

International Journal of Geography, Geology and Environment

P-ISSN: 2706-7483

E-ISSN: 2706-7491

NAAS Rating (2025): 4.5

IJGGE 2025; 7(7): 173-176

www.geojournal.net

Received: 07-05-2025

Accepted: 09-06-2025

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Determination of recharge zones and groundwater flow paths using tracers in the Kalahari

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DOI: <https://www.doi.org/10.22271/27067483.2025.v7.i7c.716>

Abstract

Groundwater recharge in semi-arid environments like the Kalahari Basin remains one of the least well-constrained components of the regional water balance. This research used stable isotope tracers ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) alongside hydrochemical parameters to delineate recharge zones and map groundwater flow paths across a 4,200 km² section of the central Kalahari in Botswana. Samples were collected from 38 boreholes, 12 shallow hand-dug wells, and 24 rainfall events between February 2021 and January 2023. Four distinct recharge zones were identified based on isotopic signatures and electrical conductivity (EC) values. Zone A, covering 18.3% of the mapped area, showed active recharge with low EC (mean 387 $\mu\text{S}/\text{cm}$) and isotopic signatures close to the local meteoric water line. Zone D, a discharge area in the southeastern lowlands, exhibited high EC (mean 1,243 $\mu\text{S}/\text{cm}$) and enriched isotopic values. Tritium dating indicated mean residence times ranging from 8 to 47 years across the four zones. Flow path analysis revealed two dominant recharge corridors linked to ephemeral pan systems that funnel infiltration during episodic rainfall events. These findings offer a framework for sustainable groundwater extraction planning in the central Kalahari region.

Keywords: Recharge zones, groundwater flow paths, stable isotopes, hydrochemical tracers, electrical conductivity, Kalahari Basin, aquifer dynamics, tritium dating, water resource mapping, semi-arid hydrology

Introduction

The Kalahari is not a desert in the conventional sense it receives enough rainfall to support scattered tree cover and seasonal wetlands but its deep sandy soils and high evapotranspiration rates make recharge estimation extraordinarily difficult ^[1]. Across much of the basin, annual potential evapotranspiration exceeds 2,000 mm while rainfall struggles to reach 450 mm, leaving a slim margin for water to reach the water table ^[2]. And yet boreholes drilled into Kalahari sandstones and underlying formations do yield water, sometimes in surprising quantities, which means recharge is happening somewhere. Identifying where and how that recharge occurs has been a persistent challenge. Traditional water balance methods tend to produce wide uncertainty ranges when applied to semi-arid environments, partly because they cannot distinguish between diffuse recharge through the soil matrix and focused recharge through preferential pathways such as pans, riverbeds, and fracture systems ^[3]. Isotopic tracers offer a way around this problem. The stable isotopes of oxygen and hydrogen in water molecules act as natural tags, recording the conditions under which precipitation formed and the degree to which it was modified by evaporation before reaching the aquifer ^[4].

Previous isotopic work in the Kalahari has been concentrated in Namibia and the western portions of Botswana, leaving the central basin relatively under-sampled ^[5]. This research aimed to fill that gap by collecting groundwater and rainfall isotope data across a 4,200 km² area in central Botswana, combining isotopic evidence with hydrochemical parameters and tritium age estimates to delineate recharge zones and trace flow directions ^[6].

Research Area Description

The mapped area is located in the Central District of Botswana, centred on coordinates 22°15'S, 24°30'E, and spans elevations from 940 to 1,080 m above sea level. The landscape is characterised by flat to gently undulating terrain covered with Kalahari sand deposits

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of variable thickness (5-80 m), underlain by Karoo-age sedimentary rocks and, at greater depth, Precambrian basement^[7]. Annual rainfall averages 420 mm, concentrated between November and March, with high interannual variability (coefficient of variation 35%). Mean annual temperature is 22.6°C, and potential evapotranspiration exceeds 2,100 mm per year. The drainage network is ephemeral, with water flowing only after heavy rainfall events, feeding into a series of clay-floored pans that serve as local depressions where surface water collects temporarily^[8].

Material and Methods

Material

This research was coordinated from the National Geological Institute of Warsaw, Poland, with field campaigns conducted in the Central District of Botswana between February 2021 and January 2023. Groundwater samples were collected from 38 production boreholes (depths 40-180 m) and 12 hand-dug wells (depths 3-8 m) distributed across the mapped area. Rainfall samples (n = 24) were collected using a modified IAEA-type collector at three stations positioned along a north-south transect. All water samples were filtered through 0.45 µm membranes in the field and stored in HDPE bottles with zero headspace. Temperature, pH, EC, and dissolved oxygen were measured in situ using a YSI Professional Plus multiparameter meter^[9]. Tritium samples were collected in 1-litre glass bottles from 20 selected boreholes representing different aquifer depths and positions.

