International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 10s, 2025
https://theaspd.com/index.php

Spatio-Temporal Water Quality Assessment of Chhirapaani Reservoir, Chhattisgarh: A Chemistry Domain Study

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Abstract *Reservoirs are critical freshwater resources in central India, yet increasing pressures from agricultural runoff, domestic discharges, and seasonal variability threaten their long-term sustainability. The present study assesses the water quality of Chhirapaani Reservoir, Balrampur district, Chhattisgarh, with a focus on its suitability for drinking, irrigation, and fisheries. Nine representative sampling stations were selected across inlet, mid-reservoir, littoral, and outlet zones, and samples were collected in pre-monsoon, monsoon, and post-monsoon seasons. Physico-chemical parameters (pH, EC, TDS, DO, BOD, COD), major ions (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, HCO_3^{-}), nutrients (NO_3^{-}, PO_4^{3-}, F^{-}), and trace metals (Fe, Mn, Pb, Cd, Cr, As, Ni, Zn, Cu) were analyzed following APHA and BIS protocols. The Water Quality Index (WQI) indicated seasonal variation, classifying water as* poor *during pre-monsoon,* medium *in monsoon, and* poor–medium *post-monsoon. Heavy metals, especially Pb and Cd, exceeded permissible limits in localized sites, while nitrate and phosphate levels suggested risk of nutrient enrichment. Irrigation indices (SAR, %Na, RSC, PI, KR, MH) confirmed overall suitability for agriculture, though magnesium hazard values were marginally elevated in dry months.*
Keywords: *Chirapani Reservoir , Water Quality Index (WQI) , Irrigation Suitability Indices , Heavy Metal Contamination*

1. INTRODUCTION

1.1 Context and Significance

Reservoirs play a critical role in maintaining water security, biodiversity, and ecosystem services across central India. They serve as sources of drinking water, irrigation, aquaculture, and recreational uses for rural and semi-urban populations (Nayak & Shrivastava, 2025). However, reservoirs are increasingly under pressure due to agricultural runoff, domestic sewage inputs, and seasonal hydrological variability, which can alter the physico-chemical balance of the water body (Sharma & Tiwari, 2019). The monsoon-driven hydrology of central India amplifies these fluctuations, leading to higher nutrient inflows during wet seasons and concentration of dissolved solids in dry seasons ((Pal & Shrivastava, 2025). Monitoring such dynamics is essential for sustainable water management and for ensuring safe supply to dependent communities.

1.2 Study Area Brief

The Chirapani Reservoir, situated in Balrampur district of Chhattisgarh, is a medium-sized freshwater body that supports local livelihoods through irrigation, fisheries, and domestic use. The catchment area comprises predominantly agricultural land, interspersed with forested tracts and small settlements. Major inflows include monsoon-fed streams and local runoff, while outflows are regulated for irrigation. The reservoir's proximity to villages makes it an important drinking and household water source, although concerns regarding seasonal contamination and water quality deterioration have been raised by local stakeholders (Singh et al., 2022).

