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# Tracing Urban Hydrological Connectivity in the Highly Altered Patiño Aquifer, Asunción, Paraguay

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## ABSTRACT

The Patiño Aquifer is a key groundwater source for the metropolitan region of Asunción, Paraguay, supporting domestic, industrial and agricultural demands. Increasing pressure on this resource highlights the need to better understand recharge processes and groundwater flow dynamics. This study (2019–2026) applied stable water isotopes ($\delta^2H$, $\delta^{18}O$ and *d*-excess) and dissolved radon ($^{222}Rn$) to evaluate urban hydrological connectivity. Precipitation isotopes showed a clear seasonal pattern controlled by atmospheric systems, particularly the South American Low-Level Jet and the South Atlantic Subtropical High. Surface waters and urban wells, especially in the northern metropolitan sector, exhibited higher $\delta^{18}O$ and lower *d*-excess values, indicating potential secondary evaporation effects and influence of urban return flows. In contrast, groundwater in the middle and southeastern more rural sectors displayed isotopic compositions closer to precipitation, suggesting recharge with limited evaporation. Radon activities showed a consistent trend, with low values in surface waters and increasing concentrations in groundwater towards the southeast. This spatial pattern may reflect greater interaction between groundwater and aquifer materials and is consistent with progressive evolution along inferred flow paths towards the Paraguay River. These findings improve understanding of aquifer dynamics and highlight the influence of urbanisation and extreme rainfall events on groundwater recharge and quality under changing climatic conditions.

## 1 | Introduction

The Patiño Aquifer constitutes one of the most critical groundwater systems in Paraguay, underlying the Metropolitan Area of Asunción (~2.6 million inhabitants) (Canese de Estigarribia et al. 2019) and supplying drinking water to a substantial proportion of the country's population (Foster and Garduño 2002; Báez et al. 2019; Gadea-Villalba 2019). This unconfined aquifer, developed primarily within the sandstones of the Patiño Formation, is highly accessible and widely exploited through thousands of shallow and deep wells (~2800; Báez et al. 2021), making it a critical resource for urban, industrial and domestic water supply systems (Foster and Garduño 2002; Rojas et al. 2017; Almada-Dominguez 2021). However, the hydrogeological characteristics of the aquifer, particularly the shallow water table and limited natural protection, also make the system highly vulnerable to contamination and overexploitation (Ortigoza-Caceres 2018; Gadea-Villalba 2019; Arrabal and Álvarez 2019).

Rapid urbanisation over the aquifer has introduced significant pressures on both groundwater quantity and quality (Arrabal and Álvarez 2019) in the recent decades. The expansion of urban infrastructure, combined with inadequate sewage systems and widespread use of septic tanks, has led to the proliferation of contamination sources across the aquifer system quality (Ortigoza-Caceres 2018; Báez et al. 2019; Facetti et al. 2019; Almada-Dominguez 2021). It is estimated that ~8000 direct and diffuse potential pollution sources exist, including household waste disposal systems, industrial activities and fuel storage facilities (Báez et al. 2021). As a result, groundwater quality deterioration has been widely documented, with elevated concentrations of nitrates, coliforms and hydrocarbons (e.g., methyl tert-butyl ether) (Facetti et al. 2019; Báez et al. 2021). In some cases, contamination affects a significant portion of the aquifer, with large areas classified as medium to high risk, particularly within the city of Asunción (north and northwestern regions of the Patiño Aquifer). Additionally, deeper salinisation processes linked to hydrogeological interactions (i.e., paleo-saline waters) with neighbouring aquifers further complicate water quality dynamics across the northern regions (Gadea-Villalba 2019).

These anthropogenic and hydrogeological factors highlight the need for improved understanding of the hydrological processes governing the Patiño Aquifer. A key aspect of this understanding is the interaction between groundwater and surface water systems. In urban catchments overlying an aquifer, streams and drainage networks are strongly influenced by subsurface contributions, particularly during baseflow conditions (Lerner 2002; Hamel et al. 2013; Liu et al. 2013). Conversely, during storm events, rapid recharge and surface runoff could enhance connectivity between surface and subsurface systems, mobilising contaminants and altering water quality in both domains (Ku et al. 1992; Meriano et al. 2011; Fletcher et al. 2024). Studies in urban basins in Asunción have shown that streams respond rapidly to precipitation inputs, reflecting the combined effects of surface runoff and subsurface flow pathways, which are often modified by urban infrastructure and land use changes (Sanders et al. 2019; Beyer 2023; Aguilar et al. 2025; Thiessen-Anttila et al. 2025).

These dynamic interactions highlight the need to characterise groundwater-surface water connectivity to better understand the overall resilience of the aquifer system to both anthropogenic and climate-driven pressures (Ward 2013; Coronel et al. 2015; Nagy et al. 2016; Rojas et al. 2017; Almada-Dominguez 2021). In this context, environmental tracers such as stable water isotopes ($\delta^{18}O$ and $\delta^{2}H$) (Kuhlemann et al. 2020; Vystavna et al. 2019; Wallace et al. 2021; Sánchez-Murillo et al. 2024; Watson et al. 2026) and dissolved radon ($^{222}Rn$) (Bonotto and Caprioglio 2002; Ortega et al. 2022; Vital et al. 2022; Petitta and Bonotto 2025) have emerged as powerful tools for investigating hydrological processes in complex and highly altered urban and natural systems such as the Patiño Aquifer. Stable water isotopes provide insights into the origin of water, recharge mechanisms and mixing processes between different sources, enabling the identification of flow pathways and water residence time from atmospheric to subsurface endmembers. Meanwhile, $^{222}Rn$, a naturally occurring radioactive gas enriched in groundwater relative to surface water (Genereux and Hemond 1990; Baskaran 2016; Esquivel-Hernández et al. 2024), serves as an effective tracer of groundwater discharge into streams and other surface water bodies.

In Paraguay, the availability of detailed lithological records, well-construction logs and long-term water level observations remains sparse across much of the Patiño Aquifer system, hindering the development of robust hydrogeological conceptualisations and modelling based solely on traditional datasets. Similarly, hydrometric time series are often discontinuous, spatially heterogeneous, or of insufficient duration to fully capture the temporal variability of recharge and groundwater-surface water interactions. Under these conditions, environmental tracers provide an independent and complementary line of evidence for evaluating hydrological connectivity among precipitation, groundwater and surface water, helping to identify recharge characteristics, water sources and subsurface interactions that may not be readily resolved through conventional monitoring approaches alone.

Therefore, this study provides a preliminary tracer-based assessment of hydrological connectivity among precipitation, surface water and groundwater in the Patiño Aquifer system, Asunción, Paraguay. Monthly stable water isotope measurements ($\delta^{2}H$, $\delta^{18}O$ and *d*-excess) (Dansgaard 1964) were analysed in rainfall samples (2019–2025) to establish a local meteoric isotope baseline and characterise seasonal variability in precipitation isotopic composition. HYSPLIT air-mass back-trajectory clustering analysis (Draxler and Hess 1998; Stein et al. 2015) was used as a qualitative tool to provide atmospheric context for the observed seasonal isotope patterns. Spatial measurements of $\delta^{18}O$ and dissolved $^{222}Rn$ in surface water and groundwater samples (2025–2026) were used to explore hydrological connectivity and identify tracer patterns consistent with variable recharge conditions, groundwater-surface water interaction and possible urban influences. Given the limited hydrometric data availability, our results are interpreted as complementary evidence supporting an initial conceptual understanding of the system. Overall, this study contributes a new precipitation isotope baseline and preliminary tracer observations that can support future hydrogeological investigations and modelling efforts of the Patiño Aquifer, particularly in the context of urbanisation and projected changes in the frequency and intensity of extreme precipitation events under climate change (Coronel et al. 2015).

