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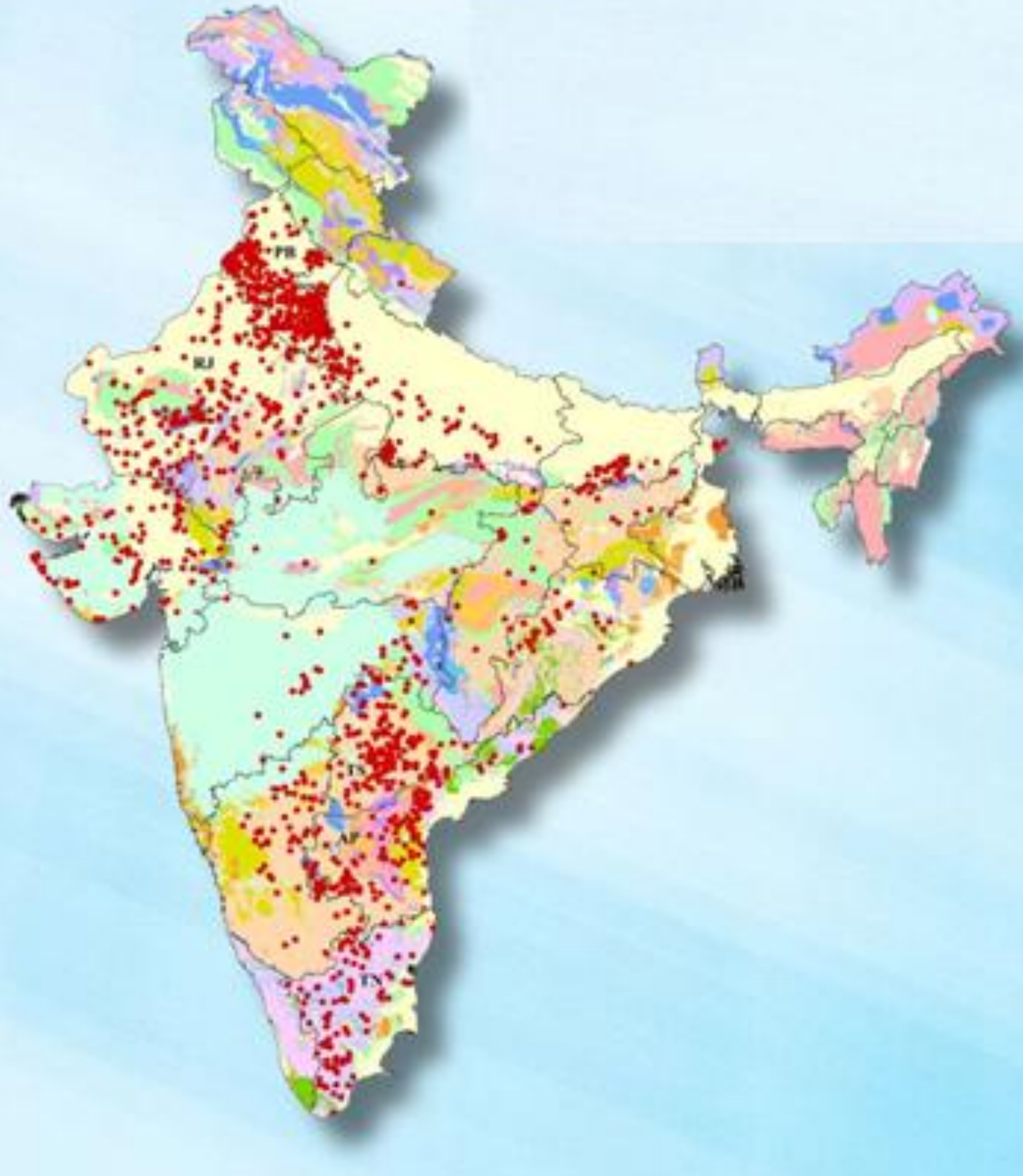
Government of India
जल शक्ति मंत्रालय,
Ministry of Jal Shakti,
जल संसाधन, नदी विकास और गंगा संरक्षण विभाग,
Department of Water Resources,
River Development and
Ganga Rejuvenation

केंद्रीय भूमि जल बोर्ड
Central Ground Water Board

ANNUAL GROUND WATER QUALITY REPORT, 2024



सी आर पाटील
C R Paatil

जल शक्ति मंत्री
भारत सरकार
Minister of Jal Shakti
Government of India

MESSAGE

It is with great pride and a sense of responsibility that I present the **Ground Water Quality in Shallow Aquifers of India Report– 2024**, a landmark initiative by the Central Ground Water Board (CGWB). Groundwater is the lifeline of our nation, sustaining agriculture, drinking water needs, and industries. Ensuring its quality and availability is central to our vision of a water-secure and prosperous India.

For the first time, a Standard Operating Procedure (SOP) for groundwater quality monitoring has been developed, marking a major step towards scientific and standardized management of this critical resource. This report, built on rigorous data collection and analysis, sheds light on the state of groundwater quality across the country, identifying areas of concern and opportunities for improvement. The report also highlights the benefits of practices like monsoon recharge, which show promise in improving water quality. It is our collective duty to address these issues with innovative solutions, efficient policies, and grassroots involvement.

This report provides a clear roadmap for action, and I urge all stakeholders—government agencies, researchers, and citizens—to work together to protect and preserve our precious groundwater resources. Let us move forward with determination to ensure clean, safe, and sustainable water for all.I laud the efforts of the team CGWB, who have put their best to bring out the report. I am confident that there port would serve as an excellent source material for all the stakeholders

C R PAATIL

जल शक्ति अभियान
संचय जल, बेहतर कल

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वी. सोमण्णा
V. SOMANNA

सत्यमेव जयते

राज्य मंत्री
जल शक्ति एवं रेलवे मंत्रालय
भारत सरकार
Minister of State
Jal Shakti and Railways
Government of India

MESSAGE

I am honoured to share the Ground Water Quality in Shallow Aquifers of India Report– 2024, a significant accomplishment by the Central Ground Water Board (CGWB). Groundwater is a cornerstone of India's drinking water supply, and its quality is critical to ensuring the health and well-being of our people.

This report offers a comprehensive assessment of groundwater quality across the nation, highlighting key challenges such as contamination from nitrates, fluoride, arsenic, and uranium. It also provides valuable insights into regional and seasonal variations in groundwater quality, which are essential for guiding sustainable water management practices.

As we work towards achieving **Jal Jeevan Mission**, which envisions providing safe and adequate drinking water to every household, this report serves as a vital tool for informed planning and action. It underscores the importance of protecting our groundwater resources and addressing contamination hotspots to secure clean and safe water for all.

I commend the CGWB for their dedicated efforts in producing this detailed report and call upon all stakeholders to use its findings as a foundation for ensuring a water-secure and healthier future for every citizen.

(V. Somanna)
Minister of State

27th December, 2024
New Delhi

Department of Drinking Water and Sanitation: Room No.- 901, B-1 Wing, Pandit Deendayal Antyodaya Bhawan, CGO Complex, Lodhi Road, New Delhi-110003, Tel : 011-24368617, 24368618, 24368622, E-mail - mosoffice-mdws@nic.in

डॉ. राज भूषण चौधरी
Dr. Raj Bhushan Choudhary

जल शक्ति राज्य मंत्री
भारत सरकार
नई दिल्ली-110001
MINISTER OF STATE FOR JAL SHAKTI
GOVERNMENT OF INDIA
NEW DELHI - 110001

MESSAGE

It gives me great pride to share the **Ground Water Quality in Shallow Aquifers of India Report– 2024**, a testament to our nation's commitment to safeguarding groundwater, one of our most precious resources. This report represents a milestone in the scientific understanding and management of groundwater quality across the country.Ground water is an important and critical resource for socio-economic development of our country. It caters a major share of the domestic, irrigation and industrial demand of water.

The chemical quality of ground water varies significantly depending upon the nature and extent of rock-water interaction and also influenced from inputs from sources which are not related to nature. During recent years ground water contamination is being reported from aquifers throughout the country affecting its potability with the constituents exceeding the limits prescribed by BIS.

This report is not just a document—it is a call to action for all of us. It provides invaluable insights that must guide our efforts to protect and preserve groundwater for future generations. With collective resolve and scientific innovation, we can ensure clean and sustainable water for every citizen of our great nation.

This report presents the analytical insights derived from the assessment of groundwater quality across India, conducted by theCGWB. I commend the Central Ground Water Board for their dedicated work and urge all stakeholders to use this report as a foundation for action, moving together toward a water-secure and prosperous India.

(Dr. Raj Bhushan Choudhary)

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भारत 2023 INDIA
वसुधैव कुटुम्बकम्
ONE EARTH • ONE FAMILY • ONE FUTURE

देवश्री मुखर्जी
Debashree Mukherjee
सचिव
SECRETARY

सत्यमेव जयते
आज़ादी का अमृत महोत्सव

भारत सरकार
जल शक्ति मंत्रालय
जल संसाधन, नदी विकास
और गंगा संरक्षण विभाग
GOVERNMENT OF INDIA
MINISTRY OF JAL SHAKTI
DEPARTMENT OF WATER RESOURCES,
RIVER DEVELOPMENT & GANGA REJUVENATION

MESSAGE

It is with great satisfaction that I present the **Ground Water Quality Report of India – 2024,** an important contribution by the Central Ground Water Board (CGWB) to the understanding and management of the nation's groundwater resources. This report reflects the continued efforts of CGWB to ensure the sustainable utilization of this vital resource.

Anewly developed Standard Operating Procedure (SOP) for groundwater quality monitoring has been introduced. This SOP establishes a standardized framework for data collection, analysis, and reporting, thereby promoting uniformity and accuracy in groundwater quality assessments across the country.

The report provides a detailed analysis of groundwater quality, highlighting areas of concern such as contamination from nitrates, fluoride, arsenic, and uranium, as well as its suitability for irrigation based on key indicators like Sodium Adsorption Ratio (SAR) and Residual Sodium Carbonate (RSC). These findings offer valuable insights for the sustainable management of groundwater, addressing challenges related to agricultural practices, drinking water supply, and resource over-extraction.

The outcomes of this report serve as a significant reference for policymakers, researchers, and field practitioners, providing a scientific basis for formulating strategies to mitigate groundwater contamination, enhance recharge, and manage resource extraction sustainably. It is imperative for all stakeholders—government bodies, research institutions, and communities—to work together in addressing identified challenges and ensuring the longevity of groundwater resources.

I appreciate the efforts of CGWB in preparing this comprehensive report and encourage its use as a guiding document for informed decision-making and planning in groundwater management. Let us continue our collective endeavour towards sustainable groundwater management and resource security for the nation.

(Debashree Mukherjee)

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सुबोध यादव
SUBODH YADAV
अपर सचिव
ADDITIONAL SECRETARY

सत्यमेव जयते

आज़ादी का अमृत महोत्सव

भारत सरकार
जल शक्ति मंत्रालय
जल संसाधन, नदी विकास
और गंगा संरक्षण विभाग
GOVERNMENT OF INDIA
MINISTRY OF JAL SHAKTI
DEPARTMENT OF WATER RESOURCES,
RIVER DEVELOPMENT & GANGA REJUVENATION

Message

The **Ground Water Quality Report in Shallow Aquifers of India-2024** marks a significant scientific milestone in the assessment and management of groundwater resources across the country. This report is the first to adopt a **Standard Operating Procedure (SOP)** for groundwater quality monitoring, ensuring uniformity in data collection, analysis, and interpretation. The use of internationally recognized methods further enhances the credibility and technical rigor of the findings.

The report provides a granular analysis of groundwater quality through **background monitoring, trend analysis**, and **hotspot identification.** With a robust dataset derived from over **15,000 monitoring locations** and focused assessments at **4,982 trend stations,** the report delivers critical insights into groundwater quality variations across spatial and temporal scales.

Key findings reveal both challenges and opportunities. Some regions face sporadic contamination from **nitrates, fluoride, arsenic, and uranium.** Importantly, the report correlates uranium contamination with areas of groundwater over-exploitation, highlighting the interplay between hydrological stress and water quality. Seasonal trends observed in parameters like **Electrical Conductivity (EC)** and **fluoride** provide evidence of monsoon recharge effects, which temporarily improve water quality.

From an agricultural perspective, the analysis of **Sodium Adsorption Ration (SAR)** and **Residual Sodium Carbonate (RSC)** reinforces the generally favorable suitability of groundwater for irrigation, with over **81% of samples** meeting safe thresholds. However, localized issues of high sodium content and RSC values demand targeted interventions to prevent long-term soil degradation.

This report serves as a critical scientific baseline for policymakers, researchers and stakeholders engaged in groundwater management. The data-driven approach and evidence-based findings provide a foundation for inform decision-making aimed at enhancing groundwater sustainability, mitigating contamination risks, and promoting adaptive water use practices.

I commend the Central Ground Water Board (CGWB) for their meticulous effort in preparing this report and urge its wide utilization across domains. As we move forward, the integration of such scientific knowledge into resource management will be pivotal in ensuring water security for the nation.

12.12.24
(Subodh Yadav, IAS)

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डॉ. सुनील कुमार अम्बष्ट
अध्यक्ष
Dr. Sunil Kumar Ambast
Chairman

भारत सरकार
जल शक्ति मंत्रालय
जल संसाधन, नदी विकास और गंगा
संरक्षण विभाग
केंद्रीय भूमि जल बोर्ड

Government of India
Ministry of Jal Shakti
Department of Water Resources, River Development and Ganga Rejuvenation
Central Ground Water Board

FOREWORD

Being a common pool and hidden resource, and because of a perpetual belief that groundwater is risk free from pollution and can easily be drawn on demand, exploitation of groundwater resources in many places in the country has taken place indiscriminately without caring for the consequences that may emerge in the long run. One of the resulting effects is deteriorated groundwater quality whose sources are hazardous contaminants of geogenic or anthropogenic origin. Groundwater quality deterioration is emerging as a grave impinging issue to scarcity of fresh groundwater resources and thereby to demand management.

Groundwater also plays a significant role in the ecological functions of various ecosystems. However, as a consequence of population growth, urbanization, industrialization, irrigation, mining and waste disposal practices, a large number of anthropogenic contaminants have emerged as serious threat to groundwater resources. At the same time, geogenic contamination like arsenic, fluoride and uranium etc. have been reported in groundwater which have grave implications to human health.

Central Ground Water Board routinely carries out groundwater quality monitoring by analysing water samples collected from its quality monitoring stations every year. The **Report on Ground Water Quality in Shallow Aquifers of India, 2024** includes the compilation and detailed analysis of water quality data generated throughout the country and will surely be helpful in policy planning as well as dealing with groundwater quality issues in the country.

The sincere efforts of the officers who have put their best to bring out this report is highly appreciable. I am confident that the report would serve as an excellent source material for the stakeholders including planners, researchers and end users in planning and management of ground water.

(Dr. Sunil Kumar Ambast)
Chairman

पी. के. त्रिपाठी
सदस्य (उत्तर और पश्चिम)
P. K. Tripathi
Member (North & West)

भारत सरकार
जल शक्ति मंत्रालय
जल संसाधन, नदी विकास और गंगा संरक्षण विभाग
केंद्रीय भूमि जल बोर्ड

Government of India
Ministry of Jal Shakti
Department of Water Resources, River Development and Ganga Rejuvenation
Central Ground Water Board

PREFACE

Groundwater is a priceless resource occurring beneath the surface of earth. The vulnerability of groundwater to overuse and water-quality degradation was not widely understood until recently. Monitoring ground water quality in the 21st century is a challenge because of the large number of chemicals used in our everyday lives, agriculture and industry that can make their way into our groundwater systems. Significant advances have been made in almost all phases of groundwater technology in recent years.

The quality of groundwater is described in terms of the concentration of some of the contaminants present in the water, together with certain physio-chemical characteristics of the water. Since last six decades Central Ground Water Board is engaged in routinely monitoring the ground water quality across the country. For the monitoring of ground water quality monitoring CGWB has a dedicated netwotk of groundwater quality monitoring stations. From 2024, CGWB has come up with a SOP for monitoring of ground water quality and analysis of groundwater qulity to bring uniformity in the national and regional groundwater quality reporting.

The **Report on Groundwater Quality of Shallow Aquifers in India -2024** is a compilation of the data from groundwater quality monitoring during 2023 and provides insights into the groundwater quality under natural environment as well as impact of anthropogenic activities. I am sure, this report would be of useful in policy planning and implementation by scientists, academicians, user agencies, NGOs and Individuals. Findings of this report will pave ways to ensure quality of this vital natural resource for sustainable and human development.

I congratulate the contributors for compiling the data and preparing this report in its present form. Their efforts are highly commendable.

(P. K. Tripathi)
Member (N & W)

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https://cgwb.gov.in/cgwbpnm/public/uploads/documents/17355632661671451888file.pdf

Executive Summary

This report presents the findings from the nationwide groundwater quality monitoring exercise based on a standardized methodology, following the newly established Standard Operating Procedure (SOP) by the Central Ground Water Board (CGWB). Implemented across India in 2023, this uniform approach aims to establish a comprehensive baseline for groundwater quality, enabling targeted interventions to address emerging concerns.

❖ **Monitoring and Baseline Establishment**: A total of 15,259 groundwater monitoring locations were selected nationwide to assess groundwater quality. These sites form the foundation for future evaluations, offering a clear baseline for ongoing monitoring efforts. To examine trends, 25% of the wells, identified as vulnerable to contamination based on BIS 10500 standards, were chosen for detailed analysis. Groundwater quality was sampled at 4,982 trend stations during pre-monsoon and post-monsoon periods to assess the impact of seasonal recharge on groundwater quality. Standard procedures as given in APHA, 2012 (Standard Methods for the Examination of Water & Waste Water American Public Health Association) were used for the sample collection and analysis of water sample.

❖ **Key Findings and Water Quality Parameters:** Objective of this report is to look into wide spectrum of inorganic water quality parameters in groundwater used for drinking and agriculture purpose. These parameters consist of physico-chemical parameters (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, TH, CO_3^{2-}, HCO_3^{-}, Cl^{-}, SO_4^{2-}, F^{-}, PO_4^{3-} and NO_3^{-}) and trace elements (As, Fe and U). Significant concerns have emerged from the analysis, particularly the high concentrations of nitrate, fluoride, arsenic, and iron in groundwater. Almost 20% of the samples exceeded the permissible limit for nitrate, while 9.04% of samples had fluoride levels above the limit. Arsenic contamination was found in 3.55% of samples.

❖ **Regional Variability and Seasonal Trends:** Groundwater quality varies considerably across India. In certain states such as Arunachal Pradesh, Mizoram, Meghalaya and Jammu and Kashmir, 100% of the water samples met the BIS standards. In contrast, states like Rajasthan, Haryana, and Andhra Pradesh faced widespread contamination. Interestingly, the monsoon season showed some improvement in water quality, particularly in areas affected by high electrical conductivity (EC) and Fluoride. Post-monsoon, a modest reduction in EC levels and Fluoride was observed in some regions, indicating that monsoon recharge can temporarily improve water quality by diluting salts. However, certain districts such as Barmer and Jodhpur (Rajasthan) showed a rising trend in EC levels, signaling a deeper issue of groundwater salinization.

❖ **Hydrochemical Facies and Salinization:** In terms of cation chemistry, calcium dominates the ion content, followed by sodium and potassium. For anions, bicarbonate is the most prevalent, followed by chloride and sulfate. This cation-anion distribution further highlights the role of bicarbonate in contributing to high alkalinity levels, which can exacerbate sodicity when coupled with high sodium concentrations. States like Rajasthan and Gujarat face high chloride concentrations due to the natural hydrochemical processes at play and **Na-Cl type** formations are prevalent. Over long periods, the aquifers have undergone repeated cycles of wetting and drying. During these cycles, highly soluble **Na-Cl salts** become concentrated in the aquifers. When groundwater levels drop, these salts become encrusted in the alluvium bed. Upon precipitation or recharge during the monsoon, these encrusted salts re-dissolve into the groundwater, enriching the chloride concentration and contributing to the increasing salinity levels.

❖ Specific Contaminants of Concern:

- Nitrate Contamination: States like Rajasthan, Tamil Nadu, and Maharashtra have some of the highest incidences of nitrate contamination, with over 40% of water samples exceeding the permissible limit. This is primarily linked to agricultural runoff and overuse of fertilizers.

- Fluoride Contamination: Fluoride concentrations exceeding the permissible limit are a major concern in Rajasthan, Haryana, Karnataka, Andhra Pradesh and Telangana. Although the monsoon season led to some improvement in fluoride levels in these states, the overall contamination levels remain alarmingly high.

- Elevated arsenic levels (>10 ppb) were found in several states, particularly in the **floodplains of the Ganga and Brahmaputra rivers**. This includes regions of **West Bengal**, **Jharkhand**, **Bihar**, **Uttar Pradesh**, **Assam**, and **Manipur**, as well as areas in the **Punjab**, and **Rajnandgaon** district in **Chhattisgarh**.

- Uranium Contamination: A notable concern in the groundwater quality report is the elevated levels of uranium in several regions. **42% of samples** with uranium concentrations exceeding 100 ppb came from **Rajasthan**, and **30% from Punjab**, indicating regional hotspots of uranium contamination. Moreover, groundwater samples with uranium concentrations greater than 30 ppb were clustered in areas identified as **Over-exploited, Critical, and Semi-Critical groundwater stress zones**, such as **Rajasthan, Gujarat, Haryana, Punjab, Tamil Nadu, Andhra Pradesh, and Karnataka**. This overlap points to the exacerbating effect of over-exploitation and deepening water levels on uranium contamination in these regions.

- The states of Rajasthan, Delhi, Gujarat, Haryan, Punjab, Telangana and Andhra Pradesh and Karnataka are the most severely affected by high EC value in groundwater.

❖ **Irrigation Suitability:** This report presents a comprehensive assessment of groundwater quality in India for Irrigation suitability. This report evaluates Sodium Adsorption Ratio (SAR) and Residual Sodium Carbonate (RSC) values, which are key indicators of water suitability for irrigation.

- According to SAR classification, 100% of the water samples from regions like Arunachal Pradesh, Assam, Andaman & Nicobar, Chandigarh UT, Himachal Pradesh, Kerala, Meghalaya, Nagaland, Pondicherry, and Tripura fall within the excellent category (S1), meaning the groundwater in these areas is highly suitable for irrigation.

- It was found that in Andhra Pradesh, Gujarat, Haryana, Punjab, Rajasthan and Uttarpradesh 0.96%, 1.27%, 0.34%, 0.76%, 12.38% and 0.14% samples fall in Very high sodium range and are unsuitable for use in irrigation practices

- On the positive side, the majority of groundwater samples from 2022 and 2023 have low sodium content, which is generally safe for irrigation purposes. This is essential for ensuring the sustainability of agricultural practices in most regions.

- Nationwide, 81.49% of the groundwater samples had RSC values less than 1.25, which indicates that the water is safe for use in irrigation. However, 10.43% of samples were found to have RSC values greater than 2.5, making them unsuitable for irrigation due to the risk of sodicity and soil degradation.

- The percentage of unsuitable water samples for irrigation increased slightly from 7.69% in 2022 to 8.07% in 2023, which reflects a concerning trend of increasing alkalinity and sodicity in certain groundwater sources. This trend suggests a growing need for targeted interventions to manage water quality, particularly in areas where alkalinity and salinity levels are rising.

- The suitability of groundwater for irrigation in India is generally favorable, with the majority of samples exhibiting safe levels of sodium and alkalinity. However, regions with high sodium content (e.g., Rajasthan) and those with rising RSC values require attention to prevent long-term soil degradation. The slight increase in the percentage of unsuitable groundwater samples suggests that careful monitoring and appropriate management practices should be adopted.

The findings of this report provide a crucial baseline for ongoing efforts to safeguard groundwater resources in India and ensure their sustainability for future generations.

1. Introduction

Groundwater is a critical source of drinking water, irrigation, and industrial usage worldwide., especially for rural and semi-urban populations. As per the **2021, World Water Development Report (UNESCO)**, the global use of freshwater has increased six-fold over the past 100 years, with a growth rate of about 1% per year since the 1980s. This increased water consumption, combined with rapid industrialization, urbanization, and agricultural activities, has led to severe challenges in water quality worldwide, and India is no exception. Groundwater plays a crucial role in meeting the water demands of India. Eighty-seven per cent groundwater extracted is used in the agricultural sector and about eleven percent in domestic sector. In India, shallow aquifers are a primary source of water, and their quality has a direct impact on public health, agricultural productivity, and overall environmental sustainability.

Despite its importance, groundwater quality in India is increasingly facing degradation. Groundwater quality in shallow aquifers in India is under significant threat due to a combination of natural and anthropogenic factors. With increasing population pressures, industrial activities, and agricultural practices, maintaining and improving groundwater quality has become more challenging. Shallow aquifers, in particular, are more susceptible to contamination due to their proximity to surface activities.

Key factors contributing to this decline in groundwater quality include:

- **Industrialization**: Rapid industrial growth, especially in urban areas, has led to the contamination of groundwater through the discharge of untreated industrial waste, including heavy metals, chemicals, and solvents.
- **Agricultural Practices**: Excessive use of fertilizers and pesticides in farming has resulted in the infiltration of harmful chemicals into groundwater, leading to nitrate contamination. Additionally, over-extraction of groundwater for irrigation is depleting aquifers and causing issues like salinization.
- **Urbanization**: As urban areas expand, improper waste disposal, sewage leakage, and landfill contamination contribute to the pollution of shallow aquifers. Industrial effluents and household waste also pose risks to groundwater quality.
- **Climate Change**: Changes in precipitation patterns and the over-extraction of groundwater can affect the natural replenishment of aquifers, leading to deteriorating water quality.

This report is an overview of the chemical ground water quality as observed by analyzing and interpreting the data obtained for the samples collected from hydrograph network stations, by Central Ground Water Board, covering the entire nation, taping shallow aquifer.

2. Ground Water Quality Monitoring

The report follows the newly introduced **Standard Operating Procedure (SOP)** established by the **Central Ground Water Board (CGWB)**. This is the first time such a uniform SOP has been implemented across India for groundwater quality monitoring, marking a significant milestone in standardizing the methodology for data collection, analysis, and reporting. The introduction of the SOP ensures that:

- **Consistency in Methodology**: By following a standardized procedure for sampling, testing, and data analysis, the study guarantees that results from all monitoring stations are comparable.
- **Reliable Data Quality**: Adhering to the CGWB's SOP enhances the reliability of the data and ensures that the analysis is based on scientifically robust and consistent methods. This increases the confidence in the accuracy and validity of the findings, making them more actionable for decision-makers and policymakers.
- **Data Reporting**: The SOP outlines a standardized format for reporting data, ensuring that the results from different monitoring stations are comparable and transparent. This also helps in the consistent interpretation of findings across diverse regions and seasons, facilitating data integration and synthesis at the national level.

As per the SOP, the study follows a rigorous methodology for data collection and analysis, focusing on different types of analyses such as **trend analysis**, **background analysis**, and **hotspot identification**. The analysis is designed to capture the seasonal and year-wise trends in groundwater quality, with a specific focus on how contamination levels vary over time and location.

- **Background Analysis**: A total of **15,259 monitoring locations** have been selected across the nation to establish a baseline for groundwater quality. These baseline stations will offer critical data points on groundwater conditions and the levels of contaminants present in aquifers at the start of the monitoring program. These stations will be monitored every **5 years** to track long-term trends in groundwater quality. The data collected will provide an overview of changes in water quality over time, including the accumulation of contaminants. The primary goal is to establish a comprehensive understanding of baseline groundwater conditions, identify regional patterns of contamination, and help predict trends over the coming years.

- **Trend Analysis**: **25% of the monitoring wells** deemed vulnerable to contamination as per BIS, 10500 were specifically selected for **trend analysis**. Wells identified for trend analysis will be subject to **annual monitoring** to ensure that any significant change in water quality is detected early. These wells will be monitored **annually**, specifically during **pre-monsoon** and **post-monsoon** periods. Monitoring at these times is crucial because the monsoon can influence groundwater quality, both positively (by diluting contaminants) and negatively (by introducing runoff pollution).

Groundwater samples were analysed for Ca^{2+}, Mg^{2+}, TH, Na^{+}, K^{+}, F^{+}, CO_3^{2-}, HCO_3^{-} , SO_4^{2-} Cl NO_3^{-}, SiO_2, PO_4^{3}, EC, pH, As, Fe and U. As it is well established that, Arsenic, Fluoride, Uranium, Nitrate pose serious health risks, either through direct toxicity or long-term exposure. EC serves as an indirect measure of water quality and an early warning system for the presence of other pollutants. High EC can be indicative of contamination from a variety of sources, including agricultural runoff, industrial discharge, or saline intrusion. Ingesting high concentrations of iron in drinking water (particularly in ferrous form) can lead to nausea, vomiting, diarrhea, and stomach cramp. Because of their potential health risks, regulatory importance and role as indicators of broader water quality issues these parameters have been discussed in the report.

2.1 Data Validation / Data Quality Control

i. Groundwater quality data validation is crucial in ensuring the accuracy, reliability, and consistency of the information used for assessing groundwater quality.

ii. Checking of Data Consistency: Checking of the data for consistency by comparing the measurements of a particular parameter over time. This will help identify any changes in the groundwater quality due to measurement methodology or equipment.

iii. Checking the correlation between EC and TDS:

   a. The relationship between the two parameters is often described by a constant (commonly between 0.55 and 0.95 for freshwaters).
   b. Thus: TDS (mg/l) ~ (0.55 to 0.95) x EC (mS/cm).
   c. The value of the constant varies according to the chemical composition of the water. For freshwaters, the normal range of TDS can be calculated from the following relationship:
   d. 0.55 conductivity (mS/cm) < TDS (mg/l) < 0.95 conductivity (mS/cm).
   e. Typically, the constant is high for chloride rich waters and low for sulphate rich waters.

iv. Checking the cation-anion balance

When a water quality sample has been analysed for the major ionic species, one of the most important validation tests can be conducted: the cation-anion balance.

$$\text{Sum of cations} = \text{sum of anions}$$

where:

cations = positively charged species in solution (meq/l)
anions = negatively charged species in solution (meq/l)

The Electronic charge balance is expressed as follows:

$$\text{Electronic Charge Balance (ECB \%)} = \frac{[\sum \text{cations} - \sum \text{anions}]}{[\sum \text{cations} + \sum \text{anions}]} \times 100$$

All concentrations should be in epm. Error charge balance has been computed for the chemical results of 2023-24 and analysis showing more than 10% ECB has not been accepted as it indicates that there has been an error made in at least one of the major cation/anion analyses.

2.2 Drinking Water Evaluation

A key component of the study is the comparison of measured water quality parameters with the **Bureau of Indian Standards (BIS)** for drinking water quality.

This study determines whether groundwater from shallow aquifers meets the quality standards for safe drinking water and other uses as per guidelines, established by the Bureau of Indian Standards (BIS), 10500 **(Table 1).** This comparison helps assess whether the groundwater from the shallow aquifers meets the established safety thresholds for drinking water and other uses.

Table 1: The Indian Bureau of Standards guidelines for contaminants levels in drinking water.

Indian Bureau of Standards Guidelines			
Analyte	**Acceptable Limit**	**Permissible Limit in Absence of Alternative Source**	**Health effects**
EC (µs/cm at 25°c)	750	3000	Anesthetic effect, May lead to Cardiovascular complications
Cl (mg/L)	250	1000	Eye/nose irritation; stomach discomfort
F (mg/L)	1	1.5	Bone disease (pain and tenderness of the bones); children may get mottled teeth
Fe (mg/L)	1	None	Anesthetic effect, promotes iron bacteria
Nitrate (mg/L)	45	None	High nitrate levels in drinking water can cause blue baby syndrome
As (µg/L)	10	No relaxation	Skin damage, increased risk of cancer
U(µg/L)	30	No relaxation	Increased risk of cancer, kidney toxicity

2.3 Water Quality Criteria for Irrigation Purpose

Groundwater is a critical resource for irrigation in India, particularly in regions with insufficient surface water. The quality of groundwater used for irrigation directly affects soil health and crop productivity. Many problems originate due to inefficient management of water for agriculture use, especially when it carries high salt loads.

Areas that rely heavily on irrigation face significant salinity issues. When water is extracted from groundwater for irrigation purposes, salts that were once contained in the groundwater can accumulate on the soil's surface, leading to **soil salinization**. This, in turn, reduces crop yields and degrades soil health, further exacerbating the water quality crisis in these regions.

Table 2: Safe Limits for electrical conductivity for irrigation water (IS:11624-1986)

Nature of soil	Crop Growth	Upper permissible safe limit of Electrical Conductivity in water µs/cm at 25°C
Deep black soil and alluvial soilshaving clay content more than 30%; soils that are fairly to moderately well Drained	Semi- tolerant	1500
	Tolerant	2000
Textured soils having clay contents of 20-30%; soils that are well drained internally and have good surface drainage system	Semi- tolerant	2000
	Tolerant	4000
Medium textured soils having clay 10-20%; internally very well drained and having good surface drainage system	Semi- tolerant	4000
	Tolerant	6000

These effects are visible in plants by their stunted growth, low yield, discoloration and even leaf burns at margin or top. The safe limits of electrical conductivity for crops of different degrees of salt tolerances under varying soil textures and drainage conditions are presented in **Table - 2.**

2.3.1 Sodium Adsorption Ratio (SAR) & Residual Sodium Carbonate (RSC)

SAR is an important parameter used to assess the suitability of groundwater for irrigation in terms of **sodium content**. It is the ratio of the concentration of sodium (Na^{+}) to the concentrations of calcium (Ca^{2+}) and magnesium (Mg^{2+}) in water.

$$\mathbf{SAR} = \frac{\mathbf{Na}}{\sqrt{(\mathbf{Ca} + \mathbf{Mg})/2}}$$

High levels of sodium in water can lead to the dispersion of soil particles, resulting in **soil structure degradation** and reduced **water infiltration**. This condition is known as **alkali soil** or **sodium toxicity**, which can severely reduce crop growth. A SAR value of less than 10 is considered **suitable** for most soils (Table 3).

Residual Sodium Carbonate (RSC) is an important index that helps assess the potential for water to cause alkalinity in the soil. Alkaline water can adversely affect soil structure, crop yield, and overall land productivity. RSC is a measure of the excess amount of carbonate ions in water, which can combine with calcium and magnesium in the soil, leading to soil sodicity (high levels of sodium).

The formula to calculate RSC is as follows:

$$\mathbf{RSC = (HCO3 + CO3) - (Ca + Mg)}$$

Sodium Percentage (Na%) refers to the proportion of **sodium ions (Na^+)** relative to the total cation concentration (which includes sodium, calcium, and magnesium ions) in the water. It is an important indicator for assessing the **sodicity** potential of irrigation water, as high sodium concentrations can lead to **soil dispersion** and reduce soil permeability, which makes it harder for water and air to reach plant roots. The formula to calculate the **Sodium Percentage (Na%)** is:

$$\%\mathbf{Na} = \frac{\mathbf{(Na + K)}}{\mathbf{(Ca + Mg + Na + K)}} * \mathbf{100}$$

Table 3 : Guidelines for evaluation of quality of irrigation water.

Water Class	SAR	RSC	%Na
Low	< 10	< 1.25	< 20
Medium	>10 – 18	1.25 – 2.5	20 - 60
High	>18 – 26	>2.5	> 60
Very High	> 26		

2.4 Groundwater Quality Assessment Using Hydrogeochemistry Plots

Hydrogeochemistry plots such as Piper Diagrams and various scatter plots help visualize the ionic composition of groundwater samples in a way that makes it easier to identify the dominant ions and to classify the water type (e.g., sodium chloride, calcium bicarbonate). By plotting the relative proportions of cations (e.g., calcium, sodium, magnesium) and anions (e.g., bicarbonate, sulfate, chloride), they provide a clear picture of Groundwater chemistry. Both Piper diagrams and XY ionic plots help present complex chemical data in a visually appealing and easily interpretable format, making it easier for stakeholders (e.g., water resource managers, regulators, and the general public) to understand the data. This section describes the **use of hydrogeochemistry plots** to assess the groundwater quality across the study area, focusing on key parameters such as **cations**, **anions**, and other critical elements.

3. Principal Aquifers of India

The groundwater movement and occurrence is mainly controlled by the geological settings. Based on the groundwater exploration and aquifer mapping in India, fourteen principle aquifers have been mapped (Fig-1). Each aquifers are characterised by the groundwtaer potential such as porosity, permeability and storativity. Each rock type of aquifers has different mineralogical compositions, which directly affect the groundwater quality in terms of hardness, ionic concentrations and the presence of contaminants. For instance, metamorphic and igneous rocks such as **Gneiss and Granite** contain fluoride bearing minerals, which releases fluoride into groundwater due to the interaction with rock types.

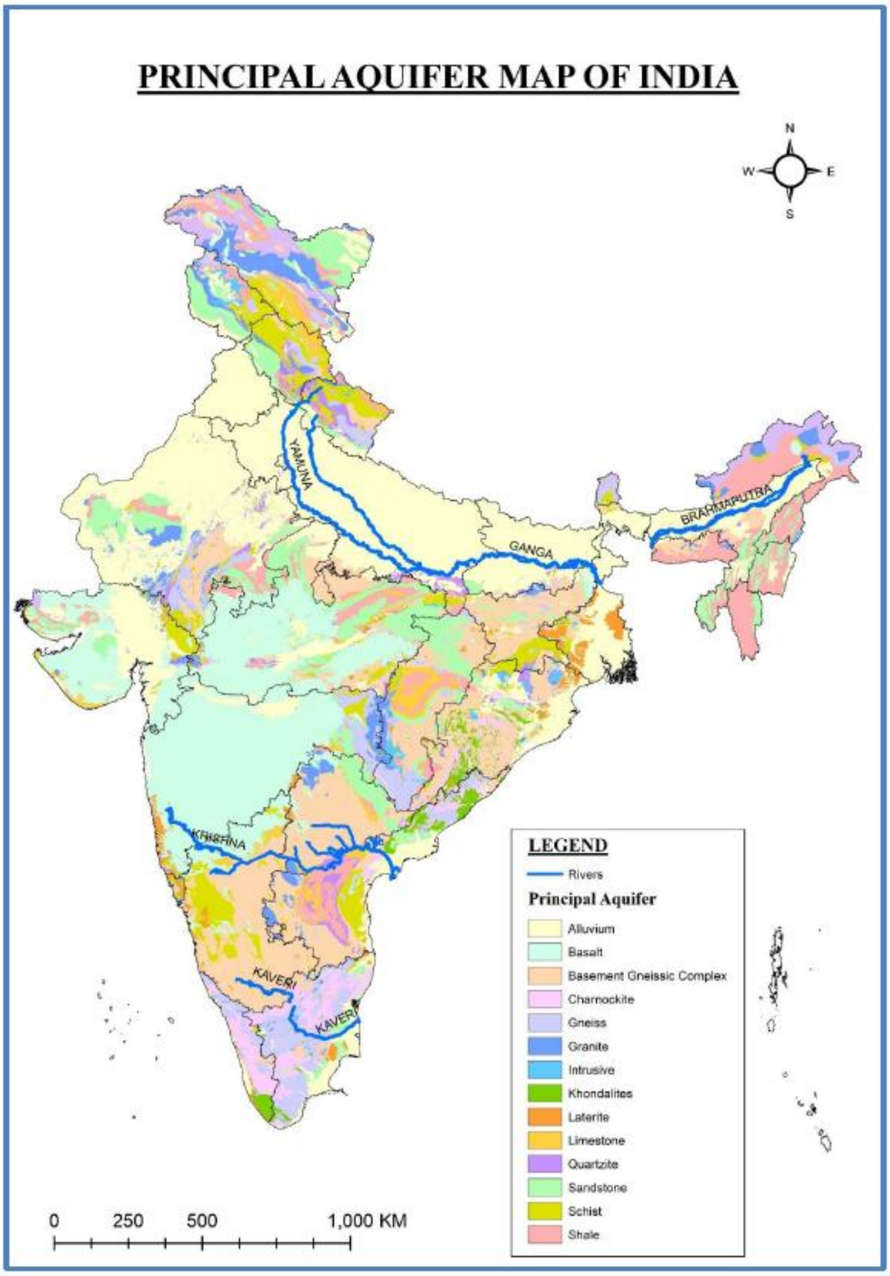


Figure 1: Principal Aquifers in India.