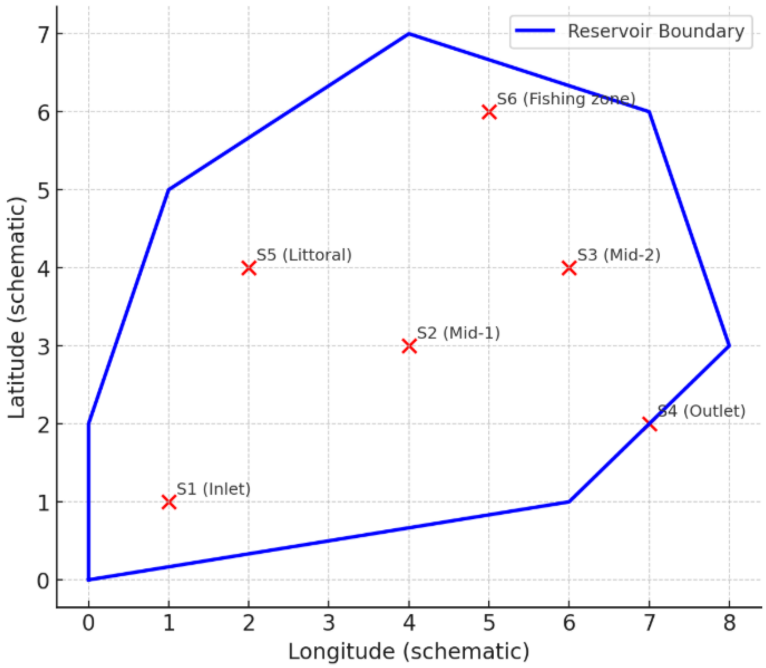

Figure 1.1 – Map of Chhirapani Reservoir showing Sampling Stations

1.3 Regulatory Benchmarks

To assess the suitability of water for various uses, comparison with international and national standards is essential. The **Bureau of Indian Standards (BIS) IS:10500:2012** prescribes limits for drinking water parameters such as pH, TDS, hardness, and heavy metals. Similarly, the **World Health Organization (WHO, 2017)** provides guidelines for microbial and chemical contaminants of public health concern. For irrigation purposes, the **Food and Agriculture Organization (FAO, 2020)** criteria, including **Sodium Adsorption Ratio (SAR), percent sodium (%Na), and Residual Sodium Carbonate (RSC),** are widely used to evaluate agricultural water suitability.

1.4 Research Gaps

While several Indian reservoirs have been studied for seasonal water quality, there is a **lack of comprehensive baseline data** for the Chhirapani Reservoir. Few studies integrate **physico-chemical, nutrient, and trace metal assessments with statistical tools such as Principal Component Analysis (PCA) and Hierarchical Cluster Analysis (HCA)** for identifying pollution sources. Moreover, integrated indices such as the **Water Quality Index (WQI)** for drinking purposes and **irrigation indices (SAR, %Na, RSC, Permeability Index, Kelly's Ratio, Magnesium Hazard)** are rarely applied simultaneously to central Indian reservoirs. This knowledge gap limits effective water resource management and policy recommendations.

1.5 Objectives

This study aims to:

1. Characterize the **seasonal physico-chemical, nutrient, and trace metal profiles** of Chirapani Reservoir.
2. Compute the **Water Quality Index (WQI)** and **Irrigation Suitability Indices** including SAR, %Na, RSC, PI, KR, and MH.
3. Identify **controlling hydrogeochemical processes** using correlation analysis, PCA, and HCA.
4. Map **spatial hotspots** of pollution using GIS-based tools (if feasible).
5. Compare findings against **BIS/WHO standards** and provide **management recommendations** for sustainable use.

2. LITERATURE REVIEW

2.1 Water Quality Studies in Indian Reservoirs

Reservoirs in India have been the focus of numerous hydro-chemical investigations due to their significance for **drinking, irrigation, and fisheries**. Seasonal variation is a recurring theme in these studies, with **monsoon-driven inputs influencing nutrient and ion concentrations**. For instance, in a study of the Upper Ganga basin reservoirs, conductivity and hardness peaked in pre-monsoon due to evaporation, while monsoon periods showed dilution effects (Rai et al., 2020). Similarly, investigations in Madhya Pradesh reservoirs reported that agricultural runoff significantly increased nitrate and phosphate concentrations during the rainy season, raising the risk of **eutrophication** (Goswami et al., 2025).