Seasonal Variations: Sampling was timed to capture both wet and dry season conditions. Wet season campaigns (February-March 2021 and 2022) coincided with peak rainfall, when episodic recharge events were most likely. Dry season campaigns (August 2021 and 2022) provided baseline conditions when water table levels had stabilised after the cessation of rainfall. EC values in shallow wells showed seasonal fluctuations of up to 28%, while deep boreholes varied by less than 5%, confirming that the deeper aquifer is hydraulically buffered against short-term climatic inputs^[10].

Methods: Stable isotope ratios ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) were measured by wavelength-scanned cavity ring-down spectroscopy (Picarro L2130-i) at the Warsaw Isotope Laboratory, with analytical precision of $\pm 0.1\text{‰}$ for $\delta^{18}\text{O}$ and $\pm 0.8\text{‰}$ for $\delta^2\text{H}$. Tritium activity was determined by electrolytic enrichment followed by liquid scintillation counting at the same facility, with a detection limit of 0.3 TU. Hydrochemical analysis included major ions (Na^+ , K^+ , Ca^{2+} , Mg^{2+} , Cl^- , SO_4^{2-} , HCO_3^-) measured by ion chromatography^[11]. Recharge zone classification was based on a composite index incorporating EC, $\delta^{18}\text{O}$ deviation from the local meteoric water line, and tritium content, using hierarchical cluster analysis in R 4.2. Groundwater flow directions were inferred from potentiometric surface maps interpolated from static water level measurements using ordinary kriging in ArcGIS Pro 3.0^[12].

Results

Table 1: Summary of recharge zone characteristics based on isotopic and hydrochemical classification

Zone	Area (%)	Mean EC (µS/cm)	Mean $\delta^{18}\text{O}$ (‰)	Mean ^3H (TU)	Residence Time (yr)
A	18.3	387	-5.6	3.8	8-15
B	31.7	624	-4.9	2.1	15-28
C	33.2	893	-4.1	0.8	28-42
D	16.8	1,243	-3.4	<0.3	>47

Cluster analysis separated the 50 sampling points into four recharge zones with distinct hydrochemical and isotopic fingerprints (Table 1). Zone A, identified as the active recharge area, was concentrated around ephemeral pan

systems in the northern portion of the mapped area, where sandy substrates and topographic depressions facilitate focused infiltration during heavy rainfall.

Table 2: Major ion chemistry (mg/L) across the four recharge zones

Zone	Na^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}	HCO_3^-	TDS
A	42	28	14	36	18	156	248
B	78	46	23	68	34	214	412
C	124	71	38	108	56	276	589
D	198	96	54	178	89	318	824

Major ion concentrations increased progressively from Zone A to Zone D, consistent with longer water-rock interaction times along the flow path (Table 2). The Na^+/Cl^- ratio shifted from 1.17 in Zone A to 1.11 in Zone D, suggesting a slight increase in halite dissolution contribution with distance from recharge areas.

Comprehensive Interpretation

The isotopic scatter pattern (Figure 1) shows a clear evaporative trend among shallow well samples, plotting below and to the right of the Global Meteoric Water Line, which indicates that recharge water undergoes partial evaporation in the unsaturated zone before reaching the

water table. Deep borehole samples cluster more tightly, reflecting longer residence times and mixing that dampens isotopic variability.

Discussion

The identification of focused recharge corridors associated with ephemeral pan systems aligns with findings from western Kalahari research, where de Vries and colleagues documented preferential infiltration beneath clay pans during high-intensity rainfall events^[5]. The relatively young tritium ages in Zone A (8-15 years) confirm that active recharge is occurring on decadal timescales, even in this semi-arid setting, which contradicts earlier assumptions

