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

Godavari River Basin Nutrient and Sediment Load Management

April 2026

Back of cover page

BLANK

Godavari River Basin Nutrient and Sediment Load Management

National River Conservation Directorate (NRCD)

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

www.nrcd.nic.in

Centres for Godavari River Basin Management Studies (cGodavari)

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

www.cGodavari.org

Centre for Ganga River Basin Management and Studies (cGanga)

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

www.cganga.org

Acknowledgment

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

Disclaimer

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

CSIR-NEERI Team (Lead Institute)

Mentors

Dr. S. Venkata Mohan	Director, CSIR-NEERI
Dr. Rajesh Biniwale	Senior Principal Scientist
Dr. Amit Bansiwal	Senior Principal Scientist

The Team

Dr. Rakesh Kadaverugu	Principal Scientist
Ms. Gayatri Shende	Project Associate

IIT Hyderabad Team (Fellow institute)

Lead persons

Prof. B.S. Murty	Director, IIT Hyderabad
Prof. Asif Qureshi	Professor

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 Godavari River Basin Management Studies

Contents

List of Figures

List of Tables

1 Introduction

The Godavari River, which is also called as “Dakshin Ganga”, is one of the India’s largest river basins, originates from the Brahmagiri mountain near Trimbakeshwar in the Nashik District of Maharashtra, which flows about 1,465 km and empties into the Bay of Bengal. The River flows across various states, including Maharashtra, Andhra Pradesh, Telangana, Chhattisgarh, Odisha, Madhya Pradesh, Karnataka, and Puducherry. The basin (Figure 1) has extensive drainage network with major tributaries such as Pravara, Purna, Penganga, Wainganga, Manjira, Indravati, Sabari, Maner, which are having major diverse topographies from the Western Ghats to the Eastern Ghats. It experiences a tropical climate with an average annual rainfall of about 1,100 mm mostly between June to September. Around 60% of the basin’s area is used for Agriculture, 25-30% is covered by forests and in remaining urbanization is expanding in various major cities. Because of its large catchment size, diverse land uses, and seasonal rains, it has major influence on regional water resources, farming and food supply and coastal environment.

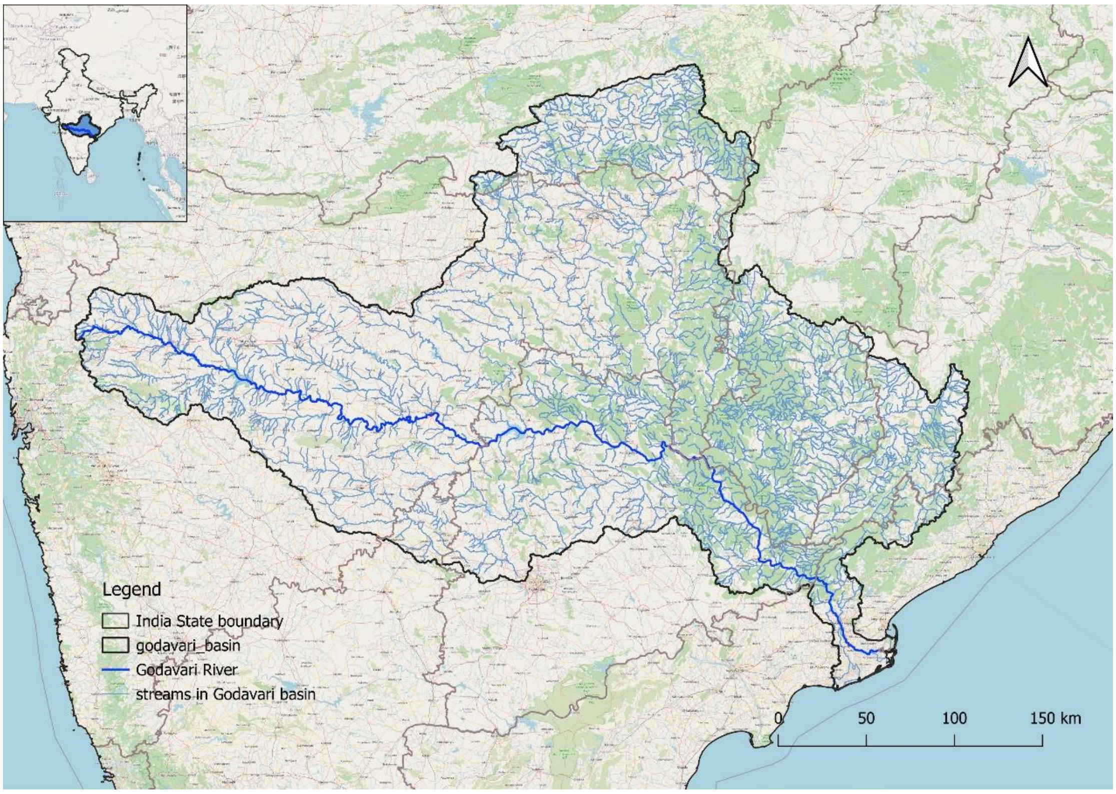


Figure 1 Location of Godavari River basin

Nutrient and sediment export in the basin has remained a major challenge due to high intensity precipitation events and land use and land cover changes. The sediment and nutrient fluxes in the basin are contributed from various sources, out of which croplands that covers a majority of the basin’s area is a major contributor of dissolved and particulate nutrients. In agricultural areas, excessive use of fertilizers, animal manure, and soil erosion adds nitrogen and phosphorus to rivers, while wastewater, sewage, and industrial effluents further increases nutrient levels. The increase in nutrient and sediment concentration in river also result from human activities such as urban runoff, deforestation, mining, and poor land management. As we know Godavari River is a low-latitude river basin, soil erosion from upland and degraded landscapes supplies the bulk of suspended sediments. Natural disasters such as floods and landslides also transport large amounts of sediment into rivers. Every year, Godavari River delivers about 170 million tonnes of sediments to the Bay of Bengal (Usman et al., 2018). Some studies show that sediment yield in the Godavari River Basin varies widely across its sub-basins, from very low to extremely high levels. The variation depends on various factors such as landform type, rock structure, vegetation cover, and rainfall intensity. Sub-basins of Godavari River with steep slopes, exposed soils, or intensive land use produce more sediment than stable, forested sub-basins (Das et al., 2022).

Both nutrient and sediment dynamics in the basin create multiple management challenges including finding out where most of the nutrients and sediments are coming from and how they travel through the catchment, as excessive nutrients and sediments are coming from agriculture, soil erosion, urban wastewater, and natural processes, which are strongly influence river health and downstream ecosystems. In the present report, the quantification of nutrient and sediment loads are done using the empirical mathematical models implemented through InVEST suite (Sharp et al.,2022). This analysis with remote sensing data demonstrated the total amount of sediments and nutrients exported from across the watershed to nearby rivers or lakes, ultimately draining into the Bay of Bengal. The outcomes of the report will help in understanding the major hotspots in the basin contributing to the sediment and nutrient export, identifying the most affected areas, supporting decision-making for river management, and guiding farmers and local authorities toward better practices.

2 Key sources of nutrient and sediment

Key sources of nutrients and sediments in a river basin generally come from both natural processes and anthropogenic activities. The description of the sources is mentioned in the following sections.

2.1 Sources of nutrients

2.1.1 Agricultural runoff

Several analyses show the Godavari River is one of India’s major riverline exporters of nitrogen and phosphorus to the Bay of Bengal. According to some research in the basin using particulate organic matter, isotopes and river chemistry identify synthetic fertilizers and agricultural runoff as clear contributors to particulate and dissolved N during high-flow and low-flow seasons in parts of the Godavari. (Moturi Srirama Krishna) Land-use changes, expanding irrigation, and long-term accumulation of nutrients in soils further strengthen this contribution.

2.1.2 Sewage and various anthropogenic factors

The Godavari basin shows a signs of significant domestic sewage and urban wastewater loading. One of the study on in one stretch of the basin states that domestic wastewater generation is estimated at ~3.5 MLD and no adequate treatment facilities are available (MPCB). Domestic sewage contains high amounts of nitrogen (from urea in urine, proteins, detergents) and phosphorus (from soaps, detergents, food waste, and human waste). When this wastewater is not properly treated and is directly discharged into drains or rivers, these nutrients enter the water in large quantities. Urban runoff during rainfall further washes nutrients from solid waste dumps, open drains, animal waste, and roadside areas into nearby rivers.

2.1.3 Manure and livestock waste

The Godavari basin has large populations of cattle, buffalo, goats, sheep, and rapidly growing poultry farms, especially in Maharashtra, Telangana and Andhra Pradesh. Manure from these animals contains high concentrations of nitrogen (ammonia and organic nitrogen) and phosphorus, if this waste is not properly collected or treated it gets washed into nearby drains, village streams and tributaries during rainfall. This accumulated waste easily mobilized as surface runoff, adding nutrients, organic matter, pathogens and suspended solids to river water. As a result, livestock-dominated regions show higher levels of ammonia, nitrate and phosphate in nearby water bodies. Along with agricultural runoff and untreated sewage, animal waste contributes to nutrient enrichment, eutrophication and overall water-quality deterioration in several parts of the Godavari, especially during the rainy season.

2.1.4 Crop residue

In the Godavari River basin, decomposing plant residue such as crop stalks, husks, leaves, and natural leaf litter acts as a natural source of nutrients. In the basin's large agricultural areas, especially where paddy, sugarcane, cotton and soybean are grown, large amounts of crop residue remain on the soil surface after harvest. When this plant material breaks down, it releases nitrogen, phosphorus and organic matter into the soil. During the monsoon, heavy rainfall can wash these dissolved nutrients and fine organic particles from fields into nearby drains, streams and tributaries and, eventually, into the Godavari River. Forested parts of the upper Godavari also contribute small but continuous nutrient inputs through leaf litter decomposition.

2.2 Sources of Sediments

2.2.1 Soil erosion

Surface soil erosion is a major source for the large amount of sediment entering the Godavari River. During the monsoon, heavy rainfall loosens the topsoil from agricultural fields, hill slopes, degraded forests and construction areas. This soil travels with runoff into small streams and tributaries, eventually in Godavari River. In cultivated regions of Maharashtra, Telangana, and Andhra Pradesh, repeated tillage, removal of vegetation cover, and poor land-management practices make the soil more vulnerable to erosion. Upland areas in the Western Ghats and parts of the Pranhita, Manjira, and Wardha sub-basins also contribute large sediment loads due to steep slopes and high rainfall. All this eroded soil increases significant sedimentation, which can reduce water quality, increase turbidity, silt up riverbeds and reservoirs, also affect aquatic habitats.

2.2.2 Deforestation and Land Use Change

Deforestation and changes in land use significantly increase soil erosion. Removal of trees reduces root binding and soil stability, making the land more prone to erosion. When forests are converted into agricultural land or settlements, the protective vegetation cover is lost, and soil becomes exposed to rainfall impact. This leads to higher sediment production and transport into river systems.

2.2.3 Riverbank erosion

This is another major source of entering sediments into the Godavari basin. During the monsoon period, the river's water level rises and flows with strong force, which cuts into and loosens the soil along the banks. In many stretches of the Godavari especially in middle and lower basin areas of Maharashtra, Telangana, and Andhra Pradesh, the banks are mostly made up of soft alluvial soil which easily breaks during heavy flow. Human activities like sand mining, removal of vegetation, and construction close to the riverbank weaken the banks even more, causing larger sections to collapse into the river. As these eroded bank materials get carried downstream, they increase the sediment load, make the water muddy, and contribute to siltation in reservoirs and riverbeds.

2.2.4 Hilly and Upland Areas

Hilly and upland regions such as the Eastern Ghats and parts of the Deccan Plateau are major sources of sediment in the Godavari River Basin. These areas have steep slopes and receive high rainfall during the monsoon season, which increases the speed of surface runoff. As water flows down the slopes, it removes topsoil and carries it into streams and rivers. In addition, sparse vegetation in some upland areas further increases erosion, making these regions important sediment source zones.

2.2.5 Agricultural Activities

Agriculture is one of the major human-induced sources of sediment in the Godavari Basin. Farming activities such as ploughing, tilling, and removal of crop cover leave the soil exposed, making it more vulnerable to erosion. During the monsoon season, heavy rainfall generates strong surface runoff, which easily carries this loose soil into nearby streams and rivers. Crops like cotton and soybean, which are widely grown in the basin, often require intensive land preparation and fertilizer application, further increasing soil disturbance. In addition, lack of soil conservation practices such as contour bunding, terracing, and cover cropping increases the risk of erosion.

2.2.6 Mining Activities

Mining activities, particularly open-cast mining, expose large areas of soil and rock, creating highly erodible surfaces. The removal of vegetation and topsoil increases the risk of erosion, and loose materials generated during mining are easily transported by runoff. These exposed surfaces are highly vulnerable to erosion, particularly during rainfall events. In regions where mining is active, such as parts of Chhattisgarh and Telangana, large quantities of fine particles and waste materials are generated. During the monsoon, runoff water transports these materials into nearby streams and rivers, increasing sediment load.

3 Sediment and Nutrient load assessment

The Godavari River Basin (GRB) carries a very large amount of soil and sand every year. According to the study conducted by Biksham & Subramanian (1988) and Probst & Sigha (1989) the river transported about 150-170 million/y. In recent years, studies show that total sediment load has reduced sharply to about 47 million tonnes/y during the period between 2010 to 2019 as this decline is mainly due to large reservoirs and dams that trap sediment and control river flow (Das et al., 2022). Sediment yield varies widely across different sub-basins. Some stable areas produce less than 30 tonnes/km²/y, while erosion-prone regions of the Deccan Plateau produce more than 3,000 tonnes/km²/y. This difference is mainly controlled by land use, soil type, slope, and the intensity of monsoon rainfall (Das et al., 2022). The basin has strong monsoon dominance as most sediment is transported during the monsoon season, especially during a few high-flow events, while sediment movement is very low during the dry season (Sarma et al., 2010). The long-term reduction in sediment supply has also caused erosion and physical changes in the Godavari delta. These trends show the need for better soil conservation in high-erosion areas and improved reservoir management to protect river and coastal systems (India-WRIS, 2014; Das et al., 2022). The trends in the sediment export estimation in the basin are presented in

Table 1, the sediment load variations according to the spatial scale are presented in Table 2, and the classification of sediments based on the type is presented in Table 3.

Table 1 Sediment Load estimates by various studies in Godavari River Basin

Time Period	Sediment Load (Mt/year)	Description	Method	Reference
Pre-major reservoir era (1970)	150–170 Mt/ year	Historical high sediment transport before large dam construction	Gauging station data & sediment rating curves	Biksham & Subramanian (1988); Probst & Sigha (1989)
1980	115 Mt/ year	Beginning of decline due to increasing reservoir storage	Long-term basin analysis	Das et al. (2022), Science of the Total Environment
1990	98 Mt/ year	Continued reduction due to flow regulation	Decadal sediment budget analysis	Das et al. (2022)
2000	48 Mt/ year	Sharp decline linked to reservoir trapping	Multi-station sediment analysis	Das et al. (2022)
2010-2019	47 Mt/ year	Recent stabilized lower sediment export	Trend analysis (1970-2019)	Das et al. (2022)

Table 2 Sediment Load by Spatial Scale

Spatial Scale	Value	Unit	Location Example	Reference
Entire Godavari Basin	47	Mt/year	Basin outlet	Das et al. (2022)
Gauging station (Polavaram)	91.82	Mt/year	Lower basin	Das et al. (2022)

Gauging station (Saigaon)	1.49	Mt/year	Upper basin	Das et al. (2022)

Table 3 Classification based on Sediment Type

Sediment Type	Reported Value	Context	Reference
Suspended Sediment Load (SSL)	170 Mt/year (historic)	Water column sediment transport	Biksham & Subramanian (1988)
Suspended Sediment Load (recent)	47 Mt/ year	Post-dam measurement	Das et al. (2022)
Particulate Organic Carbon (POC) export	2.8 Mt/ year	Organic sediment flux to Bay of Bengal	Balakrishna et al. (2005)
Particulate Nitrogen (PN)	0.29 Mt/ year	Associated with sediment transport	Balakrishna et al. (2005)

3.1 Input Data Preparation for SDR and NDR modeling

3.1.1 Land Use and Land Cover

Figure 2 and Figure 3 show the land use and land cover (LULC) distribution of the Godavari River Basin for the years 2017 and 2024, which were obtained from ESRI (https://livingatlas.arcgis.com/landcoverexplorer/) having 10 m spatial resolution. In both years, agriculture remains the dominant land use across most parts of the basin. Forest area mainly concentrated in the eastern and south-eastern regions, while urban areas appear as scattered patches around major towns and cities. Water bodies are visible along the main river channels and reservoirs. The comparison of the LULC for two years help understanding the changes in land use patterns over time, including shifts in agricultural areas, forest cover, and urban expansion within the basin.