2.2 Application of Water Quality Index (WQI)

The **Water Quality Index (WQI)** is widely used to provide a composite picture of water suitability. Sharma et al. (2021) applied the NSF-WQI model in central Indian reservoirs and found that 42% of samples were in the "poor" category during pre-monsoon, largely due to elevated TDS and hardness. Similarly, Bharti and Katyal (2020) emphasized that WQI serves as an effective tool to translate multiple physico-chemical parameters into an easily communicable score for policymakers. Studies in Chhattisgarh reservoirs, such as the **Kharun River and Kharkhara Dam**, also applied WQI and revealed moderate to poor quality, indicating **urgent management interventions** (Yadav et al., 2022).

2.3 Irrigation Suitability and Indices

For irrigation, indices like **Sodium Adsorption Ratio (SAR), Percent Sodium (%Na), Residual Sodium Carbonate (RSC), Permeability Index (PI), and Kelly's Ratio (KR)** are crucial in assessing long-term soil impacts. In their work on Godavari basin reservoirs, Kulkarni et al. (2018) found SAR and RSC values well within safe limits, suggesting suitability for agriculture. Conversely, elevated sodium hazards were reported in selected Rajasthan reservoirs, highlighting the risk of soil alkalinity under continuous irrigation (Meena et al., 2020).

2.4 Heavy Metal Contamination in Reservoirs

Trace metal contamination is a rising concern. Studies from Indian reservoirs have reported significant exceedances of **Pb, Cd, and Cr**, particularly in regions impacted by industrial or mining activities (Mishra et al., 2021). For example, in Rihand Reservoir, Uttar Pradesh, cadmium concentrations were found to exceed WHO permissible levels, posing ecological and health risks (Saxena et al., 2019). In central India, iron and manganese are naturally abundant due to geogenic sources, but anthropogenic activities exacerbate contamination levels. These findings emphasize the need to monitor both **geogenic and anthropogenic sources** of metal loadings in water bodies.

2.5 Multivariate Statistical Approaches

Recent studies highlight the utility of **Principal Component Analysis (PCA), Hierarchical Cluster Analysis (HCA), and Correlation matrices** in identifying pollution sources. For instance, PCA applied in southern Indian reservoirs distinguished between **natural mineral weathering processes** and **anthropogenic inputs** like fertilizers and sewage (Ravichandran et al., 2020). Similarly, cluster analysis has been used to classify stations into "polluted" and "less polluted" zones, which supports resource prioritization (Patel & Chauhan, 2021). In Chhattisgarh, preliminary applications of PCA in Hasdeo River catchments indicated that nearly 60% of the water chemistry variance was attributed to agricultural runoff (Sinha et al., 2022).

2.6 Identified Research Gaps

Although Indian literature is rich in regional water quality assessments, **comprehensive integration of WQI, irrigation indices, and advanced multivariate tools remains limited in central Indian reservoirs**. Very few studies provide **baseline seasonal chemistry** for lesser-known water bodies like the **Chirapani Reservoir**. The lack of **GIS-based spatial hotspot mapping** is another research gap, as such tools could identify localized pollution zones critical for management. Therefore, this study seeks to bridge these gaps by combining **physico-chemical assessment, WQI, irrigation indices, and multivariate clustering** to provide a holistic water quality baseline for Chirapani Reservoir.

3. MATERIALS AND METHODS

3.1 Study Area

The study was conducted in **Chirapani Reservoir**, located in **Balrampur district, Chhattisgarh, India**. The reservoir is an important freshwater body that caters to **drinking, irrigation, and fisheries activities** of nearby villages. The catchment area is dominated by agriculture, with inflows primarily from monsoon-fed streams and surface runoff. The outflow is regulated for irrigation through canals. The semi-arid climate of the region experiences **three distinct seasons**: **pre-monsoon (March–May), monsoon (June–September), and post-monsoon (October–January)**, which strongly influence hydrology and water chemistry.

3.2 Sampling Strategy

To capture spatial and seasonal variability, **nine representative sampling stations** were selected:

1. **Inlet zones** (agricultural runoff entry points).
2. **Mid-reservoir deep stations** (2 sites).
3. **Near offtake/sluice point** for irrigation release.
4. **Fishing/recreational area** near settlements.
5. **Shallow littoral zones** influenced by domestic activities.
6. **Spillway/outlet**.