The geological framework of an area significantly impacts the quality of groundwater, especially in terms of the presence and concentration of certain contaminants like **fluoride**, **uranium**, **iron** and **arsenic**. The specific rock types, along with their weathering characteristics, mineral composition, and hydrological properties, influence how these elements are mobilized or dissolved into groundwater under favorable conditions.

4. Ground Water Quality Scenario in India

Ground water samples were collected from **15,259 background monitoring network stations** in May 2023. About 4982 groundwater samples were collected from trend stations for both **pre-monsoon** and **post-monsoon** analysis to assess the impact of **monsoon recharge** on groundwater quality. The goal of this extensive monitoring is to track seasonal variations in groundwater quality and to identify any emerging contamination issues.

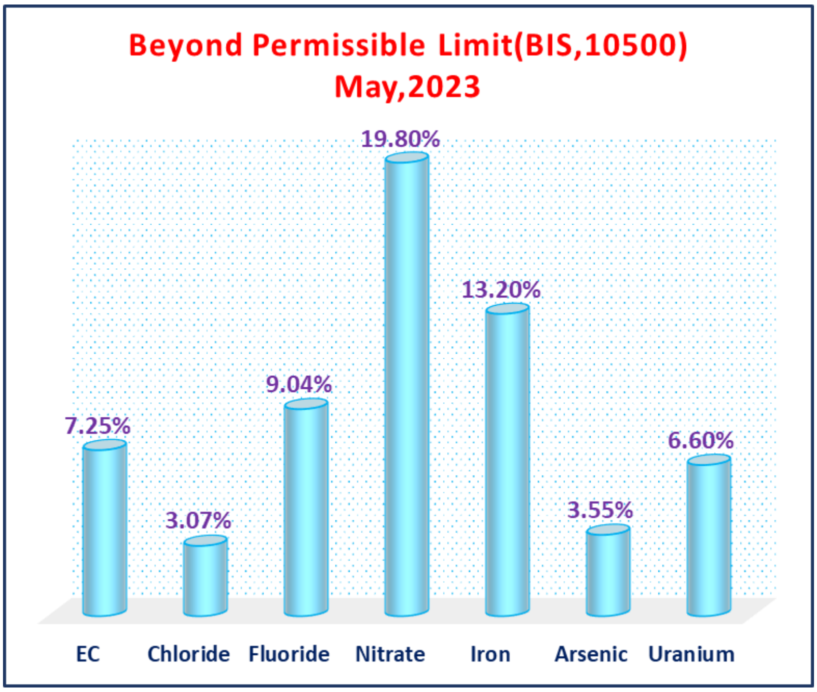


Figure 2: % of Groundwater samples beyond permissible limit as per BIS,10500.

The groundwater quality analysis in **May 2023 (pre-monsoon)** reveals several critical issues with **nitrate**, **fluoride**, **iron**, and **arsenic** concentrations exceeding permissible limits in a significant percentage of samples. The most significant concern appears to be **nitrate contamination**, with nearly **20%** of the samples exceeding the permissible limit. Both **fluoride (9.04%)** and **arsenic (3.35%)** are exceeding permissible limits in a considerable portion of groundwater samples (Fig.2 & Table 4)). This is particularly worrying because long-term exposure to both contaminants can have severe health consequences, including **fluorosis** (for fluoride) and **cancer** or **skin lesions** (for arsenic). **Iron contamination** (13.20%

of samples exceeding the limit) and **EC** (7.25% of samples exceeding the limit) is mostly a concern for **aesthetic quality**. The percentage of samples exceeding uranium limits is **6.60%**, indicating that uranium contamination remains a concern in specific regions, especially those with **granite** or **basement rock** formations. Chronic exposure to uranium can lead to **kidney damage.**

Table 4: Summarized results of groundwater quality ranges, (May 2023).

Parameters	Range		No. of samples	% of samples
EC µs/cm at 25°c	Fresh	< 750	6244	40.92
	Moderate	750- 3000	7908	51.83
	Highly mineralized	> 3000	1107	7.25
Chloride (mg/L)	Desirable limit	< 250	12808	83.93
	Permissible limit	251-1000	1983	13.00
	Beyond permissible limit	> 1000	468	3.07
Fluoride (mg/L)	Desirable limit	< 1.0	11959	78.37
	Permissible limit	1.0 - 1.5	1921	12.59
	Beyond permissible limit	>1.5	1379	9.04
Nitrate (mg/L)	Permissible limit	< 45	12238	80.20
	Beyond permissible limit	> 45	3021	19.80

4.1 Ground Water Quality Hot Spots in Unconfined Aquifers of India

Unconfined aquifers are extensively tapped for water supply across the country; therefore, its quality is of paramount importance. Unconfined aquifers are directly influenced by surface conditions and less protected by impermeable layers. The chemical parameters like TDS, Chloride, Fluoride, Iron, Arsenic and Nitrate etc are main constituents defining the quality of ground water in unconfined aquifers. Therefore, presence of these parameters in ground water beyond the permissible limit in the absence of alternate source has been considered as groundwater quality hotspots. Groundwater quality hot spot maps of the country have been prepared depicting six main parameters based on their distribution shown on the separate maps.

The **hotspot maps** developed for each of these parameters allow for identifying areas where the concentration of these constituents is above the defined thresholds, helping to highlight regions that require attention for water quality management and remediation efforts.

- Electrical Conductivity (>3000 µS/cm at 25°C)
- Fluoride (> 1.5 mg/L)
- Nitrate (> 45mg/L)
- Chloride (> 1000 mg/L)
- Iron (>1.0mg/L)

- Arsenic (> 10 ppb)
- Uranium (> 30 ppb)

4.2 Electrical Conductivity

Electrical Conductivity (EC) is a measure of the ease with which water conducts electricity. It is actually the measure of mineralization of water and indicative of the degree of salinity of ground water. The reason that the conductivity of water is important is because it can tell us how much dissolved substances, chemicals, and minerals are present in the water**.** Higher amounts of these impurities will lead to a higher conductivity. When various chemicals and salts dissolve into the water, they will turn into negatively charged and positively charged ions. The positively charged ions that can affect water include ***calcium, potassium, magnesium, and sodium***. On the other hand, negatively charged ions include ***bi-carbonate, chloride, and sulfate***. Even a meagre number of dissolved salts and chemicals can heighten the conductivity of water.

Electrical conductance is directly related to the abundance of charged ionic compounds (Hem 1985). Salinity always exists in ground water but in variable amounts. It is mostly influenced by aquifer material, solubility of minerals, duration of contact and factors such as the permeability of soil, drainage facilities, and quantity of rainfall and above all, the climate of the area. The salinity of groundwater in coastal areas in addition to the above may be due to air borne salts originating from air water interface over the sea and due to over pumping of fresh water which overlays saline water in coastal aquifer systems.

BIS has recommended a drinking water standard for total dissolved solids a limit of 500 mg/L (corresponding to EC of about 750 µS/cm at 25^0C) that can be extended to a TDS of 2000 mg/L (corresponding to EC of about 3000 µS/cm at 25^0C) in case of no alternate source. Water having TDS more than 2000 mg/L is not suitable for drinking purpose. In the pre-monsoon EC is ranging from 11.5 to 34180 µS/cm. During post-monsoon, water quality is affected by the monsoon recharge. In post monsoon, EC is ranging from 17.1 to 36920 µS/cm. Districts in which anomalous values of EC > 3000 µS/cm in Groundwater was detected at one or more location in Different States of India (Pre- Monsoon 2023) have been presented in Table 6.

In **Fig. 3**, the EC values (in µS/cm at 25^0C) of ground water from observation/monitoring wells have been used to show distribution patterns of electrical conductivity in different ranges of suitability for drinking purposes. It is apparent from the map that majority of the waters having EC values less than 750µS/cm at 25^0C occur mostly in the states of J & K, Himachal

Pradesh, Uttarakhand, N-Uttar Pradesh, Kerala, Sikkim, Chhattisgarh, Orissa, Western Ghats of Maharashtra & Karnataka and North- Eastern states such as Asam, Meghalaya, Arunachal Pradesh, Tripura etc., of the country.

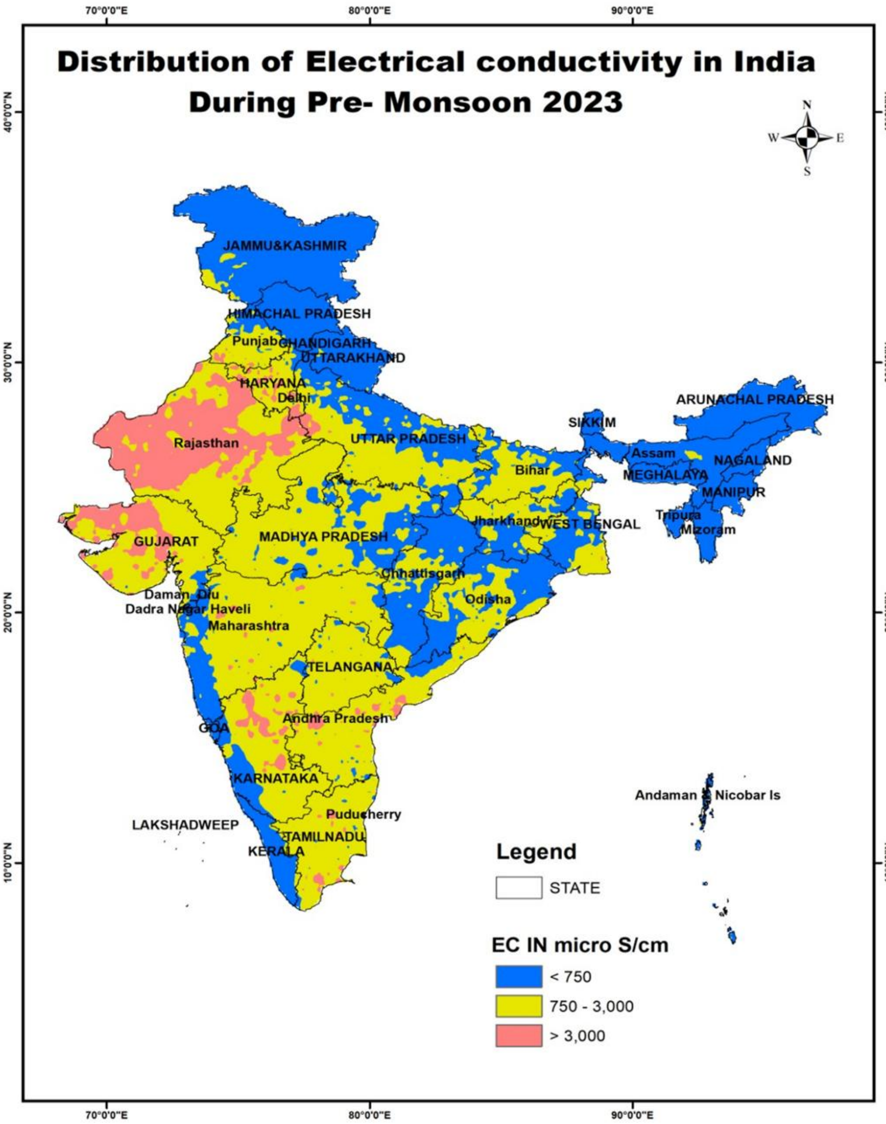


Figure 3: Distribution of Electrical Conductivity in India during Pre-monsoon (May, 2023).

Groundwater with EC ranging between 750 and 3000μS/cm at 250C falling under 'permissible' range are confined mainly to parts of Uttar Pradesh, Madhya Pradesh, Bihar, West Bengal, Andhra Pradesh, Karnataka, Tamil Nadu, Maharashtra, Jharkhand and Punjab. However, in some cases, relatively high values of EC in excess of 3000 μS/cm are observed in many parts of the country. Especially in Rajasthan, Gujarat, Haryana, Andhra Pradesh, Maharashtra, Tamil Nadu, Karnataka etc. Coastal states like Tamil Nadu, Andhra Pradesh, Gujarat and Maharashtra face **seawater intrusion** in coastal aquifers. As freshwater levels deplete, saltwater from the sea moves inland, raising EC levels. This is especially true in areas where groundwater extraction rates are higher than recharge rates. In arid and semi-arid regions such as **Rajasthan**, **Punjab**, and **Haryana**, high evaporation rates lead to **concentration of salts** in groundwater. When water evaporates, salts in the soil or groundwater become more concentrated, contributing to higher EC.

In comparison to 2017 (Fig. 4 & Table 5), it has been observed that the no. of districts having EC more than 3000 µS/cm detected at one or more location in different states of India in various States has slightly increased in 2023. State-wise no. of water samples analysed and no. of locations having EC >3000 µS/cm during pre-monsoon is presented in Fig.5.

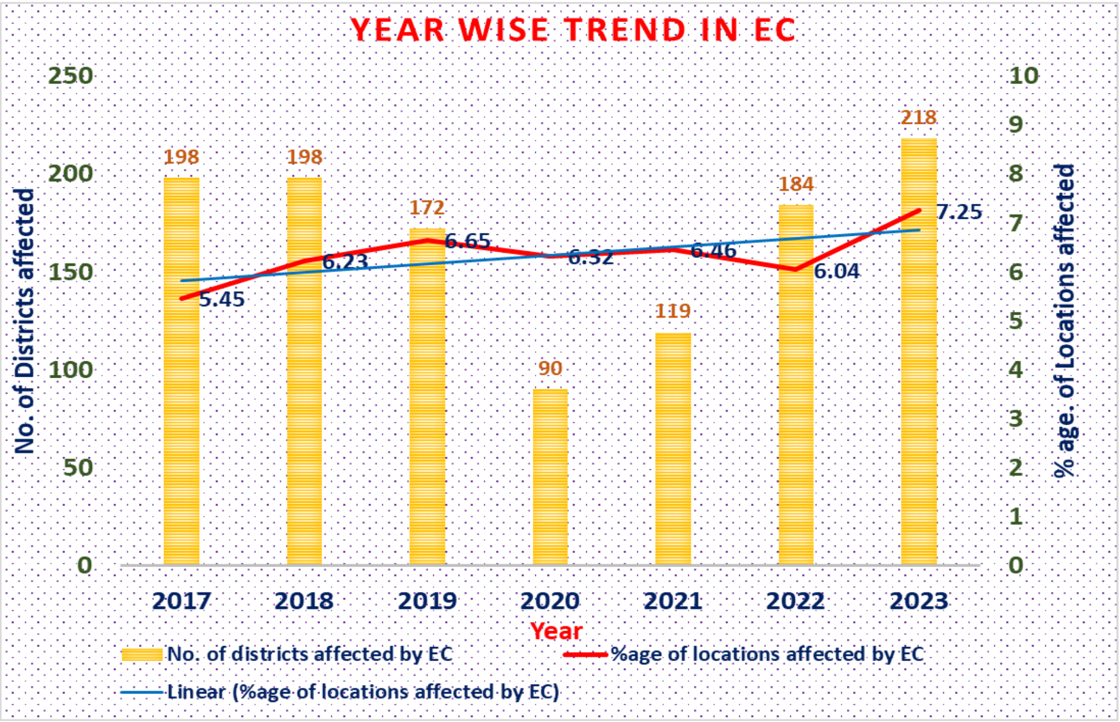


Figure 4: Year wise trend in Electrical Conductivity in Pre-Monsoon Samples During 2017-2023.

Table 5: Percentage of locations having EC>3000 µS/cm during the period 2017-2023

Year	Total Number of samples analysed	No. of districts affected by EC	Total No. of locations affected by EC	% of locations affected by EC (EC>3000 µS/cm)
2017	13200	198	720	5.45
2018	13247	198	825	6.23
2019	12503	172	832	6.65
2020	6582	90	416	6.32
2021	8427	119	544	6.46
2022	15507	184	937	6.04
2023	15259	218	1107	7.25

Table 6: Districts in which anomalous values of Salinity (EC > 3000 µS/cm) in Groundwater was detected at one or more location (Pre- Monsoon 2023).

State/UT	Name of District(s)
Andhra Pradesh	Anakapalli, Ananthapur, Annamayya, Bapatla, Chittoor, East Godavari, Eluru, Guntur, Kakinada, Konaseema, Krishna, Kurnool, Nellore, NTR, Palnadu, Parvathipuram Manyam, Prakasham, Sri Satya Sai, Srikakulam, Tirupathi, Vizianagaram, West Godavari, YSR Kadapa
Assam	Morigaon
Bihar	Buxar, Jehanabad, Lakhisarai, Siwan, Vaishali
Chhattisgarh	Bemetara, Mungeli
Daman and Diu	Diu
Delhi	North, Northwest, Shahdara, Southwest, West
Gujarat	Ahmedabad, Amreli, Anand, Banaskantha, Bharuch, Bhavnagar, Botad, Chhota udepur, Devbhoomi Dwarka, Gir Somnath, Jamnagar, Junagadh, Kachchh, Mahesana, Morbi, Narmada, Navsari, Patan, Porbandar, Rajkot, Sabarkantha, Surendranagar, Vadodara, Valsad
Haryana	Ambala, Bhiwani, Charkhi Dadri, Faridabad, Fatehabad, Gurugram, Hisar, Jhajjar, Jind, Kaithal, Mahendragarh, Mewat, Palwal, Panchkula, Panipat, Rewari, Rohtak, Sirsa, Sonipat
Karnataka	Bagalkot, Belgaum, Bellary, Bijapur, Chamarajanagara, Chikkamagaluru, Chitradurga, Davanagere, Dharwad, Gadag, Koppal, Raichur, Tumkur, Vijayanagara, Yadgir
Madhya Pradesh	Bhind, Datia, Gwalior, Neemuch, Shivpuri
Maharashtra	Ahmednagar, Akola, Amravati, Aurangabad, Beed, Buldhana, Chandrapur, Jalgaon, Jalna, Nagpur, Nanded, Nandurbar, Nashik, Parbhani, Raigad, Ratnagiri, Sangli, Satara, Solapur, Thane, Wardha
Odisha	Angul, Balangir, Nuapada, Puri
Punjab	Bathinda, Faridkot, Fazilka, Ferozepur, Mansa, Muktsar, Nawanshahr, Patiala, SAS Nagar
Rajasthan	Ajmer, Alwar, Barmer, Bharatpur, Bhilwara, Bikaner, Bundi, Chittaurgarh, Churu, Dausa, Ganganagar, Hanumangarh, Jaipur, Jaisalmer, Jalore, Jhunjhunu, Jodhpur, Karauli, Nagaur, Pali, Rajsamand, Sawai Madhopur, Sikar, Sirohi, Tonk, Udaipur
Tamil Nadu	Chennai, Coimbatore, Dharmapuri, Dindigul, Erode, Kancheepuram, Krishnagiri, Nagapattinam, Namakkal, Nilgiris, Perambalur, Pudukkottai, Ramanathapuram, Salem, Theni, Thiruvallur, Tirunelveli, Tiruvallur, Tiruvarur, Trichy, Tuticorin, Vellore, Villupuram, Virudhunagar
Telangana	B Kothagudem, J Bhupalapally, Jangaon, Jogulamba, KB Asifabad, Khammam, Mancherial, Medak, Nagarkurnool, Nalgonda, Pedapalle, Rangareddy, Sangareddy, Siddipet, Warangal, Yadadri Bhuvanagiri
Uttar Pradesh	Agra, Aligarh, Amethi, Etawah, Firozabad, G.B. Nagar, Ghaziabad, Ghazipur, Hamirpur, Hathras, Mainpuri, Mathura, Unnao
West Bengal	Bankura, Howrah, Malda, Purulia, South 24 Parganas

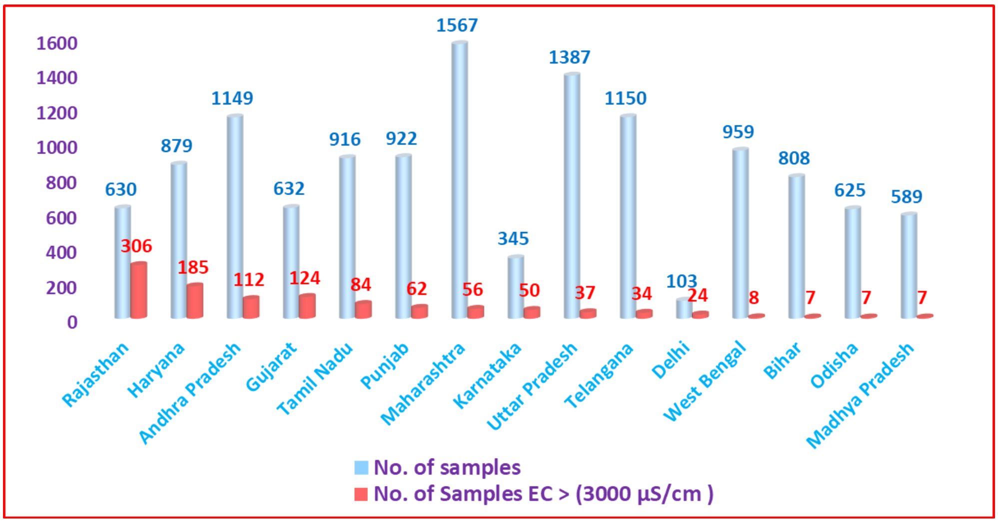


Figure 5: State-wise no. of water samples analysed and no. of locations having EC >3000 µS/cm during pre-monsoon,2023.

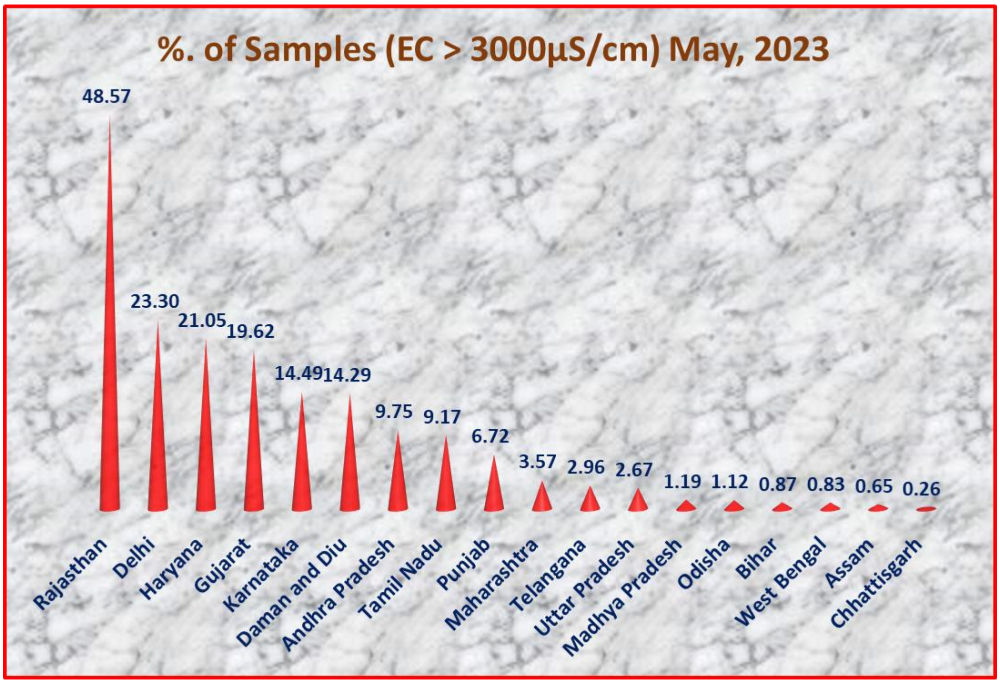


Figure 6: State-wise % of water samples having EC value more than permissible limit during pre-monsoon,2023.

* In *Arunachal Pradesh, Dadra and Nagar Haveli, Goa, Himachal Pradesh, Jammu and Kashmir, Jharkhand, Kerala, Uttarakhand, Meghalaya, Mizoram and Nagaland* 100% water samples are within permissible limit as per BIS, 100500.

4.2.1 Analysis of States/Districts with High EC Values

A significant proportion of water samples across several states in India show EC value exceeding the permissible limit of **3000 µS/ cm** as per BIS, 10500 (Fig. 5 & 6). The states of Rajasthan (48.57%), Delhi (23.30%), Gujarat (19.62%) and Karnataka (14.49%) are the most severely affected by high EC value in groundwater, with more than 10 % of water samples exceeding the EC permissible limit. In **Arunachal Pradesh, Dadra and Nagar Haveli, Goa,**

Himachal Pradesh, Jammu and Kashmir, Jharkhand, Kerala, Uttarakhand, Meghalaya, Mizoram and Nagaland all the water samples are well within the permissible limit as per BIS, 10500.

The following states have consistently had a significant number of districts where the Electrical Conductivity (EC) of groundwater exceeds the permissible limit of 3000 µS/cm: **Rajasthan, Gujarat**, **Tamilnadu, Karnataka, Maharashtra, Andhra Pradesh, Haryana, Uttar Pradesh and Punjab**. Year-wise Comparison of Districts Exceeding EC Limit (2015–2023) has been presented in Fig. 6**.** Rajasthan, Maharashtra, Uttar Pradesh and Punjab show relatively stable or constant trends over the years, with the number of districts exceeding the permissible EC limit fluctuating but not showing a significant increase or decrease. This suggests that the groundwater quality with respect to Electrical conductivity in these states are longstanding and persistent, with no major improvement or deterioration in the number of affected districts over the years. **Karnataka, Andhra Pradesh, Haryana, Gujarat** show an **increasing trend** in the number of districts exceeding the EC limit over the years.

This indicates that the problem of high EC levels is becoming more widespread, likely due to rising groundwater extraction, changing agricultural practices, or climatic changes that are reducing groundwater recharge.

On the basis of available data 15 districts in India have been identified as mostly affected with high EC values (Table 7). **Haryana** has the highest number of districts with EC values exceeding the permissible limit, accounting for **6 out of the top 15 districts**. **Andhra Pradesh** follows with **3 districts** in the top 15 and **Punjab** has **2 districts** in the top 15. This data suggests that **Haryana** is the most severely impacted state in terms of groundwater quality, with the largest proportion of its districts facing salinity problems.

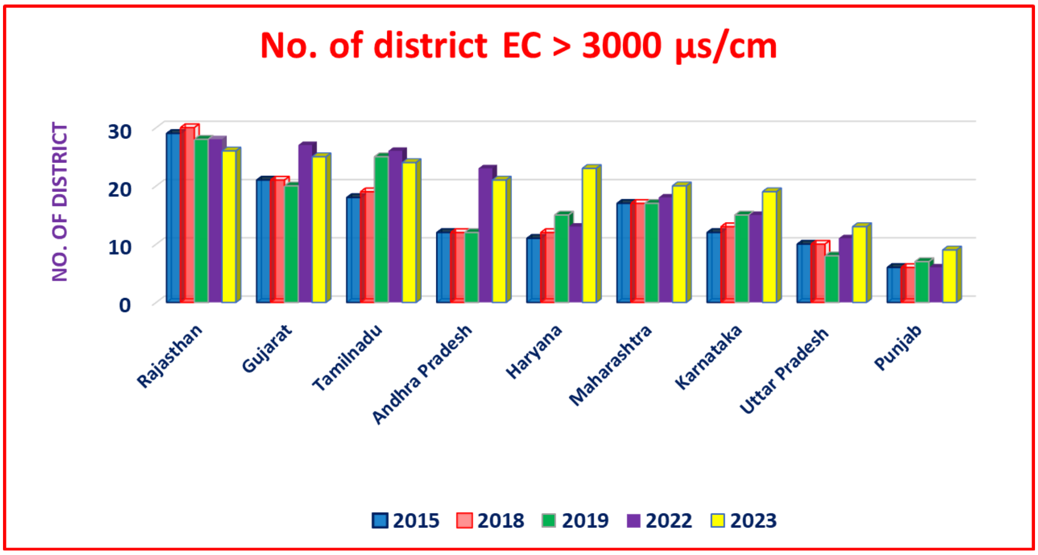


Figure 7: Year-wise Comparison of Districts with EC Exceeding 3000 µS/cm (2015–2023).

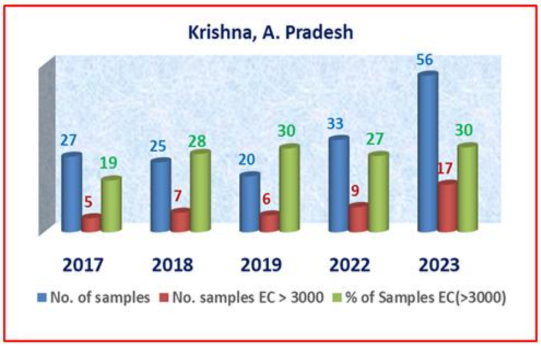
The state's dependence on groundwater for irrigation, over-extraction of groundwater coupled with rising salinity in its aquifers, is likely contributing to the increased number of affected districts. **Andhra Pradesh** and **Punjab** also show significant concerns, though to a lesser extent.

Andhra Pradesh's 3 districts in the top 15 reflect a growing concern regarding **groundwater over-extraction**, especially in the **coastal** regions of the state. **Salinity ingress** due to excessive pumping of groundwater, especially in the coastal regions may be one of reason for high salinity in Andhra Pradesh.

Table 7: State-wise Distribution of Top 15 Affected Districts

State	District	Total analysed	No. of samples EC>3000 µS/cm	% Samples EC>3000 µS/cm
Andhra Pradesh	Krishna	56	17	30.36
Rajasthan	Barmer	56	45	80.36
Rajasthan	Jodhpur	73	50	68.49
Punjab	Fazilka	55	20	36.36
Haryana	Sirsa	67	24	35.82
Haryana	Hisar	58	19	32.76
Haryana	Bhiwani	72	22	30.56
Gujarat	Surendranagar	52	15	28.85
Haryana	Sonipat	53	15	28.3
Haryana	Jind	60	14	23.33
Andhra Pradesh	Palnadu	70	16	22.86
Maharashtra	Ahmednagar	79	15	18.99
Haryana	Gurugram	48	9	18.75
Tamil Nadu	Villupuram	48	8	16.67
Punjab	Bathinda	50	8	16
Andhra Pradesh	Prakasham	102	12	11.76

In Barmer and Jodhpur district of Rajasthan a rising trend in EC has been observed. In Sirsa and Bhiwani district of Haryan EC levels have remained relatively stable. In Krishna District of Andhra Pradesh also EC levels have remained relatively stable (Fig. 8). In Barmer and Jodhpur district of Rajasthan there is a slightly increasing trend.



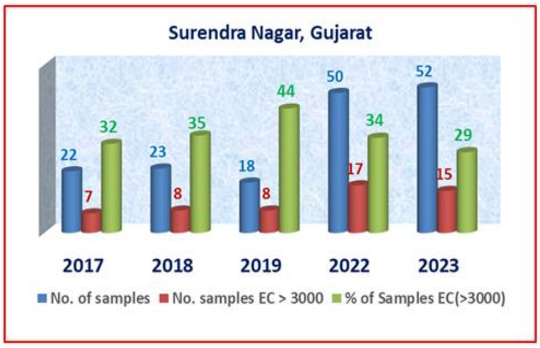
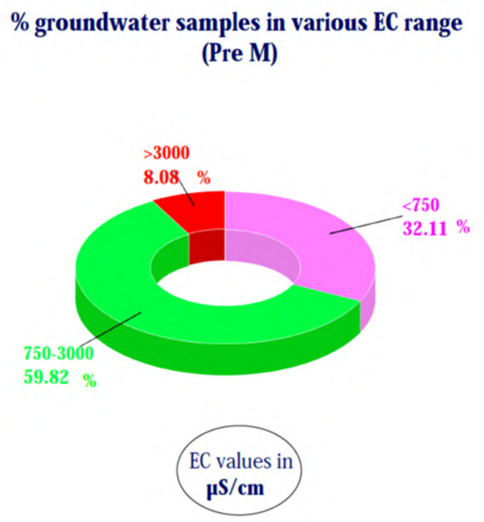


Figure 8: Yearly trend of EC values more than permissible limit in Krishna district of A. Pradesh

Surendranagar District in Gujarat has shown significant **fluctuations** in the number of districts exceeding the permissible EC limit of 3000 µS/cm from **2017 to 2023** (Fig.8). These fluctuations suggest that **groundwater quality** in the region may have been influenced by a combination of factors that vary year by year. Groundwater quality in regions like Surendranagar can vary significantly from year to year due to **seasonal factors** such as rainfall and recharge levels. Years with higher rainfall may lead to a **recharge** of aquifers, diluting the salinity and reducing EC values, while **drier years** could lead to higher EC values due to reduced recharge and more concentrated salts.

4.2.2 Pre- and post-monsoon comparison of EC Values: Understanding the Impact of Monsoon Recharge

One interesting aspect of water quality is how it changes with seasons particularly before and after monsoon. In the **pre-monsoon** period, **8.08%** of the samples had **EC values greater than 3000 µS/cm**, after the **monsoon recharge**, this percentage decreased to **7.49%**, showing a **slight improvement** in groundwater quality in post-monsoon, likely due to the **recharge effect** of rainfall, which dilutes the salts in the aquifers (Fig. 9). The **post-monsoon period** showed a **modest improvement** in groundwater quality, as indicated by the slight reduction in high EC values. Pre-Post changes in EC in Ground Water in states have been presented in Table 8.



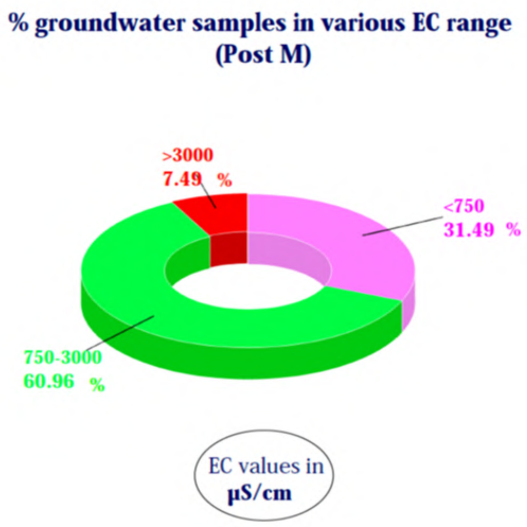


Figure 9: Percentage groundwater samples in various EC range, 2023 (Pre &Post).

Table 8: Effect of monsoon recharge on salinity at common locations during pre and post monsoon.

State/ UT	No. of Pre/Post samples	Improved locations	Detriorated Locations	Sites with EC> 3000 µS/cm			
				Pre		Post	
				No.	%	No.	%
A & N Islands	29	18	11	0	0.00	0	0.00
Andhra Pradesh	280	147	133	45	16.07	37	13.21
Assam	123	68	55	1	0.81	0	0.00
Bihar	180	102	78	4	2.22	3	1.67
Chhattisgarh	156	131	25	0	0.00	0	0.00
Delhi	24	11	13	11	45.83	13	54.17
H. Pradesh	29	15	14	0	0.00	0	0.00
Haryana	77	40	37	35	45.45	36	46.75
J&K	30	11	19	0	0.00	2	6.67
Jharkhand	132	51	81	0	0.00	0	0.00
Karnataka	176	92	84	26	14.77	28	15.91
M.Pradesh	531	230	301	6	1.13	0	0.00
Maharashtra	746	332	414	38	5.09	28	3.75
Meghalaya	35	12	23	0	0.00	0	0.00
Mizoram	3	0	3	0	0.00	0	0.00
Nagaland	5	2	3	0	0.00	0	0.00
Odisha	116	67	49	7	6.03	3	2.59
Pondicherry	2	1	1	0	0.00	0	0.00
Punjab	39	22	17	14	35.90	12	30.77
Rajasthan	90	44	46	61	67.78	56	62.22
Tamil Nadu	198	110	88	19	9.60	21	10.61
Telangana	355	242	113	14	3.94	10	2.82
Tripura	74	29	45	0	0.00	0	0.00
Uttar Pradesh	341	118	223	19	5.57	27	7.92
West Bengal	186	78	108	2	1.08	3	1.61
Total	**3969**	**1985**	**1984**	**302**	**7.61**	**279**	**7.03**

In several states in India monsoon rains have a significant impact by reducing EC levels. Here is a look how monsoon has positively influenced water samples in five states **(Fig. 10)**. In **Rajasthan**, **32%** of the water samples have significant showed improvement, with EC values falling below **3000 µS/cm** in post-monsoon. In **Andhra Pradesh**, **28%** of the water samples showed improvement, with their EC values dropping to less than **3000 µS/cm** after the monsoon. In **Haryana**, **27%** of the water samples improved significantly, with EC values falling below **3000 µS/cm** in post-monsoon. Tamilnadu also benefitted with **16%** of the water samples showing improvement. This reflects the effectiveness of **monsoon rains** in reducing the EC levels, potentially due to increased groundwater recharge and dilution of salts during the monsoon period.

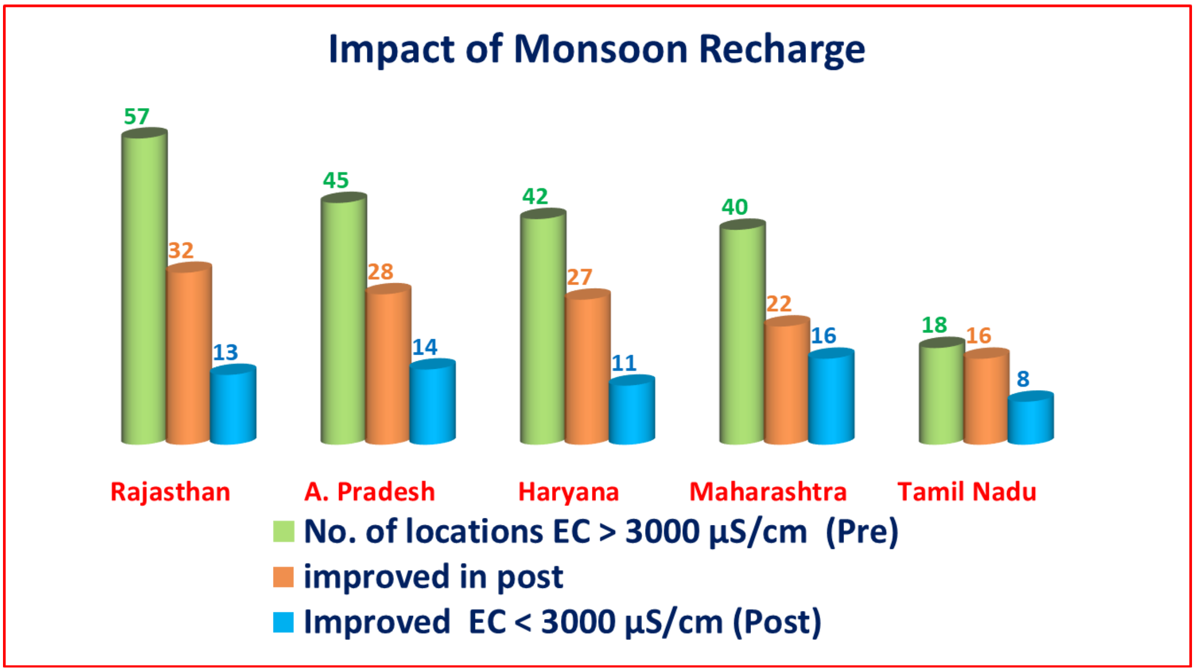


Figure 10: Impact of Monsoon recharge in five key states.

While monsoon rains generally help **dilute salts** and improve groundwater quality in many regions, there is an opposite effect, leading to an **increase in EC levels**. In Andhra Pradesh and Haryana **4%** of the water samples showed deterioration, with **EC values rising above 3000 µS/cm** during post-monsoon. **2%** of water samples in Rajasthan and 2% in Tamilnadu showed a deterioration in water quality, with **EC values exceeding 3000 µS/cm** after the monsoon **(Fig.11).** This suggests that while monsoon rains generally contribute to **recharge**, they may also lead to **increased salinity** in certain areas, potentially due to **surface runoff** carrying salts into the **shallow saline aquifers** mixing with groundwater. It is crucial to adopt

sustainable water extraction practices to maintain the gains from monsoon recharge, ensuring that the groundwater remains within permissible EC limits throughout the year.

