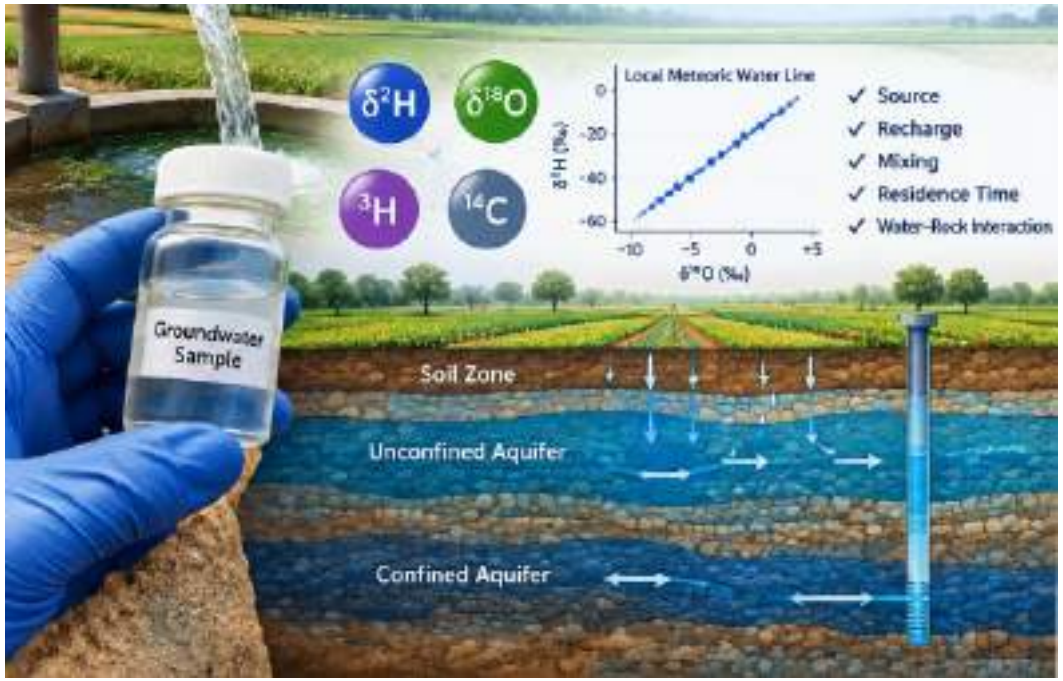
Deciphering Groundwater Systems through Isotopes: Case Studies Supporting Aquifer Management in Northwest India



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Content

- **Background & Motivation**
  Groundwater dependence, overexploitation, and emerging quality concerns in Punjab and Haryana
- **Study Areas & Objectives**
  Amritsar, Punjab, and Behal–Loharu, Bhiwani, Haryana
- **Approach & Methodology**
  Hydrochemistry, environmental isotopes, groundwater age, and spatial analysis
- **Groundwater Quantity & Recharge**
  Groundwater levels, recharge sources, flow processes, and renewal potential
- **Groundwater Quality & Geochemical Processes**
  Salinity, fluoride, nitrate, arsenic, iron, and manganese
- **Isotopic Evidence & Groundwater Age**
  $\delta^{18}O$, $\delta^{2}H$, d-excess, and tritium-based assessment of recharge and residence time
- **Key Findings & Implications**
  Identification of vulnerable zones, recharge processes, and groundwater-quality controls
- **Management Strategies**
  Sustainable groundwater management, recharge enhancement, and **Managed Aquifer Recharge (MAR)**

Motivation

- **High groundwater dependence:** Punjab and Haryana's agricultural belt depends almost entirely on groundwater for irrigation and drinking.

- **Unsustainable abstraction:** Intensive year-round farming draws water far faster than the monsoon can replenish it.

- **Depletion of older groundwater:** Extraction has moved to deep layers (approaching 100 m); tritium shows this water is ancient, i.e., finite reserves are being permanently depleted, highlighting limited contemporary replenishment of deeper aquifers..

- **Emerging groundwater-quality concerns:**
  Under oxygen-starved conditions, reductive dissolution of alluvial sediments releases geogenic Arsenic (with Fe and Mn) in Amritsar, Punjab, making raw groundwater unsafe in several border villages.

  Bhiwani district faces groundwater challenges, including overexploitation, salinity, hardness, nitrate, and fluoride enrichment, high salinity, hardness, and elevated nitrate concentrations.

- **Need for an integrated assessment: Environmental isotopes + hydrochemistry + spatial analysis**: identify recharge sources, evaluate groundwater age and renewal, understand contaminant mobilization, and support sustainable groundwater management and MAR strategies.

Contaminations moving to deeper aquifers

North-west India

AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2015GL065798

Key Points:
- Tracers reveal low regional anisotropy in the sedimentary aquifer system of NW India
- Local meteoric recharge sources dominate in both shallow and deep aquifers
- Evidence of enhanced modern recharge at depth due to intensive abstraction

Groundwater recharge and age-depth profiles of intensively exploited groundwater resources in northwest India

D. J. Lapworth[1], A. M. MacDonald[2], G. Krishan[3], M. S. Rao[3], D. C. Gooddy[1], and W. G. Darling[1]

[1]British Geological Survey, Wallingford, UK, [2]British Geological Survey, Edinburgh, UK, [3]National Institute of Hydrology, Roorkee, India

Abstract Intensive irrigation in northwest India has led to growing concerns over the sustainability of current and future groundwater abstraction. Environmental tracers and measurements of groundwater

Contaminations moving to deeper aquifers

North-west India

Science of the Total Environment 599–600 (2017) 1433–1444

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Groundwater quality in the alluvial aquifer system of northwest India: New evidence of the extent of anthropogenic and geogenic contamination

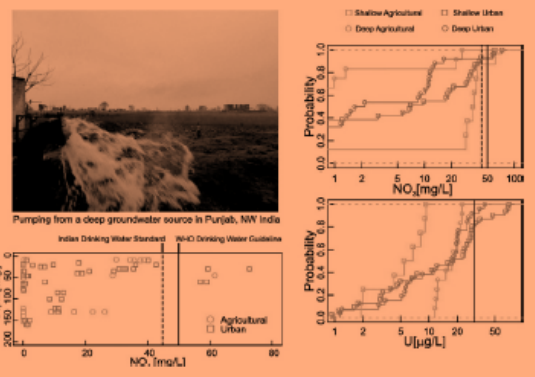
D.J. Lapworth [a,*], G. Krishan [b], A.M. MacDonald [c], M.S. Rao [b]

[a] British Geological Survey, Maclean Building, Wallingford, UK
[b] National Institute of Hydrology, Roorkee, Uttarakhand, India
[c] British Geological Survey, Lyell Centre, Edinburgh, UK

HIGHLIGHTS

- Distinct urban, agricultural and geogenic sources of groundwater contamination
- Elevated uranium occurrence, exceeding 30 μg/L in 10% of sites
- Shallow aquifer system has significantly enhanced salinity, and nitrate and selenium concentrations.
- There is evidence of salinity and nitrate breakthrough to depths >100 m due to pumping.

GRAPHICAL ABSTRACT



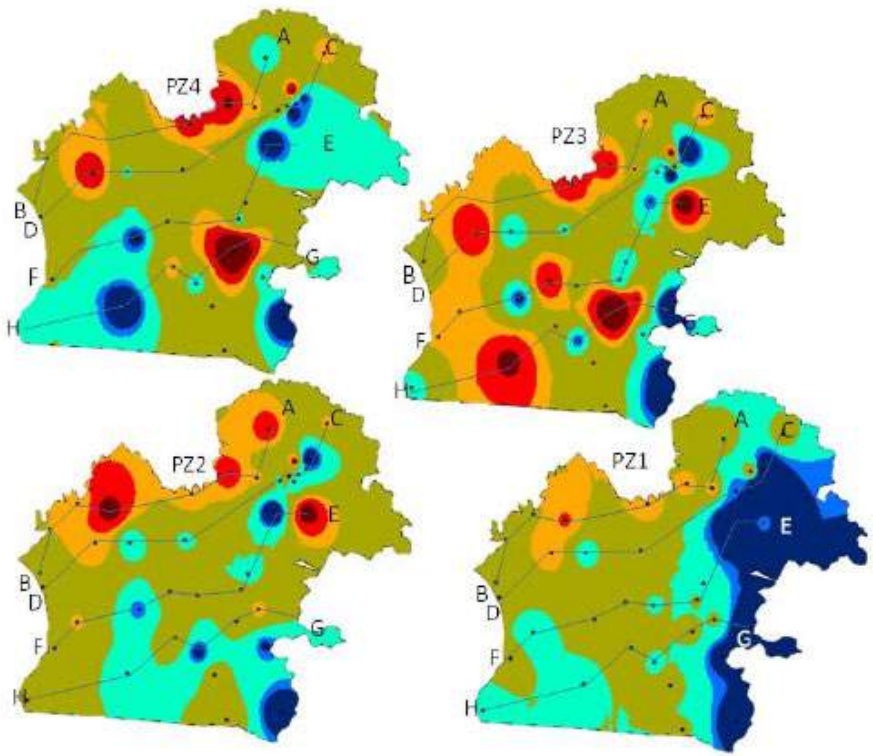
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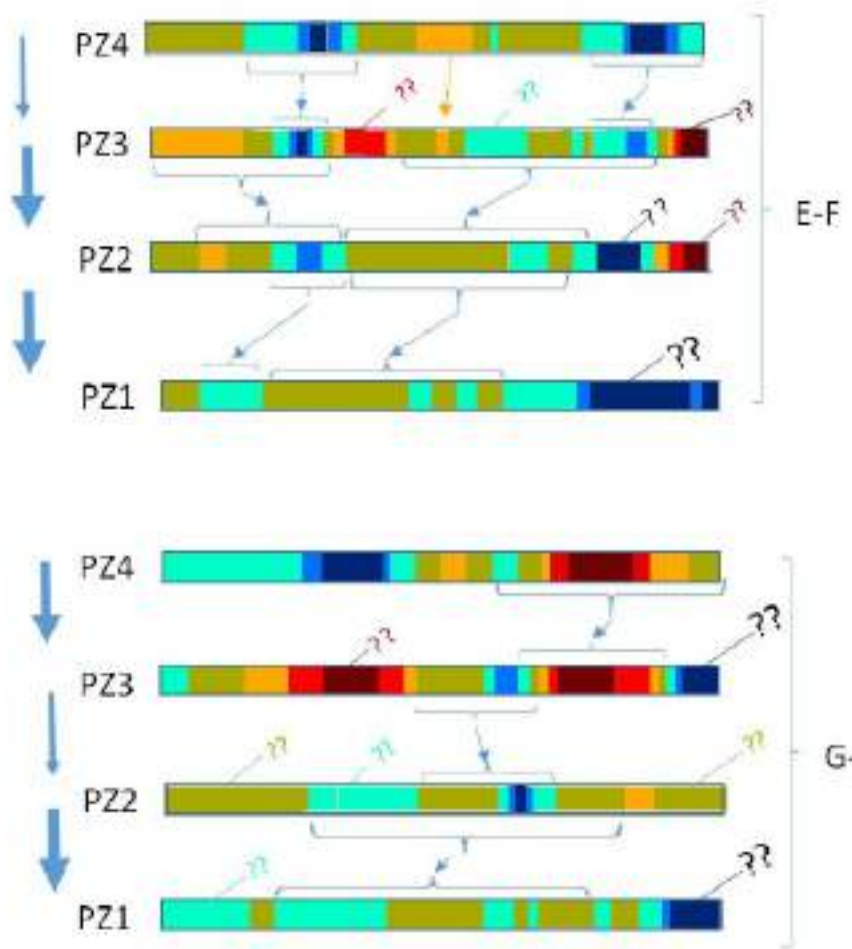
MDPI

Article

Isotopic Assessment of Groundwater Salinity: A Case Study of the Southwest (SW) Region of Punjab, India

Gopal Krishan [1], Mavidanam Someshwar Rao [1], Rajesh Vashisht [2], Anju Chaudhary [1], Jaswant Singh [3] and Amit Kumar [1,4]





Brackets and line enclosed zone indicates aquifer interaction region; ? (unknown) indicates zone of recharge area lying outside the study area.
R, C, R + C, RHE, RME indicate the recharge sources as rain, canal, rain + canal, rain – highly evaporated water, and rain – moderately evaporated water, respectively, as well as the extent of evaporation prior to the recharge process.

Figure 15. Interactions in E–F and G–H cross-sections.

Science of the Total Environment 789 (2021) 148051

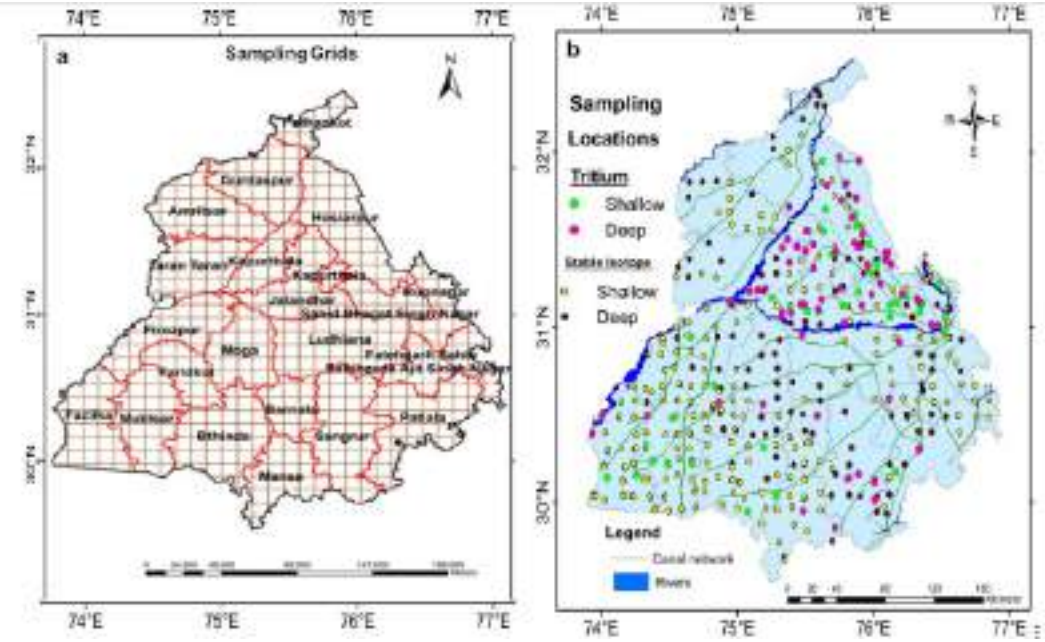
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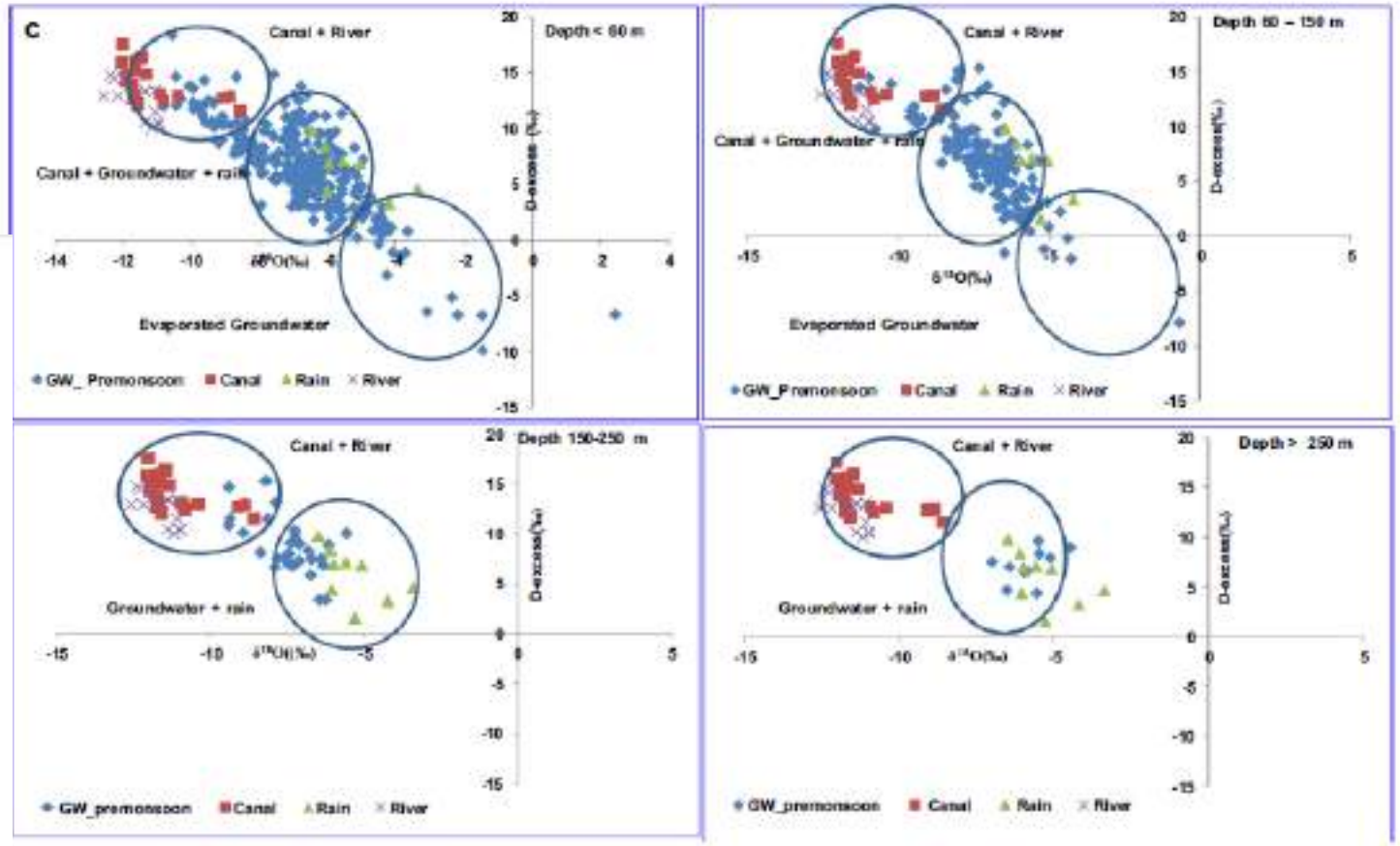
Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Isotopes ($\delta^{18}O$, δD and ^{3}H) variations in groundwater with emphasis on salinization in the state of Punjab, India

Gopal Krishan[a,*], Bhishm Kumar[a,b], Natarajan Sudarsan[a], Mavidanam Someshwar Rao[a], Narayan Chandra Ghosh[c], Ajay Kumar Taloor[d], Prosun Bhattacharya[e], Surjeet Singh[a], Chander Prakash Kumar[a], Anupma Sharma[a], Sharad Kumar Jain[a,f], Balwinder Singh Sidhu[g], Sumant Kumar[a], Rajesh Vasisht[h,i]





Objectives

- **Goal:** decoding the hydrogeochemical and isotopic framework of the Amritsar transboundary aquifers and the Behal–Loharu blocks of Bhiwani District, semi-arid southwestern Haryana

- **Isotopic tracing & age-dating** - delineate active recharge sources and assess groundwater residence times using stable isotopes ($\delta^{18}O$, $\delta^{2}H$) and radioactive tracer (^{3}H)

- **Aquifer dynamics** - characterize groundwater movement and recharge mechanisms through integrated isotopic and hydrogeological investigations.