## 2 | Study Area: Hydrogeological and Climate Characteristics

The Patiño Aquifer (1176 km$^2$) is a strategically important unconfined groundwater system underlying a large portion of Asunción (Paraguay), composed of more than 300 m of weakly cemented Cretaceous sands deposited within a NW-SE oriented graben approximately 20–30 km wide (Figure 1) (Foster and Garduño 2002; Monte Domecq and Baez 2007; Arrabal and Álvarez 2019). The lithology of the Patiño Aquifer is generally characterised by a basal unit composed of red, sandy-matrix pebble conglomerates (Gomez 1991). Upward in the sequence, these grade into red, coarse- to medium-grained sandstones

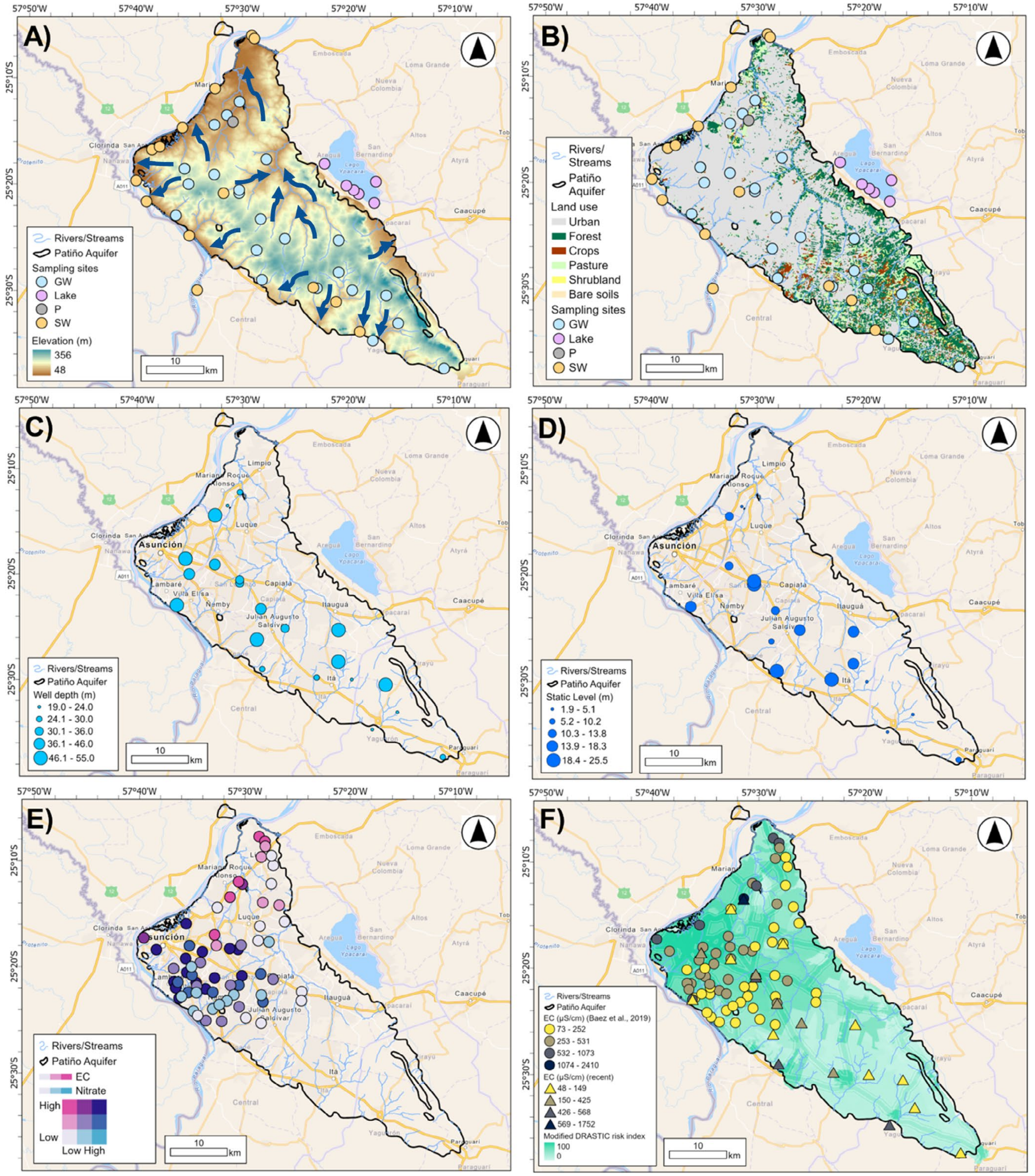


**FIGURE 1** | (A) Sampling sites (colour coded per water type) and elevation (m asl) across the Patiño Aquifer (black line polygon), Asunción, Paraguay. Blue arrows represent potential flow lines from high to low topographic areas towards the Paraguay River and San Lorenzo stream. (B) Land use classification across the Patiño Aquifer, modified after Báez et al. 2019. (C) Sampling well depth (m) and (D) groundwater static level (m) across the Patiño Aquifer. (E) Bivariate spatial distribution for groundwater electrical conductivity (EC) and nitrates across the Patiño Aquifer, modified after Báez et al. 2019. (F) Recent and archived EC (μS/cm) (Báez et al. 2019) across the Patiño Aquifer. A modified DRASTIC groundwater contamination risk index (nitrates and coliforms) (Báez et al. 2019) is shown as background in shaded green colours.

(Palacios formations), with occasional interbedded clayey sands and clay lenses (Monte Domecq and Baez 2007). These deposits have been assigned a Late Cretaceous age, as the sandstones contain clasts derived from Early Cretaceous basalts, providing a well-defined stratigraphic constraint on their age (Gomez 1991; Arguello-Fernández 2015).

The area includes the city of Asunción and its metropolitan area, as well as the districts of Limpio, Mariano Roque Alonso, Lambaré, Fernando de la Mora, San Lorenzo, Luque, Areguá, Capiatá, J. Augusto Saldívar, Itauguá, Itá, Ypané, Guarambaré, Villa Elisa, Ñemby, San Antonio, Yaguarón and parts of Paraguarí and Ypacaraí. The system is characterised by moderate well productivity, supporting widespread abstraction through public supply systems, private 'aguaterías' (i.e., a private company or small community entity that provides drinking water to households and businesses) and numerous domestic wells. Godoy (1991) noted that rapid lateral transitions between pelitic (fine-grained) and sandy sediments strongly control the exploitable yield of the aquifer. Due to this lithological heterogeneity, hydraulic conductivity varies between 0.1 and 3.4 m/day, while transmissivity ranges from 0.2 to 135 $m^2$/day. Well data reported by SENASA (2007) indicate that the specific capacity of wells commonly falls between 0.5 and 2.0 $m^3$/h/m. Because of the regional morphology, the Paraguay River and Lake Ypacaraí are not considered significant recharge sources for the Patiño Aquifer. Recharge most likely occur through direct infiltration of local precipitation, while groundwater discharge occurs mainly through subsurface flow towards the Paraguay River. Relevant hydrogeological information in the area has been obtained primarily from deep tubular wells ranging from 50 to 200 m in depth (Arguello-Fernández 2015). While well perforations up to 200 m have been reported, well depths typically range from 20 to 55 m, with static levels between 1.9 to 25.5 m (Figure 1).

Recharge rates are estimated at 300–400 mm/year in natural conditions and potentially higher in urban areas due to leakage from water supply networks, sanitation systems and recurrent urban flooding events (Foster and Garduño 2002). Total recharge is estimated at 259 $Mm^3$/year. The aquifer exhibits moderate to low permeability, with groundwater flow generally controlled by topography and discharging into surface water bodies (~136 $Mm^3$/year) such as the Paraguay River (~14 $Mm^3$/year), Lake Ypacaraí (López Moreira M et al. 2018) and regional urban and peri-urban stream systems (Arrabal and Álvarez 2019) (Figure 1). The system currently maintains a positive water balance, with recharge exceeding abstractions, although localised drawdowns are observed in heavily exploited urban areas (Báez et al. 2019).

Groundwater quality is typically characterised by low mineralisation and slightly acidic conditions, with two main hydrochemical facies, calcium-chloride (almost present in the entire aquifer) and sodium-chloride (mainly in the northern region and nearby the Paraguay River), reflecting different water origins and flow paths (Ortigoza-Caceres 2018; Arrabal and Álvarez 2019; Gadea-Villalba 2019; Báez et al. 2019, 2021). The limited monitoring and regulation, together with the hydrogeological characteristics, emphasise the aquifer's dual role as both a critical water resource and a system highly susceptible to degradation, underscoring the need for integrated management. Recent studies have indicated a high risk of water quality degradation (e.g., nitrates and coliforms) (Figure 1), mainly in the Gran Asunción area (Báez et al. 2019, 2021).

In the Patiño Aquifer area, the climate is humid subtropical, with an average annual precipitation of 1315 ± 354 mm, an average annual temperature of 24.6°C ± 5.4°C (ranging from 7.6°C to 35.9°C) (International Airport Silvio Pettirossi station) (Figure 2D). Precipitation shows a seasonal pattern, with the highest rainfall and temperatures occurring between November and February. Elevation across the aquifer ranges from 49 to 356 m asl (Figure 1). Roughly two thirds of the area are covered by urban development, followed by shrublands, forested and crop land in the southern portion of the aquifer. Water levels of the Paraguay River ranged from 7.58 m (5/29/2019) to −1.61 m (11/2/2024) (Figure 2E).

