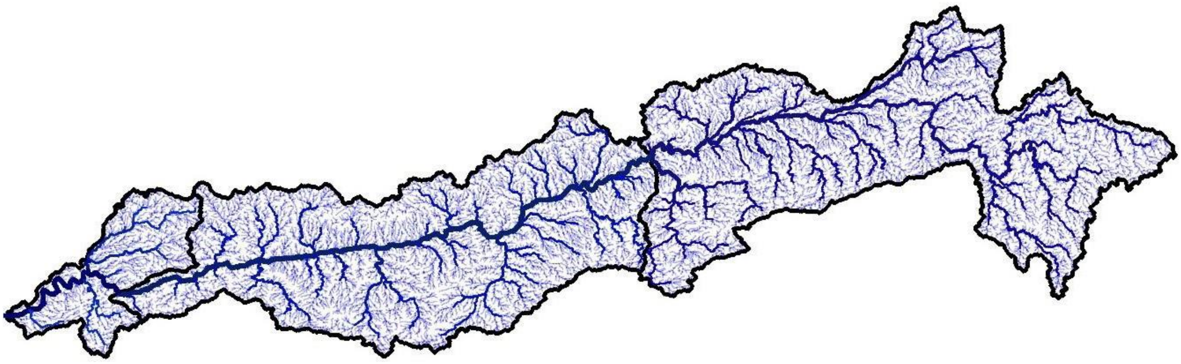
National River Conservation Directorate
Ministry of Jal Shakti,
Department of Water Resources,
River Development & Ganga Rejuvenation
Government of India

Nutrient and Sediment load Report



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Acknowledgments

This report is a comprehensive outcome of the project jointly executed by IIT Gandhinagar (Lead Institute) and IIT Indore (Fellow Institute) under the supervision of cGanga at IIT Kanpur. It was submitted to the National River Conservation Directorate (NRCD) in 2025. We gratefully acknowledge the individuals who provided information for this report.

Disclaimer

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

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PREFACE

The Narmada River, often referred to as the lifeline of central and western India, holds unparalleled significance for the region's water resources, ecosystems, and communities. Its hydrological complexity, combined with its ecological and cultural heritage, underscores the critical need for its preservation and sustainable management.

This report, focusing on nutrient and sediment load analysis and management strategies in the Narmada River Basin, aims to provide an in-depth analysis of increasing nutrient concentrations, particularly in central and lower stretches, where intensive agriculture and expanding urban settlements contribute to higher anthropogenic inputs, which directly and indirectly affect the river health in terms of water quality and also ecological health. The collection and compilation of data of both the Upper and Middle Basins will provide valuable insights into the Narmada Basin.

The findings and recommendations presented in this report are intended to serve as a guiding framework for policymakers, researchers, and practitioners committed to sustainable management of these nutrients and sediments in the Narmada Basin. By identifying trends and challenges, it aspires to support the development of policies, thereby facilitating ecological preservation alongside socioeconomic progress in the Narmada River Basin.

We are deeply grateful to all individuals, organizations, and institutions that contributed to the preparation of this report. Their dedication, expertise, and support have been instrumental in shaping this study. It is our hope that this report will inspire collaborative efforts and meaningful action toward the long-term health and sustainability of the Narmada River and its Basin.

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

1. Table of Contents

List of Tables

Abbreviations & Acronyms

CWC	Central Water Commission
CPCB	Central Pollution Control Board
GSI	Geological Survey of India
MPPCB	Madhya Pradesh Pollution Control Board
GPCB	Gujarat Pollution Control Board
NWIC	National Water Informatics Centre
NRCD	National River Conservation Directorate
I-WRIS	Indian Water Resource Information System
IWMP	Integrated Watershed Management Programme
SLUSI	Soil and Land Use Survey of India
N	Nitrogen
LULC	Land Use / Land Cover
KT	Kilo tonnes (thousand tonnes)
t/ha/yr	Tonnes per hectare per year
CWC	Central Water Commission
NSE	Nash–Sutcliffe Efficiency
N:P: Si	Nitrogen : Phosphorus : Silicon
NO_2+NO_3	Nitrite plus Nitrate (oxidized inorganic nitrogen)
PO_4	Phosphate
SWAT	Soil and Water Assessment Tool
USLE	Universal Soil Loss Equation
SAGA-GIS	System for Automated Geoscientific Analyses – Geographic Information System
DEM	Digital Elevation Model
SUFI-2	Sequential Uncertainty Fitting, version 2
CN2 – SCS	(Soil Conservation Service) Curve Number for moisture condition II
GAMLSS	Generalized Additive Models for Location, Scale and Shape
NVDA	Narmada Valley Development Authority
ICP-MS	Inductively Coupled Plasma–Mass Spectrometry
CF	Contamination Factor
PLI	Pollution Load Index
EF	Enrichment Factor

1. Introduction

1.1. Narmada Basin

India’s diverse landscapes are defined by its magnificent river systems, which originate from the Himalayas and extend to the Western and Eastern Ghats. These rivers are the nation’s lifelines, nourishing its vast plains, nurturing its ecosystems, and sustaining its people. The Narmada River ranks as the fifth-longest river in India and is the longest river flowing westward. The Narmada traverses the states of Madhya Pradesh and Gujarat and is often referred to as the “Lifeline of Madhya Pradesh and Gujarat” due to its substantial contributions to these states. The Narmada is a crucial source of water for irrigation, drinking, and hydroelectric power, and holds immense cultural and spiritual importance. Originating from the Amarkantak Plateau in the Anuppur district of Madhya Pradesh, the Narmada forms the traditional boundary between North and South India. It flows westward for 1,312 km before emptying into the Arabian Sea through the Gulf of Khambhat, situated 30 km west of Bharuch city in Gujarat. The Narmada basin extends from 21° 40’ 12’’ to 23° 41’ 24’’ N latitudes and 72° 48’ 36’’ to 81° 45’ 36’’ E longitudes, covering a total area of 98,796 sq. km, which is nearly 3% of the total geographical area of India (3,297,427.32 sq. km). The Narmada basin exhibits an elongated shape with a maximum length of 915.65 km from east to west and 236 km from north to south. The upper part of the river basin primarily comprises hilly regions, whereas the middle and lower reaches are fertile and broad, making them well suited for cultivation. The annual water potential of the basin is 45.65 billion cubic meters (BCM), with a utilizable water potential of 34.50 BCM (75.57%). The entire stretch of River Narmada can be primarily divided into three sub-basins/segments based on their geomorphology, ecology and rheology

Upper Narmada sub-basin: ≈ 720 km Amarkantak to Hoshangabad
Middle Narmada sub-basin: ≈ 485 km Hoshangabad to Navagam
Lower Narmada sub-basin: ≈ 145 km Navagam to Gulf of Khambhat

The drainage network of the Narmada River consists of 19 major tributaries (a total of 41 tributaries). According to the 2011 Census, the total population of the basin is 61,243,103, with 32,396,859 males (52.89%) and 30,264,244 females (47.11%). The Narmada flows through a rift valley, surrounded by the Vindhyas to the north, the Maikala range to the east, the Satpuras to the south, and the Arabian Sea to the west. It lies at the northern extremity of the Deccan plateau and covers major portions of the states of Madhya Pradesh and Gujarat, along with smaller parts of Chhattisgarh and Maharashtra. The Narmada River travels through Madhya

Pradesh (1,077 km), Maharashtra (74 km), including along the border between Madhya Pradesh and Maharashtra (39 km), then the border between Maharashtra and Gujarat (74 km), and finally Gujarat (161 km).4. The basin spreads broadly over 40 districts, comprising 27 districts of Madhya Pradesh, seven districts of Gujarat, four districts of Chhattisgarh, and two districts of Maharashtra. (cNarmada River Atlas,2025)

1.2. Overview

This report focused on the various aspects of the nutrients, sediment sources, and their management, specifically in the Narmada Basin. Nutrient and sediment sources in the Narmada Basin encompass various types of point and non-point sources, including municipal discharges, agricultural runoff, and monsoon-induced overflow. Nutrient load sources include municipal sewage, industrial effluents, ghat and religious discharges, which are part of point sources, and agriculture runoff, diffuse urban runoff, and atmospheric leaching, which are part of non-point sources. Similarly, point sources for sediments include construction and dam-related discharges, industrial runoff, and non-point sources, such as agricultural soil erosion, deforestation, land use change, and Bank erosion. All these sources contribute to an increase in the nitrogen and phosphorus concentrations in the river water. Data was collected from the Geological Survey of India (GSI) to understand the spatial variability of nutrients and sediment loads across the Narmada Basin. According to the stream sediment geochemical dataset, the elements reported are categorized into three functional categories: first, major oxides; second, nutrient-related elements; and third, toxic elements and co-transported contaminants. The data is presented sub-basin-wise for these categories, i.e., for Upper, Middle, and Lower Basins.

Furthermore, the report also included existing practices that are affecting nutrient recycling in the Narmada Basin. These practices broadly include two major segments: one is Agricultural and Land management, and the second is Wastewater, industrial, and catchment practices in the Narmada River Basin. Practices such as cropping patterns, the use of excessive fertilizers, crop residue management, various types of irrigation practices, riverbank and floodplain farming, urban expansion, and sand mining all cumulatively affect nutrient recycling, which ultimately impacts the availability of nutrients and sediments. Apart from these, municipal wastewater generation and disposal also contribute to nutrient recycling. And also to study nutrient and sediment load in Narmada River we have used river water quality data on quarterly basis obtained from GPCB. In this report, data is compiled to identify the best management and nature-based practices that can support policymakers.

2. Nutrient and Sediment Load Sources in the Narmada River

Nutrient loads in the Narmada River basin primarily originate from point sources, such as municipal sewage discharges and industrial effluents, alongside dominant non-point sources from agricultural runoff that carries nitrogen and phosphorus fertilizers. Sediment loads are overwhelmingly non-point in nature, driven by soil erosion in agricultural lands, deforested slopes, and monsoon-induced overland flow in upper and middle sub-basins. These pollutants degrade water quality, promote eutrophication, and alter channel morphology, with SWAT modeling revealing downstream nutrient concentrations 6-8 times higher than in tributaries. (Kansara & Lakshmi, 2021)

2.1. Basin Context and Hydrogeomorphic Setting

The Narmada River basin spans 98,796 km² across Madhya Pradesh (majority), Gujarat, Maharashtra, and Chhattisgarh, flowing westward from Amarkantak (1,352 m elevation) through relatively flat terrain with slopes mostly under 10°. Agriculture covers 53% of the area, forests 42%, with clay-loam soils prevalent; upper hilly regions generate over 70% of streamflow, depositing sediments and nutrients in central fertile plains. Monsoon precipitation (June-September) dominates hydrology, peak surface runoff and pollutant transport, while population growth (23% from 1991-2011 to ~132 million) intensifies anthropogenic pressures via urbanization and intensified farming. Central Water Commission (CWC) monitors 29 stations, with 17 for streamflow and 11 for nutrients like $NO_2 + NO_3$, highlighting spatial heterogeneity: main channel shows elevated loads due to adjacent croplands (cNarmada Report, 2025; Kansara & Lakshmi, 2021; Water Quality Data Book Narmada Basin, 2019).

Land-use changes exacerbate issues; agricultural expansion, from 62.1% to 66.7% (2000-2018), correlates with fertilizer use averaging 42 kg/ha of nitrogen, which washes into streams via overland flow, without accounting for crop rotation in models. Reservoirs like Sardar Sarovar trap sediments (reducing downstream supply) but concentrate nutrients; tributaries deliver diffuse loads, amplifying main-stem pollution (Narmada River Basin Hydrology Data Report, 2024; Kansara & Lakshmi, 2021; Narmada River at a Glance Report, 2024)

2.2. Nutrient Load Sources: Point and Non-Point Differentiation

2.2.1. Point Sources of Nutrients

Point sources deliver concentrated nutrient pulses at identifiable discharge points, contributing organic nitrogen/phosphorus via untreated or partially treated effluents.

- **Municipal Sewage:**
  Urban centers like Jabalpur, Hoshangabad, and Bharuch discharge high biochemical oxygen demand (BOD) wastewater through outfalls and inadequate STPs, elevating $NO_2 + NO_3$ by 2-10 mg/L during monsoons; Handia station records peaks up to 10 mg/L from sewage wash-off. (Indian Council of Agricultural Research, 2009)

- **Industrial Effluents:**
  Textile, chemical, and paper industries in the middle/lower reaches Narmada basin release nutrient-laden wastewater via pipes; these add to organic loads, with bypasses from STPs compounding inputs (Katakwar & Katakwar, 2016).

