others	6,361.4 ha	**3.6%**
Anthropogenic	1,814.8 ha	**1.0%**

Water erosion dominant at 95.4%. Degradation intensity of 33.58% is above the basin average, reflecting vulnerable upland terrain.

Lower Mahanadi Main | 14.23% degraded (93,046.4 ha)		
Water Erosion	74,556.2 ha	**80.1%**

Water Logging	8,984.6 ha	**9.7%**
Salinisation / Alkalisation	2,946.9 ha	**3.2%**
Anthropogenic	2,741.8 ha	**2.9%**
Acidification	1,260.7 ha	**1.4%**
Others	2,556.2 ha	**2.7%**

The most process-diverse sub-basin. Lowest degradation percentage (14.23%) but unique in showing significant waterlogging (9.7%) and the only sub-basin with notable salinisation/alkalisation (3.2%), reflecting coastal / deltaic influence near the Bay of Bengal outfall.

Jonk | 24.26% degraded (83,826.2 ha)		
Water Erosion	74,249.8 ha	**88.6%**
Others	9,455.0 ha	**11.3%**
Water Logging	37.0 ha	**0.04%**
Acidification	84.4 ha	**0.1%**

Moderate degradation at 24.26%. The 'Others' category (barren rocky/stony waste) is proportionally higher than most sub-basins at 11.3%.

Pairi | 20.12% degraded (65,231.6 ha)		
Water Erosion	64,583.4 ha	**99.0%**
Others	605.2 ha	**0.9%**
Acidification	43.0 ha	**0.1%**

The smallest degraded area in absolute terms. Water erosion is virtually the sole degradation agent at 99.0%, with negligible other process contributions.

4.3.5.4 Key Observations and Policy Implications

❖ **High-Priority Sub-Basins for Reclamation**

Ib (44.49%) and Tel (43.81%) exhibit the highest degradation intensities and must be treated as critical priority zones for soil and water conservation. Both are dominated by severe water erosion.

Ong (38.08%) and Middle Mahanadi Main (33.78%) also exceed the basin average significantly, warranting immediate attention given their high absolute degraded areas.

- **Water Erosion as the Universal Driver**

Water erosion accounts for over 90% of degradation in eight of eleven sub-basins, confirming it as the primary threat to soil health and agricultural productivity across the entire basin.

Sub-basins with large areas of moderate-to-severe sheet erosion (Tel, Middle Mahanadi Main, Seonath) face chronic nutrient depletion, reduced soil organic carbon, and increasing dependency on fertiliser inputs.

- **Anthropogenic Hotspots**

Hasdeo and Ib show the highest anthropogenic degradation loads, driven by coal mining activity in the Hasdeo-Arand and Ib valley coalfields. These require specialised post-mining land restoration and effluent management interventions.

Seonath carries the highest absolute anthropogenic degradation area (13,124 ha), associated with industrial and mining zones in the upper basin.

- **Coastal Influence on the Lower Basin**

The Lower Mahanadi Main is unique in exhibiting significant waterlogging (9.7%) and salinisation/alkalisation (3.2%), processes absent or negligible elsewhere. These are associated with tidal backwater influence and coastal soil dynamics near the Bay of Bengal.

Reclamation strategies for this sub-basin must address multi-process degradation conventional erosion-control measures alone are insufficient.

- **Upper Mahanadi Main – Structural Barrenness**

The Upper Mahanadi Main's high 'Others' share (21%) reflects substantial areas of inherently unproductive barren rocky and stony wasteland, which may require a different management paradigm (e.g., agroforestry, silvo-pastoral systems) rather than conventional crop-based reclamation.

Acidification in this sub-basin (4,333 ha) is the highest in the basin and may be linked to weathering of acidic geological formations in the upland areas.

5. Agriculture–River System Interactions

5.1 Agricultural Water Demand and River Flows

Agriculture sector is the dominant consumptive water user across the MRB. The basin's monsoonal precipitation pattern, with approximately 85.7% of annual rainfall concentrated between June and September, means that natural river flows and Kharif crop water demand largely coincide. This alignment enables run-of-river diversions and tank-based storage systems to support the dominant paddy cultivation during the growing season. In contrast, the Rabi season depends almost entirely on stored water reservoir releases, tanks, and groundwater as post-monsoon river flows decline sharply.