## 3 | Methods

### 3.1 | Precipitation Sampling

Monthly rainfall samples ($N$ = 73) were collected using a passive Palmex RS2 collector (Gröning et al. 2012) at the Silvio Pettirossi International Airport, AISP (Lat: −25.2358 degrees, Long: −57.51473 degrees, 83 m a.s.l.) between 2019 and 2025 (Figure 1). Samples were transferred into 30 mL glass bottles filled with no headspace and stored at 5°C until analysis. Daily and monthly precipitation amounts (mm), ambient temperature and water levels of the Paraguay River at Asunción were obtained from the Dirección Nacional de Aeronaútica Civil, Dirección de Meteorología e Hidrología of Paraguay (Dirección de Meteorología e Hidrología 2026).

### 3.2 | Groundwater and Surface Water Sampling

Wells ($N$ = 24) were sampled (April–August 2025) at depths ranging from 19 m to 55 m (Figure 1). Static groundwater levels ranged from ~2 to 26 m (Figure 1). The analysed wells included both active production wells and monitoring wells; for the latter, established protocols were followed (IAEA-FAO 2018), involving prior purging of the water before sample collection.

Surface waters (i.e., San Lorenzo, Itá, Yaguarón, Aveiro streams and Paraguay River) were sampled ($N$ = 16) (April 2025 to March 2026) from flowing stream or river sections or Lake Ypacaraí shoreline ($N$ = 6). All samples were collected in 60 mL HDPE bottles, hermetically sealed with parafilm and stored at 5°C until analysis at the Laboratory of the Comisión Nacional de Energía Atómica of Paraguay. Although the sample size is small relative to the total aquifer area, the monitoring points were strategically selected to represent the regional groundwater flow path, from the recharge zones in the topographic highs to the discharge areas near the Paraguay River, Lake Ypacaraí and other urban streams. This targeted sampling approach ensures that the isotopic variability captured reflects the major hydrogeological processes and anthropogenic influences across the urban-to-rural gradient.

Groundwater and surface water samples were collected during snapshot sampling campaigns in April 2025 (end of the rainy season), August 2025 (baseflow period) and March 2026 (during rainy season). In general, sampling locations were selected to provide a preliminary assessment of hydrological connectivity across the Patiño Aquifer by including representative samples from the principal hydrological compartments investigated in

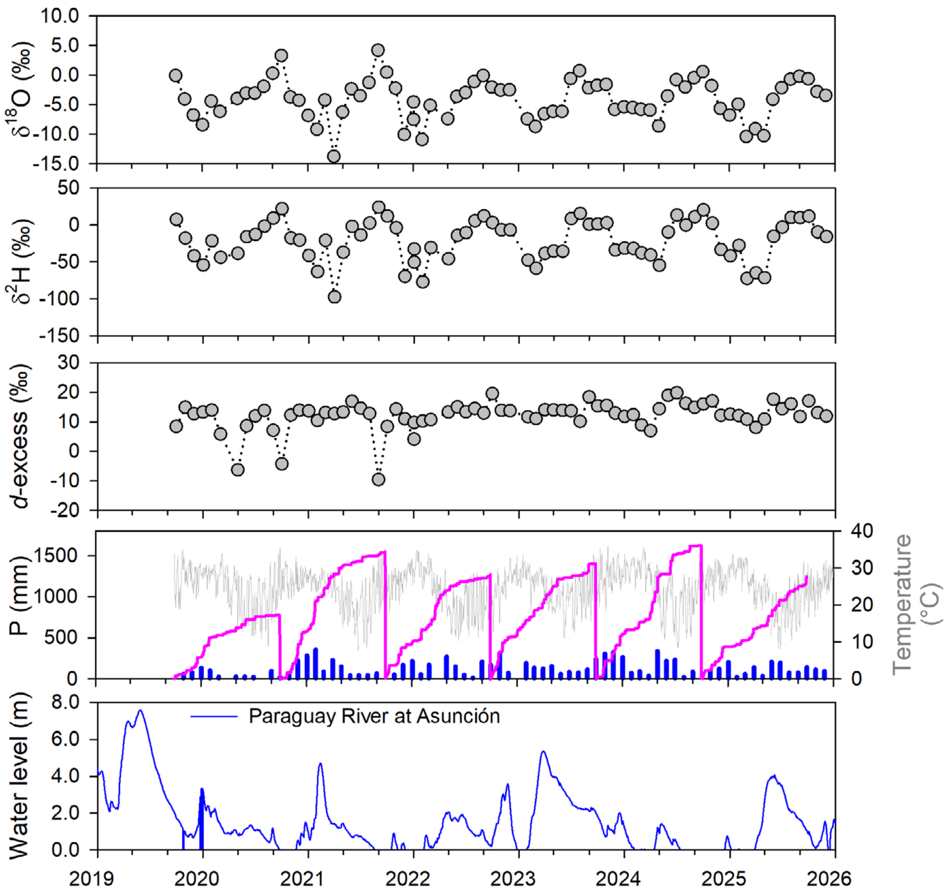


**FIGURE 2** | Time series of $\delta^{18}O$ (A), $\delta^2H$ (B), *d*-excess (C), monthly precipitation, cumulative precipitation and ambient temperature (D) and Paraguay River water level (E) in Asunción, Paraguay. Blue and red boxes in panel (D) represent El Niño and La Niña phases based on the Oceanic Niño Index (ONI).

this study, namely groundwater, surface water and urban stream systems. Sampling sites were distributed across different sectors of the aquifer to capture spatial variability associated with contrasting land-use settings and well depths, including urbanised and less-developed areas. In addition, site selection was influenced by practical constraints common to urban hydrogeological studies, including site accessibility, landowner permissions, well availability and safe access to sampling locations. Given the availability of sampling locations and site-access considerations, the sampling strategy was designed to provide representative spatial coverage of the principal hydrological compartments and support a preliminary assessment of hydrological connectivity across the Patiño Aquifer.

### 3.3 | Isotopic Analysis

Stable water isotope analysis ($\delta^2H$ and $\delta^{18}O$) was initially conducted at the IAEA Isotope Hydrology Laboratory (2019–2022) (Vienna, Austria). Since 2022, the isotopic analysis has been conducted at the Laboratory of the Comisión Nacional de Energía Atómica of Paraguay using a cavity ring-down spectroscopy (CRDS) analyser (Picarro L2130-*i*). For calibration and quality control, two secondary standards provided by the International Atomic Energy Agency (IAEA) were used (std1: $\delta^{18}O = +2.67‰$ and $\delta^2H = +35.80‰$ and std2: $\delta^{18}O = -19.64‰$ and $\delta^2H = -151.10‰$). These standards were previously calibrated against the VSMOW-SLAP international scale. In addition, an internal control standard was included in each analytical run to monitor instrument stability and potential drift (control: $\delta^{18}O = -10.87‰$ and $\delta^2H = -75.60‰$).

Each water sample was analysed through seven sequential injections. To minimise memory effects and ensure measurement stability, the first four injections were discarded and the last three were used for calculating isotopic values. Isotopic results are reported in delta (δ) notation in per mil (‰) relative to the VSMOW-SLAP scale (Equation 1). Overall analytical precision was ±0.1‰ for $\delta^{18}O$ and ±0.50‰ for $\delta^2H$. The data were processed with the LIMS software to ensure traceability and quality control.

$$\delta = \left[\left(R_s / R_{std}\right) - 1\right] \times 1000 \quad (1)$$

where $R$ represents the $^2H/^1H$ or $^{18}O/^{16}O$ abundance ratio and $R_s$ and $R_{std}$ are the ratios in the sample and standard, respectively. The deuterium excess (hereafter *d*-excess) (Dansgaard 1964) was calculated as follows:

$$d - excess = \delta^2H - 8 \cdot \delta^{18}O \quad (2)$$

Precipitation-weighted annual values were computed as follows (Camacho-Puerto et al. 2025):

$$\delta_P = \frac{\sum_{j=1}^{n} P_j \cdot \delta_{Pj}}{\sum_{j=1}^{n} P_j} \quad (3)$$

where $P$ represents precipitation (mm), $\delta_P$ represents the precipitation isotope content and subscript $j$ refers to an event reporting both isotope content and precipitation amount.

