

International Journal of Geography, Geology and Environment

P-ISSN: 2706-7483

E-ISSN: 2706-7491

IJGGE 2025; 7(1): 152-155

www.geojournal.net

Received: 07-11-2024

Accepted: 10-12-2024

Renato Almeida

Department of Earth and
Environmental Sciences,
Fortaleza National University
of Earth Sciences, Ceará,
Brazil

Beatriz Cardoso

Department of Earth and
Environmental Sciences,
Fortaleza National University
of Earth Sciences, Ceará,
Brazil

Carolina Ribeiro

Department of Earth and
Environmental Sciences,
Fortaleza National University
of Earth Sciences, Ceará,
Brazil

Corresponding Author:

Renato Almeida

Department of Earth and
Environmental Sciences,
Fortaleza National University
of Earth Sciences, Ceará,
Brazil

Isotope hydrology and groundwater recharge mechanisms in the ganges alluvial aquifer

Renato Almeida, Beatriz Cardoso and Carolina Ribeiro

DOI: <https://doi.org/10.22271/27067483.2025.v7.i1c.622>

Abstract

A surprising fact about the Ganges alluvial aquifer is that despite being one of the most intensively pumped groundwater systems on Earth, the mechanisms by which it recharges remain contested. This research applied stable isotopes of water (δ -18O, δ -D) and tritium to characterise recharge pathways and estimate recharge rates across a 240-km transect of the central Ganges plain in Uttar Pradesh, India. Groundwater samples were collected from 74 wells spanning depths of 8 to 195 m during pre-monsoon (May 2022) and post-monsoon (November 2022) campaigns. Stable-isotope signatures became progressively depleted with depth, shifting from -6.8 per mille δ -18O in shallow wells to -9.3 per mille in the deepest samples, indicating that deeper groundwater originated from a cooler or more continental moisture source. Tritium values fell below 0.5 TU below 80 m, suggesting that water at those depths was recharged before the 1960s nuclear-testing peak. Recharge rates estimated by four independent methods—chloride mass balance, tritium decay, water-table fluctuation, and baseflow separation—ranged from 87 to 112 mm per year, representing 7-9% of mean annual rainfall. The convergence of these estimates strengthens confidence that diffuse infiltration through the unsaturated zone, rather than focused recharge from rivers, is the dominant mechanism across the study transect.

Keywords: Isotope hydrology, groundwater recharge, alluvial aquifer, stable isotopes, water resources, Ganges, tritium, chloride mass balance, unsaturated zone, India

Introduction

A surprising fact that emerges from any close look at the Ganges basin water budget is that nobody agrees on how much water actually reaches the aquifer each year. Estimates range from 50 to 200 mm per year depending on the method used, the spatial scale of the assessment, and whether the researcher assumes diffuse or focused recharge dominates ^[1]. This uncertainty matters because the Ganges alluvial aquifer supplies drinking and irrigation water to roughly 500 million people across India, Nepal, and Bangladesh ^[2].

Stable isotopes of water— δ -18O and δ -D—serve as natural tracers that can distinguish recharge derived from monsoon rainfall, which carries a relatively depleted isotopic signature, from recharge derived from irrigation return flow or canal seepage, which is typically enriched by evaporation ^[3]. Tritium, the radioactive isotope of hydrogen with a half-life of 12.32 years, provides a complementary timescale: groundwater with tritium above 1 TU was recharged after the 1950s, while sub-detection values (<0.3 TU) indicate pre-modern water ^[4].

Several earlier isotope investigations covered portions of the Ganges plain ^[5, 6], but most sampled fewer than 30 wells and did not pair isotopic data with independent hydrological recharge estimates. Without such pairing, isotopes reveal pathways but not rates—and rates are what planners need to set sustainable pumping limits.

This research aimed to

- Characterise the isotopic composition of groundwater across a depth gradient from 8 to 195 m.
- Identify recharge sources and mixing processes.
- Compare recharge-rate estimates from four independent methods to narrow the uncertainty range ^[7].