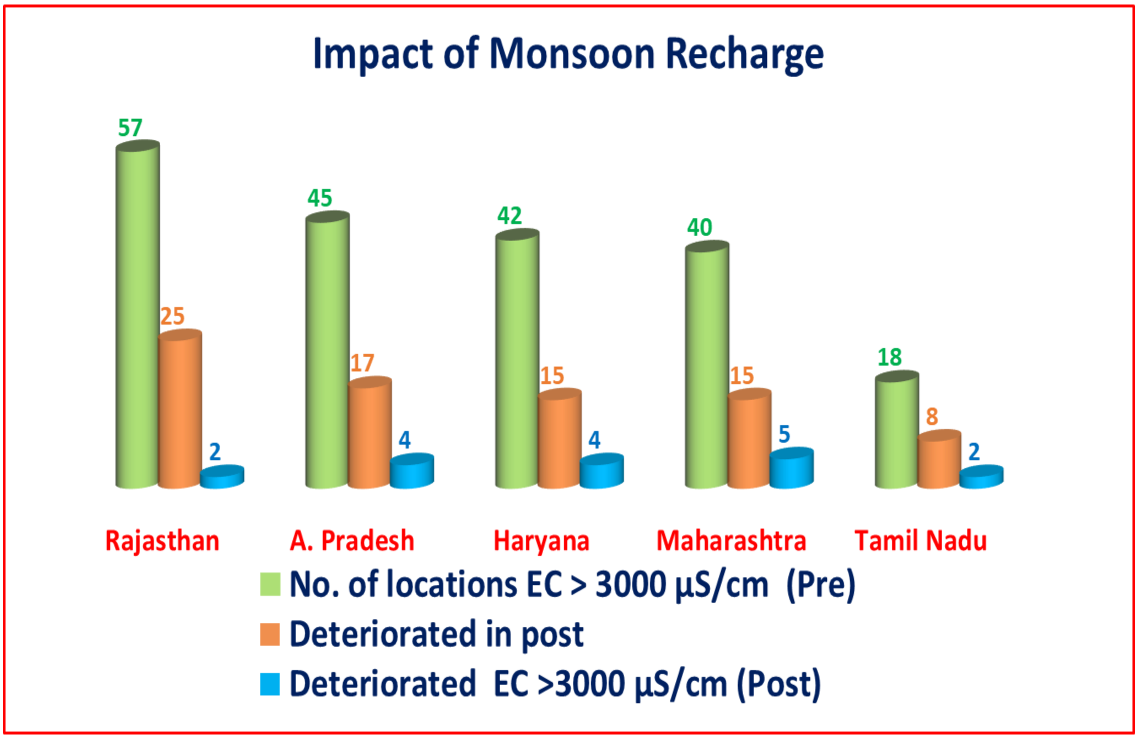


Figure 11: Impact of monsoon recharge on EC values in Five key states.

4.2.3 Impact of Over-Extraction on Groundwater Elevated EC Levels

In the context of groundwater quality, **over-exploitation** and **contamination** are often interconnected, particularly in regions where water extraction rates exceed the natural replenishment of aquifers. The **over-extraction of groundwater** can exacerbate water quality problems, leading to higher concentrations of certain pollutants like **salinity**. This section compares areas that are **over-exploited** (i.e., regions where groundwater extraction rates are significantly higher than natural recharge rates) with **high salinity** contamination areas to highlight the compounded challenges these regions face in terms of both water quantity and quality.

Excessive groundwater extraction leads to a drop in the water table, reducing the natural recharge capacity of aquifers. As groundwater levels decline, there is less dilution of salts, which results in higher EC values. In these over-exploited areas, the inability of aquifers to naturally replenish exacerbates the concentration of dissolved salts, making the water increasingly saline.

In coastal regions, **over-exploitation** of groundwater can lead to saline water intrusion, where saltwater from nearby bodies of water infiltrates fresh groundwater aquifers. In inland areas, excessive extraction from deep aquifers can draw up more naturally saline water from deeper strata, further elevating EC values.

States like **Rajasthan**, **Punjab**, **Haryana** and **Western Uttar Pradesh** rely heavily on groundwater for irrigation. Over-extraction, coupled with **high evaporation rates** in these semi-arid regions, results in a **concentration of salts** in the remaining groundwater, leading to **high EC values**.

4.2.4 Mapping Over-Exploitation and EC Levels:

Maps of **over-exploited areas** in Haryana, Rajasthan, Gujarat, Punjab, Western Uttar Pradesh and Tamil Nadu show a striking similarity with **high EC value maps**, underscoring the link between over-extraction and **groundwater salinization (Fig. 12)**. In these regions, areas of **over-extraction** coincide with zones where **EC values** exceed permissible limits, indicating a direct impact of **over-exploitation** on groundwater EC levels.

Rainwater harvesting, artificial recharge techniques, and water-efficient agricultural practices could help mitigate the impact of over-extraction on groundwater quality and EC levels.

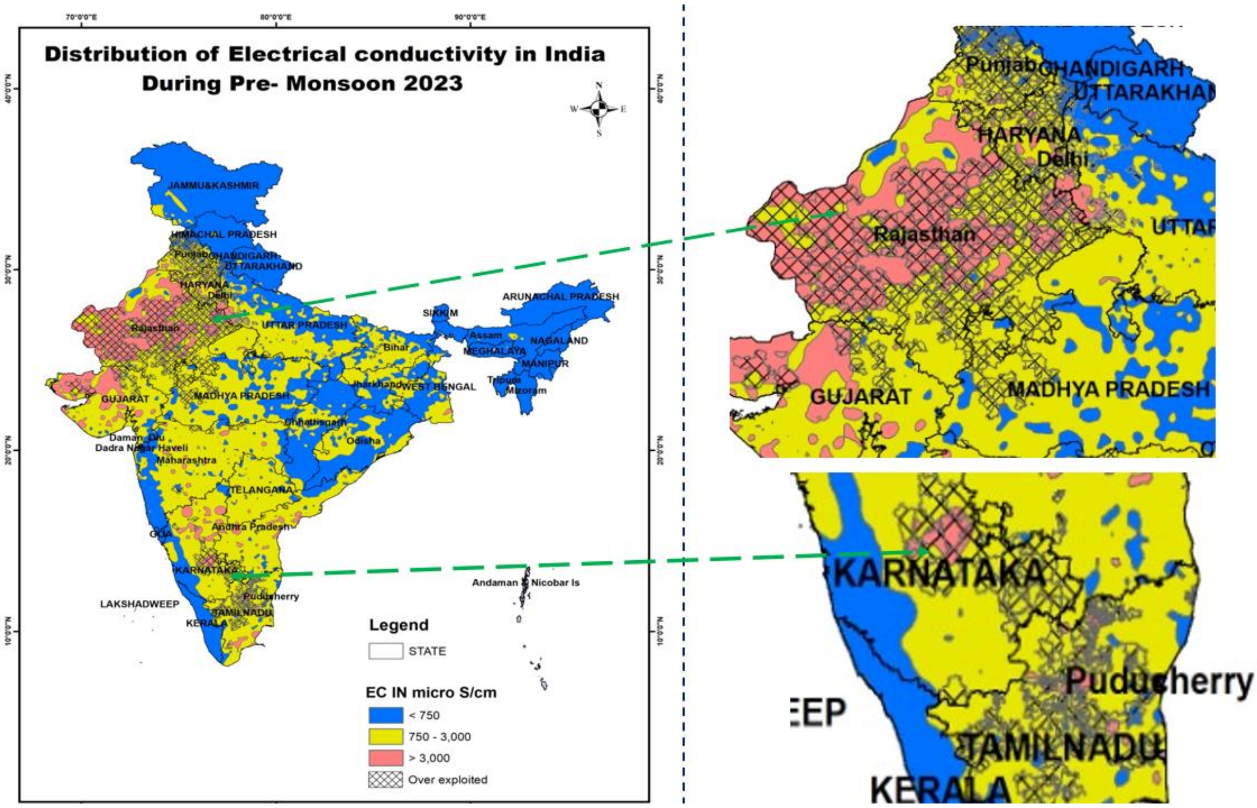


Figure 12: over-exploited areas show a striking similarity with high EC value.

4.3 Fluoride

High fluoride contents in groundwater used for consumption are harmful to human health. Long-term intake of groundwater with excessive fluoride concentrations often leads to waterborne fluorosis, such as dental and skeletal fluorosis.

The origin of F in groundwater is closely related to geologic setting or anthropogenic activities. The geological origin is diverse and complex, mainly contributed by the dissolution of fluorinebearing minerals such as biotite, muscovite, fluorite, hornblende, mica, fluorapatite and tourmaline etc., found in sedimentary, metamorphic and igneous rocks.

Concentration of fluoride in the continental crust is 611 mg/kg. Various rock types contain fluoride at different levels: basalt, 360 µg/g; granites, 810 µg/g; limestone, 220 µg/g; sandstone, 180 µg/gm; shale 800 µg/gm; oceanic sediments, 730 µg/gm and soils, 285 µg/gm.

Most fluoride is sparingly soluble and is present in natural waters in small amounts. Due to its high electro negativity, it forms only fluorides and no other oxidation states are found in waters. In low PH water, the species found is HF. With aluminum, beryllium & iron (III) fluoride forms strong complexes, below neutrality. The fluoride ion has the same charge and radius as OH^-. Hence, they can replace each other and can form series of F-OH complex with metals. In the acid medium fluoride could well be associated with silica in a six coordinated structure though rarely.

In the hard rock areas, in some water samples fluoride concentration has been found more than permissible limit. In the fluoride affected area, decreasing Ca concentrations have been found under alkaline conditions with a corresponding rise in Na.

Earlier also so many researchers have opined that, Na-HCO_3 type water provides favourable condition for dissolution of fluoride.

$$CaF_2 + Na_2CO_3 \rightarrow CaCO_3 + 2Na^{+} + 2F^{-}$$

pH value of aquifer solution between 5-6.5 leads to adsorption of F^- on clay minerals. The reverse is the situation in alkaline conditions having pH value more than 7. In these circumstances, OH^- group replaces the exchangeable F^- of clay minerals (biotite, muscovite, apatite, hornblende, and amphiboles), as both of these contain almost identical ionic radius (0.136 nm), consequently resulting in enhanced F^- concentration in aquifer. Besides these minerals, the anthropogenic activitiesinclude agriculture and industry may also contribute a certain amount of fluorife to groundwater. Unlike the rather slow natural process of fluoride mobilization through rock-water interaction, its mobilization increases manifold during phosphate fertilizer production due to the strongly acidic reaction conditions encountered. Single superphosphate (SSP) is a popular phosphate fertilizer.

The occurrence of fluoride in natural water is affected by the type of rocks, climatic conditions, nature of hydrogeological strata and time of contact between rock and the circulating ground water. Presence of other ions, particularly bicarbonate and calcium ions also affect the concentration of fluoride in ground water. It is well known that small amounts of fluoride (less than 1.0 mg/L) have proven to be beneficial in reducing tooth decay. However, high concentrations such as 1.5 mg/L of F and above have resulted in staining of tooth enamel while at still higher levels of fluoride ranging between 5.0 and 10 mg/L, further pathological changes such as stiffness of the back and difficulty in performing natural movements may take place.

BIS has recommended an upper desirable limit of 1.0 mg/L of F^- as desirable concentration of fluoride in drinking water, which can be extended to 1.5 mg/L of F in case no alternative source of water is available. The distribution of ground water samples with fluoride concentration more than 1.5 mg/L have been depicted on the map as **Fig. 13**. It is observed that there are several locations in the States of Andhra Pradesh, Gujarat, Karnataka, Madhya Pradesh, Rajasthan, Chhattisgarh, Haryana, Orissa, Punjab, Tamilnadu, Kerala, Telangana, Uttar Pradesh West Bengal, Bihar, Delhi, Jharkhand, Maharashtra, and Assam where the fluoride in ground water exceeds 1.5 mg/L. State-wise no. of water samples analysed, no. of samples F > 1.5mg/L and no. of locations having F > 1.5 mg/L during pre-monsoon is presented in **Fig.14, Fig.15** and Table 9. Districts in which anomalous values of F > 1.5 mg/L in Groundwater was detected at one or more location in Different States of India (Pre- Monsoon 2023) have been presented in Table 11. In comparison to 2017 **(Fig. 16 & Table 10),** it has been observed that the no. of districts having F > 1.5 mg/L detected at one or more location in different states of India in various States has slightly increased in 2023. Percentage of locations with F > 1.5 mg/L increased by 2.27 % in 2023 with respect to 2022. This significant increase in percentage of locations has been mainly contributed by states like Rajasthan, Haryana, Punjab and Telangana. The details of locations where fluoride concentration is more than 1.5 mg/L (Pre 2023) is given in Annexure III.

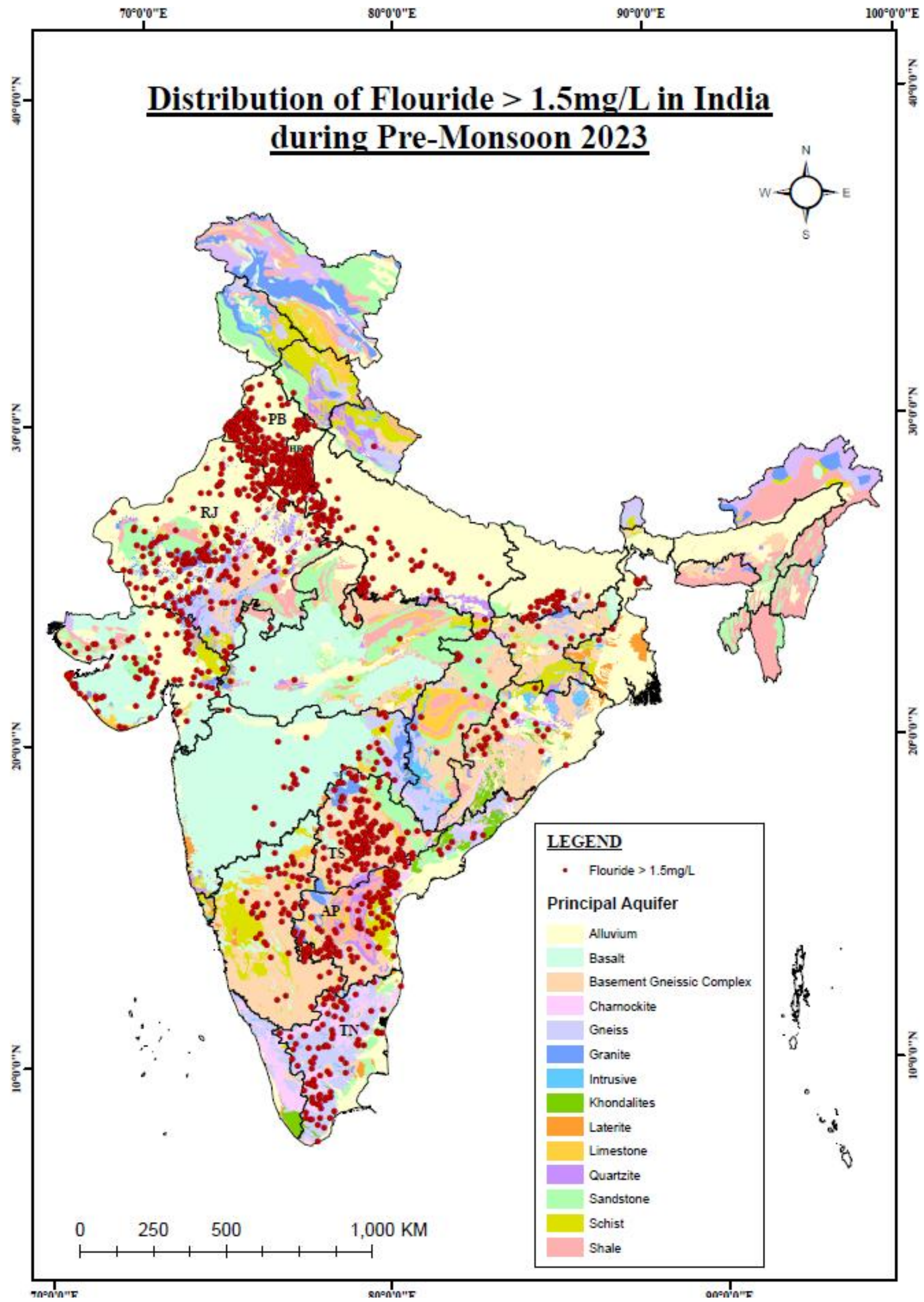


Figure 13: Locations having Fluoride concentration > 1.5 mg/L during Pre-Monsoon 2023.

Table 9: State-wise percentage of wells having fluoride >1.5mg/L (Pre,2023).

State/UT	No. of samples analysed	Min	Max	No. of Samples (F >1.5 mg/L)	% of samples (F> 1.5mg/L)
A & N Islands	113	0	0.69	0	0.00
Andhra Pradesh	1149	0.009	4.39	130	11.31
Arunachal Pradesh	12	0.03	0.08	0	0.00
Assam	155	0	1.30	0	0.00
Bihar	808	0	2.47	37	4.58
Chandigarh UT	8	0.45	1.27	0	0.00
Chhattisgarh	783	0	4.30	14	1.79
D & N Haveli	10	0.17	0.54	0	0.00
Daman and Diu	7	0.23	0.82	0	0.00
Delhi	103	0.28	3.70	17	16.50
Goa	10	0.02	0.06	0	0.00
Gujarat	632	0	7.70	88	13.92
Haryana	879	0.012	22.00	208	23.66
Himachal Pradesh	171	0	3.38	2	1.17
Jammu& Kashmir	250	0	1.30	0	0.00
Jharkhand	397	0	1.91	11	2.77
Karnataka	345	0	6.44	61	17.68
Kerala	342	0	2.00	1	0.29
Madhya Pradesh	589	0	2.46	6	1.02
Maharashtra	1567	0.036	4.40	30	1.91
Meghalaya	39	0	0.12	0	0.00
Mizoram	3	0	0.01	0	0.00
Nagaland	6	0	0.15	0	0.00
Odisha	625	0	8.00	28	4.48
Pondicherry	4	0.56	0.68	0	0.00
Punjab	922	0	14.00	127	13.77
Rajasthan	630	0.0065	18.20	272	43.17
Tamil Nadu	916	0.06	4.48	89	9.72
Telangana	1150	0.012	6.86	171	14.87
Tripura	81	0	1.10	0	0.00
Uttar Pradesh	1387	0	8.20	79	5.70
Uttarakhand	207	0	1.70	1	0.48
West Bengal	959	0	6.50	7	0.73

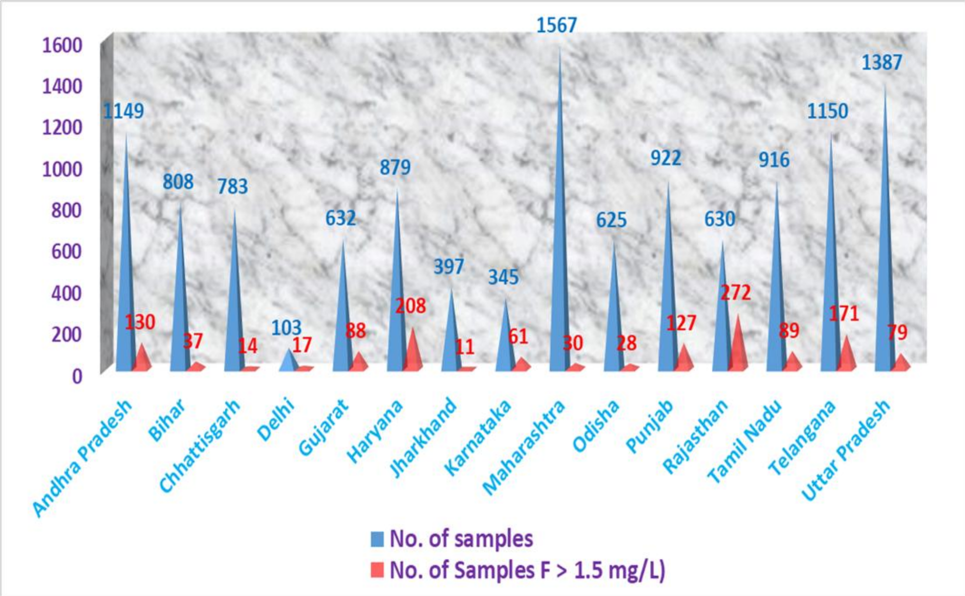


Figure 14: State-wise no. of water samples analysed and no. of locations having F > 1.5 mg/L during pre-monsoon,2023.

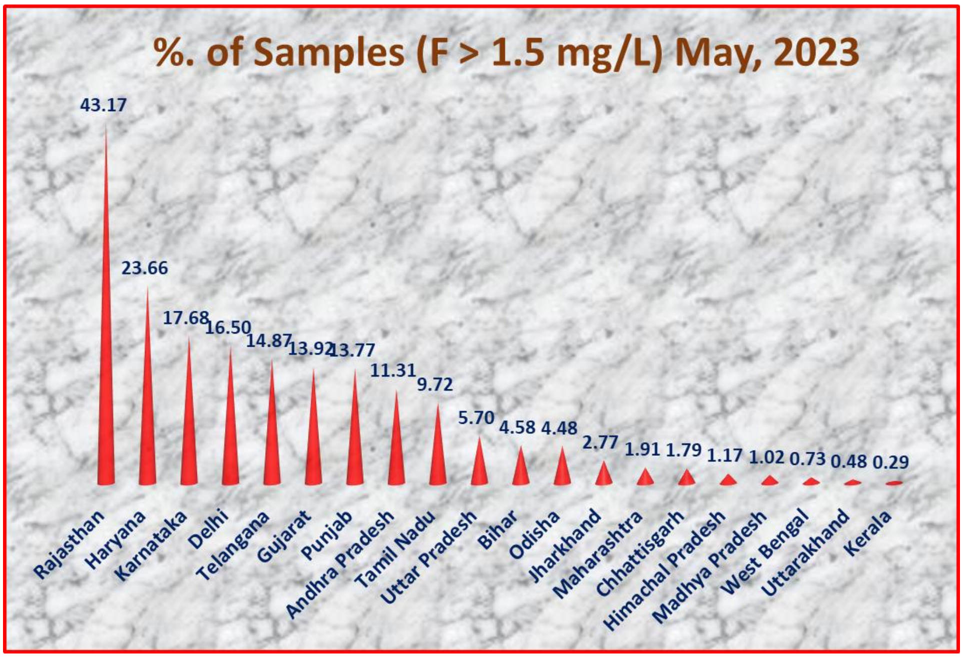


Figure 15: State-wise % of water samples with Fluoride concentration > 1.5 mg/L during pre-monsoon,2023.

* In *Arunachal Pradesh, Asam, Dadra and Nagar Haveli, Daman and Diu, Goa, Pondicherry, Jammu and Kashmir, Meghalaya, Mizoram and Nagaland* 100% watersamples are well within the permissible limit as per BIS, 10500.

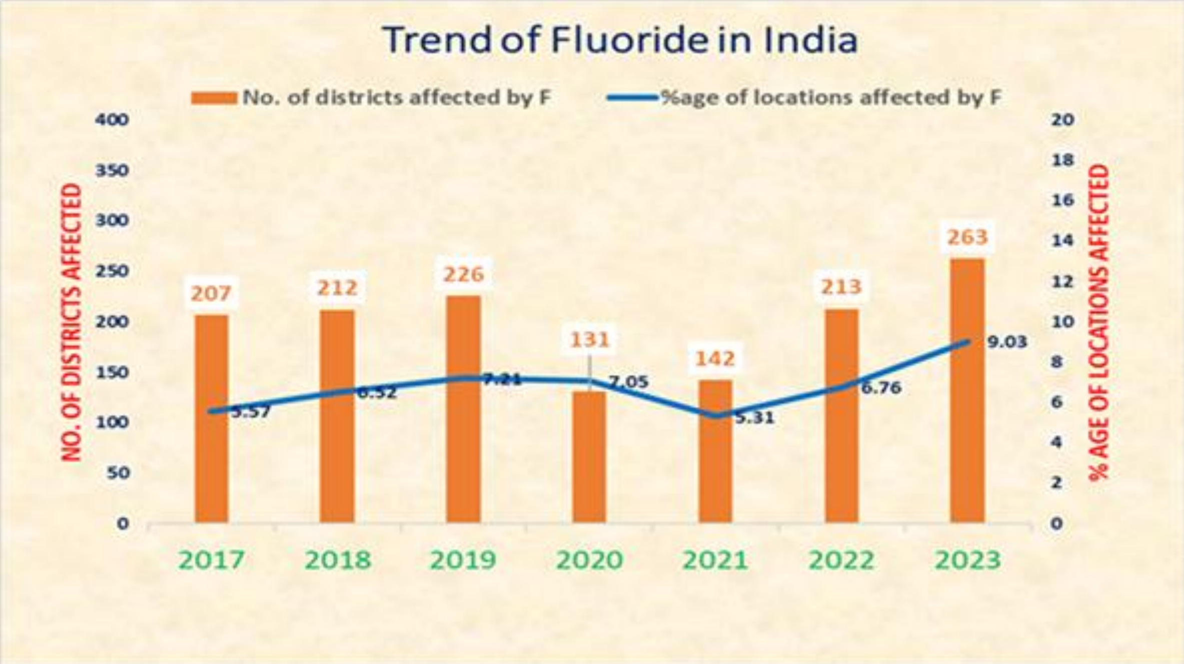


Figure 16: Year wise trend of Fluoride concentration in Pre-Monsoon (2017-2023).

Table 10: Percentage of locations having F > 1.5 mg/L during the period 2017-2023.

Year	Total No. of samples analysed	No. of districts affected by F > 1.5 mg/L	No. of locations affected by F > 1.5 mg/L	% of locations affected by F >1.5mg/L
2017	13225	207	736	**5.57**
2018	13229	212	862	**6.52**
2019	12475	226	899	**7.21**
2020	6366	131	449	**7.05**
2021	8482	142	450	**5.31**
2022	15507	213	1048	**6.76**
2023	15259	263	1379	**9.03**

Table 11: Districts in which anomalous values of Fluoride (F > 1.5 mg/L) in groundwater was detected at one or more location.

State/UT	No. of Districts	Name of Districts
Andhra Pradesh	17	Alluri sita rama raju, Anakapalli, Ananthapur, Annamayya, Bapatla, Chittoor, East Godavari, Kurnool, Nandyal, Nellore, NTR, Palnadu, Prakasham, Sri Satya Sai, Srikakulam, Tirupathi, YSR Kadapa
Bihar	6	Banka, Gaya, Jamui, Nalanda, Nawada, Seikhpura
Chhattisgarh	8	Janjgir Champa, Kanker, Korba, Koriya, Mahasamund, Raigarh, Rajnandgaon, Surajpur
Delhi	6	New Delhi, North, North West, Shahdara, South, South West
Gujarat	25	Ahmedabad, Amreli, Anand, Arvalli, Banaskantha, Bhavnagar, Botad, Chhota udepur, Dahod, Devbhoomi Dwarka, Gir Somnath, Jamnagar, Junagadh, Kachchh, Mahesana, Morbi, Narmada, Panchmahal, Patan, Porbandar, Rajkot, Sabarkantha, Surat, Surendranagar, Vadodara

Haryana	17	Bhiwani, Charkhi Dadri, Fatehabad, Gurugram, Hisar, Jhajjar, Jind, Karnal, Mahendragarh, Mewat, Palwal, Panchkula, Panipat, Rewari, Rohtak, Sirsa, Sonipat
H. Pradesh	2	Sirmour, Una
Jharkhand	8	Bokaro, Chatra, Dhanbad, Godda, Koderma, Latehar, Palamu, Ramgarh
Karnataka	19	Bellary, Bengaluru Rural, Bijapur, Chikballapur, Chitradurga, Davanagere, Dharwad, Gadag, Gulbarga, Haveri, Kolar, Koppal, Mandya, Mysore, Raichur, Ramanagara, Tumkur, Vijayanagara, Yadgir
Kerala	1	Palakkad
M. Pradesh	6	Alirajpur, Chhindwara, Dewas, Dhar, Katni, Mandla
Maharashtra	10	Akola, Bhandara, Buldhana, Chandrapur, Gadchiroli, Hingoli, nandurbar, Osmanabad, Parbhani, Yavatmal
Odisha	10	Anugul, Balangir, Bargarh, Jharsuguda, Nayagarh, Nuapada, Puri, Sambalpur, Sonapur, Sundargarh
Punjab	17	Amritsar, Bathinda, Faridkot, Fatehgarh sahib, Fazilka, Ferozepur, Gurdaspur, Hoshiarpur, Jalandhar, Mansa, Moga, Muktsar, Nawanshahr, Patiala, Sangrur, SAS Nagar, Tarn Taran
Rajasthan	31	Ajmer, Alwar, Banswara, Barmer, Bharatpur, Bhilwara, Bikaner, Bundi, Chittaurgarh, Churu, Dausa, Dhaulpur, Dungarpur, Ganganagar, Hanumangarh, Jaipur, Jaisalmer, Jalore, Jhalawar, Jhunjhunu, Jodhpur, Karauli, Nagaur, Pali, Pratapgarh, Rajsamand, Sawai madhopur, Sikar, Sirohi, Tonk, Udaipur
Tamil Nadu	21	Ariyalur, Chennai, Coimbatore, Cuddalore, Dharmapuri, Dindigul, Erode, Karur, Krishnagiri, Madurai, Namakkal, Nilgiris, Perambalur, Pudukkottai, Salem, Theni, Tirunelveli, Tuticorin, Vellore, Villupuram, Virudhunagar
Telangana	28	Adilabad, B. Kothagudem, Hanamkonda, Hyderabad, Jagtial, Jangaon, Kamareddy, Karimnagar, KB Asifabad, Khammam, Mahabubnagar, Mancherial, Medak, Medchal Malkanjgiri, Nagarkurnool, Nalgonda, Nirmal, Nizamabad, Pedapalle, R. Sircilla, Rangareddy, Sangareddy, Siddipet, Suryapet, Vikarabad, Wanaparthy, Warangal, Yadadri Bhuvanagiri
Uttar Pradesh	27	Agra, Aligarh, Auraiya, Azamgarh, Bulandshahar, Farrukhabad, Fatehpur, Firozabad, G.B. Nagar, Ghazipur, Hathras, Jhansi, KannauJ, Kanpur Dehat, Kanpur Nagar, Kaushambi, Lalitpur, Lucknow, Mahoba, Mainpuri, Mathura, Meerut, pratapgarh, Prayagraj, Raebareli, Sonbhadra, Unnao
Uttarakhand	1	Almora
West Bengal	3	Birbhum, Dakshin Dinajpur, Paschim Bardhaman

4.3.1 Analysis of States/Districts with Enriched Fluoride values

The issue of **fluoride contamination** in groundwater is a significant concern in several states of India. A significant proportion of water samples across several states in India show fluoride concentration exceeding permissible limit of **1.5 mg/L** as per BIS, 10500 (Fig. 14 & 15). The states of Rajasthan (43.17%), Haryana (23.66%), Karnataka (17.68%), Telangana (14.87%), Gujarat (13.92%), Punjab (13.77%) and Andhra Pradesh (11.31%) are the most severely affected by high fluoride concentration in groundwater, with more than 10 % of water samples exceeding the fluoride permissible limit. In **Arunachal Pradesh, Asam, Dadra and Nagar**

Haveli, Daman and Diu, Goa, Pondicherry, Jammu and Kashmir, Meghalaya, Mizoram and Nagaland all the water samples are well within the permissible limit as per BIS, 10500.

The following states have consistently had a significant number of districts where the fluoride concentration of groundwater exceeds the permissible limit of 1.5 mg/L:

Rajasthan, Gujarat, Uttar Pradesh, Tamilnadu, Karnataka, Telangana, Maharashtra, Andhra Pradesh and Haryana. Year-wise Comparison of Districts exceeding fluoride limit (2015–2023) has been presented in **Fig. 17.** In states like **Rajasthan, Maharashtra, and Karnataka**, the number of districts with fluoride levels above the permissible limit has remained relatively stable or constant over the past several years (2015–2023). This suggests that the groundwater quality with respect to Fluoride in these states are longstanding and persistent, with no major improvement or deterioration in the number of affected districts over the years.

On the contrary, states like Gujarat, Uttar Pradesh, Tamil Nadu, Telangana, Andhra Pradesh, and Haryana have shown an increasing trend in the number of districts with fluoride concentrations exceeding the permissible limit from 2017 to 2023.

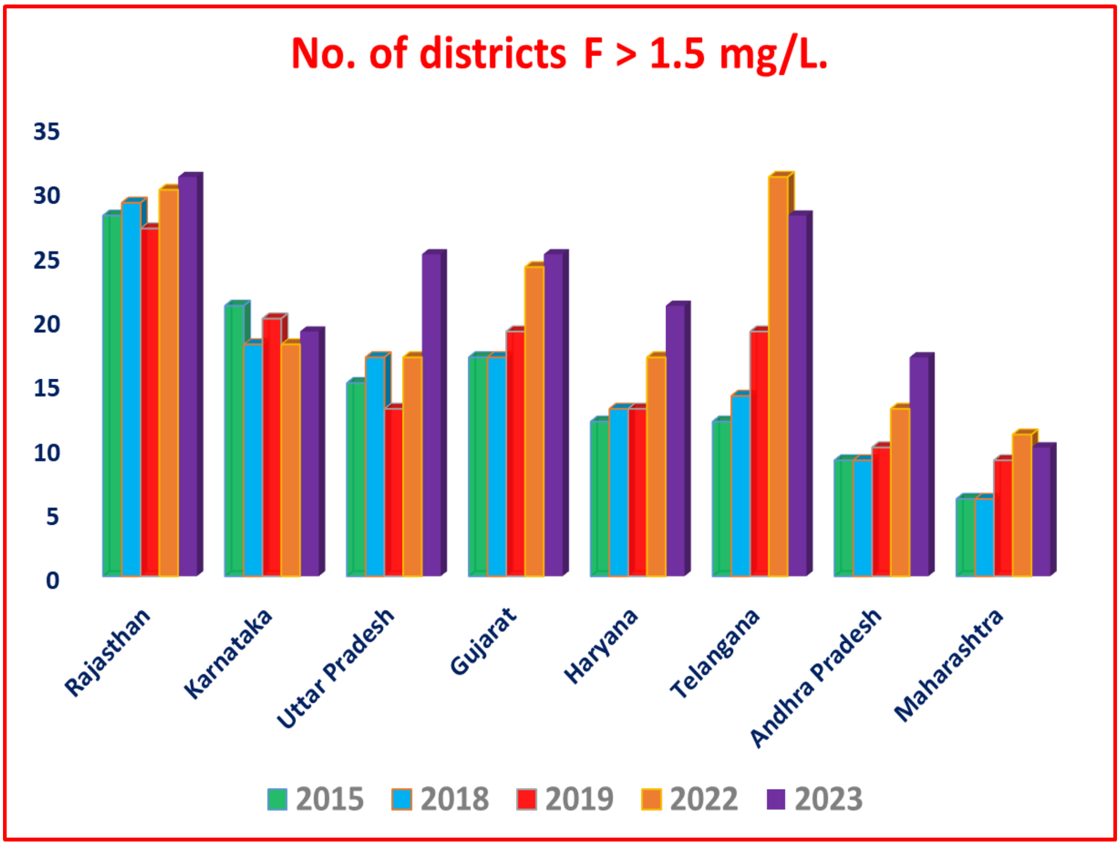


Figure 17: Year-wise Comparison of Districts with F exceeding permissible limit (2015–2023).

On the basis of available data 15 districts in India have been identified as mostly affected with enriched fluoride values (Table 12).

Among the top 15 districts with the highest fluoride concentrations exceeding the permissible limit of 1.5 mg/L, the distribution of affected districts is concentrated in a few states, with Haryana, Rajasthan, and Andhra pradesh. While Haryana, Rajasthan, and Andhra Pradesh have the highest number of affected districts, other states like Telangana and Punjab also feature prominently in the top 15 list of fluoride-affected districts, though with fewer affected districts compared to the aforementioned states.

In Barmer and Jodhpur district of Rajasthan a rising trend in fluoride concentration has been observed. In Sirsa district of Haryan and Sri Satya Sai district of Andhra Pradesh fluoride concentration have remained relatively stable (Fig. 18).

Table 12: State-wise Distribution of Top 15 Affected Districts with Excessive F concentration

State	District	Total analysed	No. of samples F>1.5 mg/L	% samples F>1.5 mg/L
Rajasthan	Nagaur	43	27	62.79
Rajasthan	Jodhpur	73	45	61.64
Haryana	Jind	60	32	53.33
Haryana	Sonipat	53	27	50.94
Telangana	Y. Bhuvanagiri	43	21	48.84
Rajasthan	Churu	42	20	47.62
Punjab	Fazilka	55	26	47.27
Rajasthan	Barmer	56	23	41.07
Haryana	Bhiwani	72	25	34.72
Andhra Pradesh	Sri Satya Sai	85	27	31.76
Haryana	Sirsa	67	21	31.34
Andhra Pradesh	Palnadu	70	19	27.14
Haryana	Panipat	53	14	26.42
Andhra Pradesh	Prakasham	102	25	24.51
Haryana	Hisar	58	14	24.14

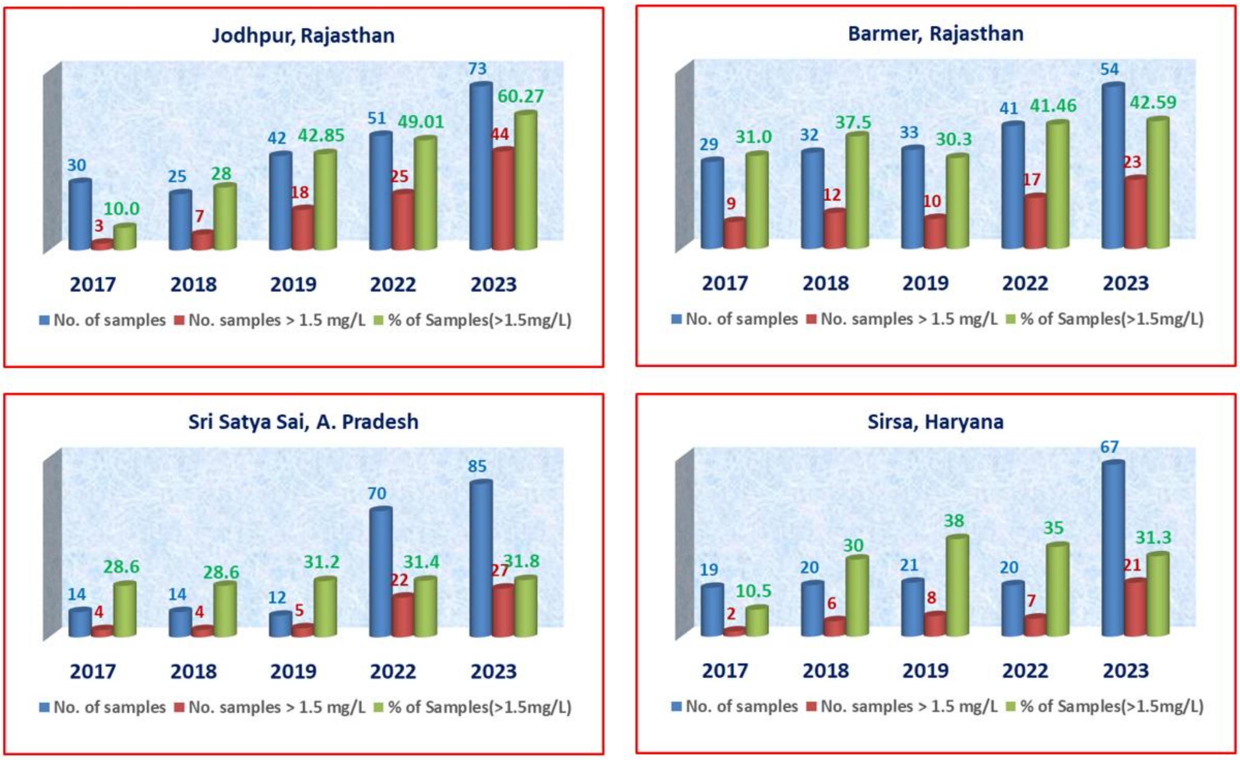


Figure 18: Yearly trend of F more than permissible limit in some districts.