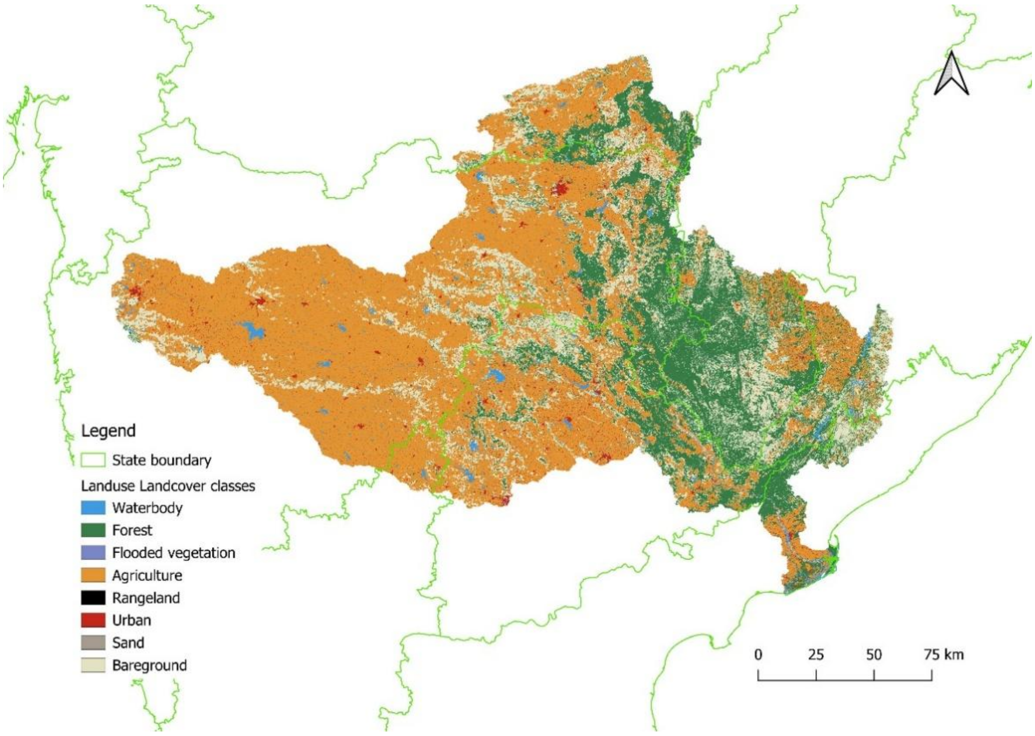


Figure 2 Spatial Distribution of Land Use/Land Cover Classes in the Godavari Basin (2017)

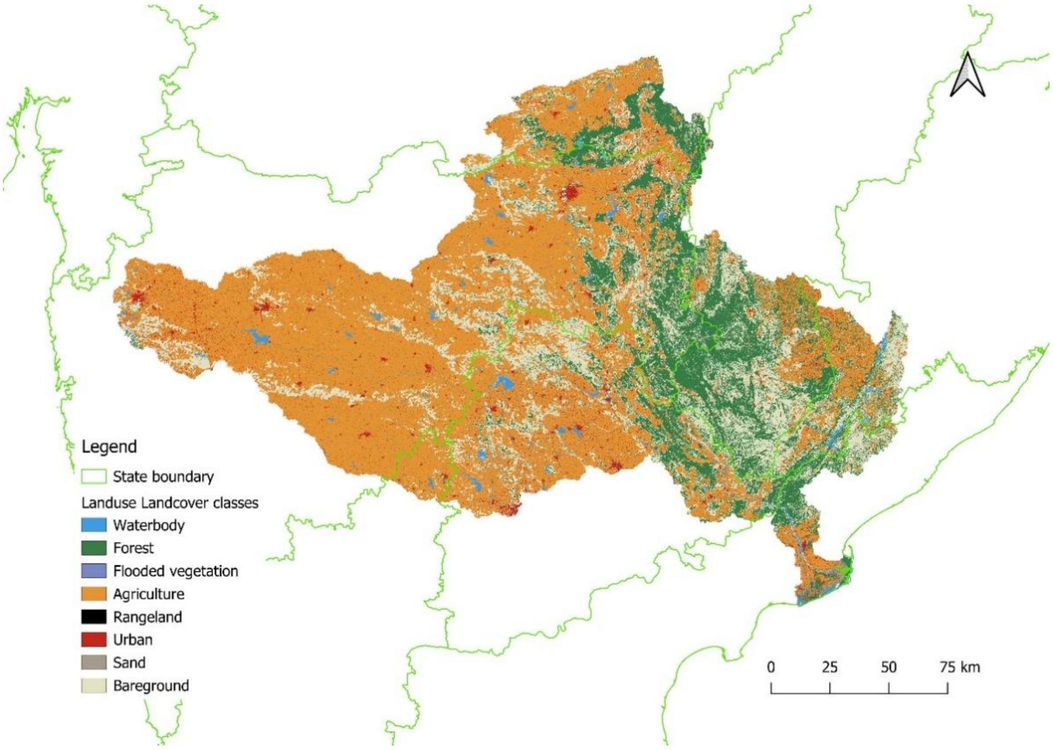


Figure 3 Spatial Distribution of Land Use/Land Cover Classes in the Godavari Basin (2024)

3.1.2 Soil Erodibility (k)

Figure 4 shows the spatial distribution of soil erodibility (K-factor) across the Godavari River Basin. The K-factor represents how easily soil can be eroded based on properties like texture, structure, and organic matter. Higher values indicate soils that are more prone to erosion, while lower values indicate more stable soils. This parameter is used as an important input in the InVEST SDR model to estimate sediment loss. In the present study the soil erodibility data was obtained from HydroSense Lab IIT Delhi (Raj et al., 2022a).

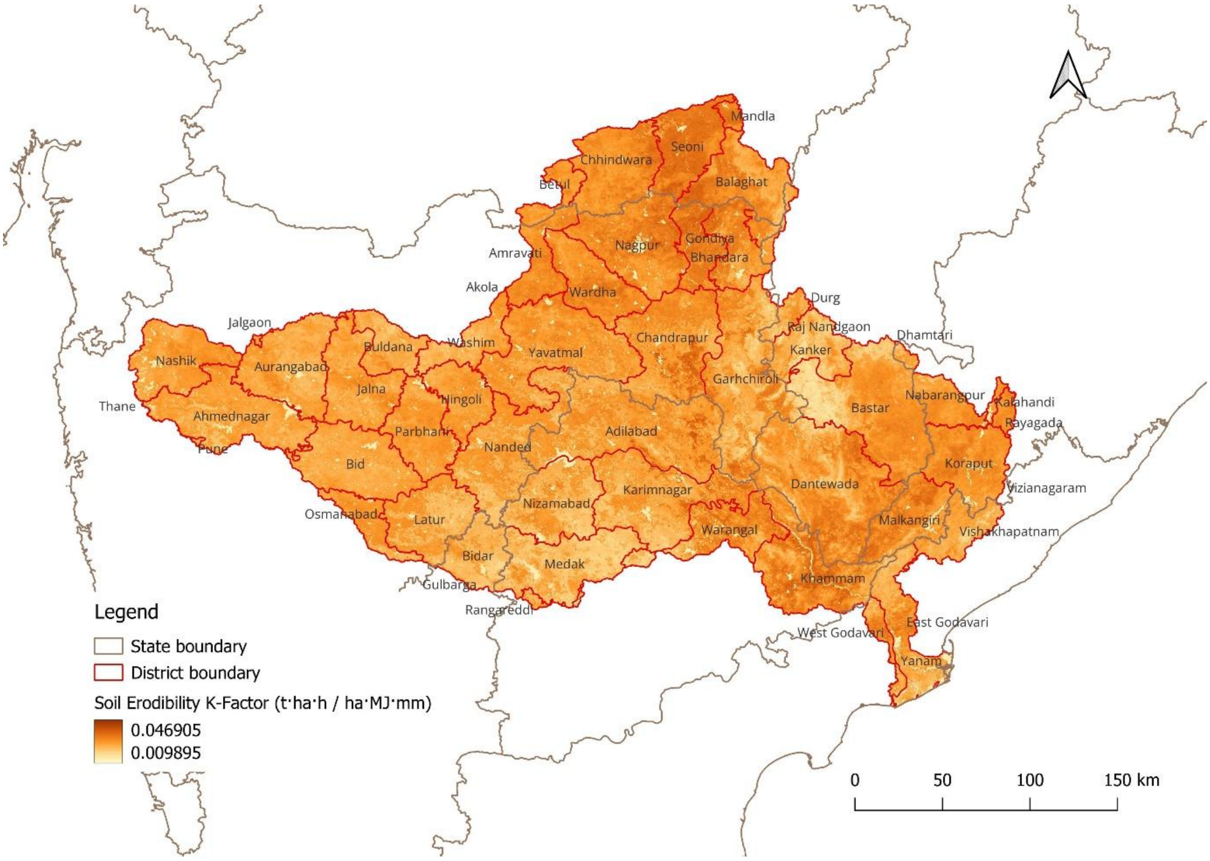


Figure 4 Spatial Variability of Soil Erodibility (K-Factor) in the Godavari River Basin for Sediment Modelling

The K-factor ranges approximately from 0.009 to 0.047 t·ha·h / (ha·MJ·mm), indicating varying susceptibility of soils to erosion. Higher K-factor values are mainly observed in the northern, eastern and south-eastern parts of the basin, including regions such as Gondia, Seoni, Bhandara, Bastar, Dantewada, Koraput, and Khammam Districts**.** As a result, these regions contribute significantly to sediment generation within the basin. In contrast, the western and upper parts of the basin, including districts like Nashik, Ahmednagar, and parts of Aurangabad, show lower K-factor values. These areas are characterized by more stable soils, better vegetation cover, and relatively gentle topography, which reduces their susceptibility to erosion. The central regions of the basin exhibit moderate K-factor values, indicating intermediate erosion potential influenced by land use and local soil conditions.

3.1.3 Rainfall Erosivity (R-Factor)

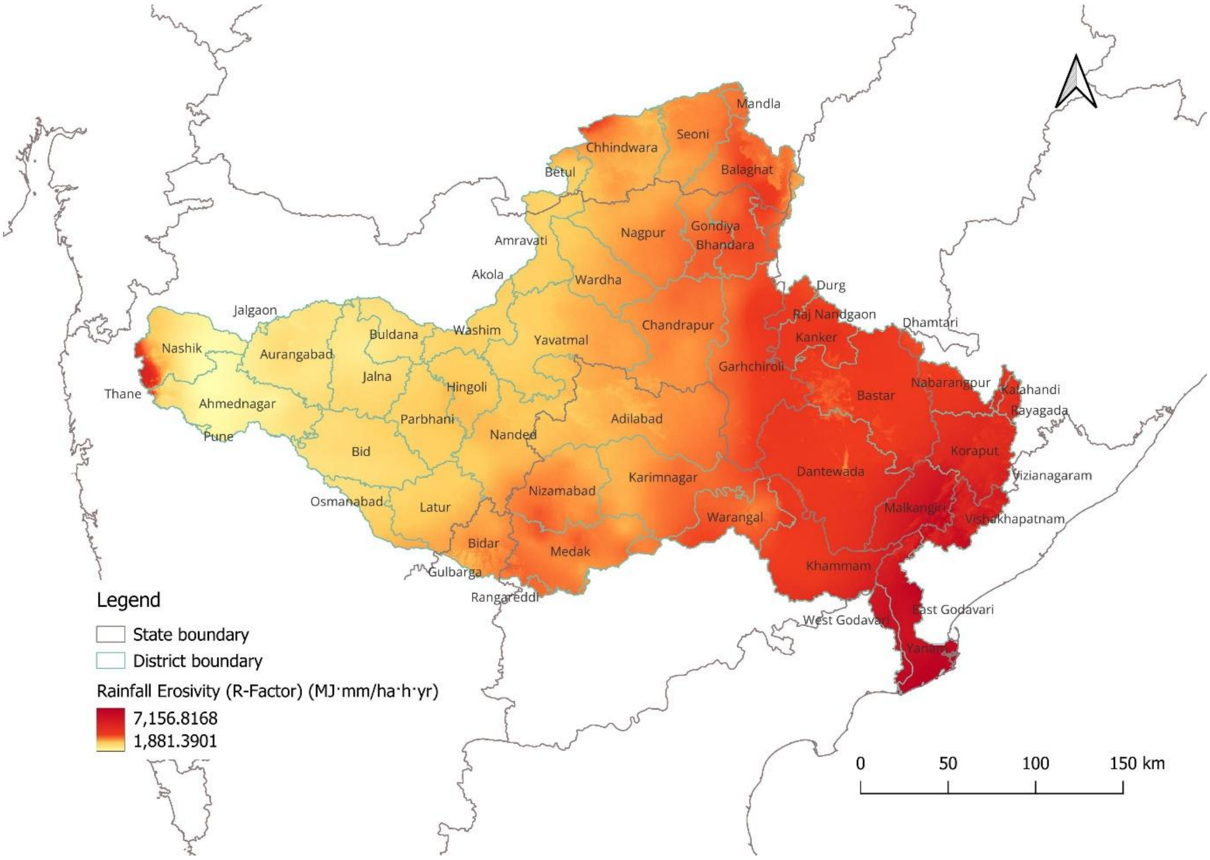


Figure 5 Spatial Distribution of Rainfall Erosivity (R-Factor) in the Godavari River Basin for Sediment modelling

Figure 5 shows the rainfall erosivity data in different parts of the Godavari River Basin. Higher values (shown in red) mean rainfall is more intense and can cause more soil erosion. The values range approximately from 1880 to 7156 MJ·mm/ha·h·yr, indicating significant variation across the basin. Lower values (yellow areas) indicate less intense rainfall and lower erosion risk. The western and upper parts of the basin, including districts such as Nashik, Ahmednagar, Aurangabad, and Pune region, exhibit low R-factor values (light yellow shades). These areas receive relatively lower rainfall intensity and therefore have lower erosion potential due to rainfall. Moving towards the central basin regions (Nagpur, Wardha, Nizamabad, Karimnagar), the R-factor values are moderate, indicating moderate rainfall intensity and corresponding erosion potential. The eastern and southeastern parts of the basin, including districts such as Bastar, Dantewada, Koraput, Malkangiri, Khammam, and

East Godavari, show very high R-factor values (dark red shades). These regions experience high-intensity monsoonal rainfall, which significantly increases the erosive power of rainfall and leads to higher soil erosion risk. The data was obtained from HydroSense IIT Delhi (Raj et al., 2022b).

3.1.4 Digital Elevation Model (DEM)

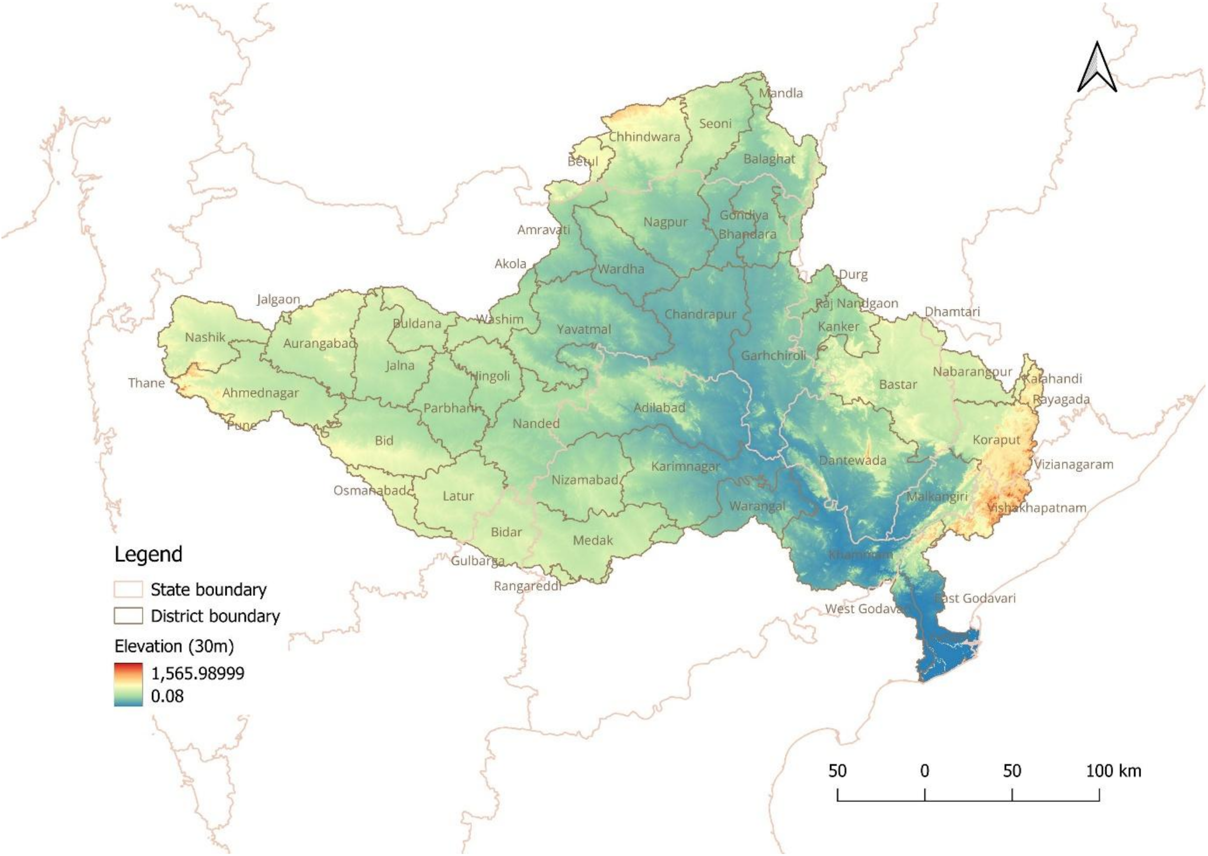


Figure 6 Digital Elevation Model (DEM) 30M of the Godavari River Basin.

Figure 6 shows the elevation of the Godavari River Basin, which is downloaded from FABDEM (Forest and Buildings removed Copernicus DEM) at 30 m resolution. The elevation values vary significantly across the basin, ranging from low-lying coastal areas to high upland regions in the western and eastern ghat regions. Moderately elevated regions are mainly observed in the eastern and north-eastern parts of the basin, particularly in districts like Koraput and Bastar, indicating hilly and mountainous terrain. Moderate elevations are also seen in the central region, including areas like Nagpur, Yavatmal, and Adilabad Districts. Lower elevations are found in the downstream and coastal regions, especially in East and West Godavari Districts, where the terrain is flat and close to sea level.

3.2 Sediment Delivery Ratio (SDR) Modelling

3.2.1 Overview of the InVEST SDR Model

The Sediment Delivery Ratio (SDR) model implemented in the InVEST framework estimates soil loss and sediment export at the watershed scale. The model is based on the Revised Universal Soil Loss Equation (RUSLE), shown in Eq. 1, combined with a sediment delivery component to determine how much eroded soil actually reaches the stream network.

$$A = R \times K \times LS \times C \times P \qquad (1)$$

Where

A = Annual soil loss (tonnes/ha/year)
R = Rainfall erosivity factor (MJ.mm/(ha.hr.y))
K = Soil erodibility factor (ton.ha.hr/(MJ.ha.mm))
LS = Slope length and steepness factor (unitless)
C = Cover-management factor (unitless)
P = Support practice factor (unitless)

Based on Borselli et al. (2008), the SDR model first calculates the Connectivity Index (IC) for each pixel, which represents the hydrological connection between sediment sources (land surface) and sinks (streams). Higher IC values indicate that a larger portion of eroded sediment is likely to reach the stream, typically in areas with steep slopes, short flow paths, and low vegetation cover. Lower IC values occur in flatter, well-vegetated areas where sediment transport is limited.