### 3.4 | Radon Analysis

The $^{222}$Rn activity was measured in the Paraguay River ($N$=8), streams ($N$=4; Yukyry, San Lorenzo, Capiatá and Pirayú), Lake Ypacaraí ($N$=16) and wells ($N$=11) using a RAD8 radon detector (Durridge Co., USA). Water was collected in 250 mL glass bottles and was analysed at the Laboratory of the Comisión Nacional de Energía Atómica of Paraguay, using a RAD-H2O kit. Samples were collected during snapshot sampling campaigns between August–September 2025 and January–February 2026. For each sample, seven measurement cycles of 4 min each were carried out. The first three cycles were discarded to ensure measurements under equilibrium conditions and the last four cycles were used to estimate the average $^{222}$Rn activity. Samples were typically analysed within 24 h after collection. Activities are expressed in Bq L$^{-1}$ with an analytical uncertainty of $\pm 2\sigma$ at a 95% confidence interval. The $^{222}$Rn activity was corrected for decay following Equation (4):

$$^{222}Rn_i = {}^{222}Rn_t \cdot e^{\left(\frac{t}{132.4}\right)} \quad (4)$$

where $^{222}Rn_i$ is the $^{222}$Rn activity in the water sample, $^{222}Rn_t$ is the $^{222}$Rn activity measured at the laboratory after time $t$ and $t$ is the time elapsed since water collection and the analysis at the laboratory.

### 3.5 | Air Mass Back Trajectory Clustering Analysis

Backward air-mass trajectories (96 h) were calculated using HYSPLIT (Draxler 1997, 1999; Draxler and Hess 1998; Stein et al. 2015) to characterise the dominant seasonal atmospheric transport patterns affecting the study region during precipitation sampling periods (2019–2025). The trajectory analysis is intended to provide a qualitative atmospheric context for interpreting seasonal variations in precipitation isotope composition and to identify broad differences in air-mass transport associated with wet- and dry-season conditions. Because precipitation isotope data were obtained from monthly integrated samples rather than individual precipitation events, trajectories were not linked to specific storm isotope signatures, and no event-scale trajectory-isotope analysis was performed. Furthermore, HYSPLIT trajectories were not used for quantitative moisture-source attribution, as backward trajectories alone do not account for moisture uptake, recycling, mixing, or condensation processes along transport pathways. Accordingly, the trajectory results are interpreted only as indicators of seasonal atmospheric circulation patterns and are used as complementary information to support the isotopic observations.

Specifically, air mass back-trajectories arriving over Asunción (Paraguay) were computed using NCAR/NCEP global reanalysis data following the methods described by (Sánchez-Murillo et al. 2025). The clustering process involves the calculation of the spatial variance (SV) between each endpoint $k$ of trajectory $j$ within its cluster $i$ using Equation (5):

$$\mathrm{SV}_{i,j} = \Sigma_k \left(P_{j,k} - \mathrm{M}_{i,k}\right)^2 \quad (5)$$

where $P_{j,k}$ is the position of the trajectory point and $M_{i,k}$ is the corresponding point on the cluster's mean trajectory. The cluster spatial variance (CSV) for each cluster is then the sum of the SV values for all trajectories within that cluster (Equation 6):

$$\mathrm{CSV}_i = \Sigma_j \mathrm{SV}_{i,j} \quad (6)$$

Finally, the total spatial variance (TSV) is the sum of all cluster spatial variances across the clusters (Equation 7):

$$\mathrm{TSV} = \Sigma_i \mathrm{CSV}_i \quad (7)$$

Once the clusters were established, individual trajectories within each cluster were averaged to generate a cluster-mean trajectory that represented the overall transport pattern for that group. The cluster percentage (%) represents the proportion of total trajectories (N) assigned to a specific cluster related to moisture source provenance (Equation 8). This approach allowed us to examine variability in air mass transport and identify distinct atmospheric transport regimes affecting Asunción (Paraguay) during the hydrological year.

$$\text{Cluster}\ (\%) = \left(\frac{n_i}{N}\right) \cdot 100 \quad (8)$$

### 3.6 | Data Analysis

The data analysis included the estimation of a Local Meteoric Water Lines (LMWL; reduced major axis regression method; Crawford et al. 2014) to evaluate the meteoric origin of groundwater and surface water sources as well as potential secondary evaporation processes. Spatial visualisations were conducted in ArcGIS Pro 3.5 (ESRI 2025). The R program packages used for data visualisation, linear regressions and descriptive statistics include 'ggplot2', 'ggpubr', 'cowplot', 'dplyr' and 'patchwork' (Wickham et al. 2014; Wilke 2015; Kassambara 2016; Wickham 2016; Pedersen 2019).

## 4 | Results

### 4.1 | Precipitation Isotope Variability

Precipitation isotopes revealed a clear sinusoidal seasonality (Allen et al. 2019). In Asunción, $\delta^{18}$O varied between −13.8‰ and −4.2‰ (mean = −4.1‰ ± 3.4‰) and $\delta^2$H ranged between −97.5‰ and 23.8‰ (mean = −20.9‰) (Figure 2A,B). The $d$-excess exhibited a mean of 12.9‰ ± 5.0‰ and varied between 19.9‰ and −9.6‰ (Figure 2C). Overall, the arithmetic (precipitation-weighted) $\delta^2$H, $\delta^{18}$O and $d$-excess corresponded to −20.9‰ (−26.0‰), −4.1‰ (−4.9‰) and 12.1‰ (13.1‰), respectively (Table 1). In general, $\delta^{18}$O and $\delta^2$H were lower during the triple-dip La Niña (2020–2022) than El Niño (2023–2024) or neutral phases (2024–2025) (Figure 2D). Lower $d$-excess values were also observed during the La Niña (2020–2022).

**TABLE 1** | Summary of precipitation totals (mm) and arithmetic and precipitation-weighted (w) values (in ‰) for $\delta^{18}O$, $\delta^{2}H$ and *d*-excess per year.

| Year | *N* | P (mm) | $\delta^{18}O$ | $\delta^{18}O_w$ | $\delta^{2}H$ | $\delta^{2}H_w$ | *d*-ex | d-ex$_w$ |
|---|---|---|---|---|---|---|---|---|
| 2020 | 12 | 605 | −3.2 | −4.5 | −17.5 | −25.6 | 8.3 | 10.3 |
| 2021 | 12 | 1582 | −4.3 | −6.9 | −23.0 | −43.4 | 11.0 | 11.8 |
| 2022 | 12 | 1564 | −4.8 | −4.9 | −26.3 | −27.4 | 12.4 | 12.1 |
| 2023 | 11 | 1545 | −4.0 | −4.1 | −18.6 | −19.1 | 13.6 | 13.7 |
| 2024 | 12 | 1994 | −3.8 | −4.5 | −16.2 | −21.1 | 14.0 | 14.7 |
| 2025 | 12 | 1370 | −4.8 | −4.4 | −24.7 | −21.2 | 13.4 | 13.9 |

**TABLE 2** | Summary of precipitation totals (mm) and arithmetic and precipitation-weighted (w) values (in ‰) for $\delta^{18}O$, $\delta^{2}H$ and *d*-excess per season.

| Season | *N* | $\delta^{18}O$ | $\delta^{18}O_w$ | $\delta^{2}H$ | $\delta^{2}H_w$ | *d*-ex | d-ex$_w$ |
|---|---|---|---|---|---|---|---|
| Spring | 19 | −0.8 | −1.4 | 5.4 | 2.9 | 11.8 | 14.0 |
| Summer | 18 | −6.5 | −6.6 | −40.5 | −41.4 | 11.8 | 11.7 |
| Fall | 16 | −7.4 | −7.9 | −49.4 | −51.6 | 10.1 | 12.0 |
| Winter | 18 | −2.4 | −2.5 | −4.5 | −3.9 | 14.5 | 16.0 |

Across all years, summer (−6.6‰) and fall (−7.9‰) seasons exhibited lower precipitation-weighted $\delta^{18}O$ than winter (−2.5‰) and spring (−1.4‰) (Table 2). A similar pattern was observed for precipitation-weighted $\delta^{2}H$. Higher precipitation-weighted *d*-excess values were observed in spring (14.0‰) and winter (16.0‰) compared to summer (11.7‰) and fall (12.0‰) seasons. The precipitation-weighted isotope values reveal clear interannual variability, with the most distinct isotopic compositions observed during 2021, coinciding with La Niña conditions. Among the study years, 2021 exhibited the lowest precipitation-weighted $\delta^{18}O$ (−6.9‰) and $\delta^{2}H$ (−43.4‰) values. Similarly, *d*-excess (11.8‰) displayed notable interannual variability, with 2021 characterised by the lowest values observed during the study period. Seasonal comparisons also indicate substantial year-to-year variability in the isotopic composition of precipitation, particularly during austral winter and fall. The *d*-excess exhibited similar seasonal patterns, reflecting variations in atmospheric transport and local precipitation conditions among years.

Monthly precipitation amounts varied from 355 mm (Summer 2021) to 3 mm (Spring 2020) with a mean of 121 ± 92 mm (Figure 2D). Annual rainfall totals ranged from 774 mm (2020) to 1729 mm (2023), with a mean of 1315 ± 354 mm. In general, the wettest seasons correspond to fall (monthly mean = 129 mm) and summer (monthly mean = 163 mm), followed by spring (monthly mean = 111 mm) and winter (monthly mean = 87 mm).