4.3.2 Impact of Monsoon Recharge on Fluoride Concentrations in Groundwater

Water samples were collected during the **pre-monsoon** and **post-monsoon** periods to assess the impact of **monsoon recharge** on fluoride levels in groundwater. The data shows a reduction in fluoride concentrations after the monsoon season, indicating that the monsoon rains have a positive effect on lowering fluoride concentrations in groundwater.

In the **pre-monsoon** period, **9.14%** of the water samples had fluoride concentrations exceeding **1.50 mg/L**, which is above the permissible limit for drinking water. After the **monsoon** season, this percentage decreased to 7.74% in the post-monsoon period, indicating a reduction in the number of samples with high fluoride levels **(Fig.19)**. The percentage of samples with fluoride levels between **1.00 and 1.50 mg/L** also showed a decrease. In the **pre-monsoon** period, **10.97%** of samples had fluoride levels within this range. In the **post-monsoon** period, this percentage decreased slightly to **10.21%**, indicating a marginal improvement in fluoride concentrations following the monsoon rains.

The reduction in the percentage of water samples with fluoride levels exceeding **1.50 mg/L** and those between **1.00–1.50 mg/L** suggests that monsoon recharge helps dilute the fluoride concentration in groundwater. The influx of rainwater likely dilutes the naturally occurring fluoride in aquifers, leading to a decrease in fluoride levels. It highlights the potential of

monsoon rains to help **dilute** the concentration of fluoride in groundwater, improving water quality to some extent. Further efforts in **rainwater harvesting** and **recharge programs** could enhance this effect, leading to long-term improvements in groundwater quality. Pre-Post changes in Fluoride concentratiomn in Ground Water in various states have been presented in Table 13.

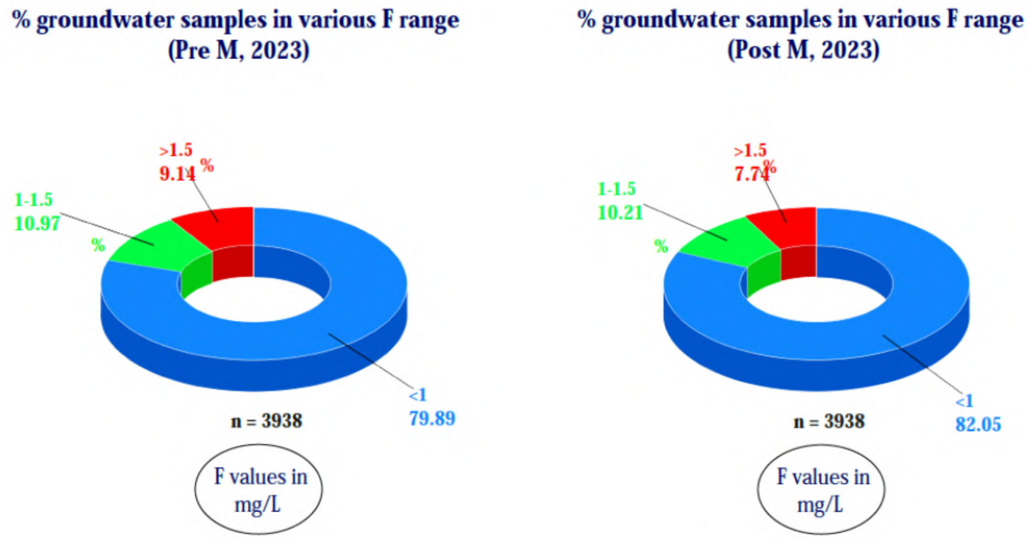


Figure 19: Percentage groundwater samples in various F range (Pre & Post,2023).

Table 13: Effect of monsoon recharge on Fluoride concentration at common locations during pre and post monsoon.

State/ UT	No. of Pre/Post samples	Improved locations	Detriorated Locations	Locations with Fluoride> 1.5 mg/L			
				Pre		Post	
				No.	%	No.	%
A & N Islands	29	14	15	0	0.00	0	0.00
Andhra Pradesh	280	158	122	56	20.00	41	14.64
Arunachal Pradesh	12	1	11	0	0.00	0	0.00
Assam	122	52	70	0	0.00	1	0.82
Bihar	180	119	61	13	7.22	13	7.22
Chhattisgarh	156	109	47	6	3.85	3	1.92
Delhi	24	10	14	7	29.17	9	37.50
Himachal Pradesh	29	25	4	1	3.45	0	0.00
Haryana	77	39	38	29	37.66	25	32.47
Jharkhand	132	44	88	5	3.79	3	2.27
Karnataka	176	89	87	31	17.61	27	15.34
Madhya Pradesh	531	228	303	6	1.13	3	0.56
Maharashtra	746	535	211	14	1.88	3	0.40
Meghalaya	35	23	12	0	0.00	0	0.00
Mizoram	3	3	0	0	0.00	0	0.00
Nagaland	5	0	5	0	0.00	0	0.00
Odisha	116	61	55	11	9.48	11	9.48
Pondicherry	2	2	0	0	0.00	0	0.00
Punjab	39	28	11	17	43.59	15	38.46

Rajasthan	90	34	56	44	48.89	50	55.56
Tamil Nadu	198	144	54	23	11.62	18	9.09
Telangana	355	209	146	71	20.00	55	15.49
Tripura	74	26	48	0	0.00	0	0.00
Uttar Pradesh	341	202	139	24	7.04	24	7.04
West Bengal	186	94	92	2	1.08	4	2.15
Total	**3938**	**2249**	**1689**	**360**	**9.14**	**305**	**7.75**

The observed improvements in fluoride concentrations due to monsoon recharge across various key states in India (Andhra Pradesh, Rajasthan, Karnataka, Haryana, and Tamil Nadu) provide valuable insights into the dynamics of groundwater quality and the impact of seasonal changes **(Fig. 20).**

Summary of Post-Monsoon Data:

- **Andhra Pradesh**: Out of 56 pre-monsoon samples exceeding the permissible fluoride limit, 41 showed improvements in fluoride concentration due to dilution from monsoon recharge. Additionally, 25 of these samples fell below the permissible limit in post-monsoon.
- **Rajasthan**: Out of 44 pre-monsoon samples exceeding the limit, 20 showed improvements, and 8 of them fell below the permissible limit after recharge.
- **Karnataka:** Out of 31 pre-monsoon samples exceeding the limit, 22 showed improvement, and 11 samples fell below the permissible limit after monsoon recharge.
- **Haryana:** Out of 29 pre-monsoon samples exceeding the limit, 17 showed improvement, and 13 samples dropped below the permissible limit.
- **Tamil Nadu:** Out of 23 pre-monsoon samples exceeding the limit, 23 showed improvement, and 10 samples fell below the permissible limit after monsoon recharge.

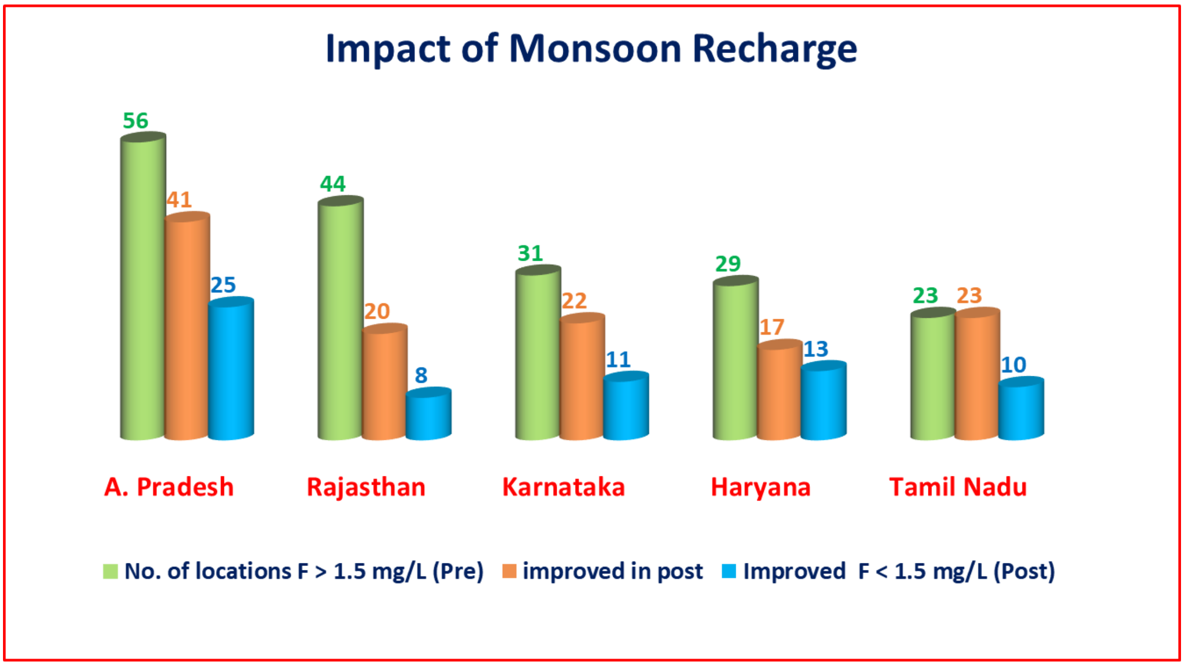


Figure 20: Impact of Monsoon recharge in five key states on fluoride concentration.

The monsoon recharge appears to have had a **dilution effect** on the fluoride concentrations in groundwater across all the states, as reflected by the significant number of samples showing improvement in fluoride levels after recharge.

Given that Andhra Pradesh had the highest number of pre-monsoon samples with fluoride concentrations above the permissible limit (56 samples), the improvement in 41 samples indicates a **substantial dilution effect** due to monsoon recharge. A significant proportion of these samples (25 out of 56) fell below the permissible limit post-monsoon, suggesting that monsoon recharge had a **pronounced positive impact** in reducing fluoride concentrations in many areas. Rajasthan, which also had a high pre-monsoon fluoride contamination rate (44 samples), saw an improvement in 20 samples. This indicates that although the dilution effect was less pronounced than in Andhra Pradesh, it was still significant. The fact that 8 samples came below the permissible limit after monsoon recharge is a **positive outcome**, indicating that recharge did reduce fluoride levels in certain areas. **Karnataka's** pre-monsoon fluoride contamination was relatively moderate (31 samples), and post-monsoon, 22 samples showed improvement, with 11 falling below the permissible limit. This suggests that monsoon recharge had a **favorable impact** on reducing fluoride concentrations. Haryana, with 29 samples exceeding the permissible limit pre-monsoon, also saw improvement in fluoride levels in 17 samples, with 13 of them falling below the permissible limit. This suggests that monsoon recharge had a **moderate but effective effect** in diluting fluoride concentrations in several parts of the state. **Tamil Nadu (23 samples improved)**: Despite having the lowest pre-monsoon fluoride contamination (23 samples), Tamil Nadu still saw improvements in all samples (23 out of 23), with 10 falling below the permissible limit post-monsoon. This indicates that **even in relatively lower fluoride areas**, monsoon recharge was effective in reducing fluoride concentrations.

4.3.3 Impact of Groundwater Over-Extraction on Fluoride Concentration

Excessive abstraction of groundwater, especially in regions that are already facing over-exploitation, may raise fluoride concentration in the groundwater. The water samples most affected by fluoride contamination are primarily concentrated in the southern and western states, which are known for over-extraction of groundwater.

This phenomenon is primarily observed in the states of **Haryana, Punjab, Rajasthan, Gujarat, Western Uttar Pradesh, Karnataka and Tamilnadu**, where a significant number of water samples exceed the permissible limit of **1.5 mg/L** for fluoride, often concentrated in areas categorized as **over-exploited**, **critical**, and **semi-critical (Fig. 21)**.

4.3.4 Mechanisms Driving Increased Fluoride in Over-Exploited Regions:

Several mechanisms can explain why excessive groundwater extraction exacerbates fluoride contamination in these areas:

- **Lowering of the Water Table**: Over-exploitation often results in the **lowering of the groundwater table**. In regions with **fluoride-rich geological formations** (such as rocks containing fluoride-bearing minerals like fluorite, mica, or apatite), lowering the water table can cause **increased release** of fluoride into the groundwater. As the water level drops, water interacts more with fluoride-rich layers, leading to higher concentrations of fluoride.
- **Increased Groundwater Flow Path Disturbance**: Over-extraction can disturb the natural flow of groundwater. This disturbance may lead to **mobilization of fluoride** from deeper layers or sediments that typically do not contribute to fluoride levels under normal conditions. In such situations, shallow wells and tubewells (commonly used for extraction) begin to access water that is naturally high in fluoride.
- **Reduced Recharge and Dilution**: Excessive abstraction reduces the volume of water available for recharge, limiting the natural process of **dilution** of contaminants like fluoride. This lack of recharge, combined with excessive withdrawal, makes it more difficult for the aquifers to maintain lower fluoride concentrations, thus exacerbating contamination.
- **Increased Concentration Due to Evapotranspiration**: In over-exploited areas, especially in semi-arid regions like Rajasthan and Gujarat, increased groundwater extraction and increased evaporation rates may increase concentration of contaminants like fluoride in the remaining groundwater. Without adequate replenishment or recharge, the fluoride concentration can rise as water evaporates.

It is evident from **Fig. 22** that high fluoride samples are clustered where the depth to water level is more than 20 meters or where fluoride-bearing rocks such as Basement Gneissic Complex, Gneiss, Shale, Charnockite, and Intrusive rocks are present in aquifer system.

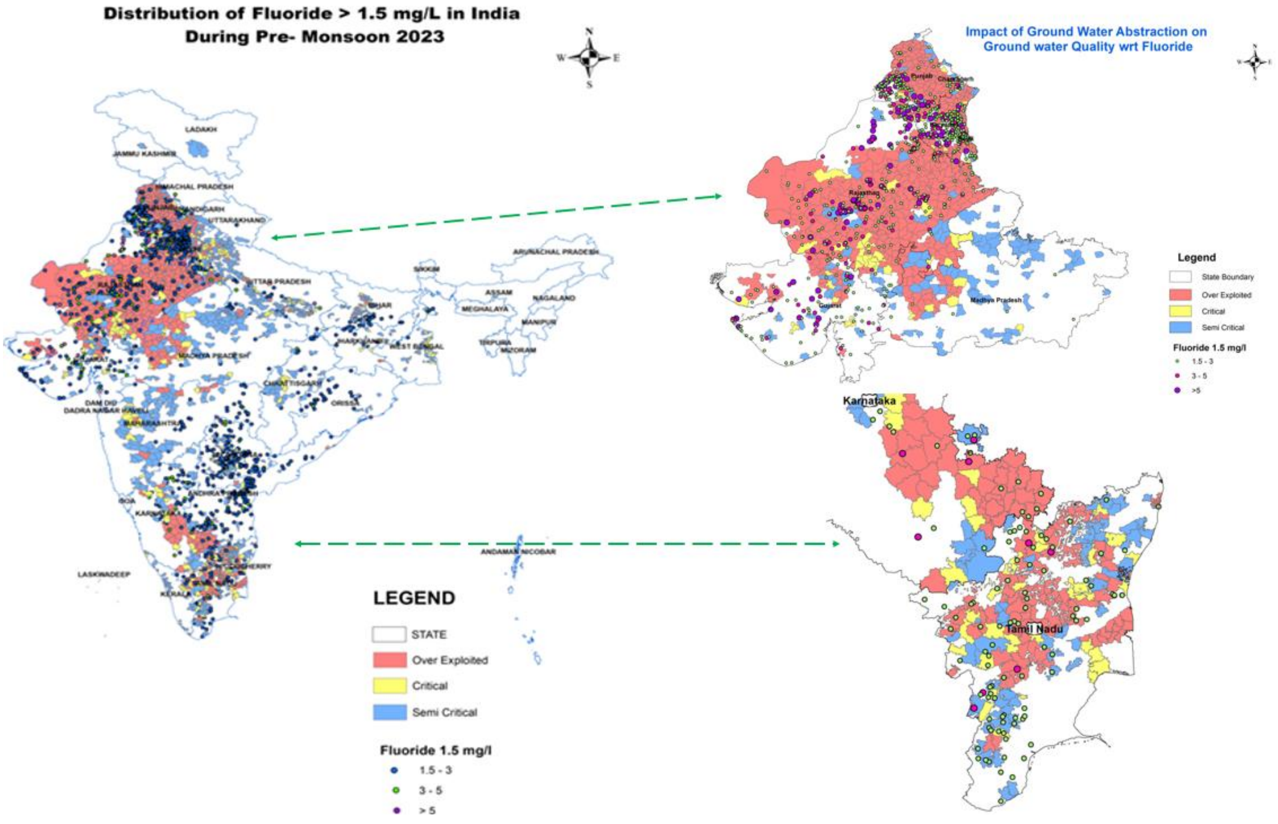


Figure 21: Over-exploited areas show a striking similarity with enriched F concentration.

Fluoride-bearing rocks (such as Basement Gneissic Complex, Gneiss, Shale, Charnockite, and Intrusive rocks) contain minerals that can release fluoride into the groundwater through weathering and dissolution. These rocks are often naturally rich in minerals like fluorite, apatite, and mica, which can leach fluoride into groundwater over time.

The increased **residence time** of groundwater in contact with these fluoride-bearing rocks allows more fluoride to dissolve into the water, causing concentrations to exceed the **permissible limit** (1.5 mg/L).

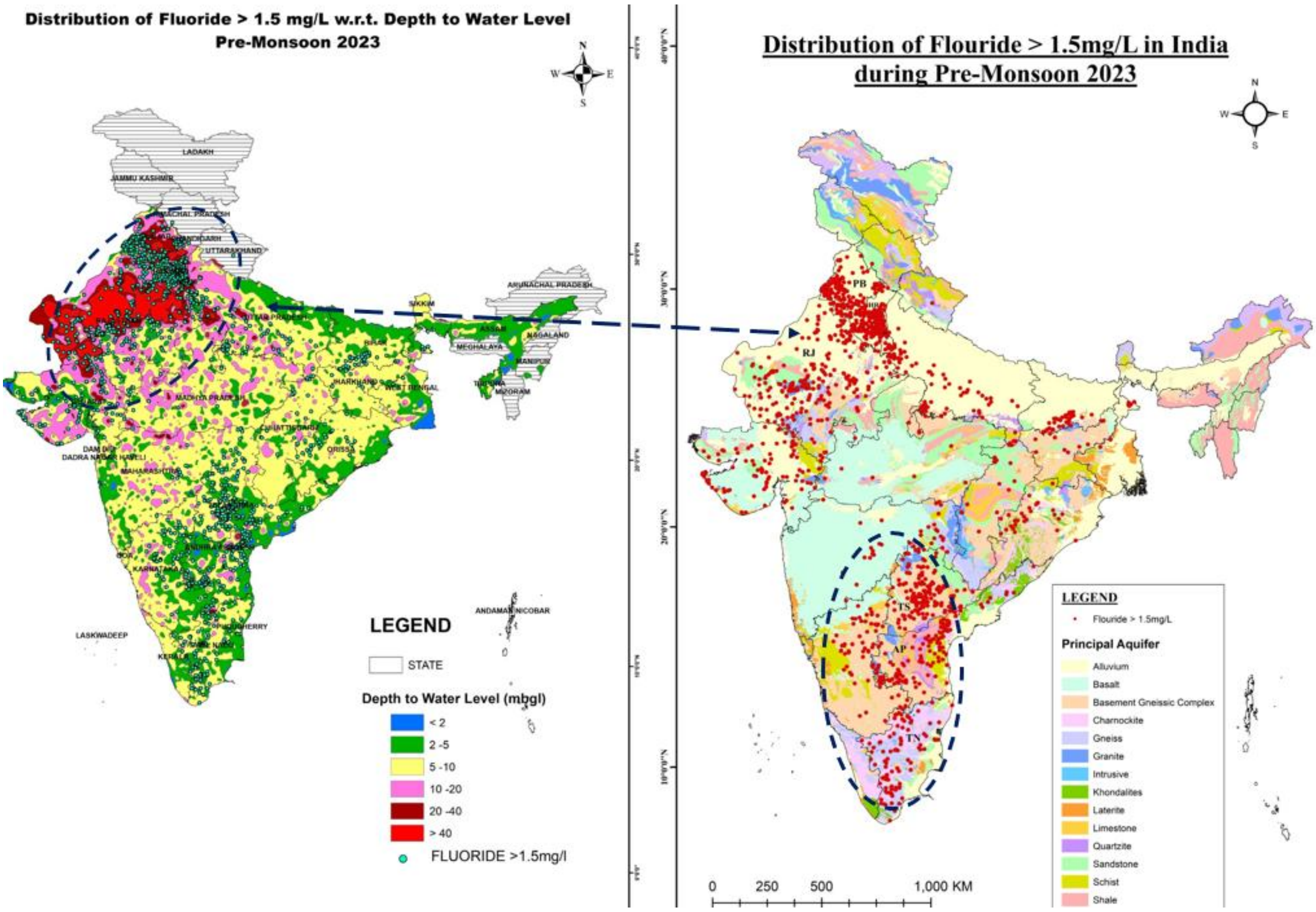


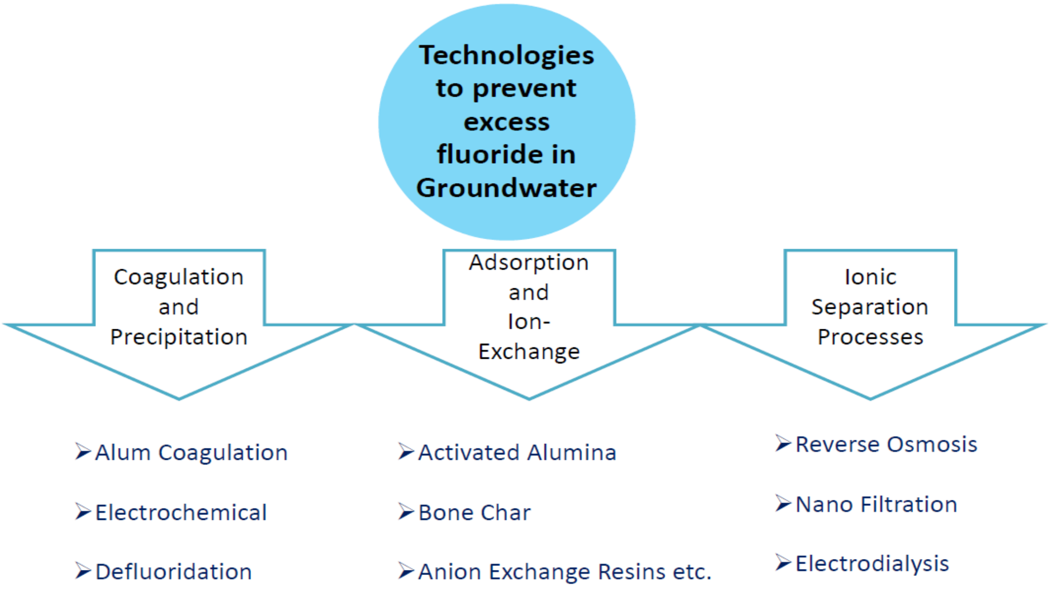
Figure 22: Map Showing High Fluoride Concentrations in Relation to Depth to Water Level and Principal aquifers.

In areas where due to over-extraction or seasonal variation **depth to water level exceeds 20 meters**, fluoride-contaminated layers may be accessed, leading to higher fluoride concentrations. In regions where the water table is deeper, the rate of evaporation may also increase. As water evaporates, it leaves behind fluoride ions in the remaining groundwater, concentrating the fluoride and raising its levels above the permissible limits.

Shallow aquifers often receive more recharge from surface water, which may dilute the fluoride concentrations. However, with lowering of water table, **recharge is limited**, and any fluoride present in the rocks is less likely to be diluted, leading to a higher concentration of fluoride in the groundwater.

4.3.5 Remedial Measures for Fluoride

The fluoride remedial measures broadly adopted are ex-situ techniques. They can be classified into three major categories.



(a) Adsorption and ion exchange

This technique functions on the adsorption of fluoride ions onto the surface of an active agent such as activated alumina, red mud, bone char, brick pieces column, mud pot and natural adsorbents where fluoride is removed by ion exchange or surface chemical reaction with the solid bed matrix.Amidst the commonly employed methods for fluoride removal, the adsorption approach provides a outstandingly effective and economical procedure for reducing fluoride levels from water within the permissible level of 1.5 mg/L. In adsorption process fluoride enriched water is passed through a contact bed of adsorbent used, the Fluoride gets adsorbed on adsorbent surface and easily gets removed by ion exchange or surface chemical reaction. After a period of operation, saturated adsorbents must be refilled or regenerated. Various adsorbents used for fluoride removal include Activated Alumina (AA), Bone char, Bauxite, Hematite, Magnesia, various rareearth materials, fly ash, limestone and clay, polymericresins, granular ceramics.

(b) Coagulation-precipitation

Precipitation methods are based on the addition of chemicals (coagulants and coagulant aids) and the subsequent precipitation of a sparingly soluble fluoride salt as insoluble. Fluoride removal is accomplished with separation of solids from liquid. Aluminium salts (eg. Alum), lime, Poly Aluminium Chloride, Poly Aluminium Hydroxy sulphate and Brushite are some of the frequently used materials in defluoridation by precipitation technique. The best example for this technique is the famous Nalgonda technique.

Nalgonda Technique

Nalgonda technique involves addition of Aluminium salts, lime and bleaching powder followed by rapid mixing, flocculation, sedimentation, filtration and disinfection. It is opined that this technique is preferable at all levels because of the low price and ease of handling, is highly versatile and can be used in various scales from household level to community scale water supply.

The Nalgonda technique can be used for raw water having fluoride concentration between 1.5 and 20 mg/L and the total dissolved solids should be <1500 mg/L, and total hardness < 600 mg/L. The alkalinity of the water to be treated must be sufficient to ensure complete hydrolysis of alum added to it and to retain a minimum residual alkalinity of 1 - 2 meq/L in the treated water to achieve a pH of 6.5 - 8.5 in treated water. Several researchers have attempted to improve the technique by increasing the removal efficiency of fluoride using Poly Aluminium Chloride (PAC) and Poly Aluminium Hydroxy Sulphate (PAHS).

(c) Ionic Separation Processes

Reverse osmosis, nanofiltration, dialysis and electro dialysis are physical methods that have been tested for defluoridation of water. Though they are effective in removing fluoride salts from water, owever, there are certain procedural disadvantages that limit their usage on a large scale.

4.3.6 Management Interventions

- High yielding wells with low fluoride concentrations should be identified. These high yielding wells containing low fluoride concentrations should be used to provide drinking water to communities with enriched fluoride wells.
- Wells with high fluoride concentration should be connected with wells with low fluoride concentration. This blending may lower fluoride concentration to desired limit.
- There should be construction of multi-village piped water supply schemes with conventional treatment, using surface water.
- It is recommended that appropriate drinking water projects should be constructed according to the economic conditions and geological conditions of study area.
- Reducing the concentration of fluoride in water and the duration of continuous exposure are necessary to control population health risk of dental and skeletal fluorosis.
- With no alternate source of potable water, the Water Treatment Plant may be used. Public Health Engineering Department, Government of Bihar has installed Water Treatment Plant to provide drining water to households in rural areas.
- In areas of high concentration of Fluiride, Public should be made aware about the adverse health effects of consumption of fluoride contaminated water.

- In endemic fluorosis areas, even if the water fluoride level is well controlled, health education and health promotion strategies are still necessary, and their importance must be highly valued.

- Drilling of exploratory wells in fluoride affected areas by individuals should be regulated and supervised by authorities.

4.4 Nitrate

Nitrate contamination in groundwater is a significant environmental and public health concern, particularly in agricultural regions where the use of nitrogen-based fertilizers and animal waste is prevalent. In India, approximately **19.8% of water samples** across the country exceed the permissible limit for nitrate concentration of **45 mg/L**, which is the threshold recommended by the World Health Organization (WHO) and Bureau Indian standards (IS 10500) for drinking water quality. The elevated nitrate levels in groundwater can lead to **methemoglobinemia (blue baby syndrome)** in infants. Adults can tolerate little higher concentrations. The specified limits are not to be exceeded in public water supply. If the limit is exceeded, water is considered to be unfit for human consumption.

Aqueous geochemical behavior of nitrogen is strongly influenced by vital importance of the element in plant and animal nutrition. The most common contaminant identified in ground water is dissolved nitrogen in the form of nitrate in sub surface waters. Since, the nitrogen content of soil is generally quite low the farmers have to look for external sources of nitrogen by using ammonium nitrate, calcium nitrate, urea, diammonium hydrogen phosphate etc.

Although nitrate is the main form in which nitrogen occurs in ground water, dissolved nitrogen also occurs in the form of ammonium (NH^{+4}), ammonia (NH_3), nitrate (NO_2), nitrogen (N_2), nitrous oxide (N_2O) and organic nitrogen, nitrogen which is incorporated in organic substance. Nitrate in ground water generally originates from nitrogen sources on the land surface in the soil zone or a shallow subsoil zone where nitrogen rich wastes are buried. In some situations, nitrate that enters the ground water system originates as nitrate in wastes or fertilizers applied to the land surface.

The occurrences of Nitrate in ground water beyond permissible limit (45 mg /L) have been shown on the map as a point source in **Fig 23** and also given in Annexure-IV. It has been observed that there is no significant trend in the no. of districts having Nitrate concentration more than 45 mg/L detected at one or more location in different states of India in various States during year 2017 to 2023 **(Fig. 24 & Table 14).** State-wise no. of water samples analysed, no. of locations having Nitrate > 45 mg/L and % of locations having Nitrate > 45 mg/L during pre-monsoon is presented in **Fig. 25 & Fig. 26**.

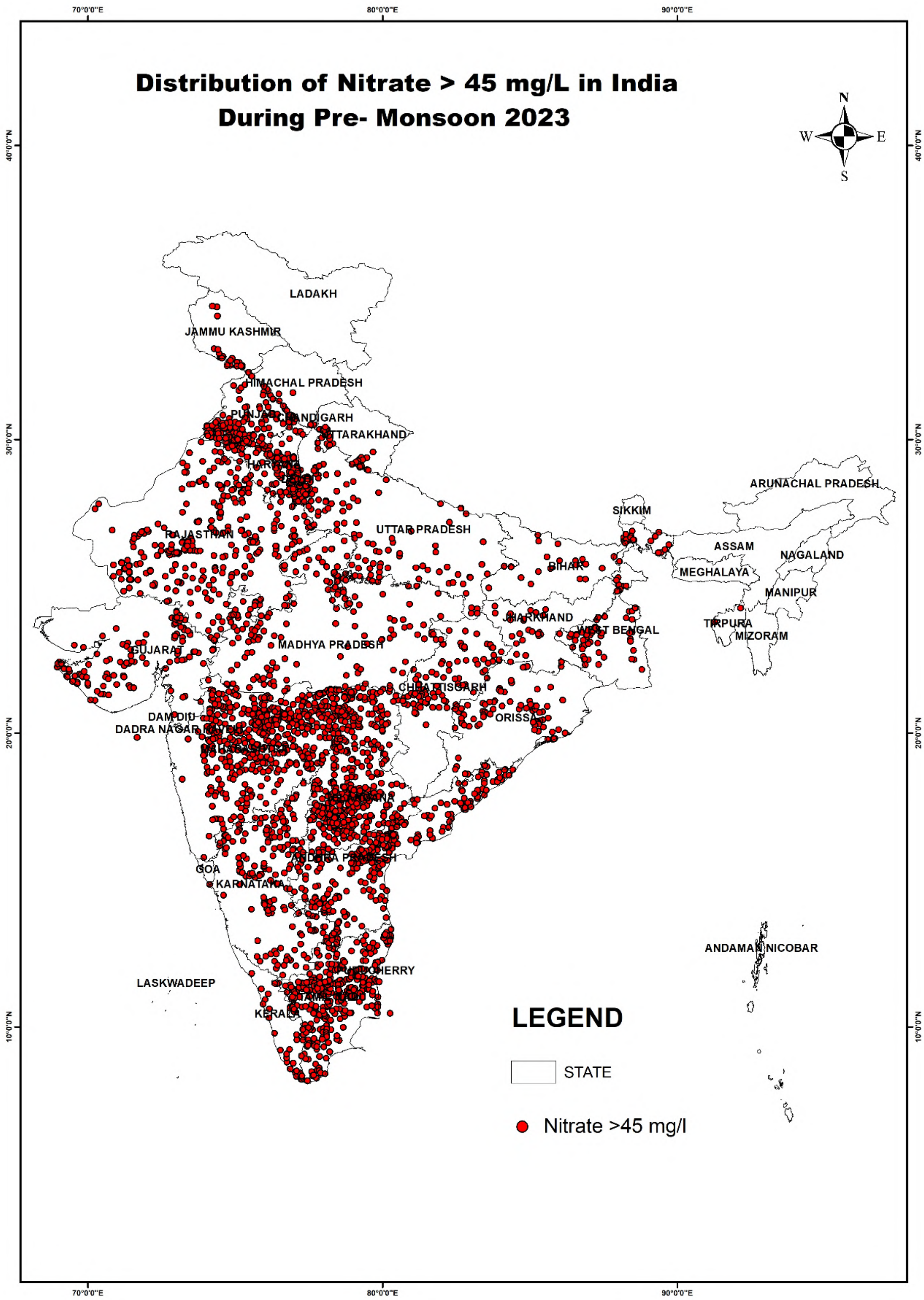


Figure 23: Locations having Nitrate concentration > 45 mg/L during Pre monsoon 2023.

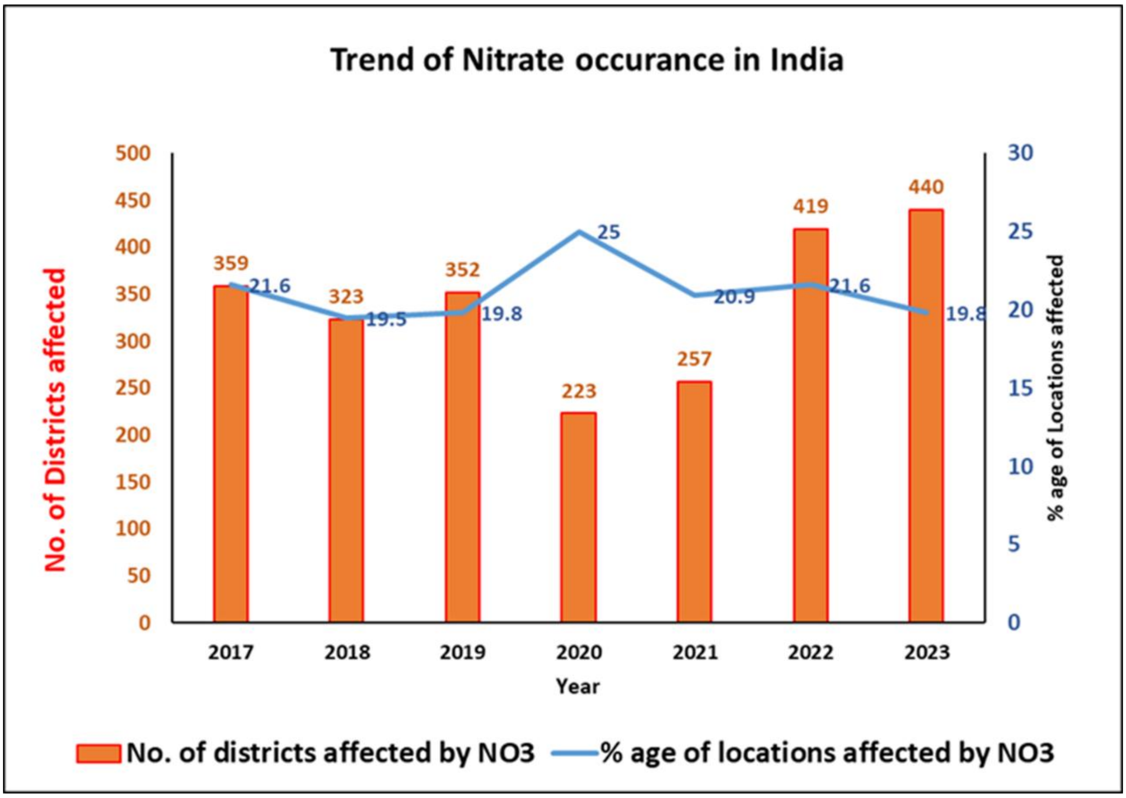


Figure 24: Trend in Nitrate concentratio in Pre-Monsoon Samples During 2017-2023.

Table 14: Percentage of wells Exceed Nitrate > 45 mg/L during the period of 2017-2023.

Year	Total Number of samples analysed	No. of districts affected by Nitrate	No. of locations affected by Nitrate	% of samples affected by Nitrate (NO_3 >45 mg/L)
2017	13028	359	2812	**21.6**
2018	13205	323	2569	**19.5**
2019	12503	352	2476	**19.8**
2020	6284	223	1574	**25.0**
2021	8427	257	1761	**20.9**
2022	15507	419	3348	**21.6**
2023	15259	440	3021	**19.8**

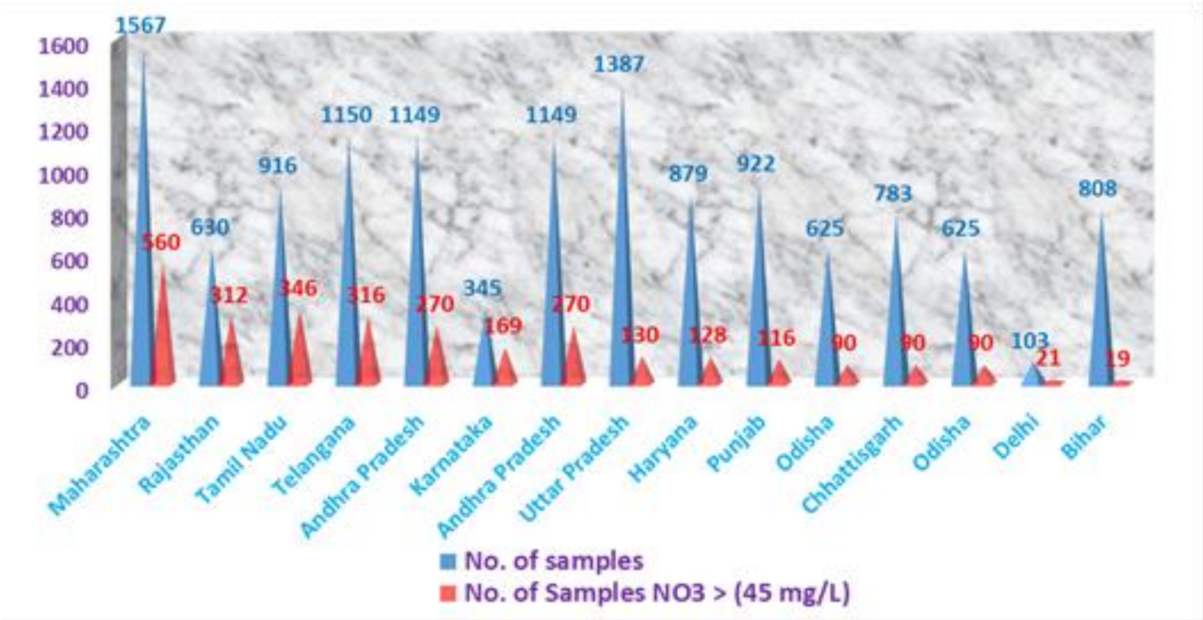


Figure 25: State-wise no. of water samples analysed and no. of locations having Nitrate > 45 mg/L during pre-monsoon,2023.