- **Ghat and Religious Discharges:**

  Temple complexes and pilgrimage sites (e.g., Omkareshwar) channel organic waste via discrete drains, spiking localized phosphorus during festivals. SWAT models underestimate peaks (bias up to 7 mg/L at Handia, 2013 monsoon) due to unmodeled point inputs, but fluxes match better ($R^2 > 0.2$ at main channel stations). Gove references at each data point (Indian Council of Agricultural Research, 2009).

2.2.2. Non-Point Sources of Nutrients

Non-point sources dominate (agricultural runoff primary), diffusely transporting via surface/groundwater flows (Katakwar & Katakwar, 2016).

- **Agricultural Runoff:**
  Fertilizer excess (N-P rich) from rainfed/irrigated croplands (rice, soybean, wheat) near main channel yields 200-500 KT monsoon flux downstream; boundary sub-basins show 0.0001-0.002 mg/L/yr $NO_2 + NO_3$ increase from forest-to-agriculture land conversion (Narmada River Basin Hydrology Data Report 2024, 2025; Kansara & Lakshmi, 2021).

- **Diffuse Urban/Rural Runoff:**
  Stormwater carries detergents, animal waste from unsewered settlements; tributaries integrate these, delivering to the main stem.

- **Atmospheric Deposition and Leaching:**
  Minor nitrogen via wet/dry deposition, enhanced by biomass burning in ag-forest transitions. Monsoon concentrations (0.4-0.8 mg/L main channel) exceed pre/post-monsoon by 2x due to runoff; trends (Mann-Kendall) indicate significant increases in peripheral sub-basins.

- **Sediment Load Sources**
  Sediment loads (total suspended solids) far exceed nutrients volumetrically, with basin yields varying by sub-basin; USLE/SWAT estimates highlight erosion hotspots.

2.2.3. Point Sources of Sediments

Minimal compared to non-point; discrete inputs include:

- **Construction and Dam-Related Discharges:**
  Channelized silt from urban works or reservoir flushing; minor at gauging sites.
- **Quarry/Industrial Runoff:**
  Localized gravel mining drains but regulated under Narmada Control Authority.

2.2.4. Non-Point Sources of Sediments

Over 95% from diffuse erosion, peaking monsoons (70% annual load).

- **Agricultural Soil Erosion:**
  Cropland on moderate-steep slopes (Watershed-63: 47.79 t/ha/yr severe class) via sheet/rill erosion; USLE factors (R= rainfall erosivity, K=soil erodibility, LS=slope length) drive high yields (19.14 t/yr in study sub-watershed).
- **Deforestation and Land-Use Change:**
  Forest loss exposes basalt-derived soils; Mohgaon watershed models link ag expansion to elevated yields.
- **Gully/Bank Erosion:**
  Steep upper tributaries (Vindhya/Satpura flanks); monsoon overland flow in transition zones. SAGA-GIS/USLE thematic maps (DEM from SRTM) classify Watershed-63 (Narmada-Nandurbar districts) as high-risk due to drainage density, moderate LULC; basin-wide, sediments reduce reservoir capacity (e.g., Sardar Sarovar). SWAT hydrology captures peaks (NSE 0.72 calibration), linking erosion to CN2/ESCO parameters. (Kansara & Lakshmi, 2021) Data of point and non-point source contribution and literature review of nutrient and point sources of the Narmada basin are provided in the Table 1-3.

Table 1: Summary of Point and Non-Point Source Contributions to Nutrient and Sediment Loads in the Narmada River Basin

Parameter	**Point Sources Contribution**	**Non-Point Sources Contribution**	**Key Quantification**	**Primary Driver**	**Authors**
Nutrients (N)	20-30% (sewage/industry)	70-80% (ag runoff)	0.4-0.8 mg/L monsoon main channel; 200-500 KT flux	Fertilizer (42 kg/ha) + runoff	Kansara & Lakshmi, 2021)
Sediments	<5% (construction)	>95% (erosion)	47.79 t/ha/yr (severe); 19.14 t/yr sub-watershed	Slopes + ag LULC change	Parmar 2019
Nutrients (NO_3^-, PO_4^{3-}, SiO_2)	NA	Agricultural runoff, soil erosion	Reduced value of DIP (0.84 to 0.38 µM), DIN (from 43 to 1.5 µM) and DSi (470 to 214 µM)	River discharge (monsoon)	Gupta, H., et al.2021
Estuarine Nutrient Flux	Urban wastewater near estuary	Diffuse riverine inputs	DIN (0.037 ± 0.011 mg/l to 0.067 ± 0.003 mg/l) and DIN(0.009 ± 0.002 mg/l to 0.52 ± 0.027 mg/l)	Tidal mixing and freshwater inflow	Sonal, D., et al 2014
(DOC),(NO_3^-), ($PO_4^{3-),}$ (H_4SiO_4)	Localized anthropogenic inputs	Catchment-scale erosion	PO_4^{3-} (0.2 mg l^{-1}) NO_3^-(0.17 to 4.96 mg l^{-1}),H_4SiO_4 (11.6 mg l-1) and DOC (6.75 and 7.60 mg l^{-1})	Soil erosion and runoff	Sharma, S.K. and Subramanian, V., 2010
Nitrate, DOC	Fertilizer and sewage	Atmospheric deposition	DOC (0.3 to 33.9 mg l^{-1})	Agricultural land use	Sanjay Kumar Sharma and V. Subramanian 2008

Table 2: Literature Review: Nutrient Load Sources in the Narmada River Basin

Model/Method	**Key Nutrient Sources**	**Quantification**	**Region/Sub-basin**	**Key Findings**	**Authors**
SWAT (2001-2019, CWC calibration NSE 0.63-0.72)	Non-point ag runoff (70-80%); point sewage	Monsoon 0.4-0.8 mg/L NO_2+NO_3 main channel; 200-500 KT flux; 6-8x tributary conc.	Basin-scale (29 CWC stations)	Boundary sub-basins +0.0001-0.002 mg/L/yr from forest-to-ag; underestimated point peaks	(Kansara & Lakshmi, 2021)
N:P: Si stoichiometry analysis	Anthropogenic N/P enrichment; natural Si weathering	P-limitation; excess Si from lithology	West-flowing tributaries (Narmada incl.)	Eutrophication risk from N/P imbalance	(Reddy et al., 2024)
Seasonal sampling (5 stations, 2009-2010)	Fertilizers, sewage, erosion wash-off	NO_3 0.109-0.300 mg/L; PO_4 0.07-1.9 mg/L	Main channel stations	Monsoon spikes from mixed sources	(Singh Baghel, 2023)
Site-specific physicochemical analysis	Sewage oxidation, domestic inputs	NO_3 12.6-21.2 mg/L near urban sites	Polluted urban stretches	Organic N spikes from wastewater	(N. Gupta et al., 2017)
Water quality monitoring	Urban sewage, agricultural runoff	Spatial gradients NO_3/PO_4	Main Narmada stretches	Ag-urban gradient controls patterns	(Indian Council of Agricultural Research, 2009)
Macrophyte-based nutrient indexing	N gradients from mixed sources	15-station N correlation with biota	Central India (Narmada incl.)	Eutrophication linked to N loads	(Singh Baghel, 2023)
Seasonal water characterization	Anthropogenic pollution (sewage/ag)	DO/BOD/N spikes monsoon	Sampling sites along Narmada	Non-point dominance in rural areas	(Sarsaiya et al., 2025)
Spatial distribution mapping	Trace metals + nutrients from age/sewage	N/P distribution patterns	Narmada & Tapti basins	Mixed lithogenic/anthropogenic sources	(Sulochana Patil & Sharma, 2016)

Table 3: Literature Review: Sediment Load Sources in the Narmada River Basin

Model/Method	Key Sediment Sources	Quantification	Region/Sub-basin	Key Findings	Authors/Journal
USLE/SAGA-GIS (SRTM-DEM)	Agricultural soil erosion, steep slopes (LS-factor), moderate land use (C-factor), drainage density	Avg. 19.14 t/ha/yr; severe >47.79 t/ha/yr (23% area)	Watershed-63 (Narmada-Nandurbar, Gujarat-Maharashtra)	High-risk erosion zones from thematic maps; moderate slopes and land practices amplify yields	(D. Gupta et al., 2025a)
SWAT (SUFI-2 calibration)	Slope, land cover change, CN2 (curve number), channel erodibility	NSE 0.72 flow, 0.66 sediment; R^2 0.83-0.90 monthly	Mohgaon watershed (upper Narmada)	Sensitive to land cover/slope; reliable for ungauged similar watersheds	(D. Gupta et al., 2025b)
GAMLSS/Monte Carlo (CWC/NVDA data)	Dam trapping efficiency, suspended sediment reduction	-211% monsoon sediment (2005-2019 post-dam)	Downstream of Indira Sagar Dam	No flow change but major downstream load drop; aids sediment/flood management	(Rahi et al., 2024)
ICP-MS, pollution indices (CF, PLI, EF)	Anthropogenic/agricultural runoff, riverbank erosion, soil from fields	Fe 750 mg/kg avg. in sediments; seasonal peaks (monsoon As/Cu/Fe)	Six stations along main Narmada	Low-moderate contamination; cluster analysis links to runoff and wastewater	(Rahi et al., 2024)
Suspended sediment rating curves	Bedrock incision, sand mining, stored alluvial remobilization	0.5-2 m/yr incision	Garudeshwar-Garvasad (middle alluvial)	Post-dam supply limitation drives morphological change	(Singh et al., 2025)
Back propagation neural network	Daily discharge-sediment correlations (implied basin erosion)	Predicted daily sediment discharge	Basin-scale (Narmada case study)	NN training effective for prediction from hydrological drivers	(Bisoyi et al., 2019)
Effective discharge analysis	Suspended sediment transport in regulated flows	Effective discharge for pre/post-dam periods	Regulated Narmada reaches	Quantifies transport shifts due to regulation	(Chamyal et al., 1997)
Sedimentological profiling	Alluvial fan deposition, tectonic reconfinement	Up to 60,000 m^3/s discharges	Narmada alluvial fan (western India)	Tectonic reactivation controls feeder channel sediments	(Chamyal et al., 1997))

3. Current Status and Trends of Nutrient and Sediment Load in the Narmada River Basin

3.1. Data Source and Basin Coverage

To understand the spatial variability of nutrient and sediment loads across the Narmada River Basin, stream-sediment geochemical data were compiled from four 1° × 1°degree sheets that collectively represent the longitudinal profile of the basin from its uppermost reaches to the lower sections. This structure allows systematic interpretation of sediment characteristics as the river traverses diverse geological terrains. Information about the degree sheets is given in Table-4.

Table 4: Degree sheets information. (Data extracted from the Degree sheets information provided by the Geological survey of India - GSI)

Degree Sheet	Basin Zone	Districts Covered
55N	Upper Basin	Mandla, Jabalpur, Seoni, Narsimhapur, Chhindwara
55J	Upper Basin	Narsimhapur, Chhindwara, Hoshangabad, Betul, Raisen, Sehore
55E	Upper–Middle Basin Transition	Raisen, Bhopal, Sehore
46J	Middle–Lower Basin Transition	Dhar, Barwani, Alirajpur, Jhabua, Chhota Udaipur
46F	Lower basin	Chhota Udaipur, Panch Mahal, Dahod, Vadodara, Narmada
46G	Lower basin	Narmada, Vadodara, Bharuch, Surat
46C	Lower basin	Bharuch, Surat

3.2. Approach to Nutrient and Sediment Load Assessment

3.2.1. Classification of Elements

For the assessment of nutrient and sediment loads in the Narmada River Basin, the elements reported in the stream-sediment geochemical dataset are grouped into three functional categories. The first category comprises major oxides, including SiO_2, Al_2O_3, Fe_2O_3, TiO_2, CaO, MgO, MnO, Na_2O, K_2O and P_2O_5 (considered here as a major oxide). These oxides define the bulk mineralogical and lithological character of sediments and help explain variations in sediment supply, weathering intensity and source rock composition. The second category includes nutrient-related elements, which act either as proxies for macronutrients or as micronutrients in sediment systems. These include nutrient-bearing oxides such as P_2O_5, K_2O, CaO and MgO, along with trace metals like Fe, Mn, Cu, Zn, Ni, Co, Sr and Ba. Rare earth elements (La–Lu) are also considered within this group due to their ability to trace sediment provenance and indicate the adsorptive capacity of sediments for nutrients. The third category consists of toxic elements and co-transported contaminants, such as As, Pb, Cd, Hg, Sb, Se, Bi, Cr, V, and Mo, along with radiogenic elements (U, Th, Cs, W, Ta, Hf). These elements are important because they often travel attached to fine sediments and Fe–Mn oxide phases, allowing toxic metals to move alongside nutrient-rich particles through the river system. Together, these three categories establish a comprehensive framework for interpreting how nutrients and contaminants are bound, transported, and redistributed across the upper, middle, and lower Narmada Basin.