The irrigation intensity analysis in Section 3 reveals a critical inefficiency in the use of stored water. Several of the basin's most heavily irrigated districts viz Janjgir–Champa, Bargarh, Baloda Bazar, and Sambalpur maintain cropping intensities only marginally above the basin median, despite irrigation coverage ranging from 69% to nearly 90%. This pattern suggests that Rabi canal water is either not reaching farmers reliably, is not being fully demanded due to crop system inertia, or is being diverted to competing uses, including urban and industrial withdrawals in rapidly growing districts. The result is a de facto under utilisation of the basin's stored water resources for agriculture during the season when it is most critical for intensification.

Conversely, districts such as Boudh, Nayagarh, Rajnandgaon, and Surguja achieve relatively high cropping intensity despite limited formal irrigation. This indicates that effective rainfall utilisation, shorter-duration crop varieties, and groundwater access can partially compensate for limited canal infrastructure. However, as the LSWI and CWSI data in Section 4.2 indicate, basin-wide moisture deficits outside the monsoon period impose a clear limit on rainfed intensification, making supplemental water storage a structural necessity rather than an optional enhancement.

The implication for river basin management is clear that the agricultural water demand in the MRB is shaped less by absolute water scarcity and more by allocation, scheduling, and crop system dynamics. Bridging the gap between irrigation availability and actual utilisation without increasing total water withdrawals represents the most effective opportunity for improving water management in the basin.

5.2 Floodplain Agriculture and Seasonal Inundation

Across the lower Mahanadi delta, communities have historically practised flood-recession cultivation, planting short-duration crops on alluvial enriched soils after the monsoon recedes. This system transforms seasonal inundation from a pure hazard into a productive input, utilising the same hydrological connectivity that also generates flood risk. The tension between these two dimensions flooding as a resource and flooding as a threat defines the core management challenge of the lower basin's agricultural system.

The SAR-based flood assessment in Section 4.1 shows that this tension is quantitatively significant. In the Lower Mahanadi Main sub-basin, as 808.69 km² of agricultural land (9.42% of its total agricultural area) is exposed to recurrent flooding, with peak inundation occurring in August and September, coinciding with the critical reproductive stages of Kharif paddy. Notably, the same districts Cuttack, Puri, Kendrapara, and Jagatsinghpurthat experience the highest flood exposure also record some of the basin's highest cropping intensities and consistently fall within the High Irrigation–High Cropping Intensity typology. Fertile alluvial soils, post-flood moisture retention, and well-developed canal networks together sustain high agricultural productivity in these deltaic regions despite their climatic vulnerability.

The management implication is clear: interventions in these districts should not aim to eliminate flooding which would require hydrological engineering far beyond current capacity and would undermine the ecological and soil fertility benefits of inundation but rather to modify the timing and intensity of flood exposure. Specifically, reducing the frequency of destructive early-season floods (June–July), which damage standing crops, while retaining moderate late-season inundation that enhances soil fertility for the next cycle, is key. Achieving this balance requires coordinated reservoir operation protocols particularly for Hirakud along with improved embankment management and adaptive crop planning.

5.3 Impact of Agricultural Practices on River Health

The land degradation data presented in Section 4.3 establishes the most significant quantitative link between agricultural practices and river health in the MRB. Water erosion, acting on 3.87 million hectares of agricultural and degraded land, delivers substantial sediment loads into the Mahanadi system during the monsoon. This contributes to channel bed aggradation, reduced reservoir storage capacity, a direct constraint on irrigation availability discussed in Section 3 and increased turbidity, with associated impacts on aquatic ecosystems.

The sub-basin erosion analysis identifies the major sediment source zones: Ib (44.49% degraded), Tel (43.81%), Ong (38.08%), and Middle Mahanadi Main (33.78%). These are primarily upland and plateau sub-basins, where intense monsoon rainfall coincides with poorly vegetated agricultural land. The lack of adequate soil conservation infrastructure allows topsoil loss to proceed largely unchecked. The cumulative effects, progressive decline in soil organic carbon, reduced water retention capacity, and increasing fertiliser dependency, as described in Section 4.3.4 represent a slow-onset agricultural productivity crisis that also manifests in the river system through rising sediment loads.