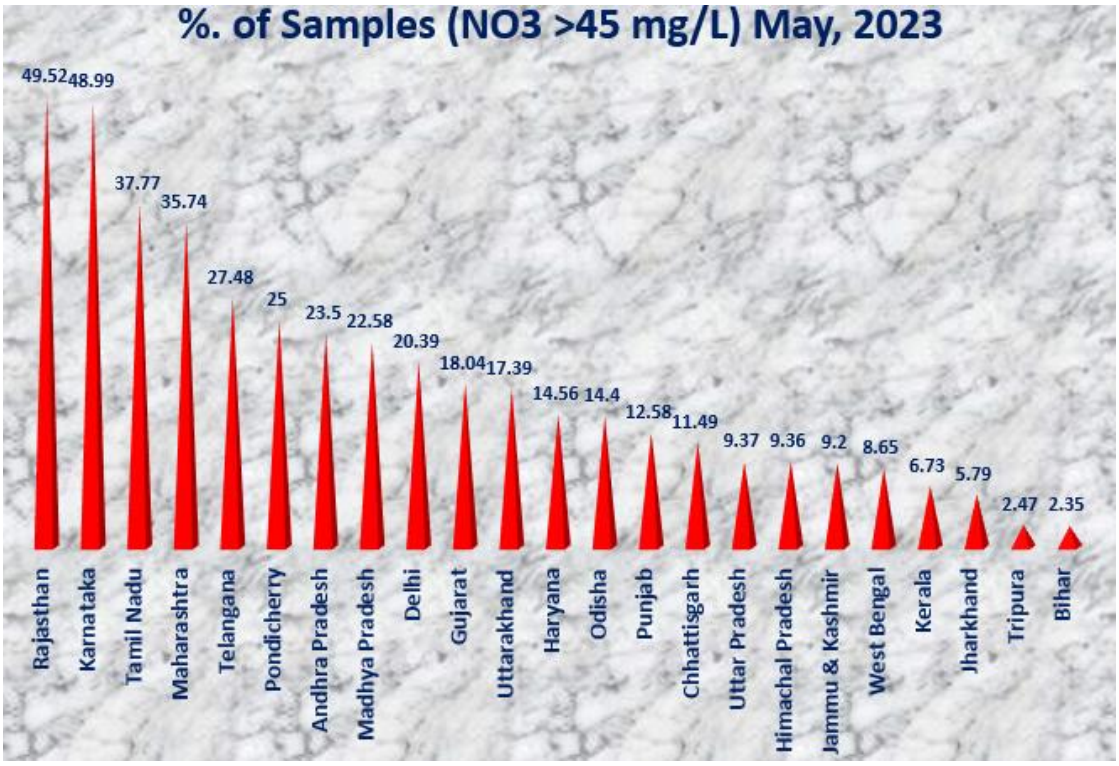


Figure 26: State-wise % of water samples having Nitrate > 45 mg/L during pre-monsoon,2023.

Table 15 : State-wise percentage of wells having Nitrate > 45 mg/L during Pre 2023.

State	No. of samples analysed, Pre 2023)	Min	Max	No. of Samples (NO_3 >45 mg/L)	%. of Samples (NO_3 >45 mg/L)
A & N Islands	113	0	42	0	0
Andhra Pradesh	1149	0	2296.36	270	23.5
Arunachal Pradesh	12	0.28	7.5	0	0
Assam	155	0	42.38	0	0
Bihar	808	0	119	19	2.35
Chandigarh UT	8	1.4	18	0	0
Chhattisgarh	783	0	187.52	90	11.49
Delhi	103	0	994	21	20.39
Goa	10	0	9	0	0
Gujarat	632	0	772	114	18.04
Haryana	879	0	780.75	128	14.56
Himachal Pradesh	171	0	155.56	16	9.36
Jammu & Kashmir	250	0	181.46	23	9.2
Jharkhand	397	0	121.24	23	5.79
Karnataka	345	0	1926	169	48.99
Kerala	342	0	152.7	23	6.73
Madhya Pradesh	589	0	347	133	22.58
Maharashtra	1567	0	633.42	560	35.74
Meghalaya	39	0	27.22	0	0
Mizoram	3	1.27	4.26	0	0
Nagaland	6	0	42.64	0	0
Odisha	625	0	350	90	14.4
Pondicherry	4	28	47	1	25
Punjab	922	0	950	116	12.58
Rajasthan	630	0	1180	312	49.52
Tamil Nadu	916	0	433	346	37.77
Telangana	1150	0	1988.58	316	27.48
Tripura	81	0	45.73	2	2.47
Uttar Pradesh	1387	0	730	130	9.37
Uttarakhand	207	0	701	36	17.39
West Bengal	959	0	161	83	8.65
Total	**15259**	**0**	**2296.36**	**3021**	**19.8**

4.4.1 Analysis of States/Districts with High Nitrate Values

A significant proportion of water samples across several states in India show nitrate concentrations exceeding the permissible limit of **45 mg/L** as per BIS, 10500 **(Fig. 25 & 26)**. The states of Rajasthan, Karnataka, and Tamil Nadu are the most severely affected by nitrate contamination in groundwater, with more than 40% of water samples exceeding the nitrate permissible limit. Maharashtra (35.74%), Telangana (27.48%), Andhra Pradesh (23.5%) and Madhya Pradesh (22.58%) also show notable levels of nitrate contamination, pointing towards growing concern in central and southern regions of India. Uttar Pradesh (9.37%), Kerala (6.73%), Jharkhand (5.79%), and Bihar (2.35%) have comparatively lower percentages of water samples exceeding the limit. In **Arunachal Pradesh, Asam, Goa, Meghalaya, Mizoram and Nagaland** all the water samples are well within the permissible limit as per BIS, 10500.

Year-wise Comparison of Districts exceeding Nitrate limit (2015–2023) has been presented in **Fig. 27**. In states like **Rajasthan, Madhya Pradesh and Gujarat** the number of districts with nitrate levels above the permissible limit has remained relatively stable or constant over the past several years (2015–2023). This suggests that the groundwater quality with respect to nitrate in these states are longstanding and persistent, with no major improvement or deterioration in the number of affected districts over the years.

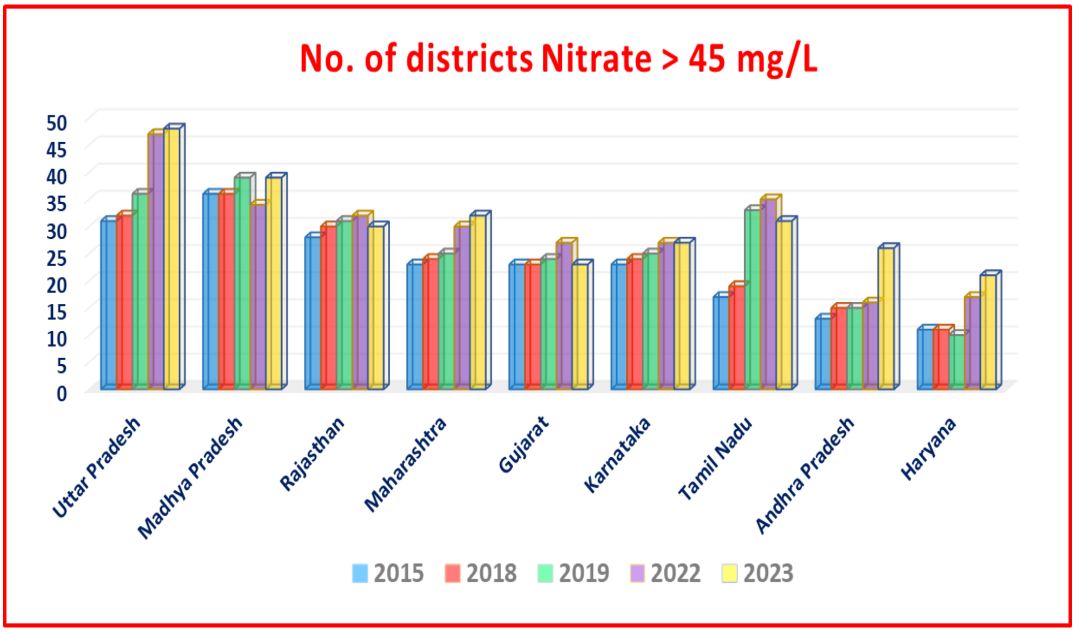


Figure 27: Year-wise Comparison of Districts with Nitrate exceeding permissible limit of >45 mg/L (2015–2023).

On the contrary, states like Uttar Pradesh, Tamil Nadu, Andhra Pradesh and Haryana have shown an increasing trend in the number of districts with nitrate concentrations exceeding the permissible limit from 2017 to 2023. On the basis of available data 15 districts in India have been identified as mostly affected with enriched nitrate concentration in groundwater **(Table 16).**

Among the top 15 districts with the highest nitrate concentrations exceeding the permissible limit of 45 mg/L, the distribution of affected districts is concentrated in a few states, with Maharashtra, Rajasthan, Telangana and Andhra Pradesh. Maharashtra has the highest number of affected districts. Telangana also features prominently in the top 15 list of nitrate-affected districts, with three affected districts.

Table 16: State-wise Distribution of Top 15 Affected Districts with Nitrate concentration exceeding permissible limitof 45 mg/L as per BIS,10500.

State	District	Total analysed samples	No. of samples $NO_3 > 45$ mg/L	% samples $NO_3 > 45$ mg/L
Rajasthan	Barmer	56	37	66.07
Maharashtra	Wardha	53	34	64.15
Telangana	Rangareddy	70	44	62.86
Tamil Nadu	Villupuram	48	27	56.25
Rajasthan	Jodhpur	73	41	56.16
Maharashtra	Buldhana	72	39	54.17
Maharashtra	Amravati	77	40	51.95
Andhra Pradesh	Palnadu	70	36	51.43
Maharashtra	Nanded	46	22	47.83
Maharashtra	Beed	63	30	47.62
Telangana	Adilabad	51	24	47.06
Telangana	Siddipet	51	24	47.06
Punjab	Bathinda	50	23	46
Maharashtra	Yavatmal	68	31	45.59
Maharashtra	Jalgaon	52	23	44.23

In Barmer and Jodhpur district of Rajasthan nitrate concentration have remained relatively stable. a rising trend in nitrate concentration has been observed **(Fig. 28).**

Figure 28: Yearly trend of nitrate more than permissible limit in some districts.

4.4.2 Impact of Monsoon Recharge on Nitrate Concentration

While monsoon rains can improve water quality, it can also lead to increased concentration of other parameters. One significance concern is rise in nitrate levels which may be primarily attributed to agricultural run off. Following monsoon season nitrate concentration often increase due to surface run off from agriculture fields. During heavy rain fertilizers and other contaminants can wash into aquifer elevating nitrate level. Pre - Post changes in nitrate concentration in Ground Water in various states have been presented in **Table 18**.

Pre-Monsoon vs. Post-Monsoon Nitrate Concentration

- In the pre-monsoon season, **30.77%** of the water samples exceeded the permissible nitrate contamination limit (45 mg/L).
- After monsoon recharge, **32.66%** of the water samples exceeded the permissible nitrate limit, indicating a slight increase in contamination levels post-monsoon **(Fig. 29).** However, it is important to note that the impact of monsoon recharge varied across different states.

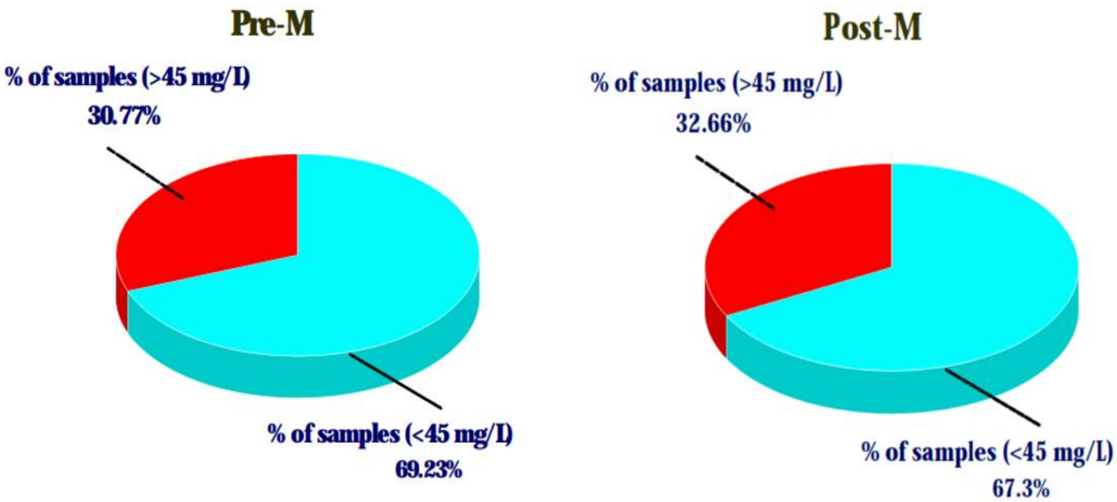


Figure 29: Trend of Nitrate occurrence in samples collected during Pre and Post Monsoon in the year 2023.

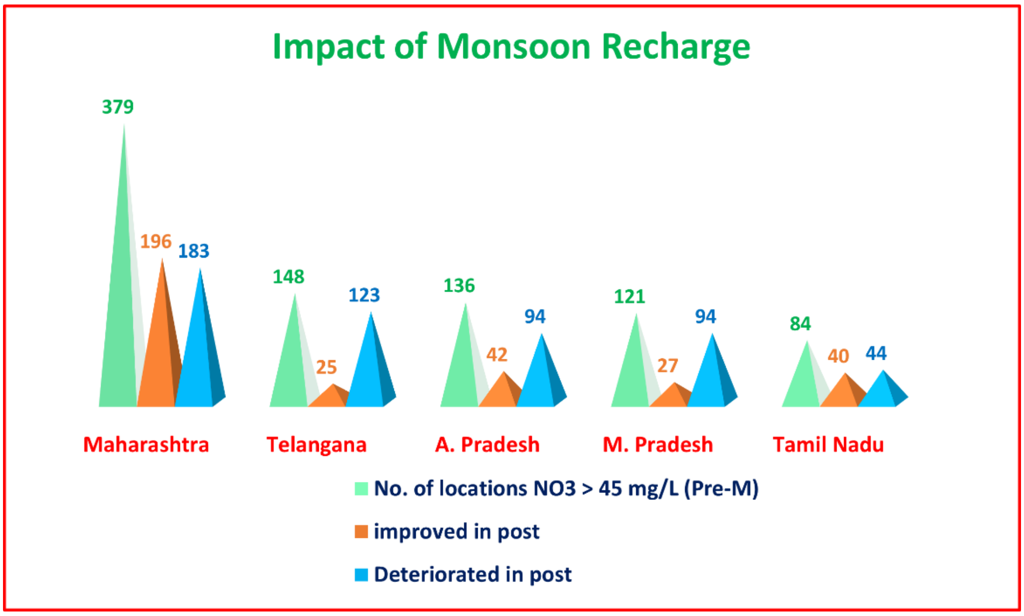


Figure 30: Impact of Monsoon recharge in five key states on nitrate concentration.

The following states are identified as key regions where nitrate contamination is a significant issue:

Maharashtra

- **Pre-Monsoon**: 379 water samples exceeded the permissible limit for nitrate contamination **(Fig. 30)**.
- **Post-Monsoon**:
  - **Improvement**: 196 locations showed a decrease in nitrate levels.
  - **Deterioration**: 183 locations saw an increase in nitrate contamination post-monsoon.

Telangana

- **Pre-Monsoon**: 148 water samples exceeded the permissible limit for nitrate contamination.
- **Post-Monsoon**:
  - **Improvement**: 25 locations showed a decrease in nitrate levels.
  - **Deterioration**: 123 locations showed an increase in nitrate contamination after monsoon recharge.

Andhra Pradesh

- **Pre-Monsoon**: 136 water samples exceeded the permissible limit for nitrate contamination.
- **Post-Monsoon**:
  - **Improvement**: 42 locations showed a decrease in nitrate levels.
  - **Deterioration**: 94 locations showed an increase in nitrate contamination post-monsoon.

Tamil Nadu

- **Pre-Monsoon**: 84 water samples exceeded the permissible limit for nitrate contamination.
- **Post-Monsoon**:
  - **Improvement**: 40 locations showed a decrease in nitrate levels.
  - **Deterioration**: 44 locations showed an increase in nitrate contamination after the

The monsoon precipitation appears to have a dual effect on groundwater quality. While it may help dilute nitrate concentrations in some areas, it also leads to a higher leaching of contaminants from the surface to the groundwater, worsening the situation in other locations. In states of intensive agriculture activities, particularly the cultivation of crops like wheat and rice, relies heavily on synthetic fertilizers. Improper irrigation practices also contribute to this rise. Excessive irrigation can cause nitrates from fertilizers to percolate more deeply into the soil, reaching the groundwater. As water is applied in large quantities, it carries dissolved nitrates down through the soil layers, contaminating aquifers. Additionally, livestock farming and improper management of animal waste can contribute to nitrate pollution. Animal waste, if not managed properly, releases nitrates into the soil, which can eventually infiltrate groundwater. Population growth and urbanization may have led to more wastewater and sewage contamination, which also contains high levels of nitrates. In some areas, poor sewage disposal practices and septic system leaks can add to the nitrate load in groundwater. Finally, reduced groundwater recharge due to urban development and climate change may exacerbate the problem, as less water is available to dilute nitrate concentrations in affected aquifers.

Decrease in locations with nitrate concentrations exceeding 45 mg/L at some locations indicate a positive trend in managing nitrate pollution. Several key factors likely contributed to this reduction. Increased awareness of the environmental impact of excessive fertilizer use has led to better management practices among farmers. Techniques such as soil testing and precision farming are being promoted to optimize nitrogen-based fertilizer application, helping to minimize overuse and reduce nitrate leaching into groundwater. Additionally, the adoption of organic farming practices, which typically involve fewer synthetic fertilizers, may have further contributed to lowering nitrate levels in certain regions.

The introduction of more efficient irrigation methods, such as drip irrigation and sprinkler systems, has played a significant role in this improvement. These techniques minimize water wastage and reduce the risk of nitrate leaching caused by over-irrigation, which can carry fertilizers into groundwater sources. Improved management of livestock waste and wastewater treatment has also likely reduced nitrate contamination. By ensuring proper disposal and treatment of animal waste and sewage, the entry of nitrates into groundwater can be significantly curtailed.

This suggests the need for better groundwater management practices, including monitoring of both groundwater quality and agricultural practices. To mitigate nitrate contamination, an integrated approach that combines improved irrigation management, wastewater treatment, and better agricultural practices is essential.

Table 17: Effect of monsoon recharge on Nitrate concentration at common locations during pre and post monsoon

State/ UT	No. of Pre/Post samples	Improved locations	Detriorated Locations	Sites with Nitrate> 45 mg/L			
				Pre		Post	
				No.	%	No.	%
A & N Islands	29	18	11	0	0	0	0
Andhra Pradesh	280	138	142	136	48.57	117	41.79
Arunachal Pradesh	12	9	3	0	0	0	0
Assam	123	44	79	0	0	1	0.81
Bihar	180	120	60	12	6.67	11	6.11
Chhattisgarh	157	73	84	20	12.74	17	10.83
Delhi	24	16	8	4	16.67	6	25
Himachal Pradesh	29	19	10	8	27.59	9	31.03
Haryana	77	46	31	20	25.97	25	32.47
J&K	30	22	8	16	53.33	20	66.67
Jharkhand	132	98	34	11	8.33	14	10.61
Karnataka	176	86	90	93	52.84	93	52.84
Madhya Pradesh	531	351	180	121	22.79	120	22.6
Maharashtra	746	432	314	379	50.8	441	59.12
Meghalaya	35	16	19	0	0	0	0
Mizoram	3	2	1	0	0	0	0
Nagaland	5	5	0	0	0	0	0
Odisha	116	74	42	14	12.07	28	24.14
Pondicherry	2	0	2	0	0	0	0
Punjab	39	19	20	22	56.41	18	46.15
Rajasthan	90	53	37	55	61.11	60	66.67
Tamil Nadu	198	122	76	84	42.42	99	50
Telangana	355	138	217	148	41.69	125	35.21
Tripura	74	18	56	2	2.7	0	0
Uttar Pradesh	341	230	111	57	16.72	59	17.3
West Bengal	186	111	75	18	9.68	31	16.67
Total	**3970**	**2260**	**1710**	**1220**	**30.73**	**1294**	**32.59**

Table 18: Districts in which anomalous values of Nitrate (NO_3 > 45 mg/L) in groundwater was detected at one or more location.

State/UT	No. of Districts	Name of Districts
Andhra Pradesh	26	Alluri sita rama raju, Anakapalli, Ananthapur, Annamayya, Bapatla, Chittoor, East Godavari, Eluru, Guntur, Kakinada, Konaseema, Krishna, Kurnool, Nandyal, Nellore, NTR, Palnadu, Parvathipuram Manyam, Prakasham, Sri Satya SaiSrikakulam, Tirupathi, Visakhapatnam, Vizianagaram, West Godavari, YSR Kadapa
Bihar	15	Arwal, Bhagalpur, Bhojpur, Buxar, Jehanabad, Kaimur, Katihar, Madhepura, Madhubani, Muzzafarpur, Patna, Saharsa, Samastipur, Sheohar, Sitamarhi

Chhattisgarh	20	Balod, Balodabazar, Bemetara, Bilaspur, Dhamtari, Durg, Gariyabandh, Janjgir Champa, Jashpur, Kanker, Kawardha, Korba, Koriya, Mahasamund, Mungeli, Raigarh, Raipur, Rajnandgaon, Surajpur, Surguja
Delhi	7	New Delhi, North, North West, South, South East, South West, West
Gujarat	23	Ahmedabad, Amreli, Anand, Arvalli, Bharuch, Bhavnagar, Chhota udepur, Dahod, Devbhoomi Dwarka, Jamnagar, Junagadh, Kachchh, Kheda, Morbi, Panchmahal, Porbandar, Rajkot, Sabarkantha, Surat, Surendranagar, Tapi, Vadodara, Valsad
Haryana	21	Ambala, Bhiwani, Faridabad, Fatehabad, Gurugram, Hisar, Jhajjar, Jind, Kaithal, Karnal, Kurukshetra, Mahendragarh, Mewat, Palwal, Panchkula, Panipat, Rewari, Rohtak, Sirsa, Sonipat, Yamunanagar
Himachal Pradesh	6	Bilaspur, Hamirpur, Mandi, Sirmour, Solan, Una
Jammu & Kashmir	6	Baramulla, Jammu, Kathua, Kupwara, Rajouri, Samba
Jharkhand	9	Chatra, Garhwa, Gumla, Hazaribagh, Latehar, Loherdaga, Palamu, Ranchi, Simdega
Karnataka	27	Bagalkot, Belgaum, Bellary, Bengaluru Rural, Bidar, Bijapur, Chamarajanagara, Chikballapur, Chitradurga, Davanagere, Dharwad, Gadag, Gulbarga, Hassan, Haveri, Kodagu, Kolar, Koppal, Mandya, Mysore, Raichur, ramanagara, shivmoga, Tumkur, Uttara Kannada, Vijayanagara, Yadgir
Kerala	10	Alappuzha, Idukki, Kannur, Kollam, Kozhikode, Malappuram, Palakkad, Pathanamthita, Thrissur, Trivandrum
Madhya Pradesh	39	Agar malwa, Anuppur, Balaghat, Barwani, Bhind, Burhanpur, Chhindwara, Damoh, Datia, Dewas, Dhar, Guna, Gwalior, Harda, Indore, Jabalpur, Jhabua, Katni, Khandwa, Khargone, Mandla, Mandsaur, Morena, Narsinghpur, Neemuch, Panna, Rajgarh, Ratlam, Rewa, Sagar, Satna, Shahdol, Shajapur, Sheopur, Shivpuri, Sidhi, Tikamgarh, Ujjain, Umaria
Maharashtra	32	Ahmednagar, Akola, Amravati, Aurangabad, Beed, Bhandara, Buldhana, Chandrapur, Dhule, Gadchiroli, Gondia, Hingoli, Jalgaon, Jalna, Kolhapur, Latur, Nagpur, Nanded, Nandurbar, Nashik, Osmanabad, Parbhani, Pune, Raigad, Sangli, Satara, Sindudurg, Solapur, Thane, Wardha, washim, Yavatmal
Odisha	15	Anugul, Balangir, Bargarh, Cuttack, Dhenkanal, Kendujhar, Khordha, Koraput, Mayurbhanj, Nayagarh, Nuapada, Puri, Sambalpur, Sonapur, Sundargarh
Pondicherry	1	Pondicherry
Punjab	20	Amritsar, Barnala, Bathinda, Faridkot, Fazilka, Ferozepur, Gurdaspur, Hoshiarpur, Jalandhar, Ludhiana, Mansa, Moga, Muktsar, Nawanshahr, Pathankot, Patiala, Rupnagar, Sangrur, SAS Nagar, Tarn Taran
Rajasthan	30	Ajmer, alwar, banswara, baran, barmer, bharatpur, bhilwara, bikaner, bundi, chittaurgarh, churu, dausa, ganganagar, hanumangarh, jaipur, jaisalmer, jalore, jhalawar, jhunjhunu, jodhpur, karauli, nagaur, pali, pratapgarh, rajsamand, sawai madhopur, sikar, sirohi, tonk, Udaipur
Tamil Nadu	31	Ariyalur, Chennai, Coimbatore, Cuddalore, Dharmapuri, Dindigul, Erode, Kancheepuram, Kanyakumari, Karur, Krishnagiri, Madurai, Nagapattinam, Namakkal, Nilgiris, Perambalur, Pudukkottai, Ramanathapuram, Salem, Sivaganga, Thanjavur,

		Theni, Thiruvannamalai, Tirunelveli, Tiruvallur, Tiruvarur, Trichy, Tuticorin, Vellore, Villupuram, Virudhunagar
Telangana	32	Adilabad, B. Kothagudem, Hanamkonda, J. Bhupalapally, Jagtial, Jangaon, Jogulamba, Kamareddy, Karimnagar, KB Asifabad, Khammam, Mahabubabad, Mahabubnagar, Mancherial, Medak, Medchal Malkanjgiri, Mulugu, Nagarkurnool, Nalgonda, Narayanpet, Nirmal, Nizamabad, Pedapalle, R. SIRCILLA, Rangareddy, Sangareddy, Siddipet, Suryapet, Vikarabad, Wanaparthy, Warangal, Yadadri Bhuvanagiri
Tripura	2	North Tripura, West Tripura
Uttar Pradesh	48	Agra, Aligarh, Allahabad/ Prayagraj, Amethi, Amroha, Auraiya, Baghpat, Balrampur, banda, Budaun, Bulandshahar, Chitrakoot, etah, Etawah, Fatehpur, firozabad, G.B. Nagar, ghaziabad, Ghazipur, Gorakhpur, Hamirpur, Hapur, Hathras, Jalaun, Jaunpur, Jhansi, Kanpur Dehat, Kanpur Nagar, kasganj, Kaushambi, Lalitpur, Lucknow, mahoba, mainpuri, Mathura, Meerut, Mirzapur, Moradabad, Pilibhit, Rampur, Sambhal, Sant Ravidas Nagar, Shahjahanpur, Shrawasti, Siddharth Nagar, Sonbhadra, Unnao, Varanasi
Uttarakhand	5	Almora, Dehradun, Haridwar, Nainital, Udham Singh Nagar
West Bengal	18	Alipurduar, Bankura, Birbhum, Cooch Behar, Dakshin Dinajpur, Darjeeling, Hooghly, Jalpaiguri, Jhargram, Malda, Murshidabad, Nadia, North 24 Parganas, Paschim Bardhaman, Paschim Medinipur, Purulia, South 24 Parganas, Uttar Dinajpur

4.4.3 Remedial Measures for Nitrate

For removal of nitrate both non-treatment techniques like blending and treatment processes such as ion-exchange, reverse osmosis, biological denitrification and chemical reduction are useful. The most important thing is that neither of these methods is completely effective in removing all the nitrogen from the water.

a) Methods involving no treatment: In order to use any of these options the nitrate problem must be local-scale. Common methods are –

- Raw water source substitution
- Blending with low nitrate waters

This greatly reduces expenses and helps to provide safer drinking water to larger numbers of people.

b) Methods involving Treatment:

They are as follows

- Adsorption/Ion Exchange
- Reverse Osmosis
- Electrodialysis
- Bio-chemical Denitrification **(**By using denitrifying bacteria and microbes)
- Catalytic Reduction/Denitrification (using hydrogen gas)

The mechanism of nitrate pollution in subsurface porous unconfined/confined aquifer is governed by complex biogeochemical processes. Apart from recharge conditions, groundwater chemistry may be impacted by the mineral kinetics of water-rock interactions. Consequently, suitable nitrate removal technologies should be selected. Nitrate is a very soluble ion with limited potential for co-precipitation or adsorption. This makes it difficult such as chemical coagulation, lime softening and filtration which are commonly used for removing most of the chemical pollutants such as fluoride, arsenic and heavy metals. According to King et al., 2012 nitrate treatment technologies can be classified in two categories in two categories, i.e., nitrate reduction and nitrate removal options. Nitrate removal technologies involve physical processes that does not necessarily involve any alteration of the chemical state of nitrate ions. Bio-chemical reduction options aim to reduce nitrate ions to other states of nitrogen, e.g., ammonia, or a more innocuous form as nitrogen gas. In-situ bioremediation is also effectively used in used in nitrate treatment of contaminated groundwater. Reverse Osmosis, catalytic reduction and blending are effective methods for nitrate removal from groundwater. For nitrate removal, operating trans-membrane pressure of RO unit generally ranges from 20 to 100 bar.

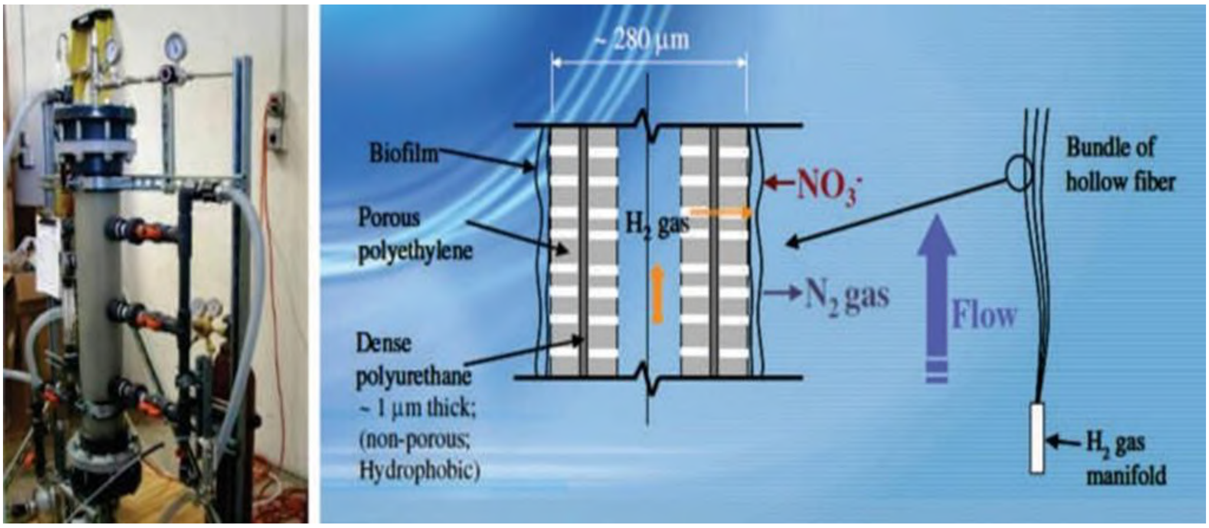


Figure 31: Advanced Nitrate Reduction Hollow Fiber Membrane Reactor (Source: Hand Book for Drinking Water Treatment, JJM, Ministry of Jal Shakti, Gov. of India)

4.5 Chloride

The Cl^- in groundwater mainly originates from natural (chloride-rich minerals) or anthropogenic diffused sources, e.g., domestic effluents, fertilizers and septic tanks. Chloride is present in all-natural waters, mostly at low concentrations. It is highly soluble in water and moves freely with water through soil and rock. In ground water the chloride content is mostly below 250 mg/L except in cases where inland salinity is prevalent and in coastal areas. BIS (Bureau of Indian Standard) have recommended a desirable limit of 250 mg /L of chloride in drinking water; this concentration limit can be extended to 1000 mg/L of chloride in case no alternative source of water with desirable concentration is available. However, ground water having concentration of chloride more than 1000 mg /L are not suitable for drinking purposes. The State-wise distribution of Chloride in various range during Pre monsoon 2023 is given in Table 20. In **Fig. 32**, the concentration of chloride (in mg/L) in ground water from observation wells have been used to show distribution patterns of chloride in different ranges of suitability. It is apparent from the map that majority of the samples having chloride values less than 250 mg/L are found mostly in the states of J & K, Himachal Pradesh, Uttarakhand, Uttar Pradesh, Bihar, Jharkhand, Chhattisgarh, Orissa, M.P, Kerala, Maharashtra, West Bengal, North - Punjab, Sikkim & North-Eastern states.

Rajasthan, **Delhi**, **Haryana**, and **Gujarat** have been identified as having significant levels of chloride contamination, with chloride concentrations exceeding the permissible limit of **1000 mg/L** set by the Bureau of Indian Standards (BIS, 10500).

In areas of inland salinity such as Rajasthan and Gujarat, upon evaporation hydrochemical facies result in Na-Cl type brine. In present-day condition, it is apparent that over geologic period of time when the aquifers got subjected to many annual wetting and drying cycles, the highly soluble Na-Cl salts get enriched. The encrusted salt in alluviam bed re-dissolves in aquifer during precipitation. It is emanant from the map that the elevated level of chloride has also noticed in the coastal areas of Andhra Pradesh, Gujarat, Tamilnadu Thiruvallur and Ramanathapuram due to coastal salinity and isolated pockts in the the districts of dharmapuri, Karur, Namakkal, Perambalur, Salem, Vellore, Villupuram and Virudhunagar districts are due to industrial activities. State-wise percentage of wells having chloride >1000 mg/L is shown as a bar diagram in **Fig.33** and detail of locations is given in Annexure-II.

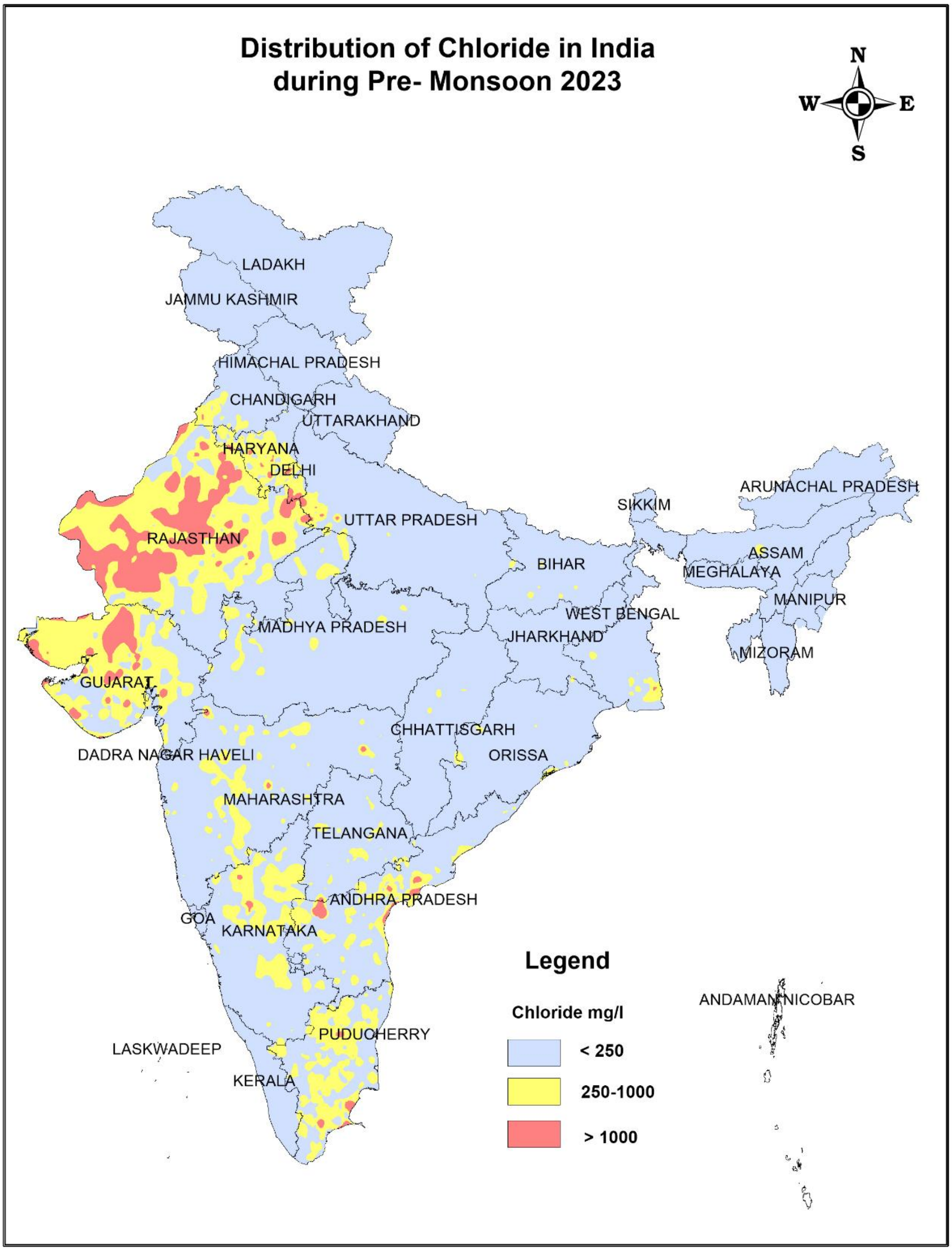


Figure 32: Spatial Distribution of Chloride during Pre-Monsoon 2023.

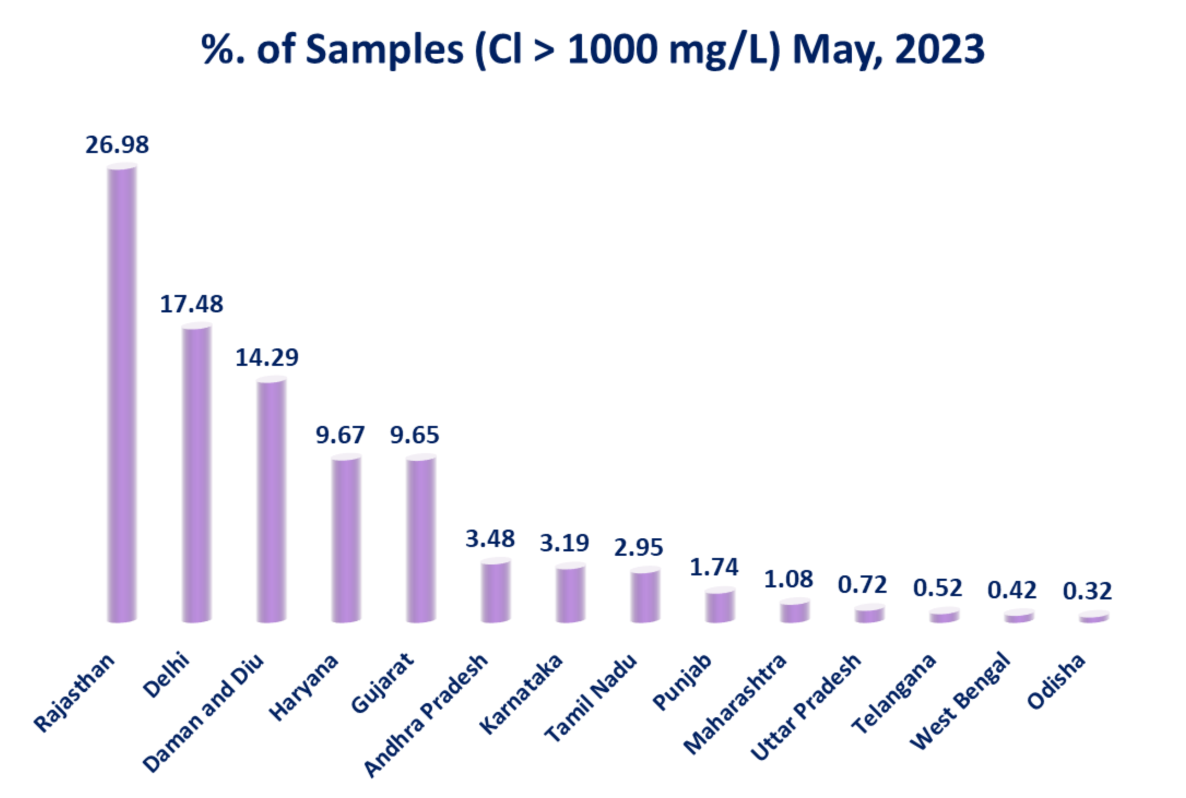


Figure 33: State-wise % of water samples with Chloride > 1000 mg/L during pre-monsoon,2023.