### 4.2 | Atmospheric Moisture Sources

The air mass back trajectory clustering analysis indicates a clear seasonal cycle in atmospheric transport to Asunción, Paraguay, dominated by shifting contributions from the Amazon Basin and the South Atlantic (Figure 3). Winter (JJA) shows a reduced area of influence from northwestern transport pathways (65%) with contributions from southerly and southeasterly transport pathways (35%), indicating a stronger role of subtropical jet systems and reduced tropical moisture input, resulting in an overall weaker moisture supply and occasional cold fronts migration.

In spring (SON), this Amazonian transport contribution begins to strengthen, covering a larger transport area to the north and northeast (65%), with mixed inflow from both the northeast and east, likely linked to the intensification of the South American Low-Level Jet (SALLJ). During summer (DJF), atmospheric transport was strongest and primarily originates from the north and northwest (54%) and nearby warm fronts (34%), reflecting intense Amazonian influence associated with the South American Monsoon System (SAMS) and enhanced continental moisture recycling. In contrast, fall (MAM) represents a transitional phase in which Amazonian influence weakens and a more balanced contribution from eastern (Atlantic) and northern sources emerges.

### 4.3 | LMWL, Groundwater and Surface Water Isotopes and Radon Variability

The Local Meteoric Water Line (LMWL) for Asunción, Paraguay (2019–2025, $N = 73$) was defined as $\delta^{2}H = (8.00 \pm 0.24)\ \delta^{18}O + (12.10 \pm 1.41;\ R^2 = 0.98;\ p\text{-value} < 0.001)$ (Figure 4A). Lake Ypacaraí $\delta^{18}O$ varied between −2.3‰ and 0.1‰ (mean = −1.0‰ ± 1.3‰) with a mean *d*-excess of 4.7‰ ± 2.1‰, which indicates typical evapoconcentration conditions (i.e., evaporation-induced increase in $\delta^{18}O$ and $\delta^{2}H$ and decrease in *d*-excess values resulting from preferential loss of lighter water molecules) in this shallow lake (~3 m depth) (Figure 4A,B) (Bowen et al. 2018). The Paraguay River and urban streams exhibited $\delta^{18}O$ ranging from −5.5‰ to −3.0‰ with a mean of −4.6‰ ± 0.8‰, while surface water *d*-excess varied

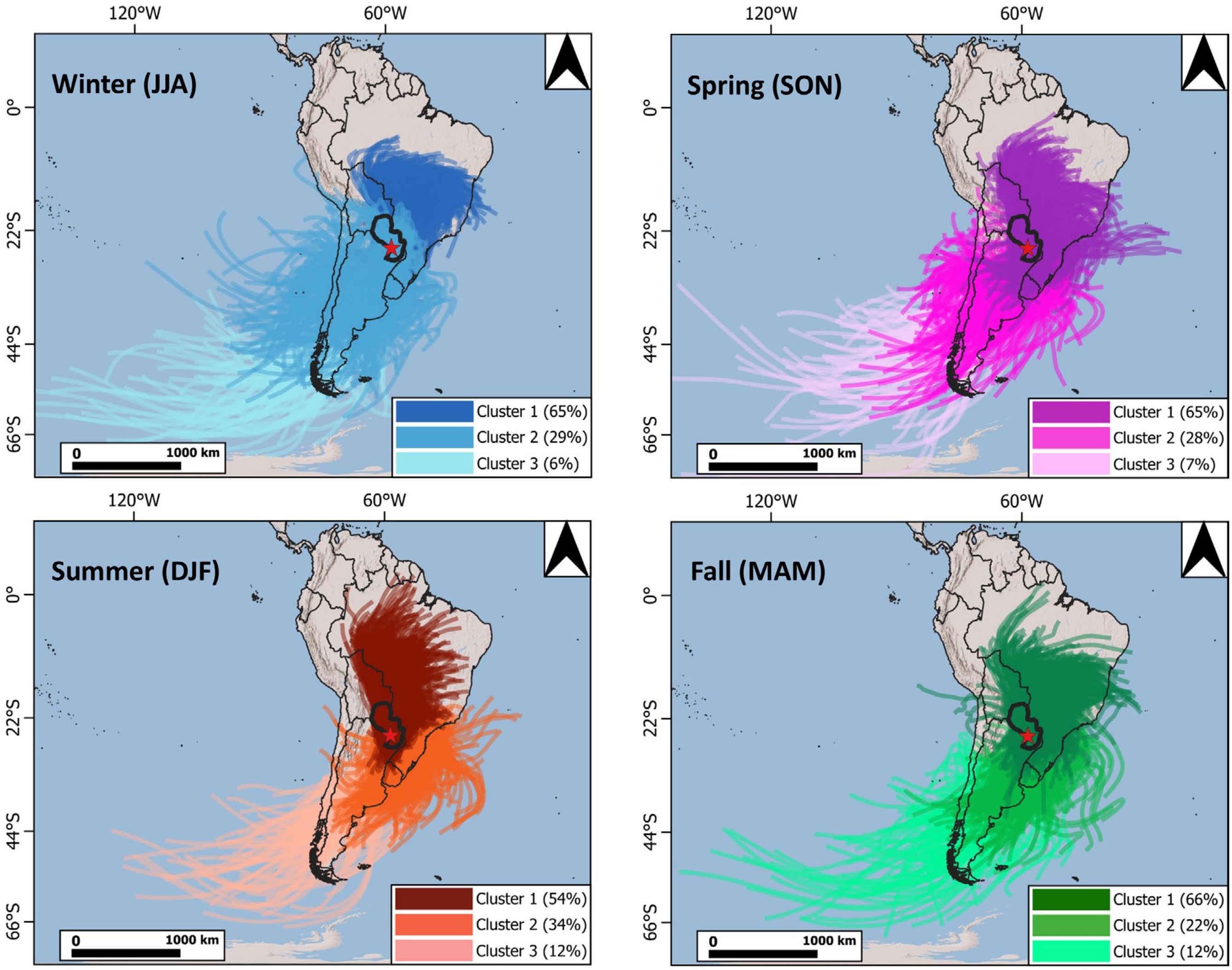


**FIGURE 3** | HYSPLIT air mass back trajectory clusters per season (2019–2025) for the monitoring station in Asunción, Paraguay (red star).

between 13.2‰ and 2.0‰ with a mean of 6.5‰ ± 3.6‰. Wells showed $\delta^{18}O$ ranging from −6.4‰ to −4.4‰ with a mean of −5.5‰ ± 0.5‰. Groundwater *d*-excess varied between 14.0‰ to 6.4‰ (mean = 11.6‰ ± 3.6‰) (Figure 4A,B).

In general, $\delta^{18}O$ and *d*-excess values showed a spatial pattern across the study area (Figure 5). Higher $\delta^{18}O$ accompanied by lower *d*-excess values were consistently reported in Lake Ypacaraí, but also along the Paraguay River and in wells within the Gran Asunción metropolitan area. Lower $\delta^{18}O$ (higher *d*-excess) values were concentrated in the middle and southern areas of the aquifer.

Radon activities were low across the shoreline and across Lake Ypacaraí with values typically lower than 0.20 Bq/L (Figure 6). Urban streams (Yukyry, San Lorenzo, Capiatá and Pirayú streams) showed higher activities, ranging from 0.25 to 0.71 Bq/L (Figure 6). The Paraguay River exhibited very uniform values, ranging from 0.11 to 0.28 Bq/L, with a mean of 0.20 ± 0.05 Bq/L. Greater $^{222}Rn$ variability was observed in groundwater, with values ranging from 0.98 to 18.44 Bq/L (mean = 6.4 ± 0.05 Bq/L) (Figure 6). Overall, $^{222}Rn$ activity increased in a southeastern direction along inferred flow lines.

## 5 | Discussion

### 5.1 | Atmospheric Transport and Precipitation Isotope Variability

The isotopic composition of precipitation in Asunción (Paraguay) exhibited a well-defined seasonal pattern driven by large-scale atmospheric circulation (Figure 3). The dominance of Amazonian moisture transport during summer and transitional seasons results in lower $\delta^{18}O$ values, while increased contributions from Atlantic and subtropical sources during winter and spring lead to relatively higher isotopic values. This seasonal alternation is consistent with the shifting influence of the SALLJ and the South Atlantic Subtropical High (SASH) and associated synoptic systems (e.g., SAMS and warm/cold fronts). Similar isotope patterns have been observed in La Plata Basin (Argentina), northwestern Argentina and southeastern Brazil (Rozanski and Araguás Araguás 1995; Dos Santos et al. 2019; Poca et al. 2020; Dos Santos, Gastmans, et al. 2024; Valdivielso et al. 2024; Quiroz Londoño et al. 2025).