The IC depends on two components (shown in Eq. 2), the upslope contributing area (D_{up}) and the downslope flow path to the nearest stream (D_{dn}). If the upslope area is large, with gentle slopes and good vegetation cover (low C factor), (D_{up}) is low, indicating reduced sediment availability. Similarly, if the downslope path is long, flat, and well vegetated, (D_{dn}) is low, reducing sediment delivery. The spatial representation of the D_{up} and D_{dn} is shown in Figure 7. The datasets and the parameters needed for SDR model are shown in Figure 8.

$$IC = \log_{10}\left(\frac{D_{up}}{D_{dn}}\right) \qquad (2)$$

The SDR component estimates the fraction of eroded soil that actually reaches the stream network based on terrain and connectivity, according to the Eq. 3, where, SDR is the sediment delivery ratio at i^{th} pixel. The SDR is assigned as 1 if the pixel is a stream pixel, whereas for other pixels, SDR value is calculated from SDR_{max}, IC_0, IC_i, and k values, which are described in the InVEST SDR model manual (Sharp et al., 2022). Here, k represents the Borselli parameter, which controls the sediment connectivity (k=2 considered in the model). IC_0 represents the connectivity index threshold, which defines sediment transport efficiency (selected it as 0.5). SDR_{max} represents the maximum sediment delivery ratio, selected as 0.8 in the present study.

$$\text{Total\_export}_i = A_i * SDR_i \tag{3}$$

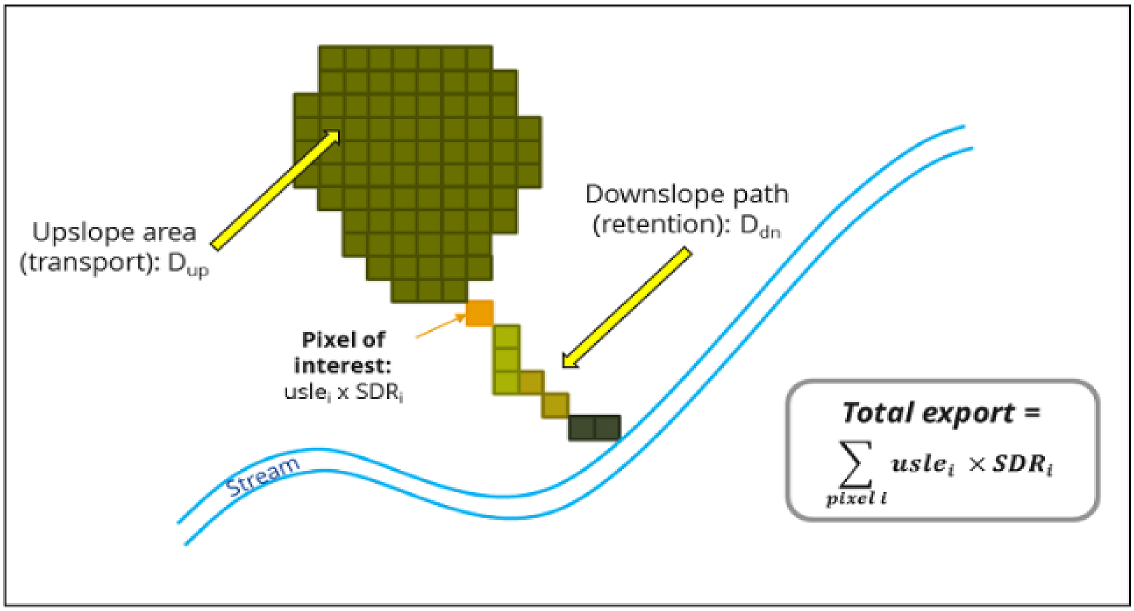


Figure 7 Conceptual approach used by SDR model in calculating Connectivity Index (IC) (Sharp et al., 2022)

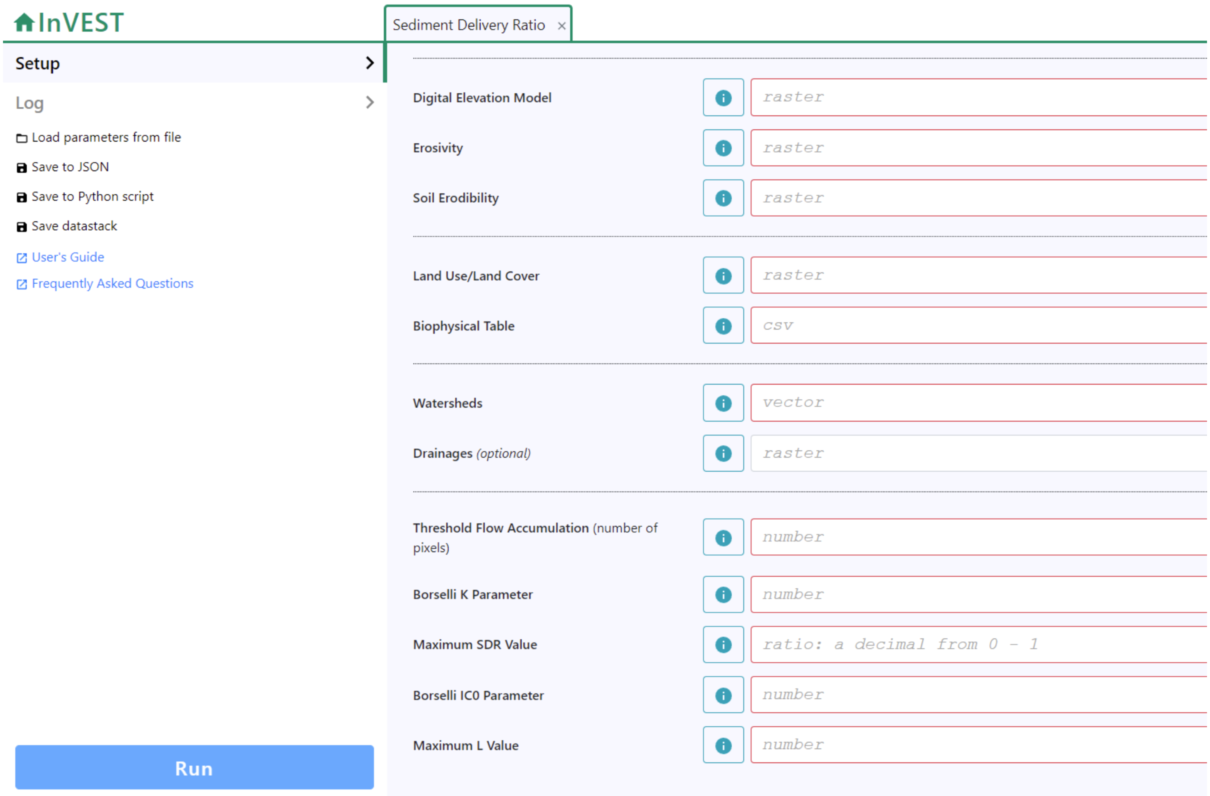


Figure 8 Screenshot of InVEST SDR model

Further, for biophysical table needed for referencing the C and P values with respect to various LULC categories is prepared based on the literature and the values provided in InVEST model based on RUSLE studies. Lower C values were assigned to forest and vegetation, while higher values were assigned to cropland and bare land. Similarly, lowest P values were assigned to LULC that has better management practices in order to reduce the soil erosion. The biophysical table values used in the model is provided in Table 4.

Table 4 Biophyscial values used in SDR model

LULC classes	lucode	usle_c	usle_p
Waterbody	1	0	0
Forest	2	0.003	0.5
Other vegetation	3	0.02	1
Flooded vegetation (wetland)	4	0	0
Agriculture	5	0.3	0.5
Rangeland	6	0.05	1
Urban	7	0	0

sand	8	0.45	1
Snow/Ice	9	0	0
Clouds	10	0	0
Bare ground	11	0.05	1

3.2.2 Sediment Export

3.2.2.1 2017

The pixel-wise sediment export in the basin is shown in Figure 9, which is the output of the InVEST SDR model simulated for 2017. Figure 10 shows the choropleth of the sediment export in the GRB for year 2017. The sediment exported from each pixel in the basin are summed district-wise. The analysis shows that the cumulative sediment exported values vary significantly across the districts due to differences in land slope, rainfall, and human activities. Very high sediment export is seen in Koraput (~844,096 tonnes/year), Visakhapatnam (~668,300 tonnes/year), and Chhindwara (~667,617 tonnes/year) Districts. These areas are located in hilly regions such as the Eastern Ghats and Deccan uplands. Because of steep slopes and uneven terrain, water flows faster during rainfall, which increases soil erosion. Heavy rainfall in these regions also plays an important role in carrying more sediment. Remaining districts like Ahmednagar (~485,661 tonnes/year), Bid (~480,738 tonnes/year), Yavatmal (~442,653 tonnes/year), Adilabad (~404,142 tonnes/year), and Nashik (~369,572 tonnes/year) also contributed to high sediment export in the basin. These areas mainly have intensive farming. Frequent ploughing and leaving the soil uncovered make it easy for soil to be washed away, even if the land is not very steep.

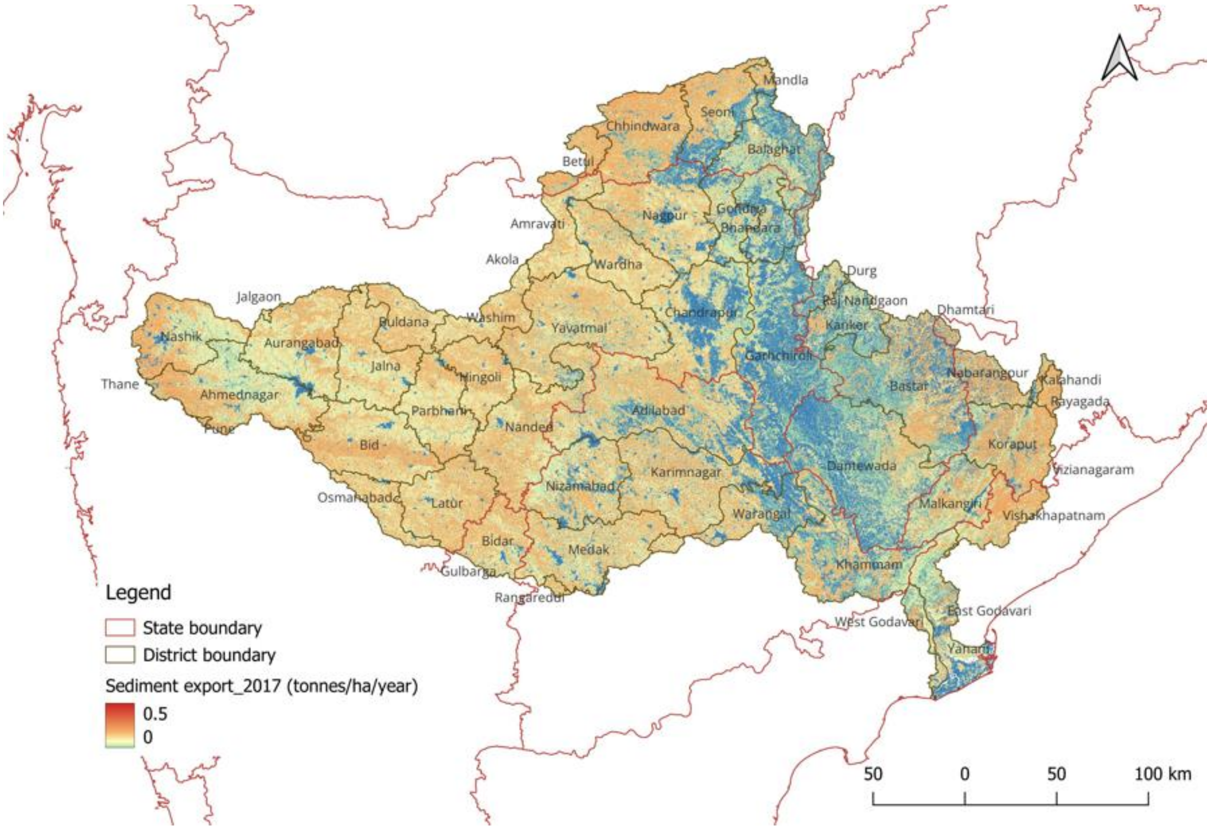


Figure 9 Pixel-wise spatial distribution of sediment export in basin for 2017

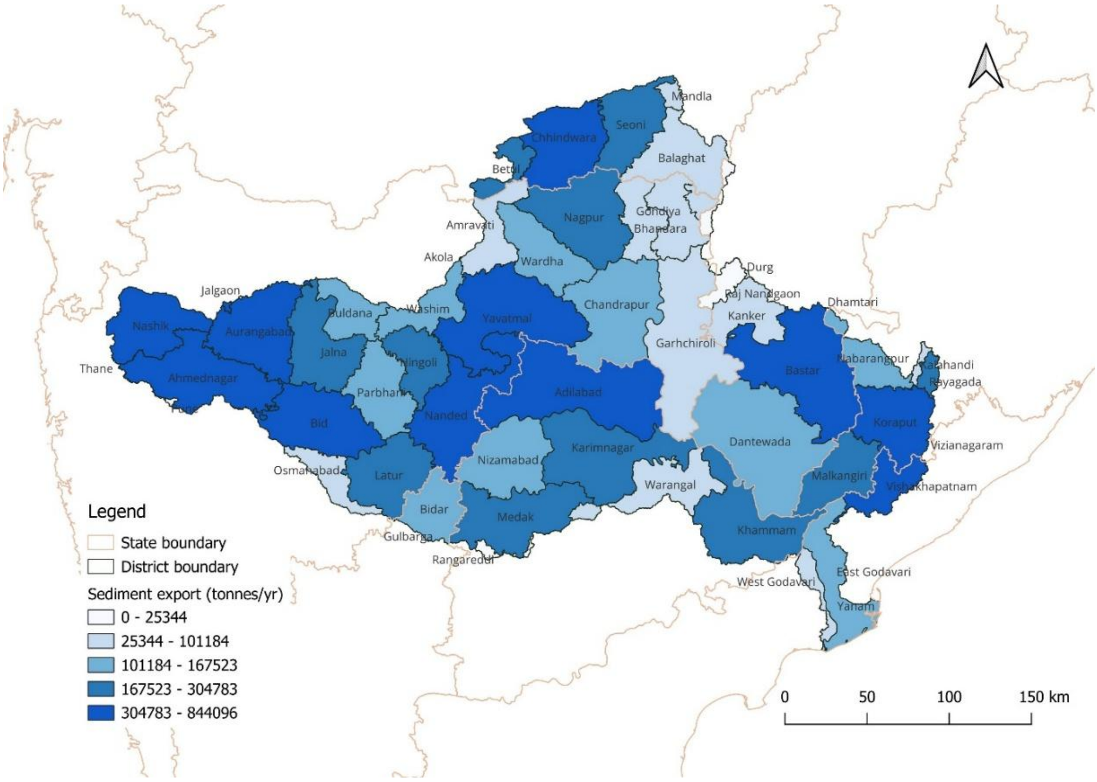


Figure 10 Sediment Export in the Godavari River Basin (tonnes/year) for the year 2017

Moderate sediment export (150,000–300,000 tonnes/year) is found in districts such as Seoni (~267,610 tonnes/year), Malkagiri (~260,268 tonnes/year), and Latur (~228,868 tonnes/year). These areas have mixed land use and medium slope conditions. On the other hand, low sediment export (<150,000 tonnes/year) is observed in districts like Gondia, Bhandara, Rajnandgaon, and East Godavari. These regions are mostly flat, have good vegetation cover, and less human disturbance, which helps reduce soil erosion.

Overall, the sediment export in the basin ranges from less than 50,000 t/y to more than 840,000 t/y. The highest values are found in areas where steep slopes, heavy rainfall, and farming activities occur together. These areas need better soil and water conservation practices.