Beyond erosion, agricultural chemical inputs interact with the river system through nutrient runoff. As documented in Section 4.3.4, soil nutrient depletion caused by erosion drives increased use of inorganic fertilisers, particularly nitrogen. During intense early monsoon events, these nutrients are transported into drainage channels and tributary streams, contributing to downstream nutrient enrichment. This process is most pronounced in the densely cultivated and intensively fertilised districts of the delta and canal command areas.

The Lower Mahanadi Main is the only sub-basin exhibiting significant salinisation and waterlogging alongside erosion is closely linked with tidal dynamics. Poor drainage leads to waterlogging, while saltwater intrusion reduces soil productivity and alters nutrient cycling, with cascading effects on the estuarine system.

5.4 Implications for Basin Management

Three structurally important implications emerge from the agriculture–river interaction analysis, each bridging the gap between water management and agricultural development.

- First, irrigation allocation reform and agricultural productivity improvement are essentially the same intervention, expressed in different institutional terms. Unused Rabi canal capacity in high-irrigation, low-intensity districts reflects both a water management failure and an agricultural income gap. Crop system diversification and irrigation scheduling reforms must therefore be planned and implemented jointly by water resource and agriculture departments, rather than in isolation, with active support from skilled manpower, particularly agricultural engineers, to ensure effective design, coordination, and on-ground execution.

- Second, sediment management in the basin cannot be addressed through reservoir operations alone. The problem originates in the degraded upland agricultural landscapes identified in Section 4.3, and its solution lies upstream, in watershed treatment, soil conservation, and land use change in the Ib, Tel, Ong, and Middle Mahanadi catchments. Reservoir de silting and structural flood management in the lower basin address the symptoms and watershed rehabilitation addresses the source.
- Third, the Lower Mahanadi delta requires a multi-hazard management framework that simultaneously addresses flood risk, salinity intrusion, waterlogging, and soil degradation. These processes, individually discussed in Sections 4.1 and 4.3, interact in ways that make single-hazard interventions insufficient. Integrated delta management planning incorporating coastal ecosystem health alongside agricultural risk reduction is therefore the most appropriate institutional response.

6. Strategic Interventions for Agricultural Development

The structural analysis in Sections 2 through 5 points toward intervention priorities that are spatially differentiated, institutionally integrative, and calibrated to the basin's dominant constraints fragmented landholdings, monsoon dependence, irrigation under utilisation, land degradation, and concentrated flood risk. The following sections translate these analytical findings into actionable strategies, organised by thematic cluster and cross-referenced to the typological frameworks developed earlier in the report.

6.1 Climate-Resilient and Sustainable Agriculture Pathways

I. Climate-Smart Agricultural Practices

The basin's climate risk profile flood concentration in the Lower Mahanadi delta (Section 4.1) and moisture deficit across 96.3% of the basin outside the monsoon (Section 4.2) defines two geographically distinct but institutionally linked priorities for climate-smart agriculture.

In flood-exposed agricultural zones, the immediate priority is varietal and agronomic adaptation. Deployment of submergence-tolerant rice varieties in the 1,331.95 km² of SAR-identified high-risk agricultural land addresses the most direct productivity threat. This does not require new infrastructure it requires seed system reform: accelerating multiplication and distribution of adapted varieties through existing input delivery channels, establishing community seed banks that can enable rapid replanting following flood recession, and aligning crop insurance trigger mechanisms with SAR-derived inundation data rather than conventional yield loss assessment, which is slow, costly, and often inequitable for marginal farmers.

In moisture-stressed zones the Mild to Moderate Drought classification covering nearly the entire upper basin the priority is extending the productive agricultural season into the Rabi window through supplemental irrigation and short-duration varieties. The CWSI analysis identifies the Seonath sub-basin as the most moisture-constrained tributary, and the Hasdeo sub-basin as a secondary priority. Agro-meteorological advisories calibrated to sub-basin CWSI trends disseminated before each Kharif sowing season can meaningfully improve farmer decision-making on sowing dates, crop selection, and input application, reducing yield variance without requiring infrastructure investment.

Across both zones, crop diversification away from long-duration kharif paddy monoculture represents the most fundamental climate resilience measure available. Single-crop paddy systems concentrate all income risk into a single climatic window and foreclose the productivity gains that the irrigation–intensity analysis (Section 3) identifies as the basin's largest unrealised agricultural potential.