- **Upper Basin**

The upper basin is represented by degree sheets 55N and 55J, covering the upstream catchments of the Narmada. Detailed Geochemical data are given in Tables 5 and 6.

- **Sediment Matrix and Major Oxides**

In the upper Narmada Basin, represented by degree sheets 55N and 55J, the sediment matrix reflects a transition from mafic to more siliceous lithologies as the river flows downstream. The average SiO_2 content is about 48% in 55N and increases to around 59% in 55J, suggesting that sediments become progressively richer in quartz and more intensely weathered in the downstream portion of the upper basin. Al_2O_3 remains relatively consistent between the two sheets, averaging around 15% in 55N and 14% in 55J, indicating a stable contribution from aluminosilicate minerals such as clays and feldspars. Iron and titanium oxides show more pronounced variability: Fe_2O_3 values are notably higher in 55N (approximately 14%) and decline to about 7.4% in 55J, while TiO_2 decreases from around 2.6% in 55N to roughly 1.4% in 55J, reflecting diminishing heavy mineral contributions downstream. Base-forming oxides, including CaO and MgO, occur in low to moderate concentrations (CaO averages 3.1% in 55N and 1.8% in 55J, and MgO averages 2.0% and 1.7% respectively), consistent with mixed carbonate silicate lithology under moderate weathering conditions. Phosphorus, treated as a major oxide (P_2O_5), displays average concentrations of around 0.14% in 55N and 0.10% in 55J, indicating a relatively uniform but slightly decreasing sedimentary phosphorus background as the river transitions from the headwaters to downstream upper basin reaches. Overall, the major oxide composition of the upper basin sediments highlights strong lithological control, moderate weathering, and a sediment load that shifts from Fe-rich upstream materials toward more siliceous downstream fractions.

○ Nutrient-Related Elements

Nutrient-related elements in the upper basin show distinct spatial patterns that reflect both lithological sources and geochemical processes governing nutrient mobility. Fe and Mn occur in substantial concentrations, with MnO reaching exceptionally high values in 55N (up to 8.4%), indicating zones enriched with Fe–Mn oxide minerals capable of strongly adsorbing phosphate and trace metals. Trace nutrient metals, such as Cu, Zn, Ni, Co, and V, also display notable variation across the upper basin. Copper is significantly enriched in 55N, with an average concentration of approximately 202 ppm, compared to roughly 66 ppm in 55J, suggesting either lithological enrichment in the upstream areas or localized anthropogenic contributions. Other nutrient-associated metals, including Zn, Ni, Co, and V, occur at moderate to high concentrations, with vanadium averaging around 361 ppm in 55N and decreasing to about 155 ppm in 55J, reflecting the decreasing influence of mafic source rocks downstream. Elements such as Ba and Sr, which are commonly associated with barite, feldspar, and carbonate minerals, also occur in substantial amounts. Ba averages about 233 ppm in 55N but increases to roughly 499 ppm in 55J, whereas Sr averages 118 ppm and 91 ppm, respectively, indicating varied mineral contributions and potential co-association with phosphorus-bearing phases. Rare earth elements (REEs), including La, Ce, Pr, and Nd, are present in moderate and relatively stable concentrations across both sheets, demonstrating consistent terrigenous influence and providing insight into the provenance and adsorptive behaviour of sediments. Collectively, the nutrient-related element patterns indicate that the upper basin acts as a major source of metal-rich and nutrient-bearing sediments, which are transported downstream and contribute significantly to the basin's geochemical load.

○ Toxic Elements and Co-Transport

Toxic elements in the upper Narmada Basin exhibit clear evidence of both natural geochemical enrichment and potential point-source influences. Arsenic concentrations average approximately 3.7 ppm in 55N and increase to about 8.3 ppm in 55J, with maximum values reaching 36–79 ppm, suggesting localized enrichment where arsenic is likely adsorbed onto Fe–Mn oxide coatings within fine sediments. Lead also displays increasing concentrations downstream within the upper basin, with average values of about 9.7 ppm in 55N rising to nearly 22 ppm in 55J. Elements such as cadmium, mercury, silver, selenium, antimony, thallium and bismuth are primarily reported within 55J and occur mostly at sub-ppm to ppb levels on average, but some display extremely high maximum values for example, silver reaching up to 1200 ppb, cadmium up to 450 ppb, and mercury up to 79 ppb, indicating possible lithological anomalies or anthropogenic signatures. These toxic elements are strongly influenced by adsorption to fine Fe–Mn-rich particulate matter, meaning that their mobility and downstream transport are closely linked to the movement of nutrient-bearing sediments. The overall geochemical pattern suggests that even within the upper basin, there are distinct zones where potentially toxic elements accumulate, posing localized contamination risks and contributing to the co-transport of nutrients and metals as sediments move downstream.

Table 5: Degree sheet 55N Stream sediment Geochemical statistical data (Data extracted from the Degree sheets information provided by the Geological survey of India - GSI)

Parameters	Min	Max	Average
SiO2(%)	36.4	81.56	48.23926
Al2O3(%)	6.36	22.65	14.97127
Fe2O3(%)	1.46	22.32	14.18836
TiO2(%)	0.15	6.54	2.622175
CaO(%)	0.27	16.96	3.080931
MgO(%)	0.09	5.46	2.041382
MnO(%)	0.02	8.41	0.498873
Na2O(%)	0.06	2.94	0.744145
K2O(%)	0.03	2.32	0.597171
P2O5(%)	0.04	0.43	0.138618
Ba_ppm	1	861	233.0793
Co_ppm	5	106	49.58109
Cr_ppm	30	494	171.0727
Cu_ppm	19	403	202.1513
Ga_ppm	9	59	25.17164
Nb_ppm	10	35	17.64582
Ni_ppm	15	166	83.408
Pb_ppm	0	81	9.689455
Sc_ppm	6	44	24.29673
Sr_ppm	23	507	118.4807
V_ppm	46	804	360.5804
Y_ppm	17	93	29.05964
Zn_ppm	18	229	114.4495
Zr_ppm	120	1223	244.9105
Be_ppm	0.15	3.01	1.024662
Ge_ppm	0.04	8.48	1.9168
As*_ppm	0.5	35.87	3.676065
Rb_ppm	2	154.52	28.95665
Sn_ppm	0.5	43.93	2.162116
La_ppm	0.79	111.87	22.92191
Ce_ppm	1.85	197.76	49.32408
Pr_ppm	2.67	23.02	6.160371
Nd_ppm	11.69	86.59	26.60744
Sm_ppm	1.13	15.42	5.531302

Eu_ppm	0.44	28.86	2.573302
Gd_ppm	2.35	67.79	6.150655
Tb_ppm	0.44	7.31	1.1868
Dy_ppm	2.83	31.96	6.657687
Ho_ppm	0.54	7.38	1.28264
Er_ppm	1.2	11.46	3.572851
Tm_ppm	0.26	5.65	0.556756
Yb_ppm	0.87	12.38	3.303011
Lu_ppm	0.26	7.84	0.528109
Hf_ppm	0	58.51	6.919869
Ta_ppm	0.1	6.26	0.929978
Th_ppm	0.74	53.39	6.521935
U_ppm	0.25	9.89	1.587396

Table 6: Degree sheet 55J Stream sediment Geochemical statistical data (Data extracted from the Degree sheets information provided by the Geological survey of India - GSI)

Parameters	**Min**	**Max**	**Average**
SiO2(%)	39.28	75.41	58.95946
Al2O3(%)	7.54	19.77	14.14231
Fe2O3(%)	1.77	20.21	7.417883
TiO2(%)	0.56	4.96	1.439113
CaO(%)	0.21	9.06	1.778051
MgO(%)	0.3	4.43	1.695415
MnO(%)	0.02	0.28	0.105315
Na2O(%)	0.09	1.73	0.501949
K2O(%)	0.24	5.69	1.966496
P2O5(%)	0.04	0.3	0.102536
Ba_ppm	85	1939	498.9163
Co_ppm	5	77	23.39038
Cr_ppm	1	276	87.80637
Cu_ppm	8	351	66.05871
Ga_ppm	7	38	19.63273
Nb_ppm	5	71	19.23235
Ni_ppm	7	129	46.4466
Pb_ppm	0	125	22.01062
Sc_ppm	4	43	15.57339
Sr_ppm	27	212	90.61774
V_ppm	22	559	154.7714
Y_ppm	19	183	43.28295

Zn_ppm	15	475	62.40849
Zr_ppm	157	3684	526.2367
Be_ppm	0.5	6.84	1.885659
Ge_ppm	0.19	2.68	1.408382
As*_ppm	0.5	78.93	8.316571
Rb_ppm	7.21	327.6	96.96587
Sn_ppm	0.5	66.2	2.565509
La_ppm	10	548.85	64.27574
Ce_ppm	21.25	1059.5	125.9809
Pr_ppm	2.7	120.11	14.55883
Nd_ppm	11.4	420.38	54.76367
Sm_ppm	2.52	66.42	10.15851
Eu_ppm	0.24	5.25	1.846334
Gd_ppm	2.38	49.84	9.033029
Tb_ppm	0.29	6.92	1.505609
Dy_ppm	1.36	30.95	8.288007
Ho_ppm	0.23	6.13	1.619169
Er_ppm	0.68	17.53	4.75
Tm_ppm	0.11	2.88	0.7506
Yb_ppm	0.75	19.45	4.855359
Lu_ppm	0.12	3.26	0.749638
Hf_ppm	2.27	117.37	17.38021
Ta_ppm	-0.14	5.72	1.447908
Th_ppm	2	212.11	26.4644
U_ppm	0.25	21.25	4.183029
Au_ppb	0.5	40.4	2.060578
Se_ppm	0.05	31	0.314831
F_ppm	50	712	341.7177
Ag_ppb	0	1200	46.99063
Cd_ppb	0	450	66.82199
Hg_ppb	0	79	14.76264
Li_ppm	0	93.5	26.78115
Mo_ppm	0	11.36	1.107901
In_ppm	0	0.34	0.055715
Sb_ppm	0	38.55	0.7204
Te_ppm	0	1.08	0.05163
Cs_ppm	0	17.39	4.567021
W_ppm	0	17.94	2.007433
Tl_ppm	0	2.35	0.498051

Bi_ppm	0	2.18	0.288732

- **Middle Basin (Upper–Middle Transition: 55E)**

  The middle basin transition (degree sheet 55E: Raisen–Bhopal–Sehore) captures the reach where the upper basin load is integrated and redistributed. Detailed Geochemical data are given in Table 7

  - **Sediment Matrix and Major Oxides**

    In the middle basin transition zone represented by degree sheet 55E (Raisen–Bhopal–Sehore), the sediment matrix shows characteristics that reflect the cumulative integration of upstream sediment loads. The average SiO_2 concentration is approximately 51%, indicating a moderately siliceous sediment composition, like that of the downstream part of the upper basin. Al_2O_3 averages around 13.3%, signifying a consistent presence of aluminosilicate minerals, largely derived from clays and feldspars. Iron oxide (Fe_2O_3) remains relatively elevated at approximately 11.6%, demonstrating the ongoing significance of Fe-oxide mineral phases, which play a crucial role in binding and transporting nutrients and trace metals through adsorption processes. The phosphorus-bearing oxide P_2O_5 averages roughly 0.12%, slightly lower than the values observed in 55N but comparable to those in 55J, indicating a maintained but not significantly elevated background level of sedimentary phosphorus within this transition segment of the basin. Collectively, the major oxide composition of the middle basin suggests a system where upstream materials continue to dominate sediment character, while fine sediment deposition and mineralogical sorting begin to influence geochemical trends as the river enters a lower-energy zone.

  - **Nutrient-Related Elements**

    Nutrient-related elements in the middle basin (55E) display notable enrichment patterns that reflect both the accumulation of upstream inputs and the geochemical behaviour of fine sediments. Concentrations of key nutrient-associated metals, such as Cu, Ni, Cr, and Zn, are significantly elevated compared to the upper basin, with copper averaging around 130 ppm, chromium at approximately 138 ppm, nickel at about 76 ppm, and zinc reaching an average of 285 ppm. These values suggest that the transitional portion of the basin serves as a zone of enhanced deposition or concentration of metal-rich fine sediments, likely due to changes in hydrodynamic conditions and sediment sorting. Barium and strontium also exhibit distinct behavior, with Ba averaging around 333 ppm, suggesting contributions from barite and feldspar-bearing minerals, while Sr remains relatively low at about 26 ppm, indicating selective retention or depletion of carbonate-associated elements. The rare earth elements (REEs) show moderate and stable concentrations, indicating no extreme enrichment but confirming a consistent terrigenous input and steady sediment provenance signal. Overall, the middle basin exhibits a geochemical environment where nutrient-bearing trace metals accumulate more prominently than in the upper basin, underscoring its role as a significant mixing and temporary storage zone for sediment-bound nutrients.

o Toxic Elements

Toxic elements within the middle basin transition zone show patterns that highlight both natural geochemical behavior and potential localized sources of contamination. Arsenic averages around 10 ppm, with maximum recorded values reaching approximately 84 ppm, indicating significant zones of enrichment likely associated with Fe–Mn oxide-bearing fine sediments. Lead also shows elevated concentrations, averaging around 21 ppm with maximum approaching 69 ppm, reflecting either lithological inheritance from upstream or localized inputs within the transition region. Uranium exhibits moderate concentrations, averaging about 1.7 ppm and reaching up to 5.4 ppm in certain locations, suggesting the influence of specific mineralogical units or adsorption onto fine-grained sediments. The presence of these toxic elements, coupled with the elevated Fe_2O_3 content in this reach, indicates that the middle basin is an active zone of adsorption, accumulation and transport of potentially hazardous metals. Their behaviour reinforces the role of this region as a critical geochemical transition zone, where both nutrients and toxic elements may accumulate before being remobilised further downstream.