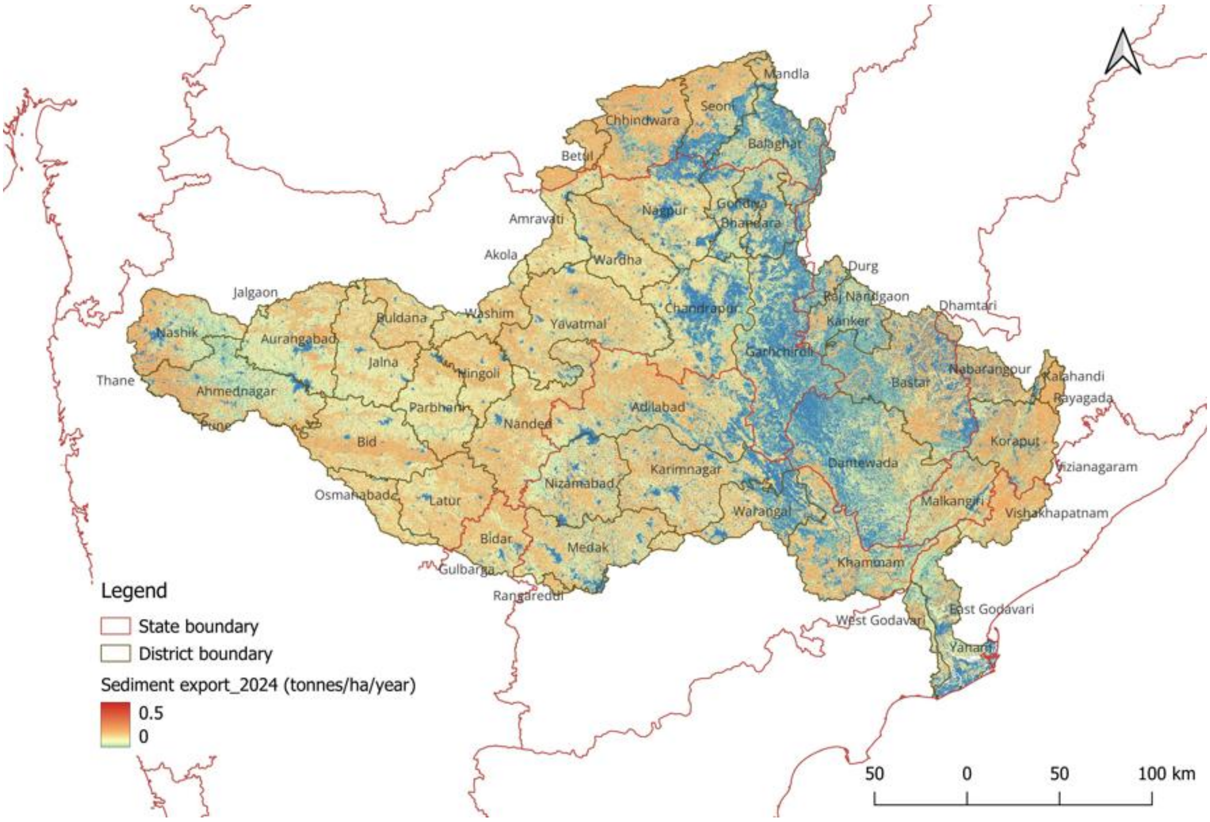


Figure 11 Pixel-wise spatial distribution of sediment export in basin for 2024

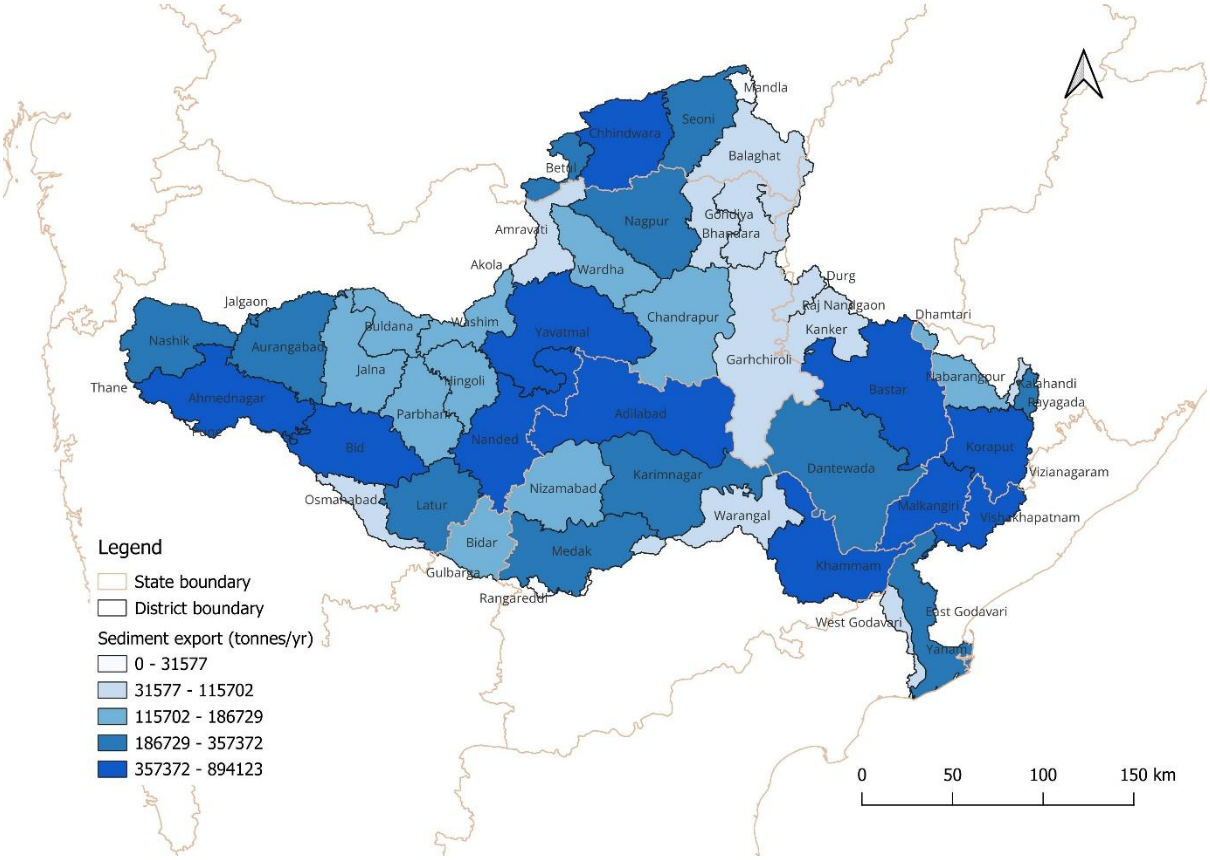


Figure 12 Sediment Export in the Godavari River Basin (tonnes/year) for the year 2024

3.2.2.2 2024

The pixel-wise sediment export in the basin is shown in Figure 11, which is the output of the InVEST SDR model simulated for 2024. The sediment export in the Godavari River Basin for the year 2024 shows large differences between districts due to changes in slope, rainfall, and land use (shown in Figure 12). Very high sediment export is seen in districts like Koraput (~894,123 tonnes/year), Chhindwara (~763,634 tonnes/year), and Visakhapatnam (~726,763 tonnes/year). These areas are hilly regions (Eastern Ghats and central highlands) with steep slopes and heavy rainfall. Because of this, water flows quickly and carries more soil, leading to higher erosion. The values in these districts have also increased compared to 2017. High sediment export (300,000–600,000 tonnes/year) is found in districts such as Adilabad (~568,030 tonnes/year), Yavatmal (~486,398 tonnes/year), Bastar (~422,658 tonnes/year), Bid (~415,437 tonnes/year), Ahmednagar (~415,353 tonnes/year), and Nanded (~413,834 tonnes/year). These areas include both hilly land and agricultural regions. Farming activities like ploughing and less use of soil conservation methods make the soil loose and easy to wash away. Moderate sediment export (150,000–300,000 tonnes/year) is seen in districts like Malkangiri (~381,414 tonnes/year), which is close to the higher range, and other central parts of the basin. These areas have medium slopes and mixed land use. On the other hand, low sediment export (<150,000 tonnes/year) is observed in districts such as Gondia, Bhandara, Rajnandgaon, and East Godavari. These regions are mostly flat, have good vegetation cover, and less human disturbance, which helps reduce soil erosion.

Overall, sediment export in 2024 ranges from less than 50,000 to about 894,000 tonnes per year, showing a clear pattern across the basin. Compared to 2017, there is an increase in sediment export and more areas falling in the high category, especially in hilly and farming regions. This shows that soil erosion is increasing, and proper soil and water conservation measures are needed.

3.2.3 Comparison of Sediment Export (2017 vs 2024)

The temporal comparison of sediment export between 2017 and 2024 in the Godavari River Basin indicates a clear increase in sediment generation across most districts (Figure 13 and Table 5). In 2017, maximum sediment export was observed in Koraput (~844,096 tonnes/year), whereas in 2024 it increased to ~894,123 tonnes/year, showing an overall rise in basin-scale sediment intensity. Several districts exhibited significant increases, particularly East Godavari (≈88.8% increase), Khammam (≈71.1%), Dantewada (≈57.5%), and Malkangiri (≈46.5%), indicating expanding erosion processes in both coastal transition zones and upland regions. Major agricultural and upland districts such as Adilabad, Bastar, and Chhindwara also showed notable increases of approximately 30–40%, reflecting the combined influence of land-use pressure and terrain-driven erosion.

High sediment export zones expanded spatially, with districts like Ahmednagar, Bid, and Yavatmal maintaining high values while showing moderate increases. Even districts previously categorized as low sediment zones, such as Gondia and Rajnandgaon, showed increases of over 40–50%, suggesting gradual intensification of erosion across the basin. Overall, the results indicate a basin-wide increase in sediment export, with percentage changes ranging from approximately 10% to nearly 90%, highlighting both natural and anthropogenic drivers of erosion. This trend suggests increasing pressure on watershed systems and emphasizes the need for targeted sediment management strategies.

Table 5 District-wise increase in sediment export (top most districts)

District	% Increase
East Godavari	+88.8%
Khammam	+71.1%
Dantewada	+57.5%
Gondia	+53.6%
Rajnandgaon	+49.0%
Malkangiri	+46.5%
Adilabad	+40.6%
Kanker	+40.4%
Bastar	+31.3%

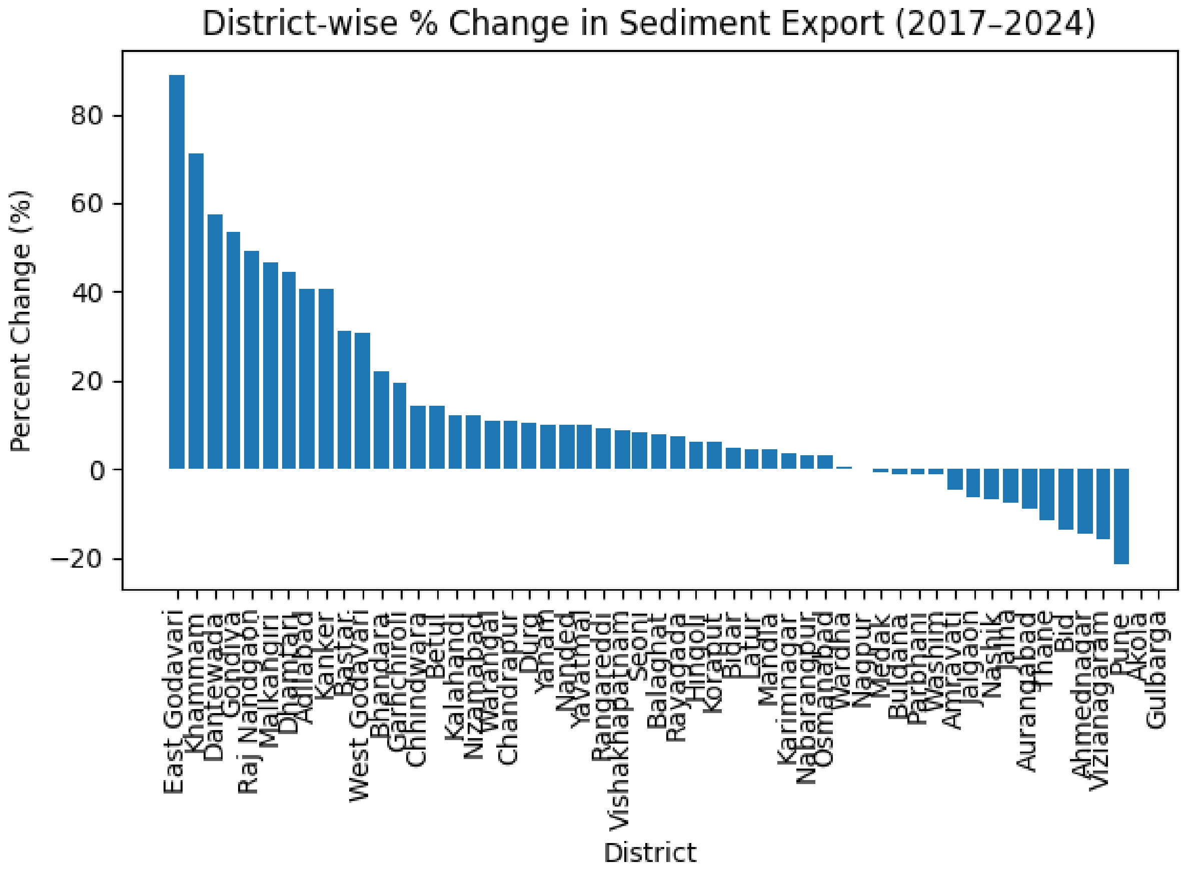


Figure 13 District-wise percentage change in sediment export (2017-2024)

3.2.4 Sediment load management - management practices, priority areas and suggestions

Sediment load management in the GRB should be based on where sediment export is highest and how it has changed between 2017 and 2024. The analysis shows that some districts such as Koraput, Bastar, Chhindwara, Adilabad, Yavatmal, Khammam, and Malkangiri have very high sediment export (more than 400,000 t/y) and have also increased over time. These districts are mainly located in hilly and upland areas like the Eastern Ghats and the Deccan Plateau. In these regions, steep slopes, heavy rainfall, and increasing human activities lead to higher soil erosion. Therefore, these areas need immediate attention as they are the main sources of sediment in the basin.

In these high-risk areas, management practices should aim to slow down runoff and protect the soil. Measures such as contour bunding, terracing, afforestation, and building check dams and gully plugs can help trap sediment and reduce its movement into rivers. Planting vegetation barriers can also improve soil stability and reduce erosion. Moderately affected districts like Ahmednagar, Bid, Nanded, Karimnagar, and Dantewada are showing increasing sediment export due to farming activities and moderate slopes. In these areas, better agricultural practices such as minimum tillage, crop rotation, cover cropping, and field bunding can help reduce soil loss by improving soil condition and reducing exposure.

Areas with mixed land use, such as Karimnagar and Dantewada, need combined approaches. Practices like agroforestry, developing vegetation along riverbanks (riparian buffers), and proper land-use planning can help balance agriculture and environmental protection. On the other hand, districts with low sediment export such as Gondia, Bhandara, Rajnandgaon, and East and West Godavari should be protected and maintained. These areas act as natural zones where sediment gets deposited and help in maintaining the stability of the river system.

Overall, sediment management in the basin should focus on areas with steep slopes, high rainfall, and intensive land use. Using a combination of structural measures, improved farming practices, and proper planning at the basin level is important to reduce sediment export and ensure long-term sustainability of the watershed.

3.3 Nutrient Load Characteristics of the Godavari River Basin

Nutrient dynamics in the GRB exhibit strong spatial and temporal variability. Estuarine measurements report mean dissolved inorganic nitrogen concentrations of approximately 18 $\mu mol\ L^{-1}$, with peak values exceeding 80 $\mu mol\ L^{-1}$ during monsoon discharge events (Sarma et al., 2010; 2011). Basin-scale export estimates indicate that the Godavari delivers approximately 2.8 million tonnes per year of particulate organic carbon and substantial nitrogen fluxes to the Bay of Bengal (Balakrishna et al., 2005). Regional modelling studies further identify the Godavari as one of the major contributors of nitrogen and phosphorus to the Bay of Bengal (Pedde et al., 2017). These findings demonstrate that nutrient transport in the basin is strongly monsoon-dominated, spatially heterogeneous, and influenced by both agricultural and urban sources. The annual load of nutrients exported into the basin as summarized by earlier studies is shown in Table 6.

Table 6 Annual Nutrient Loads and Export Flux from the Godavari Basin to the Bay of Bengal

Nutrient Type	Load	Unit	Spatial Scale	Method	Reference
Particulate Organic Carbon (POC)	2.8×10^6	tonnes/year	Basin export to Bay of Bengal	Basin mass balance estimation	Balakrishna et al. (2005)
Particulate Nitrogen (PN)	0.29×10^6	tonnes/year	Basin export	Same study	Balakrishna et al. (2005)
Dissolved Organic Carbon (DOC)	0.45×10^6	tonnes/year	Basin export	Modelling + measurement synthesis	Balakrishna et al. (2005)
Total N export (regional rivers incl. Godavari)	7.1	Tg/year	Bay of Bengal rivers	Global nutrient export model	Pedde et al. (2017), *Regional Environmental Change*
Total P export (regional)	1.5	Tg/year	Bay of Bengal rivers	Modelling study	Pedde et al. (2017)

3.3.1 Nutrient Delivery Ratio (SDR) Modelling Using InVEST

The Nutrient Delivery Ratio (NDR) model in InVEST was used to estimate the generation, retention, and export of nutrients (nitrogen and phosphorus) within the GRB. The model calculates how much nutrient is produced from different land uses and how much of it is transported to the stream network. It considers both surface runoff and subsurface flow processes, along with landscape characteristics such as topography and land cover.

The NDR model works by combining nutrient loading with a delivery ratio that represents the fraction of nutrients that reach streams after accounting for retention by vegetation and soil. The concept and schematic of the SDR model is are shown in Figure 14 and Figure 15.

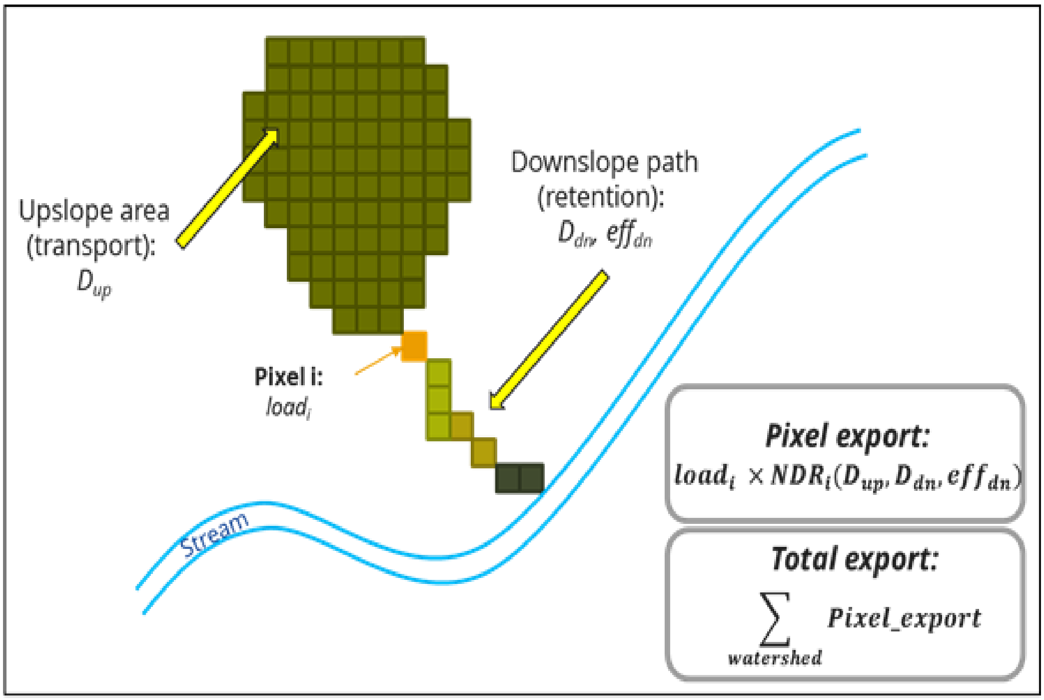


Figure 14 Conceptual representation of the NDR model (Sharp et al., 2022).