II. Water-Efficient and Low-Impact Farming

The Low Moisture classification recorded across all eleven sub-basins outside the monsoon season (Section 4.2) makes water use efficiency the central agronomic priority for Rabi intensification. Two complementary approaches are most relevant to the MRB's farming structure.

For paddy cultivation which will remain dominant in the Kharif season across the basin's irrigated belts System of Rice Intensification practices can reduce applied water by 25-50% while maintaining or improving yields, without requiring farmers to abandon paddy as a crop. This is particularly important in districts where paddy is a cultural staple and market preference as well as a subsistence crop.

For Rabi diversification into pulses, oilseeds, and horticulture the productivity pathway most directly supported by the irrigation–intensity analysis micro-irrigation expansion is the enabling infrastructure. Drip and sprinkler systems applied to smaller areas of diversified crops can generate higher water productivity per unit than flood-irrigated paddy, while reducing the pressure on canal water allocations that are currently limiting Rabi utilisation in High GIA–Low Intensity districts.

Conservation agriculture practices minimum tillage, permanent soil cover, and crop rotation reduce surface runoff velocity during the monsoon, directly mitigating the sheet erosion that drives the land degradation documented in Section 4.3. These practices serve dual functions: improving in-season water infiltration and retention while reducing the sediment delivery to river systems identified in Section 5 as a basin-level ecological and reservoir management concern.

III. Soil and Ecosystem Conservation Measures

The land degradation analysis in Section 4.3 establishes that water erosion operating across 3.87 million hectares is the dominant structural threat to soil fertility and long-term agricultural productivity in the MRB. Addressing it requires integrated watershed management at scale, not incremental farm-level soil conservation alone.

At the sub-basin level, priority investment zones are clearly identified: Ib, Tel, Ong, and Middle Mahanadi Main together account for the majority of degraded area and the highest degradation intensities (33–44%). Integrated watershed programmes in these sub-basins combining contour bunding, vegetative barriers, gully stabilisation, and check dam construction would simultaneously reduce on-farm erosion, improve groundwater recharge, and reduce the sediment load entering the Mahanadi mainstream. These are co-benefit investments: the agricultural productivity gains from soil conservation (improved water retention, reduced fertiliser dependency, higher yields on treated land) and the hydrological gains (reduced reservoir sedimentation, lower flood peaks, improved dry-season baseflows) accrue to different stakeholder groups but arise from the same physical intervention.

In the Upper Mahanadi Main, where 21% of degraded area consists of inherently unproductive barren rocky and stony wasteland rather than eroded agricultural land, the appropriate reclamation pathway is agroforestry and silvopastoral systems rather than crop-based intensification. These systems build soil organic matter progressively, provide ground cover to arrest further erosion, and generate supplementary income from tree products without placing unrealistic demands on structurally constrained soils.

For the Lower Mahanadi Main which uniquely exhibits waterlogging (9.7%), salinisation (3.2%), and coastal erosion alongside water erosion restoration of estuarine buffers and mangrove systems provides both ecological and agricultural risk management functions. Coastal vegetation attenuates tidal flooding, reduces salinity intrusion into agricultural land, and supports the fisheries economy on which many delta households partly depend.

6.2 Irrigation and Water Management Strategies

The irrigation–intensity typology in Section 3 provides the spatial targeting logic for irrigation investment across the basin. Each typology class requires a categorically different response.

High GIA–High Intensity districts (Cuttack, Ganjam, Puri, Kendrapara, Jajpur, Sonepur, Dhenkanal in Odisha; Bemetara, Mungeli, Kabirdham, Dhamtari, Durg in Chhattisgarh) have effectively converted irrigation into multi-season cropping and are approaching intensification ceilings. Here, the priority is not further irrigation expansion but productivity enhancement per unit of water precision irrigation scheduling, water-saving rice varieties, and Rabi crop mix optimisation to reduce consumptive demand while sustaining or improving output value.