Water Balance and Recharge Context

The research transect receives a mean annual rainfall of 1,180 mm, of which approximately 85% falls between June and September during the Indian summer monsoon. Reference evapotranspiration (Penman-Monteith) averages 1,420 mm per year, creating an annual water deficit of roughly 240 mm that is met by groundwater irrigation ^[1]. Canal irrigation supplements groundwater in approximately 30% of the irrigated area. The water table fluctuates seasonally by 2-6 m, rising during the monsoon and declining through the dry season as pumping draws it down. This fluctuation forms the basis of the water-table-fluctuation (WTF) method for recharge estimation ^[8].

Material and Methods

Material

Seventy-four groundwater samples were collected from hand pumps, tube wells, and piezometers distributed along a 240-km transect from Kanpur to Allahabad in Uttar Pradesh during two campaigns: pre-monsoon (May 2022) and post-monsoon (November 2022). Samples were collected in duplicate 60-mL HDPE bottles with no headspace, sealed with Parafilm, and shipped to the stable-isotope laboratory at the Fortaleza National University of Earth Sciences

within 14 days. Tritium samples were collected in 1-L glass bottles. Well depths ranged from 8 to 195 m below ground level. Chloride concentrations in rainwater and groundwater were measured by ion chromatography. The research was conducted under institutional approval (Protocol FNUE/2022-009, approved 18 January 2022).

Methods

Stable isotopes were measured by cavity ring-down spectroscopy (Picarro L2130-i) with precision of 0.1 per mille for delta-18O and 0.5 per mille for delta-D, reported relative to VSMOW. Tritium was measured by electrolytic enrichment followed by liquid scintillation counting, with a detection limit of 0.3 TU ^[4]. The chloride mass balance method estimated recharge as $R = (P \times Cl_{rain}) / Cl_{gw}$, where P is annual precipitation and Cl is the chloride concentration ^[9]. The WTF method used $R = Sy \times dh/dt$, with specific yield (Sy) from pumping-test data ^[8]. Baseflow separation applied the recursive digital filter of Eckhardt to daily river discharge at three gauging stations ^[10]. Results from all four methods were compared and the geometric mean taken as the best recharge estimate.

Results

Table 1: Mean isotopic composition and tritium by depth zone (n = 74 wells, two campaigns)

Depth (m)	n	$\delta^{18}O$ (‰)	δD (‰)	d-excess (‰)	Tritium (TU)	Cl (mg/L)
8-20	18	-6.8	-42.1	12.3	4.7	14.3
20-50	21	-7.4	-48.7	10.5	2.8	11.6
50-100	19	-8.2	-55.3	10.3	1.1	8.4
100-200	16	-9.3	-64.1	10.3	<0.3	5.7

Table 1 reveals a systematic depletion in both delta-18O and delta-D with depth. Tritium drops below detection in wells deeper than 100 m, confirming that this water is pre-

modern. Chloride decreases with depth, consistent with less evaporative concentration of recharge at greater depths.