Study Area & Sampling Network





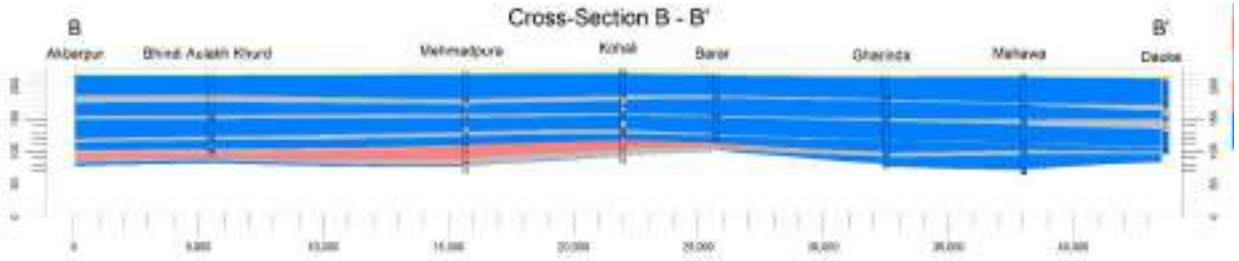


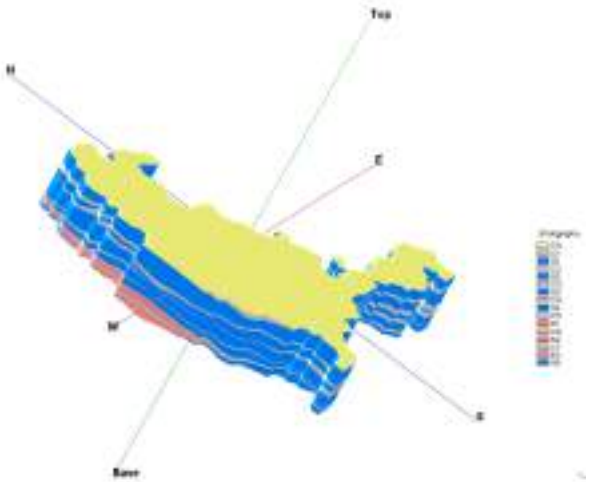


- **Study area**: two bordering blocks of the Amritsar district along the Ravi River and two blocks of the semi-arid region of the Bhiwani district.
- **Sampling network**: 75 groundwater sites in Amritsar and 57 sites in Bhiwani district.
- **Seasons covered**: pre-monsoon (June 2025;) and post-monsoon (Amritsar-December 2025; Bhiwani- November 2024).
- **Isotope inputs**: Rainfall stations (multi-event) define the local meteoric signal; the Ravi River sampled as the surface-water end-member for Amritsar and canal water in Bhiwani.
- **Tritium subset**: 17 wells selected for groundwater age-dating in Amritsar.
- **Parameters measured**: field physico-chemistry, trace metals, stable isotopes ($\delta^{18}O$, δD) and tritium (^{3}H).

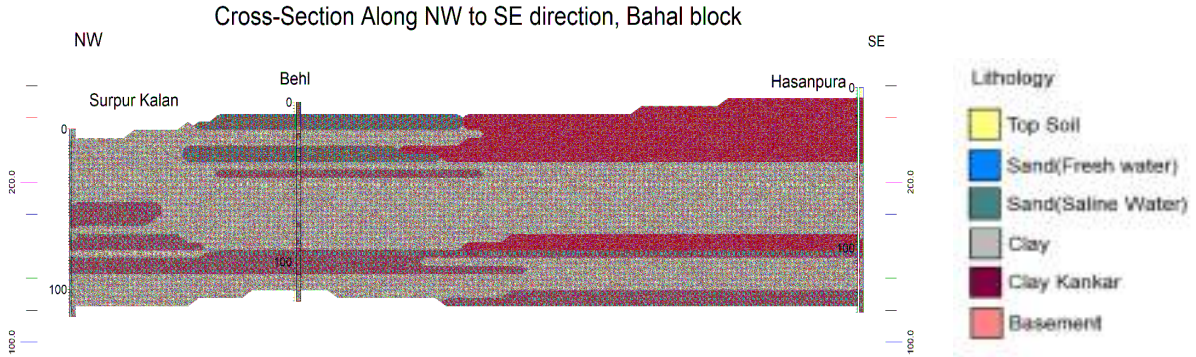
Aquifer disposition

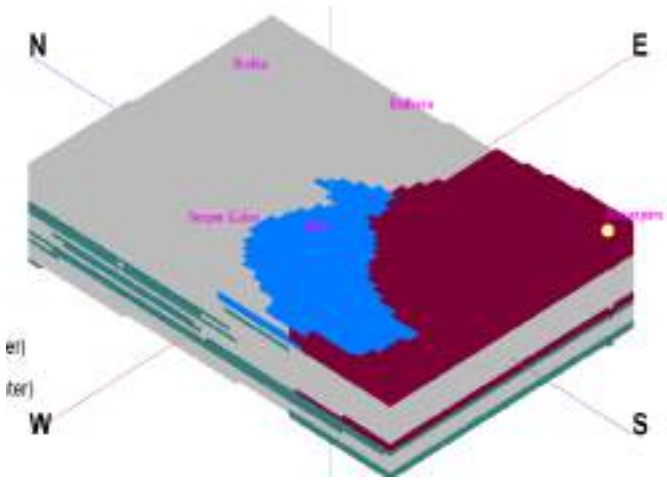
Amritsar

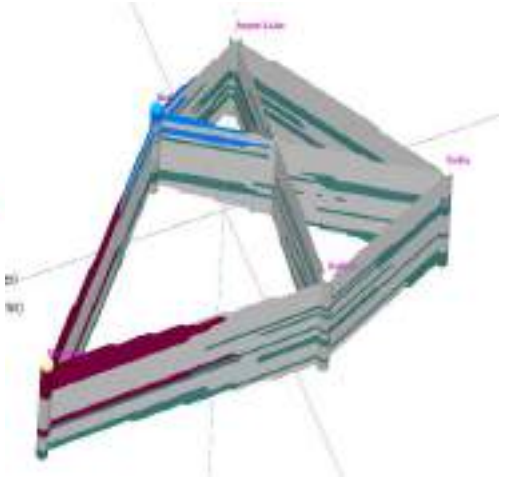




Bhiwani

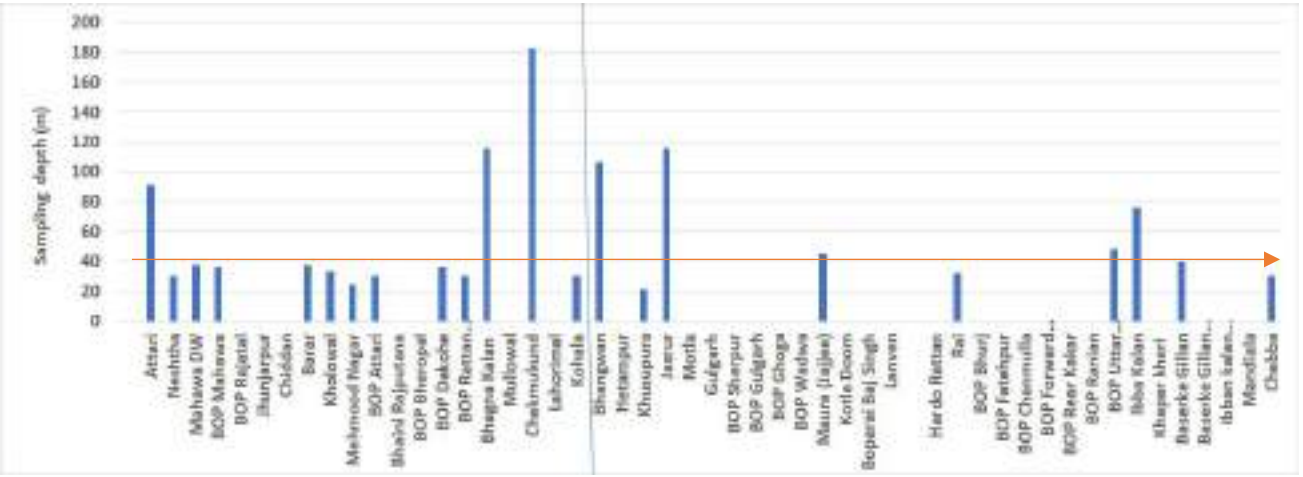




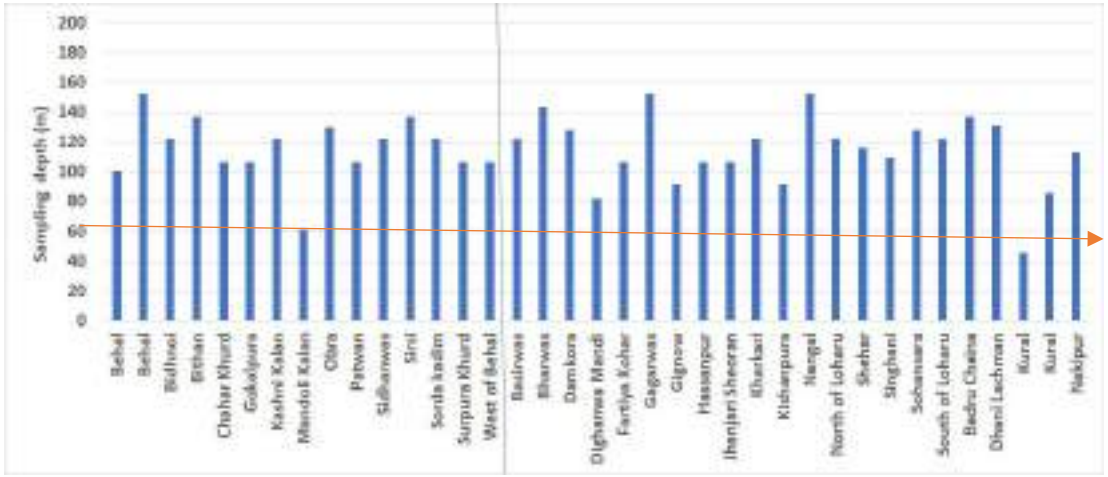


Sampling Depths

Amritsar



Bhiwani



Sample Analysis

Field measurement, laboratory analysis, and spatial interpretation

- **Field parameters**: EC, pH, ORP, temperature and TDS measured on-site with calibrated multi-parameter probes.

- **Trace metals**: samples acidified to pH < 2 (ultra-pure HNO_3), filtered, and analysed by **ICP-MS** for Arsenic (As), Iron (Fe), Manganese (Mn) and other heavy metals (Pb, Ni, Cu, Zn).

- **Stable isotopes ($\delta^{18}O$, δD)**: Analysed using CF&DI IRMS available at Nuclear Hydrology Lab

- **Tritium (^3H)**: measured by Low-Level Liquid Scintillation Counting (LSC) after electrolytic enrichment; Tritium Units (TU) separate modern from sub-modern/old groundwater.
  - **All the parameters are measured using in-house instrumentation facilities**

Isotopes – Tracers for a Sustainable Water Future

Understanding the origin, movement and age of water

What are isotopes?

Isotopes are variants of an element with the same number of protons but different number of neutrons, which gives them different atomic masses and properties.

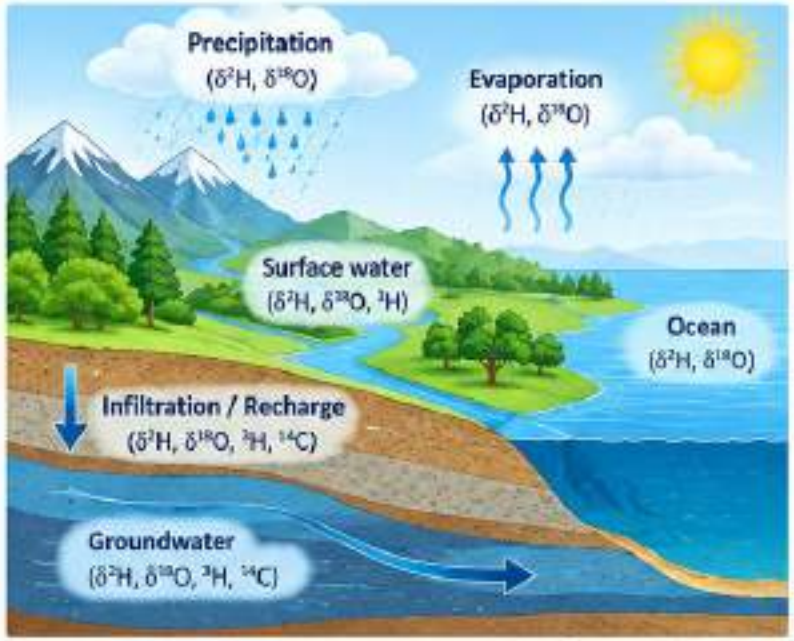
Common isotopes used in hydrology and water resources

- **^{2}H (Deuterium)**
  Stable isotope of hydrogen
- **^{18}O (Oxygen-18)**
  Stable isotope of oxygen
- **^{3}H (Tritium)**
  Radioactive isotope (half-life 12.3 years)
- **^{14}C (Carbon-14)**
  Radioactive isotope (half-life 5730 years)
- **^{210}Pb (Lead-210)**
  Radioactive isotope (half-life 22.3 years)

Isotopic composition is reported as δ (delta) values (e.g., $\delta^{2}H$, $\delta^{18}O$) or activity (e.g., ^{3}H, ^{14}C) relative to standards.

Why are isotopes useful in water resources?