Table 7:Degree sheet 55E Stream sediment Geochemical statistical data (Data extracted from the Degree sheets information provided by the Geological survey of India (GSI)

Parameters	**Min**	**Max**	**Average**
SiO2(%)	36.65	70.16	51.21614
Al2O3(%)	8.52	23.33	13.33556
Fe2O3(%)	4.21	18.83	11.62368
TiO2(%)	0.02	0.35	0.164585
CaO(%)	0.22	18.38	3.710469
MgO(%)	0.65	3.85	1.858375
MnO(%)	0.11	1.82	0.591769
Na2O(%)	0.1	2.89	0.741949
K2O(%)	0.83	7.42	2.299819
P2O5(%)	0.04	0.41	0.124079
Ba_ppm	129	938	333.2924
Co_ppm	11	76	42.14801
Cr_ppm	43	228	137.8448
Cu_ppm	18	250	129.6065
Ga_ppm	10	30	19.73285
Nb_ppm	9	24	15.26715

Ni_ppm	18	159	75.8231
Pb_ppm	1	69	20.82671
Sc_ppm	4.41	120.58	35.18908
Sr_ppm	8	59	26.49458
V_ppm	37	266	110.3755
Y_ppm	1.104912	21.82511	7.518076
Zn_ppm	80	605	285.4657
Zr_ppm	17	51	29.38267
Be_ppm	0	151	83.99278
Ge_ppm	108	948	259.0614
As*_ppm	1	84.09	10.3024
Rb_ppm	0.5	3.3	1.016348
Sn_ppm	0.275171	3.02	1.345028
La_ppm	0	9.546295	2.520439
Ce_ppm	4.07214	55.94	24.31729
Pr_ppm	9.392934	111.6172	52.77213
Nd_ppm	1.147354	12.99127	6.237007
Sm_ppm	4.841738	48.93	25.7145
Eu_ppm	1.060214	9.237345	5.428875
Gd_ppm	0.282803	8.442516	1.837869
Tb_ppm	1.029854	8.44	5.45888
Dy_ppm	0.18124	1.501291	0.976747
Ho_ppm	0.949011	8.768746	5.542271
Er_ppm	0.175166	1.606883	1.060763
Tm_ppm	0.433557	4.596908	2.974513
Yb_ppm	0.077926	0.77	0.447857
Lu_ppm	0.460784	4.65	2.7768
Hf_ppm	0.067061	0.78832	0.430951
Ta_ppm	1.336225	26.76862	7.286611
Th_ppm	0.178829	2.62	1.044729
U_ppm	0.23	5.37	1.668856

- **Lower Basin (Middle–Lower Transition: 46J)**

  Degree sheet 46J covers the transition from middle to lower basin (Dhar–Barwani–Alirajpur–Jhabua–Chhota Udaipur), where cumulative upstream inputs are expressed and additional downstream lithology and land uses influence sediment chemistry. Detailed Geochemical data are given in Table 8.

○ Sediment Matrix and Major Oxides

In the lower basin transition zone represented by degree sheet 46J (Dhar–Barwani–Alirajpur–Jhabua–Chhota Udaipur), the sediment matrix exhibits substantial lithological heterogeneity, reflecting the cumulative influence of upstream inputs and varied local geology. The concentration of SiO_2 ranges widely from 14.6% to 88.3%, with an average of about 51.9%, indicating the presence of both fine, mineral-rich sediments and coarse, quartz-dominated fractions within the same reach. Al_2O_3 maintains an average value of approximately 13.3%, indicating consistent aluminosilicate contributions, like those observed in the upper and middle basin segments. Fe_2O_3 concentrations average approximately 9.3%, suggesting the continued significance of iron oxides in governing adsorption processes for nutrients and trace metals. Phosphorus-bearing oxide (P_2O_5) shows a slight increase compared to upstream regions, with an average of about 0.16% and maximum values reaching up to 0.82%. This elevated upper range indicates localized phosphorus enrichment zones that may result from cumulative sediment transport, contributions from agricultural activities or natural concentration of P-bearing minerals. Overall, the major oxide composition of the lower basin sediments reflects a complex interaction of upstream sediment supply, local lithology and depositional processes that create spatial variability in nutrient-bearing mineral phases.

○ Nutrient-Related Elements

Nutrient-related elements in the lower basin demonstrate pronounced variability and enrichment patterns, highlighting the basin's role as a significant sink and redistribution zone for nutrient-bearing sediments. Barium and strontium are both present in elevated concentrations, with Ba averaging around 445 ppm and reaching a maximum of 3406 ppm, and Sr averaging approximately 194 ppm with a maximum of 856 ppm. These high values suggest strong inputs from barite, feldspar, and carbonate-rich lithologies, as well as the possible influence of fertilizer-derived materials from agricultural areas. Fluoride concentrations in sediments also exhibit substantial variability, ranging from 68 ppm to as high as 2732 ppm, with an average of approximately 373 ppm, indicating the presence of fluoride-bearing minerals that may influence downstream water quality. Micronutrient-associated metals, such as Cu, Zn, Ni, Co, and V, exhibit moderate but significant concentrations, with copper averaging around 89 ppm, zinc approximately 77 ppm, nickel about 53 ppm, and vanadium around 223 ppm, reflecting the continued transport and deposition of nutrient-related trace metals along the river corridor. These patterns suggest that the lower basin functions as both a depositional zone for nutrient-rich sediments and a region where localized geochemical hotspots can develop due to land use, lithology, and sediment sorting.

- ### Toxic Elements

Toxic elements in the lower basin exhibit considerable spatial variability, indicating a combination of natural geochemical controls and localized enrichment zones. Arsenic concentrations average approximately 4.8 ppm, with maximum values reaching about 59 ppm, revealing pockets of As-rich sediments likely associated with Fe–Mn oxide phases or specific mineralized zones. Lead shows an average concentration of around 13.5 ppm, with maxima of up to 73 ppm, suggesting contributions from both upstream sources and local lithological variability. Cadmium appears at low average concentrations of about 0.06 ppm but displays distinct maximum values in certain locations, indicating episodic enrichment. Mercury concentrations average around 13.5 ppb, with maxima reaching approximately 165 ppb, pointing to localized anomalies possibly linked to specific geological units or historical anthropogenic inputs. Rare earth elements exhibit notably high maximum values in this reach (for example, La exceeding 2000 ppm and Ce over 3600 ppm), likely reflecting heavy-mineral concentrations or unique lithological contributions rather than widespread enrichment. Collectively, these toxic element patterns underscore the lower basin’s role as a critical zone of deposition, where fine sediments accumulate and can retain high concentrations of both nutrient-related and potentially hazardous metals, thereby influencing long-term sediment and water quality dynamics.

Table 8:Degree sheet 46J Stream sediment Geochemical statistical data (Data extracted from the Degree sheets information provided by the Geological survey of India (GSI)

Parameters	Min	Max	Average
SiO2 (%)	14.6	88.32	51.92037
Al2O3(%)	3.8	19.12	13.30165
Fe2O3(%)	1.17	17.47	9.294235
TiO2(%)	0.07	4.6	1.818574
CaO (%)	0.2	30.74	4.728782
MgO (%)	0.11	12.01	2.556212
MnO (%)	0.02	0.8	0.126634
Na2O (%)	0.08	4	1.170184
K2O (%)	0.17	6.86	1.503091
P2O5 (%)	0.01	0.82	0.162766
Ba_ppm	12	3406	444.9504
Co_ppm	2	85	30.35679
Cr_ppm	6	2072	122.2417
Cu_ppm	5	302	88.81457
Ga_ppm	5	54	20.50979
Nb_ppm	1	538	22.90269

Ni_ppm	3	656	53.02142
Pb_ppm	0.5	73	13.50153
Rb_ppm	1	226.2476	62.40183
Sc_ppm	0	42	18.32344
Sr_ppm	6	856	194.4247
Th_ppm	0	707	19.20561
V_ppm	4	500	223.4113
Y_ppm	10	223	31.82742
Zn_ppm	10	214	76.66218
Zr_ppm	97	3627	406.7338
Au_ppb	0.5	215	1.683782
Li_ppm	2.5	372.909	13.68687
Cs_ppm	1	11.005	2.661834
As_ppm	0.1	59.08	4.798818
Sb_ppm	0.05	5.826	0.217745
Bi_ppm	0.05	3.979	0.14322
Se_ppm	0.03	9	0.305551
F_ppm	68	2732	373.0561
Cd_ppm	0.05	0.233	0.059162
Ag_ppm	0.0036	1.646	0.039912
Hg_ppb	2.5	165	13.45129
La_ppm	3.06	2167.651	60.61562
Ce_ppm	5.964	3658.478	114.0498
Pr_ppm	0.71	155.941	12.71675
Nd_ppm	2.646	524.5387	48.93193
Eu_ppm	0.133	16.913	1.98995
Sm_ppm	0.499	182.7349	9.263872
Gd_ppm	0.438	149.1066	8.228272
Tb_ppm	0.082	18.1212	1.485869
Dy_ppm	0.472	61.7934	7.418354
Ho_ppm	0.084	11.1948	1.422513
Er_ppm	0.228	30.499	4.094051
Tm_ppm	0.042	4.5459	0.622419
Yb_ppm	0.231	29.3983	3.991899
Lu_ppm	0.037	4.0451	0.592359
Sn_ppm	0.01	33.9	2.605981
Hf_ppm	0.59	109.0316	12.43062
Ta_ppm	0.01	10.008	1.373702
Mo_ppm	0.25	96.647	1.407465

W_ppm	0.25	65.47	1.156914
Ge_ppm	0.124	4.118	1.398387
Be_ppm	0.4231	8.037	1.596282
U_ppm	0.112	51.6594	2.877447

- **Lower Basin: 46F**

Degree sheet 49F covers the lower basin (Chhota Udaipur, Dahod, Panch Mahals, Vadodara, Bharuch) captures the reach where the middle basin load is integrated and redistributed. Detailed Geochemical data are given in Table 9.

  - **Sediment Matrix and Major Oxides**

In degree sheet 46F, the sediment matrix is dominantly siliceous yet retains a measurable aluminosilicate fraction and appreciable iron-oxide content at specific locations. Key statistics (see displayed table "Lower Narmada Summary (46F)") include: SiO_2 mean 62.56% (range up to 80%), indicating a strongly quartz-rich sediment composition typical of lower-energy depositional areas where resistant grains accumulate. Al_2O_3 averages around 12.21% (max 17.92%), reflecting persistent clay and feldspar contributions. Fe_2O_3 averages about 6.25% (max 16.11%), which — while variable — is high enough at multiple sites to control adsorption and partitioning of phosphorus and trace metals. The phosphorus-bearing oxide P_2O_5 averages approximately 0.13% (max 2.23), slightly higher than the 0.12% reported for the middle-basin transition (55E) and similar to other lower-basin sheets, indicating modest but meaningful sedimentary phosphorus storage where fines concentrate. Overall, 46F displays a quartz-dominated bulk composition with a fine fraction sufficient to influence nutrient and trace-metal behaviour.

  - **Nutrient-Related Elements**

Nutrient-associated trace metals in 46F show moderate means with strong localized maxima: Cu mean 43.12 ppm (maximum 133 ppm at 46F16/088/S/11-12, Toposheet 46F16, Lat 22.117, Lon 73.93). Zn averages 54.07 ppm (maximum 712 ppm at 46F16/030/S/11-12, Toposheet 46F16, Lat 22.045, Lon 73.82) and the very high Zn maximum indicates a pronounced local enrichment. Cr mean-92.42 ppm, Ni mean-34 ppm. Ba and Sr are also elevated in parts of 46F (Ba mean 477.66 ppm, Sr mean 133 ppm), suggesting inputs from barite/feldspar-bearing sources or provenance effects. The REE pattern (not detailed here) is broadly consistent with terrigenous inputs. In sum, 46F acts as a depositional sink in places for metal-bearing fines, producing local hotspots (notably for Zn and Cu).