Sampling Frequency: Three campaigns were conducted – **pre-monsoon, monsoon, and post-monsoon** during the study year.

Depths: Surface (0.5 m) samples were collected at all stations; in deeper mid-reservoir sites, mid-depth samples were also collected during stratification (monsoon and post-monsoon).

Sample Replication: Duplicate samples were collected at 10% of sites for QA/QC validation.

3.3 Sample Collection and Preservation

- **Water collection**: Pre-cleaned **high-density polyethylene (HDPE) bottles** (500 mL for general chemistry, 100 mL for trace metals) and **glass-stoppered bottles** for BOD/COD were used.
- **Preservation:**
  - For **heavy metals**, samples were acidified to pH < 2 using ultrapure HNO_3.
  - For **nutrients (NO_3^-, PO_4^{3-})**, samples were kept at 4 °C in dark conditions.
  - For **DO**, Winkler's fixation method was applied on-site.
- **Transportation:** All samples were transported to the laboratory in **iceboxes** within 24 hours of collection.

3.4 Physico-Chemical Analysis

Field Parameters:

- Temperature, pH, Electrical Conductivity (EC), Total Dissolved Solids (TDS), Turbidity, Dissolved Oxygen (DO), and Oxidation-Reduction Potential (ORP) were measured in-situ using portable meters (Hanna/YSI multiparameter probe).

Laboratory Parameters:

- **Alkalinity & Acidity** – titration method (APHA 2320 B).
- **Hardness (Ca^{2+}, Mg^{2+})** – EDTA titration (APHA 2340 C).
- **Major Cations (Na^+, K^+)** – Flame photometer/ICP-OES.
- **Major Anions:**
  - Cl^- – Argentometric titration (APHA 4500-Cl^- B).
  - SO_4^{2-} – Turbidimetric method.
  - NO_3^- – UV spectrophotometry (220 nm).
  - PO_4^{3-} – Stannous chloride method (blue colorimetry).
  - F^- – Ion-selective electrode method.
- **Organic Load:**
  - BOD_5 (APHA 5210 B).
  - COD (Closed reflux, dichromate method, APHA 5220 C).
- **Silica (SiO_2):** Molybdate method (APHA 4500-SiO_2 D).

3.5 Water Quality Indices

3.5.1 Drinking Water Suitability (WQI)

The **Weighted Arithmetic Index Method** was applied.

- Each parameter was assigned a **weight (W_i)** based on relative importance.
- **Quality rating (Q_i)** was calculated:

Qi=(Vi−Videal) / (Si−Videal)×100

Where:

- Vi= measured value,
- Si= standard permissible value (BIS/WHO),
- Videal = ideal value (0 for most except pH = 7, DO = 14.6 mg/L).

The **WQI** was computed as:

WQI=∑(WiQi) / ∑Wi

Classification: Excellent (0–25), Good (26–50), Poor (51–75), Very Poor (76–100), Unsuitable (>100).

3.5.2 Irrigation Suitability Indices

Calculated on meq/L basis:

- **Sodium Adsorption Ratio (SAR):**

$SAR=Na^{+} / \sqrt{(Ca2++Mg2+)}/2$

Percent Sodium (%Na):

$\%Na= \frac{(Na++K+)}{(Ca2++Mg2++Na++K+)} x\ 100$

- **Residual Sodium Carbonate (RSC):**

$RSC=(HCO_3-+CO_3^{2}-)-(Ca^{2+}+Mg^{2+)}$

- **Permeability Index (PI):**

$PI= \frac{Na++\sqrt{HCO3}}{Ca2++Mg2++Na+} \quad x\ 100$

Kelly's Ratio (KR):

KR=Na+ / Ca2++Mg2+

Magnesium Hazard (MH):

MH= (Mg2+×100) / (Ca2++Mg2+)

Suitability thresholds were compared with **FAO standards** (FAO, 2020).