- Act as natural tracers in the water cycle
- Help identify the source and origin of water
- Reveal mixing of different water sources
- Provide information on water residence time (age)
- Indicate processes such as evaporation, recharge, and groundwater–surface water interactions
- Support climate and palaeohydrological studies



Key Applications in Water Resources

Source Identification

- Distinguish rainfall, river, lake, groundwater and recycled water
- Understand recharge mechanisms

Mixing and Flow Paths

- Identify mixing of different water sources
- Trace flow paths in aquifers and rivers

Groundwater Age and Residence Time

- ^{3}H and ^{14}C indicate how old the water is
- Helps in sustainable groundwater management

Evaporation and Climate Signals

- $\delta^{2}H$ and $\delta^{18}O$ show evaporation effects
- Reconstruct past climate and environmental changes

Surface–Groundwater Interaction

- Understand exchange between rivers, lakes and aquifers
- Support ecosystem and river basin management

Contaminant and Water Quality Studies

- ^{14}C and ^{10}Be for young water and recharge
- Helps in assessing vulnerability and pollution sources

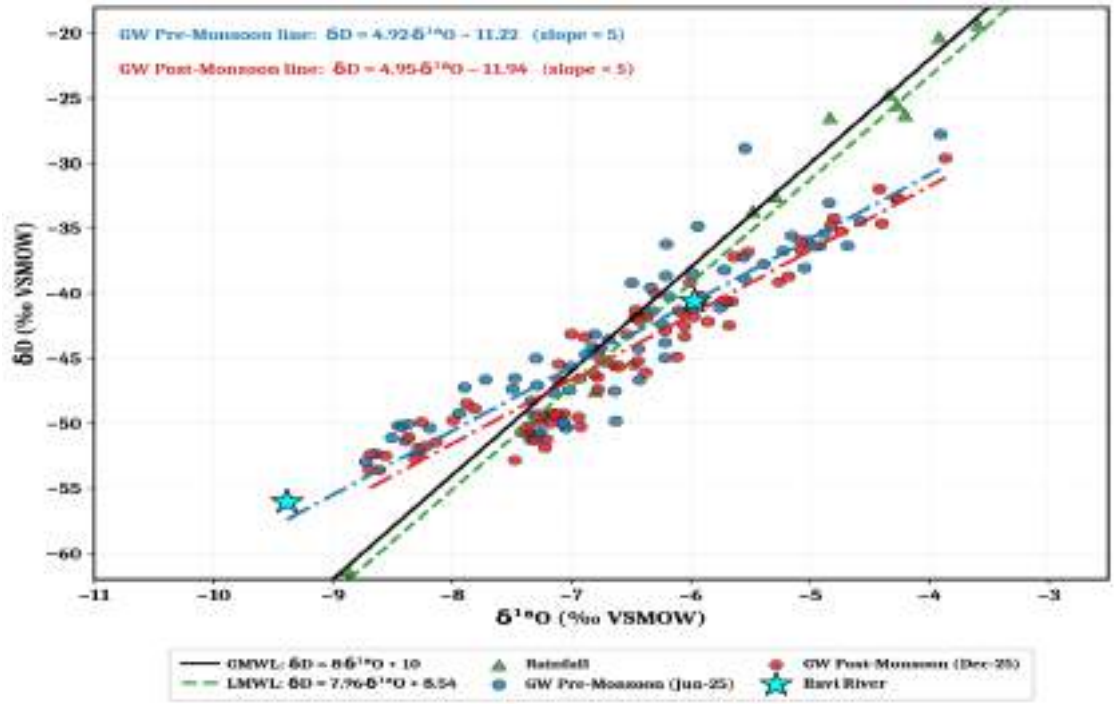
Isotopes turn water into a time machine and a natural tracer — helping us manage, protect and sustain our precious water resources.

Results

$\delta^{18}O$ – δD Relationship: Evaporation Signature

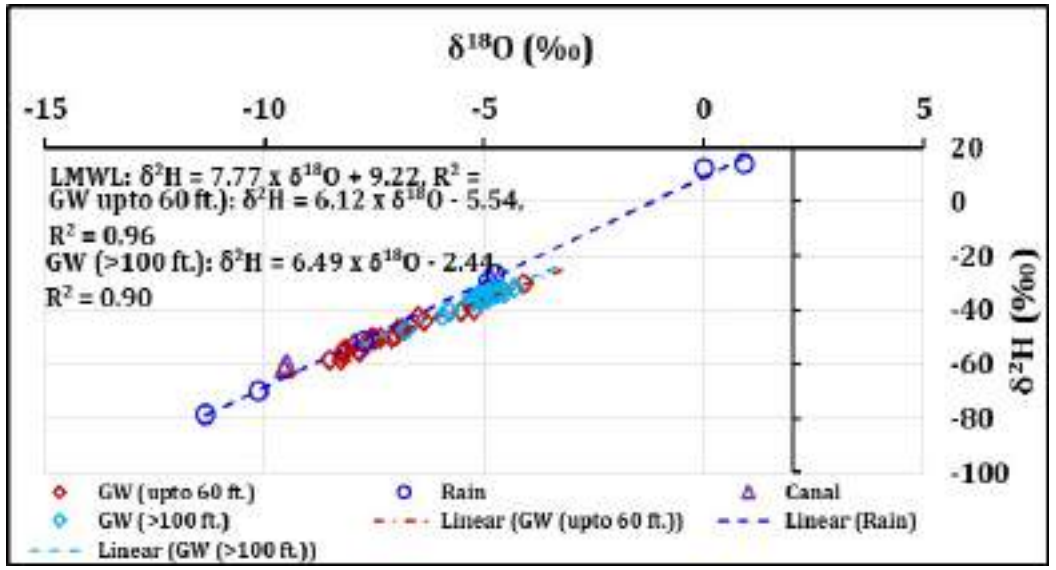
$\delta^{18}O$ – δD Dual Isotope Plot (GMWL, LMWL & Groundwater Evaporation Lines)

Amritsar



- LMWL ($\delta D = 7.96 \cdot \delta^{18}O + 8.54$, $R^2 = 0.997$)
- Groundwater slope (≈ 4.9)
- Ravi River is the most depleted, freshest end-member.

Bhiwani

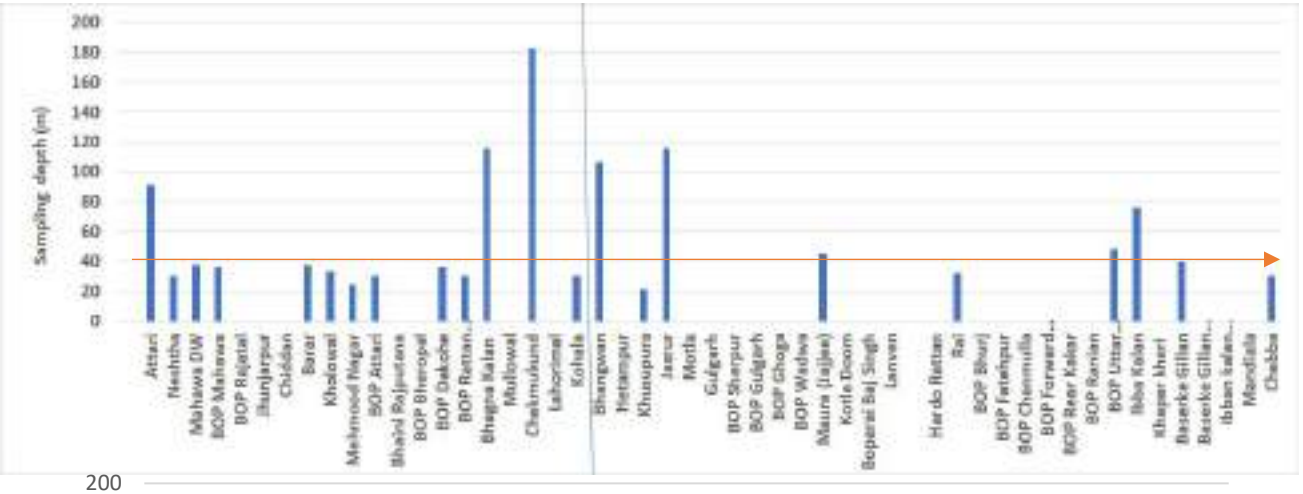


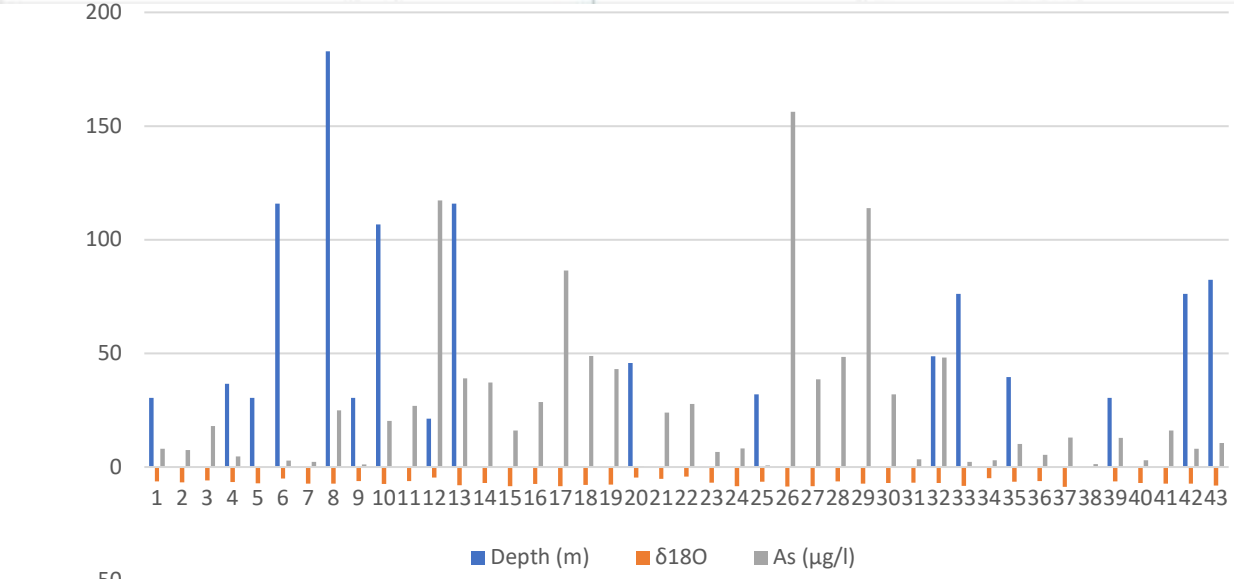
- LMWL ($\delta D = 7.77 \cdot \delta^{18}O + 9.22$, $R^2 = 0.997$)
- Groundwater slope (≈ 6)
- Loharu Canal is the depleted, freshest end-member.

Recharge is evaporation-modified water + irrigation return flow, not rapid rainfall infiltration.

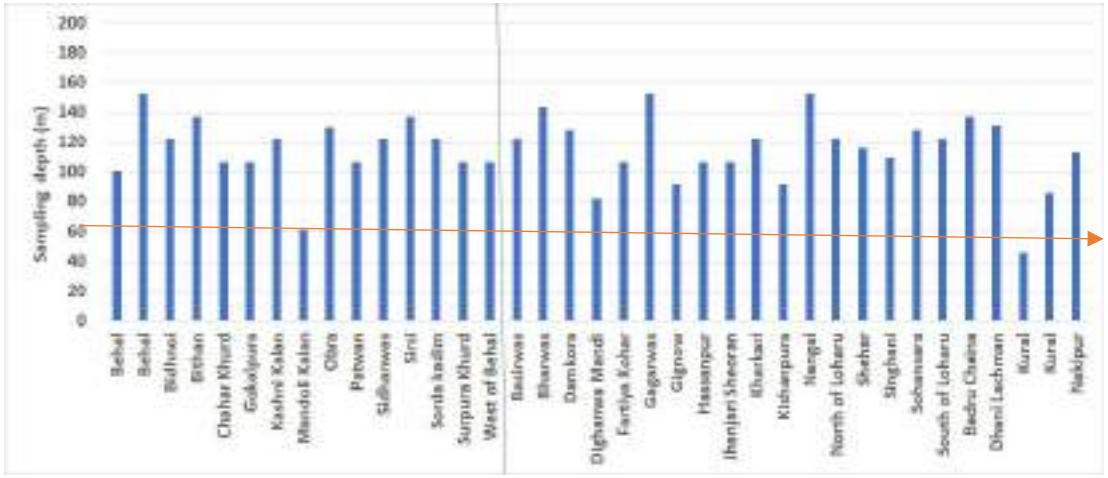
Sampling Depths

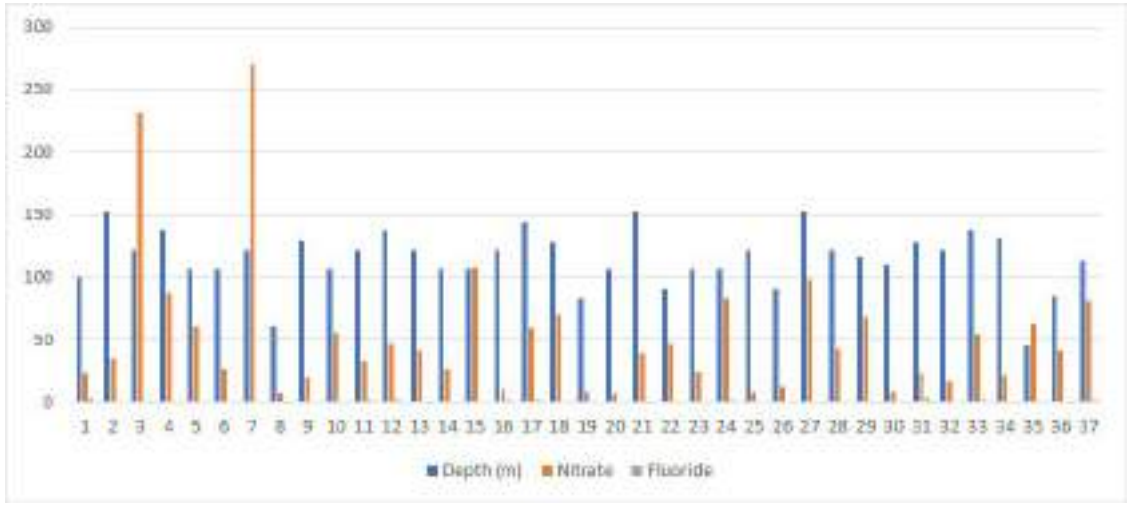
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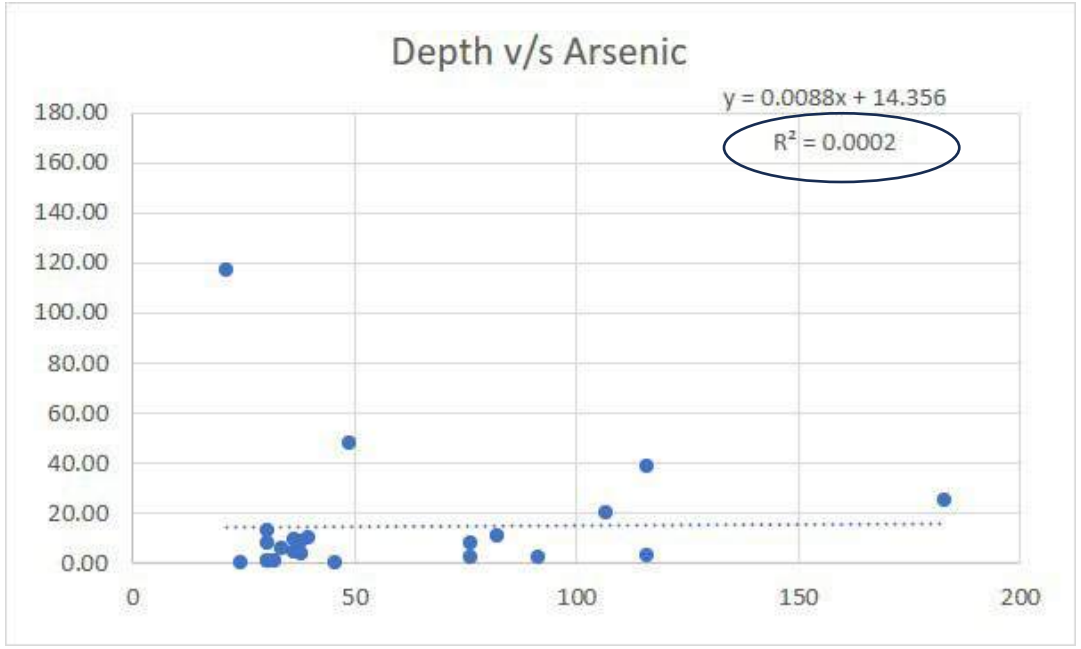
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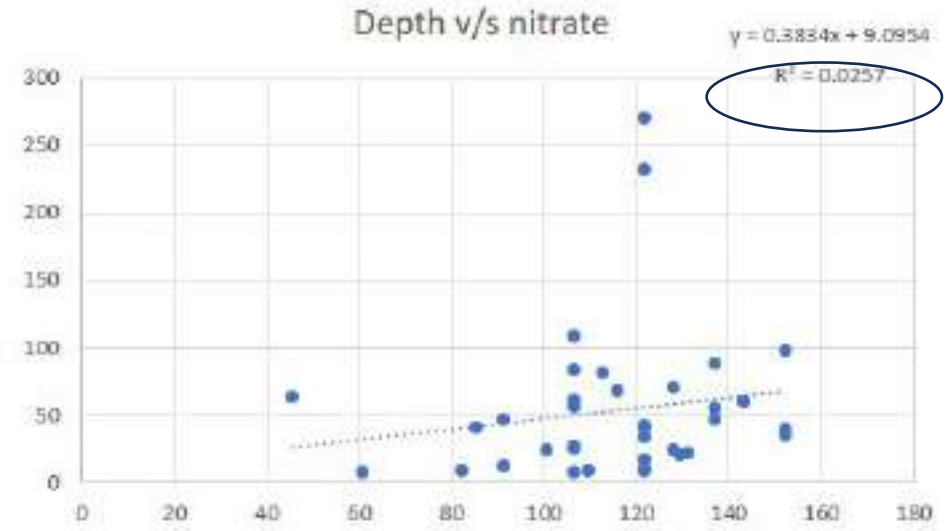