- **Toxic Elements**

Toxic elements in 46F show both moderate background levels and striking hotspots that merit follow-up. Arsenic (As) averages around 5 ppm with a maximum 20.0 ppm at sample 46F11/182/S/07 (Lat 22.4942, Lon 73.74276). Lead (Pb) averages 18.75 ppm with a maximum 70.0 ppm at 46F14/036/S/04 (Lat 22.5451, Lon 73.9341). Uranium (U) shows an elevated mean 4.5 ppm with an unusually high maximum 55.35 ppm at 46F14/024/S/04 (Lat 22.5271, Lon 73.9535). The combination of high Fe_2O_3 at several localities and elevated As/Pb/U hotspots suggest adsorption onto Fe–Mn oxide-bearing fines, but the very large uranium maxima and the extreme Zn spike (712 ppm) point to localized lithologic controls or potential anthropogenic/industrial inputs. These outliers should be prioritized for verification (duplicate lab checks) and targeted follow-up sampling.

Table 9: Degree sheet 46F Stream sediment Geochemical statistical data (Data extracted from the Degree sheets information provided by the Geological survey of India (GSI)

Parameter	Min	Max	Average
SIO2	43.49	80.14	62.51866
AL2O3	6.11	17.92	12.2081
FE2O3	2.04	16.11	6.25865
TIO2	0	8.09	1.523242
CAO	0.37	11.22	2.962472
MGO	0.38	4.48	1.801365
MNO	0.02	1.39	0.09
NA2O	0.08	4.18	1.190326
K2O	0.398	5.95	2.027712
P2O5	0.03	2.23	0.133564
BA	17	2409	471.4036
GA	0	34	16.40059
SC	0	22	11.46142
V	0	416	143.503
TH	0	1343	38.34866
PB	0	70	18.75668
NI	0	110	33.99555
CO	0	76	18.61573
RB	28	360	86.28487
SR	1	557	133.1469
Y	13	828	39.73145
ZR	1	2180	410.5964
NB	0	169	22.23145

CR	2	284	92.42136
CU	0	133	43.12166
ZN	16	712	54.15282
AU	0.5	7	1.512018
LI	0	47	14.50248
CS	0	24	7.437685
AS_	0	20	5.029703
SB	0	1.4	0.299733
BI	0	3.8	0.244585
SE	0	1.2	0.284985
AG	0	430	32.48071
CD	50	134	52.16024
HG	2.5	155	19.86149
BE	0.15	13.2247	1.936405
GE	1.02	4.1867	1.758904
MO	0.5	2.5	2.491335
SN	0.8924	39.1532	2.517718
LA	19.2402	2298.837	91.4898
CE	26.52	3992.61	167.2663
PR	4.2494	397.9346	17.40748
ND	16.4987	1448.118	64.33483
SM	3.1093	167.5258	10.79449
EU	0.4453	5.9944	1.531241
TB	0.4525	18.7391	1.50795
GD	1.16	127.2141	9.423884
DY	2.3613	96.884	7.843756
HO	0.5575	21.2628	1.618454
ER	1.5662	59.9583	4.621643
TM	0.2291	10.14	0.734834
YB	1.6902	57.7522	4.629688
LU	0.16	7.8716	0.670655
HF	3.92	76.2292	12.67991
TA	0.35	95	1.727955
W	0.05	29.08	1.438094
U	1.1595	55.3515	4.49286

- ### Lower Basin: 46G

Degree sheet 46J covers the transition from middle to lower basin (Chhota Udaipur), where cumulative upstream inputs are expressed and additional downstream lithology and land uses influence sediment chemistry. Detailed Geochemical data are given in Table 8.

Sediment Matrix and Major Oxides

In degree sheet 46G, the sediment matrix is strongly siliceous while maintaining a measurable aluminosilicate fraction and moderate iron-oxide content. The average SiO_2 concentration is approximately 53.38% (range up to 65.74%), indicating a quartz-dominated sediment signature typical of lower-energy deposition. Al_2O_3 averages around 13.25% (max 18.91%), consistent with a sustained clay and feldspar-derived component. Fe_2O_3 averages about 10.85% (max 20.81%), showing moderate iron-oxide presence that can influence adsorption of phosphorus and trace metals in fine sediments. The phosphorus-bearing oxide P_2O_5 averages roughly 0.23% (max 0.9%), slightly higher than some upstream transition values and indicating meaningful sedimentary phosphorus accumulation in depositional pockets. Overall, 46G's major-oxide composition points to a quartz-rich basin with sufficient fine fraction to affect nutrient and trace-metal partitioning where fines accumulate.

Nutrient-Related Elements

Nutrient-related trace metals in 46G show moderate means with clear localized enrichments: Cu averages approximately 101 ppm (maximum 219 ppm, sampleno 46G11/162/S/2022, Lat 21.47371102, Lon 73.62533805). Zn averages ~85.92 ppm (maximum 168 ppm, SAMPLENO 46G11/119/S/2022, Toposheet 46G11, Lat 21.42473822, Lon 73.57534178). Cr and Ni are present at measurable concentrations (Cr mean 146.28 ppm, Ni mean 57.24 ppm). Ba (mean 422.5 ppm) and Sr (mean 158.3 ppm) are relatively high in places, indicating barite/feldspar/carbonate contributions or provenance differences across the sheet. The REE profile (not detailed here) aligns with terrigenous inputs. In summary, 46G contains depositional pockets that concentrate metal-bearing fines, producing local maxima (especially for Cu and Zn) while bulk means reflect dilution by coarser, quartz-rich sediments elsewhere.

Toxic Elements

Toxic elements in 46G show generally low to moderate background levels but contain important hotspots. Arsenic (As) averages about 1.9 ppm with a maximum of 11.02 ppm (SAMPLENO 46G11/174/S/2022, Toposheet 46G11; Lat 21.49399, Lon 73.59148667). Lead (Pb) averages 4.45 ppm with maximum 12.0 ppm (SAMPLENO 46G11/164/S/2022, Toposheet 46G11). Uranium (U) averages ~1.11 ppm with a maximum 9.18 ppm at 46G5/92/SS-SW/15-16 (Toposheet 46G05; Lat 21.99384, Lon 73.47273). Although mean concentrations are not as elevated as some transition zones, the presence of localized maxima particularly within Toposheet 46G11 and the U spike at 46G05 suggests adsorption onto fine Fe–Mn oxide-bearing sediments and/or lithologic/anthropogenic controls that warrant targeted follow-up and verification.

Table 10: Degree sheet 46G Stream sediment Geochemical statistical data (Data extracted from the Degree sheets information provided by the Geological survey of India (GSI)

Parameter	**Min**	**Max**	**Avg**
SIO2	43.75	65.65	53.125
AL2O3	9.86	18.91	13.23781
FE2O3	6.3	20.9	10.85612
TIO2	1.05	8.58	2.267806
CAO	1.16	13.38	6.183929
MGO	1.12	4	2.400255
MNO	0.08	0.27	0.128929
NA2O	0.31	2.32	0.985255
K2O	0.2	1.62	1.033929
P2O5	0.1	0.91	0.234796
BA	135	742	422.2969
GA	10.4	33	17.04796
SC	11.3	38.4	22.725
V	158.7	788	310.8811
TH	2	15.5	6.28551
PB	1	12	4.457143
NI	36.6	389.3	57.24592
CO	14	69.6	35.70714
RB	2.45	68.41	33.26398
SR	64	306	158.3526
Y	16.6	40	22.27041
ZR	107.4	658.3	209.0286
NB	8.5	22.1	14.53163
CR	81	1364.2	146.0582
CU	67.7	219	101.3995
ZN	57.8	168	85.64286
AU	0.5	4	1.177959
LI	2.5	39.62	12.68929
CS	1	5	4.136531
AS_	0.44	11.02	1.924286
SB	0.1	0.95	0.215663
BI	0.05	2.23	0.362449

SE	0.025	0.51	0.130408
AG	0.9	200	29.18827
CD	50	240	59.86735
HG	2.5	67.45	9.049796
BE	0.15	14.40216	1.656994
GE	0.8	5.316467	2.359116
MO	0.25	10.47673	0.760618
SN	0.5	13.15338	0.985699
LA	8.33	54.00948	24.24338
CE	19.89	110.0393	49.92858
PR	2.178473	61.80314	6.137023
ND	8.900935	63.13	24.04069
SM	1.56141	13.65	5.103226
EU	0.308095	5.102887	1.213979
TB	0.130812	5.609176	0.662499
GD	1.408266	12.42	4.822044
DY	1.243175	12.8	5.024036
HO	0.137626	6.018514	0.764648
ER	0.661817	7.651444	2.463453
TM	0.043614	3.964017	0.299511
YB	0.496218	7.776891	2.230791
LU	0.034294	3.216536	0.267974
HF	1	18.82536	5.660878
TA	0.1	3.213912	0.688492
W	0.25	3.827907	0.438149
U	0.25	9.177444	1.175344
IN_	0.03	0.15	0.102174
F	104	292	155.6957
TE	0.01	0.1	0.034348
TL	0.025	0.26	0.161087

- **Lower Basin : 46C**

Degree sheet 46J covers the transition from middle to lower basin (Chhota Udaipur), where cumulative upstream inputs are expressed and additional downstream lithology and land uses influence sediment chemistry. Detailed Geochemical data are given in Table 8.

- ### Sediment Matrix and Major Oxides

In the lower-basin zone represented by degree sheet 46C, the sediment matrix is dominantly siliceous but preserves a consistent clay/aluminosilicate fraction. The average SiO_2 concentration is approximately 58ppm max being 70ppm indicating a more strongly siliceous sediment composition relative to the middle-basin transition. Al_2O_3 averages around 13.46 ppm, signifying persistent input of clay minerals and feldspar-derived aluminosilic ates. Iron oxide (Fe_2O_3) averages about 9.5 ppm, lower than the elevated Fe_2O_3 (11.6 ppm) reported for the middle-basin transition, but still sufficient to influence adsorption of nutrients and trace metals. The phosphorus-bearing oxide P_2O_5 averages roughly 0.25 ppm, which is actually higher than the 0.12 ppm reported for the middle-basin (55E), indicating enhanced sedimentary phosphorus storage in portions of the lower reach. Collectively, the major-oxide signature indicates a system dominated by quartz-rich framework grains with a steady fine fraction (clays/Al-silicates) and enough Fe-oxide phases to control adsorption and geochemical partitioning as the river's energy declines.

- ### Nutrient-Related Elements

Nutrient-associated and commonly bioavailable trace metals in 46C show distinct average values and localized enrichment. On average, copper (Cu) is about 95.5 ppm (max 173.8 ppm), chromium (Cr) averages 120.2 ppm (max 360 ppm), nickel (Ni) averages 60.5 ppm, and zinc (Zn) averages 76.9 ppm (max 137 ppm). These mean concentrations are generally lower than the high averages reported for the middle-basin transition, but discrete samples record pronounced maxima indicating localised accumulation zones. Barium and strontium show strong presence in 46C (Ba mean 526 ppm, Sr mean 160 ppm), with Ba notably higher than the middle-basin average cited earlier suggesting important contributions from barite/feldspar-bearing minerals or provenance differences in the lower basin. The REE suite in 46C does not display extreme enrichment; REE concentrations are broadly consistent with a terrigenous input and steady provenance signal. Overall, the lower-basin acts as a depositional sink for metal-bearing fines in places (local maxima for Cu, Cr, Zn), while bulk means reflect dilution by coarser, quartz-rich material in other locations.

- ### Toxic Elements

Toxic elements in degree sheet 46C reveal both moderate background levels and discrete hotspots. Arsenic (As) averages about 4.13 ppm across samples but reaches a local maximum of 58.11 ppm in a sample from Toposheet 46C14 (SAMPLENO 46C/14/17/SW/14; Lat 21.52709, Lon 72.81757). Lead (Pb) averages 8.68 ppm with a maximum of 35.3 ppm (sample 46C/14/30/S/15, 46C14), while uranium (U) averages 0.85 ppm and attains a maximum of 2.86 ppm (sample 46C/14/10/SW/14, 46C14). Although mean concentrations of As, Pb and U in 46C are lower than those quoted for the middle-basin transition, the presence of high local maxima clustered notably within Toposheet 46C14 points to strong adsorption onto fine Fe–Mn oxide-bearing sediments or to localized lithologic/anthropogenic sources. The coincidence of elevated Fe_2O_3 at several sites with high As and Pb supports an adsorption-driven concentration mechanism in lower-energy depositional pockets.