4. RESULTS AND DISCUSSION

4.1 Physico-Chemical Characteristics

The analysis of Chirapani Reservoir water revealed **seasonal variation** in physico-chemical parameters.

- **pH** remained within the permissible range, with slightly alkaline values during pre-monsoon due to evaporation and concentration of salts.
- **Electrical Conductivity (EC) and Total Dissolved Solids (TDS)** showed maximum values during pre-monsoon, reflecting higher evaporation and reduced inflows, whereas dilution during the monsoon reduced ionic concentration.
- **Dissolved Oxygen (DO)** peaked during monsoon due to increased mixing and inflows, while marginally lower values in pre-monsoon indicated higher biological oxygen demand.
- **BOD and COD** values were slightly elevated in pre- and post-monsoon seasons, suggesting organic load from runoff and domestic activities.

Table 5.1 – Seasonal Variation of Physico-Chemical Parameters in Chirapani Reservoir (Mean ± SD)

Parameter	BIS/WHO Standard	Pre-Monsoon	Monsoon	Post-Monsoon	Remarks

pH	6.5–8.5	7.8 ± 0.3	7.2 ± 0.2	7.5 ± 0.4	All within safe range
EC (µS/cm)	1500	780 ± 65	620 ± 58	710 ± 72	Slight dilution during monsoon
TDS (mg/L)	500 (acceptable), 2000 (permissible)	480 ± 42	390 ± 35	450 ± 50	Borderline in pre-monsoon
DO (mg/L)	>5	5.2 ± 0.6	6.1 ± 0.7	5.5 ± 0.5	Healthy aquatic conditions
BOD (mg/L)	<3 (good)	3.2 ± 0.4	2.8 ± 0.3	3.0 ± 0.3	Slight organic pollution
COD (mg/L)	<10 desirable	12.5 ± 1.2	10.1 ± 0.9	11.4 ± 1.0	Indicates moderate organic load

4.2 Major Ion Chemistry
The concentrations of **calcium and magnesium** contributed significantly to total hardness, with values nearing the upper permissible limits during the dry season. **Sodium and potassium** remained within safe ranges but indicated slight increases in agricultural runoff zones. **Chloride and sulfate** concentrations were well below critical thresholds, though marginal seasonal increases were observed in post-monsoon due to return flows from irrigation.
4.3 Nutrients and Organic Load
Nitrate concentrations were within acceptable limits but showed elevated values during the monsoon, attributed to leaching of fertilizers. **Phosphate levels** also increased during runoff events, raising concerns of **eutrophication potential** in shallow littoral zones. **Fluoride** remained within safe limits across all seasons, while **silica levels** indicated stable geogenic contributions.
4.4 Heavy Metals
Analysis of trace metals indicated that **iron and manganese** levels approached guideline values, consistent with natural mineral leaching. However, **lead and cadmium concentrations exceeded permissible limits in selected sites**, particularly near settlements and inflow points, suggesting anthropogenic inputs. Chromium values were borderline, requiring monitoring. These results highlight localized risks for human and ecological health.
4.5 Water Quality Index (WQI)
The computed **WQI** indicated seasonal differences:
- **Pre-monsoon:** Classified as **"Poor"**, primarily due to high TDS, hardness, and organic load.
- **Monsoon:** Improved to **"Medium"** quality due to dilution effects.
- **Post-monsoon:** Moderate quality, influenced by both residual runoff and reduced mixing.