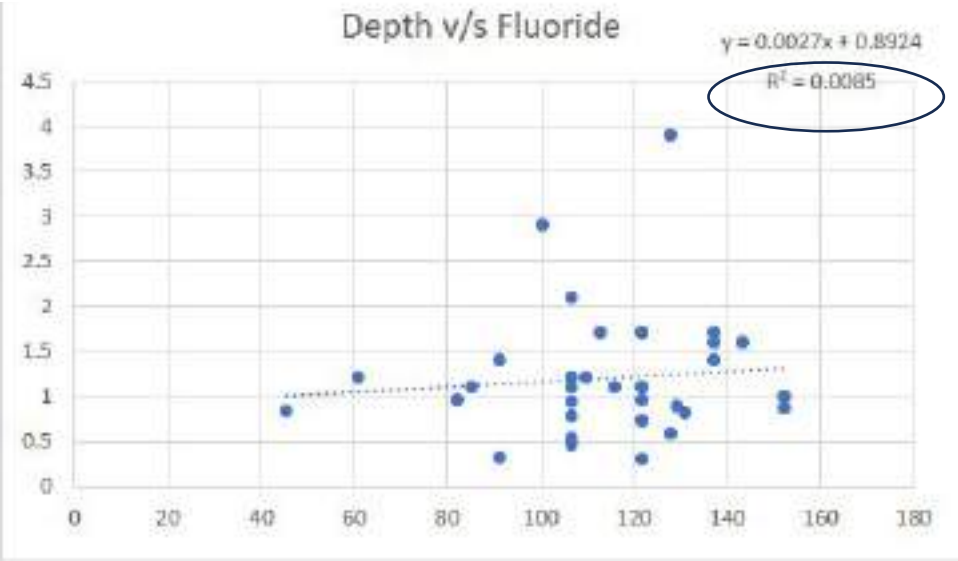
Sampling Depths

Amritsar



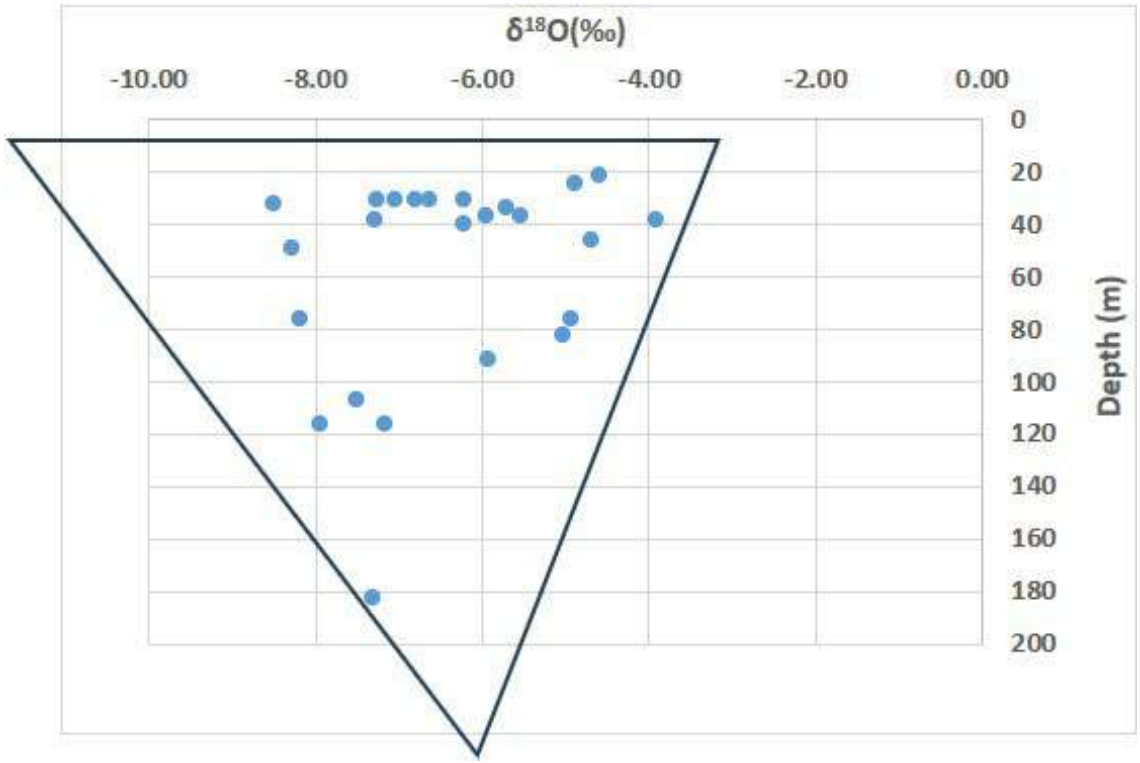
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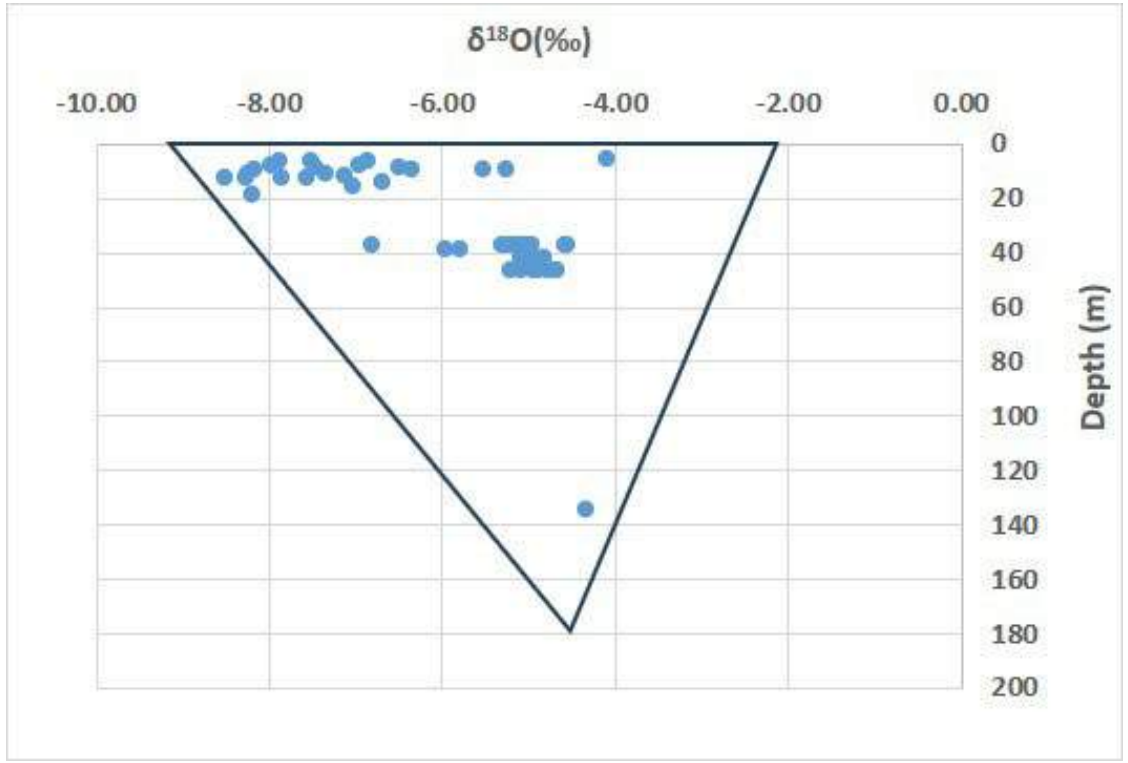


Sampling Depths

Amritsar



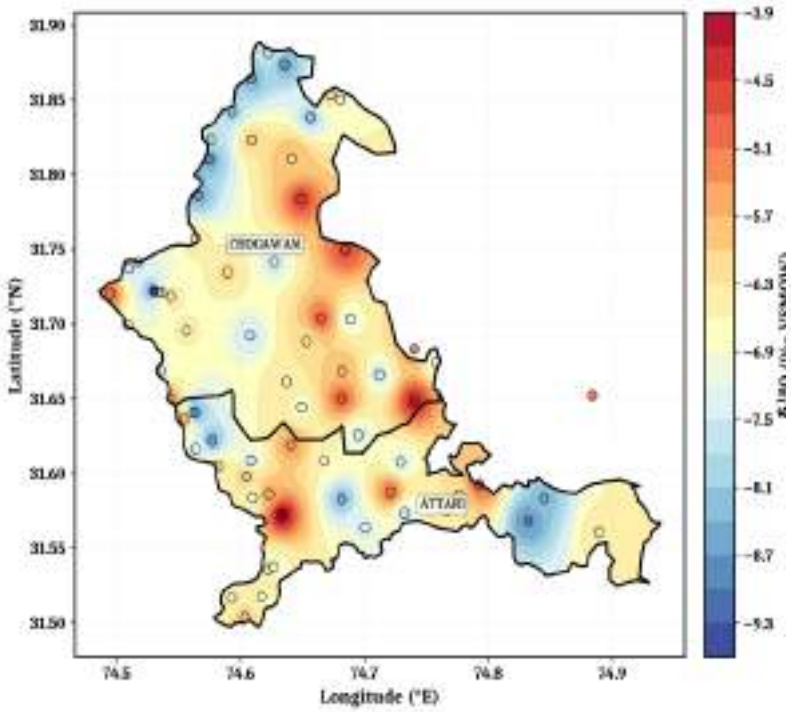
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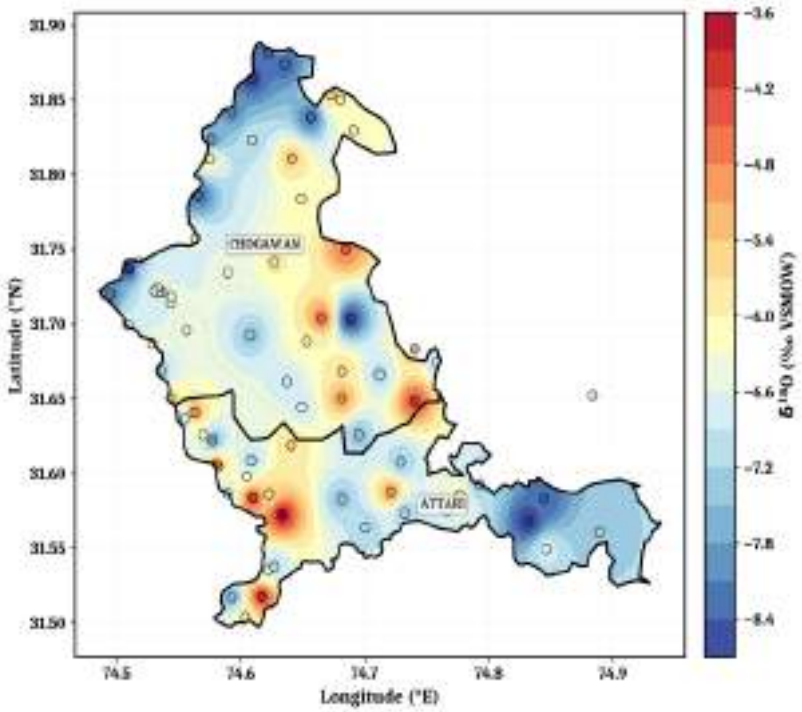
Results..

Spatial Distribution of $\delta^{18}O$ (Pre vs Post-Monsoon) Amritsar

Pre-Monsoon : June 2025



Post-Monsoon: December 2025



Stable isotopic baseline: Groundwater exhibits a remarkably consistent mean **$\delta^{18}O$ value of ~–6.6‰** in both pre- and post-monsoon seasons, indicating a relatively stable isotopic character of the groundwater system.

Distinct spatial variability: The **most isotopically depleted groundwater** occurs in the **northwestern sector near the Ravi River corridor**, whereas relatively **enriched $\delta^{18}O$ signatures** are observed in localized pockets of the central–southeastern agricultural interior.

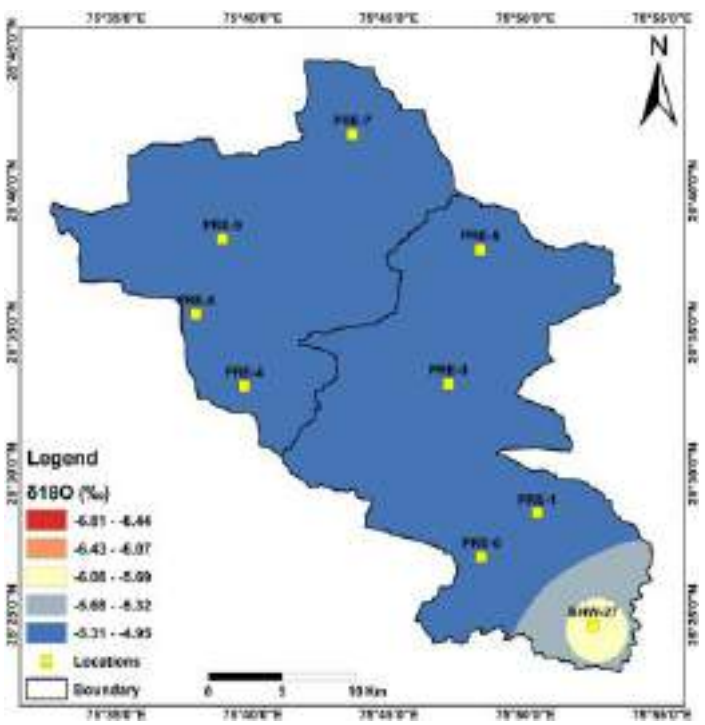
Recharge-source indication: The spatial distribution of $\delta^{18}O$ reflects differences in **recharge sources and processes**, with depleted signatures indicating relatively less evaporated meteoric recharge and enriched signatures suggesting **evaporation-modified recharge and irrigation return flow**.

Implications for groundwater management: The identified isotopic patterns help delineate **recharge pathways and zones influenced by irrigation**, providing useful evidence for targeting **managed aquifer recharge and sustainable groundwater management interventions**.

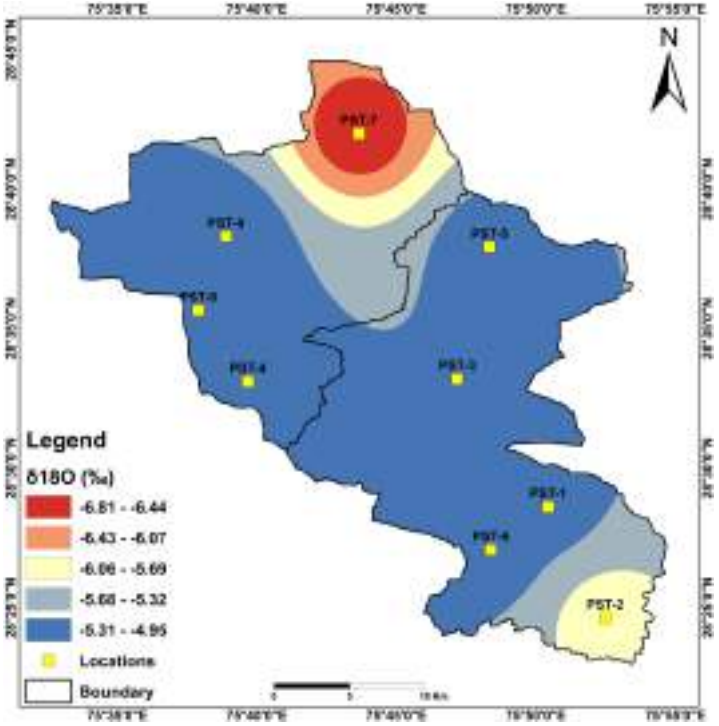
Results..

Spatial Distribution of $\delta^{18}O$ (Pre vs Post-Monsoon) Bhiwani

Pre-Monsoon : June 2025



Post-Monsoon: November 2024



Stable isotopic baseline: Groundwater shows a consistent mean **$\delta^{18}O$ value of ~–5‰** in both pre- and post-monsoon seasons, indicating a relatively stable isotopic composition of the groundwater system.

Localized isotopic depletion: The **most depleted $\delta^{18}O$ signatures occur in the northern part of the study area during the post-monsoon season**, suggesting a greater contribution from relatively depleted meteoric/monsoon recharge.

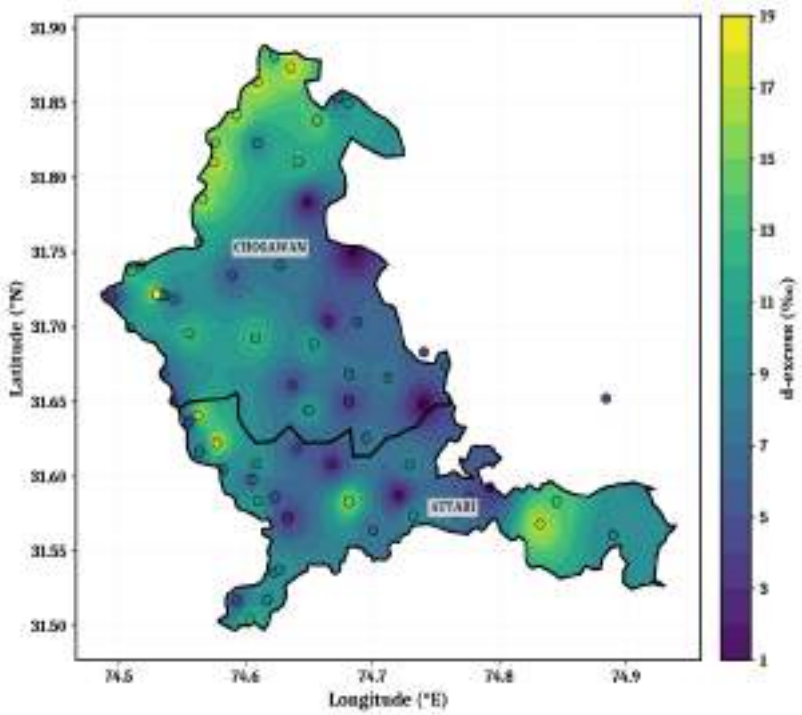
Widespread isotopic enrichment: Relatively enriched $\delta^{18}O$ values dominate **most of the study area**, indicating substantial influence of **evaporation-modified recharge and irrigation return flow**.