In general, during the summer, intense local rainfall is sustained by moisture transported southeastward by the SALLJ,

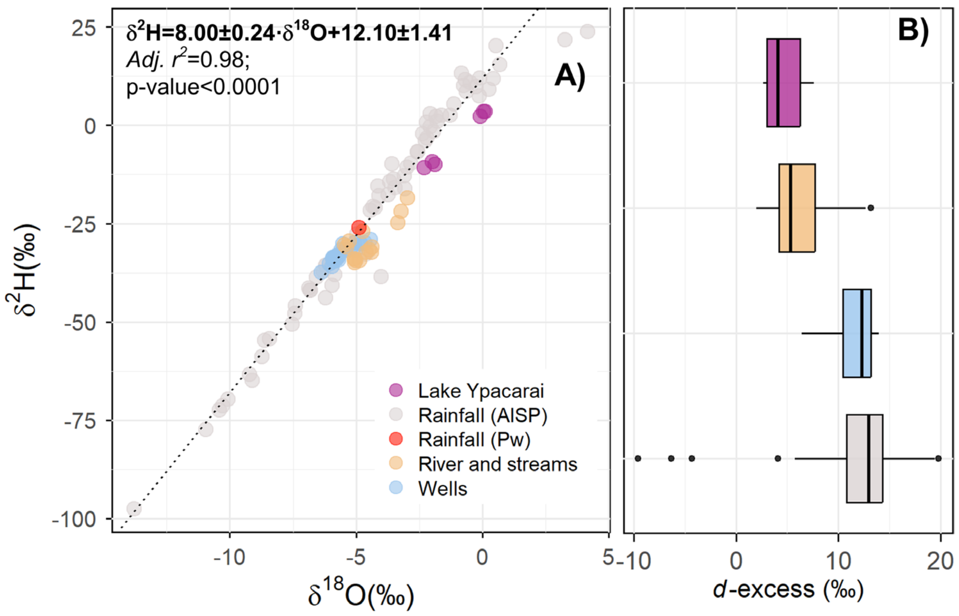


**FIGURE 4** | (A) Dual isotope plot ($\delta^2H$ vs. $\delta^{18}O$) showing different endmembers: Lake Ypacaraí, rainfall (AISP station), mean precipitation-weighted (Pw), wells and surface waters (Paraguay River and streams). The LMWL for Asunción, Paraguay is included as a reference. (B) The right panel shows a boxplot for *d*-excess. The centre line of the boxes indicates the median value, while the box represents the interquartile range (IQR: 25th to 75th percentiles). The whiskers (vertical lines) show the full range of the data and the outliers (values exceeding 1.5*IQR or ~2.7$\sigma$ above/below the median).

which is subsequently uplifted due to instability arising from the interaction between anticyclonic circulation associated with the SASH and transient fronts (Salio et al. 2007; Grimm and Zilli 2009; Dos Santos, Gastmans, et al. 2024; Orrison et al. 2024; Rehbein et al. 2026). At the local scale, high-frequency isotope measurements in inland tropics of Brazil have shown that convective intensity exerts a strong control on the isotopic composition of summer precipitation (Dos Santos, Durán-Quesada, et al. 2024; Dos Santos, Gastmans, et al. 2024). Similar processes may contribute to the isotopic variability observed in Paraguay, particularly during the warm season when deep convection and intense rainfall events are common. However, because the present study is based on monthly integrated precipitation samples, it is not possible to directly evaluate event-scale controls or quantify the influence of convective intensity on precipitation isotopes.

In addition to seasonal variations in atmospheric circulation, interannual climate variability associated with the El Niño-Southern Oscillation (ENSO) may influence the isotopic composition of precipitation in Paraguay. Previous studies have shown that El Niño events enhance precipitation across southeastern South America, including Paraguay, through the intensification of the SALLJ, which transports moisture from the Amazon Basin towards the La Plata region (Grimm et al. 2000; Grimm and Tedeschi 2009). These circulation changes are often associated with increased moisture convergence and a higher frequency of heavy precipitation events, particularly during austral spring.

From an isotopic perspective, such conditions may strengthen the classical 'amount effect' (Dansgaard 1964), resulting in lower $\delta^{18}O$ and $\delta^2H$ values during periods of sustained or intense rainfall (Sánchez-Murillo et al. 2023). In contrast, La Niña events are generally associated with reduced precipitation over Paraguay and portions of southeastern South America, reflecting weakened moisture transport from tropical regions and altered atmospheric circulation patterns (Boulanger et al. 2005; Rivera 2024). These drier conditions may result in lower *d*-excess values due to lower rainfall totals, increased sub-cloud evaporation and a greater contribution of locally recycled moisture (Quiroz Londoño et al. 2025). Consequently, ENSO-driven changes in atmospheric circulation and precipitation regimes have the potential to modulate both the isotopic composition of precipitation and the isotopic characteristics of groundwater recharge across Paraguay. Preliminary evidence of ENSO influence on precipitation isotopes in Asunción is reflected in lower *d*-excess observed during the recent triple-dip La Niña event (2020–2022). (Iwakiri et al. 2023; Shi et al. 2023) Although the mechanisms controlling these isotopic anomalies require further investigation, they suggest that large-scale circulation changes associated with ENSO may influence moisture transport pathways and precipitation isotope composition over Paraguay.

Although ENSO impacts were not explicitly evaluated in this study, the multi-year precipitation isotope record presented here provides a valuable baseline for future investigations examining the influence of interannual climate variability, moisture-source dynamics and extreme hydroclimatic events on precipitation isotopes and groundwater recharge processes in Paraguay. The influence of convective intensity on precipitation isotopes is particularly relevant for the Patiño Aquifer because local precipitation represents the principal source of groundwater recharge. Variations in rainfall-generating mechanisms, including the relative contribution of deep convective systems, can modify the isotopic composition of precipitation and consequently the isotopic signature transmitted to groundwater recharge.