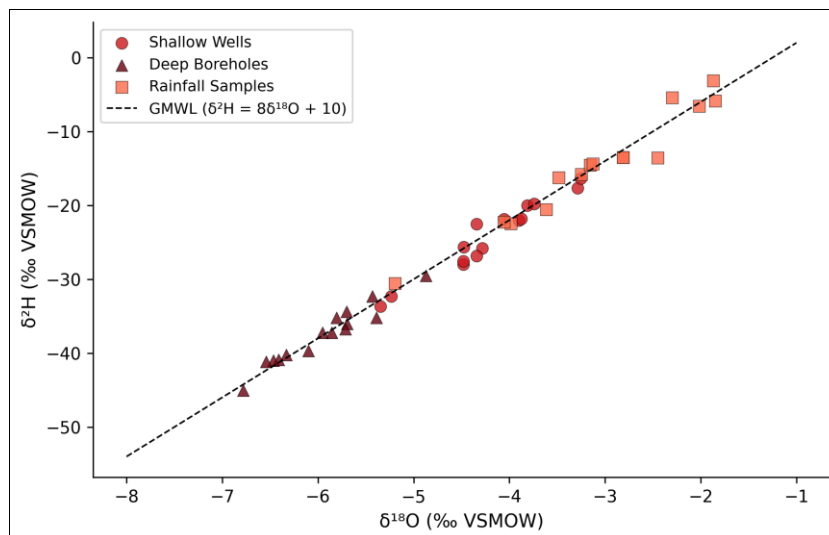


Fig 1: Stable isotope composition of groundwater and rainfall samples plotted against the Global Meteoric Water Line. Shallow wells cluster near the rainfall values while deep boreholes show evaporative enrichment.

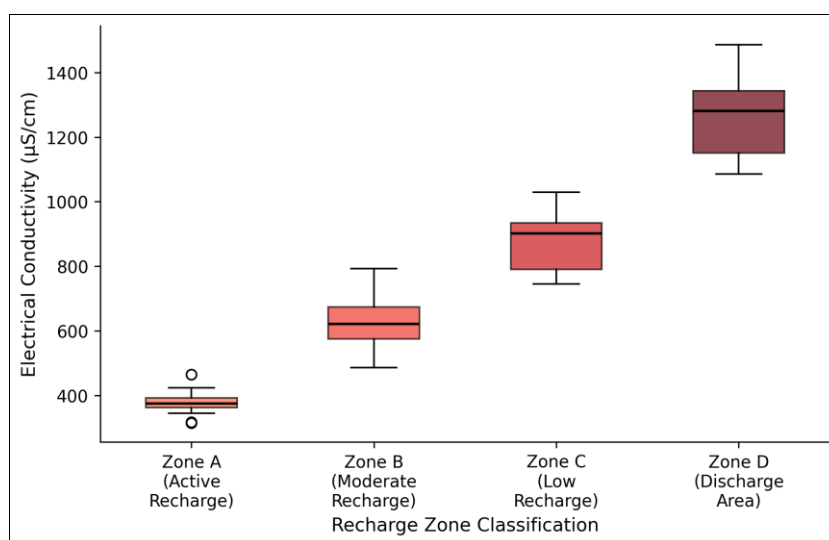


Fig 2: Electrical conductivity distribution across the four classified recharge zones. Box plots show median, interquartile range, and outliers (n = 50).

that modern recharge in the central Kalahari was negligible [13]. The progressive increase in EC and total dissolved solids from Zone A through Zone D traces a clear geochemical evolution along the flow path, driven by carbonate dissolution, cation exchange, and evaporative concentration. The hydrochemical gradient supports the potentiometric surface interpretation of a generally northwest-to-southeast flow direction, with a secondary component directed toward the Makgadikgadi depression in the east [14]. However, the tritium data also highlight the vulnerability of these recharge zones. Because active recharge is spatially concentrated in a relatively small portion of the mapped area (18.3%), any land use change such as overgrazing, pan modification, or borehole over-extraction could disproportionately reduce aquifer replenishment.

Conclusion

This research delineated four groundwater recharge zones across a 4,200 km² section of the central Kalahari using stable isotope tracers, hydrochemical parameters, and tritium dating. Active recharge was found to be concentrated in 18.3% of the mapped area, primarily associated with

ephemeral pan systems that enable focused infiltration during episodic high-intensity rainfall. Mean groundwater residence times ranged from 8 years in the active recharge zone to over 47 years in the southeastern discharge area. For water resource managers in central Botswana, the practical message is that protecting recharge corridors from degradation should be a priority. Borehole siting guidelines could incorporate the recharge zone map to avoid over-extraction in areas dependent on slow lateral flow. Future research should extend the tracer network to cover the broader Kalahari Basin and incorporate noble gas tracers to refine residence time estimates beyond the range accessible by tritium alone.

Acknowledgements

Funding Sources

This research received support from internal research allocation at the National Geological Institute of Warsaw.

Institutional Support

The authors thank the National Geological Institute of Warsaw, Masovia, Poland, for providing isotope laboratory access and analytical support.

Contributions Not Qualifying for Authorship

Field logistics support from the Botswana Department of Water Affairs and technical assistance from laboratory staff at the Warsaw Isotope Laboratory are acknowledged.

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