Recharge-process implication: The spatial isotope pattern highlights **seasonal and spatial variability in recharge sources and processes**, with evaporation and irrigation playing an important role in groundwater replenishment across the study area.

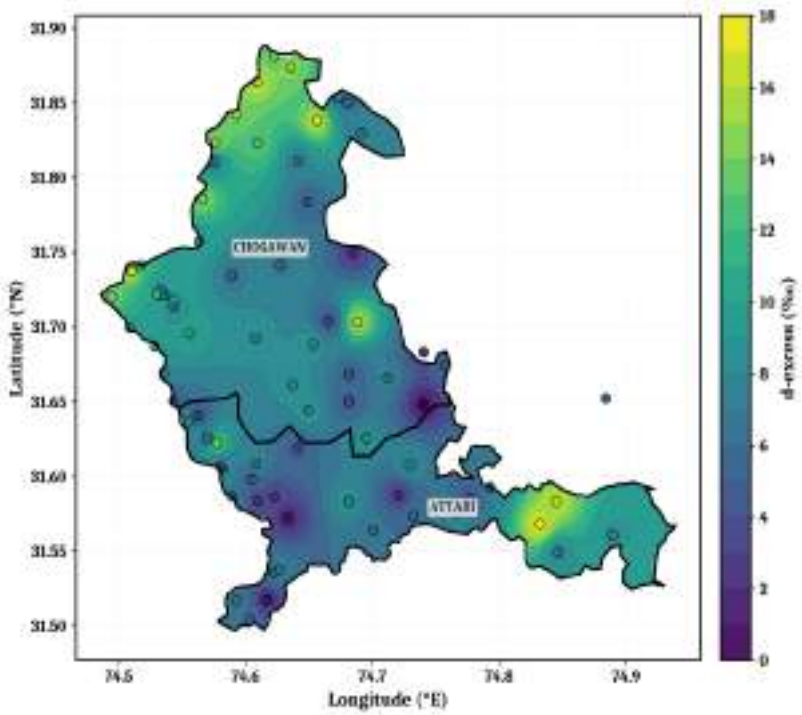
Results..

Spatial Distribution of Deuterium Excess -Amritsar

Pre-Monsoon: June 2025



Post-Monsoon: December 2025



Seasonal d-excess variation: Mean groundwater **d-excess decreases from 9.1‰ in the pre-monsoon to 8.2‰ in the post-monsoon season**, indicating increased influence of evaporation during/after the monsoon recharge period.

Low d-excess zones: Areas with **d-excess <6‰** indicate stronger **evaporative modification during recharge**, potentially associated with soil-zone evaporation and prolonged water–soil interaction.

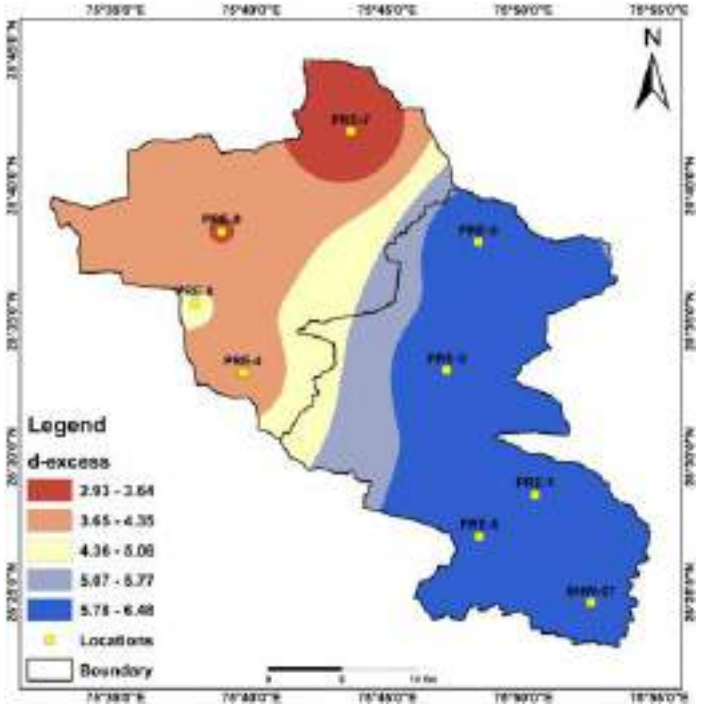
High d-excess pockets: Localized areas with **d-excess >12‰** suggest **relatively rapid and less-evaporated recharge**, particularly near river–canal corridors.

Recharge-process indicator: The spatial variability in d-excess serves as a useful tracer for distinguishing evaporated- or **irrigation-influenced recharge from relatively fresh, direct recharge pathways**.

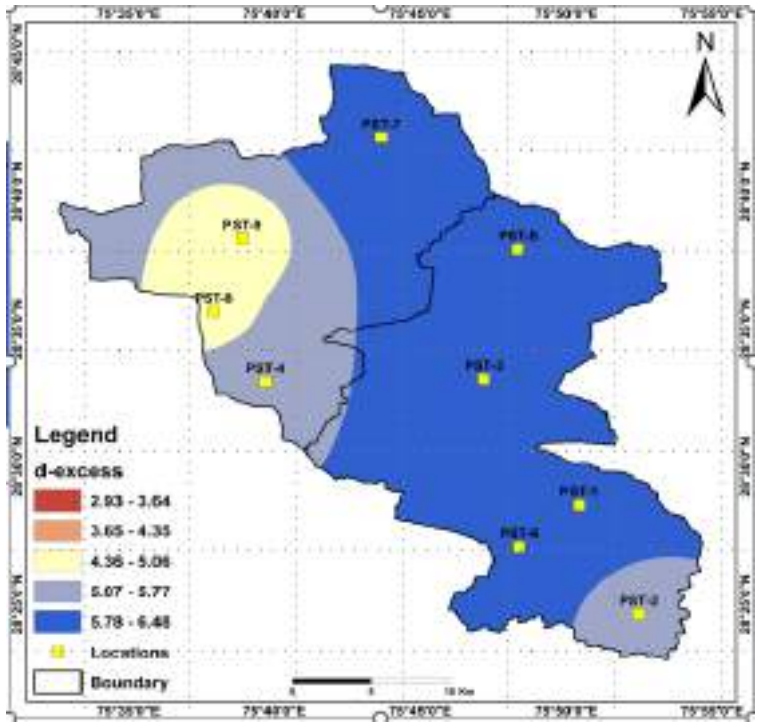
Results..

Spatial Distribution of Deuterium Excess -Bhiwani

Pre-Monsoon: June 2025



Post-Monsoon: November 2024



Seasonal shift in d-excess: Mean groundwater **d-excess increases from 2.93‰ in the pre-monsoon to 6.48‰ in the post-monsoon season**, indicating a greater contribution from relatively less-evaporated monsoon recharge following seasonal rainfall.

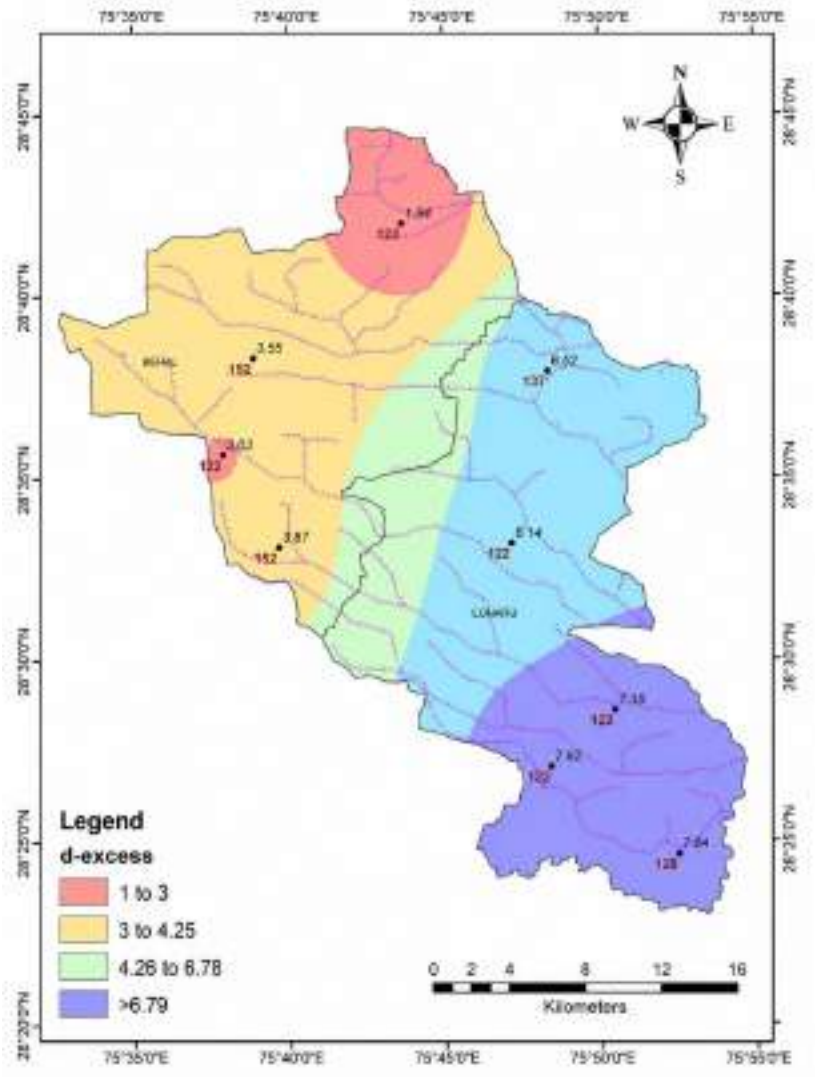
Low d-excess zones: Areas with **d-excess <5‰** indicate significant **evaporative modification during recharge**, associated with soil-zone evaporation and/or prolonged water–soil interaction.

Higher d-excess pockets: Localized areas with **d-excess >6‰** suggest **relatively fresh and less-evaporated recharge**, particularly in zones influenced by river–canal corridors.

Recharge-process implication: The pronounced spatial and seasonal variability in d-excess provides a useful indicator for **distinguishing evaporation-affected recharge from relatively direct and rapid recharge pathways**.

Results..

Spatial Distribution of Deuterium Excess -Bhiwani



Spatial variability in d-excess: Groundwater d-excess values range from approximately **1‰ to >6.79‰**, indicating substantial spatial variability in recharge conditions and the degree of evaporative modification.

Recharge-process indicators: Low d-excess (<4‰) identifies zones strongly influenced by **soil-zone/subsurface evaporation**, whereas **higher d-excess (>5‰)** indicates relatively **fresh, less-evaporated and potentially faster recharge**, particularly near river–canal corridors.

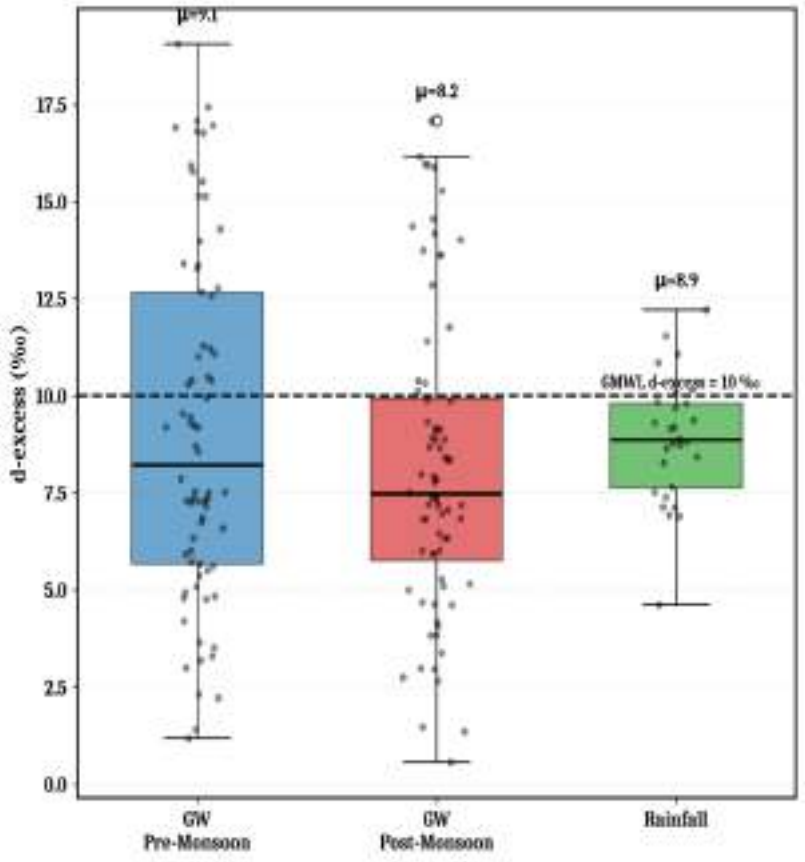
Recharge zoning: Sohansara, Basirwas and northern Loharu exhibit signatures indicative of **relatively high-quality recharge**, while **Sidhanwas, northern Behal and Sorda Kadim** show stronger evidence of **evaporation-modified recharge**.

Management implications: Eastern Loharu and Kharkari show evidence of **canal-influenced recharge**, whereas **western Behal and intensively irrigated areas** exhibit signatures consistent with **limited/poor effective recharge and greater influence of irrigation return flow**, identifying areas requiring targeted groundwater-management interventions.

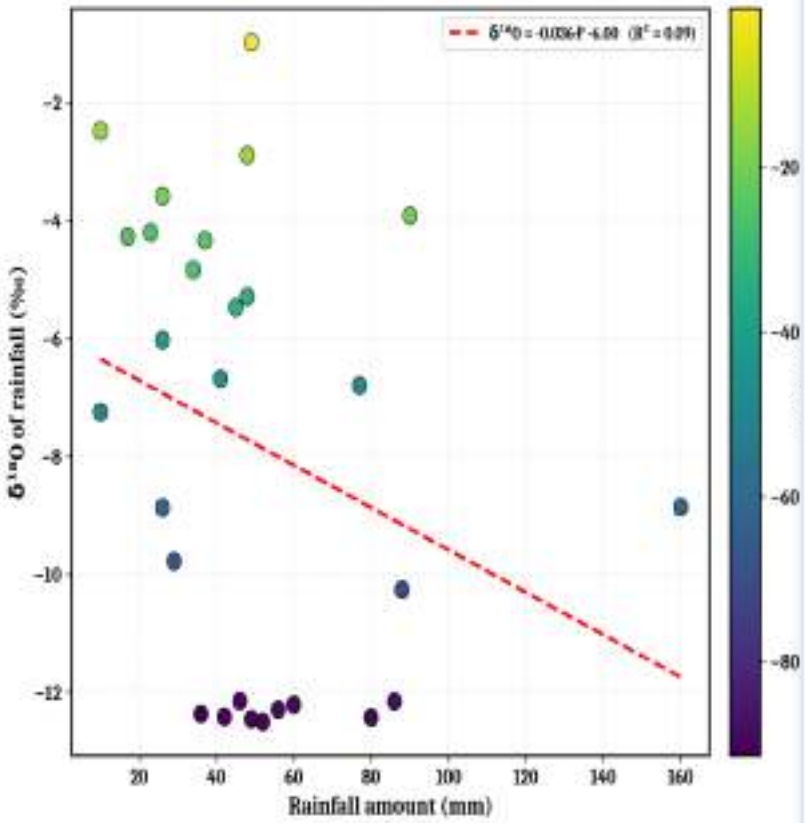
Results..

Rainfall Signal & Evaporative Enrichment- Amritsar

Deuterium Excess: Seasonal & Source Comparison



Amount Effect in Monsoon Rainfall



Rainfall isotope signature: Rainfall exhibits a mean **d-excess of ~8.9‰**, close to the global meteoric-water value of **10‰**, indicating a predominantly meteoric moisture source.

Groundwater isotope signature: Groundwater shows **lower median $\delta^{18}O$ and $\delta^{2}H$ values than rainfall**, while the post-monsoon samples exhibit a relative shift toward isotopic enrichment, consistent with **evaporation-modified recharge and mixing processes**.

Monsoon amount effect: The most intense monsoon rainfall events show markedly depleted **$\delta^{18}O$ values (down to ~–12‰)**, demonstrating a pronounced **amount effect** and providing a distinctive isotopic signature of relatively depleted monsoon recharge.

Recharge implication: The combined rainfall–groundwater isotope patterns indicate **monsoon-derived meteoric water, subsequent evaporation, and mixing with irrigation return flow**, rather than representing direct, rapid infiltration of rainfall.

Isotopic Characterization and Recharge-Bhiwani

Three-Endmember Mixing Model

Groundwater in Behal-Loharu is a mix of three distinct sources based on isotopic and chemical data.