* In *Arunachal Pradesh, Asam, Biha, Goa, Dadra and Nagar Haveli, Himachal Pradesh, Pondicherry, Jammu and Kashmir, Jharkhand, Madhya Pradesh, Meghalaya, Mizoram, Pondicherry, Tripura, Uttarakhand and Nagaland* 100% watersamples are well within the permissible limit as per BIS, 10500.

4.5.1 Understanding the Impact of Monsoon Recharge on Chloride concentration

The pie chart **(Fig. 34)** depicts the distribution of Chloride in various ranges during both Pre monsoon and Post monsoon 2023.

- In the **pre-monsoon season**, **3.07%** of the total water samples exceeded the permissible chloride limit of 1000 mg/L.
- In the **post-monsoon season**, the percentage of water samples exceeding the permissible chloride limit increased to **4.17%**.

This increase in the percentage of samples exceeding the permissible chloride limit during the post-monsoon season indicates that the monsoon recharge, rather than diluting the contamination, may be contributing to the higher chloride concentrations in some regions. In areas where shallow groundwater is in direct contact with saline surface water the monsoon recharge may facilitate the movement of chloride-rich water into the shallow aquifer, thereby raising chloride levels.

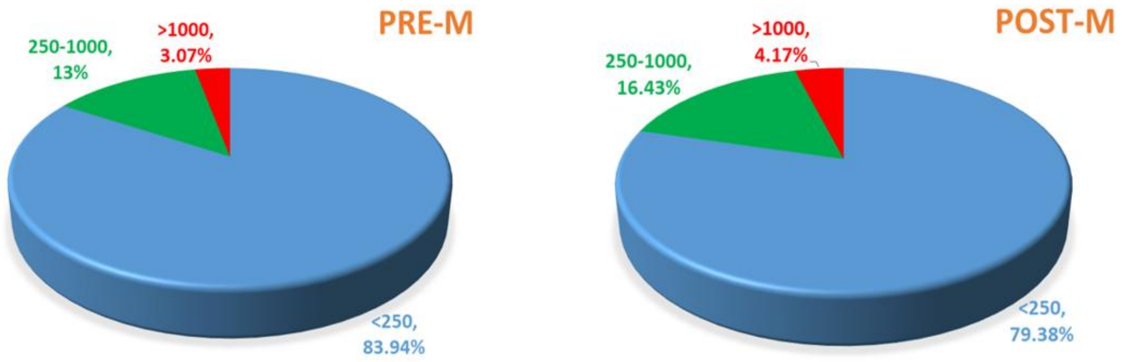


Figure 34: Percentage groundwater samples in various Cl range (Pre & Post, 2023).

Table 19: State-wise distribution of Chloride in various range during Pre monsoon 2023

State/UT	No. of samples analysed	Samples with Chloride concentration					
		< 250 mg/L		250-1000 mg/L		>1000 mg/L	
		No.	%	No.	%	No.	%
Andaman & Nicobar Islands	113	112	99.12	1	0.88	0	0
Andhra Pradesh	1149	887	77.2	222	19.32	40	3.48
Arunachal Pradesh	12	12	100	0	0	0	0
Assam	155	154	99.35	1	0.65	0	0
Bihar	808	770	95.3	38	4.7	0	0
Chandigarh UT	8	8	100	0	0	0	0
Chhattisgarh	783	767	97.96	16	2.04	0	0
Dadra And Nagar Haveli	10	10	100	0	0	0	0
Daman and Diu	7	2	28.57	4	57.14	1	14.29
Delhi	103	52	50.49	33	32.04	18	17.48
Goa	10	10	100	0	0	0	0
Gujarat	632	379	59.97	192	30.38	61	9.65
Haryana	879	562	63.94	232	26.39	85	9.67
Himachal Pradesh	171	170	99.42	1	0.58	0	0
Jammu & Kashmir	250	249	99.6	1	0.4	0	0
Jharkhand	397	388	97.73	9	2.27	0	0
Karnataka	345	244	70.72	90	26.09	11	3.19
Kerala	342	341	99.71	1	0.29	0	0
Madhya Pradesh	589	545	92.53	44	7.47	0	0
Maharashtra	1567	1409	89.92	141	9	17	1.08
Meghalaya	39	39	100	0	0	0	0
Mizoram	3	3	100	0	0	0	0
Nagaland	6	6	100	0	0	0	0
Odisha	625	576	92.16	47	7.52	2	0.32
Pondicherry	4	4	100	0	0	0	0
Punjab	922	815	88.39	91	9.87	16	1.74
Rajasthan	630	210	33.33	250	39.68	170	26.98
Tamil Nadu	916	577	62.99	312	34.06	27	2.95
Telangana	1150	1007	87.57	137	11.91	6	0.52
Tripura	81	81	100	0	0	0	0
Uttar Pradesh	1387	1322	95.31	55	3.97	10	0.72
Uttarakhand	207	206	99.52	1	0.48	0	0
West Bengal	959	891	92.91	64	6.67	4	0.42
Total	**15259**	**12808**	**83.94**	**1983**	**13**	**468**	**3.07**

4.5.2 Techniques available for Removal of Salinity

Traditionally, distillation has been the method used for desalting water for human consumption or other use. Membrane methods have emerged through the last 50 years and now predominate among the desalination practices. The following describes each of the various methods used for water desalination treatment.

1. Distillation Methods

There are several variations in distillation technology used in desalination. They are all based on the vapourization of liquid water when brought to its boiling point. The nearly pure water vapour produced is condensed and collected for use, while dissolved salts remain behind in the remaining liquid feed water. Some of the methods by which distillation is practiced are as follows:

- Multi-stage flash;
- Multiple effect;
- Vapour compression;
- Membrane distillation; and
- Solar humidification.

2. Membrane Technologies

Membrane processes involve passing of impaired feed water through a semi-permeable material which can filter out unwanted dissolved or undissolved constituents, depending on the size and treatment of the openings. Membrane technologies identified include:

- Reverse Osmosis;
- Microfiltration/Ultrafiltration/Nanofiltration;
- Electrodialysis Reversal; and
- Forward Osmosis.

3. Hybrid Technology:

A method of reducing overall costs of desalination can be the use of hybrid systems using both RO and distillation processes. Such a system could provide a more suitable match between power and water development needs.

4.6 Iron

Iron is a common constituent in soil and ground water. It is present in water either as soluble ferrous iron or the insoluble ferric iron. Water containing ferrous iron is clear and colorless because the iron is completely dissolved. When exposed to air, the water turns cloudy due to oxidation of ferrous iron into reddish brown ferric oxide. The concentration of iron in natural water is controlled by both physico-chemical and microbiological factors. It is contributed to groundwater mainly from weathering of ferruginous minerals of igneous rocks such as hematite, magnetite and sulphide ores of sedimentary and metamorphic rocks. The permissible Iron concentration in ground water is 1.0 mg/L as per the BIS Standard for drinking water. The occurrences of iron in ground water beyond permissible limit (> 1.0 mg /litre) have been shown on the maps as point sources **(Fig.35)**. It is based on the chemical analysis of water samples mostly collected from the groundwater observation wells/ springs/ hand pumps. The details of the sampling sources are given in Annexure-V. The iron point value map indicates Northern and Central India having more iron content in groundwater compare to Western Indian part. The most iron affected States are Bihar, Chhattisgarh, Jharkhand, Odisha, Uttar Pradesh and West Bengal. The summary list of districts in which iron in ground water is found to exceed the permissible limits for drinking water in localized areas is shown in Table 20.

4.6.1 Remedial Measures for Iron

a) **Oxidation and filtration:** Before iron can be filtered, it needs to be oxidized to a state in which they can form insoluble complexes. Ferrous iron (Fe^{2+}) is oxidized to ferric iron (Fe^{3+}), which readily forms the insoluble iron hydroxide complex $Fe(OH)_3$. Manganese (Mn^{2+}) is oxidized to (Mn^{4+}), which forms insoluble (MnO_2). The common chemical oxidants in water treatment are chlorine, chlorine dioxide, potassium permanganate and ozone. The dose of potassium permanganate, however, must be carefully controlled. Too little permanganate will not oxidize all the iron and manganese, and too much will allow permanganate to enter the distribution system and cause a pink color. Ozone may be used for iron and manganese oxidation. Ozone may not be effective for oxidation in the presence of humic or fulvic materials. If not dosed carefully, ozone can oxidize reduced manganese to permanganate and result in pink water formation as well. Manganese dioxide particles, also formed by oxidation of reduced manganese, must be carefully coagulated to ensure their removal.

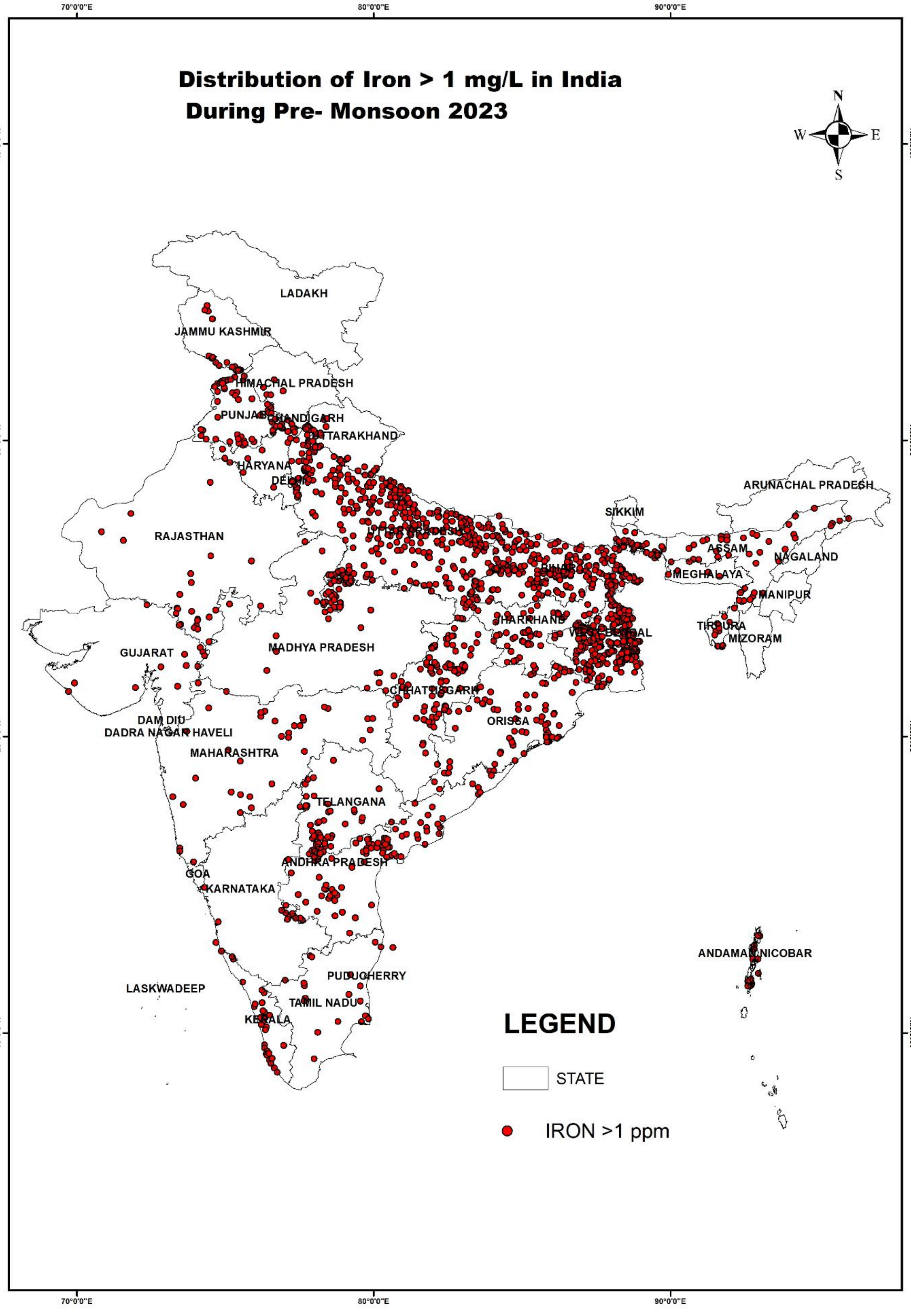


Figure 35: Map showing areas of Iron contaminated (> 1.0mg/L) groundwater in India.

Table 20: Districts in which anomalous values of Iron (Fe > 1.0 mg/L) in Groundwater was detected at one or more location in different states of India.

State/UT	No. of Districts	Name of Districts
Andhra Pradesh*	12	Ananthapur, Chittoor, East Godavari, Guntur, Kadapa, Krishna, Kurnool, Nellore, Prakasam, Srikakulam, Vizianagaram, West Godavari
Arunachal Pradesh	2	Changlang, Tirap
Assam	17	Baksa, Bongaigaon, Cachar, Dhemaji, East Karbi Anglong, Goalpara, Golaghat, Hailakandi, Jorhat, Kamrup, Karimganj, Lakhimpur, Nagaon, Sonitpur, Tinsukia, Udalguri, West Karbi Anglong
Bihar*	33	Araria, Banka, Begusarai, Bhabua, Bhagalpur, Bhojpur, Buxar, E. Champaran, Gaya, Gopalganj, Jamui, Katihar (Purnea), Khagaria, Kishanganj, Lakhisarai, Madhepura, Madhubani, Munger, Muzaffarpur, Nalanda, Nawada, Patna, Rohtas, Saharsa, Samastipur, Saran, Seikhpura, Sheohar, Sitamarhi, Siwan, Supaul, Vaishali, W. Champaran
Chattisgarh*	18	Balodabazar, Balrampur, Bastar, Bilaspur, Dhamtari, Durg, Gariyabandh, Janjgir-Champa, Kawardha, Kondagaon, Korba, Koriya, Mahasamund, Mungeli, Raipur, Rajnandgaon, Surajpur, Surguja
Delhi	3	East, Nazulland, South East
Gujarat	10	Anand, Banaskantha, Bharuch, Bhavnagar, Chhota Udepur, Dahod, Jamnagar, Panchmahal, Porbandar, Rajkot
Haryana	11	Ambala, Bhiwani, Faridabad, Hisar, Kaithal, Karnal, Palwal, Panchkula, Rewari, Sirsa, Yamunanagar
Himachal Pradesh*	5	Hamirpur, Kangra, Mandi, Sirmour, Una
Jammu & Kashmir	5	Baramulla, Jammu, Kathua, Kupwara, Samba
Jharkhand*	22	Bokaro, Chatra, Deoghar, Dhanbad, Dumka, E. Singhbhum, Giridih, Godda, Gumla, Hazaribagh, Jamtara, Khunti, Koderma, Latehar, Lohardaga, Pakur, Palamu, Ramgarh, Ranchi, Sahibganj, Simdega, W Singhbhum
Karnataka	3	Dakshina Kannada, Udupi, Uttara Kannada
Kerala*	10	Alappuzha, Ernakulam, Idukki, Kasarakode, Kollam, Kottayam, Kozhikode, Malappuram, Thrissur, Trivandrum
Madhya Pradesh	11	Ashok Nagar, Balaghat, Damoh, Gwalior, Khandwa, Neemuch, Panna, Sagar, Sehore, Shajapur, Tikamgarh
Maharashtra*	16	Ahmednagar, Beed, Buldhana, Chandrapur, Dhule, Gadchiroli, Latur, Nanded, Nandurbar, Nasik, Pune, Ratnagiri, Sindudurg, Solapur, Wardha, Wasim
Meghalaya	5	East Khasi Hills, North Garo Hills, South West Garo Hill, West Garo Hill, West Khasi Hills
Odisha	20	Anugul, Balangir, Baleshwar, Bargarh, Cuttack, Dhenkanal, Gajapati, Ganjam, Jajapur, Kendrapara, Kendujhar, Khordha, Koraput, Malkangiri, Mayurbhanj, Nayagarh, Nuapada, Puri, Sambalpur, Sonapur
Punjab	18	Amritsar, Bathinda, Faridkot, Fatehgarh Sahib, Fazilka, Gurdaspur, Hoshiarpur, Kapurthala, Ludhiana, Mansa, Muktsar, Nawanshahr, Pathankot, Patiala, Rupnagar, Sangrur, Sas Nagar, Tarn Taran
Rajasthan*	11	Ajmer, Banswara, Churu, Dhaulpur, Dungaarpur, Jaisalmer, Jhalawar, Pratapgarh, Rajsamand, Tonk, Udaipur

Tamil Nadu*	14	Coimbatore, Cuddalore, Erode, Kancheepuram, Krishnagiri, Madurai, Nagapattinam, Nilgiri, Pudukkottai, Thanjavur, Tiruvallur, Tiruvarur, Tuticorin, Villupuram
Telangana*	8	Adilabad, Hyderabad, Mahabubnagar, Medak, Nalgonda, Nizamabad, Ranga Reddy, Warangal
Tripura	5	Dhalai, Gomti, Khowai, North Tripura, South Tripura
Uttar Pradesh	69	Allahabad/ Prayagraj, Ambedkar Nagar, Amethi, Amroha, Azamgarh, Bahraich, Ballia, Balrampur, Banda, Barabanki, Bareilly, Basti, Bijnor, Budaun, Bulandshahar, Chandauli, Chitrakoot, Deoria, Etawah, Faizabad / Ayodhya, Farrukhabad, Fatehpur, Ghaziabad, Ghazipur, Gonda, Gorakhpur, Hamirpur, Hapur, Hardoi, Hathras, Jalaun, Jaunpur, Jhansi, Kanpur Dehat, Kanpur Nagar, Kasganj, Kushinagar, Lakhimpur Kheri, Lalitpur, Lucknow, Maharajganj, Mahoba, Mainpuri, Maunath
		Bhanjan, Meerut, Mirzapur, Moradabad, Muzaffarnagar, Pilibhit, Pratapgarh, Raebareli, Rampur, Saharanpur, Sambhal, Sant Kabir Nagar, Sant Ravidas Nagar, Shahjahanpur, Shamli, Shrawasti, Siddharth Nagar, Sitapur, Sonbhadra, Unnao, Varanasi
Uttarakhand	7	Champawat, Dehradun, Haridwar, Nainital, Tehri Garhwal, Udham Singh Nagar, Uttarkashi
West Bengal	21	Alipurduar, Bankura, Birbhum, Cooch Behar, Dakshin Dinajpur, Darjeeling, Hooghly, Howrah, Jalpaiguri, Jhargram, Kolkata, Malda, Murshidabad, Nadia, North 24 Parganas, Paschim Bardhaman, Paschim Medinipur, Purba Bardhaman, Purba Medinipur, South 24 Parganas, Uttar Dinajpur

* *Districts and locations affected in these states are based on sample collection and analysis of iron in the year 2019. While in the rest of the states, iron data employed was generated in the year 2023.*

4.7 Arsenic

The occurrence of Arsenic in ground water was first reported in 1980 in West Bengal in India. In West Bengal, 79 blocks in 8 districts have Arsenic beyond the permissible limit. The most affected areas are on the eastern side of Bhagirathi River in the districts of Malda, Murshidabad, Nadia, North 24 Parganas and South 24 Parganas and western side of the districts of Howrah, Hugli and Bardhman. The occurrence of Arsenic in ground water is mainly in the aquifers upto 100 m depth. The deeper aquifers are free from Arsenic contamination.

Apart from West Bengal, Arsenic contamination in groundwater has been found in the states of Assam, Bihar, Chhattisgarh, Haryana, Jharkhand, Karnataka, Punjab, and Uttar Pradesh. The occurrence of Arsenic in the states of Bihar, West Bengal and Uttar Pradesh is in alluvial formations but in the state of Chhattisgarh, it is in the volcanic rocks exclusively confined to N-S trending Dongargarh-Kotri ancient rift zone. It has also been reported in Golaghat, Jorhat, Lakhimpur, Nagaon, Nalbari, Sibsagar, Sonitpur district of Assam.

Excessive and prolonged intake of inorganic arsenic with drinking water is causing arsenicosis, a deteriorating and disabling disease characterized by skin lesions and pigmentation of the skin, patches on palm of the hands and soles of the feet. Arsenic poisoning culminates into potentially fatal diseases like skin and internal cancers. Besides carcinogen effects, longterm exposure of arsenic may result in Cardiovascular and diabetic complications.

Reductive dissolution of arsenic containing Fe-oxides lying in aquifer matrix may be held responsible for liberation of As. As a result of reduction of Fe oxyhydroxides generally Arsenic gets mobilized but there is a possibility of in-situ reoxidation of pyrite in the presence of oxygen inrush. Oxidised Fe and S may get re-reduced liberating Arsenic in solution.

According to Bhattacharya et al., (2011), water level fluctuations during pre and post precipitation delivers interchanging oxidation of sulphides and reduction of Fe oxyhydrides in soils pore. This further results in residual As and S in solution of shallow aquifer. As gets dissociated into aquifer solution according to following equation:

$$2\ FeAsS_{(S)} = 2Fe^{2+}(aq) + As_2{}^{2-}{}_{(aq)} + S_2{}^{2-}{}_{(aq)}$$

The map showing distribution of Arsenic in ground water of India **(Fig. 36)** has been generated from the data on arsenic concentration in water samples mostly collected from the groundwater observation wells/ hand pumps, Arsenic contaminated areas have been shown as points based on findings of Central Ground Water Board. The details of location exceeding the limit of 0.01mg/L (10 ppb) are given in Annexure VI. The point sources are plotted on the map **(Fig. 36).** Districts having Arsenic > 0.01 mg/L in Ground Water in Different States of India is shown in **Table-21**.

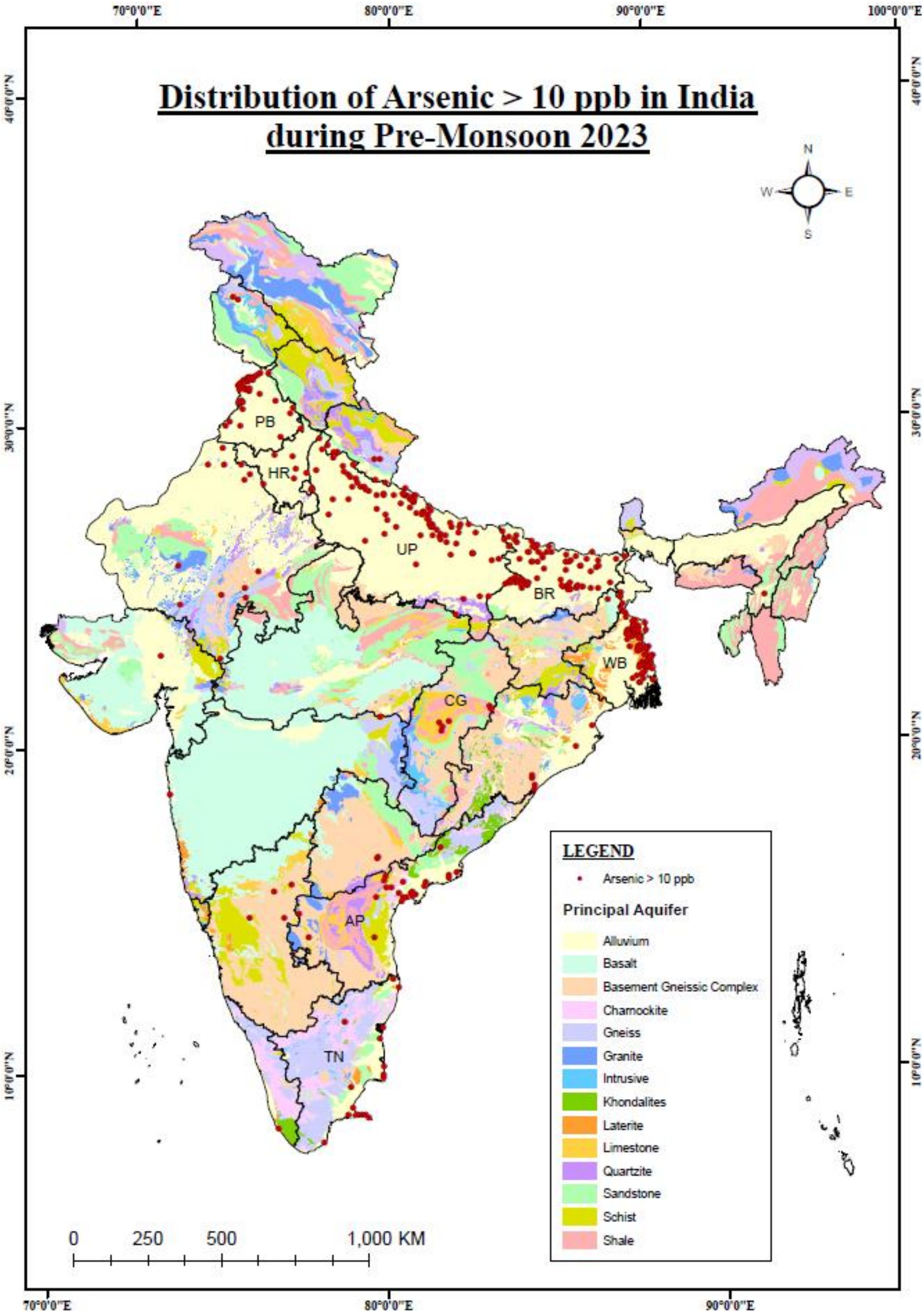


Figure 36: Map showing areas of Arsenic contaminated (> 10 ppb) groundwater in India.

Table 21: Districts in which anomalous values of Arsenic (As > 10 ppb) in Groundwater was detected at one or more location.

State/UT	No. of Districts	Name of Districts
Andhra Pradesh*	7	Ananthapur, East Godavari, Guntur, Krishna, Kurnool, Nellore, Prakasam
Assam	1	Cachar
Bihar*	20	Araria, Begusarai, Bhagalpur, Bhojpur, Buxar, Darbhanga, E. Champaran, Gopalganj, Katihar, Khagaria, Kishanganj, Madhepura, Madhubani, Muzaffarpur, Samastipur, Saran, Sheohar, Sitamarhi, Supaul, W. Champaran.
Chattisgarh*	3	Koriya, Raigarh, Raipur
Delhi	2	East, South East
Gujarat*	1	Mahesana
Haryana	5	Bhiwani, Fatehabad, Karnal, Rohtak, Sonipat
Jammu & Kashmir	2	Baramulla, Kupwara
Jharkhand*	1	Sahibganj
Karnataka	2	Gadag, Raichur
Kerala*	1	Kollam
Maharashtra*	2	Bhandara, Mumbai City
Odisha	3	Bhadrak, Cuttack, Ganjam
Punjab	12	Amritsar, Fazilka, Ferozepur, Gurdaspur, Hoshiarpur, Kapurthala, Muktsar, Pathankot, Patiala, Rupnagar, Sas Nagar, Tarn Taran
Rajasthan*	8	Banswara, Bhilwara, Churu, Ganganagar, Hanumangarh, Jodhpur, Sirohi, Tonk
Tamil Nadu*	9	Chennai, Cuddalore, Dharmapuri, Nagapattinam, Pondicherry, Ramanathapuram, Sivaganga, Tiruvallur, Tuticorin
Telangana*	1	Nalgonda
Uttar Pradesh	29	Aligarh, Ayodhya, Azamgarh, Baghpat, Bahraich, Ballia, Balrampur, Barabanki, Bareilly, Basti, Bijnor, Bulandshahr, Deoria, Gonda, Gorakhpur, Hardoi, Kushinagar, Lakhimpur Kheri, Mainpuri, Mirzapur, Moradabad, Pilibhit, Raebareli, Rampur, Saharanpur, Sambhal, Sant Kabir Nagar, Shahjahanpur, Siddharthnagar
Uttarakhand	3	Almora, Haridwar, Udham Singh Nagar
West Bengal	6	Howrah, Malda, Murshidabad, Nadia, North 24 Parganas, South 24 Parganas

* *Districts and locations affected in these states are based on sample collection and analysis of arsenic in the year 2019. While in the rest of the states, arsenic data employed was generated in the year 2023.*

In India, dissolved arsenic concentration (>10 ppb) has been reported in, West Bengal, Jharkhand, Bihar, Uttar Pradesh in the flood plain of the Ganga River; Assam and Manipur in the flood plain of the Brahamaputra and Imphal rivers, union territory of Chandigarh, Punjab, and in fractured consolidated rocks of Rajnandgaon district in Chhattisgarh state.

4.7.1 Remedial Measures for Arsenic

a) Precipitation processes- includes coagulation/filtration, direct filtration, coagulation assisted microfiltration, enhanced coagulation, lime softening, and enhanced lime softening. Adsorption co-precipitation with hydrolyzing metals such as Al^{3+} and Fe^{3+} is the most common treatment technique for removing arsenic from water. Sedimentation followed by rapid sand filtration or direct filtration or microfiltration is used to remove the precipitate. Coagulation with iron and aluminium salts and lime softening is the most effective treatment process. To improve efficiency of this method, a priory oxidation of As (III) to As (V) is advisable. Hypochlorite and permanganate are commonly used for the oxidation. Atmospheric oxygen can also be used, but the reaction is very slow. The major techniques based on this process include; Bucket treatment unit, Fill and draw treatment unit, Tubewell-attached arsenic treatment unit and Iron arsenic treatment unit.

b) Adsorptive processes- Adsorption on to activated alumina, activated carbon and iron/ manganese oxide based or coated filter media. Adsorptive processes involve the passage of water through a contact bed where arsenic is removed by surface chemical reactions. The activated alumina-based sorptive media are being used in Bangladesh and India. No chemicals are added during treatment and the process relies mainly on the active surface of the media for adsorption. Granular ferric hydroxide is a highly effective adsorbent used for the adsorptive removal of arsenate, arsenite, and phosphorous from natural water. In the Sono 3-Kolshi filter, used in Bangladesh and India zero valent iron fillings, sand, brick chips and wood coke are used as adsorbent to remove arsenic and other trace elements from groundwater.

c) Ion-exchange processes-This is similar to that of activated alumina, however, in this method the medium is synthetic resin of relatively well-defined ion exchange capacity. In these processes, ions held electrostatically on the surface of a solid phase are exchanged for ions of similar charge dissolved in water. Usually, a synthetic anion exchange resin is used as a solid. Ion exchange removes only negatively charged As (V) species. If As (III) is present, it is necessary to oxidise it.

d) Membrane processes- This includes nano-filtration, ultrafiltration, reverse osmosis and electrodialysis in which synthetic membranes are used for removal of many contaminants including arsenic. They remove arsenic through filtration, electric repulsion, and adsorption of arsenic-bearing compounds.

e) Arsenic safe alternate aquifers

This technique advocates tapping of safe alternate aquifers right within the affected areas. In India except at Rajnandgaon in Chhattisgarh state, the vast affected areas in the Gangetic Plains covering Bihar and Uttar Pradesh as well as Deltaic Plains in West Bengal is marked by multiaquifer system. The sedimentary sequence is made up Quaternary deposits, where the aquifers made up of unconsolidated sands which are separated by clay/sandy clay, making the deeper aquifer/aquifers semi-confined to confined. The contamination is confined in the upper slice of the sediments, within 80 m and affecting the shallow aquifer system. At places, like Maldah district of West Bengal single aquifer exists till the bed rock is encountered at 70-120 m bgl.

Detailed CGWB exploration, isotope and hydro-chemical modeling carried out by CGWB along with other agencies like BARC has indicated that the deep aquifers (>100 m bgl) underneath the contaminated shallow aquifer, have been normally found as arsenic free. Long duration pumping tests and isotopic studies in West Bengal and Bihar have indicated that there is limited hydraulic connection between the contaminated shallow and contamination free deep aquifers and the ground water belong to different age groups having different recharge mechanisms. The deep aquifers in West Bengal, Bihar and Uttar Pradesh have the potential to be used for community-based water supply.

4.7.2 Work Done by CGWB towards Mitigation of Arsenic Contamination

Based on the findings of the studies and experience of ground water exploration, CGWB has developed certain methods for constructing arsenic free wells by employing suitable designing of wells and cement sealing techniques. Such techniques of construction of contaminant free bore wells/ tube wells are shared with the state ground water departments to use them in similar terrains.

In the multi-aquifer system, the cement sealing technique was adopted to prevent the mixing of arsenic contaminated water with arsenic free ground water. So far, 522 exploratory wells tapping arsenic safe aquifers have been constructed under NAQUIM programme including 40 in Bihar, 188 in West Bengal and 294 in Uttar Pradesh with this technique. The innovative cement sealing technique of CGWB has been shared with the state agencies to utilize to construct arsenic free wells.

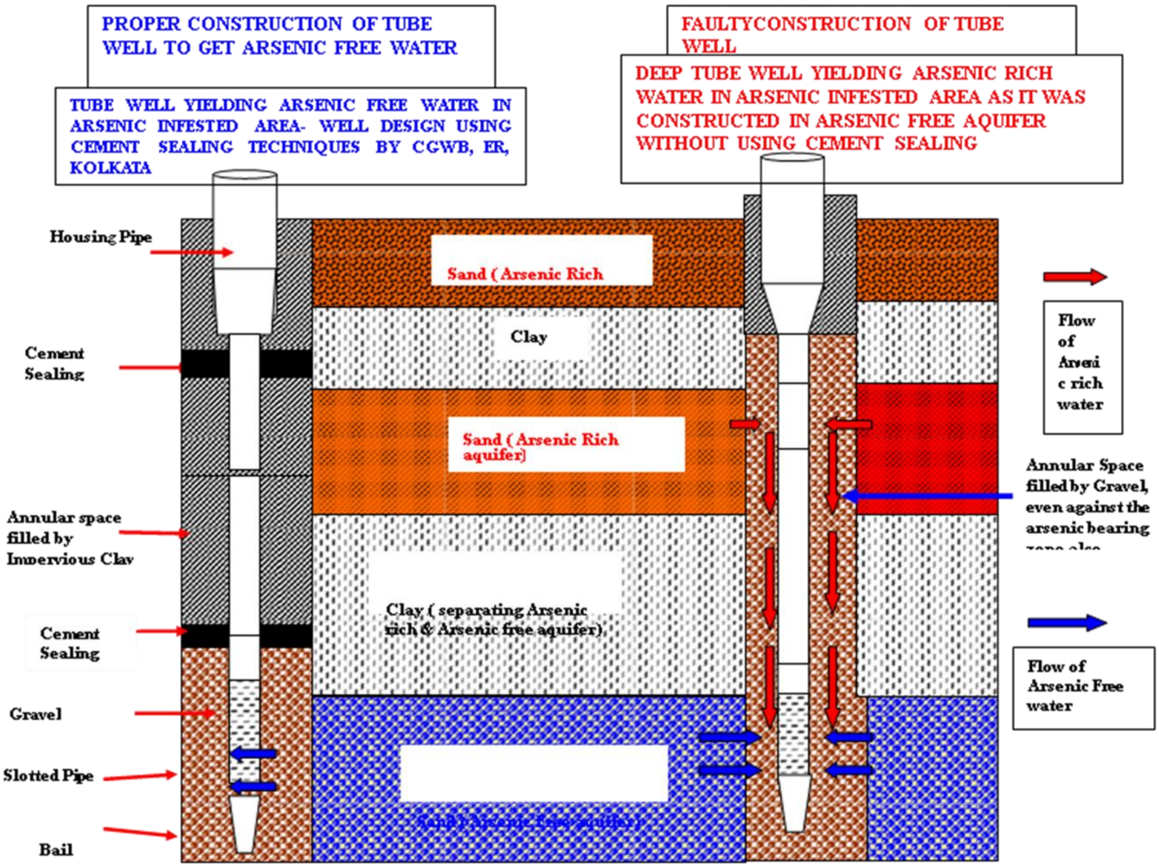


Figure 37: Cement sealing technique to prevent the mixing of arsenic contaminated water with arsenic free ground water.

4.8 Uranium

Uranium occurs naturally in groundwater and surface water. Being a radioactive mineral, high uranium concentration can cause impact on water, soil and health. Uranium has both natural and anthropogenic source that could lead to the aquifer. These sources include leaching from natural deposits, release in mill tailings, and emissions from the nuclear industry, combustion of coal and other fuels and the use of phosphate fertilizers that contains uranium and contribute to ground water pollution. Uranium enters in human tissues mainly through drinking water, food, air and other occupational and accidental exposures. Intake of uranium through air and water is normally low, but in circumstances in which uranium is present in a drinking water source, the majority of intake can be through drinking water. Permissible uranium concentration limits in drinking water across different countries is given in **Table 23.** Water with uranium concentration above the recommended maximum permissible concentration of 30 ppb (BIS,10500:2012) is not safe for drinking purposes as it can cause damage to internal organs, on continuous intake. Elevated uranium concentrations in drinking water have been associated with many epidemiological studies such as urinary track cancer as well as kidney toxicity. A recent study, found a strong correlation between uranium concentration in drinking water and uranium in bone, suggesting that bones are good indicators of uranium exposed via ingestion of drinking water. Therefore, such studies trigger further assessment of uranium's adverse health effects on humans and/or the environment for countries where elevated uranium concentration in drinking water has been observed. Hence, it becomes important to study the level of uranium in drinking water for health risk assessment.

Uranium concentration in the shallow ground water varies primarily due to recharge and discharge, which would have dissolved or leached the uranium from the weathered soil to groundwater zone. High uranium concentrations observed in groundwater may be due to local geology, anthropogenic activities, urbanization and use of phosphate fertilizers in huge quantity for agriculture purpose. Studies have shown that phosphate fertilizer possess uranium concentration ranging from 1 mg/kg to 68.5 mg/kg (Brindha K et al., 2011). Hence, the phosphate fertilizers manufactured from phosphate rocks may also contribute uranium to ground water in agriculture region. In ores, uranium is found as uranite (UO_2^{2+}) and pitchblende ($U_3O_8^{2+}$) or in the form of secondary minerals (complex oxides, silicates, phosphates, vanadates).

To assess the Uranium concentration and distribution in the ground water, Central Ground Water Board (CGWB) carried out Uranium sampling of its National Hydrograph Network Stations (NHNS) during Pre-monsoon monitoring (2023). The sample collection and storage were done according to the standard protocols prescribed by APHA (2017). The groundwater samples were collected in HDPE bottles. Uranium (U) was detected using Inductively Coupled Plasma Mass-spectrometry and LED Fluorimeter Uranium analyser. To ensure quality control, duplicate and standard checks were performed on every ten samples. In addition, a trace element standard reference material was examined.

Table 22: Summary of uranium concentrations in different types of rocks.

Rocks	Range(mg/kg)
Granite	3.4
Limestone/dolomite	2.2
Argillaceous shale	3.7
Sediments	1.4-53
Phosphates	30-100

Table 23: Standards and guidelines for uranium in drinking water in various countries.