High GIA–Low Intensity districts (Bargarh, Sambalpur, Sundargarh, Kalahandi in Odisha; Janjgir–Champa, Baloda Bazar, Mahasamund, Bilaspur in Chhattisgarh) represent the basin's largest unrealised intensification potential. These districts have irrigation infrastructure but are locked into kharif-dominant paddy systems. Canal rehabilitation addressing conveyance losses and improving tail-end water delivery is the necessary precondition, but alone insufficient. It must be paired with water user association strengthening for operational governance, flexible Rabi water allocation protocols, and crop diversification support targeted specifically at short-duration Rabi crops that can be grown within existing canal command footprints.

Low GIA–High Intensity districts (Boudh, Nayagarh, Kandhamal, Khordha in Odisha; Rajnandgaon, Surguja, Surajpur in Chhattisgarh) sustain relatively high cropping intensity through rainfall utilisation and groundwater. Supplemental irrigation farm ponds, check dams, and minor tanks is the appropriate infrastructure investment here, buffering against intra-seasonal dry spells without replicating the large canal systems inappropriate for these physiographic settings. These districts' demonstrated adaptive capacity in crop planning suggests that agronomic support, rather than large-scale infrastructure, is the binding constraint.

Low GIA–Low Intensity districts (Bolangir, Deogarh, Nuapada, Rayagada in Odisha; Jashpur, Kondagaon, Korea, Kanker in Chhattisgarh) face terrain, soil, and ecological constraints that make conventional paddy-centric irrigation expansion neither cost-effective nor appropriate. Investment should shift toward water harvesting for household and livestock use, drip irrigation for high-value horticulture on small plots, and livelihood diversification support that reduces agricultural income dependency rather than attempting to intensify a structurally constrained production system.

6.3 Crop Planning and Diversification Strategies

The income analysis in Section 2.3.4 reveals that agricultural household incomes are structurally low across much of the basin averaging ₹2,343–₹3,720 per month in several Chhattisgarh districts and that wage labour and non-farm income are increasingly compensating for insufficient farm returns. Crop diversification is the primary pathway to improving the agricultural income component of household livelihoods while simultaneously reducing climatic vulnerability.

Rabi pulse and oilseed promotion is the most immediately scalable diversification opportunity in High GIA–Low Intensity districts. These crops require 70–80% less water than transplanted paddy, improve soil nitrogen status, and benefit from existing MSP procurement support. The cropping intensity data show that Rabi utilisation in these districts is minimal despite available irrigation meaning diversification here does not compete with existing food production but fills an empty agricultural window.

In tribal-dominated and rainfed districts classified as Low GIA–Low Intensity or Low GIA–High Intensity, millets kodo, kutki, ragi, and finger millet represent the most appropriate diversification pathway. These crops are drought-tolerant, nutritionally dense, culturally familiar to tribal communities, and require far less water and inputs than paddy. Promoting them as commercial crops through MSP procurement, value chain development, and linking with tribal FPOs addresses both agricultural income and nutritional security objectives simultaneously.

Horticulture expansion vegetables, fruits, and spices is most viable in districts with micro-irrigation potential, road connectivity, and access to urban or mandim markets. The income data in Section 2.3.4 show that districts with stronger non-farm linkages Raipur, Durg, Khordha, Cuttack already have higher household incomes; horticultural diversification in their peri-urban agricultural belts can further close the agricultural-urban income gap.

Agri-horticulture integration on bunds, field margins, and degraded uplands planting fruit trees and timber species on non-crop land provides supplementary income without displacing food production, contributes to soil conservation (Section 4.3), and is particularly applicable in the Upper Mahanadi Main where large areas of barren wasteland await productive reclamation.

6.4 Mechanization and Input Optimization

The landholding structure documented in Section 2.1 where marginal holdings below 1 ha now constitute 60–74% of all operational holdings across the basin makes individual farm mechanisation economically unviable for most households. Custom Hiring Centres (CHCs) offering power tillers, reapers, transplanters, threshers, and sprayers on rental terms are the institutional mechanism that makes mechanisation accessible to small and marginal farmers without requiring ownership.

Targeting of CHC establishment should prioritise districts where the combination of high female agricultural workforce participation (Section 2.2.2) and labour-intensive Kharif operations transplanting and weeding, which are predominantly women's tasks creates the highest demand for appropriate small-scale mechanisation. Districts including Rajnandgaon, Dhamtari, Ganjam, and Rayagada, where women form a near-equal or majority share of the agricultural workforce, are priority locations for women-operated CHC networks, which simultaneously improve mechanisation access and create off-farm enterprise income for women.