Collectively, the 46C degree-sheet indicates a lower-basin environment characterised by higher bulk silica (SiO_2), steady aluminosilicate content (Al_2O_3), moderate Fe-oxide levels, and noticeable sedimentary phosphorus (P_2O_5). Nutrient-bearing trace metals show local enrichments (notably Cu, Cr and Zn maxima), and toxic elements display hotspot behaviour (As, Pb, U) that clusters in the 46C14 toposheet area consistent with fine-sediment deposition and adsorption processes and/or local inputs. These patterns identify the lower-basin as an important depositional and geochemical sorting zone where both nutrients and potentially hazardous elements can accumulate before further downstream transport or burial.

Table 11: Degree sheet 46C Stream sediment Geochemical statistical data (Data extracted from the Degree sheets information provided by the Geological survey of India (GSI)

Parameter	Min	Max	Average
SIO2	40.2	69.93	57.8331
AL2O3	8.474	20.28	13.45277
FE2O3	3.497	17.67	9.502213
TIO2	0.69	2.55	1.66957
CAO	1.98	11.67	3.832198
MGO	1.2	5.11	2.443155
MNO	0.06	0.2	0.117961
NA2O	0.27	6.743	1.248343
K2O	0.32	2.16	1.373614
P2O5	0.08	0.74	0.25087
BA	72.9	3527.2	526.9216
GA	2	26.737	16.36335
SC	8.806	36.9	20.22671
V	48.728	360.1	231.2995
TH	2	11	8.070531
PB	1	35.3	8.682444
NI	29	152.8	60.17999
CO	1.491	50	32.95975
RB	19.7	71.85	53.47751
SR	96.9	531	160.4063
Y	16.1	161.053	32.40835
ZR	97.5	362.8	217.6078

NB	6.2	21	14.01895
CR	60.531	360	120.3405
CU	24	173.778	95.50426
ZN	40	137	76.75536
AU	0.5	8.85	3.043333
LI	2.5	61	14.33652
CS	5	28.57	6.716425
AS_	0.5	58.11	4.133961
SB	0.1	1.35	0.60372
BI	0.05	4.52	1.373816
SE	0.025	2.32	0.582657
AG	10	90	16.3285
CD	50	200	63.18841
HG	2.5	81.93	14.37755
BE	0.15	10.8	0.816443
GE	0.25	13.33009	3.146555
MO	0.25	29.01547	2.403889
SN	0.5	8.936061	1.418441
LA	0.5	47.84	13.56579
CE	1	95.54	28.40672
PR	0.0375	11.05	3.223401
ND	0.028	42.73	13.43124
SM	0.045	9.78	2.948453
EU	0.003	2.44	0.726371
TB	0.014	1.68	0.410226
GD	0.076255	9.24	2.976505
DY	0.005	9.56	2.878504
HO	0.005	1.75	0.446115
ER	0.0075	4.79	1.390252
TM	0.006	0.82	0.162774
YB	0.005826	4.84	1.34086
LU	0.0115	0.66	0.144056
HF	0.25	21.21	2.629886
TA	0.1	1.88	0.502307
W	0.25	2.3	0.515317
U	0.25	2.862703	0.856326

4. Spatial and Temporal Patterns of Nutrient and Sediment Load

The spatial distribution of nutrient and sediment loads across the Narmada River Basin reveals clear longitudinal trends that reflect both lithological variations and cumulative transport processes from the upper to the lower reaches. Major oxides such as SiO_2 and Al_2O_3 remain within typical crustal ranges across the basin, although SiO_2 tends to increase downstream, especially in 55J, before showing wide variability in 46J where sediments reflect a mixture of coarse and fine fractions. Iron oxide (Fe_2O_3) exhibits its highest concentrations in the uppermost basin (55N), indicating abundant Fe-bearing minerals that play a central role in adsorbing phosphorus and trace metals, while remaining significant in the middle basin (55E) where fine-grained sediments accumulate. Phosphorus (expressed as P_2O_5) shows comparable average values across all basin segments, generally between 0.10% and 0.16%, but maximum concentrations increase notably in the lower basin (46J), where localized hotspots of P enrichment are present. Nutrient-associated trace metals such as Cu, Zn, Ni, Co and V display elevated concentrations in both the upper and middle basin transition zones, particularly in 55N and 55E, suggesting that these reaches generate or accumulate metal-rich fine sediments that are subsequently transported downstream. Toxic elements, including As, Pb and other potentially hazardous metals, occur throughout the basin, with higher average arsenic levels in the upper–middle transition region (55J and 55E) and pronounced maximum concentrations in the lower basin, indicating the influence of both natural geochemical variability and localized enrichment zones. Many of these toxic elements are closely associated with Fe–Mn oxide-rich fine sediments, meaning their downstream transport is tightly linked to the movement of nutrient-bearing particles.

From a temporal perspective, the dataset represents a single synoptic sampling effort and therefore does not provide explicit multi-season or multi-year trends. As a result, direct temporal analysis, such as determining long-term increases or decreases in nutrient or metal concentrations, is not possible from this dataset alone. However, the observed patterns reflect the integrated effects of seasonal hydrology and long-term basin processes. During monsoon periods, high flows are expected to mobilize large quantities of nutrient-rich and metal-bearing sediments from upland areas, transporting them downstream. In contrast, during low-flow conditions, these fine sediments tend to settle in floodplains, channel bars, reservoirs, and low-energy reaches. Over extended time scales, changes in land use, agricultural intensity, mining activity, and erosion rates are likely to influence both nutrient and sediment loads, contributing to the geochemical signatures captured in the current dataset. Thus, the spatial patterns observed represent a snapshot of the cumulative temporal dynamics operating within the Narmada Basin, while highlighting the need for continuous monitoring to establish definitive temporal trends.

4.1. Nutrient and Sediment Variation in Narmada River

4.1.1. Nutrient Variation

Nutrient concentrations in the Lower Narmada Basin show a clear downstream increase from Garudeshwar to Zadeshwar, reflecting increasing human activities, land-use pressure, and changing flow conditions. Data used in this section obtained from GPCB with quarterly frequency from 2015 to 2025. At Garudeshwar, nutrient levels remain consistently low throughout the study period. Nitrate concentrations range from about 0.01 mg/L to 0.30 mg/L, with most values remaining below 0.15 mg/L. Nitrite concentrations vary from below detection limit to about 0.05 mg/L, and most values remain very low. Phosphate concentrations range between 0.01 mg/L and 0.05 mg/L, with most observations confined to this narrow range. Total Kjeldahl Nitrogen varies from approximately 1.05 mg/L to 1.40 mg/L, and most values are below 1.25 mg/L, indicating low nutrient input and good dilution conditions at this upstream station.

At Panetha, nutrient concentrations show a moderate increase compared to Garudeshwar. Nitrate values range from about 0.03 mg/L to 1.87 mg/L, while most observations remain below 0.50 mg/L. Nitrite concentrations vary between 0.01 mg/L and 0.95 mg/L, with most values occurring at the lower end of the range. Phosphate concentrations range from 0.02 mg/L to 0.12 mg/L, and most values are below 0.10 mg/L. Total Kjeldahl Nitrogen ranges from 1.10 mg/L to 1.60 mg/L, with most observations below 1.40 mg/L. The rise in nutrient levels at this location is mainly linked to agricultural runoff, domestic wastewater discharge, and surface wash-off during rainfall events.

Further downstream at Zanor, nutrient levels become moderate and show greater variability. Nitrate concentrations range from about 0.01 mg/L to 1.93 mg/L, with most values remaining below 1.00 mg/L. Nitrite varies from 0.01 mg/L to 0.055 mg/L, and most values remain close to the minimum level. Phosphate concentrations range between 0.10 mg/L and 1.16 mg/L, though most observations are below 0.30 mg/L. Total Kjeldahl Nitrogen varies from 0.60 mg/L to 2.24 mg/L, with most values below 1.70 mg/L. These results indicate increased nutrient input, reduced dilution, and higher biological activity influenced by surrounding settlements and catchment runoff.

The highest nutrient concentrations and widest variation are observed at Zadeshwar, located in the downstream and estuarine reach of the river. Nitrate concentrations range from 0.02 mg/L to 2.17 mg/L, with most values below 1.50 mg/L. Nitrite varies between 0.01 mg/L and 0.074 mg/L, with most values remaining low. Phosphate concentrations range from 0.02 mg/L to 0.82 mg/L, and most observations are below 0.60 mg/L. Total Kjeldahl Nitrogen shows a wide range from 0.38 mg/L to 2.80 mg/L, with most values below 2.20 mg/L. Elevated nutrient levels at this station are influenced by industrial and municipal discharges, agricultural drainage, urban runoff, and estuarine conditions where slower water movement promotes nutrient accumulation.

Overall, the nutrient data clearly indicate a progressive downstream increase in concentration and variability within the Lower Narmada Basin. While upstream sections maintain low and stable nutrient levels, downstream and estuarine regions experience higher nutrient loading due to increasing human influence and reduced natural flushing capacity of the river.

4.1.2. Sediment Variation

Sediment characteristics in the Lower Narmada Basin show a strong downstream increase from Garudeshwar to Zadeshwar, mainly due to changes in flow condition, catchment runoff, human activities, and tidal influence. Data used in this section obtained from GPCB with quarterly frequency from 2015 to 2025. At Garudeshwar, sediment levels remain the lowest and comparatively stable. Turbidity ranges from about 0.1 NTU to 84 NTU, though most values remain below 3 NTU, indicating generally clear water conditions. Suspended solids vary from approximately 1 mg/L to 352 mg/L, but most observations are below 20 mg/L, showing that high sediment loads occur mainly during short monsoon events. The low sediment levels at this station reflect controlled releases from the dam, limited bank erosion, and minimal disturbance, with occasional increases caused by rainfall runoff.

At Panetha, sediment concentrations increase moderately compared to Garudeshwar. Turbidity values range from about 0.2 NTU to 175.8 NTU, while most values remain below 15 NTU. Suspended solids range from approximately 2 mg/L to 394 mg/L, with most observations below 30 mg/L. This increase in sediment load is linked to agricultural runoff, local drainage inputs, tributary inflow, and moderate bank erosion, especially during the monsoon season.

At Zanor, sediment levels become higher and show greater variability. Turbidity ranges from about 0.3 NTU to 86.1 NTU, though most values remain below 25 NTU. Suspended solids vary from approximately 2 mg/L to 238 mg/L, with most values below 60 mg/L. The higher sediment concentration at this station reflects increased human activities along the riverbanks, disturbance of the channel, sand movement, and greater sediment input from the surrounding catchment, particularly during high-flow periods.

The highest sediment concentrations and widest variation are observed at Zadeshwar, located in the downstream and estuarine part of the basin. Turbidity shows extreme variation, ranging from about 2 NTU to 2580 NTU, while most values remain below 80 NTU. Suspended solids range from approximately 2 mg/L to 2016 mg/L, with most observations below 150 mg/L. These high and fluctuating sediment levels are strongly influenced by tidal action, estuarine mixing, industrial and urban runoff, and frequent resuspension of fine sediments near the river mouth. Tidal movement continuously disturbs deposited sediments, leading to sudden and sharp increases in sediment concentration.

Overall, sediment data clearly indicate a progressive downstream increase in both concentration and variability across the Lower Narmada Basin. Upstream sections remain relatively stable with low sediment load, while downstream and estuarine reaches experience high sediment input and large fluctuations due to the combined effects of monsoon runoff, human activities, and tidal processes.

5. Existing Practice Affecting Nutrient Recycling in the Narmada River Basin

5.1. Agricultural and Land management in the Narmada River Basin

The Narmada River Basin, spanning across Madhya Pradesh, Gujarat, and parts of Maharashtra and Chhattisgarh, is characterized by diverse agricultural systems, ranging from rainfed farming in the upper and middle catchments to intensive irrigated agriculture in canal-command areas. These practices have a significant impact on the basin's nutrient (N-P-K) dynamics, determining how nutrients are recycled, retained, or lost to soil and water systems.