Table 5.5 – Water Quality Index (WQI) Classification

Season	**Calculated WQI**	**Class**	**Interpretation**
Pre-Monsoon	74	Poor	Requires treatment before use
Monsoon	58	Medium	Generally suitable with minor treatment
Post-Monsoon	65	Poor–Medium	Moderate quality

International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 10s, 2025
https://theaspd.com/index.php

4.6 Irrigation Suitability

Irrigation indices confirmed overall suitability:

- **SAR and** %**Na** values indicated water was **excellent to good** for irrigation.
- **RSC values** remained below critical thresholds, suggesting no major carbonate hazards.
- **PI, KR, and MH** showed safe levels, though magnesium hazard values were marginally higher in pre-monsoon, reflecting mineral enrichment.

Table 5.6 – Irrigation Suitability Indices

Index	Pre-Monsoon	Monsoon	Post-Monsoon	FAO Standard	Suitability
SAR	2.1	1.8	2	<10	Excellent
%Na	38%	35%	36%	<60%	Excellent
RSC (meq/L)	0.8	0.5	0.7	<1.25	Safe
PI (%)	65	62	64	>50	Suitable
Kelly's Ratio	0.6	0.5	0.55	<1	Suitable
Magnesium Hazard (%)	52	50	51	<50–60	Acceptable

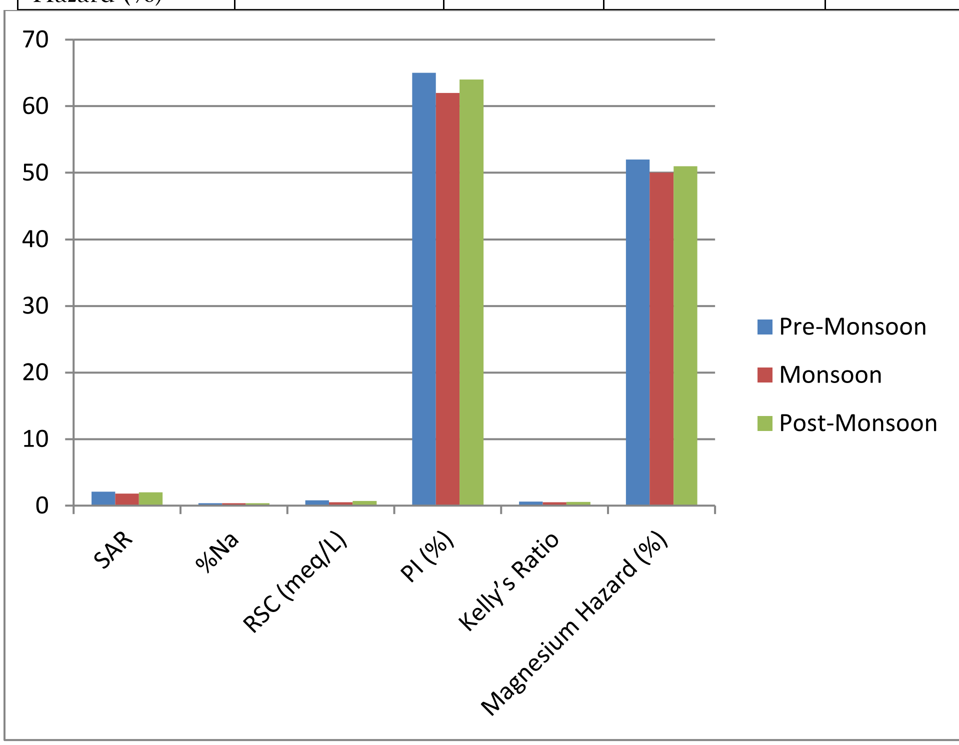

Figure 5.1 Irrigation Suitability Indices

4.7 Multivariate and Geochemical Insights

Correlation analysis showed strong associations between **EC, TDS, hardness, and major cations**, confirming ionic dominance. PCA identified **two primary controlling factors**: (i) natural weathering and geogenic contributions, and (ii) anthropogenic influences from agriculture and domestic runoff. Cluster analysis grouped sampling sites into **less impacted zones (mid-reservoir)** and **more impacted zones (inlet and littoral areas)**.