1 **Canal Water**
Fresh, Imported

\+

2 **Monsoon Rain**
Local, Episodic

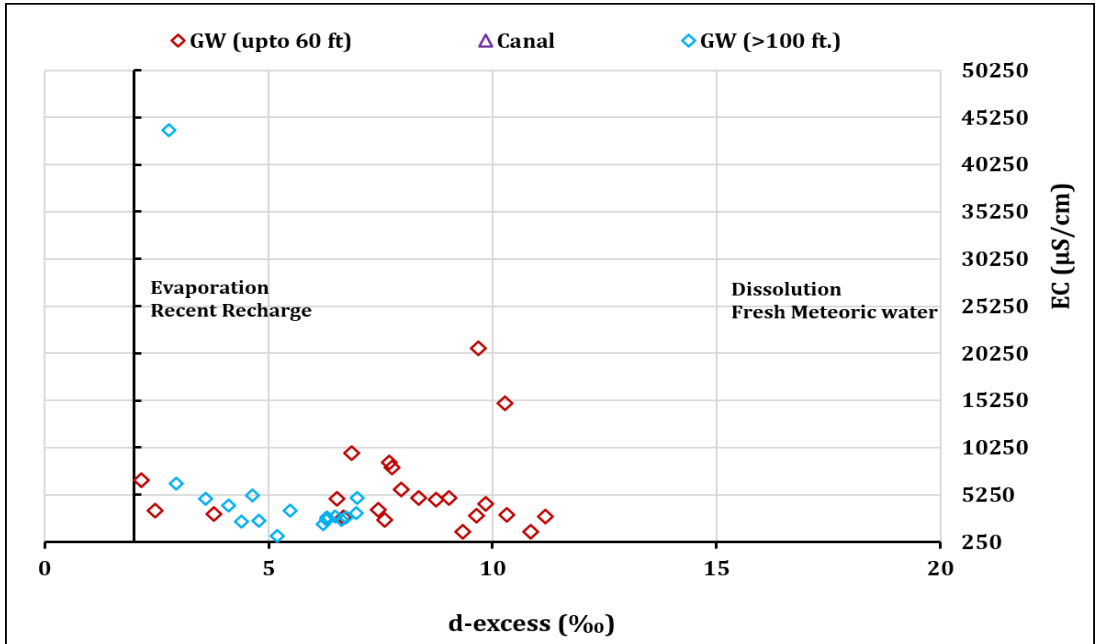
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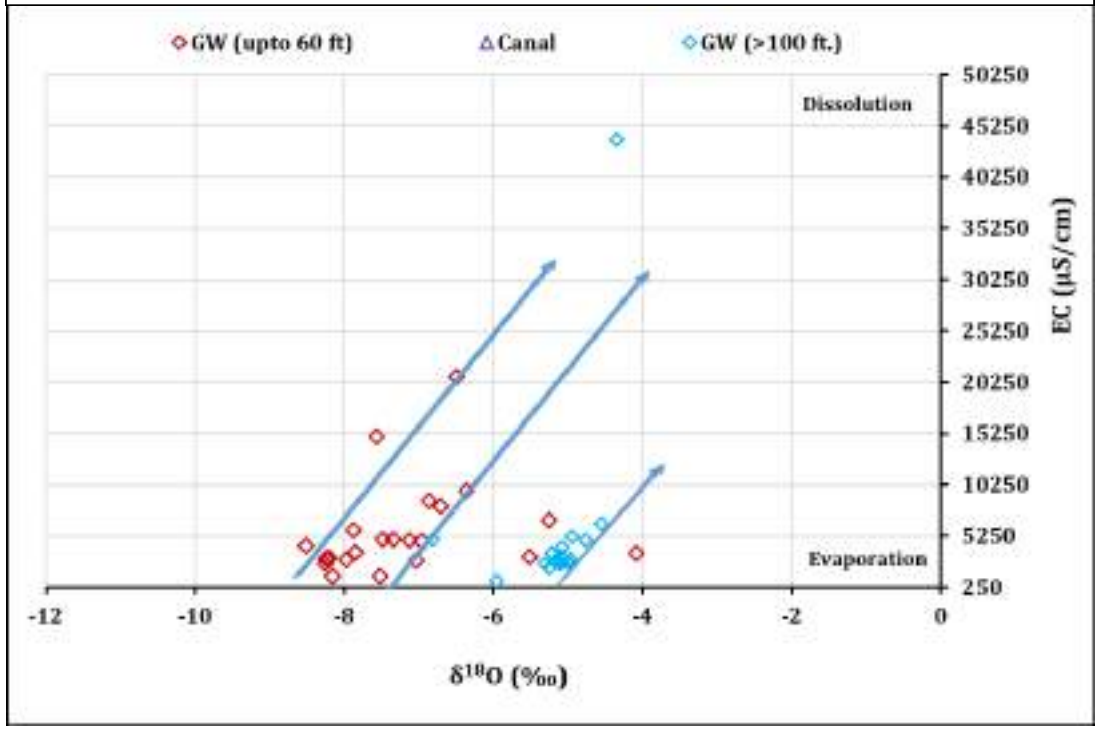
3 **Return Flow**
Saline, Evaporated

Conceptual Mixing Relationship (d-excess vs EC)



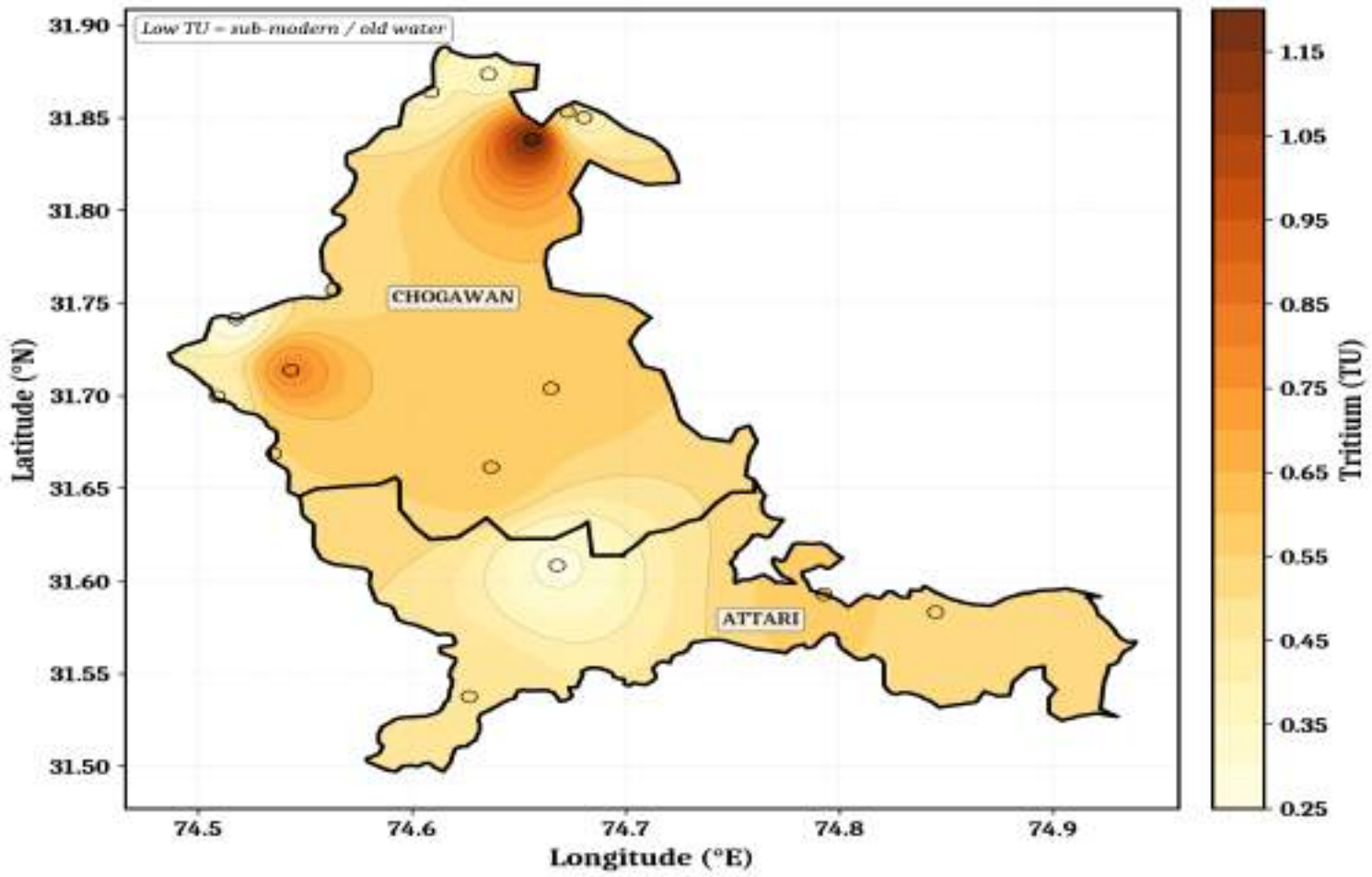
**Chart visualizes the relationship between evaporation (low d-excess) and salinity (high EC).*





Results..

Tritium (^3H): Spatial Distribution- Amritsar



Uniformly low tritium activity: Groundwater tritium concentrations range from **0.25 to 1.18 TU**, with a mean of approximately **0.5 TU**, indicating limited contribution from recent recharge.

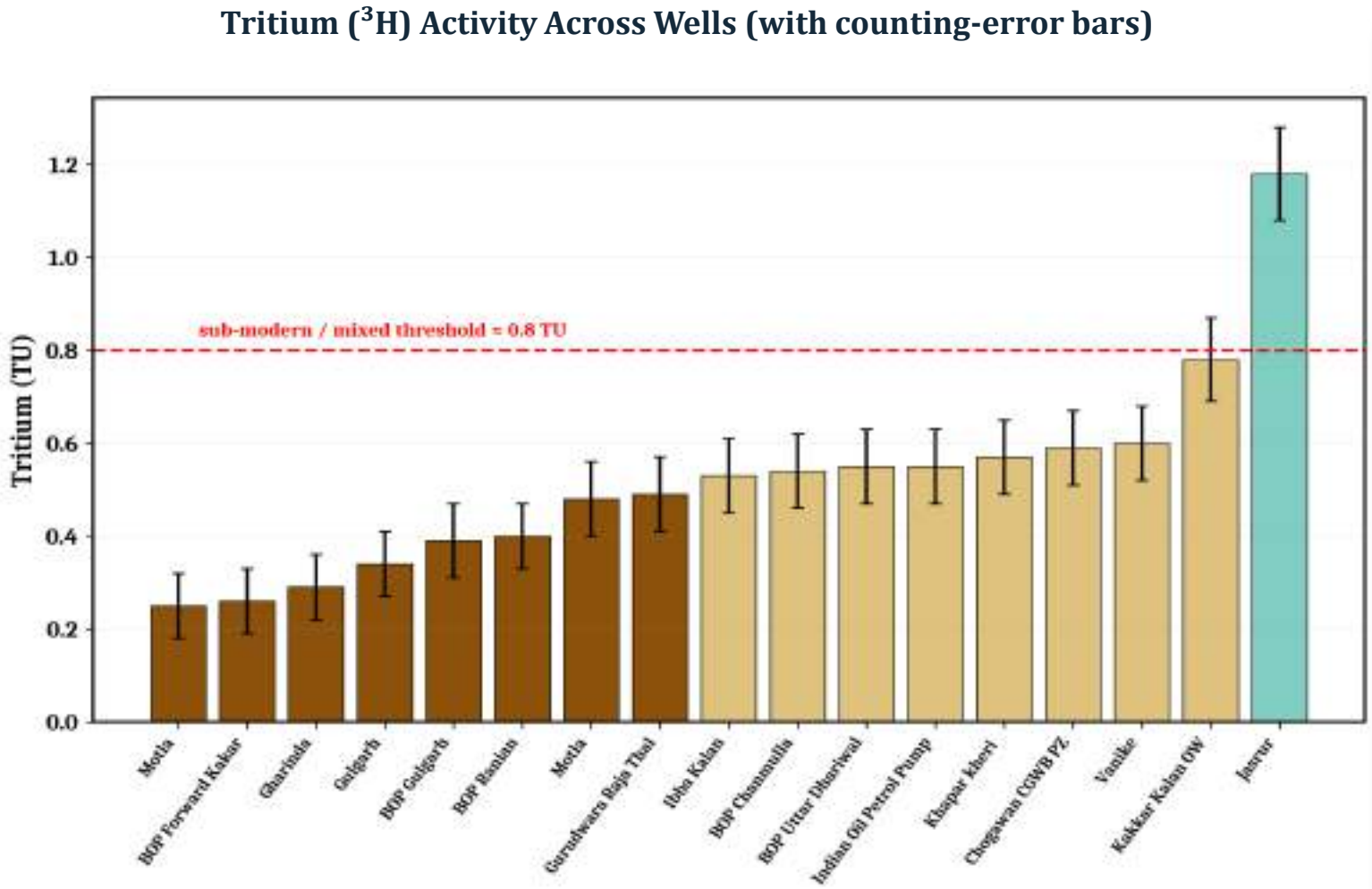
Absence of a strong modern recharge signal: None of the sampled wells exhibits a pronounced **post-bomb tritium signature**, suggesting that recent seasonal recharge is not the dominant component of the sampled groundwater.

Dominance of sub-modern groundwater: The consistently low tritium activities indicate that groundwater is predominantly **sub-modern to older**, reflecting relatively long residence times and limited direct replenishment.

Localized modern mixing: Relatively higher tritium activities at **Jasrur and Kakkar Kalan** indicate **localized contributions from modern recharge or mixing**, suggesting that active recharge occurs only in limited parts of the study area.

Results..

Tritium (^{3}H): Groundwater Age Stratification- Amritsar



Predominance of older groundwater: Most dated wells exhibit **tritium concentrations below ~0.8 TU**, indicating predominantly **sub-modern to pre-modern groundwater** with limited contribution from recent recharge.

Evidence of groundwater mining: Abstraction from **deep piezometers/aquifers is increasingly dependent on older groundwater reserves**, suggesting withdrawal of water accumulated over longer timescales rather than rapid contemporary replenishment.

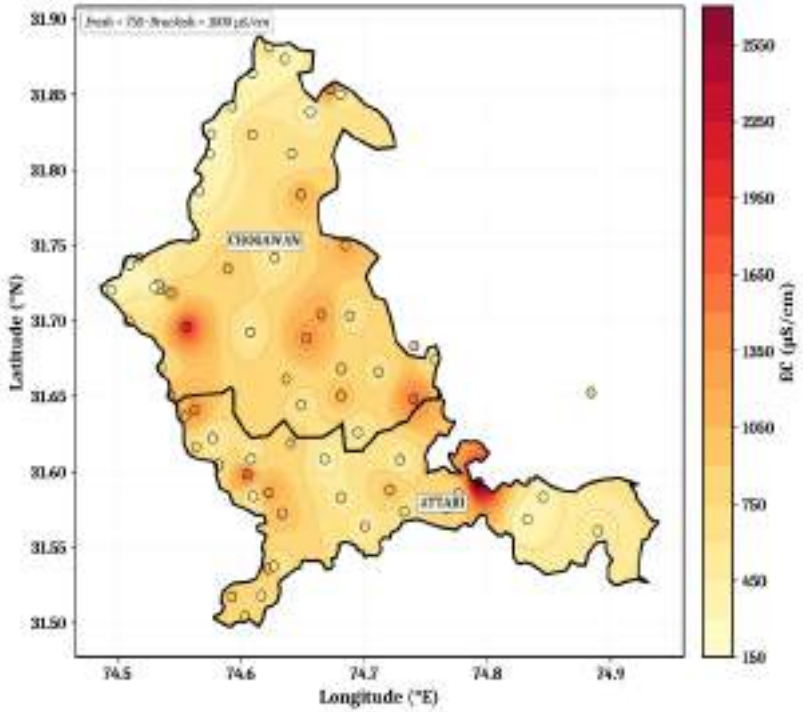
Indication of over-exploitation: The combination of **low tritium activity and weak seasonal recovery of groundwater levels** indicates a substantial imbalance between groundwater withdrawal and effective recharge, consistent with **intensive groundwater exploitation**.

Limited renewable component: Shallow wells with relatively higher tritium activities represent the principal component receiving **recent/modern recharge**, highlighting the importance of protecting shallow recharge zones and enhancing managed aquifer recharge.

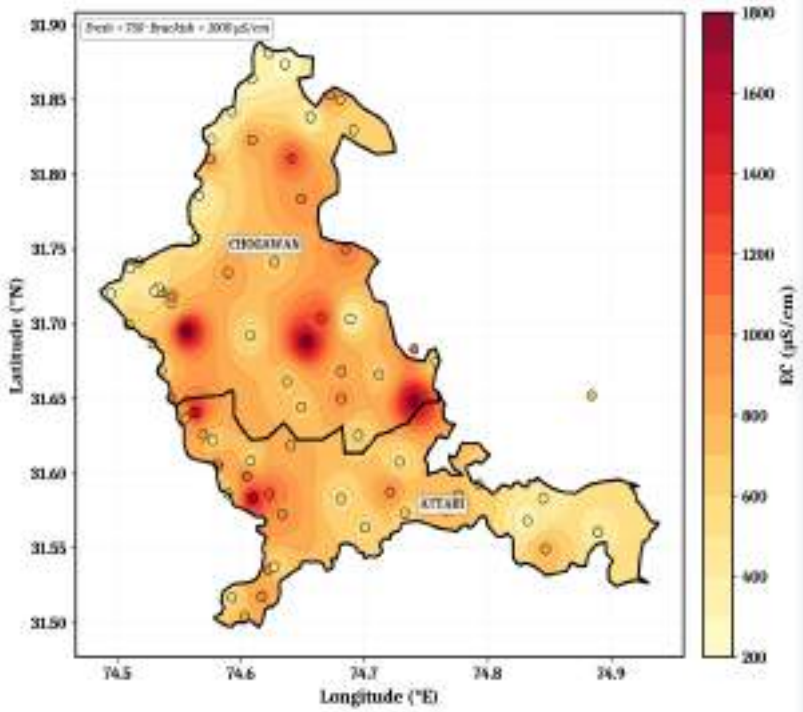
Results..