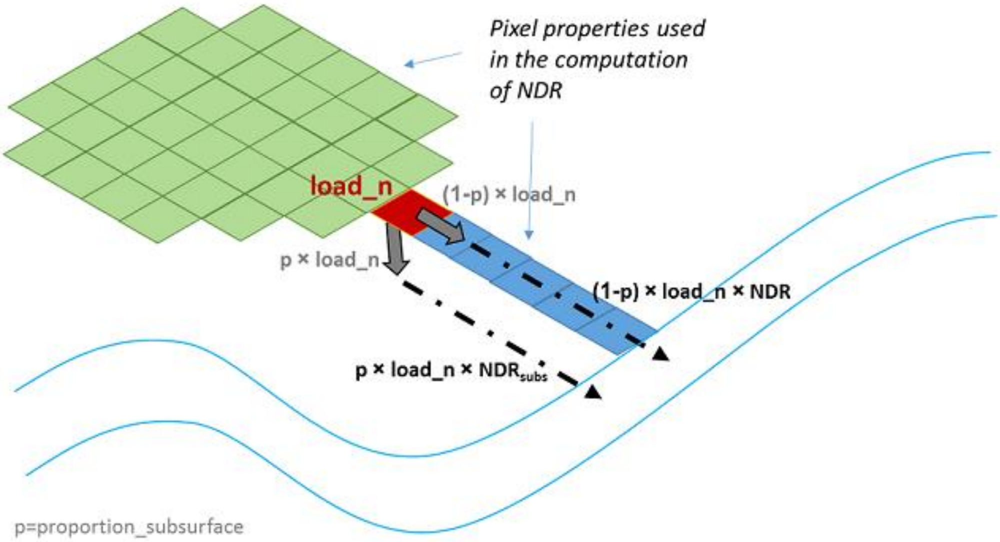
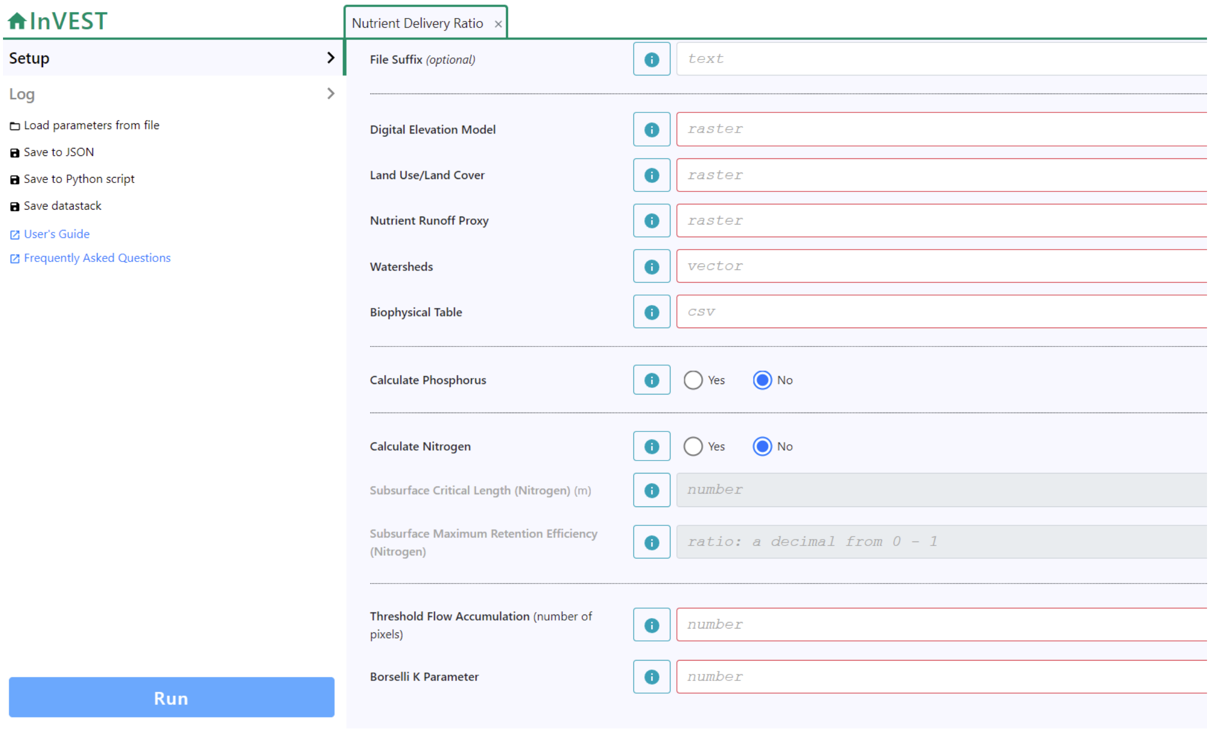


Figure 15 Conceptual representation of nutrient delivery in the model (Sharp et al., 2022)

The input data layers required for the NDR model constitute, DEM, LULC, and nutrient run-off proxy (considered to be rainfall Erosivity R) which have been discussed in Section 3.1. the InVEST NDR model requires several parameters, which are shown in Figure 16 (screenshot of the model). The biophysical table was prepared to assign nutrient loading values (kg/ha/year) for nitrogen and phosphorus to each land use class (shown in Table 7). Export coefficients were applied to estimate the fraction of nutrients that are transported from land to water. Retention efficiency and critical length parameters were also assigned based on land cover characteristics. The nutrients exported are further classified into proportion of surface and sub-surface based on the run-off phenomena. The description of the model parameters is provided in the following sections.



File Suffix (optional): text

Digital Elevation Model: raster

Land Use/Land Cover: raster

Nutrient Runoff Proxy: raster

Watersheds: vector

Biophysical Table: csv

Calculate Phosphorus: ○ Yes ● No

Calculate Nitrogen: ○ Yes ● No

Subsurface Critical Length (Nitrogen) (m): number

Subsurface Maximum Retention Efficiency (Nitrogen): ratio: a decimal from 0 - 1

Threshold Flow Accumulation (number of pixels): number

Borselli K Parameter: number

Figure 16 The InVEST NDR model variables and parameters

Table 7 Biophysical data for NDR model

lucode	lu_classes	load_n	load_p	eff_n	eff_p	crit_len_n	crit_len_p	proportion_subsurface_n	proportion_subsurface_p
1	Waterbody	0	0	0	0	0	0	0	0
2	Forest	3	0.8	0.85	0.85	300	300	0.3	0.05

3	Other vegetation	5	0.5	0.6	0.5	200	200	0.25	0.05
4	Flooded vegetation (wetland)	0	0	0.95	0.9	250	250	0.2	0.03
5	Agriculture	**19**	**6**	0.3	0.4	100	100	0.35	0.05
6	Rangeland	6	2	0.5	0.5	150	150	0.25	0.05
7	Urban	15	4	0.15	0.15	30	30	0.15	0.02
8	sand	5	1.5	0.2	0.2	50	50	0.4	0.05
9	Snow/Ice	0	0	0	0	0	0	0	0
10	Clouds	0	0	0	0	0	0	0	0
11	Bare ground	6	2	0.2	0.2	80	80	0.2	0.03

The nutrient retention efficiency parameter (in Table 7) represents the fraction of nutrients that are retained or absorbed by land cover before reaching rivers and streams in the Godavari River Basin. Retention occurs through processes such as plant uptake, soil adsorption, infiltration, and microbial activity. Forest areas in the basin were assigned high retention efficiencies (0.85 for nitrogen and 0.90 for phosphorus) because dense vegetation, litter layers, and deep root systems help trap nutrients and reduce runoff. Riparian forests and natural vegetation along streams are particularly effective in removing nutrients from surface flow (Mayer et al., 2007). Grasslands and rangelands were assigned moderate retention efficiencies because they provide vegetation cover and infiltration but generally retain fewer nutrients than dense forests. Croplands, which cover large portions of the upper and middle Godavari basin, were assigned lower retention efficiencies because agricultural practices such as tillage, fertilizer application, and irrigation increase the risk of nutrient loss through runoff. Whereas, Urban areas were assigned the lowest retention efficiencies (around 0.15 for nitrogen and 0.10 for phosphorus) because impervious surfaces such as roads, buildings, and drainage systems reduce infiltration and allow nutrients to move quickly into nearby rivers. This process is commonly described in urban watershed studies as part of the urban stream syndrome (Paul and Meyer, 2001). The selected parameter values are consistent with ranges recommended in the InVEST model documentation and ecosystem service modelling studies (Sharp et al., 2020; Redhead et al., 2018).

The critical length parameter (in Table 7) represents the average distance over which approximately 50% of nutrients are retained while moving across the landscape before reaching streams**.** Larger critical length values indicate slower runoff and greater opportunity for nutrient retention. Forested regions in the Godavari River Basin were assigned a critical length of about 300 m because dense vegetation and forest soils slow water movement and increase infiltration. Grasslands and rangelands were assigned intermediate values (150-200 m) because they provide moderate vegetation cover and moderate runoff conditions. Croplands were assigned a critical length of about 100 m because agricultural land surfaces often allow faster runoff compared to natural vegetation, especially during heavy rainfall events in the monsoon season. Urban areas were assigned a much smaller critical length (around 30 m) because water flows rapidly across impervious surfaces such as roads, pavements, and drainage networks, allowing little opportunity for nutrient retention. Similar parameter ranges have been recommended in watershed connectivity and nutrient transport studies (Vigiak et al., 2012; Sharp et al., 2020).

The subsurface proportion parameter represents the fraction of nutrients transported through groundwater pathways instead of surface runoff in the watershed. Nitrogen was assigned a higher subsurface proportion (about 0.3) because nitrate is highly soluble and can easily move through soil and groundwater systems. Many watershed studies indicate that 20-50% of nitrogen transport may occur through subsurface pathways depending on soil characteristics and hydrological conditions (Beusen et al., 2015; Howarth et al., 2012). In contrast, phosphorus strongly binds to soil particles and is therefore mainly transported through surface runoff and sediment erosion processes. For this reason, a much smaller subsurface proportion (about 0.05) was used for phosphorus. This difference in transport behaviour between nitrogen and phosphorus is well documented in watershed nutrient studies (Carpenter et al., 1998).

The subsurface critical length for nitrogen represents the distance that groundwater travels before about 50% of nitrogen is removed or retained through processes such as denitrification, plant uptake, and soil filtration. In the InVEST Nutrient Delivery Ratio (NDR) model, this parameter represents nitrogen transport through groundwater pathways rather than surface runoff and is expressed in meters (m) (Sharp et al., 2020). Literature suggests that subsurface critical length typically ranges between 100-300 m in agricultural basins**,** 200-500 m in forested watersheds, and 50-150 m in urban areas (Sharp et al., 2020; Beusen et al., 2015). For the Godavari River Basin, a value of 200 m was used. This value represents moderate groundwater attenuation, which is appropriate for the basin because it is characterized by basaltic geology of the Deccan Traps, monsoon-driven groundwater recharge, and extensive agricultural areas that contribute to nitrate leaching (Beusen et al., 2015; Sharp et al., 2020). In the InVEST model, this parameter is applied as a single value for the entire basin. Therefore, the Subsurface Critical Length (Nitrogen) was assigned to be 200 m for the quantification of nutrient export in GRB.

The subsurface maximum retention efficiency for nitrogen represents the maximum fraction of nitrogen that can be removed during groundwater transport before reaching streams, through processes such as denitrification, plant uptake, soil filtration, and microbial activity (Sharp et al., 2020). Literature suggests values of 0.4-0.6 for agricultural basins, 0.5-0.7 for forests, and 0.2-0.4 for urban areas (Sharp et al., 2020; Beusen et al., 2015; Howarth et al., 2012). In the present study on GRB, the value of 0.5 was used for sub-surface maximum retention efficiency of Nitrogen, representing moderate attenuation under basaltic geology, monsoon-driven recharge, and agricultural nitrate inputs. Thus, it is assumed that about 50% of nitrogen transported through groundwater is retained before reaching streams.

The threshold flow accumulation parameter defines the minimum number of upstream pixels required to initiate a stream channel in the model (Sharp et al., 2020). It controls the density of the stream network and nutrient delivery pathways. If the value is too small, the model generates too many streams and may overestimate nutrient delivery, while a large value may underestimate nutrient transport. In this study, a value of 1000 pixels was used. For a 30 m DEM, this corresponds to a drainage area of about 0.9 km², which falls within the typical 0.5-2 km² stream initiation range for medium-sized basins such as the Godavari River Basin. Threshold Flow Accumulation = 1000 pixels.

Other key parameters used in NDR model are similar to that of SDR model, which include: k (Borselli parameter), which controls the relationship between connectivity and delivery; IC_0 (threshold parameter), which defines the transition between low and high connectivity; Subsurface critical length, which controls nutrient movement below the surface. Other model parameters were set to default values as prescribed in the InVEST model (Sharp et al., 2022). Whereas, the nutrient loading values for cropland and other land use cover types required for NDR model (mentioned in Table 7)Table 7 were derived from fertilizer application rates. For 2024, values were estimated based on an increase from 2017 levels, reflecting gradual growth in fertilizer use. Other land cover types were assigned lower nutrient loads based on literature values. The calculation of the nutrient loading rates is discussed in the following sections.

3.3.1.1 Cropland nutrient loading estimation (2017)

Cropland nutrient loading parameters for the GRB were estimated using district-level fertilizer consumption data from seven states covered in the basin. The average fertilizer application rates were found to be 63.31 kg/ha/year for nitrogen and 30.92 kg/ha/year for phosphorus. Since only part of the applied fertilizer is transported to streams through runoff, export fractions of 30% for nitrogen and 20% for phosphorus were considered. Based on these fractions, the effective loading values used in the NDR model were 19 kg/ha/year (N) and 6 kg/ha/year (P), shown in Table 7.

3.3.1.2 Cropland nutrient loading estimation (2024)

Fertilizer use in India has increased gradually over time rather than showing sudden large changes. Long-term data indicate that the annual growth of nitrogen (N), phosphorus (P_2O_5), and potassium nutrients has remained within low percentages for several decades, with nitrogen consumption increasing by about 3% per year between 1990-91 and 2018-19 Sharma et al. (2022). In 2023-24, total nutrient consumption has increased by about 2.7% compared to the previous year, with nitrogen use increased by around 1.2% and phosphate use increased by 4.9%. The fertilizer application per hectare has also grown slowly, rising from about 165 kg/ha in 2010 to nearly 195-200 kg/ha by 2024 (Fertilizer Association of India (FAI) Annual Report 2023-24). Future projections also suggest steady growth, with expected annual increases of only about 1-2% CAGR from 2024 to 2028 over the coming years. These patterns indicate that fertilizer consumption changes gradually due to progressive increases in agricultural activities and cropping intensity. Hence, the district-level fertilizer data for 2024 are not fully available, applying a moderate increase of about 10-15% over the 2017 cropland nutrient loading rates is a reasonable and scientifically accepted approach. This adjustment represents realistic growth in fertilizer use while remaining consistent with national trends.

3.3.1.3 Nutrient Loading for Non-Cropland Land Covers

For natural land cover classes such as forest, rangeland, and other vegetation present in GRB, nutrient loading values were assigned based on published estimates of natural nutrient export from undisturbed or minimally disturbed landscapes. Forest ecosystems usually generate very low nutrient export because there is no fertilizer application and most nutrients are absorbed by vegetation, litter layers, and soil processes. Studies have shown that nitrogen export from natural forests generally ranges between 1-5 kg N/ha/y while phosphorus export is usually less than 1-2 kg P/ha/y (Howarth et al., 1996; Beusen et al., 2015). Therefore, in this study forests within the Godavari basin were assigned nutrient loading values of 3 kg N/ha/y and 0.8 kg P/ha/y**,** which fall within the typical natural export range. Areas categorized as other vegetation were assigned slightly higher nutrient loading values (4 kg N and 1.2 kg P per ha per year) because these areas may include mixed shrubs, grass patches, or partially disturbed vegetation. Compared to dense forests, these landscapes may have lower canopy cover and slightly higher runoff, which can increase nutrient export.

Rangelands and grazing areas, which occur in several parts of the Godavari basin, were assigned higher nutrient loading values (6 kg N and 2 kg P per ha per year) because nutrients can be added through livestock manure, grazing activity, and soil disturbance. Global nutrient budget studies indicate that grasslands and grazing systems can export 5-15 kg N/ha/y depending on grazing intensity (Bouwman et al., 2005).

Urban areas in the Godavari River Basin, such as cities like Nashik, Nanded, and other rapidly growing urban centers, contribute higher nutrient loads due to stormwater runoff, sewage leakage, septic systems, and organic waste accumulation. Therefore, urban land cover was assigned nutrient loading values of 15 kg N/ha/y and 4 kg P/ha/y. Previous studies show that nitrogen export from urban areas typically ranges between 10-30 kg N/ha/y depending on the level of urban development and wastewater infrastructure (Paul and Meyer, 2001; Beusen et al., 2015).

Bare land and sandy areas were assigned moderate nutrient loading values because nutrient transport from these surfaces mainly occurs through soil erosion and sediment transport, particularly for phosphorus which is often attached to soil particles during runoff events (Sharpley et al., 1994).

3.3.2 Nitrogen Export results

3.3.2.1 2017

The pixel-wise spatial distribution of nitrogen export is shown in Figure 17. Figure 18 shows the choropleth across various districts, which is the sum of the nitrogen export in the district areas in GRB for 2017. The results show clear variation due to differences in land use, farming intensity, and water flow conditions. Very high nitrogen export is seen in Karimnagar (~5.89 million kg/year), Yavatmal (~5.85 million kg/year), and Adilabad (~5.79 million kg/year) Districts. These districts are located in the central part of the basin and have intensive farming activities such as cotton and soybean cultivation. The use of large amounts of fertilizers in these areas leads to higher nitrogen runoff.

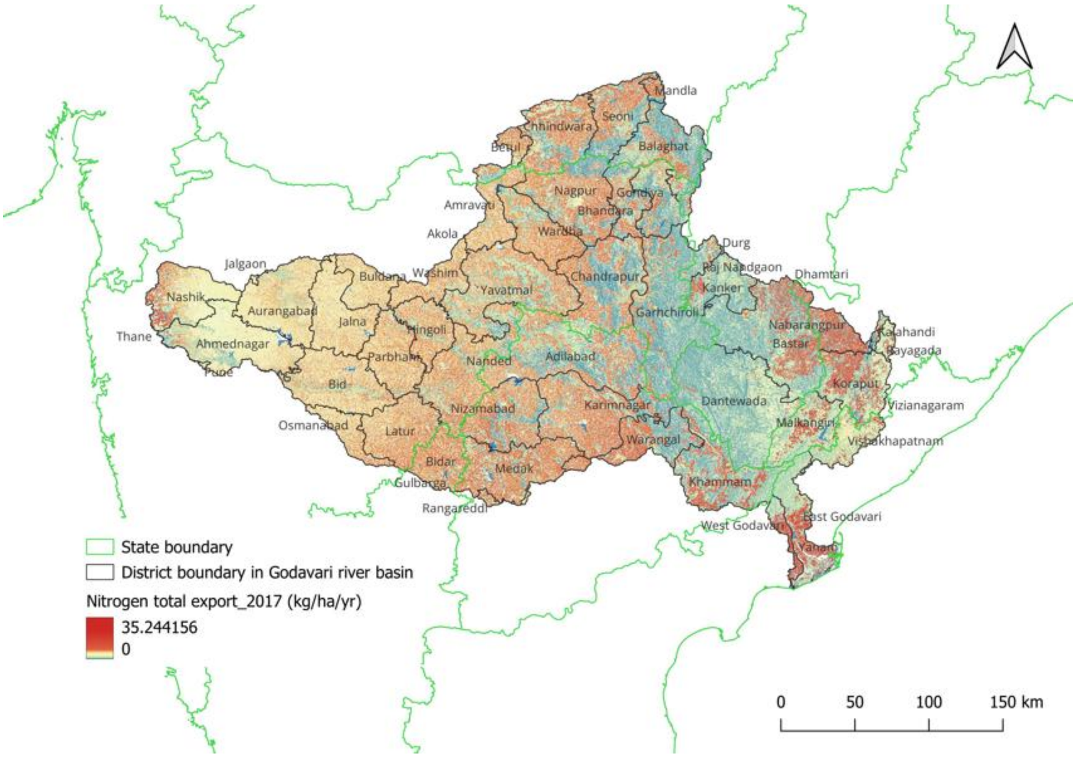


Figure 17 Pixel-wise spatial distribution of Nitrogen export in the basin for 2017