5.2. Cropping Patterns and Their Influence on Nutrient Cycling

The Narmada River Basin is home to many types of agriculture, including soybean-wheat, rice-wheat, and less common sugarcane-based crop rotations. There is also extensive horticultural and vegetable growing in the canal belt and adjacent riverbanks. In Madhya Pradesh (Nimar region - Soybean and Cotton) and parts of Maharashtra, kharif crops are planted on approximately 64000 ha of land. Major crops included in the kharif season are Soybean (8.66% of kharif area), Rice (7.76% of kharif area), Maize (10.23% of kharif area), and Tur Pulses

(8.36% of Kharif area), whereas Rabi Crops include Wheat and Grams. The average intensity of cropping is 94-127%; the irrigated systems in the Narmada Basin account for only 15-20% of the total area, with irrigated systems requiring a higher amount of inputs, including nutrients, to produce more than 1 crop per year (Namdeo, 2022; Government Of Maharashtra Water Resources Department Integrated State Water Plan For Narmada Basin In Maharashtra Tapi Irrigation Development Corrporation Jalgaon, n.d.; Narmada River Basin Agricultural Profile Report, 2025). Soybean-based cropping systems are common in the Districts of Khargone and Indore. The majority of these bean types fix nitrogen biologically through the action of Rhizobium, and the amount of nitrogen fixed can be anywhere from 50 to 100 kg N/ha. However, due to widespread residue removal or burning, which takes place on 50-70% of the fields, the loss of nitrogen fixed is estimated to be around 60-80%. Losses of nitrogen decrease the recycling potential of the previously fixed nutrients, thereby reducing organic matter in the soil. In these commercial belts, farmers therefore rely significantly on purchased fertilizers to compensate for the decreased nutrient recycling, with the average application rate being 42 kg N/ha, resulting in significant amounts of nitrogen being lost from the soil into rivers, which then contribute to elevated nitrate levels. Legume rotations will partially assist in replenishing nutrients in the soil, but the incomplete recycling will continue to exacerbate the imbalance of P and K in the vertisols' soils (Namdeo, 2022; Biswas, 2018; Kansara & Lakshmi, 2021). Sugarcane and banana production occur in the canal irrigation belts of Gujarat and southern Madhya Pradesh. These crops require high nutrient input (N ~200–400 kg/ha; P ~100–200 kg/HA) but receive excessive amounts of fertilizer, resulting in nutrient surpluses (nutrient use efficiency is <40%), and no recycling efficiencies from ratoon cropping and residue export. Therefore, these perennial systems comprise only 1 to 5% of basin areas but increase the risk of P loading into reservoirs and resulting eutrophication. Horticultural crops (e.g., bananas, mangoes, and vegetables) occupy 5% to 10% of the canal area and further increase nutrient inputs through high use of manure and fertilizers. Subsequently, poor residue management leads to high rates of nutrient loss (Narmada River Basin Hydrology Data Report 2024 & NRCD 2025; Kansara & Lakshmi, 2021; Research Achievements of AICRPs on Natural Resource Management, n.d.).

5.3. Fertilizer Use, Imbalances, and Limited Organic Inputs

Chemical fertilizers dominate agriculture across most of the Narmada River Basin, where urea and DAP supply the majority of nitrogen and phosphorus. Potassium (K), however, is often underutilized because farmers assume the region’s black soils provide sufficient K. Cropping systems, such as those involving soybeans, cotton, and sugarcane, remove large quantities of biomass and thus potassium, creating a hidden K deficiency that is not reflected in current fertilizer practices. This imbalance reduces nutrient-use efficiency, as excess nitrogen relative to phosphorus and potassium leads to nutrient losses through leaching or runoff (Namdeo, 2022; Kansara & Lakshmi, 2021). The skewed N:P: K ratios pose a major concern: high nitrogen inputs disrupt soil nutrient balance, increase nitrate leaching, and contribute to eutrophication. Although driven by yield expectations, this nitrogen-heavy strategy neglects the importance of balanced fertilization for sustaining soil health (Gangwal et al., 2016; Narmada River Basin Agricultural Profile Report, 2025). Declining use of organic manure, compost, and biofertilizers has further weakened the nutrient cycle. Reduced livestock numbers and increased dependence on chemical fertilizers have broken the traditional manure-to-soil loop. Limited awareness and affordability hinder the adoption of compost and biofertilizers, contributing to low soil organic carbon and diminished microbial activity.

5.4. Crop Residue Management and Its Effect on Nutrient Return

Crop residue management is a major barrier to nutrient return in the Narmada River Basin, where burning and removal are the dominant practices. These methods lead to substantial nutrient losses and declining soil fertility. Residues from soybean, wheat, and rice such as soybean stalks (4–6 t/ha), wheat straw (2–4 t/ha), and paddy straw (3–5 t/ha) contain significant nutrients (20–50 kg N, 5–15 kg P, 30–80 kg K, and 5–10 kg S per hectare), yet 50–80% of these are lost due to current management (Gelderman, 2009; Kalindi et al., 2025; Narmada River Basin Agricultural Profile Report, 2025). Burning, common in wheat straw (50–70% of fields), causes rapid volatilization of 80–100% of N and 75–90% of S, while P and K losses reach 20–35%. Each tonne of straw burned results in losses of 5.5 kg N, 2.3 kg P, 25 kg K, 1.2 kg S, and 60–80% of organic carbon, severely damaging microbial activity and nutrient mineralization (Bhuvaneshwari et al., 2019; CII Cleaner Air Better Life Impact Assessment Report 2020-21; Crop Residue Management, n.d.). Residue removal further results in annual losses of 40–70 kg K/ha in the Nimar region, as farmers rarely compensate for exported nutrients (Namdeo, 2022; Gelderman, 2009). Soybean stubble rich in fixed N (30–50 kg/ha) is diverted for livestock feed, weakening the crop–livestock–soil nutrient loop and increasing reliance on chemical fertilizers. Residue incorporation is practiced by fewer than 20–30% of farmers, resulting in reduced organic matter inputs, microbial activity, and soil stability, especially in sloped catchments. Although watershed programs promote mulching and no-till residue retention, adoption remains low due to equipment and labor constraints (Biswas, 2018; Crop Residue Management, n.d.).

5.5. Irrigation Practices and Nutrient Movement

Irrigation in the Narmada Basin depends largely on major dam systems such as Tawa, Bargi, Indira Sagar, and Sardar Sarovar, with more than 70% of farmers using flood irrigation. While effective for crop production, flood irrigation causes significant runoff and leaching of nitrogen and phosphorus, carrying fertilizers into drainage channels and tributaries and increasing eutrophication risks in downstream reservoirs and river stretches (Kansara & Lakshmi, 2021; Narmada River Basin Agricultural Profile Report, 2025). Groundwater overextraction, particularly in the black soil regions of Nimar, further accelerates nitrate leaching. Groundwater samples near irrigated lands have shown nitrate concentrations of up to 300 mg/L, far exceeding drinking water limits and indicating severe nutrient pollution (Gupta et al., 2023). Adoption of drip and sprinkler irrigation remains very low (<10% of irrigated acreage), despite their ability to improve fertilizer-use efficiency by 15–30% and reduce nutrient losses through precise water and nutrient delivery (cNarmada & NRCD, n.d.-a; Government of Maharashtra Water Resources Department integrated state water plan for Narmada Basin in Maharashtra Tapi Irrigation Development Corporation Jalgaon, n.d.). The broad adoption of precision irrigation systems could significantly reduce nutrient runoff, enhance nutrient uptake, and support sustainable nutrient cycling throughout the basin.

5.6. Land and Soil Management Practices

Open grazing and deforestation from agricultural expansion, especially shifting cultivation, have significantly increased soil erosion in the upper and middle catchments of the Narmada Basin (Mandla, Dindori, Chhindwara, Betul). Vulnerable sub-watersheds experience severe erosion (e.g., 46.79 t/ha/yr in Watershed 63) and fall under “high” to “very high” erosion risk (Ahirwar et al., 2019; Meshram et al., 2023; S Parmar, 2019). Watershed interventions have proven effective in reducing erosion and retaining nutrients. Measures such as contour bunding (>1 million ha created), check dams (thousands built under IWMP and MGNREGA), and vegetative barriers trap soil and nutrients locally.

5.7. Riverbank and Floodplain Agriculture

Riverbank and floodplain (diara/bah) farming along the Narmada utilizes nutrient-rich alluvial silt deposits to cultivate short-season vegetables in fertile riparian zones. These areas feature silty loam soils suitable for horticulture, with intensive cultivation relying on high fertilizer applications that contribute to nutrient runoff into the river and its tributaries, such as the Tawa and Sher. Low nutrient-use efficiency in these systems results in losses through leaching, volatilization, and surface runoff, thereby elevating nutrient concentrations and posing eutrophication risks downstream (Narmada River Basin Agricultural Profile Report, 2025).

Riparian vegetative buffers along the Narmada help filter agricultural runoff and stabilize soils, as documented in buffer zone assessments and restoration initiatives. Farmyard manure application by some farmers provides partial mitigation, while natural silt deposition supports baseline fertility. Efforts under programs like Namami Devi Narmade promote buffer restoration to enhance nutrient retention (Icass Policy Brief, n.d.; Narmada River Basin Agricultural Profile Report, 2025).

Riverbank agriculture generates higher incomes compared to upland farming but increases direct nutrient loading to the river. Implementing wider buffers and precision nutrient management could substantially reduce these losses and improve sustainability.

5.8. Land-Use Change, Urban Expansion, and Sand Mining

Urban expansion and sand mining in the Narmada Basin are rapidly disrupting the natural cycle of nutrients. Growing cities like Jabalpur, Hoshangabad, and Bharuch have replaced agricultural and forest lands with built-up areas, severing the soil–crop–vegetation linkages and introducing large nutrient loads from untreated sewage, which leads to localized eutrophication (Kansara & Lakshmi, 2021; Sarsaiya et al., 2025).

Extensive sand mining reduces the deposition of nutrient-rich alluvial sediments on floodplains, lowering soil fertility, increasing dependence on chemical fertilizers, and accelerating riverbank erosion (cNarmada & NRCD, n.d.-b; Rahi et al., 2024).

In upper basin districts such as Mandla, Dindori, and Balaghat, deforestation for agriculture and infrastructure decreases organic matter inputs, weakens soil nutrient buffering, and increases erosion and downstream nutrient flow (Kansara & Lakshmi, 2021).

5.9. Wastewater, Industrial, and catchment practices in the Narmada River Basin

Municipal wastewater, industrial effluents, and a variety of activities in the catchment area (watershed) also have a substantial influence on when and how nitrogen (N), phosphorus (P), and organic matter enter, cycle through, and exit (leach) the Narmada River system. The practices taking place in these areas are therefore instrumental in determining whether nutrients will remain in the basin or leave as pollutants (i.e., discharge) to the Narmada River and its reservoirs.

5.9.1. Municipal Wastewater Generation and Disposal

- **Urban Centers Along the Narmada**

The Narmada River flows through or adjacent to key urban and peri-urban centers, including Jabalpur (pop. ~1.4 million), Narmadapuram (Hoshangabad, ~0.2 million), Omkareshwar/Barwaha belt, Khandwa-Khargone region (~0.5 million combined), Barwani, Bharuch (~2 million), and smaller pilgrimage towns like Maheshwar and Mandla, generating 150-250 MLD municipal wastewater amid 3-5% annual urban growth. Rapid population increase (Census 2011-2025 projections: 20-30% rise), unplanned sprawl, and rising water demand (100-150 LPCD in cities) have escalated sewage production to over 200 MLD basin-wide, with only 40-50% collection coverage (Malviya, 2017; Narmada River Basin River Monitoring Protocol Report, 2025).

Sewerage infrastructure remains partial: Jabalpur has ~60% coverage (87 MLD capacity, 3 STPs), Hoshangabad ~40% (20 MLD), Bharuch ~70% (50 MLD via GIDC CETP integration), while smaller towns like Barwani and Mandla rely 70-90% on septic tanks, pit latrines, and open defecation, channeling greywater/blackwater into 500+ km of nallas. These open drains mix domestic sewage (80-90% volume), commercial sullage (from hotels and markets), and occasional industrial effluents, discharging untreated waste into the Narmada (e.g., 51 MLD directly at Jabalpur, 15 MLD at Khandwa) or its tributaries, such as the Tawa and Sher (Narmada River Basin River Monitoring Protocol Report, 2025).

Existing STPs (total ~150 MLD capacity across MP/Gujarat) underperform: Jabalpur's 45 MLD plant operates at 60-70% efficiency (BOD removal <70%), facing power cuts, sludge mismanagement, and overloading (110% hydraulic), while Bharuch's units achieve 80% but bypass during monsoons; NGT 2023-2025 orders highlight 60 MLD gaps, with effluents (BOD 20-50 mg/L, TSS 100-200 mg/L) released via canals (Report on Water Quality Hot-Spots in Rivers of India Government of India Ministry of Jal Shakti Department of Water Resources River Development and Ganga Rejuvenation Central Water Commission , 2024 (5TH Edition), n.d.).

5.9.2. Dam construction influencing the Nutrient dynamics

Dam construction has profoundly altered nutrient dynamics in the Narmada River Basin by modifying flow regulation, sediment trapping, and biogeochemical processing. Long-term observations upstream and downstream of the Sardar Sarovar Dam show that while river discharge decreased marginally (35.3 to 33.9 $km^3\ yr^{-1}$), nutrient fluxes declined sharply due to reservoir retention (Gupta et al., 2021). Dissolved silica concentrations decreased from ~470 µM upstream to ~214 µM downstream, indicating ~55 % retention. Dissolved inorganic phosphorus declined from ~0.84 to ~0.38 µM (~54 % retention), largely due to sedimentation and biological uptake. The most significant change occurred in dissolved inorganic nitrogen, which dropped from ~43 µM to ~1.5 µM, corresponding to ~96% retention. Enhanced denitrification under anoxic hypolimnetic conditions, promoted by long water residence time (~244 days) and high organic matter burial, is identified as the dominant nitrogen removal mechanism. Preferential nitrogen loss has altered downstream nutrient stoichiometry, potentially reducing coastal primary productivity in the Arabian Sea.