Nutrient management must respond directly to the soil degradation pattern documented in Section 4.3.4: progressive depletion of soil organic carbon, declining phosphorus availability, and reduced cation exchange capacity resulting from widespread sheet erosion. Blanket urea-dominant fertiliser applications the current norm do not address these specific deficiencies and can exacerbate soil acidification over time. Soil health card-based nutrient recommendations, calibrated to district-level degradation intensity, paired with organic matter restoration through compost, green manuring, and crop residue incorporation, are the appropriate response.

Post-harvest infrastructure hermetic storage, primary processing, and cold chain for horticultural produce is a critical efficiency gap in the basin's agricultural system. Post-harvest losses disproportionately affect the income of the small and marginal farmers who form the majority of the basin's agricultural population, and investment in community-level storage and processing infrastructure should accompany crop diversification programmes to ensure that productivity gains translate into household income rather than being absorbed by spoilage and market losses.

6.5 Institutional and Policy Support Measures

The effectiveness of every technical intervention above depends on an institutional environment that can deliver support to the basin's fragmented, diverse, and often marginalised farming population. Several institutional priorities are cross-cutting.

Land fragmentation the structural condition identified in Section 2.1 as the foundation of the basin's agricultural constraints requires institutional responses that improve the productivity of small holdings without mandating consolidation. Cooperative cultivation arrangements, land leasing facilitation, and joint input procurement and marketing through FPOs provide practical pathways for small and marginal farmers to access economies of scale without changes to land ownership.

Gender equity in agricultural institutions must translate from observation into design. The gender analysis in Section 2.2.2 documents substantial female agricultural workforce participation across the basin, yet women remain largely excluded from land titles, formal credit, extension services, and procurement systems. Correcting this requires joint land titling, inclusion of women as primary farmer beneficiaries in input and credit programmes, and women's representation in water user associations and FPO governance.

Agricultural extension systems must be refocused from technology dissemination to adaptive decision support providing farmers with timely, location-specific guidance on crop selection, pest management, and input use based on current agro-meteorological conditions. Integration of the sub-basin CWSI monitoring system (Section 4.2) with district extension advisories, delivered through farmer field schools and mobile platforms, provides the technical basis for this reorientation.

Disaster risk financing must become a permanent institutional feature rather than a post-disaster relief mechanism. Parametric crop insurance products using SAR-derived flood inundation maps (Section 4.1) and CWSI drought indicators (Section 4.2) as objective triggers can compensate farmers quickly following climatic events without the assessment delays and transaction costs of conventional indemnity insurance. This is particularly important for enabling farmer willingness to invest in crop diversification, which requires accepting short-term income uncertainty.

7. Way Forward for Basin-Level Agricultural Planning

The analyses in Sections 2 through 6 collectively point toward a basin agricultural planning agenda that is differentiated by district typology, integrative across sectoral silos, and grounded in spatial monitoring evidence. Two institutional instruments are essential for translating this agenda into practice: an implementation roadmap that sequences interventions realistically, and a monitoring framework that can detect progress, identify emerging failures, and enable course correction.

7.1 Implementation Roadmap

The implementation roadmap is structured around the four irrigation–intensity typology classes established in Section 3 and the two primary climatic risk zones identified in Section 4. This typology-based sequencing ensures that interventions are calibrated to district-specific constraints rather than applied uniformly across the basin's heterogeneous agricultural landscape.

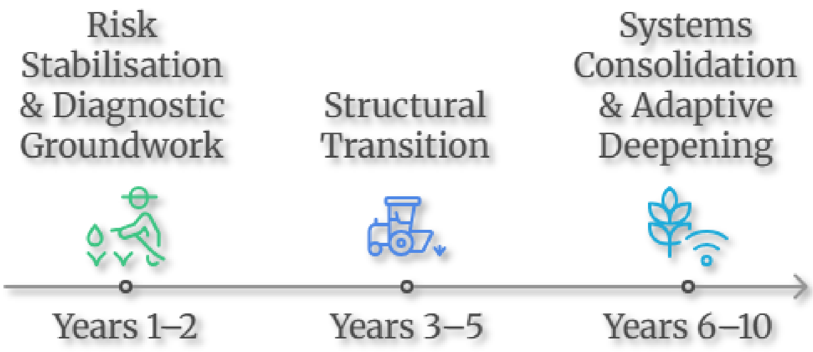


Figure 30: Mahanadi Basin Agricultural Transformation Roadmap (Years 1–10)

Phase 1: Risk Stabilisation and Diagnostic Groundwork (Years 1–2)

The immediate priority is reducing the most acute productivity risks while establishing the diagnostic and institutional foundations for structural transformation.