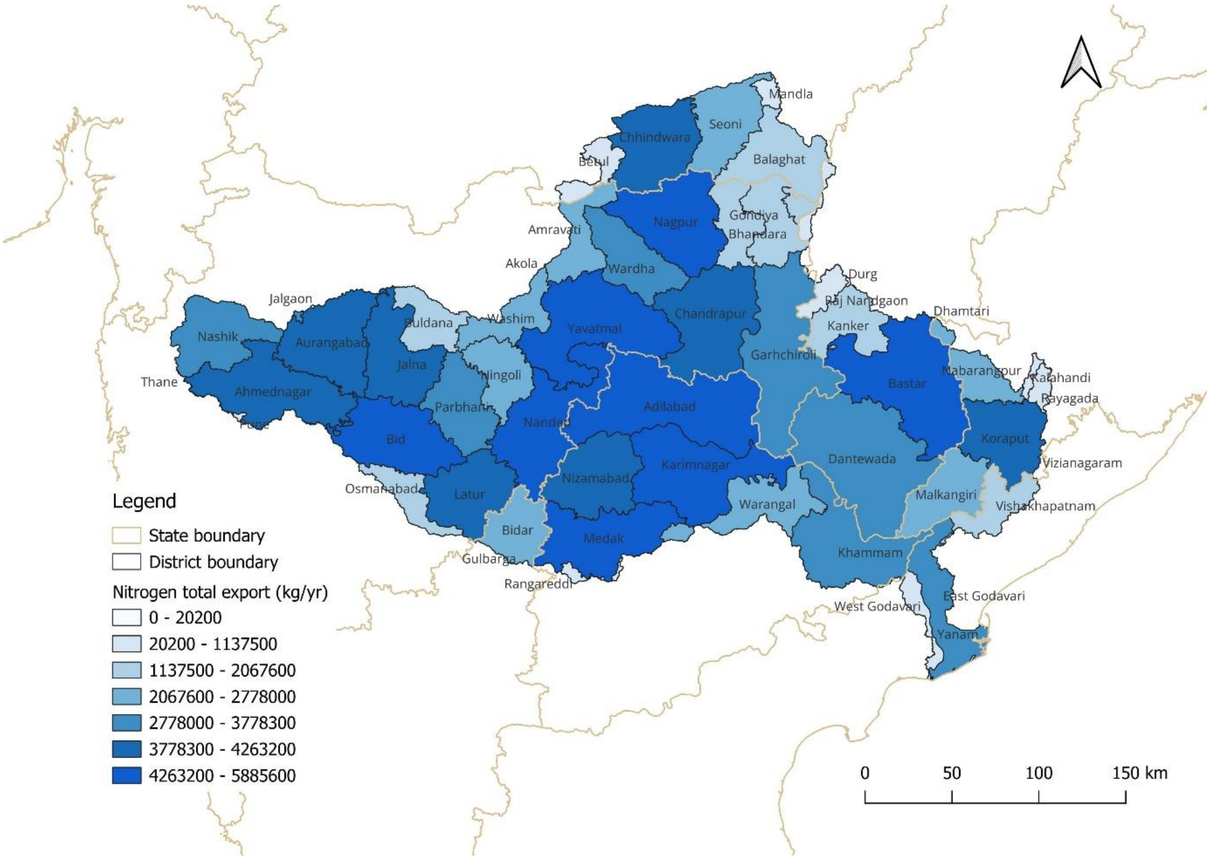


Figure 18 Nitrogen total export (kg/yr) 2017

Other districts such as Nanded (~5.19 million kg/year), Medak (~5.18 million kg/year), Bastar (~4.89 million kg/year), and Nagpur (~4.68 million kg/year) also show high nitrogen export (above 4 million kg/year). This is due to a combination of agricultural inputs and conditions that allow runoff to carry nutrients easily. Moderate nitrogen export is observed in districts like Bid (~4.39 million kg/year), Latur (~4.17 million kg/year), and Chandrapur (~4.13 million kg/year). These areas have mixed land use and moderate farming activity, so both natural conditions and agriculture influence nitrogen movement.

On the other hand, districts with more vegetation, less intensive farming, or flatter land show lower nitrogen export. In these areas, water moves more slowly and nutrients are better retained in the soil. Overall, nitrogen export in 2017 ranges from less than 1 million kg/year in low-activity areas to more than 5.8 million kg/year in highly cultivated districts. The highest values are mainly found in central agricultural regions, showing that fertilizer use and land management play a major role in nutrient loading. These results highlight the need for better nutrient management practices, especially in high-intensity farming areas, to reduce nitrogen loss and protect water quality in the basin.

3.3.2.2 2024

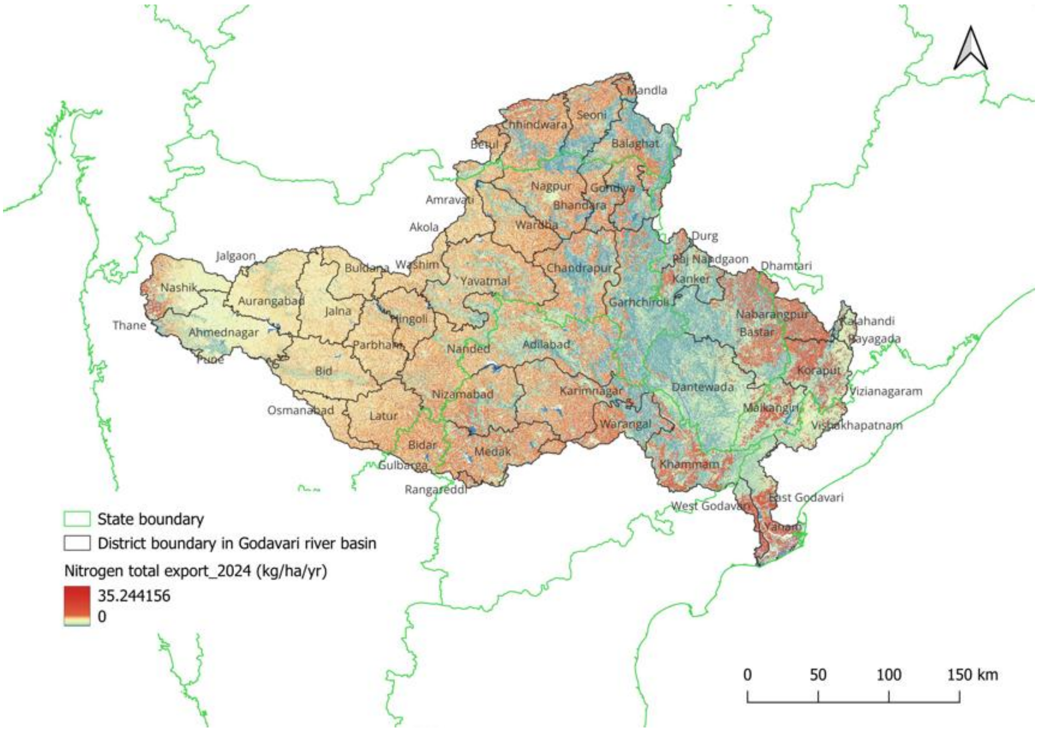


Figure 19 Pixel-wise spatial distribution of Nitrogen export in basin for 2024

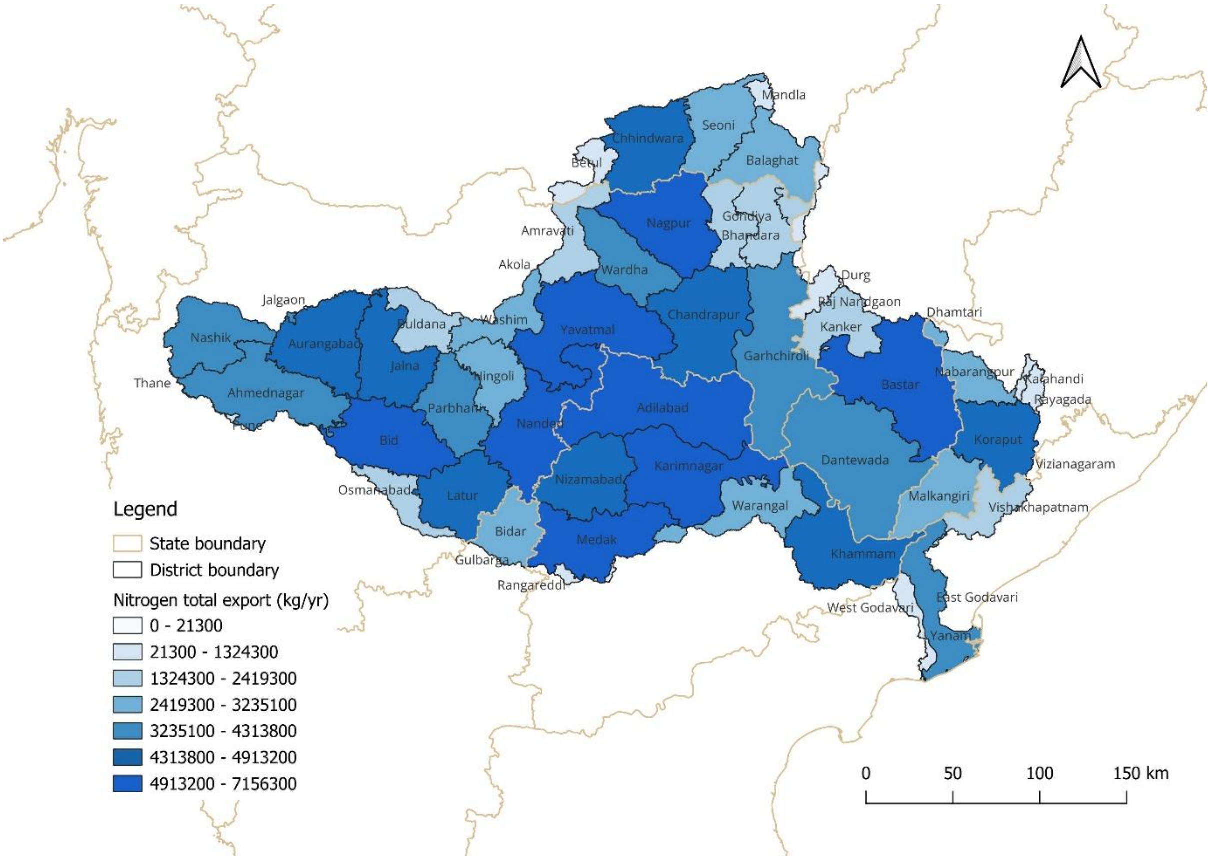


Figure 20 Nitrogen total export (kg/yr) 2024

The pixel-wise distribution of the Nitrogen export in the basin for 2024 is shown in Figure 19. The distribution of total nitrogen export across districts in the Godavari River Basin in 2024 shows a clear increase compared to 2017, with noticeable variation across the basin (Figure 20). Very high nitrogen export is observed in districts such as Adilabad (~7.1 million kg/year), Yavatmal (~7 million kg/year), and Karimnagar (~6.7 million kg/year). These districts are located in the central part of the basin and have intensive agricultural activities with higher fertilizer use, which leads to increased nitrogen runoff, especially during the monsoon season.

Other districts such as Nanded (~6.17 million kg/year), Bastar (~6.12 million kg/year), Medak (~5.93 million kg/year), and Nagpur (~5.28 million kg/year) also show high nitrogen export (above 5 million kg/year). This is due to a combination of agricultural inputs and strong hydrological connectivity, which allows nutrients to move easily into river systems. Moderate nitrogen export is observed in districts such as Bid (~4.9 million kg/year), Chandrapur (~4.8 million kg/year), and Latur (~4.8 million kg/year). These areas have mixed land use and moderate agricultural activity, so both natural conditions and human activities influence nitrogen transport. Lower nitrogen export is found in districts with less intensive farming, better vegetation cover, or flatter terrain. In these areas, runoff is lower and more nutrients are retained in the soil.

Overall, nitrogen export in 2024 ranges from less than 1 million kg/year in low-intensity regions to more than 7 million kg/year in highly cultivated districts. Compared to 2017, most districts show an increase in nitrogen export, especially in central agricultural regions. This trend highlights the growing impact of agricultural intensification on nutrient loading and the need for better nutrient management practices to reduce nitrogen loss and protect water quality in the basin.

3.3.2.3 Comparison of Nitrogen Export (2017-2024)

The comparison of nitrogen export between 2017 and 2024 shows a clear increase in nutrient loading across most districts of the Godavari River Basin. In 2017, the highest nitrogen export was recorded in Karimnagar (~5.8 million kg/year), Yavatmal (~5.8 million kg/year), and Adilabad (~5.7 million kg/year) Districts. By 2024, these values increased significantly, with Adilabad reaching ~7.1 million kg/year, Yavatmal ~7.0 million kg/year, and Karimnagar ~6.7 million kg/year. This shows a strong increase in nitrogen export, especially in the central agricultural regions of the basin.

District-wise percentage analysis shows that many districts experienced noticeable increases. Gondia recorded the highest increase (~48.6%), followed by Dhamtari (~45.1%), Rajnandgaon (~41.6%), and Bhandara (~36.2%). Other districts such as Kanker (~29.9%), Khammam (~29.3%), Malkangiri (~27.0%), Bastar (~25.3%), and Adilabad (~23.7%) also showed significant increases. These results indicate that nitrogen export is rising not only in major agricultural areas but also in regions that previously had low or moderate levels.

Overall, nitrogen export increased by about 20-50% in many districts across the basin (the values of top 10 districts are mentioned in Table 8). Higher increases are observed in transition areas and regions near forests, which may be due to expansion of agriculture and better movement of water that carries nutrients. The results show that central and eastern districts continue to be major contributors, while other districts are becoming new hotspots. This overall increase highlights the growing impact of agricultural activities and the need for better nutrient management practices to reduce nitrogen loss and protect water quality in the basin.

Table 8 District-wise increase in Nitrogen export in GRB (between 2024 and 2017)

District	% Increase
Gondia	+48.6%

Dhamtari	+45.1%
Rajnandgaon	+41.6%
Bhandara	+36.2%
Kanker	+29.9%
Khammam	+29.3%
Malkangiri	+27.0%
Bastar	+25.3%
Adilabad	+23.7%