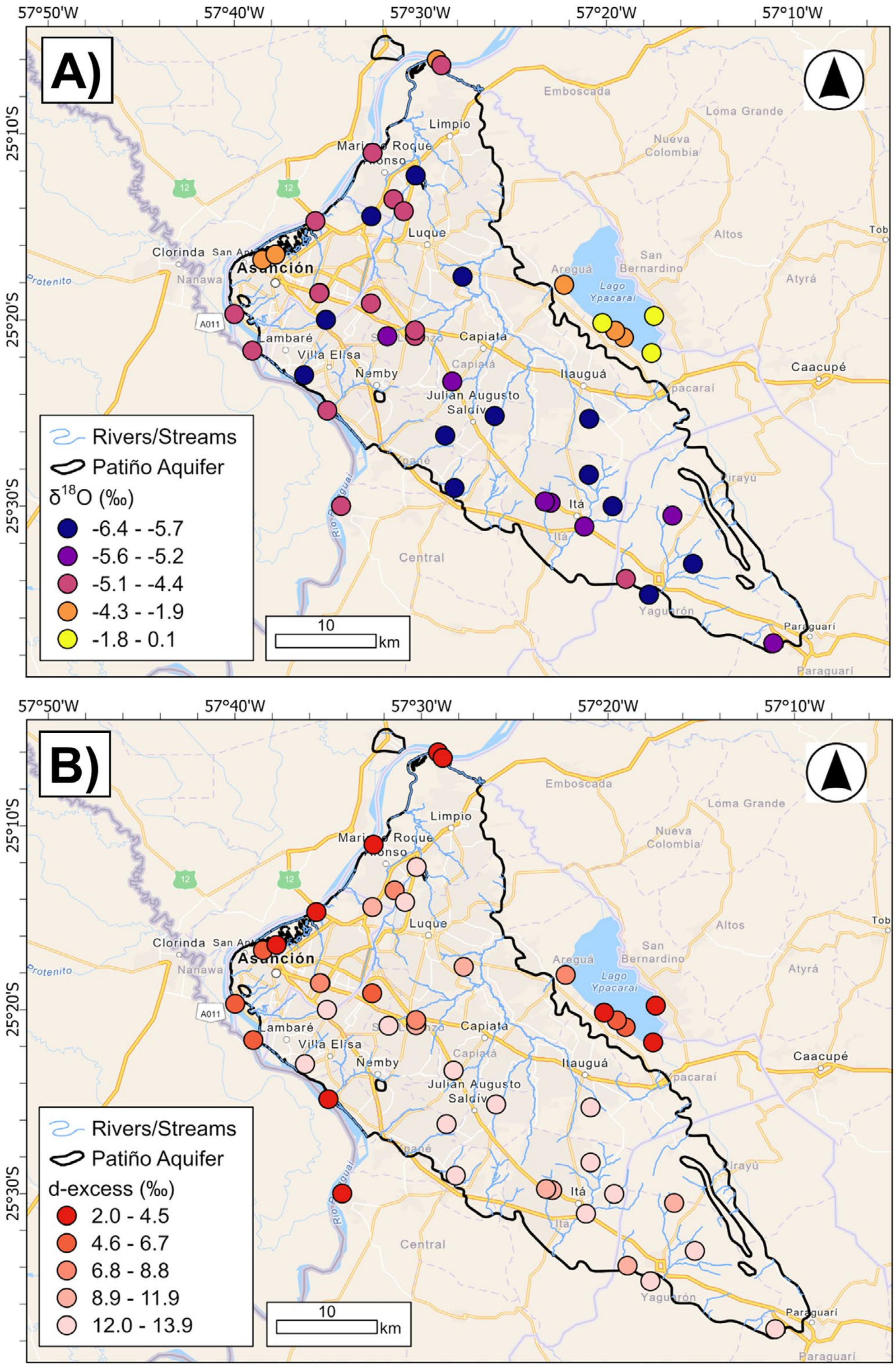


**FIGURE 5** | Rainfall, surface waters (Paraguay River, Lake Ypacaraí and urban streams) and wells $\delta^{18}O$ (A) and *d*-excess (B) spatial variability.

## 5.2 | Spatial Isotope and Radon Variability

The combined interpretation of stable water isotopes and dissolved $^{222}Rn$ provides a preliminary conceptual model of the hydrological connectivity within the Patiño Aquifer (Figure 7). Both tracers identify clear spatial contrasts between the northern metropolitan sector and the central-to-southeastern portions of the aquifer (Figures 5 and 6). Surface waters and several northern groundwater sites exhibit relatively higher $\delta^{18}O$ values and lower *d*-excess, consistent with greater evaporative modification and mixing of waters (e.g., storm runoff, untreated wastewater) potentially influenced by previously reported urban hydrological processes. In highly urbanised areas such as Asunción, recharge may be enhanced by leakage from water distribution networks, septic systems and stormwater infiltration during intense rainfall events (Foster and Chilton 2004; Kruse et al. 2013; Tubau et al. 2017; Wallace et al. 2021). These processes can introduce isotopically

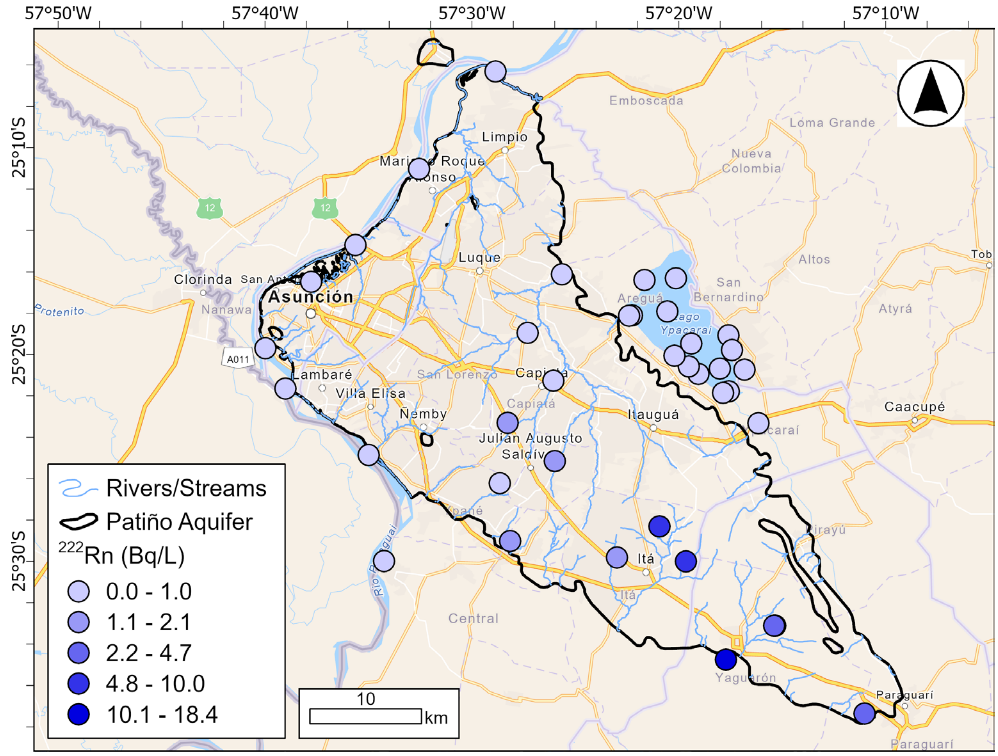


**FIGURE 6** | Surface water (Paraguay River, Lake Ypacaraí and urban streams) and groundwater $^{222}$Rn (Bq/L) spatial variability.

modified water with distinct chemical characteristics, contributing to the observed spatial gradients and the previously high concentrations of nitrate, coliforms and hydrocarbons across the metropolitan region (Ortigoza-Caceres 2018; Báez et al. 2019, 2021; Facetti et al. 2019; Gadea-Villalba 2019).

In contrast, groundwater from the central and southeastern sectors displays isotopic compositions closer to local precipitation, suggesting recharge under conditions with more limited evaporative modification. A similar spatial organisation is observed in the $^{222}$Rn dataset, where groundwater generally exhibits higher activities and greater spatial variability than surface waters. Although radon activities cannot be uniquely interpreted in terms of groundwater age or residence time, the correspondence between isotope patterns and radon distributions suggests that both tracers capture differences in groundwater-surface water interaction and subsurface conditions across the study area.

These observations support the conceptual model of spatially variable hydrological connectivity within the Patiño Aquifer (Figure 7), while also highlighting the need for additional hydrogeological, geochemical and groundwater-age data to further constrain the underlying processes. In addition, this urban imprint on groundwater highlights the importance of considering anthropogenic recharge as a significant component of the aquifer water balance (see a preliminary water balance by Arrabal and Álvarez 2019). It also underscores the complexity of groundwater flow in urban environments, where natural recharge processes are superimposed with engineered and incidental inputs that can alter both quantity and quality. The spatial alignment between isotopic indicators of urban influence and previously identified contamination risk zones suggests (Báez et al. 2019, 2021) that recharge pathways play a critical role in controlling groundwater vulnerability in the Patiño Aquifer. As climate change is expected to increase the frequency of extreme precipitation events (Ortiz et al. 2022; Thiessen-Anttila et al. 2025; Aguilar et al. 2025; González 2026), the potential for rapid contaminant mobilisation and infiltration is likely to intensify, further exacerbating risks to groundwater quality in the Patiño Aquifer.

### 5.3 | Study Limitations and Future Research Needs

This study provides a preliminary tracer-based assessment of hydrological connectivity among precipitation, groundwater and surface water systems within the Patiño Aquifer. While the combined use of stable water isotopes and dissolved $^{222}$Rn provides valuable insights into spatial variability and potential hydrological linkages, several limitations should be considered when interpreting the results. First, the hydrogeological characterisation of the aquifer remains constrained by the limited availability of detailed lithological records, well-construction logs, hydraulic testing data, groundwater-level monitoring networks and long-term hydrometric observations across much of the aquifer system. Although previous studies have reported hydraulic conductivity values (Arguello-Fernández 2015), these estimates are spatially heterogeneous and derived from localised investigations, making aquifer-wide characterisation challenging.