Country	Guideline value (µg/L)	Reference
Australia	GV 17	NHMRC, Australia (2011)
Bulgaria	ML 60	European Food Safety Authority (2009)
Canada	MAC 20	Health Canada (2019)
Finland	RV 100	European Food Safety Authority (2009)
India	RBL 60	AERB, India (2004)
India	PL 30	BIS,2012
Malaysia	MAV 2	Ministry of Health Malaysia (2004)
USA	MCL 30	USEPA (2011)
WHO	PGV 30	WHO 2011

GV, Guideline value; ML, Maximum limit; MAC, Most acceptable concentration; RV, Recommended value; RBL, Radiological based limit; PL, Permissible Limit; MAV, Maximum acceptable value; MCL, Maximum contaminant level; PGV, Provisional guideline value

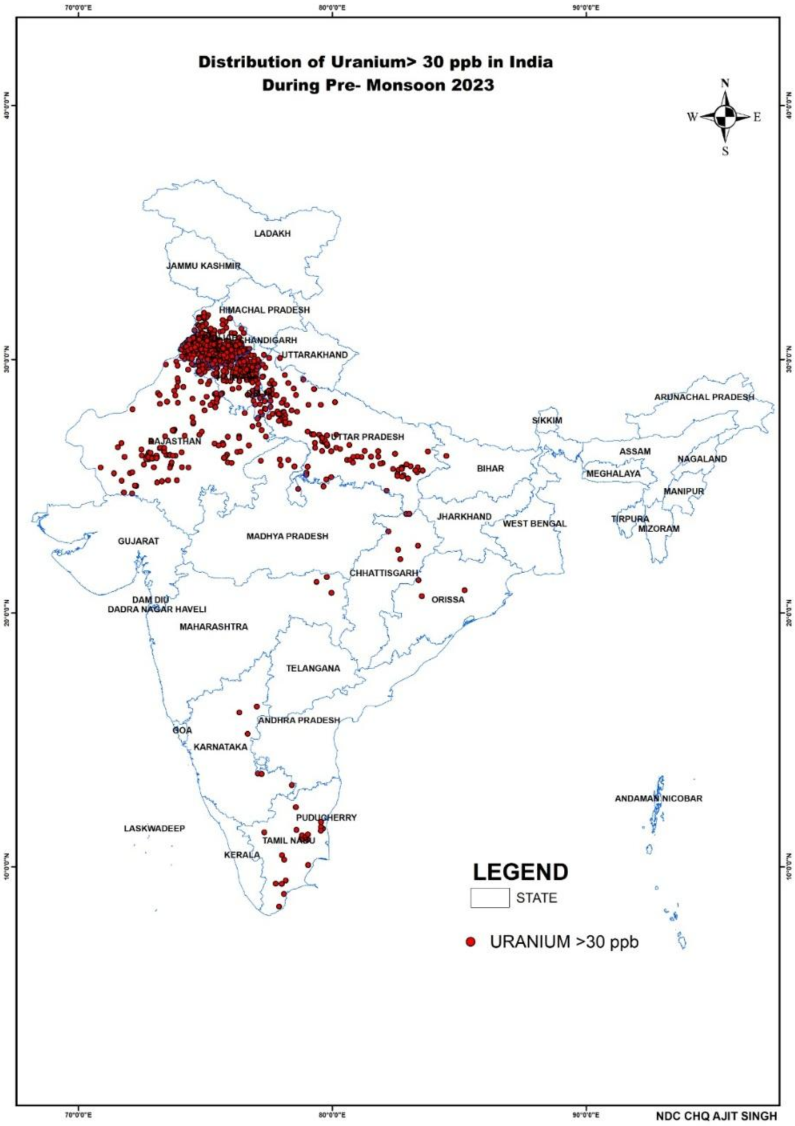


Figure 38: Map showing areas of Uranium contaminated (> 30 ppb) groundwater.

The distribution of ground water samples with Uranium concentration more than 30ppb have been depicted on the map as **Fig. 38**. **Table 24.** shows the list of districts in which anomalous values of Uranium (U > 30ppb) in groundwater was detected at one or more location in different States of India in 2023, from which samples were collected for Uranium analysis.

Table 24: Districts in which anomalous values of Uranium (U>30ppb) in Groundwater was detected at one or more location

State/UT	No. of Districts	Name of Districts
Bihar	1	Siwan
Chhattisgarh	3	Korba, Koriya, Raigarh
Delhi	6	North, North West, South, South East, South West, West
Haryana	16	Ambala, Bhiwani, Faridabad, Fatehabad, Gurugram, Hisar, Jhajjar, Jind, Kaithal, Karnal, Kurukshetra, Mewat, Palwal, Panipat, Sirsa, Sonipat
Karnataka	3	Kolar, Raichur, Tumkur
Madhya Pradesh	3	Chhatarpur, Datia, Gwalior
Maharashtra	3	Bhandara, Gondia, Nagpur
Odisha	3	Anugul, Balangir, Bargarh
Punjab	20	Amritsar, Barnala, Bathinda, Faridkot, Fatehgarh Sahib, Fazilka, Ferozepur, Gurdaspur, Hoshiarpur, Jalandhar, Kapurthala, Ludhiana, Mansa, Moga, Muktsar, Nawanshahr, Patiala, Rupnagar, Sangrur, Tarn Taran
Rajasthan	21	Alwar, Barmer, Bharatpur, Bhilwara, Bikaner, Churu, Dausa, Ganganagar, Hanumangarh, Jaipur, Jaisalmer, Jalore, Jhunjhunu, Jodhpur, Karauli, Nagaur, Pali, Rajsamand, Sawai Madhopur, Sikar, Tonk
Tamil Nadu	9	Cuddalore, Dindigul, Erode, Krishnagiri, Perambalur, Pudukkottai, Salem, Tuticorin, Virudhunagar
Uttar Pradesh	43	Agra, Aligarh, Allahabad, Amethi, Amroha, Auraiya, Azamgarh, Bareilly, Bijnor, Budaun, Bulandshahr, Deoria, Etawah, Fatehpur, G.B. Nagar, Ghaziabad, Ghazipur, Hapur, Hardoi, Hathras, Jaunpur, Jhansi, Kannauj, Kanpur Dehat, Kanpur Nagar, Kasganj, Lalitpur, Mahoba, Mainpuri, Mathura, Meerut, Mirzapur, Pratapgarh, Raebareli, Rampur, Saharanpur, Sant Ravidas Nagar, Shahjahanpur, Shamli, Sonbhadra, Sultanpur, Unnao, Varanasi
Uttarakhand	1	Haridwar

4.8.1 Distribution of Uranium Concentration Exceeding Permissible Limits in Shallow Aquifers of India

A total of 11,445 water samples were collected from shallow aquifers across various states of India. The uranium concentration in the samples was measured, and the results were classified according to the ranges specified below **(Fig. 39).** As per BIS IS 10500, the permissible limit for uranium concentration in drinking water is 30 ppb. Uranium concentration varied from 0.0 to 1035 ppb in the entire country during Pre-monsoon monitoring (May,2023), indicating that uranium concentrations in groundwater widely vary by several orders of magnitude.

Analytical data reveals that while uranium concentrations in the majority of samples were within permissible limits, a substantial number of samples exceeded the 30-ppb threshold. The majority of the samples exceeding the permissible limit fall within the 30-40 ppb range (34.5% of total exceeding samples). A smaller proportion of the samples have uranium concentrations exceeding 70 ppb (about 21.4% of total exceeding samples). 60 samples (9.14% of the exceeding samples) have uranium concentrations greater than 100 ppb **(Fig.39).**

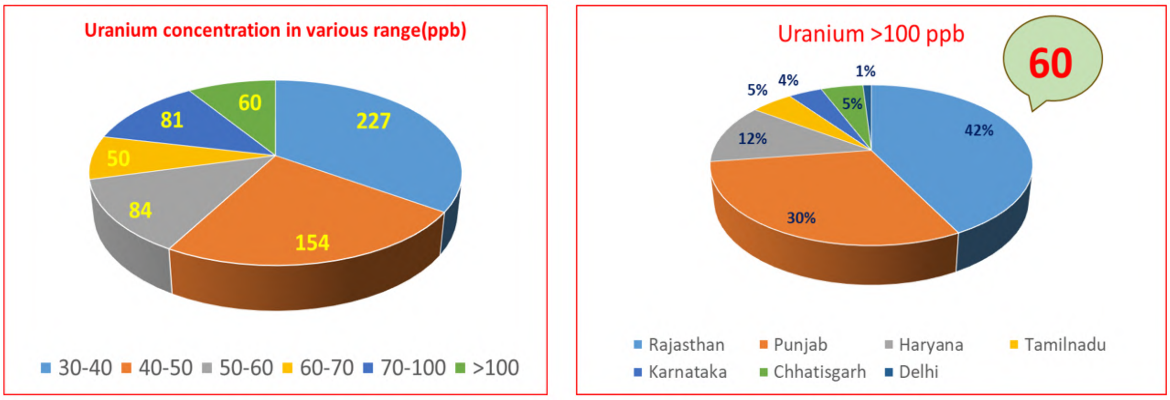


Figure 39: Distribution of Uranium Concentration Exceeding Permissible Limits.

42% of the samples with uranium concentration greater than 100 ppb are from Rajasthan and 30% of the samples with uranium concentration greater than 100 ppb are from Punjab. This indicates that these two states contribute significantly to the higher uranium concentration in groundwater, with Rajasthan alone contributing a substantial proportion of the high-concentration samples. As, **Rajasthan** and **Punjab** are identified as regions with a significant concentration of high uranium levels in groundwater, further investigation is required to understand the specific geochemical processes that lead to elevated uranium concentrations in these regions.

Some other states such as Haryana Karnataka, Uttar Pradesh, Madhya Pradesh, Tamilnadu, Chhattisgarh, Maharashtra, and Bihar have also been observed to have Uranium concentration above the permissible level of 30 µg/L in some localized pockets.

The high Uranium concentration in states such as Punjab, Uttar Pradesh, and Haryana may be due to leaching through soil by heavy use of fertilizers in the agriculture lands. Since an extensive concentration of bicarbonate and phosphate have also been observed in groundwater samples of Punjab (Tripathi et al.2012), this may be a reason for high concentration observed in groundwater samples from shallow depths as phosphate and bicarbonates present in soil enhance the leaching and mobility of uranium. Further studies may be carried out to ascertain the effect of phosphate fertilisers leading to anthropogenic Uranium contamination in Groundwater.

In states such as Tamilnadu, Karnataka and Chhatisgarh enhanced uranium concentration in groundwater may be due to geogenic inputs. The enhanced elemental concentration of uranium is usually found in hard rocks due to the partial melting and fractional crystallization of magma which enables uranium to be concentrated in silicate rocks.

4.8.2. Comparative analysis of districts Exceeding the Permissible Limit (2019 vs. 2023)

The data on uranium contamination for the year 2019 was compared with data for 2023, focusing on the number of districts where uranium levels exceeded 30 ppb **(Fig. 40).**

In Madhya Pradesh and Karnataka, there was a significant decrease in the number of districts with uranium contamination exceeding the permissible limit in 2023 compared to 2019. On the other hand, Uttar Pradesh showed a significant increase in the number of districts with uranium contamination exceeding 30 ppb in 2023. A key factor contributing to this increase is the **increase in the number of water samples** collected in 2023 (by approximately 700 samples), which likely led to the identification of more contaminated areas.

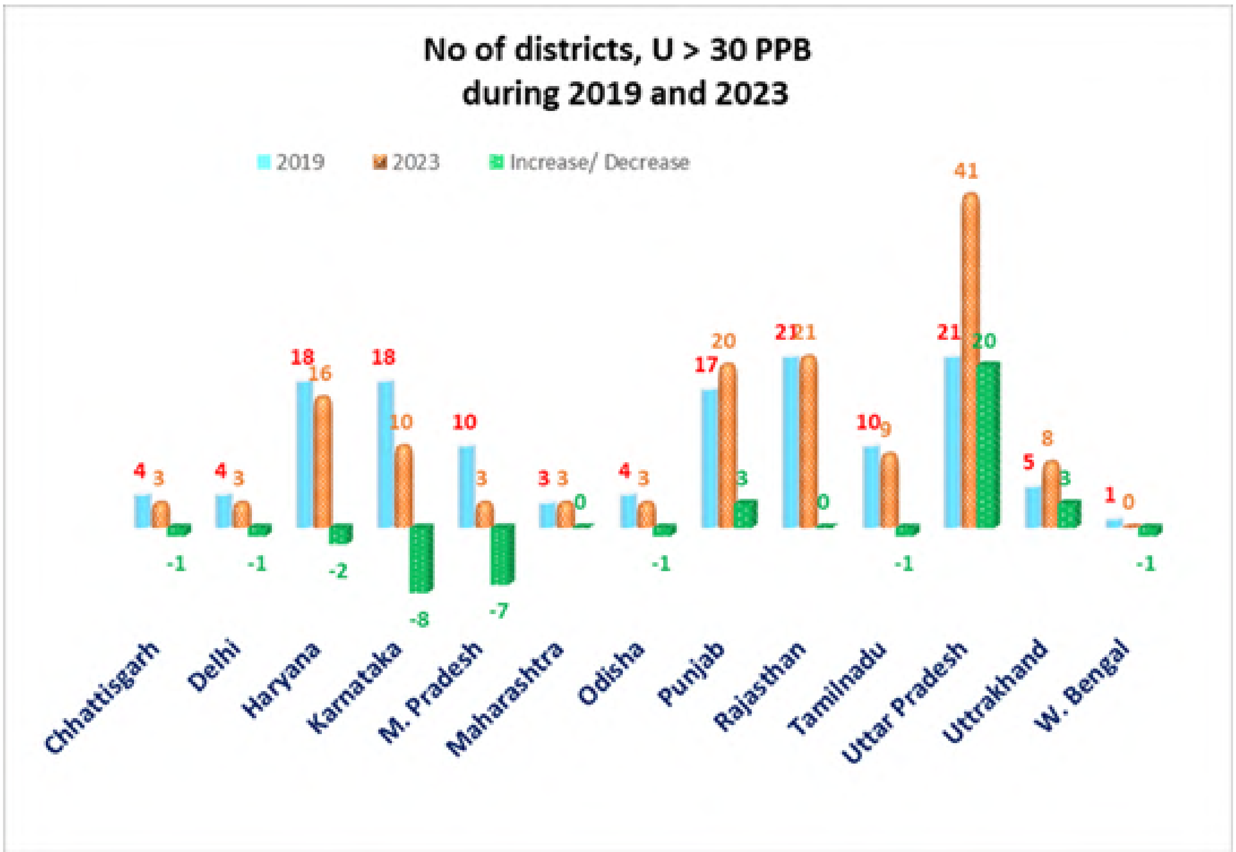


Figure 40: Comparative analysis of districts Exceeding the Permissible Limit (2019 vs. 2023).

4.8.3 Spatial Distribution of Uranium exceedance in Relation to Groundwater Stress Zones

This section expands upon the findings of uranium contamination by correlating the areas with high uranium levels (exceeding the permissible limit of 30 ppb) with groundwater stress zones across India. Groundwater stress zones are categorized into Over-exploited, Critical, and Semi-Critical zones based on the depletion of groundwater resources. The purpose of this analysis is to understand whether regions with high uranium concentrations also correspond to areas facing significant groundwater stress.

The points representing water samples exceeding 30 ppb uranium were overlaid on the map of groundwater stress zones to identify geographical clusters of uranium contamination in areas already under groundwater stress **(Fig. 41).**

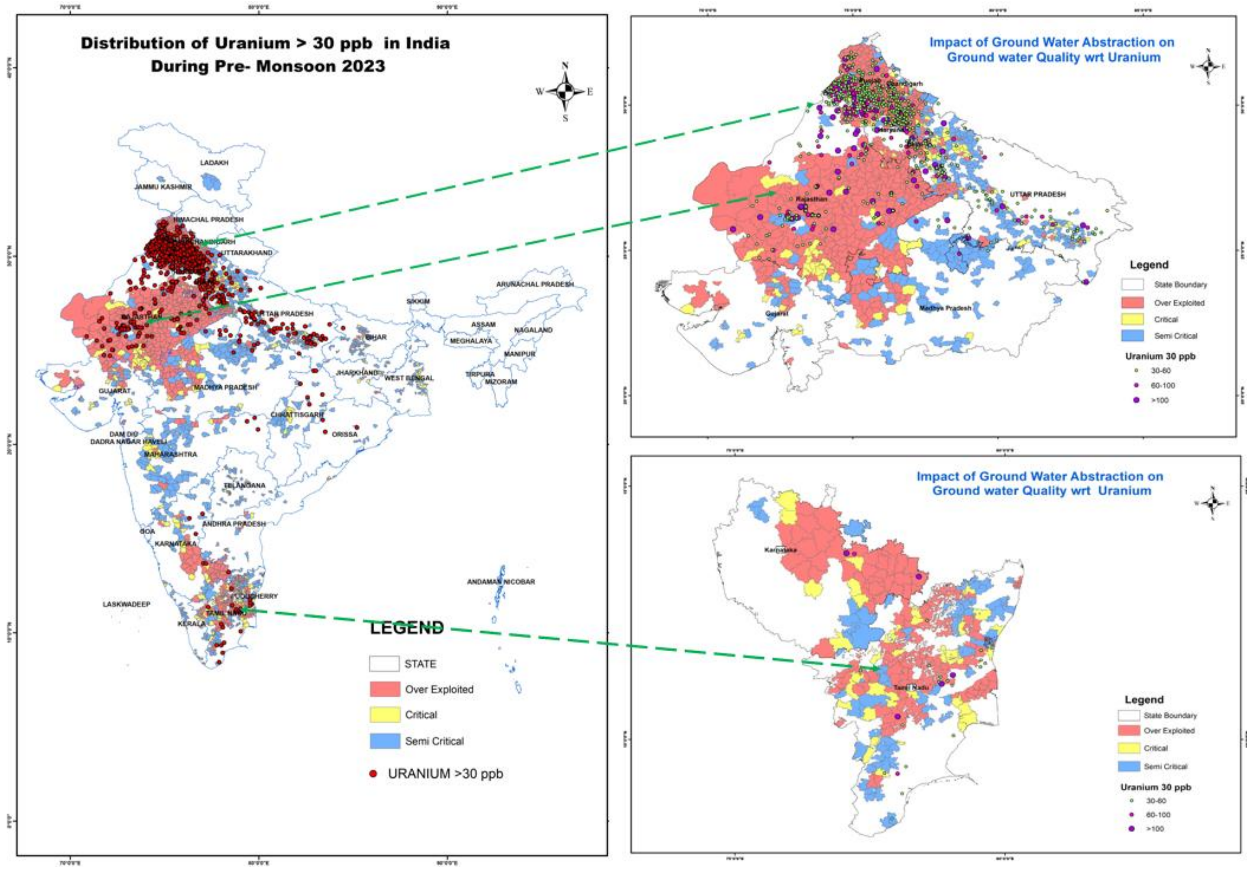


Figure 41: Over-exploited areas show a striking similarity with enriched Uranium concentration.

The analysis revealed that the majority of the samples with uranium concentrations exceeding 30 ppb cluster in regions identified as **Over-exploited**, **Critical**, and **Semi-Critical** groundwater stress zones. The key regions where this overlap occurs include Rajasthan, Gujarat, Haryana, Punjab, Tamilnadu, Andhra Pradesh and Karnataka. Excessive abstraction reduces the volume of water available for recharge, limiting the natural process of **dilution** of contaminants like uranium. This lack of recharge, combined with excessive withdrawal, makes it more difficult for the aquifers to maintain lower uranium concentrations, thus exacerbating contamination. This phenomenon is particularly concerning in regions where the aquifers are already under pressure from over-extraction.

4.8.4. Remedial Measures

Finding a remedy for the uranium contaminated groundwater effectively and thoroughly, has become need of day. Remediation technologies can be classified into physical, chemical and biological methods. Bioremediation is divided into plant and microorganism methods. Each method consists of both advantages and disadvantages and the appropriate mitigation techniques should be need based.

Adsorption has a high removal efficiency, but costs are also higher. The coagulation process is simple and comparatively economical, but the standard effluent concentration is hard to reach, so there is a need for follow-up treatment. Combined with adsorption, coagulation can remove 99% of U. The extraction process can remove effluent U concentrations of less than 0.05mg / L, but it will produce a lot of sludge. Reverse osmosis is referred as a best technology, but due to its high cost it can not be used on community scale. The evaporation method is simple and effective, the removal rate is high, but there are high costs and sludge needs that must be dealt with. A review of various treatment technologies for Uranium removal from water and their technical achievability as reported by various researchers are given below in **Table 25**.

Table 25: Comparison of treatment methods for removal of Uranium.

Treatment Method	Technical Achievability (%)
Coagulation/filtration at high pH (10+)	> 95
Lime softening	85-99
Anion exchange	99
Reverse osmosis	>95
Activated alumina	90
Coagulation/filtration	80-89

(Source: Hand Book for Drinking Water Treatment, JJM, Ministry of Jal Shakti, Gov. of India).

4.9 Suitability of Groundwater for Irrigation Purpose

The **quality of groundwater** is critically important for determining its **suitability for irrigation** because it directly influences both the **health of the soil** and the **growth of crops**. Poor quality groundwater can result in long-term damage to soil structure, plant health, and overall agricultural productivity. Poor water quality (e.g., high concentrations of sodium, chloride, or bicarbonates) can interfere with a plant's ability to absorb essential nutrients, resulting in **nutrient deficiencies**. High **sodium (Na)** can be toxic to plants, affecting their **photosynthesis**, growth, and root development.

In areas where natural drainage is inadequate, the irrigation water infiltrating the root zone will cause water table to rise excessively. In addition to problems caused by excessive concentration of dissolved solids, certain constituents in irrigation water are especially undesirable and some may be damaging even when present in small concentrations. Irrigation indices viz. Sodium Adsorption Ratio (SAR) and Residual Sodium Carbonate (RSC) have been evaluated to assess the suitability of ground water for irrigation purposes.

4.9.1 Alkali Hazard Assessment and Its Impact on Irrigation Suitability

In the irrigation water, it is characterized by absolute and relative concentrations of cations. If the sodium concentrations are high, the alkali hazard is high and if the calcium & magnesium levels are high, this hazard is low. The alkali soils are formed by the accumulation of exchangeable sodium and are characterized by poor tilt and low permeability. The U.S. Salinity laboratory has recommended the use of sodium adsorption ratio (SAR) as it is closely related to adsorption of sodium by the soil.

SAR is derived by the following equation:

$$\boldsymbol{SAR} = \frac{\boldsymbol{Na^{+}}}{\sqrt{\frac{\boldsymbol{Ca^{2+}Mg^{2+}}}{\boldsymbol{2}}}}$$

The water with regard to SAR is classified into four categories

- **S_1 – Low Sodium Water** (SAR <10)

Such waters can be used on practically all kinds of soils without any risk or increase in exchangeable sodium.

- **S_2 – Medium Sodium Water** (SAR 10-18)

Such waters may produce an appreciable sodium hazard in fine textured soil having high cation exchange capacity under low leaching.

- **S_3 – High Sodium Water** (SAR >18-26)

Such waters indicate harmful concentrations of exchangeable sodium in most of the soil and would require special management, good drainage, high leaching and addition of organic matter to the soil. If such waters are used on gypsiferrous soils the exchangeable sodium could not produce harmful effects.

- **S_4 – Very High Sodium Waters** (SAR >26)

Generally, such waters are unsatisfactory for irrigation purposes except at low or perhaps at medium salinity where the solution of calcium from the soil or addition of gypsum or other amendments makes the use of such waters feasible.

The computed SAR values range from 0.003 to 63.65. The maximum SAR value has been found at Parihara of Churu district in Andhra Pradesh. It is apparent from **Fig. 43** that 94.82% samples belong to excellent category (S_1) and only 0.73% water samples are associated with very high sodium category (S_4) and is unsuitable for irrigation. According to SAR classification, 100% of water samples in Arunachal Pradesh, Assam, Andaman & Nicobar, Chandigarh UT, Himachal Pradesh, Kerala, Meghalaya, Nagaland, Pondicherry and Tripura fall in excellent category (S_1). While in Andhra Pradesh, Delhi, Rajasthan, Gujarat, Haryana 5.13%, 12.62%, 26.19, 7.28% and 7.51% samples are associated with medium sodium hazard and can be classified as good category(S_2) for irrigation use **(Table 26).**

It was found that in Andhra Pradesh, Gujarat, Haryana, Punjab, Rajasthan and Uttarpradesh 0.96%, 1.27%, 0.34%, 0.76%, 12.38% and 0.14% samples fall in Very high sodium range and are unsuitable for use in irrigation practices **(Fig. 42)**. Districts in which high values of SAR (SAR > 26) in Groundwater was detected at one or more location in Different States of India (2023) is presented in **Table. 27**.

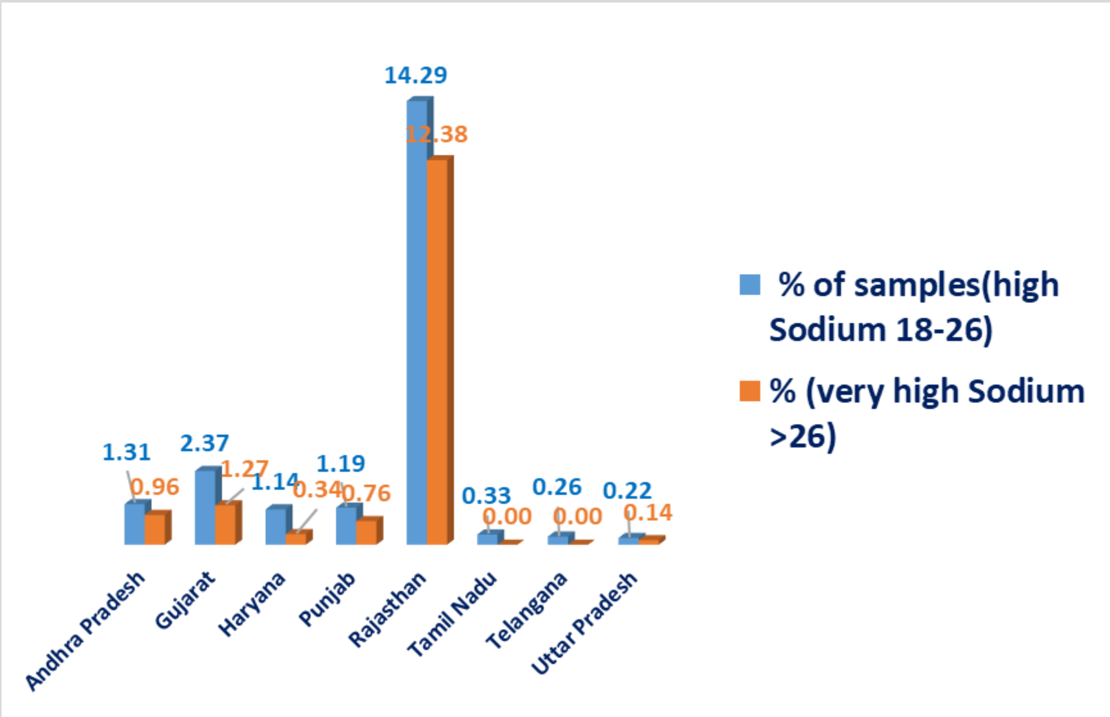


Figure 42: States with percentage of samples in S3 & S4 categories with respect to SAR values.

Table 26: Summary of irrigation quality of the groundwater samples in various states based on SAR classifications.

State/UT	Low Sodium (<10)	Medium Sodium (10-18)	High Sodium (18-26)	Very High Sodium (>26)
A & N Islands	100	0	0	0
Andhra Pradesh	92.6	5.13	1.31	0.96
Arunachal Pradesh	100	0	0	0
Assam	99.35	0.65	0	0
Bihar	99.75	0.25	0	0
Chandigarh UT	100	0	0	0
Chhattisgarh	99.74	0.13	0.13	0
Dadra And Nagar Haveli	100	0	0	0
Daman and Diu	85.71	14.29	0	0
Delhi	85.44	12.62	1.94	0
Goa	100	0	0	0
Gujarat	89.08	7.28	2.37	1.27
Haryana	91.01	7.51	1.14	0.34
Himachal Pradesh	100	0	0	0
Jammu & Kashmir	100	0	0	0
Jharkhand	99.75	0.25	0	0
Karnataka	95.94	3.48	0.58	0
Kerala	100	0	0	0
Madhya Pradesh	99.83	0.17	0	0
Maharashtra	99.43	0.57	0	0

Meghalaya	100	0	0	0
Mizoram	100	0	0	0
Nagaland	100	0	0	0
Odisha	99.52	0.48	0	0
Pondicherry	100	0	0	0
Punjab	91.43	6.62	1.19	0.76
Rajasthan	47.14	26.19	14.29	12.38
Tamil Nadu	97.71	1.97	0.33	0
Telangana	98.52	1.22	0.26	0
Tripura	100	0	0	0
Uttar Pradesh	96.9	2.74	0.22	0.14
Uttarakhand	98.55	1.45	0	0
West Bengal	98.75	0.94	0.1	0.21

Table 27: Districts in which high values of SAR (SAR > 26) in Groundwater was detected at one or more location in Different States of India (2023).

State/UT	No. of Districts	Name of Districts
Andhra Pradesh	6	Bapatla, Eluru, Krishna, Kurnool, Palnadu, Ysr Kadapa
Gujarat	7	Ahmedabad, Amreli, Anand, Bhavnagar, Botad, Kachchh, Porbandar
Haryana	3	Fatehabad, Gurugram, Sirsa
Punjab	5	Bathinda, Faridkot, Fazilka, Ferozepur, Mansa
Rajasthan	16	Ajmer, Barmer, Bharatpur, Bikaner, Churu, Ganganagar, Hanumangarh, Jaipur, Jaisalmer, Jalore, Jhunjhunu, Jodhpur, Karauli, Nagaur, Pali, Sawai Madhopur
Uttar Pradesh	2	Mainpuri, Mathura
West Bengal	2	North 24 Parganas, South 24 Parganas

4.9.2 Changes in Alkali Hazard in Groundwater (2022-2023):

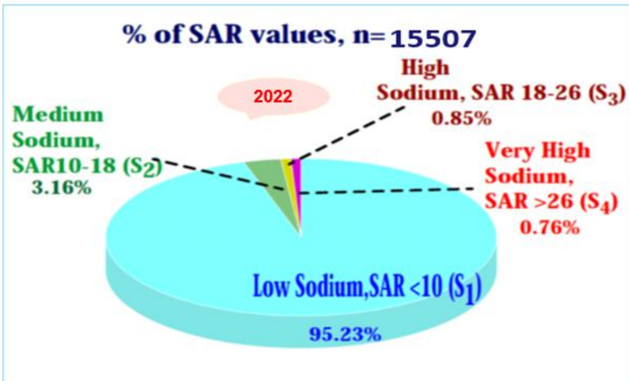
- **Low Sodium Water**: In 2022, 95.23% of the samples fell under the "low sodium" category, indicating that the majority of the groundwater samples had low sodium concentrations, which is beneficial for most crops. In 2023, the percentage of low sodium samples slightly decreased to **94.82%**, but it still represents the vast majority of groundwater samples. This suggests that, overall, sodium levels remain within safe limits for irrigation, with minimal risk of alkali hazard.

- **Medium Sodium Water**: In 2022, 3.16% of samples were classified as medium sodium, indicating a small proportion of groundwater samples may have moderate risks of **sodicity**. In 2023, this increased slightly to **3.43%**, suggesting a small increase in the proportion of groundwater samples that may require additional management practices (like **leaching** or using salt-tolerant crops) to avoid soil degradation from sodium.

- **High Sodium Water**: In 2022, 0.85% of the samples had high sodium levels, which can lead to **sodicity problems** like soil dispersion, reduced permeability, and poorer water infiltration. This percentage increased slightly in 2023 to **1.02%**, indicating a minor increase in high-sodium groundwater samples. Such waters are typically unsuitable for irrigation without proper management strategies.

- **Very High Sodium Water**: The percentage of very high sodium samples remained quite low, at **0.76% in 2022** and **0.73% in 2023**. Though this is a small proportion, very high sodium content is a serious concern, as it could lead to **severe sodicity** and soil structure damage over time if these waters are used for irrigation.

The majority of the groundwater samples in both 2022 and 2023 have **low sodium content**, which is generally **safe** for irrigation purposes. However, there is a slight **increase in the proportion of medium to high sodium samples**, especially in 2023. This increase, while small, suggests a **gradual shift** in the quality of groundwater towards slightly higher sodium levels, which could pose a risk for long-term irrigation if the trend continues.



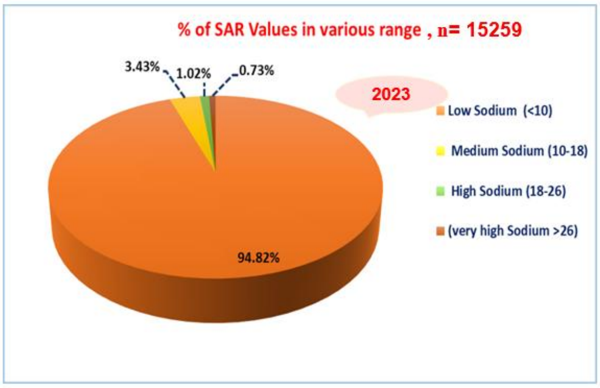


Figure 43: Percentage of groundwater samples according to SAR classifications (2022 & 2023).

In Gujarat Ahmedabad, Amreli and Bhavnagar, in Rajasthan Barmer, Bharatpur, Bikaner, Churu, Jalore, Jhunjhunu, Jodhpur, in Haryana Sirsa, in Andhrapradesh Karnool, Palnadu and Baptalu district some samples are associated with category S_4 and exhibit SAR value more than 26 and are unsuitable for irrigation are not suitable for irrigation.

4.9.3 Residual Sodium Carbonate (RSC) and its impact on Irrigation Suitability

If the enriched carbonate (residual) concentration becomes relatively high, carbonates get together with calcium and magnesium to form precipitates. The relative abundance of sodium in comparison to alkaline earths and the quantity of bicarbonate and carbonate in excess of alkaline earths also influences the suitability of water for irrigation. This excess is represented in terms of “Residual Sodium Carbonate” (RSC). The highly soluble sodium carbonate known as residual sodium carbonate (RSC) is defined as;

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

Waters with high RSC produces harmful effects on plant development and is not suitable for irrigation. Waters associated with RSC < 1.25 are of excellent irrigation quality and can be safely applied for irrigation for almost all crops without the risks associated with residual sodium carbonate (Wilcox et al.,1954). If the RSC values lie between 1.25 and 2.5, the water is of an acceptable quality for irrigation. Waters associated with RSC values higher than 2.5 are not acceptable for irrigation. In **Fig. 45**, it can be seen that in India 81.49% collected water samples are associated with RSC values less than 1.25 and are safe for use in irrigation practices. Only 10.43% water samples are associated with RSC values more than 2.5 and are unsuitable for irrigation. The water with high RSC values if applied for irrigation causes soil to become infertile owing to deposition of sodium. **Table 28**, summarizes the irrigation quality of the groundwater samples in various states based on RSC values. States with percentage of samples with RSC values in (1.25-2.5) and > 2.5 is represented in Fig. 43. Districts in which high values of RSC (RSC > 2.5) in Groundwater was detected at one or more location in Different States of India (2023) is presented in **Table. 29**.

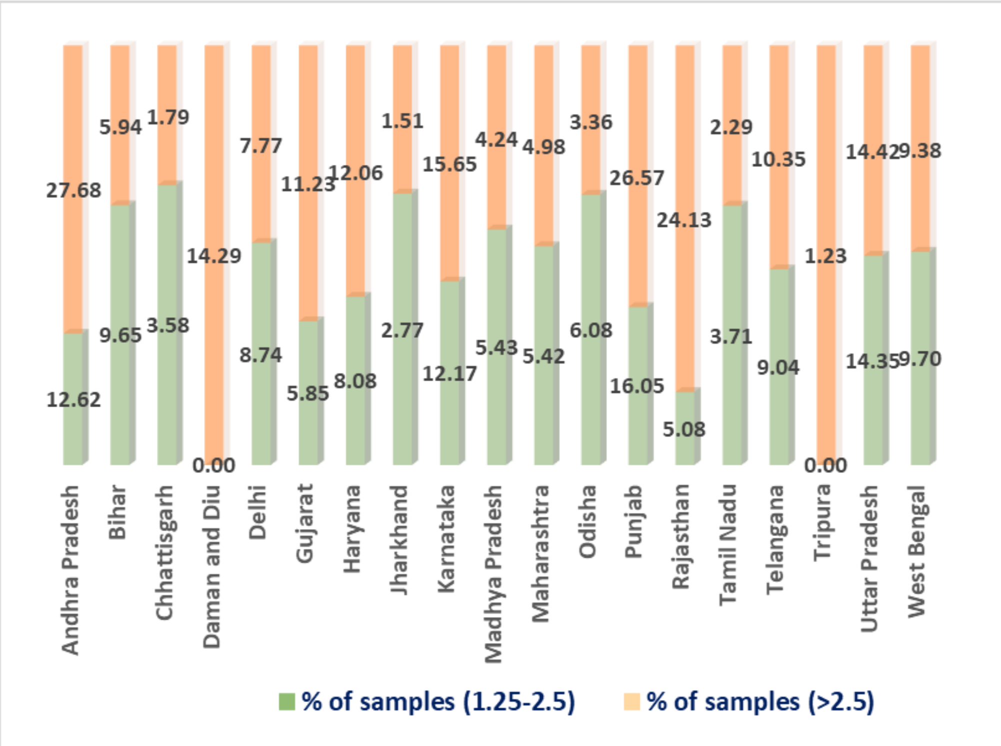


Figure 44: Percentage of samples with respect to RSC values.

According to RSC classification 100% of water samples in Arunachal Pradesh, Assam, Andaman & Nicobar, Meghalaya and Nagaland fall in very safe category with RSC values less than 1.25.

Table 28: Summary of irrigation quality of the groundwater samples in various states based on RSC values.

State/ UT	%. of samples in various RSC range		
	<1.25	1.25-2.5	>2.5
	Very safe	Marginally safe	Unsuitable
Andaman & Nicobar Islands	92.92	6.19	0.88
Andhra Pradesh	59.7	12.62	27.68
Arunachal Pradesh	100	0	0
Assam	97.42	1.94	0.65
Bihar	84.41	9.65	5.94
Chandigarh UT	87.5	12.5	0
Chhattisgarh	94.64	3.58	1.79
Dadra And Nagar Haveli	100	0	0
Daman and Diu	85.71	0	14.29
Delhi	83.5	8.74	7.77
Goa	100	0	0
Gujarat	82.91	5.85	11.23
Haryana	79.86	8.08	12.06
Himachal Pradesh	92.98	5.26	1.75
Jammu & Kashmir	92.8	4.8	2.4
Jharkhand	95.72	2.77	1.51
Karnataka	72.17	12.17	15.65
Kerala	99.42	0.58	0
Madhya Pradesh	90.15	5.43	4.24
Maharashtra	89.6	5.42	4.98
Meghalaya	97.44	2.56	0
Mizoram	100	0	0
Nagaland	100	0	0
Odisha	90.56	6.08	3.36
Pondicherry	75	25	0
Punjab	57.38	16.05	26.57
Rajasthan	70.79	5.08	24.13
Tamil Nadu	94	3.71	2.29
Telangana	80.61	9.04	10.35
Tripura	98.77	0	1.23
Uttar Pradesh	71.23	14.35	14.42
Uttarakhand	93.72	4.83	1.45
West Bengal	80.92	9.7	9.38

Table 29: Districts in which high values of RSC (RSC > 2.5) in Groundwater was detected at one or more location in Different States of India (2023).