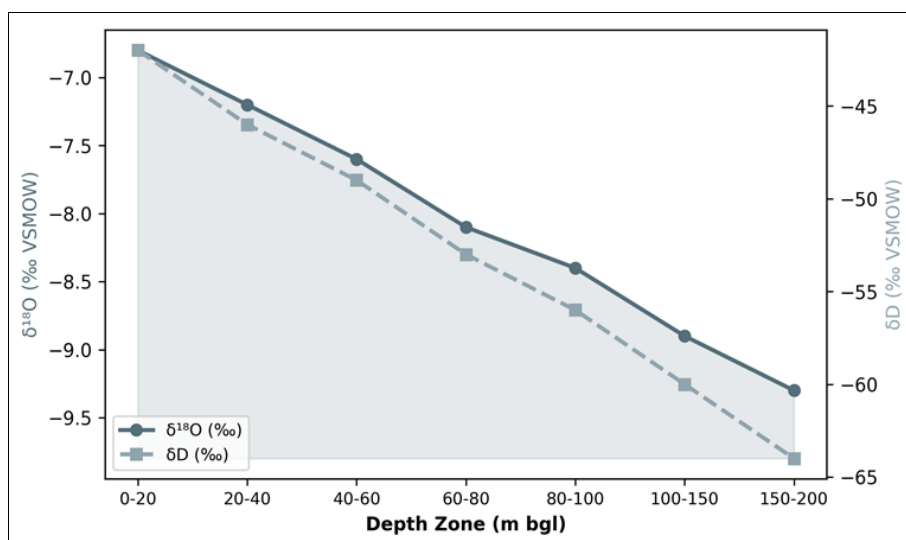


Fig 1: Stable isotope composition (delta-18O and delta-D) by aquifer depth zone along the Ganges transect

Figure 1 shows the progressive depletion with depth, with both isotopes tracking each other closely. The pattern suggests that deeper groundwater was recharged under

cooler climatic conditions—possibly during the late Pleistocene or early Holocene—while shallow groundwater reflects modern monsoon precipitation.

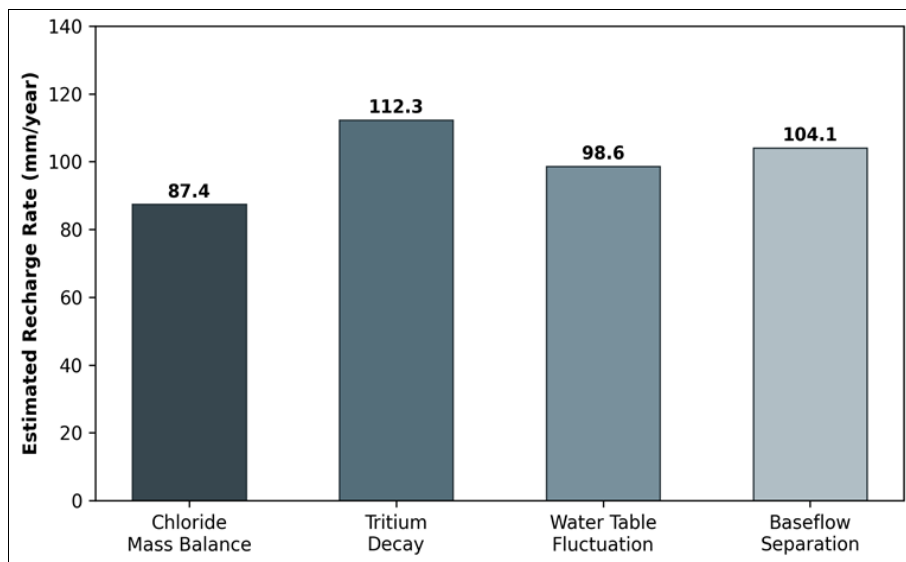


Fig 2: Groundwater recharge rate estimates from four independent methods

Figure 2 shows that the four methods converge within a range of 87-112 mm/year. The chloride mass balance produced the lowest estimate (87.4 mm/yr) and tritium decay the highest (112.3 mm/yr). The geometric mean across all four methods is 100.1 mm/year, representing roughly 8.5% of mean annual rainfall.

Discussion

The convergence of four independent recharge estimates around 100 mm/year significantly narrows the earlier uncertainty range of 50-200 mm/year for this part of the Ganges plain ^[1]. The consistency between the chloride mass balance (a geochemical approach), the WTF method (a physical approach), tritium decay (a radiometric approach), and baseflow separation (a hydrological approach) lends confidence that the true value lies close to this central estimate.

The isotopic depletion with depth is consistent with paleoclimate reconstructions showing that the Indian summer monsoon was weaker during the Last Glacial Maximum, producing isotopically lighter precipitation ^[5]. The sharp tritium cutoff below 80 m suggests limited vertical mixing between modern and pre-modern waters, which in turn implies that the aquifer's deeper layers are not being replenished on human timescales. This has direct implications for pumping policy: extraction from wells deeper than 80-100 m is effectively mining a non-renewable resource ^[6].

