Direct rapid recharge controls the hydrological response in a peri-urban mountainous tropical catchment

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Abstract

In the wet tropics, the seasonal changes in rainfall amounts are altering catchment storage, and consequently, groundwater to surface water connectivity. However, estimations of water source contributions to streamflow remain poorly constrained across mountainous headwater catchments. Here we use stable isotopes ($\delta^{18}O$ and $\delta^{2}H$), ^{222}Rn activity, and electrical conductivity (EC) to characterise the hydrological responses in the northern mountainous region of the Central Valley, Costa Rica. Temporal trends revealed a clear response in groundwater-surface water connectivity to rainfall inputs. Streamflow transitioned from being dominated mainly by groundwater during the dry season to a greater contribution of subsurface flow during the wet season. We found that direct rapid recharge regulates this hydrological connectivity during the rainiest periods, as demonstrated by increased ^{222}Rn activity in both springs and streams. Using a mass balance approach, we estimated monthly groundwater contributions to streamflow using ^{222}Rn activity (5.9 – 63.1 %) and EC (37.2 – 84.0 %). A Bayesian endmember mixing model yielded similar mean groundwater contributions compared to the mass balance approach depending on tracer selection (EC – ^{222}Rn: 56.2 ± 12.7 %, $\delta^{18}O$ – ^{222}Rn: 51.1 ± 11.6 %, and $\delta^{18}O$ – EC: 89.2 ± 5.2 %). Our findings are useful for future assessments on the impact of climate change in rainfall amount and seasonality on groundwater recharge and streamflow generation in tropical mountainous catchments.

Keywords

Bayesian modelling, groundwater recharge, radon-222, groundwater-surface water interactions, stable isotopes, hydrological response, streamflow, tropical aquifer

1 Introduction

The dynamic exchange between groundwater and surface water is a fundamental component of

the global hydrological cycle (Ma et al., 2024). These two reservoirs interact across multiple spatial and temporal scales, regulating water and solute budgets (Carroll et al., 2024; Krause et al., 2007) and driving complex physical and biogeochemical processes (Conant et al., 2019; Irvine et al., 2024; Stegen et al., 2016). Climate change and land use practices are altering this exchange, making it more dynamic and difficult to predict. For instance, rising global surface temperatures are increasing the frequency of heavy rainfall events (Berg et al., 2013) while simultaneously intensifying drought severity (Gebrechorkos et al., 2025). These shifts affect evapotranspiration rates, soil water content, streamflow generation, and groundwater recharge (Green et al., 2011; Sterling et al., 2012). The resulting short- and long-term impacts, particularly in regions highly sensitive to hydrological changes, have also strong implications for water resource management.

Tropical mountainous catchments play an important role in groundwater recharge and downstream flow generation (Encalada et al., 2019; Viviroli et al., 2007). Their steep topography, dense vegetation, and well-structured soils generate rapid, highly variable responses to rainfall (Birkel et al., 2021; Muñoz-Villers & McDonnell, 2012). In these catchments, streamflow is often dominated by shallow subsurface flow paths because intrinsic soil properties promote high infiltration rates and lateral transport (Barthold & Woods, 2015; Bonell et al., 2009; Elsenbeer, 2001). Extensive macropore networks also favour vertical percolation, sustaining groundwater recharge even during intensive rainfall (Jasechko & Taylor, 2015). Although saturated overland flow contributes less frequently to streamflow, it can become significant under specific conditions, such as very high rainfall intensities combined with saturated soils (Lim et al., 2022). Recent work highlights the relative importance of these mechanisms, emphasising strong seasonal effects (Correa et al., 2017; Lim et al., 2022; Mosquera et al., 2016). In general, water source contributions to streamflow vary temporally and spatially depending on antecedent catchment and rainfall conditions. However, uncertainties remain regarding how streamflow is generated (Penna, 2026), especially in many understudied tropical mountainous catchments in Central America. In this region, rainfall amount and seasonality are shifting rapidly (Fu & Wu, 2024; Song et al., 2023). Thus, there is a need to constrain how water is initially partitioned between groundwater and surface water and to quantify how water source contributions change temporally.

The common approach to characterising water source contributions to streamflow involves high frequency hydrometric data with soil infiltration measurements (Ma et al., 2024). The combination of environmental tracer analysis and endmember modelling has emerged as a powerful alternative to quantify this hydrological response (Cook, 2012; Hooper et al., 1990). This approach is particularly useful in data scarce regions or where high frequency measurements are challenging (Birkel et al., 2020; Birkel et al., 2021), which is the case of many tropical mountainous catchments that lack hydrometric monitoring (Krabbenhoft et al., 2022). Tracers such as electrical conductivity (EC), major ions, stable isotopes, and radiogenic isotopes have been used for calculating water source contributions. Among these, water stable isotopes ($\delta^{18}O$ and $\delta^{2}H$) are particularly useful (Klaus & McDonnell, 2013). Their applicability for investigating rainfall dynamics and groundwater to surface water interactions across tropical ecosystems has been widely demonstrated (Bedaso & Wu, 2021; Esquivel-Hernández et al., 2022; Klaus & McDonnell, 2013; Rhodes et al., 2006; Sánchez-Murillo & Birkel, 2016). However, to improve water source identification and reduce uncertainties in contributions,