State/UT	No. of Districts	Name of Districts
Andaman & Nicobar Islands	1	South Andaman
Andhra Pradesh	26	Alluri Sita Rama Raju, Anakapalli, Ananthapur, Annamayya, Bapatla, Chittoor, East Godavari, Eluru, Guntur, Kakinada, Konaseema, Krishna, Kurnool, Nandyal, Nellore, Ntr, Palnadu, Parvathipuram Manyam, Prakasham, Sri Satya Sai, Srikakulam, Tirupathi, Visakhapatnam, Vizianagaram, West Godavari, Ysr Kadapa
Assam	1	Nagaon
Bihar	13	Buxar, Darbhanga, East Chamapran, Gaya, Madhubani, Muzzafarpur, Nalanda, Rohtas, Samastipur, Saran, Sheohar, Sitamarhi, Vaishali
Chhattisgarh	9	Balodabazar, Bemetara, Bilaspur, Koriya, Mungeli, Raigarh, Raipur, Rajnandgaon, Surguja
Daman and Diu	1	Daman
Delhi	6	Central, New Delhi, North, North West, South, South West
Gujarat	25	Ahmedabad, Amreli, Anand, Banaskantha, Bharuch, Bhavnagar, Botad, Chhota Udepur, Dahod, Devbhumi Dwarka, Jamnagar, Junagadh, Kachchh, Kheda, Mahesana, Morbi, Navsari, Panchmahal, Porbandar, Rajkot, Sabarkantha, Surat, Surendranagar, Vadodara, Valsad
Haryana	15	Ambala, Bhiwani, Charkhi Dadri, Fatehabad, Gurugram, Hisar, Jhajjar, Jind, Kaithal, Karnal, Kurukshetra, Mahendragarh, Panipat, Sirsa, Sonipat
Himachal Pradesh	3	Bilaspur, Sirmour, Una
Jammu & Kashmir	3	Jammu, Kathua, Samba
Jharkhand	3	E. Singhbhum, Godda, Palamu
Karnataka	20	Bagalkot, Bellary, Bengaluru Rural, Bengaluru Urban, Bijapur, Chamarajanagara, Chikballapur, Chikkamagaluru, Chitradurga, Davanagere, Gadag, Kolar, Koppal, Mandya, Mysore, Raichur, Ramanagara, Tumkur, Vijayanagara, Yadgir
Madhya Pradesh	18	Agar Malwa, Ashok Nagar, Balaghat, Bhind, Bhopal, Chhindwara, Datia, Guna, Gwalior, Harda, Jhabua, Morena, Rajgarh, Sehore, Seoni, Sheopur, Singrauli, Tikamgarh
Maharashtra	26	Ahmednagar, Akola, Amravati, Beed, Bhandara, Buldhana, Chandrapur, Dhule, Gadchiroli, Jalgaon, Latur, Nagpur, Nanded, Nandurbar, Nashik, Osmanabad, Parbhani, Pune, Raigad, Sangli, Satara, Solapur, Thane, Wardha, Washim, Yavatmal
Odisha	11	Anugul, Balangir, Bargarh, Cuttack, Dhenkanal, Khordha, Nayagarh, Nuapada, Puri, Sambalpur, Sonapur
Punjab	22	Amritsar, Barnala, Bathinda, Faridkot, Fatehgarh Sahib, Fazilka, Ferozepur, Gurdaspur, Hoshiarpur, Jalandhar, Kapurthala, Ludhiana, Mansa, Moga, Muktsar, Nawanshahr, Pathankot, Patiala, Rupnagar, Sangrur, SAS Nagar, Tarn Taran

Rajasthan	27	Ajmer, Alwar, Banswara, Barmer, Bharatpur, Bhilwara, Bikaner, Bundi, Churu, Dausa, Dhaulpur, Ganganagar, Hanumangarh, Jaipur, Jaisalmer, Jalore, Jhalawar, Jhunjhunu, Jodhpur, Karauli, Nagaur, Pali, Rajsamand, Sawai Madhopur, Sikar, Tonk, Udaipur
Tamil Nadu	13	Chennai, Coimbatore, Kancheepuram, Kanyakumari, Nilgiris, Perambalur, Pudukkottai, Salem, Tiruvallur, Trichy, Vellore, Villupuram, Virudhunagar
Telangana	27	Adilabad, B. Kothagudem, Hanamkonda, J. Bhupalapally, Jagtial, Jangaon, Karimnagar, Kb Asifabad, Khammam, Mahabubabad, Mahabubnagar, Mancherial, Medak, Mulugu, Nagarkurnool, Nalgonda, Narayanpet, Nirmal, Nizamabad, Pedapalle, R. Sircilla, Siddipet, Suryapet, Vikarabad, Wanaparthy, Warangal, Yadadri Bhuvanagiri
Tripura	1	Khowai
Uttar Pradesh	52	Agra, Aligarh, Allahabad/ Prayagraj, Auraiya, Azamgarh, Baghpat, Balrampur, Banda, Barabanki, Bareilly, Basti, Budaun, Bulandshahar, Chandauli, Chitrakoot, Etawah, Farrukhabad, Fatehpur, Firozabad, G.B. Nagar, Ghaziabad, Ghazipur, Hamirpur, Hapur, Hathras, Jalaun, Jaunpur, Jhansi, Kannauj, Kanpur Dehat, Kanpur Nagar, Kasganj, Kaushambi, Lalitpur, Mahoba, Mainpuri, Mathura, Meerut, Mirzapur, Muzaffarnagar, Pratapgarh, Prayagraj, Raebareli, Sant Kabir Nagar, Shahjahanpur, Shamli, Shrawasti, Siddharth Nagar, Sitapur, Sonbhadra, Unnao, Varanasi
Uttarakhand	2	Haridwar, Udham Singh Nagar
West Bengal	14	Bankura, Birbhum, Dakshin Dinajpur, Darjeeling, Jalpaiguri, Kolkata, Malda, Murshidabad, Nadia, North 24 Parganas, Paschim Medinipur, Purba Bardhaman, Purba Medinipur, South 24 Parganas

4.9.4 Changes in Residual Sodium Carbonate in Groundwater (2022-2023):

Distribution of RSC-based water classification for 2022 and 2023 **(Fig. 45)** is as follows:

- **Very Safe (< 1.25)**: The proportion of **very safe** water samples dropped slightly from **85.77%** in 2022 to **81.49%** in 2023. While this is a reduction, the majority of the water samples still fall into the **very safe** category, meaning they are well within acceptable limits for irrigation without causing harm to soil or crops.
- **Marginally Safe Water**: The percentage of **marginally safe** water samples increased from **6.66%** in 2022 to **10.43%** in 2023. This suggests a slight deterioration in water quality, as more samples are being classified as marginally safe, which may require special management practices.
- **Unsuitable Water**: The percentage of **unsuitable** water samples increased slightly from **7.69%** in 2022 to **8.07%** in 2023. This indicates that a small but notable portion of the groundwater is moving towards being unsuitable for irrigation, likely due to

higher levels of **alkalinity** or **sodicity**, which could affect soil structure and crop health over time.

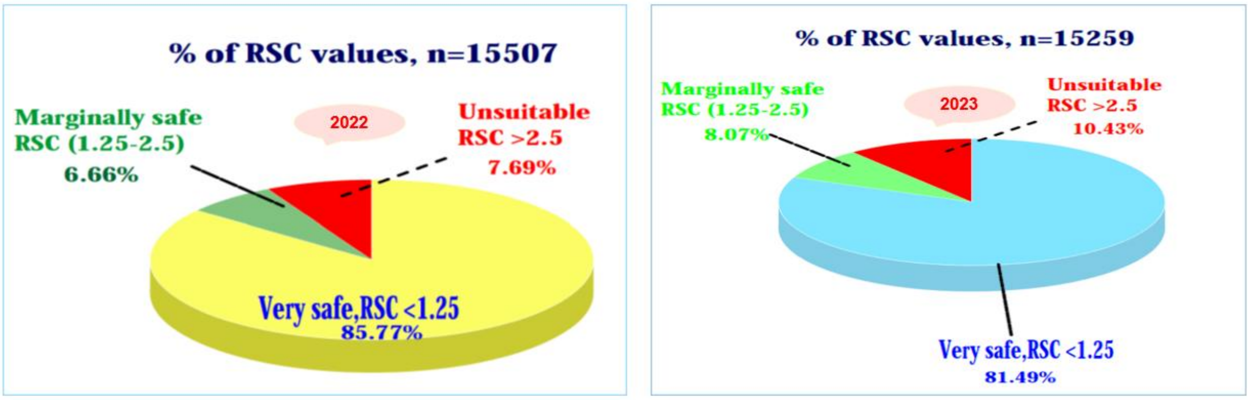


Figure 45: Percentage of groundwater samples in various categories according to RSC classifications (2022 & 2023).

4.9.5 Wilcox Diagrams

EC and sodium concentration are very important in classifying irrigation water. The Wilcox diagram (Wilcox 1948) relating EC and % Na shows **(Fig. 46)** that all the samples are plotted in excellent to good and good to permissible categories in most of the water samples indicating their suitability for irrigation. Most of the samples associated with doubtful to unsuitable zone for irrigation belong to Andhra Pradesh, Gujarat, Haryana, Rajasthan and Punjab. Wilcox diagram of some of the States of India is presented as Fig. 47 to 50.

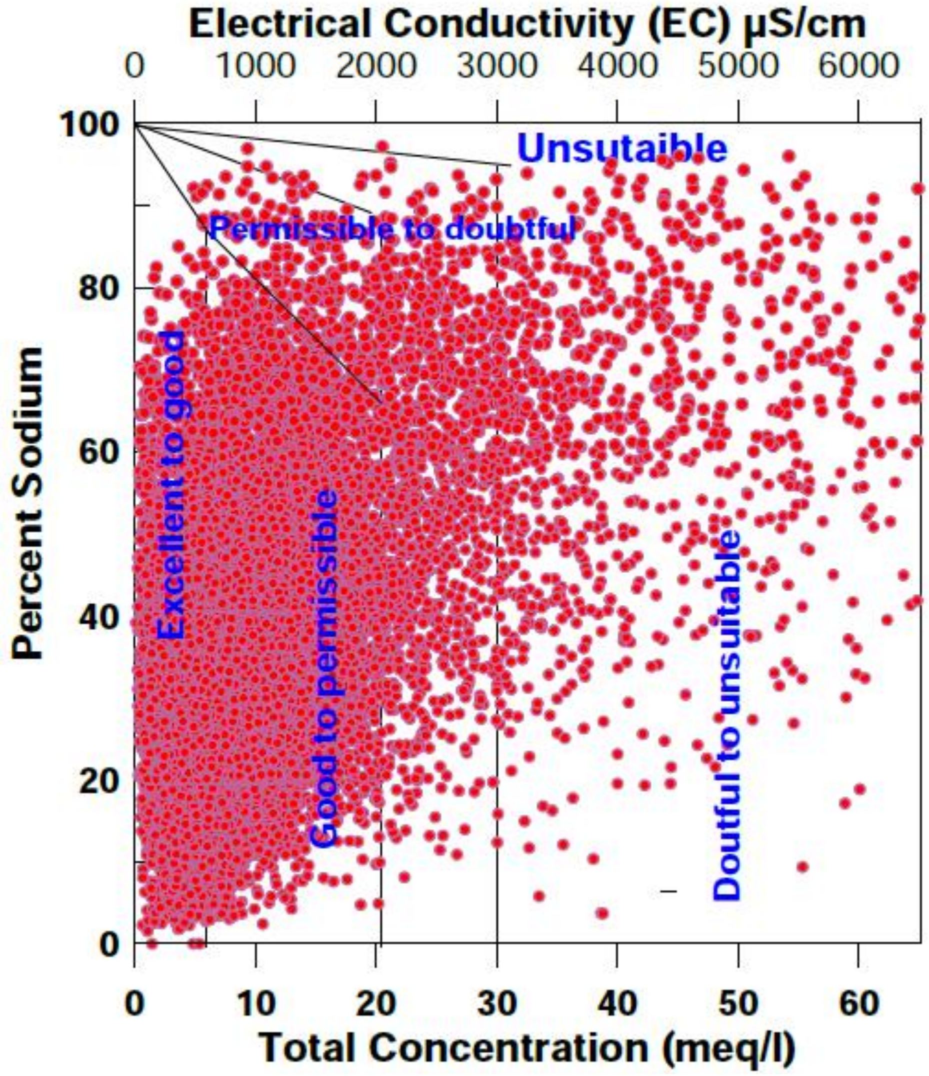


Figure 46: Plots of sodium percent verses electrical conductivity (after Wilcox 1955) in groundwater samples of India.

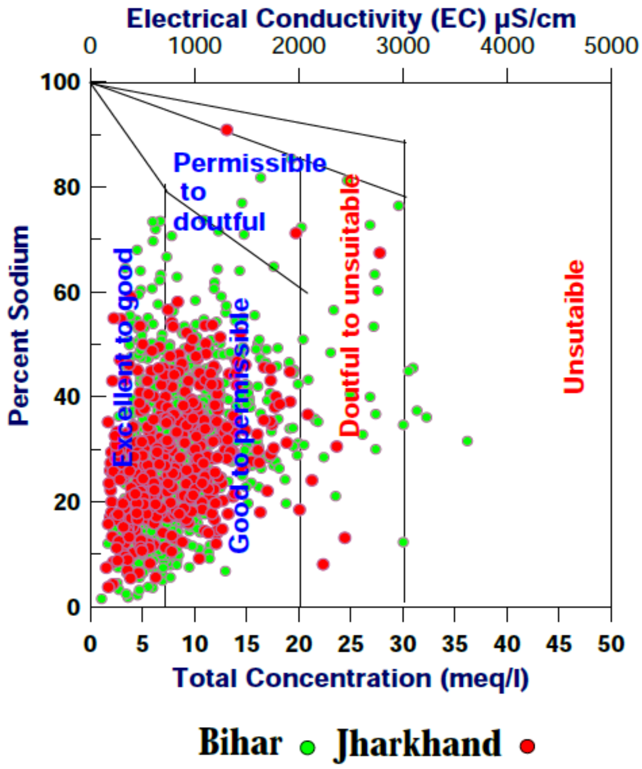


Figure 47: Plots of sodium percent verses electrical conductivity (after Wilcox 1955) in groundwater samples Bihar and Jharkhand.

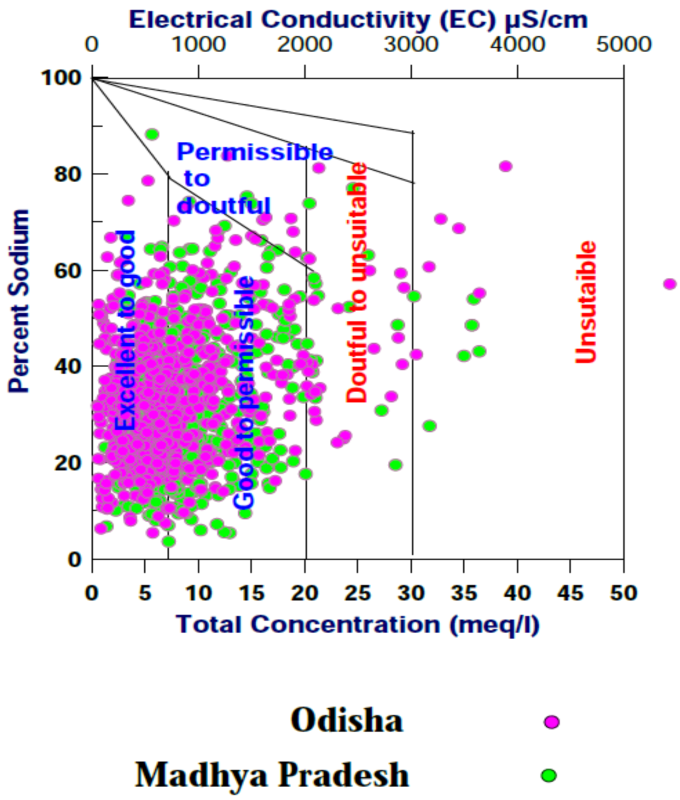


Figure 48: Plots of sodium percent verses electrical conductivity (after Wilcox 1955) in groundwater samples in Odisha and Madhya Pradesh.

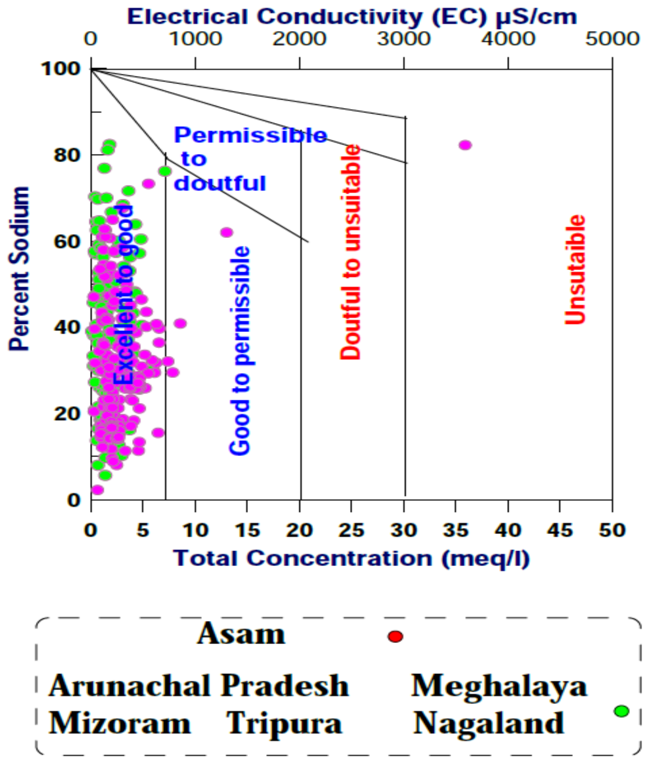


Figure 49: Plots of sodium percent verses electrical conductivity (after Wilcox 1955) in groundwater samples in North Eastern States.

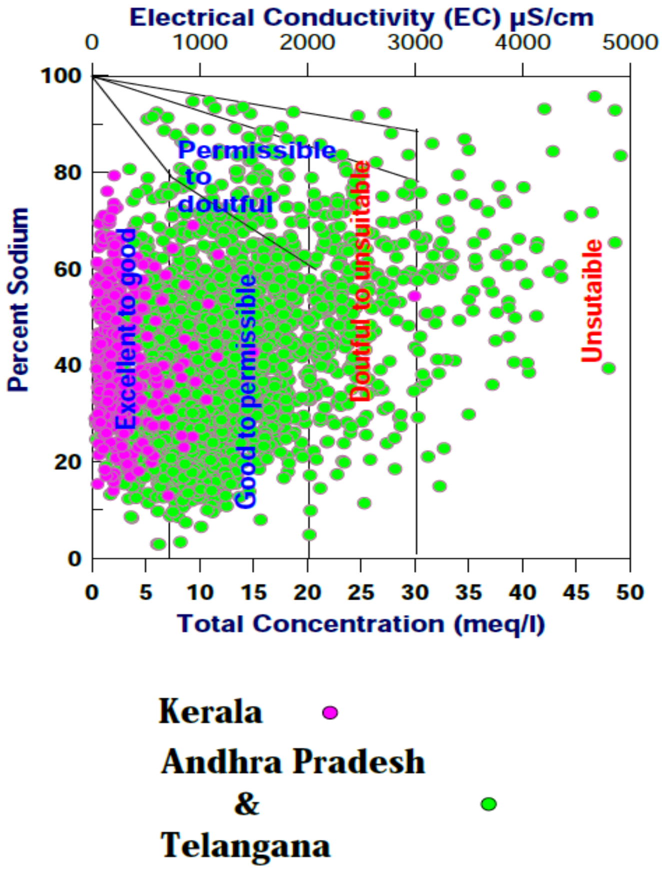


Figure 50: Plots of sodium percent verses electrical conductivity (after Wilcox 1955) in groundwater samples in Kerala, Andhra Pradesh and Telangana.

5. Hydrogeochemical Plots

Hydrogeochemistry plots are valuable tools for assessing groundwater quality data. These plots help visualize the chemical composition of groundwater and reveal important trends, relationships, and potential issues related to the water quality.

- **Piper plot** (Piper 1944) is a crucial tool in a water quality report, especially for groundwater studies, as it provides a clear visual representation of the chemical composition of groundwater quality data. It helps **interpret complex ionic data** and enables the comparison of water samples based on their dominant ion composition. Water quality reports often contain complex and voluminous data, including numerous ionic concentrations. The Piper plot simplifies this complexity by condensing the data into a **single visual representation**, making it easier for stakeholders to understand the water quality status and its implications. Based on the major cation and major anion content in the water samples and plotting them in the trilinear diagram, hydrochemical facies could be identified.

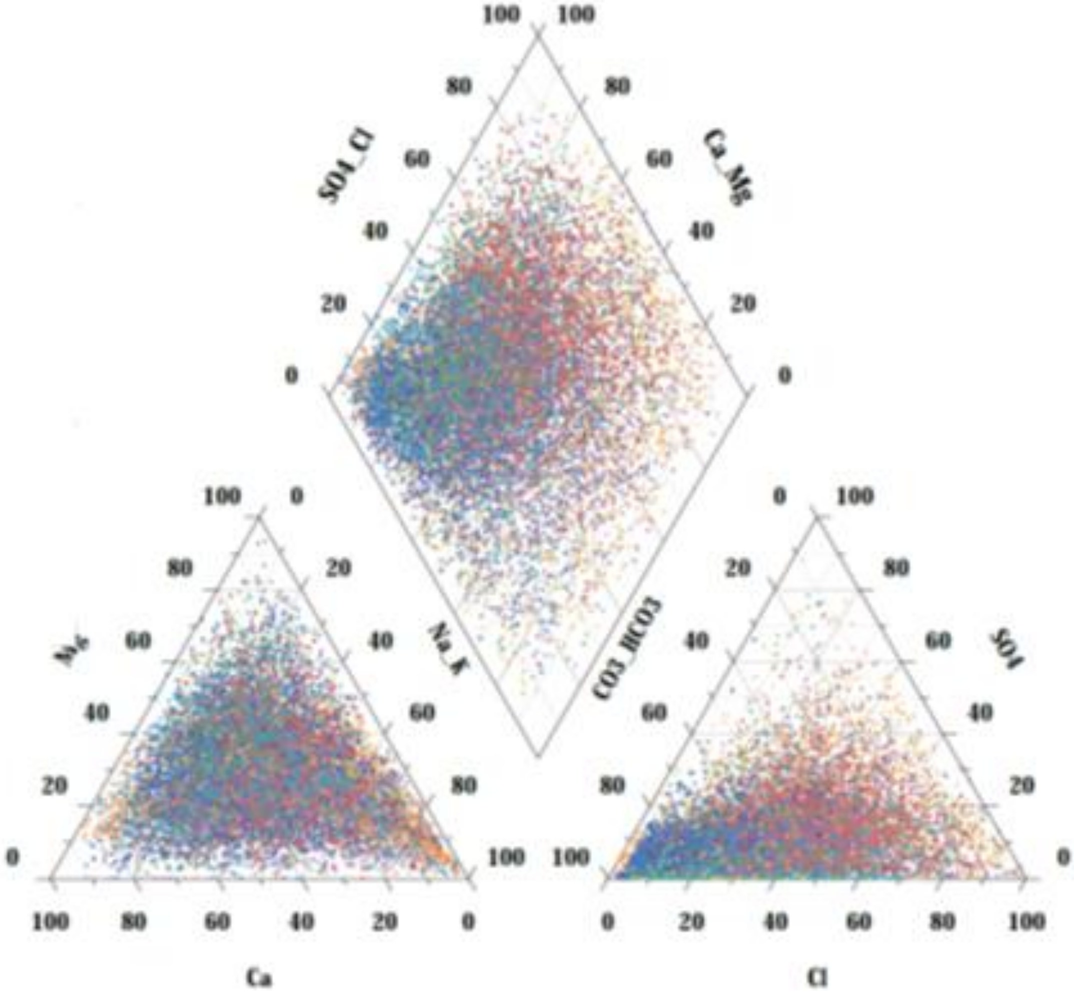


Figure 51: Piper diagram of groundwater of India.

Hydro-chemical facies are very useful in investigating diagnostic chemical character of water in hydrologic systems. Different types of facies within the same group formations are due to characteristic ground water flow through the aquifer system and effect of local recharge. The types of facies are inter-linked with the geology of the area and distribution of facies with the hydrogeological controls. Hydrochemical facies are delineated by plotting percentage reacting value of major ions on tri-linear diagrams know as Piper Diagram. In India, cation chemistry is dominated by calcium is followed by Calcium, Sodium and Potassium. In anion side bicarbonate is dominating anion followed by chloride and sulphate. The facies mapping shows **(Fig.51)** that Ca-HCO_3 is the dominant hydrogeochemical facies followed by mixed chemical character of hydrogeochemical facies. The Piper Plots showing hydrochemical species in Madhya Pradesh and Telangana are displayed in **Fig. 52 & 53**.

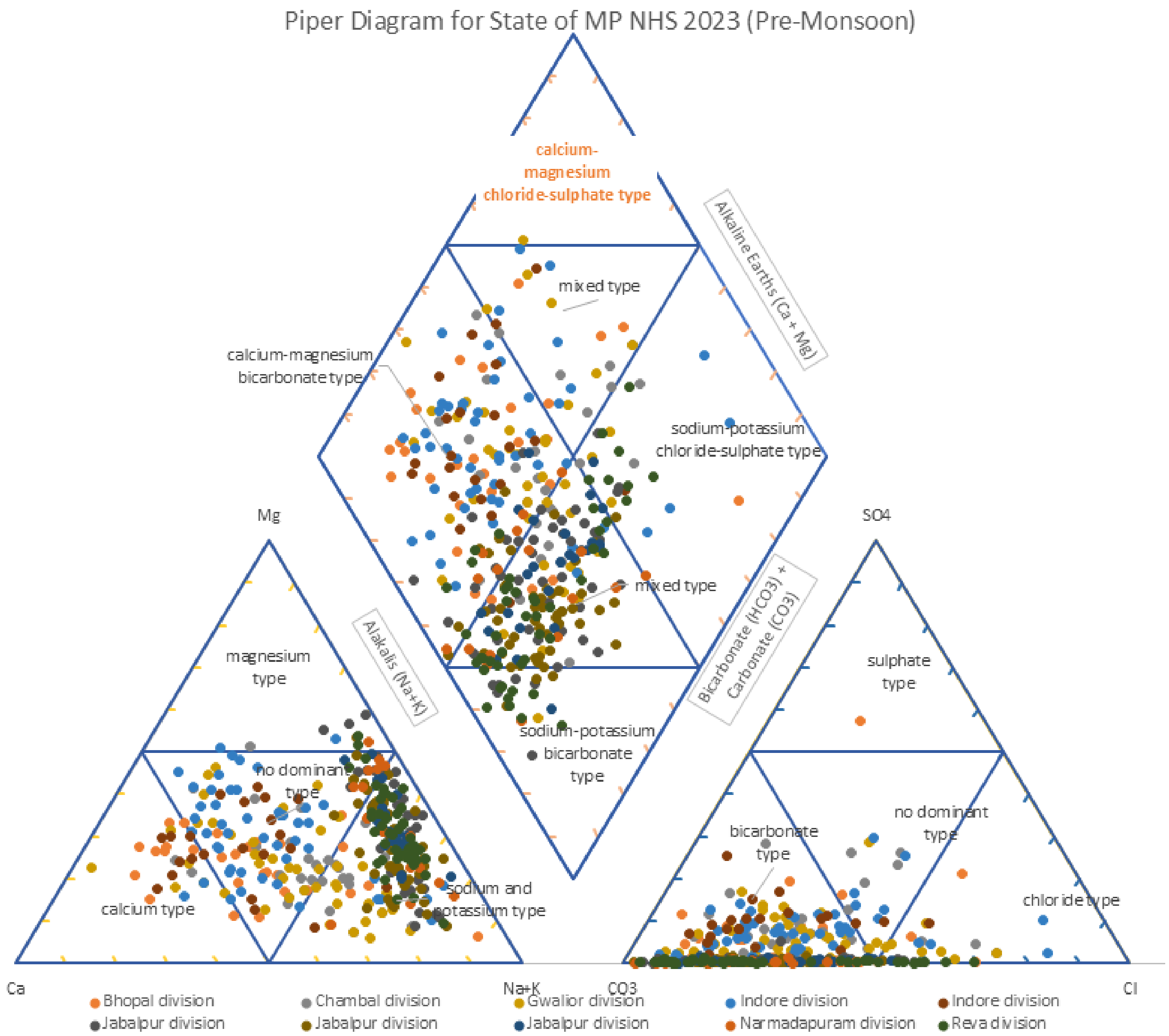


Figure 52: Piper diagram of groundwater of Madhya Pradesh.

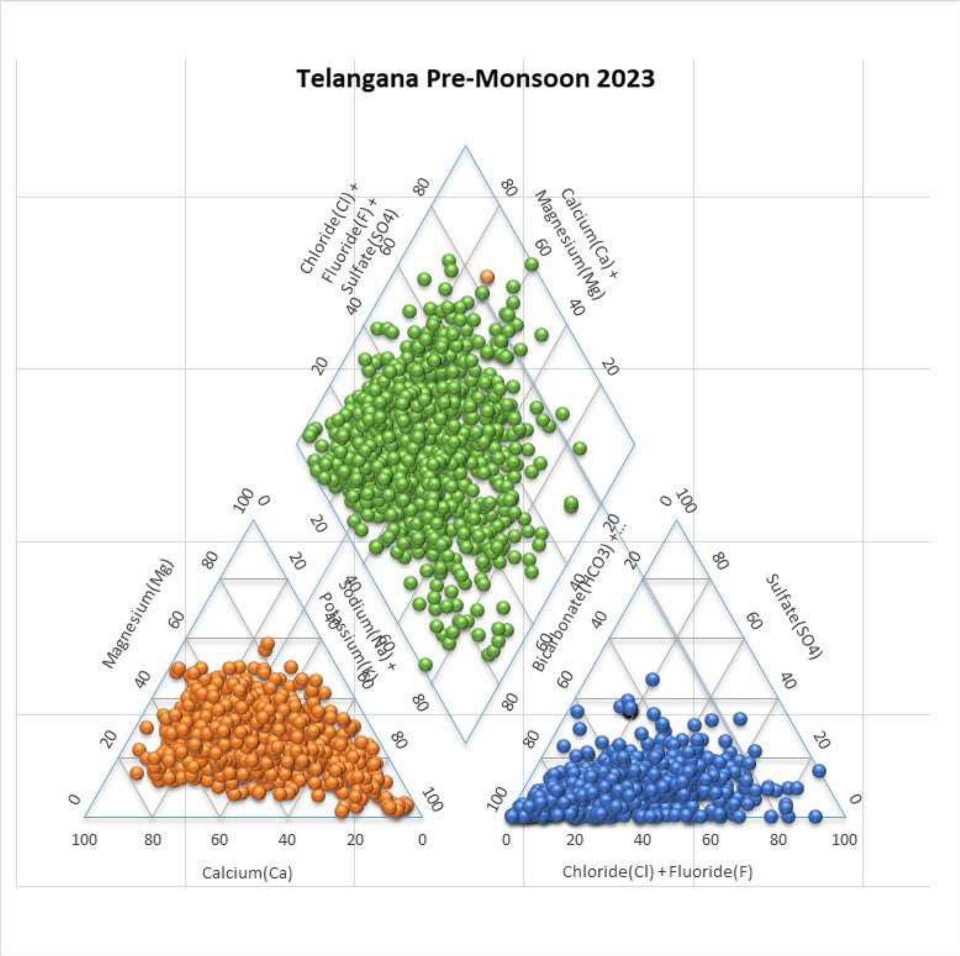


Figure 53: Piper diagram of groundwater of Telangana.

The piper plot of the Madhya Pradesh exhibits that the groundwater is mostly Ca-HCO3 type in nature. In Jharkhand ground water is mix to Ca-HCO_3 in nature. In Karnataka it is Mix to Na-Cl type in nature. In Northen States it is Ca-HCO_3 in nature and in Chhattisgarh majority of groundwater is Ca-HCO_3 in nature, where as in few locations it is Na-HCO_3 in nature.

- **X-Y Plots**: If halite dissolution is responsible for the sodium, the Na+/Cl- ratio is approximately one, whereas a ratio greater than one, it is typically interpretated as Na+ released from Silicate weathering reaction. In the water samples of the shallow aquifers of India, 28% of the samples fall along the equilibrium in the Na+/Cl- plot, indicating common source of halite for both the ions **(Fig.54)**. In the water samples of the shallow aquifers of India, 45.4% of the samples have molar ratio greater than one indicating ion exchange is the major process. It is where Na montmorillonite clay reacts with calcium and magnesium and releases sodium (sometimes called natural softening).

$$2Na^{+} - clay + Ca^{2+} \quad = \quad Ca^{2+} - clay + Na^{+}$$

The observed $Na^{+}/Cl^{-} < 1$, may be attributed to groundwater interaction with connate seawater in coastal areas and Cl^{-} enrichment from anthropogenic sources such as irrigation return flows or domestic waste disposal in another areas. Bivariant plots of India, Tamilnadu, Rajasthan and Gujarat, are shown in **Fig.54.** In Uttar Pradesh sodium and chloride enriched in groundwater by halite dissolution, ion exchange and silicate weathering processes.

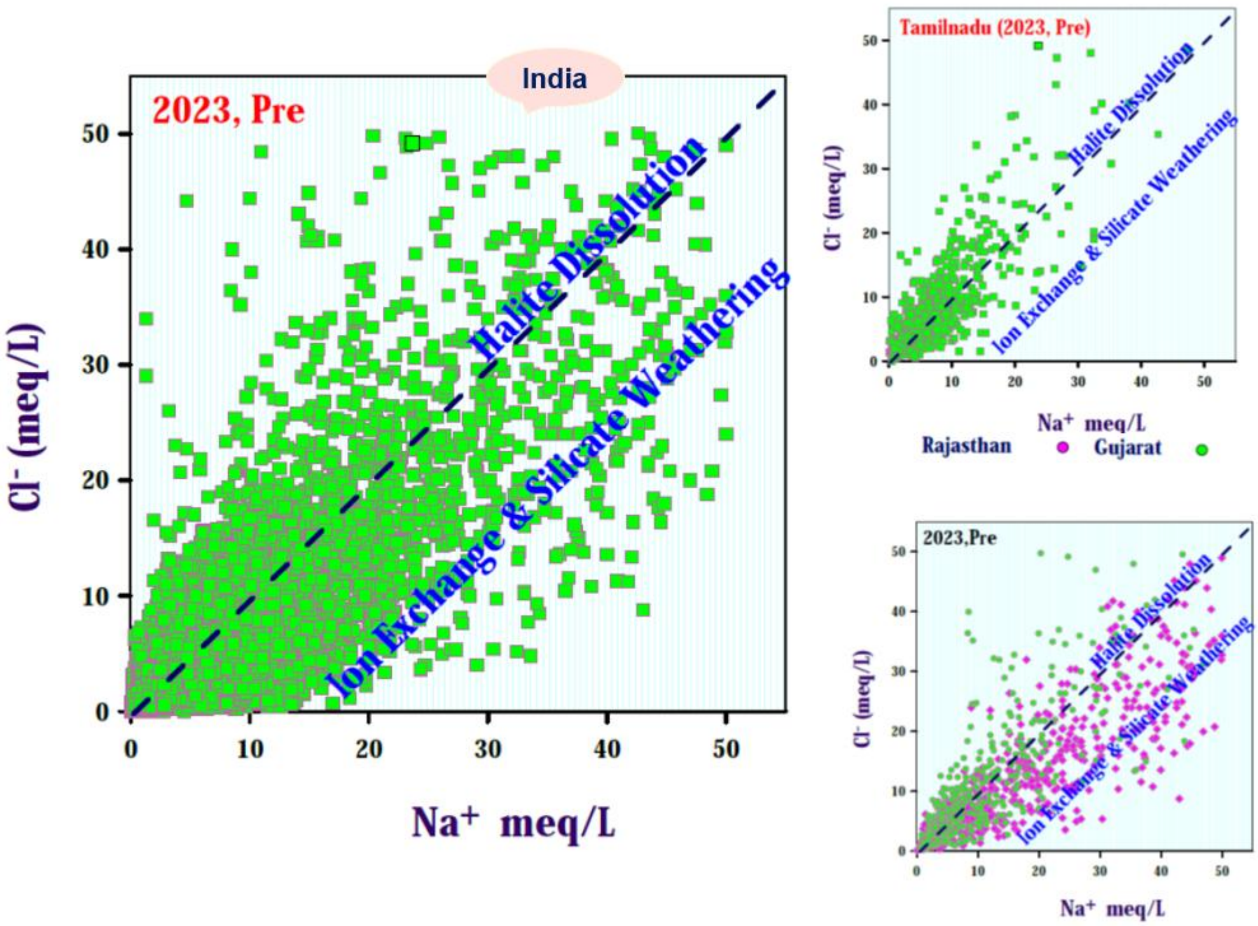


Figure 54: The plot for Na versus Cl in groundwater samples of India, Tamil Nadu, Rajasthan and Gujarat.

In West Bengal ion exchange is main mechanism for sodium and chloride enrichment in groundwater and in Rajasthan and Gujarat ion exchange and halide dissolution both of the processes are responsible for sodium and chloride enrichment in groundwater.

In summary, the Na+/Cl- ratio is a powerful tool for identifying the key processes that influence groundwater chemistry. In the shallow aquifers of India, it helps differentiate between natural processes like halite dissolution and silicate weathering, and anthropogenic influences such as irrigation and waste disposal. The ratio also helps to identify regions where natural softening due to ion exchange may be occurring, as well as areas where the groundwater has been impacted by seawater intrusion or human activities.

6.0 References

- APHA (2012) - Standard Methods for the Examination of Water & Waste Water American Public Health Association, AWWA, AIHA, Washington, D.C.
- B.I.S (1991) - Indian Standard Specifications for drinking water, B.S. 10500.
- Batabyal, A.K., 2017. Hydrogeochemical processes and contaminants enrichment with special emphasis on fluoride in groundwater of Birbhum district, West Bengal, India. *Environmental Earth Sciences*, *76*(7), p.285.
- Bhattacharya, P., Mukherjee, A. and Mukherjee, A.B., 2011. Arsenic in groundwater of India. Encyclopedia of Environmental Health. DOI: 10.1016/B978-0-444-52272-6.00345-7
- Buckman, H.O (1960) - The Nature and Properties of Soils, 6th Ed: Macmilan & Brady, N.C. Co., New York, pp 567.
- Dynamic Ground Water Resources of India (Central Ground Water Board, 2023)

- Dynamic Ground Water Resources of India (Central Ground Water Board, 2023)

- Eaton, F.M (1950) - Significance of Carbonates in Irrigation Waters. Soil Science 69 pp 123-133.
- Handa, B.K (1975) - Technical Manual on Modern Methods of Analysis, Tech. Manual no. 3, pp-160.
- Harvey, C.F., Swartz, C.H., Badruzzaman, A.B.M., Keon-Blute, N., Yu, W., Ali, M.A., Jay, J., Beckie, R., Niedan, V., Brabander, D. and Oates, P.M., 2002. Arsenic mobility and groundwater extraction in Bangladesh. Science. 298(5598), 1602-1606.
- Hem, J.D (1989) - Study and Interpretation of Chemical Characterstics of Natural Waters, U.S.G.S. Water Supply Paper 2254.
- Kumar, S., Singh, R., Venkatesh, A.S., Udayabhanu, G. and Sahoo, P.R., 2019. Medical Geological assessment of fluoride contaminated groundwater in parts of Indo-Gangetic Alluvial plains. *Scientific reports*, *9*(1), pp.1-16.
- Machiwal, D., Jha, M.K. and Mal, B.C., 2011. Assessment of groundwater potential in a semi-arid region of India using remote sensing, GIS and MCDM techniques. *Water resources management*, *25*, pp.1359-1386.
- Postma, D., Larsen, F., Thai, N.T., Trang, P.T.K., Jakobsen, R., Nhan, P.Q., Long, T.V., Viet, P.H. and Murray, A.S., 2012. Groundwater arsenic concentrations in Vietnam controlled by sediment age. Nature geoscience. 5(9), 656-661.
- Suresh Kumar, S.K., Rambabu Singh, R.S., Venkatesh, A.S., Udayabhanu, G. and Sahoo, P.R., 2019. Medical geological assessment of fluoride contaminated groundwater in parts of Indo-Gangetic Alluvial Plains.

- Tossou, Y.Y.J., Orban, P., Gesels, J., Otten, J., Yessoufou, S., Boukari, M. and Brouyère, S., 2017. Hydrogeochemical mechanisms governing the mineralization and elevated fluoride\left (F^-\right) F-contents in Precambrian crystalline aquifer groundwater in central Benin, Western Africa. *Environmental Earth Sciences, 76,* pp.1-14.
- UNESCO, 2021. *The United Nations world water development report 2021: valuing water*. United Nations.
- UNESCO, 2021. *The United Nations world water development report 2021: valuing water*. United Nations.
- W.H.O (1984) - Guidelines for Drinking Water Quality Vol. 1, WHO, Geneva.

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