Groundwater Salinity: Electrical Conductivity (EC) - Amritsar

Pre-Monsoon — June 2025



Post-Monsoon — December 2025



Fresh groundwater along the western corridor: Groundwater with **EC <750 µS/cm** is predominantly observed near the **western river–canal corridor**, indicating relatively fresh recharge and better flushing conditions.

Progressive mineralisation in the agricultural interior: The **central to southeastern agricultural sectors** generally exhibit **EC >1000 µS/cm**, reflecting enhanced mineralisation associated with prolonged water–rock interaction and irrigation influences.

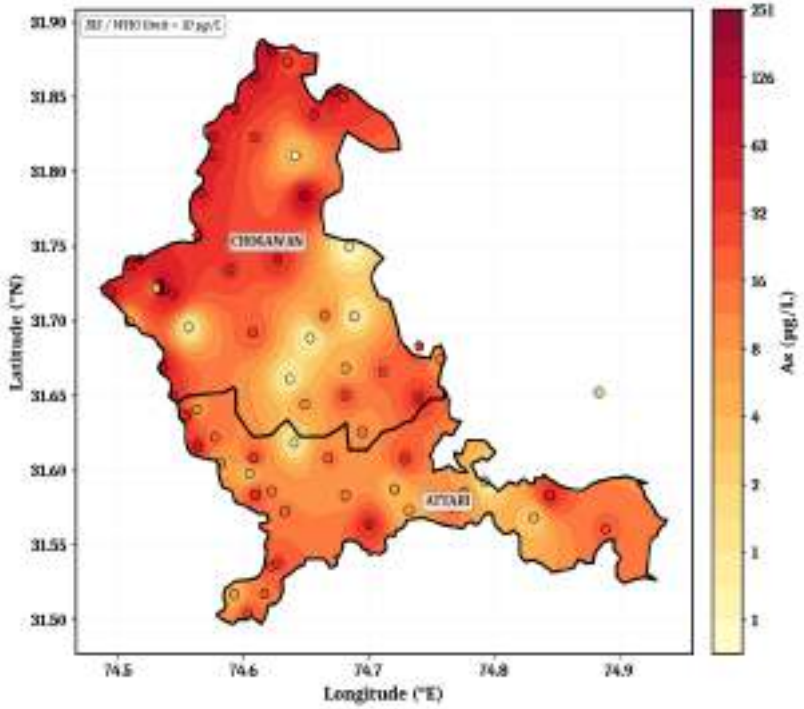
Persistent salinity hotspots: Localized areas of elevated EC persist despite seasonal recharge, indicating **ongoing salt accumulation and cyclic salt loading through irrigation return flow**.

Management implication: The spatial EC pattern highlights areas requiring **improved irrigation-water management, control of return-flow salinity, and targeted managed aquifer recharge** to reduce progressive groundwater mineralisation.

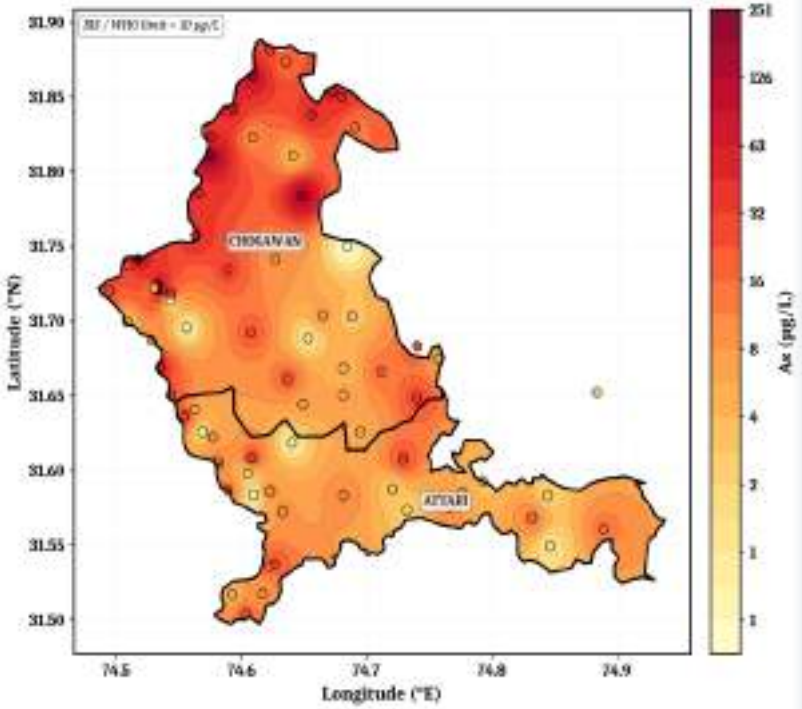
Results..

Arsenic (As) Contamination- Amritsar

Pre-Monsoon — June 2025



Post-Monsoon — December 2025



Widespread geogenic arsenic (As) enrichment: Pre-monsoon As concentrations mean of approximately **33 µg/L**, reaching a maximum of **280 µg/L**, substantially exceeding the **10 µg/L guideline value** in several wells.

Partial post-monsoon dilution: mean As concentration decreased to approximately **25 µg/L**, with a maximum of **211 µg/L**, indicating partial dilution but continued As enrichment in affected groundwater.

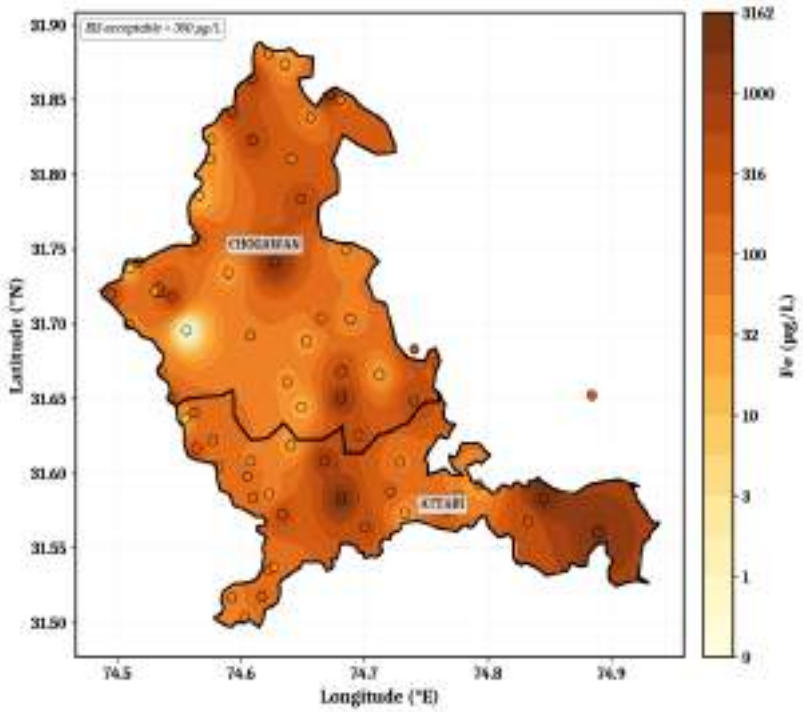
Improvement in safe wells: The proportion of wells with **As <10 µg/L** increased from **26% pre-monsoon to 35% post-monsoon**, suggesting d groundwater quality following seasonal recharge.

Persistent groundwater-quality concern: Despite the post-monsoon decline, **elevated As concentrations remained widespread**, indicating that monsoon recharge alone is insufficient to eliminate arsenic contamination and that **redox-controlled geogenic mobilisation** remains an important factor.

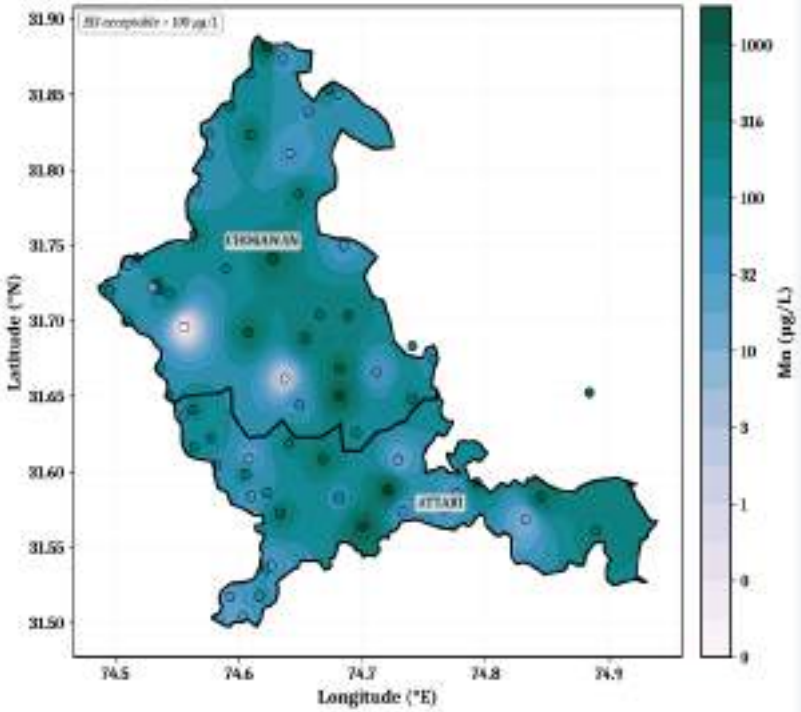
Results..

Redox Metals: Iron (Fe) & Manganese (Mn) - Amritsar

Iron (Fe) — Pre-Monsoon



Manganese (Mn) — Pre-Monsoon



Elevated iron (Fe): Mean Fe concentration was approximately **430 µg/L**, exceeding the **300 µg/L permissible limit** in several wells, indicating widespread iron enrichment.

Widespread manganese (Mn) enrichment: Mn concentrations frequently exceeded the **100 µg/L limit**, particularly across the agricultural interior, indicating significant groundwater-quality concerns.

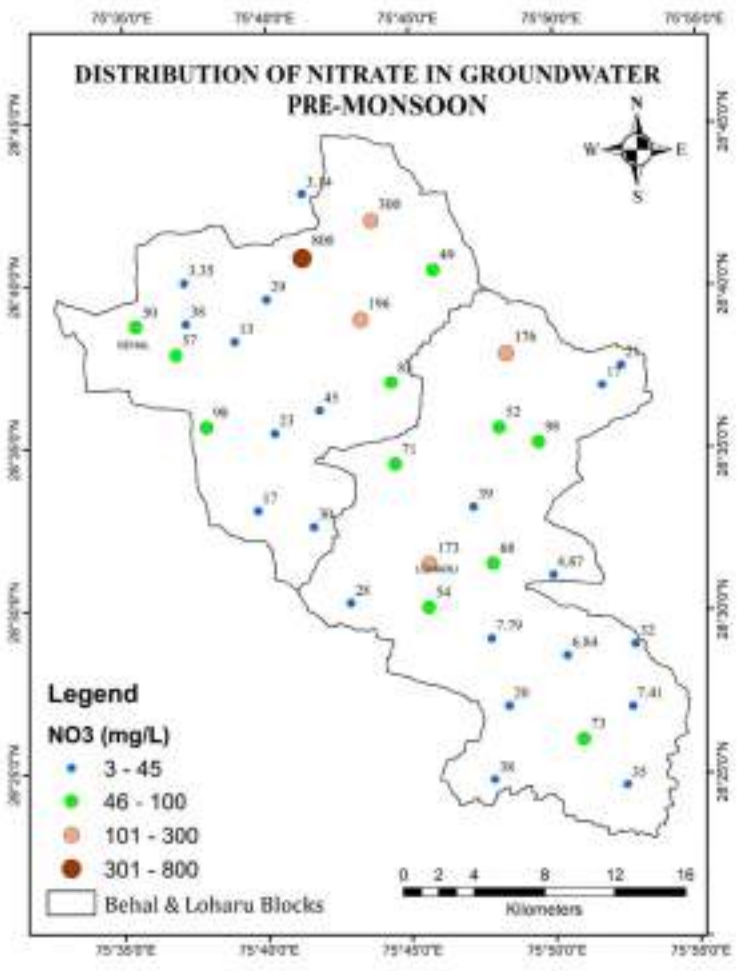
Co-occurrence with arsenic (As): Elevated **Fe, Mn and As** occur spatially together, suggesting that **reducing groundwater conditions** promote the release and mobilization of these redox-sensitive elements.

Redox-driven mobilisation: The observed Fe–Mn–As enrichment is consistent with **redox-controlled metal mobilisation within an evaporated irrigation-return-flow system**, highlighting the combined influence of recharge history, groundwater circulation and reducing geochemical conditions.

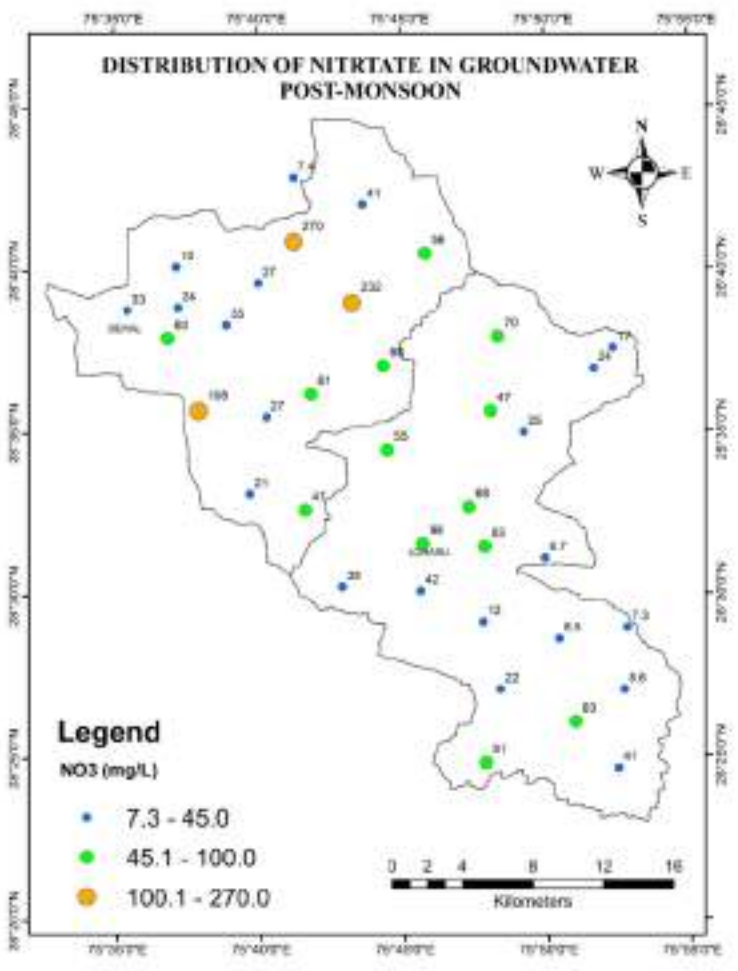
Results..

Nitrate (NO_3) Contamination-Bhiwani

Pre-Monsoon — June 2025



Post-Monsoon — November 2024



Widespread nitrate (NO_3^-) contamination: Pre-monsoon concentrations **3.14 to 800 mg/L**, with a maximum of **800 mg/L**,

Post-monsoon decline: NO_3^- concentrations decreased to approximately **7–270 mg/L**, indicating partial dilution by monsoon recharge.

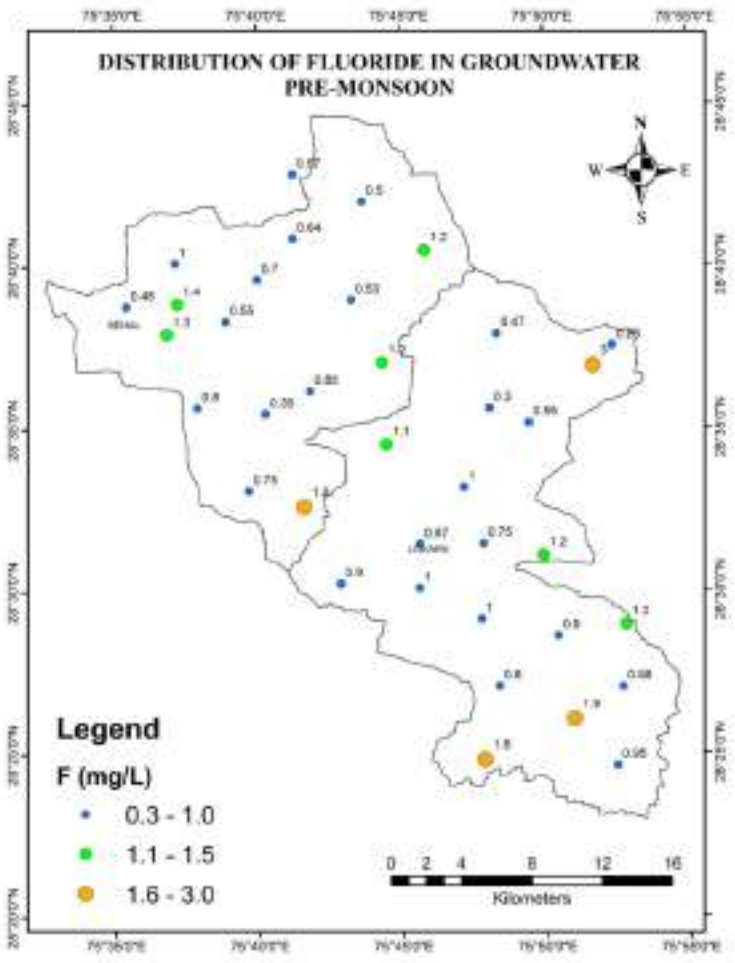
Improved groundwater quality: The proportion of wells with **NO_3^- <10 mg/L** increased from **26% pre-monsoon to 35% post-monsoon**, although elevated nitrate persisted in several locations.