3.3.3 Phosphorous Export results (2017 vs 2024)

3.3.3.1 2017

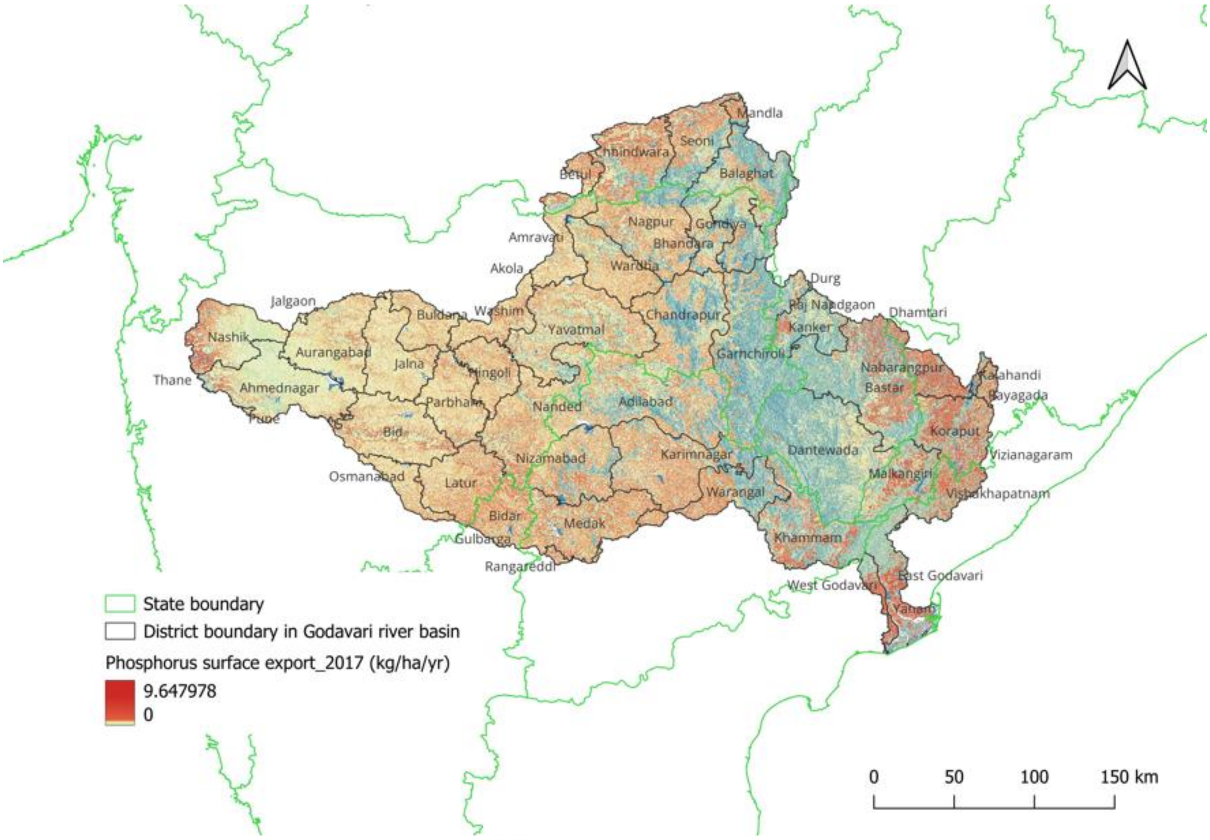


Figure 21 Pixel-wise distribution of Phosphorous in Godavari River Basin in 2017

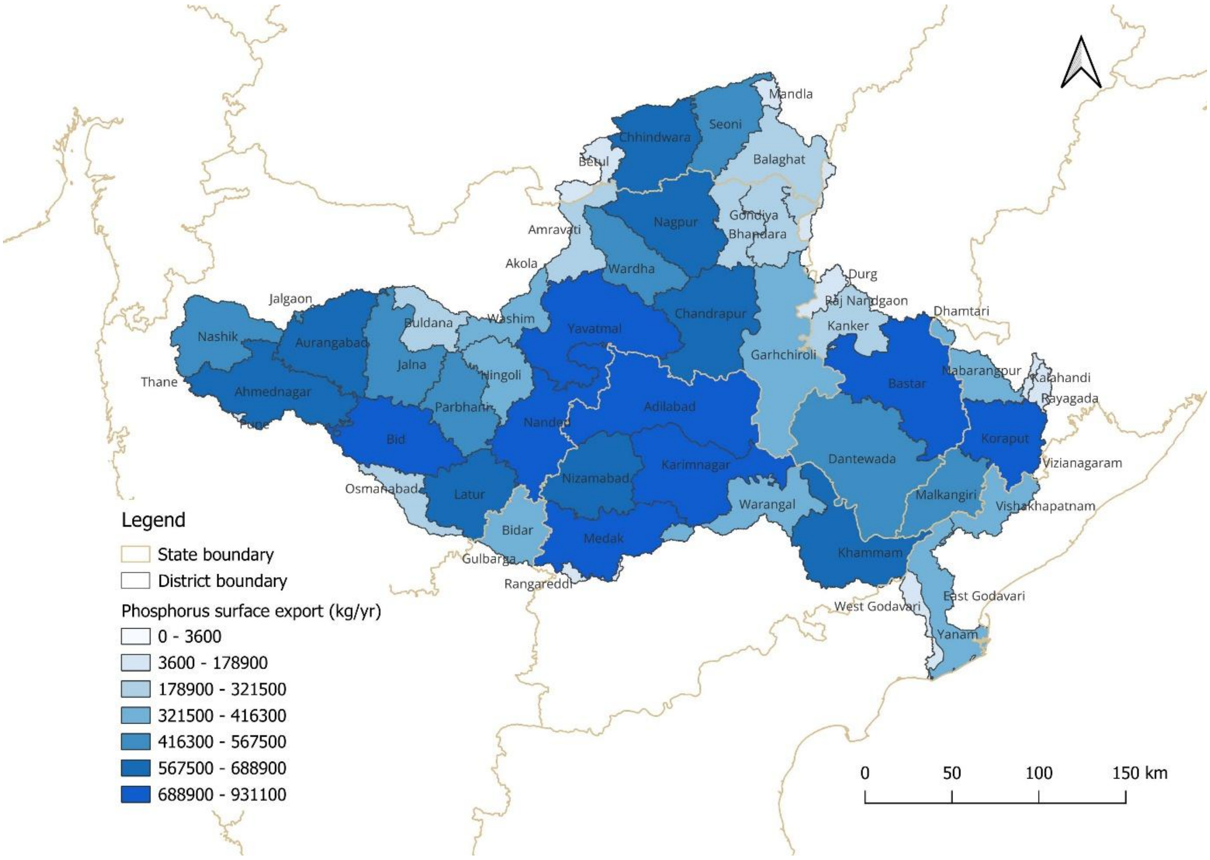


Figure 22 Phosphorous surface export (kg/yr) 2017

The pixel-wise distribution of Phosphorous in the basin simulated by InVEST NDR model for year 2017 is shown in Figure 21.The district-wise distribution of total Phosphorous export across districts in the Godavari River Basin in 2017 (Figure 22) shows clear variation mainly due to farming practices, soil properties, and water flow conditions. Very high phosphate export is seen in districts such as Yavatmal (~931,107 kg/year), Adilabad (~921,558 kg/year), and Karimnagar (~885,058 kg/year). These districts are located in the central part of the basin and are dominated by intensive agriculture. High fertilizer use and strong surface runoff, especially during the monsoon, lead to increased phosphorus transport. High phosphorus export (600,000–900,000 kg/year) is also observed in districts such as Nanded (~818,653 kg/year), Bastar (~794,500 kg/year), Medak (~788,531 kg/year), Koraput (~694,561 kg/year), Bid (~690,646 kg/year), Nagpur (~687,624 kg/year), and Chhindwara (~677,176 kg/year). In these areas, both agricultural inputs and terrain conditions, such as slopes, contribute to the movement of phosphorus. Moderate phosphorus export is found in districts with mixed land use and moderate farming activity. In these regions, both natural factors and human activities influence nutrient transport, making them transition zones between high and low export areas.

Lower phosphorus export is generally seen in districts with better vegetation cover, less fertilizer use, or flatter land. In these areas, runoff is lower and phosphorus is more likely to remain in the soil due to natural retention processes. Overall, phosphorus export in 2017 ranges from less than 100,000 kg/year in low-intensity regions to more than 900,000 kg/year in highly cultivated districts. The highest values are mainly found in central agricultural areas, showing that fertilizer use and surface runoff play a major role in phosphorus transport. These results highlight the need for better nutrient management practices, especially in high-export districts, to reduce phosphorus loss and prevent water quality problems such as eutrophication.

3.3.3.2 2024

The pixel-wise spatial distribution of Phosphorous in the basin simulated by InVEST NDR model for 2024 is shown in Figure 23. The district-wise distribution of total phosphorus export across districts in the Godavari River Basin in 2024 (Figure 24) shows a clear increase compared to 2017. This increase is mainly due to higher agricultural activities and the movement of water during rainfall. Very high phosphorus export is observed in districts such as Adilabad (~1,171,045 kg/year), Yavatmal (~1,119,542 kg/year), and Karimnagar (~1,025,698 kg/year). These districts are located in the central part of the basin and have intensive fertilizer use along with strong runoff, which increases phosphorus transport during the monsoon.

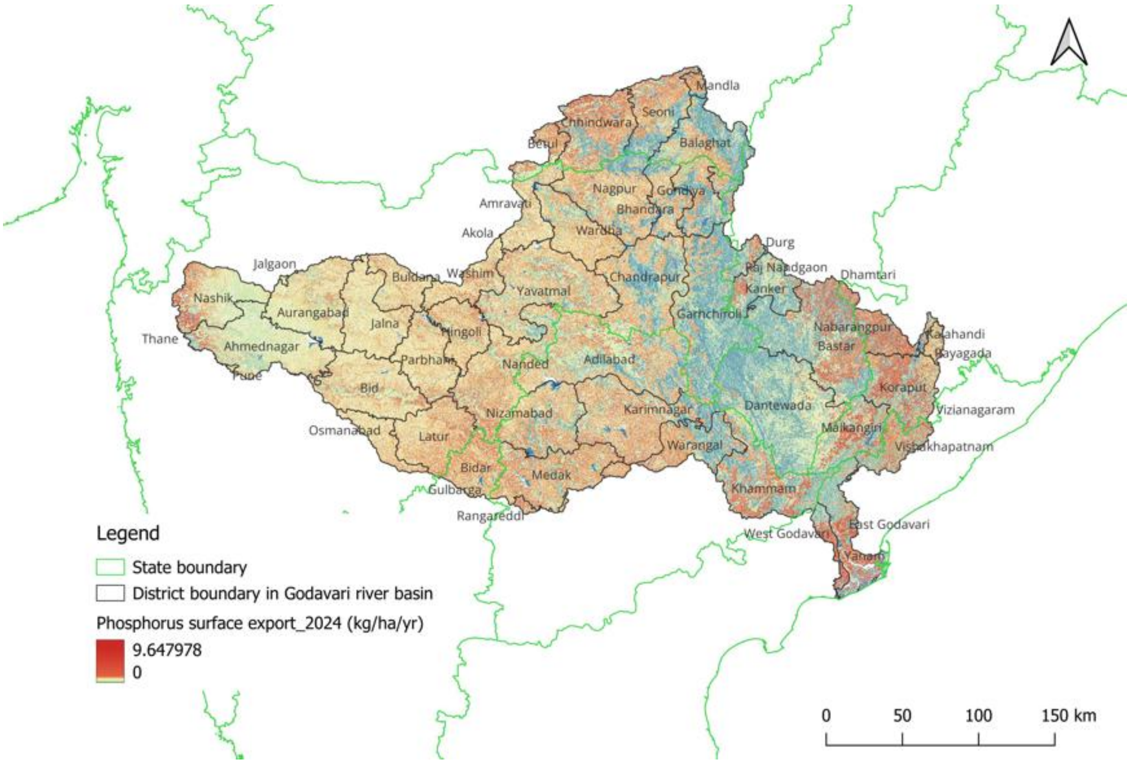


Figure 23 Pixel-wise distribution of Phosphorous export in the basin in 2024

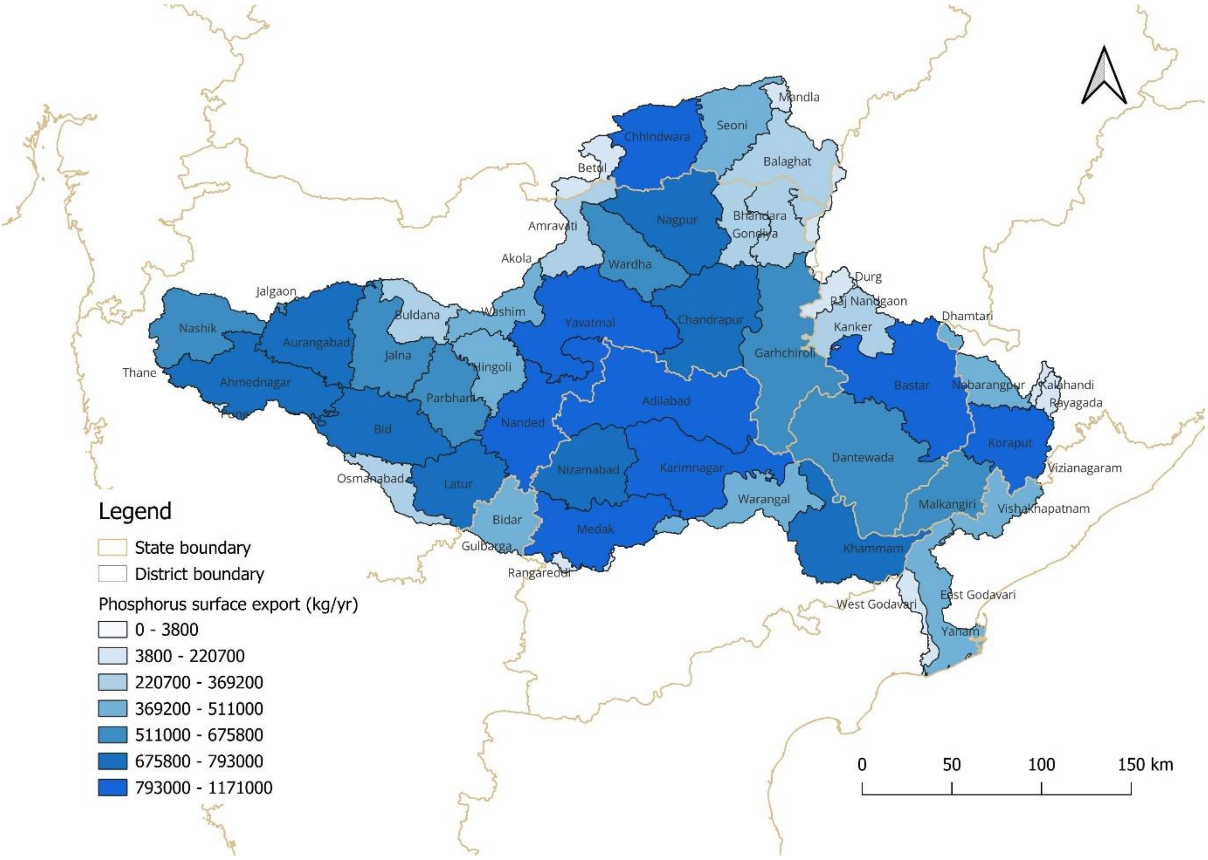


Figure 24 Phosphorus surface export (kg/yr) 2024

High phosphorus export (above 800,000 kg/year) is also seen in districts such as Bastar (~1,008,407 kg/year), Nanded (~979,960 kg/year), Medak (~910,884 kg/year), Koraput (~811,423 kg/year), and Chhindwara (~805,912 kg/year). In these areas, agriculture, terrain conditions, and rainfall together contribute to higher nutrient movement. Moderate phosphorus export is observed in districts such as Nagpur (~783,366 kg/year) and Bid (~782,536 kg/year), where mixed land use and moderate farming activity influence nutrient transport. Lower phosphorus export is found in districts with less fertilizer use, better vegetation cover, or flatter land. In these areas, runoff is lower and phosphorus is more likely to stay in the soil. Overall, phosphorus export in 2024 ranges from less than 100,000 kg/year to more than 1,171,045 kg/year, showing a strong variation across the basin.

3.3.3.3 Comparison of Phosphorus Export (2017-2024)

The comparison of phosphorus export between 2017 and 2024 shows a steady increase in nutrient loading across most districts of the GRB (Table 9). In 2017, the highest phosphorus export was recorded in Yavatmal (~0.931 million kg/year), Adilabad (~0.92 million kg/year), and Karimnagar (~0.88 million kg/year). By 2024, these values increased significantly, with Adilabad reaching ~1.17 million kg/year, Yavatmal ~1.11 million kg/year, and Karimnagar ~1.02 million kg/year. This shows a strong increase in phosphorus export, especially in central agricultural regions.

The district-wise percentage analysis shows that many districts experienced noticeable increases. Gondia recorded the highest increase (~41.9%), followed by Dhamtari (~37.9%), Rajnandgaon (~37.3%), and Khammam (~35.4%). Other districts such as Bhandara (~31.8%), Kanker (~29.9%), Malkangiri (~29.1%), Dantewada (~28.8%), Adilabad (~27.1%), and Bastar (~26.9%) also showed significant increases. These results indicate that phosphorus export is rising not only in major agricultural areas but also in districts that previously had lower or moderate levels. Overall, phosphorus export increased by about 13-42% in most districts across the basin. Higher increases are seen in transition areas and regions near forests, likely due to expansion of agriculture and increased runoff. The pattern shows that central and eastern districts continue to be the main contributors, while other districts are becoming new hotspots. This increasing trend reflects higher fertilizer use and stronger runoff, which raises concerns about nutrient buildup and eutrophication in downstream water bodies.

Table 9 District-wise increase in Phosphorus export in GRB (between 2024 and 2017)

District	% Increase
Gondia	+41.9%
Dhamtari	+37.9%
Rajnandgaon	+37.3%
Khammam	+35.4%
Bhandara	+31.8%
Kanker	+29.9%
Malkangiri	+29.1%
Dantewada	+28.8%
Adilabad	+27.1%
Bastar	+26.9%

3.3.4 Nutrient load management - management practices priority areas and suggestions

Nutrient load management in the GRB should focus on areas where nitrogen and phosphorus export is high and increasing between 2017 and 2024. The results show that nutrient export has increased in most districts, especially in areas with intensive farming and in transition zones. This indicates growing pressure on water quality.

High-priority areas include districts such as Adilabad, Yavatmal, Karimnagar, Nanded, Medak, and Bastar, which show very high nitrogen (more than 6 million kg/year) and phosphorus (more than 1 million kg/year) export in 2024. These districts are located in the central agricultural region of the basin and are characterized by high fertilizer use, rainfed farming, and strong runoff, which carries nutrients into rivers. In addition, districts like Khammam, Malkangiri, Dantewada, and Kanker are emerging hotspots, as they show high increases (20–40%) in nutrient export and need immediate attention.

In these high-risk agricultural areas, management practices should focus on using fertilizers more efficiently and reducing nutrient loss. Practices such as soil testing-based fertilizer application, applying fertilizers in smaller doses (split application), and using precision farming techniques can help reduce excess nutrient use. Conservation agriculture practices like minimum tillage, crop rotation, and cover crops can improve soil condition and reduce runoff. Planting vegetation along riverbanks (riparian buffers) can also help trap nutrients before they reach water bodies.

In transition areas and regions near forests, combined approaches such as agroforestry and proper land-use planning are needed. These areas often show increasing nutrient export due to expansion of agriculture into previously less disturbed land. On the other hand, districts with low nutrient export, such as Gondia, Bhandara, and East Godavari, should be protected by maintaining vegetation cover and using sustainable farming practices. Overall, nutrient management should focus on districts with high export and rapid increases. Using better farming practices, proper land management, and regular monitoring can help reduce nutrient loss and prevent problems like eutrophication in downstream water bodies.

3.4 Impact on environment

3.4.1 Excess nutrients (N, P)

Excess nitrogen and phosphorus in the Godavari basin, mainly from fertilizers, sewage, and some industries, causes seasonal water pollution. This leads to various negative impacts such as algal blooms, low oxygen levels in water, changes in aquatic life, and problems for fisheries. It also increases the cost of treating drinking water and carries excess nutrients to the Bay of Bengal. These problems are strongest during the monsoon and vary from place to place across the basin. Some of the major impacts are described in following sections.

3.4.1.1 Eutrophication

Due to increase in nitrogen and phosphorus content it results in high contamination of water bodies affecting various components in ecosystems. In the GRB, nearly 60% of the land is covered under farmlands, which contribute to the high amount of nutrients exported due to the use of excessive fertilizers in the basin. Due to high nutrient load in water bodies, rapid growth of algal blooms takes place, which makes the water turn green and turbid as the layer of algae blocks sunlight reaching to submerged plants, reducing their ability to photosynthesize and eventually die. Due to the dead algae and plants, which consumes significant amount of dissolved oxygen in the decay process. This reduction in oxygen levels called hypoxia caused deadly condition for fish and other aquatic organisms. In GRB, particularly in reservoirs such as Jayakwadi, Sriramsagar, Indravati, and Polavaram backwaters are prone to this condition.

3.4.1.2 Water quality degradation

When excess nutrients cause algal growth and increase organic matter in river water, more treatment is needed to make the water safe for drinking. This means using extra chemicals, better filtration, and regular checking for algal toxins, which increases the cost of water treatment. Cities like Nashik, which depend on the Godavari, face these higher costs, and government reports have pointed out sewage and water-quality problems in urban areas along the river.

3.4.1.3 Higher drinking-water treatment costs

Extra nutrients in river water cause more algae and organic matter to grow. This makes water harder to clean and requires additional treatment steps like better filtration, use of activated carbon, and regular checking for algal toxins. As a result, drinking-water treatment becomes more expensive and complicated for cities along the Godavari, such as Nashik, and for smaller towns that do not have proper sewage treatment systems.

3.4.1.4 Altered food webs and reduced biodiversity

When excess nutrients enter into the Godavari river for a long time, fast-growing algae increase. These algae block sunlight and worsen the living conditions in the water. As a result, sensitive fish, and aquatic vegetation decline, while only tolerant species can survive and affects natural processes like nutrient recycling, food availability, and habitat for larger organisms.

3.4.1.5 Strong monsoon-driven nutrient pulses

Most nutrients are carried into the Godavari River during the monsoon season. Heavy rainfall increases runoff and soil erosion, which washes large amounts of nutrients into the river at once. This causes sudden pollution events that affect downstream areas and even coastal regions.

3.4.1.6 Increased Pathogen and Contaminant Transport

High nutrient-rich runoff and sewage also carry fine soil particles, organic waste, harmful metals, and faecal germs into the river. This increases pollution risks and makes river cleaning and public health protection more difficult. In parts of the Godavari River basin, nutrient-rich runoff mixed with untreated sewage leads to high levels of faecal bacteria and disease-causing organisms.

3.4.1.7 Reservoir and flow-regulation effects on nutrient dynamics

Dams and reservoirs in the Godavari basin change how and when nutrients move downstream. They trap soil and nutrient particles, hold water for longer time, and allow nutrients to be processed inside the reservoir. This changes the amount and timing of nutrients reaching downstream rivers and affects eutrophication and seasonal water-quality patterns (Balakrishna et al., 2005).