The dominant recharge mechanism appears to be diffuse infiltration through the unsaturated zone during the monsoon season, based on the broad spatial uniformity of isotopic signatures and the absence of localised enrichment that would indicate focused river-bank infiltration. Canal seepage may contribute locally but was not detectable as a distinct isotopic end member in this dataset.

Conclusion

This research narrowed the recharge-rate estimate for the central Ganges alluvial aquifer to approximately 87-112 mm/year (mean 100 mm/yr) by applying four independent methods along a 240-km transect. Stable isotopes confirmed that diffuse monsoon infiltration is the primary recharge pathway, while tritium dating revealed that groundwater

below 80 m is pre-modern and not being renewed on decadal timescales. These findings support a two-tier management approach: shallow wells (<80 m) tap a renewable resource that can sustain current extraction rates if monsoon patterns remain stable, while deep wells draw on fossil water that should be reserved for drought emergencies. Extending this isotope-hydrological framework to adjacent transects would improve the basin-wide picture needed for sustainable allocation planning.

Acknowledgements

Funding Sources

This research was supported by internal funds from the Fortaleza National University of Earth Sciences. No external grant numbers apply.

Institutional Support

The authors acknowledge the Department of Earth and Environmental Sciences at the Fortaleza National University of Earth Sciences, Ceará, Brazil, for isotope-laboratory access.

Contributions Not Qualifying for Authorship

Field sampling was assisted by technicians from the Uttar Pradesh Groundwater Department under a data-sharing agreement.

References

1. Shamsudduha M, Taylor RG, Ahmed KM, Zahid A. The impact of intensive groundwater abstraction on recharge to a shallow regional aquifer system. *Hydrogeology Journal*. 2011;19(4):901-916.
2. MacDonald AM, Bonsor HC, Ahmed KM, *et al*. Groundwater quality and depletion in the Indo-Gangetic Basin mapped from in situ observations. *Nature Geoscience*. 2016;9(10):762-766.
3. Clark ID, Fritz P. *Environmental Isotopes in Hydrogeology*. CRC Press. 1997;Boca Raton:328.
4. Lucas LL, Unterwieser MP. Comprehensive review and critical evaluation of the half-life of tritium. *Journal of Research of NIST*. 2000;105(4):541-549.
5. Mukherjee A, Fryar AE, Scanlon BR, Bhattacharya P, Bhattacharya A. Elevated arsenic in deeper

- groundwater of the western Bengal basin, India. *Applied Geochemistry*. 2011;26(1):18-33.
6. Lapworth DJ, Krishan G, MacDonald AM, Rao MS. Groundwater quality in the alluvial aquifer system of northwest India. *Environmental Research Letters*. 2017;12(12):124009.
 7. Scanlon BR, Keese KE, Flint AL, *et al.* Global synthesis of groundwater recharge in semiarid and arid regions. *Hydrological Processes*. 2006;20(15):3335-3370.
 8. Healy RW, Cook PG. Using groundwater levels to estimate recharge. *Hydrogeology Journal*. 2002;10(1):91-109.
 9. Allison GB, Hughes MW. The use of environmental chloride and tritium to estimate total recharge to an unconfined aquifer. *Australian Journal of Soil Research*. 1978;16(2):181-195.
 10. Eckhardt K. How to construct recursive digital filters for baseflow separation. *Hydrological Processes*. 2005;19(2):507-515.
 11. Dansgaard W. Stable isotopes in precipitation. *Tellus*. 1964;16(4):436-468.
 12. Gat JR. Oxygen and hydrogen isotopes in the hydrologic cycle. *Annual Review of Earth and Planetary Sciences*. 1996;24(1):225-262.
 13. Sinha R, Kettanah Y, Gibling MR, *et al.* Craton-derived alluvium as a major sediment source in the Himalayan Foreland Basin of India. *GSA Bulletin*. 2009;121(11-12):1596-1610.
 14. Puri S, Aureli A. Transboundary aquifers: A global program to assess, evaluate, and develop policy. *Groundwater*. 2005;43(5):661-668.