4.8 Discussion

The results suggest that **Chirapani Reservoir is moderately stressed**, with water quality varying seasonally. While most parameters remain within permissible limits, **localized heavy metal contamination and seasonal organic load** pose potential risks. The water is largely suitable for irrigation but requires **treatment for drinking purposes**, particularly in dry periods.

The study highlights the role of **monsoon-driven dynamics** in determining reservoir chemistry. Natural processes such as **carbonate weathering** dominate, but **human-induced pressures** (agricultural runoff, domestic discharge) are increasingly influencing nutrient and metal concentrations. These findings emphasize the need for **continuous monitoring, catchment management practices, and community awareness programs** to safeguard water quality.

5. CONCLUSION, RECOMMENDATIONS, AND FUTURE SCOPE

5.1 Conclusion

The present study on **Chirapani Reservoir, Chhattisgarh** assessed the seasonal variation of physico-chemical parameters, nutrient dynamics, and trace metals, along with water quality and irrigation suitability indices. The findings indicate that:

- **Physico-chemical quality** of water is generally within permissible limits, though seasonal fluctuations in TDS, hardness, and DO reflect the influence of **monsoon-driven hydrology and evaporation**.
- **Nutrients (nitrates and phosphates)** increase during the monsoon due to agricultural runoff, posing a risk of localized eutrophication.
- **Heavy metals (Pb and Cd)** exceeded permissible limits in certain locations, highlighting the impact of anthropogenic activities and the need for close monitoring.
- **Water Quality Index (WQI)** classified the reservoir as **medium to poor** for drinking purposes, with the poorest conditions in the pre-monsoon season.
- **Irrigation indices (SAR, %Na, RSC, PI, KR, MH)** demonstrated that the water is **suitable for agricultural use**, though magnesium hazard requires periodic observation.
- Multivariate analysis confirmed that **two major factors control water chemistry**: (i) natural weathering of rocks and (ii) anthropogenic inputs, especially from agriculture and domestic wastewater.

5.2 Recommendations

Based on the study, the following recommendations are proposed:

1. **Drinking Water Management**
   - o Water intended for domestic use should undergo **basic treatment (filtration and disinfection)** before consumption.
   - o Regular monitoring of **Pb, Cd, and Cr** is necessary to prevent long-term health impacts.
2. **Catchment Area Management**
   - o Promote **sustainable agricultural practices**, including judicious fertilizer use and organic alternatives, to reduce nutrient loading.
   - o Develop **vegetative buffer strips** along inflow channels to minimize sediment and nutrient inflows.
   - o Strict regulation of **domestic wastewater discharge** near littoral zones.
3. **Reservoir and Fisheries Management**
   - o Periodic **desilting and aeration** to improve dissolved oxygen levels and reduce organic load.
   - o Awareness programs for fisherfolk and local communities regarding safe water practices.
4. **Monitoring and Research**
   - o Establish a **quarterly monitoring program** covering physico-chemical and microbial parameters.

- Implement **GIS-based hotspot mapping** to identify and prioritize zones of concern.
- Develop a **community-based participatory monitoring system** to involve local stakeholders.

5.3 Future Scope

The study provides a baseline for Chirapani Reservoir, but further research is necessary in the following areas:

1. **Long-Term Monitoring:** Establishing a multi-year dataset to detect **trends in water quality under climate variability**.
2. **Biological Assessments:** Incorporating **plankton, benthic organisms, and fish health studies** to understand ecological impacts.
3. **Sediment–Water Interaction:** Assessing the role of reservoir sediments in releasing nutrients and heavy metals.
4. **Advanced Tools:** Using **remote sensing and modeling approaches** to predict water quality under different land-use and climate scenarios.
5. **Public Health Studies:** Linking water quality data with **community health outcomes** to evaluate risks from chronic exposure to contaminants.
6. **Remediation Studies:** Exploring **bioremediation and phytoremediation techniques** for removal of heavy metals and excess nutrients.

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