- In flood-exposed districts of the Lower Mahanadi delta, the priority is seed system reform: accelerating availability of submergence-tolerant paddy varieties, establishing community seed banks in flood-vulnerable blocks, and pilot-testing parametric flood insurance using the SAR-derived risk maps from Section 4.1 as the triggering instrument.
- In High GIA–Low Intensity districts the basin's largest unrealised productivity opportunity the priority is diagnosis before large-scale investment: rapid assessment of canal system condition, tail-end water delivery performance, and Rabi crop demand constraints in pilot districts (Janjgir–Champa and Bargarh, as the most extreme examples

identified in Section 3) to identify the specific bottlenecks preventing intensity improvement.

- In high-degradation sub-basins (Ib, Tel, Ong), initiate soil health card surveys and commission detailed watershed treatment plans, establishing the baseline against which conservation investment outcomes will be measured.

Across all districts, operationalise the sub-basin CWSI monitoring protocol as an early-warning agricultural advisory system, establishing the seasonal bulletin structure before the Kharif 2026 sowing season.

Phase 2: Structural Transition (Years 3–5)

The medium-term phase implements the interventions diagnosed in Phase 1 and initiates the crop system diversification that underpins long-term income and resilience improvement.

- Roll out Rabi diversification programmes supported by improved seed access, assured procurement, and market linkage in High GIA–Low Intensity districts, with district-specific cropping intensity improvement targets. Canal rehabilitation and water user association strengthening are the prerequisite investments.
- Scale watershed treatment across priority sub-basins, targeting a minimum of 3,000–5,000 km² of integrated treatment in Ib, Tel, Ong, and Middle Mahanadi Main, with monitored outcomes on erosion reduction and soil organic carbon restoration.
- Establish Custom Hiring Centre networks in high female workforce participation districts, prioritising women-operated centres with dedicated mechanisation packages suited to transplanting, weeding, and post-harvest operations.
- Expand micro-irrigation coverage for horticultural diversification in Low GIA–High Intensity districts and in peri-urban agricultural belts of major urban centres, supported by credit linkage and market infrastructure.
- Institutionalise parametric crop insurance using both flood (SAR) and drought (CWSI) triggers as a permanent feature of the basin's agricultural risk management architecture.

Phase 3: Systems Consolidation and Adaptive Deepening (Years 6–10)

The long-term phase consolidates structural transitions and embeds adaptive management as the basin's standard agricultural planning mode.

- Achieve measurable reduction in the irrigation utilisation gap across former High GIA–Low Intensity districts, with cropping intensities trending toward 140–150% in districts currently stagnant at 110–115%.
- Complete degraded land reclamation across high-priority sub-basins, with verified soil organic carbon improvements and demonstrated reductions in sediment delivery to the Mahanadi mainstream.
- Develop and operationalise a basin-level agricultural water accounting framework tracking consumptive agricultural demand against sub-basin water balances to enable evidence-based allocation decisions that balance agricultural intensification, environmental flows, and inter-sectoral demand.
- Mainstream gender equity in agricultural institutions: measurable targets for women's land titling, credit access, and FPO membership across the basin.

7.2 Monitoring and Adaptive Management Framework

The spatial and temporal monitoring infrastructure required to track the implementation roadmap above draws directly on the methodological approaches developed in Sections 4.1 and 4.2, extending them from one-time analytical exercises into institutionalised routine monitoring.

Remote Sensing Monitoring

The Google Earth Engine-based analytical platform used for both the SAR flood analysis (Section 4.1) and the CWSI drought assessment (Section 4.2) should be institutionalised as the basin's primary agricultural monitoring infrastructure. Annual updates to three core monitoring products are required:

Sentinel-1 SAR flood mapping during the Kharif monsoon season (June–October), maintaining the 2017–2023 baseline methodology to track changes in flood-prone agricultural area year-on-year particularly in response to embankment maintenance, watershed treatment, and reservoir operation changes.