multi-tracer approaches are often required (Cook et al., 2003; Laudon & Slaymaker, 1997). Radon-222 (hereafter ^{222}Rn) can be particularly useful to trace groundwater inputs to surface water (Adyasari et al., 2023; Sukanya et al., 2022). ^{222}Rn is a radiogenic noble gas with a half-life of 3.82 days that is produced by the radioactive decay of radium-226 in most sediments (Schubert et al., 2006). Since ^{222}Rn is diffused to the atmosphere via gas transfer, its concentration in surface water is lower than in groundwater. Applications of ^{222}Rn have been reported in lakes, coastal areas, and river catchments (Bourke et al., 2014; Lamontagne et al., 2021; Petermann et al., 2018), but the applications in the wet tropics are still very limited (Barquero et al., 2005; Esquivel-Hernández et al., 2024; Sánchez-Murillo et al., 2016)

Here we investigated the hydrological response within a tropical mountainous catchment in the northern region of the Central Valley, Costa Rica, an important area for groundwater recharge and drinking water supply (Sánchez-Murillo et al., 2022). Our objectives were to i) examine how groundwater and streamflow respond to seasonal rainfall inputs, and ii) infer streamflow generation mechanisms. We first evaluated temporal responses of groundwater and surface water to rainfall using stable isotopes (δ^2H and $\delta^{18}O$), ^{222}Rn activity, and EC. We then quantified the relative contribution of groundwater to streamflow using both mass balance and Bayesian endmember mixing modelling approaches. We hypothesised that increasing rainfall during the wet season enhances direct, rapid recharge, causing a shift from groundwater dominated streamflow in the dry season to greater contributions from subsurface flow during the wet season. Characterising these hydrological responses and their seasonality is central to water resource management and to predict how climate change (e.g., increased convective rainfall or droughts) will affect highly dynamic catchments and overall water supply to lowland urban and peri-urban settlements.

2 Materials and methods

2.1 Study area

Our study was conducted in the northern mountainous region of Central Valley, Costa Rica. This region is located within the Virilla river catchment and the recharge area of the Barva aquifer (~275 km^2) (Figure 1). The Virilla river catchment covers most of Central Valley, the main urban centre of the country (INEC, 2022), flowing from the north-east to south-west where it confluences with the Grande de Tárcoles river. The Barva aquifer, which is part of the Barva-Colima multi-aquifer system, is flanked by the Central Volcanic Front, and the slopes of the Barva volcano. Its geological composition is mainly Quaternary volcanic rocks, primarily in the form of andesitic and andesitic-basaltic lava flows that originated from the surrounding volcanic systems (Darling et al., 1989). The saturated thickness ranges from 4 to 85 m and includes inter-bedded ash and lapilli layers (Madrigal-Solís et al., 2017; Ramírez, 2007). The Barva formation is divided into four hydrogeological members: i) the Cráter member, formed by mostly recent pyroclastic deposits, ii) Los Ángeles and Los Bambinos, independent shallow lava flows that include a group of small, perched aquifers above 2000 m a.s.l. in Los Bambinos known as Upper Barva, iii) Carbonal and Porrosatí with coarse volcanic sand and weathered tuffs, and iv) Bermúdez, fractured andesitic lavas including a large unconfined aquifer known as Lower Barva (Ramírez, 2007; Sánchez-Murillo et al., 2022).

Figure 1. Location of study sites within the Barva-Colima multi-aquifer system and the Virilla River catchment in the Central Valley of Costa Rica. Land use from Sánchez-Murillo et al. (2022).

The Barva aquifer exhibits large vertical and horizontal hydrogeological complexity (Madrigal-Solís et al., 2017; Sánchez-Murillo et al., 2022). Low-permeability tuffs allow water accumulation on the upper layers, with permeability ranging from 1 to 10 m d^{-1}, transmissivity values from 100 — 500 m^2 d^{-1}, and a storage coefficient of approximately 0.10 (Espinoza et al., 2004). Soils from volcanic origin are characterised by high filtration and high permeability, favouring groundwater recharge and storage (Madrigal-Solís et al., 2017; Reynolds-Vargas & Fraile, 2009). Possible recharge mechanisms are infiltration, vertical percolation, losing rivers, and direct rainfall over areas without overlying aquifers (Arias-Salguero et al., 2006; Ramírez, 2007; Reynolds-Vargas & Fraile, 2009; Sánchez-Murillo et al., 2022). The mean transit time is ~1.2 years (Salas-Navarro et al., 2019).