5.9.3. Implications for Nutrient Recycling

Municipal wastewater from urban centers in the Narmada Basin contributes significant nutrient loads, acting primarily as point-source pollution to rivers rather than being reused agriculturally. Discharges from cities like Jabalpur and Hoshangabad elevate total nitrogen and phosphorus concentrations downstream, with hotspots noted at urban confluences (Kansara & Lakshmi, 2021; Sarsaiya et al., 2025).

Low-flow conditions amplify these impacts, leading to dissolved oxygen depletion, eutrophication risks, and algal blooms in reservoirs such as Indira Sagar. Monitoring data indicate organic loading and nutrient hotspots associated with urban inputs (Rahi et al., 2024; Saini et al., 2025).

Informal peri-urban irrigation reuses some wastewater for crops near Jabalpur and Khargone, recycling nutrients but posing risks of groundwater nitrate contamination, pathogens, and heavy metal accumulation in soils and produce. Initiatives like the Clean Narmada Mission aim to promote treated reuse, though implementation gaps persist (Narmada River Basin Hydrology Data Report 024 & Rahi et al., 2024).

6. Challenges and Gaps

6.1. Data Issues

Nutrient and sediment load assessments in the Narmada River basin suffer from sparse and outdated monitoring networks, with Central Water Commission (CWC) data covering only 11 stations for $NO_2 + NO_3$ nutrients post-2016 and limited sediment observations at 14 sites, leading to unreliable SWAT model validations characterized by low R^2 values below 0.2 in tributaries and biases up to 7 mg/L for unmodeled sewage peaks. Phosphorus dynamics remain largely unmonitored, hindering comprehensive eutrophication risk evaluations, while short-term datasets fail to capture decadal trends influenced by dam trapping that reduces downstream sediment delivery by 70-211%. Integrated nutrient-sediment measurements are absent basin-wide, forcing reliance on static district-level fertilizer data averaging 42 kg/ha nitrogen without accounting for dynamic crop rotations or land-use changes, exacerbating uncertainties in spatial flux estimates where main-channel concentrations exceed tributaries by 6-8 times (Das, 2021).

6.2. Policy Issues

Pollution control enforcement remains weak despite Narmada Water Disputes Tribunal mandates, as illegal sewage discharges and under-capacity STPs persist without specific nutrient or sediment load reduction targets integrated into basin management plans. Inter-state coordination under the Narmada Control Authority prioritizes water apportionment over pollutant budgeting, neglecting non-point agricultural runoff that constitutes 70-80% of nitrogen loads and sediment erosion from mining or dam operations. National policies advocate remote sensing for hydrology but lack requirements for mandatory SWAT or USLE modeling to forecast loads from fertilizer overuse in high-risk zones, resulting in fragmented responses to monsoon-driven fluxes that carry most annual pollutants (Narmada River at a Glance Report, 2024).

6.3. Institutional Issues

Weak coordination among agencies related to water, agriculture, and environment in the Narmada River basin constrains effective management of sediment and nutrient loads. The Narmada Basin Organization operates 68 hydrometry stations, focusing primarily on flow and floods rather than dedicated nutrient or sediment laboratories, and lacks real-time, integrated monitoring networks spanning Madhya Pradesh, Gujarat, and Maharashtra (CWC/NBO; Narmada River Basin Hydrology Data Report, 2024). State-level agencies such as the Narmada Valley Development Authority (NVDA), the Central Water Commission (CWC) field units, and the Madhya Pradesh Pollution Control Board (MPPCB) often function in silos, with no unified protocols for data sharing or joint analysis, despite cNarmada initiatives explicitly calling for participatory, basin-wide monitoring that remains largely unimplemented under a basin authority with limited mandate (Narmada River Basin Hydrology Data Report , 2024; Narmada Legal and Institutional Landscape Report). Consequently, research outputs from hydrological and SWAT-based modeling studies—documenting upstream overestimations, boundary sub-basin trends, and source-specific contributions to sediment and nutrient loads—rarely feed into Narmada Control Authority advisories or state technical committees, perpetuating a persistent disconnect between scientific evidence and on-the-ground decision-making (Narmada River Basin Hydrology Data Report, 2024; SWAT-India proceedings).

7. Sustainable Nutrient and Sediment Management in the Narmada Basin: Best Practices, Nature-Based Solutions, and Governance Pathways

The Narmada River Basin is one of India's most ecologically dynamic and socio-economically important river systems, shaped by a diverse geological framework, strong monsoonal influences and an intricate mosaic of agricultural, urban and forested landscapes. Its sediment and nutrient characteristics form a complex pattern in which fine Fe–Mn oxide–rich particles, originating largely in the upper mountainous regions, are transported downstream and progressively enriched with nutrients and trace metals. Longitudinal variations observed across the basin indicate increasing nutrient concentrations, particularly in central and lower stretches, where intensive agriculture and expanding urban settlements contribute to higher anthropogenic inputs. This emerging imbalance between natural biogeochemical processes and human-induced pressures has led to growing concerns over eutrophication, declining river health, and a reduction in the basin's ecological resilience.

Evidence from national water quality assessments further reinforces these trends. Monitoring reports consistently identify the Narmada as a river experiencing elevated nitrogen, phosphorus, and organic loads in stretches influenced by fertilizer-intensive agriculture, untreated or partially treated wastewater, and sand mining–related geomorphic disturbances (Central Water Commission, 2024). The cNarmada River Monitoring Protocol (2023) highlights critical reaches where non-point agricultural runoff and point-source urban discharges intersect, creating nutrient hotspots during both monsoon-driven runoff episodes and low-flow periods. These observations demonstrate that nutrient and sediment management in the Narmada Basin requires a basin-scale understanding that integrates hydrological, ecological and socio-economic dimensions.

Designing Best Management Practices for the Narmada Basin must begin with improvements to agricultural nutrient stewardship. Sustainable nutrient management approaches, such as soil-test-based fertilizer application, split dosing of nitrogen, accounting for soil organic matter, and using balanced N:P: K formulations, are essential for reducing losses from farmlands (Food and Agriculture Organization, 2021; Indian Council of Agricultural Research, 2020). These measures directly address the concern that large quantities of nutrient-rich crop residues are removed or burned each season, reducing soil fertility and contributing to nutrient losses to water bodies. Conservation agriculture techniques, including reduced tillage, residue retention and diverse crop rotations, have been systematically demonstrated in Indian watershed programs to reduce erosion, improve infiltration and enhance soil structure (Government of India, 2011, 2019). In erosion-prone upper basin districts where steep slopes and fragile land systems dominate, these practices become indispensable to reducing sediment-bound nutrient transport and stabilizing headwater catchments.

Another essential component of effective management is the restoration and protection of riparian ecosystems. Historically, the Narmada's floodplain and riparian zones provided natural buffers that filtered sediments and nutrients before they entered the main channel. Over time, pressures from riverbank agriculture, sand mining and infrastructure expansion have severely reduced the width and continuity of these vegetated strips. Research on Indian riparian systems demonstrates that well-designed buffer zones can trap 60–80% of sediment and significantly reduce dissolved nutrient inputs (The Nature Conservancy India, 2023). Restoring these transitional ecosystems using native plant species enhances infiltration, stabilizes banks, increases biodiversity and re-establishes ecological connectivity along the river corridor. Given that downstream sediment fractions exhibit a high phosphorus adsorption capacity, intercepting these particles through riparian restoration is crucial for controlling nutrient movement and preventing the long-range transport of contaminants.

A second dominant contributor to nutrient loading is urban wastewater. Only about half of the wastewater generated in key urban centers such as Jabalpur, Barwani, Hoshangabad and Bharuch is treated before being discharged into the river system (Central Water Commission, 2024). As a result, stretches adjacent to urban municipalities consistently show elevated BOD, ammonia and phosphate levels. Inadequate sewerage networks, overburdened sewage treatment plants, monsoon-induced bypass flows and ineffective septage management all contribute to this situation. Decentralized wastewater treatment systems and constructed wetlands present highly suitable solutions for the basin due to their lower energy demands, reduced operational complexity and strong nutrient removal efficiencies. Global technical assessments show that constructed wetlands can remove 30–70% of nitrogen and phosphorus, offering an effective complement to centralized treatment plants in semi-urban areas (United Nations Environment Programme, 2020). Integrating such nature-based infrastructure along peri-urban reaches of the basin would reduce pollution loads while also providing ecological co-benefits such as habitat creation and groundwater recharge.

Sediment dynamics present another notable challenge. Large multipurpose reservoirs in the basin trap a significant proportion of upstream sediment, altering natural sediment delivery to downstream ecosystems. National sedimentation studies show that such reservoirs can retain up to 90% of sediment inflow (Central Water Commission, 2019). This retention disrupts downstream geomorphic functioning, reduces the fertility of floodplain systems and intensifies bank erosion as channels adjust to lower sediment supply. Ensuring environmental flow releases that better approximate natural hydrological cycles can help restore sediment transport processes, support aquatic habitat conditions and maintain geomorphic stability. Sustainable sand mining practices, guided by sediment replenishment rates, remote-sensing-derived extraction limits, and strict enforcement regimes, are also essential to reducing anthropogenic alterations to the sediment balance.

Success in improving BMP adoption and implementing nature-based solutions depends heavily on the coordination of policy frameworks and inclusive governance. The Narmada Basin spans multiple states with diverse priorities and regulatory structures. The Narmada Control Authority manages water allocation and reservoir operations across states but does not currently hold formal authority over water quality regulation or sediment management (Narmada Control Authority, 2023). This division of responsibilities results in fragmented monitoring, limited data sharing and inconsistent enforcement across jurisdictions. A basin-wide nutrient and sediment management framework, supported by unified monitoring protocols, centralized data platforms and coordinated regulatory standards, would significantly strengthen decision-making and help align state-level interventions with broader basin objectives.

Stakeholder involvement is equally critical. Local communities including farmers, tribal groups, self-help organizations and civil society networks play a central role in shaping land and water management practices. Incorporating community knowledge into watershed management, riparian restoration and pollution monitoring enhances the sustainability and social legitimacy of interventions. Participatory watershed committees, river-watch groups and Payment for Ecosystem Services (PES) programs can incentivize conservation action while ensuring equitable distribution of benefits. Such community-driven models have demonstrated success in similar environmental programs across India and offer a pathway for scaling interventions in the Narmada Basin.

Strengthening monitoring infrastructure is also essential for achieving long-term improvements in water quality and sediment management. Current monitoring networks are limited in terms of spatial coverage, sampling frequency, and data integration. A modernized basin-wide system incorporating real-time water quality sensors, sediment load trackers, remote-sensing assessments and unified data dashboards would greatly enhance the ability of agencies to identify pollution trends, forecast ecological risks and evaluate the impacts of management actions. Hydrological and sediment modelling frameworks, such as those recommended in national water resource management programs, can support targeted interventions and scenario-based planning.

Overall, the future of the Narmada Basin hinges on the integration of scientific evidence, nature-based solutions and inclusive governance. Precision agriculture, conservation tillage, riparian restoration, decentralized wastewater treatment, environmental flows, sediment budgeting and community participation collectively offer a pathway toward ecological resilience. Implementing these strategies in a coordinated and adaptive manner will help restore balance between human needs and environmental health. The Narmada, long regarded as a lifeline for millions, can continue to sustain its ecological, cultural and economic functions if guided by informed, collaborative and forward-looking stewardship.

8. Conclusion

The present nutrient and sediment load assessment study indicates that there are various sources for the sediment accumulation in the river. These sources includes both natural and anthropogenic activities which includes soil erosion from agriculture lands, riverbank erosion, surface runoff during heavy rainfall, construction activities, discharge of treated and partially treated wastewater.

Stream geo-chemical sediment data analysis revealed that the categories of metal oxides, nutrient related elements, toxic elements establish a comprehensive framework for interpreting how nutrients and contaminants are bound, transported, and redistributed across the upper, middle, and lower Narmada Basin. The study revealed different geochemical pattern in each sub-basin of the Narmada River Basin.

Overall study highlights that due to natural and human activities there is increase sediment load which not only affecting the physical and hydrological characteristics of the river but also affecting the ecological life. There is need of effective sediment load strategies such as soil erosion control measures, sustainable agricultural practices, proper waste treatment, and regular monitoring are essential to reduce sediment input and associated chemical contamination. At last, these implementations will contribute to improve water quality, ecosystem health and also long-term conservation of aquatic sources.

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