CWSI sub-basin drought assessment annually, producing pre-Kharif (May) and pre-Rabi (October) seasonal outlooks to guide contingency crop planning and advisory services.

MODIS/Sentinel-2 based cropping intensity monitoring tracking Gross Cropped Area, cropping calendar shifts, and crop type distribution to assess progress against the irrigation–intensity improvement targets in the Phase 2 roadmap.

Biennial land degradation monitoring in priority sub-basins (Ib, Tel, Ong, Middle Mahanadi Main) using optical spectral indices and SAR coherence, measuring change against the NRSC 2015–16 baseline to assess the effectiveness of watershed treatment investments.

Administrative Data Integration

Remote sensing monitoring must be integrated with administrative agricultural data from the Odisha Agricultural Statistics Report and the Directorate of Economics and Statistics, Chhattisgarh to maintain the district-level temporal series that underpin the landholding, workforce, income, and irrigation analyses in Section 2. Agriculture Census cycles (every five years) provide the structural anchors; annual state statistics provide the trend tracking between censuses.

Institutional Review Mechanism

A Basin Agricultural Review Panel comprising state agriculture and water resource departments, the basin authority, agricultural research institutions (ICAR, OUAT, IGKV), and civil society representatives from farming communities should convene annually to review monitoring findings against roadmap targets. The panel's core function is adaptive: when monitoring evidence indicates that interventions are underperforming or that environmental stresses are diverging from projected trajectories, it should have the mandate and technical capacity to recommend course corrections in time to influence subsequent-year planning and budget cycles.

District Agrarian Resilience Scorecards synthesising irrigation utilisation performance, cropping intensity trends, degradation status, and climate risk exposure into a standardised comparative dashboard should be published annually to support public accountability and enable cross-district learning within the basin.

The monitoring framework must treat itself as adaptive: methodological updates at five-year intervals will be necessary to incorporate advances in remote sensing capability, improved agro-climatic models, and refined understanding of the agriculture–river interactions documented in Section 5. The goal is not a fixed monitoring architecture but a learning system capable of improving its own diagnostic precision alongside the agricultural system it tracks.

Acknowledgement

The Centre for Mahanadi River Basin Management and Studies (cMahanadi), NIT Raipur and NIT Rourkela expresses its sincere gratitude to the following agencies and institutions for their invaluable support and contributions in the preparation of the "**Assessment of Gross Agricultural Structure**" report for the Mahanadi Basin.

We extend our thanks to the following agencies for providing data and support in the preparation of the report –

- Population Census 2011, Office of the Registrar General & Census Commissioner, Government of India.
- Agriculture Census (2005–06, 2010–11, 2015–16), Department of Agriculture & Farmers Welfare, Government of India.
- Directorate of Economics & Statistics, Government of Odisha.
- Directorate of Economics & Statistics, Government of Chhattisgarh.
- Odisha Agricultural Statistics Report (1995–96 to 2023–24), Directorate of Agriculture & Food Production, Government of Odisha.
- National Remote Sensing Centre (NRSC), Land Degradation Dataset (2015–16), Indian Space Research Organisation, Government of India.
- National Commission on Population, Ministry of Health & Family Welfare, Government of India.
- Central Water Commission (CWC), Government of India.
- National Disaster Management Authority (NDMA), Government of India.
- Google Earth Engine Platform, Google LLC — for processing of Sentinel-1 SAR, MODIS, CHIRPS, and SRTM datasets.
- European Space Agency (ESA) — Sentinel-1 GRD SAR Imagery (Interferometric Wide Mode, 2017–2023).
- UCSB Climate Hazards Group — CHIRPS v2.0 Daily Precipitation Dataset (2000–2023).
- NASA — MODIS Land Cover (MCD12Q1), Land Surface Temperature (MOD11A2), Vegetation Index (MOD13A2), and Surface Reflectance (MOD09A1) Products.
- NASA/USGS — SRTM Digital Elevation Model.
- JRC Global Surface Water Dataset, European Commission Joint Research Centre.

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