Second, groundwater and surface-water snapshot sampling campaigns were designed to provide representative coverage of the principal hydrological settings and land-use conditions

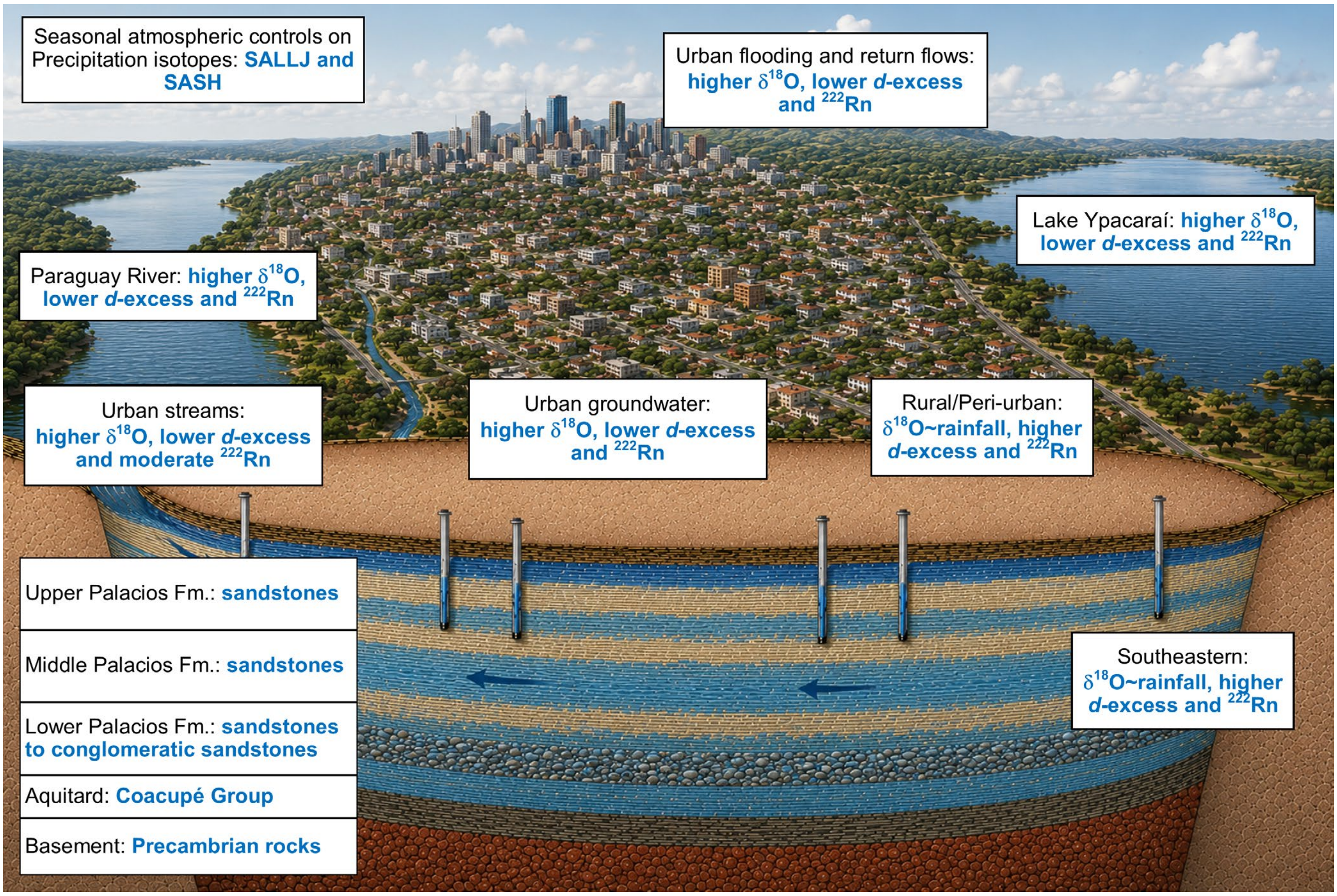


**FIGURE 7** | Conceptual model of hydrological connectivity in the Patiño Aquifer system, Paraguay. The landscape includes the Asunción metropolitan area, the Paraguay River and Lake Ypacaraí, highlighting the contrasting hydrological settings present across the study area. Precipitation derived from regional atmospheric circulation provides the primary source of aquifer recharge through diffuse infiltration. The subsurface section depicts the principal hydrostratigraphic units (not to scale) (Monte Domecq and Baez 2007) of the aquifer system, including the Upper, Medium and Lower Palacios formations, underlain by the Coacupé Group aquitard and Precambrian basement. Groundwater flow is shown schematically towards the Paraguay River, which represents the principal regional discharge zone. Urban drainage, flooding, infrastructure leakage and return flows may locally influence recharge (isotopic) conditions in developed areas, while diffuse infiltration of precipitation predominates in less urbanised sectors.

present within the study area. However, the number and distribution of sampling locations remain limited relative to the overall extent and heterogeneity of the Patiño Aquifer. Site accessibility, landowner permissions and institutional authorisations, well availability and safe field access also influenced the final sampling network. Consequently, the observed tracer patterns should be interpreted as indicators of spatial variability and potential hydrological connectivity rather than definitive evidence of regional groundwater flow pathways or recharge processes.

Third, interpretations based on dissolved $^{222}$Rn should be considered qualitative. Although elevated groundwater radon activities may reflect increased groundwater interaction with aquifer materials and reduced exchange with the atmosphere, radon activities are influenced by multiple factors, including lithology, uranium and radium content, emanation efficiency, groundwater flow conditions, dilution processes and gas exchange. Therefore, the radon dataset is primarily used here to identify spatial contrasts among hydrological compartments and to complement the stable isotope observations rather than to directly infer groundwater age or residence times.

Similarly, the atmospheric trajectory analysis was intended to provide seasonal atmospheric context for interpreting precipitation isotope variability. Because precipitation isotopes were obtained from monthly integrated samples rather than individual precipitation events, the HYSPLIT analysis was not used for event-scale isotope attribution or quantitative moisture-source determination. Backward trajectories alone do not account for moisture uptake, recycling, mixing, or condensation processes and should therefore be interpreted as indicators of broad seasonal atmospheric circulation patterns represented by the trajectory-clustering analysis rather than definitive moisture-source diagnostics.

Finally, the absence of dedicated groundwater age tracers (e.g., tritium, $SF_6$, CFCs, or noble gases) limits the ability to constrain groundwater residence times and recharge chronology. Consequently, interpretations related to recharge conditions, groundwater evolution and hydrological connectivity are presented as a conceptual framework supported by tracer observations and prior studies rather than a fully constrained hydrogeological model. Future research integrating environmental tracers with groundwater-level monitoring, hydraulic testing, geochemical characterisation, age-dating techniques and numerical groundwater flow modelling would substantially improve understanding of recharge dynamics, groundwater-surface water interactions and the impacts of urbanisation and climate variability on the Patiño Aquifer. In particular, the incorporation of groundwater-age tracers such as $^3H$, $^3H/^3He$, $SF_6$ and noble gases represents a promising next step towards developing a fully constrained conceptual and numerical model of the aquifer system.

## 6 | Conclusions

This study provides a preliminary tracer-based assessment of hydrological connectivity among precipitation, groundwater and surface-water systems in the Patiño Aquifer, Paraguay. The integration of stable water isotopes and dissolved $^{222}Rn$ provides new insights into the spatial and seasonal variability of water sources and subsurface interactions within this highly altered and intensively utilised aquifer system. The multi-year precipitation isotope record (2019–2025) revealed distinct seasonal variations in $\delta^2H$, $\delta^{18}O$ and *d*-excess that are consistent with changes in regional atmospheric transport pathways. HYSPLIT trajectory clustering analysis provided qualitative atmospheric context for these patterns, highlighting seasonal changes between Amazonian and Atlantic/southern air-mass influences. Groundwater and surface-water isotope compositions exhibited clear spatial variability across the study area. Groundwater in the central and southeastern sectors generally displayed isotopic compositions closer to local precipitation, whereas surface waters and some wells in the northern metropolitan area exhibited higher $\delta^{18}O$ and lower *d*-excess values, consistent with greater evapoconcentration and mixing. These patterns suggest that recharge conditions and hydrological connectivity vary across the aquifer and may be influenced by land use and urban development. Dissolved $^{222}Rn$ activities were consistently lower in surface waters than in groundwater and exhibited substantial spatial variability throughout the aquifer system. The observed radon patterns are consistent with differences in groundwater-surface water interaction and groundwater contact with aquifer materials, providing an independent and complementary line of evidence to support the stable isotope observations.

Overall, the tracer observations highlight the heterogeneous nature of the Patiño Aquifer and support the development of an initial conceptual framework linking precipitation, groundwater and surface-water systems. Given the limited availability of detailed lithological information, groundwater-level monitoring and long-term hydrometric records in Paraguay, environmental tracers provide valuable complementary information for investigating hydrological connectivity in data-scarce settings. Future research should integrate environmental tracers with groundwater-level observations, hydraulic testing, hydrochemical analyses, groundwater-age tracers and numerical modelling to further constrain recharge conditions, groundwater-surface water interactions and the influence of urbanisation and climate variability (e.g., ENSO) on the aquifer recharge, storage and groundwater quality. Such efforts will contribute to a more comprehensive understanding of the Patiño Aquifer and support sustainable groundwater management under increasing urban and climatic pressures.


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The authors have nothing to report.

### Conflicts of Interest

The authors declare no conflicts of interest.


### Data Availability Statement

All isotope data is available at CUAHSI's online data repository HydroShare (Montiel et al. 2026) at https://doi.org/10.4211/hs.5ee6119e09e54610a0cb865307dbc96c, reference number 10.4211/hs.5ee6119e09e54610a0cb865307dbc96c.

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