3.4.1.8 Increased greenhouse-gas and carbon cycling consequences in estuaries

Large amounts of organic waste entering the Godavari estuary increase microbial activity. Microorganisms use more oxygen to break down this organic matter, releasing more carbon dioxide (CO_2) and methane from the estuary into the air. During calm or stagnant periods, these gases can escape from the water into the atmosphere, adding to greenhouse gas emissions.

3.4.2 Impacts of excess Sediments

Excess of sediment in rivers slows the flow of water, reduces reservoir storage capacity, decrease water quality, and damages fish and plant habitats. In the Godavari River Basin, increased soil erosion from land-use changes have made all these problems worse causing unstable river channels and less sediment reaching downstream areas and coastal ecosystem. Some of the major impacts caused by the excess sediments in the river are discussed in the following sections.

3.4.2.1 Reservoir siltation

River-borne sediment settles in reservoirs over time, filling storage space and reducing their ability to supply water, control floods, and generation of hydropower. As storage declines, flood risk increases during high-flow periods and water shortages become more severe during dry seasons. In GRB several studies show that the Godavari River carries large amount of sediment loads, much of which is trapped in reservoirs, results in reducing sediment reaching the coast and decreasing reservoir storage capacity.

3.4.2.2 Downstream sediment depletion

When reservoirs trap large amount of sediment, the sediment supply to downstream river reaches and the coast is significantly reduced. This sediment starvation causes rivers and coastlines to erode existing beds, banks, and shorelines, leading to channel degradation and coastal erosion. In the Godavari River Basin, extensive sediment trapping by large reservoirs like Jayakwadi, Sriramsagar/SRSP, Nizamsagar, Polavaram, and other several large barrages such as Medigadda/Kaleshwaram and Kaddam trap very large fractions of the upstream sediment load, contributing to channel erosion and sediment starvation in the delta and coastal regions (Sumit Das et al., 2021).

3.4.2.3 Water-quality degradation

Suspended sediments degrade water quality by increasing turbidity, which limits light penetration and slows the growth of aquatic plants. These sediments also carry nutrients and harmful pollutants like heavy metals and pesticides, disturbing natural processes in the river and complicating drinking-water treatment, particularly during monsoon periods. This elevated turbidity in monsoon and post-monsoon periods raises treatment costs for municipal water supplies and can intensify contamination of fisheries and irrigation water. Some studies carried out in GRB have shown that agricultural runoff and urban activities are the main sources of sediment and associated pollutants, and the reservoir sediment trapping has significantly altered water quality and sediment transport patterns (Hussain et al. 2017, Das 2021, Central Water Commission, 2019).

3.4.2.4 River morphology changes

Excess sediment deposited in river channels and floodplains causes the riverbed to rise (bed aggradation) and leads to the formation of sand bars within the channel. These deposits change the shape of the river, resulting in narrowing or widening of the channel and making riverbanks more unstable. When the riverbed rises in certain reaches, the channel can carry less water, so floods occur more easily and spread over a larger area. In contrast, in some reaches where sediment supply is low, the river may erode its bed, which can destabilize banks and damage nearby land and structures. In some tributaries and river reaches in GRB, local sediment built up (aggradation) has been observed, which makes the river channel shallower. This problem is especially noticeable in urban areas, where regular desiltation works are required to maintain flow capacity, such as around Nashik and other major towns along the Godavari River. Changes in such channel complicate and river and engineering structures like bridges, piers, and embankments (Sangharsha Gambhir et al., 2020).

3.4.2.5 *Agriculture and floodplain fertility*

Periodic sediment deposition during floods helps in replenishing floodplain soils and maintain their natural fertility, which supports agriculture. However, when sediment deposition is too heavy, contains coarse materials such as sand or gravel, or if occurs suddenly, it can bury standing crops, change soil properties, and lower farm productivity. In addition, when sediment supply to downstream farmlands is reduced, often due to sediment trapping in upstream parts, soil nutrients are not naturally renewed, leading to a decline in long-term soil fertility. Periodic flooding of the GRB historically supported highly productive floodplain and deltaic agriculture by depositing fine sediments rich in nutrients and organic matter, thereby maintaining soil fertility, moisture retention, and favourable soil structure. However, extensive dam and reservoir construction across the basin has significantly reduced downstream sediment transport, disrupting this natural replenishment process. As a result, floodplain and delta soils increasingly depend on external fertiliser inputs to sustain crop yields.

3.4.2.6 *Economic and infrastructure impacts*

Excess sediment in rivers has clear economic and infrastructure impacts. When too much sediment accumulates in river channels, reservoirs, and canals, authorities must carry out frequent dredging and desiltation, which is expensive and needs regular funding. Sediment deposition reduces the depth of rivers, making navigation difficult for boats and inland transport, and increases maintenance problems for irrigation canals, pumping stations, and water intake structures. Sediment can also collect around bridge piers and foundations, increasing the risk of structural damage during floods. In the GRB, local governments regularly undertake desiltation works in urban and riverine stretches, placing a financial burden on municipal and water resource departments. In reservoirs, sedimentation leads to loss of dead and live storage, which reduces irrigation water availability and lowers hydropower generation potential, causing long-term economic losses. National-level studies on reservoir siltation in India show that sedimentation imposes significant recurring costs and reduces the effective life of major water infrastructure, making sediment management a major economic concern.

4 Optimal management practices and policies

GRB faces serious problems due to high nutrient and sediment loads**.** These problems mainly arise from intensive agricultural activities, where excessive use of fertilizers leads to nutrient runoff, and from rapid urban growth, which produces large amounts of untreated or partially treated wastewater. In addition, soil erosion in upland areas and sediment trapping by reservoirs and dams disturb the natural movement of sediments in the river system. The basin is strongly influenced by the monsoon climate, during which heavy rainfall causes high runoff and carries large amounts of nutrients and sediments into the river in a short time. Therefore, to manage the Godavari River Basin properly, it is necessary to plan land use carefully, improve sewage and wastewater treatment systems, protect and restore natural areas like riversides and floodplains, and strict enforcement of environmental rules.

4.1 Integrated watershed soil conservation and erosion control

Practice: Implementation of soil and water conservation measures (contouring, terracing, vegetative filter strips) in upland sub-basins reduces sediment generation and transport toward the Godavari mainstream. Studies in similar tropical basins show that terracing, contour farming and grass filter strips can reduce sediment yield by 40-70% when applied in erosion-prone parts of catchments.

Policy: Watershed programs at the basin level should make soil conservation practices compulsory in agricultural areas that produce high amounts of sediment. Farmers in these areas should be supported through subsidies, training, and technical help under state watershed development schemes, especially in the upper Godavari catchment (Das et al. 2023).

4.2 Riparian Zone Restoration and Floodplain Buffer Establishment

Practice: Growing natural plants along riverbanks and small streams helps to stop soil and nutrients from reaching the river, keeps the riverbanks stable, and reduces runoff from nearby land.

Policy: The government should officially mark no-development zones along the Godavari River and its tributaries, where activities like construction and farming are restricted, similar to the riverbank protection rules used in other Indian river basins such as the Ganga.

4.3 Land-Use Planning and Regulation to Reduce Soil Disturbance

Practice**:** Land clearing and intensive farming should be limited on steep slopes and weak soils in the Deccan Plateau areas of the Godavari basin to reduce soil erosion. Studies of the basin show that bare or degraded land areas produce much more sediment, especially during the monsoon, because heavy rainfall and sloping land wash soil into rivers.

Policy: State government plans for farming, forests, and rural areas should look at how easily soil gets washed away, so that farming is not started or expanded in places where soil erosion is high.

4.4 Reservoir and Dam Sediment Management

Practice: Reservoirs and dams should be operated in a way that removes excess sediment, such as by releasing sediment during high flows, so that storage capacity is maintained and some sediment can move downstream. National guidelines explain that actively managing sediment in reservoirs helps dams work properly for a long time and also protects the natural shape and health of rivers downstream.

Policy: Rules for operating dams in the Godavari basin should balance water supply, flood control, and environmental flow needs**,** so that too much sediments are not trapped inside reservoirs. These rules should be included in basin-level water management policies.

4.5 Urban Sewage Collection & Treatment Enhancements

Practice: Building new sewage networks and upgrading sewage treatment plants in cities along the Godavari, such as Nashik, Nanded, Nagpur and Paithan, helps stop untreated wastewater from flowing directly into the river. Recent projects in Paithan show this approach, where new sewage treatment plants and underground drainage systems are being built to divert wastewater away from the Godavari.

Policy: City authorities should ensure that all sewage is collected and properly treated before discharge into rivers. This requires strong rules, decentralized treatment facilities, sufficient funding, and strict monitoring by state pollution control boards.

4.6 Integrated Nutrient Management in Agriculture

Practice: Farmers should use soil testing to decide fertilizer amounts, apply fertilizers in small doses at the right crop stages, and use organic manures. This helps reduce extra nitrogen and phosphorus washing into rivers. Studies show that applying fertilizers more precisely is one of the best ways to reduce nutrient loss from agricultural fields.

Policy: The state should introduce mandatory nutrient management plans in areas with intensive farming in the Godavari basin, supported by farmer training, advisory services, and better fertilizer subsidy policies.

4.7 Stormwater Pollution Control in Urban Areas

Practice: In cities like Nashik and Nanded should use simple stormwater control methods such as grassed drains, vegetated channels, and small ponds to stop soil and nutrients from washing into rivers during rainfall. Studies show that managing stormwater properly can greatly reduce the amount of sediment and nutrients carried by rainwater into rivers.

Policy: Urban rules should make it compulsory to treat stormwater in large housing and commercial projects before allowing construction approval.

4.8 Community Engagement and Awareness Campaigns

Practice: Farmers, city residents, and communities living near the Godavari should be actively involved in programs related to soil conservation, proper fertilizer use, and improved sanitation. River basin studies show that public participation and awareness are essential for long-term and sustainable river management.

Policy: River basin plans should provide training, awareness programs, and financial support through local watershed committees to encourage communities to take responsibility for protecting the river.

4.9 Pollution Control Policy Integration

Practice: Local activities such as soil conservation, wastewater treatment, and fertilizer use in agriculture should be planned in line with national and state water policies, so that all efforts work in the same direction. The GRB is already part of national water resource planning, which recommends coordinated action across different sectors like agriculture, urban development, and water management.

Policy: Basin management plans should be updated to follow the National Water Policy and guidelines of state irrigation departments and pollution control boards, ensuring that all agencies work together to control pollution effectively.

5 Summary

The present study provides a holistic and comprehensive assessment of nutrient and sediment dynamics in the Godavari River Basin employing the InVEST NDR and SDR modelling frameworks. The models integrate land use, topography, rainfall, and soil properties to quantify the nutrient and sediment loads in the basin. The results reveal that sediment and nutrient exports are highly heterogeneous and strongly controlled by spatial disparities due to monsoon-driven hydrology, agricultural intensification, and landscape connectivity. Hotspots leading to high sediment exports are concentrated in high elevated uplands and hilly districts, while increased nitrogen and phosphorus loads are dominant in intensively cultivated central. The analysis was performed for two years viz. 2017 and 2024 to draw temporal trends in the sediment and nutrient export, majorly impacted by changes in LULC. A clear temporal increase (2017–2024) in both sediment (up to ~90% in some hotspots) and nutrient loads (20–50%) indicates growing anthropogenic pressure, particularly from fertilizer overuse, land-use change, and inadequate wastewater management.

The present analysis of sediment and nutrient load export in the basin offers a robust decision-support framework for prioritizing interventions at the district and sub-basin scales for managing the load. Identification of critical source areas enables targeted implementation of soil conservation measures (e.g., contour bunding, afforestation, check dams) in erosion-prone uplands, and nutrient management strategies (e.g., precision fertilization, riparian buffers, wastewater treatment) in agricultural and urban hotspots. Importantly, the integration of sediment and nutrient modelling highlights the need for synchronized land–water management policies rather than isolated sectoral approaches. The findings support basin-wide planning by linking upstream processes with downstream impacts such as reservoir siltation, eutrophication, and coastal degradation. Overall, this study advances the understanding on river basin management by providing actionable insights into source–transport–impact pathways, enabling policymakers to adopt evidence-based, spatially targeted interventions. Such an integrated approach is essential for improving water quality, sustaining agricultural productivity, and enhancing the ecological resilience of the Godavari River system.

6 References

Balakrishna, K, 2005. Organic carbon transport and C/N ratio variations in a large tropical river: Godavari as a case study, India.

Beusen, A.H.W. et al. (2015). Global river nutrient export modelling. *Global Biogeochemical Cycles.*

Biksham, G., & Subramanian, V. (1988). *Sediment transport of Indian rivers.* Journal of Hydrology.

Carpenter, S.R. et al. (1998). Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological Applications.*

Central Water Commission (CWC). (2015). *Handbook on reservoir sedimentation.* Ministry of Jal Shakti, Government of India.

Central Water Commission (CWC). (2019). *Reservoir sedimentation studies of major reservoirs in the Godavari Basin* (Jayakwadi, Sriramsagar). Government of India.

CWC, n.d. Handbook for Assessing and Managing Reservoir Sedimentation.

Das, M., et al. (2022). *Decadal decline in sediment load of the Godavari River and implications for delta erosion.* Science of the Total Environment.

Das, S. (2021). *Recent decline in streamflow and sediment discharge in the Godavari River Basin (1965–2015).* Science of the Total Environment

Das, S., Kandekar, A.M., Sangode, S.J., 2022. Natural and anthropogenic effects on spatio-temporal variation in sediment load and yield in the Godavari basin, India. Science of The Total Environment 845, 157213. https://doi.org/10.1016/j.scitotenv.2022.157213

Das, S., Sangode, S.J., Kandekar, A.M., Meshram, D.C., Tarolli, P., 2023. Interrelation between factors controlling sediment yield in the largest catchment of Peninsular India. Journal of Hydrology 622, 129680. https://doi.org/10.1016/j.jhydrol.2023.129680

Fertiliser Association of India (FAI) Annual Report 2023-24 - Official statistics show modest year-on-year increases in nutrient consumption (N up ~1.2 %, P_2O_5 up ~4.9 % in 2023-24).

Forecast Data for Fertilizer Consumption 2024-2028 - Projections show steady growth with a compound rate of ~1.2 % per year.

G. Biksham, n.d. Sediment transport of the Godavari River basin and its controlling factors. https://doi.org/10.1016/0022-1694(88)90040-6

Howarth, R.W. et al. (1996). Nitrogen budgets and riverine nitrogen export. *Biogeochemistry.*

Howarth, R.W. et al. (2012). Nutrient pollution in coastal rivers and seas. *Issues in Ecology.*

https://indiawris.gov.in/downloads/Godavari%20Basin.pdf?utm_source=chatgpt.com

Hussain, J., et al. (2017), n.d. Assessment of heavy metal contamination and water quality in the Godavari River Basin, India. Environmental Earth Sciences.

India-WRIS (2014). *Godavari Basin Water Resources Assessment.* Ministry of Jal Shakti, Government of India.

Interrelation between factors controlling sediment yield in the largest catchment of Peninsular India. *Journal of Hydrology, 624*, 129925. https://doi.org/10.1016/j.jhydrol.2023.129925

Kantharajan, G., et al. (2023). Quantitative assessment of sediment delivery and retention in four watersheds in the Godavari River Basin, India using the InVEST model. *Environmental Science and Pollution Research, 30*, 15815–15832. https://doi.org/10.1007/s11356-022-23507-9

Mayer, P.M. et al. (2007). Effectiveness of riparian buffers in nutrient removal. *Journal of Environmental Quality.*

Moturi Srirama Krishna, n.d. Role of synthetic fertilizers on stable isotope ratios of particulate organic matter in the Godavari River.

Mr. Sangharsha Gambhir, et al., 2020. DE-SILTING WORK OF GODAVARI RIVER IN NASHIK CITY FOR FLOOD. https://issuu.com/irjet/docs/irjet-v7i7190

Navasakthi, S., Pandey, A., Dandautiya, R., Hasan, M., Khan, M.A., Perveen, K., Alam, S., Garg, R., Qamar, O., 2023. Assessment of Spatial and Temporal Variation in Water Quality for the Godavari River. Water 15, 3076. https://doi.org/10.3390/w15173076

Oelsner, G.P., Stets, E.G., 2019. Recent trends in nutrient and sediment loading to coastal areas of the conterminous U.S.: Insights and global context. Science of The Total Environment 654, 1225–1240. https://doi.org/10.1016/j.scitotenv.2018.10.437

Paul, M.J. & Meyer, J.L. (2001). Streams in the urban landscape. *Annual Review of Ecology.*

Pmc, n.d. Evaluation of best management practices to reduce sediment yield in the upper Gilo watershed, Baro akobo basin, Ethiopia using SWAT.

Probst, J.-L., & Sigha, N. (1989). *Sediment discharge of the Godavari River.* Hydrological Sciences Journal.

Raj, R., Saharia, M., & Chakma, S. (2022a). Indian Soil Erodibility Dataset (ISED) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.8011445

Raj, R., Saharia, M., Refieinasab, A., & Chakma, S. (2022b). Indian Rainfall Erosivity Dataset (IRED) [Data set]. In CATENA (Vol. 214, Number 106256). Zenodo. https://doi.org/10.5281/zenodo.6505510

Redhead, J.W. et al. (2018). National scale ecosystem service modelling. *Ecosystem Services.*

Sarma, V. V. S. S., et al. (2010). *Intra-annual variability in nutrients and sediments in the Godavari estuary.* Continental Shelf Research.

Sarma, V.V.S.S., n.d. Influence of river discharge on plankton metabolic rates in the tropical monsoon driven Godavari estuary, India.

Sharma et al. (2022) — Analysis of growth trends shows long-term fertilizer nutrient consumption growth in India was generally in the low single digits per year, especially for nitrogen.

Sharp, R. et al. (2022). *InVEST User Guide.* Natural Capital Project.

Sharpley, A.N. et al. (1994). Managing agricultural phosphorus for water protection. *Journal of Environmental Quality.*

Sumit Das, et al. 2021. Recent decline in streamflow and sediment discharge in the Godavari basin, India (1965–2015). https://doi.org/10.1016/j.catena.2021.105537

V.V.S.S. Sarma, n.d. Intra-annual variability in nutrients in the Godavari Estuary, India.

Vigiak, O. et al. (2012). Sediment connectivity modelling in watersheds. *Hydrological Processes.*

सीएसआईआर
CSIR
भारत का नवाचार इंजन
The Innovation Engine of India

नीरी
NEERI

cGodavari

भारतीय प्रौद्योगिकी संस्थान हैदराबाद
Indian Institute of Technology Hyderabad

ganga
cGanga

भारतीय प्रौद्योगिकी संस्थान कानपुर
INDIAN INSTITUTE OF TECHNOLOGY KANPUR