Key controlling factors: excessive nitrogen-fertilizer application and rapid leaching through sandy/loamy soils, with additional contributions from **manure, animal waste and domestic sewage**; prolonged groundwater residence time and circulation may further influence nitrate accumulation.

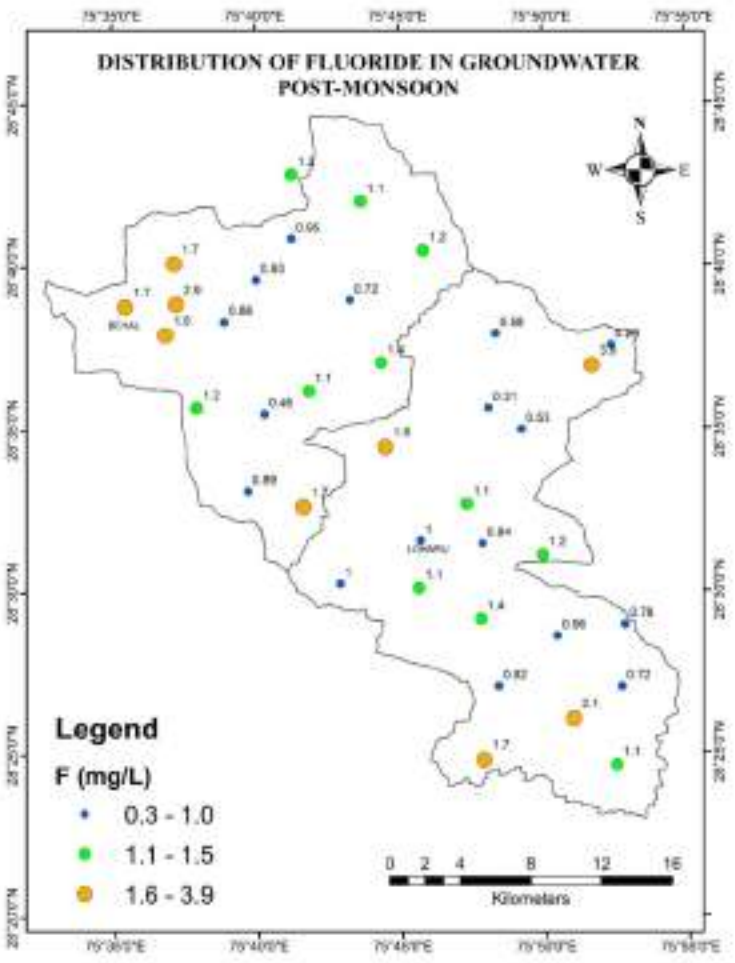
Results..

Fluoride (F) Contamination-Bhiwani

Pre-Monsoon — June 2025



Post-Monsoon — November 2024



Widespread fluoride enrichment: Pre-monsoon fluoride (F^-) **0.26 to 3.00 mg/L**, exceeding the **1.5 mg/L permissible limit** in several wells.

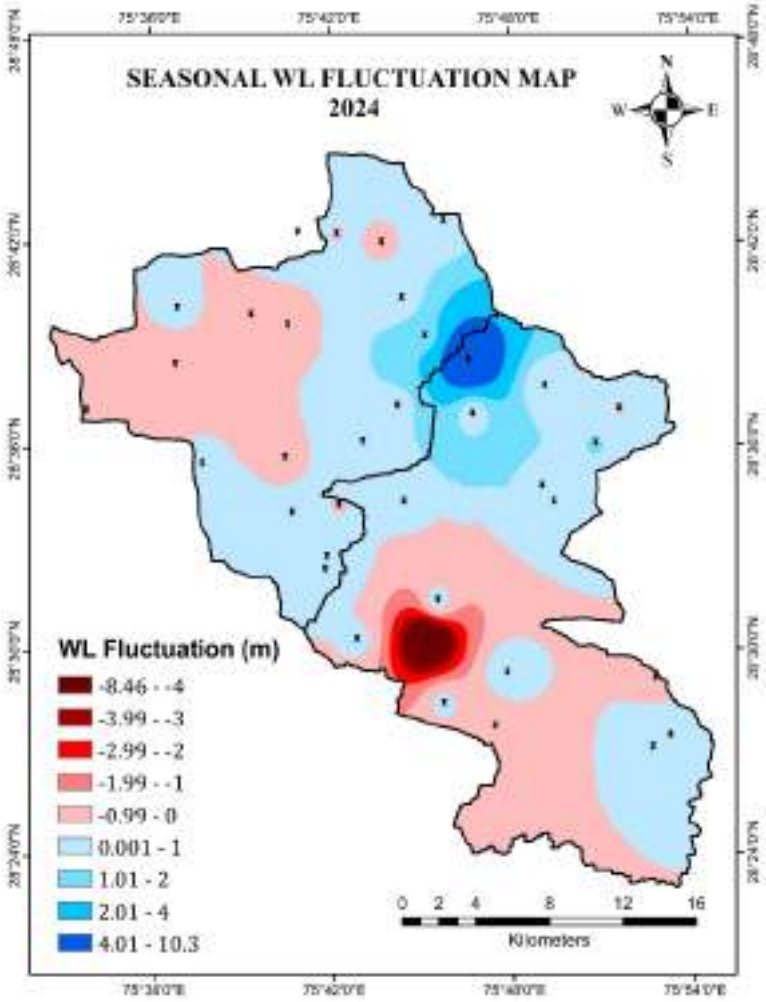
Post-monsoon increase: F^- concentrations increased **3.90 mg/L**, indicating persistence and possible seasonal intensification of fluoride enrichment.

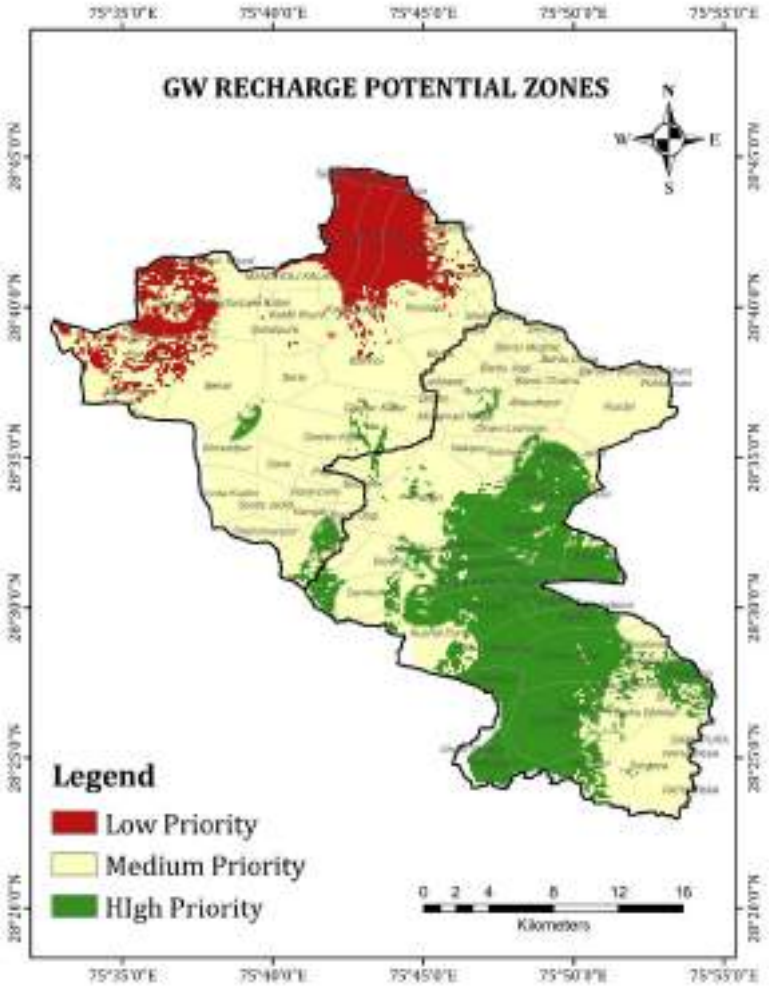
Expansion of fluoride-affected wells: The proportion of wells exceeding **1.5 mg/L F^-** increased from **11% during the pre-monsoon period to 24% post-monsoon**, suggesting that monsoon recharge did not uniformly dilute fluoride concentrations and may have enhanced fluoride mobilization in some locations.

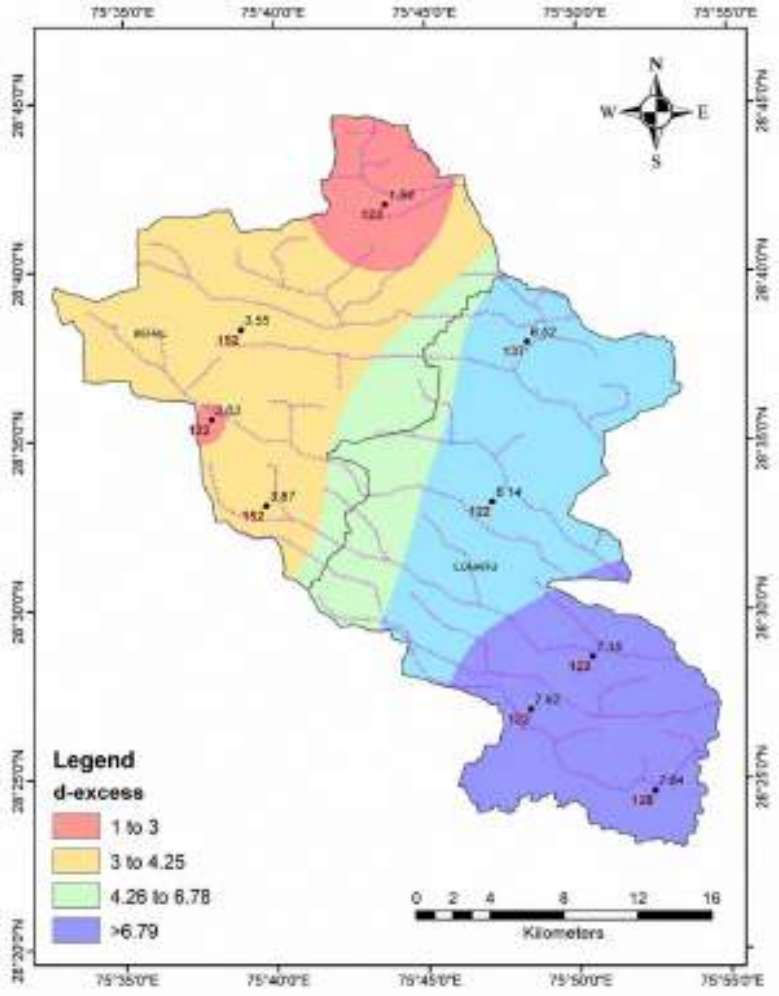
Controlling factors: Elevated fluoride is primarily attributed to the **dissolution of fluoride-bearing minerals**, enhanced by **low Ca^{2+} concentrations**, which reduce fluoride removal through mineral precipitation. **Evaporation and prolonged water–rock interaction** may further concentrate and mobilize fluoride.

Role of agriculture: Agricultural inputs are considered a secondary influence, potentially contributing to fluoride enrichment through irrigation practices and associated return flow, but the dominant control appears to be **geogenic hydrogeochemical processes**.

Isotope Results Validation- Bhiwani







Conclusion

- **Stable isotopes (δ^2H and $\delta^{18}O$)** indicate that groundwater recharge is predominantly derived from **evaporation-modified meteoric water and irrigation return flow**, suggesting recharge through relatively slow pathways rather than rapid, direct infiltration.
- **Tritium concentrations (0.25–1.18 TU)** indicate a predominance of **sub-modern groundwater in Amritsar**, with limited contribution from recent seasonal recharge. This highlights the vulnerability of deeper groundwater to depletion under intensive abstraction.
- Groundwater quality in **Amritsar** is characterized by widespread **geogenic arsenic enrichment**, with mean concentrations decreasing from approximately **33 to 25 µg/L**, along with elevated Fe and Mn. These enrichments are consistent with **reducing hydrogeochemical conditions** within the recycled-recharge system.
- **Electrical conductivity (EC)** reveals a distinct spatial pattern: relatively fresh groundwater along the western river–canal corridor, whereas more mineralized groundwater occurs across the **central to southeastern agricultural interior**. The limited reduction in salinity following the monsoon suggests that seasonal recharge is insufficient to completely flush the accumulated dissolved salts.
- In **Bhiwani district**, elevated **nitrate and fluoride concentrations** reflect the combined influence of **anthropogenic activities and geogenic processes**, underscoring the need for targeted monitoring and source-specific groundwater quality management.
- The **strong spatial correspondence between the isotope-derived d-excess pattern and the GIS-based I map** demonstrates the utility of environmental isotopes as an independent tool for **validating recharge assessments, delineating recharge zones, and identifying priority areas for sustainable groundwater management and managed aquifer recharge (MAR).**

Overall, the findings support **prioritizing managed aquifer recharge along the river–canal corridor**, together with **reduction of excessive deep-aquifer abstraction**, improved irrigation-water management, and systematic isotope and water-quality monitoring to enhance groundwater sustainability and resilience.



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Acknowledgement

Collective thought process

Thanks for your Patience !!

Themes for ISMAR-13

- T1 Climate-Resilient Managed Aquifer Recharge Systems
- T2 Artificial Intelligence, Digital Twins and Smart MAR
- T3 Financing MAR: Investments, Economics and Water Security Markets
- T4 Urban MAR and Sponge City Infrastructure
- T5 MAR and Circular Water Economy
- T6 Nature-Based Solutions and Ecosystem-Centered MAR
- T7 Managed Aquifer Recharge for Agricultural Resilience
- T8 MAR in Coastal Aquifers and Small Islands
- T9 Emerging Contaminants, Water Quality and Risk Governance
- T10 MAR Monitoring, Remote Sensing and Hydroinformatics
- T11 Community-Centered and Indigenous Recharge Systems
- T12 MAR Policy, Governance and Legal Frameworks
- T13 Energy, Carbon and MAR Nexus

13th INTERNATIONAL SYMPOSIUM ON MANAGED AQUIFER RECHARGE

ISMAR-13

Recharging the Future: Innovations in Managed Aquifer Recharge for Water Security

October 20-22, 2027

Roorkee, India

Organized jointly by

National Institute of Hydrology (NIH), Roorkee, India

Indian National Chapter of the International Association of Hydrogeologists (INC-IAH) & Commission on Managed Aquifer Recharge

About the Conference

The International Symposium on Managed Aquifer Recharge (ISMAR) is the premier international event on MAR research and practice, held every 3 or 4 years under the auspices of the International Association of Hydrogeologists (IAH), the American Society of Civil Engineers (ASCE), and the United Nations Educational, Scientific, and Cultural Organization (UNESCO). This series of conferences advances the goal of IAH's Commission on MAR "to expand water resources and improve water quality in ways that are appropriate, environmentally sustainable, technically viable, economical, and socially desirable".

The present Conference aims at bringing Scientists, Researchers, Students, Engineers, Water Resources Specialists, Government Administrators, NGOs, and all those interested in groundwater and environmental problems to a common platform and offer the opportunity to exchange ideas, knowledge, experience, techniques, and know-how in various aspects of groundwater research carried out in the last few decades in India and elsewhere.

Key Dates

- Abstract Submission till 31st March 2027
- Early Bird Registration till 30th April 2027

About NIH

National Institute of Hydrology (NIH) is a premier Research and Development organization under the Ministry of Jal Shakti, Department of Water Resources, River Development and Ganga Rejuvenation, Government of India. It was established as an autonomous body in 1978 with its headquarters at Roorkee. The main objectives of NIH are to undertake, aid, promote and coordinate systematic and scientific work in all aspects of hydrology.

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Registration Fee

Registration Category	Early Bird Registration (till 30th April 2027)	Late Registration (After 30th April 2027)
Indian Delegates	INR 8,000	INR 10,000
Delegates from Low- and Middle-Income Countries (LMICs)	USD 250	USD 300
Delegates from High-Income Countries (HICs)	USD 400	USD 500
Indian Research Scholars/Students	INR 3,000	INR 5,000
Research Scholars/Students/Postdocs from Low- and Middle-Income Countries (LMICs)	USD 150	USD 200
Research Scholars/Students/Postdocs from High-Income Countries (HICs)	USD 250	USD 300

LMIC and HIC classifications shall be as per the latest World Bank country income classification applicable on the date of registration.