The climate regime is characterised by two well-defined seasons: a dry season (December – April) and a wet season (May – November). This distinctive pattern is a product of the influence of the northeast trade winds (i.e., 'vientos alisios'), cold continental outbreaks, the seasonal shift of the Intertropical Convergence Zone, and the sporadic influence of tropical cyclones over the country (Sánchez-Murillo et al., 2020). These air circulation processes produce two rainfall peaks: one in May – June and another in September – October. The period between July and August is, however, characterised by relative drier than normal conditions, known as Mid-Summer Drought or 'veranillo', due to the intensification of the trade winds over the Caribbean Sea (Magaña et al., 1999). Topography also plays a major role in climate conditions as the mountain range extending from northeast to southwest across the country creates a topographic barrier and a distinct precipitation regime between the Caribbean and Pacific drainage domains. In the Barva aquifer, rainfall usually ranges from 2800 to 5000 mm yr^{-1} at high elevation areas. Mean annual temperature varies between ~10 °C and ~27 °C depending on elevation and region (Salas-Navarro et al., 2019; Sánchez-Murillo et al., 2022).

2.2 Sampling

We collected rainfall from two stations, and water samples from three springs and three streams from September 2023 to December 2024 (Figure 1). Rainfall samples were collected manually using passive collectors (Palmex Ltd., Croatia; Gröning et al., 2012) at: the main campus of Universidad Nacional (-84.1099 W, 10.0016 N, 1169 m a.s.l.) on every rainy day in the morning (7 – 8 am), and the Sacramento spring, where composite samples were collected every two weeks. We also recorded hourly meteorological variables (e.g., relative humidity, air temperature, and rainfall amount) using two Vantage Pro2 weather stations (Davis Instruments, USA) installed at the main campus of Universidad Nacional and the Braulio Carrillo National Park (Barva Volcano; -84.1213 W, 10.1333 N, 2684 m a.s.l.).

The spring and stream sites were located within the estimated range of recharge elevations for the Barva aquifer (1350 – 2670 m a.s.l.), where land cover is dominated by forest and pasture (Sánchez-Murillo et al., 2022). Springs included: Chagos (-84.1078 W, 10.0922 N, 1990 m a.s.l.), Arrieta (-84.1036 W, 10.1075 N, 2253 m a.s.l.) and Sacramento (-84.1127 W, 10.1138 N, 2450 m a.s.l.). The streams

were: Segundo River (-84.0892 W, 10.0578 N, 1726 m a.s.l.), Ciruelas River (-84.1036 W, 10.1075 N, 2253 m a.s.l.), and Dantas Creek (-84.1177 W, 10.0975 N, 2005 m a.s.l.). The maximum linear distance between the spring and stream sites is ~6 km (Figure 1). These samples were collected every two weeks. Temperature, pH, and EC were measured in situ using hand-held multi-parameters Hanna Instruments HI98121 and HI98311 (Hanna Instruments, RI, USA), respectively. At the Sacramento spring and Segundo River, continuous water level column was measured using a HOBO sensor U20L Water level logger (U20L-01) at 15-min resolution. Weekly spring discharges were additionally carried out to develop rating curves.

2.3 Laboratory analysis

The analysis of δ^2H and $\delta^{18}O$ in rainfall, spring, and stream water samples was carried out at the Stable Isotopes Research Group Laboratory at the Universidad Nacional (Heredia, Costa Rica) using an IWA-45EP water analyzer (Los Gatos Research, Inc., California, USA) with a precision of ± 0.80 ‰ for δ^2H and ± 0.08 ‰ for $\delta^{18}O$ (1σ; 5 injections). Isotopic reference materials, USGS45 (δ^2H = -10.30 ‰, $\delta^{18}O$ = -2.24 ‰), USGS47 (δ^2H = -150.2 ‰, $\delta^{18}O$ = -19.80 ‰), and calibrated secondary standard PGW (δ^2H = -52.64 ‰, $\delta^{18}O$ = -8.20 ‰), were used for data normalisation and to assess the quality and drift control procedures. $^{18}O/^{16}O$ and $^{2}H/^{1}H$ ratios are presented in delta notation and reported as per mille (‰) relative to the VSMOW-SLAP scale. $\delta^{18}O$ and δ^2H values were used to calculate the *d*-excess as: $\delta^2H - 8*\delta^{18}O$ (Dansgaard, 1964).

We measured the ^{222}Rn activity in the spring and stream water samples using a RAD7 radon detector (Durridge Co., USA). Water was collected in 250 mL glass bottles and was analysed in the laboratory using the accessories to measure radon in grab samples (RAD H2O kit). For each sample, we carried out seven measurement cycles of five minutes each. The first three cycles were discarded to ensure measurements in equilibrium conditions and the last four cycles were used to estimate the average ^{222}Rn activity. Samples were analysed within 24 hours after collection. The activities are expressed in Bq L^{-1} with an analytical uncertainty of ± 2σ at a 95 % confidence interval. The ^{222}Rn activity was corrected for decay following:

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

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.

2.4 Hydrological response

The variations in the hydrological response within the recharge area of the Barva aquifer were estimated using ratios based on $\delta^{18}O$ and ^{222}Rn activity (Jasechko & Taylor, 2015). For calculations and interpretation, we converted $\delta^{18}O$ values to concentrations in ppm (Clark, 2015) following:

$$^{18}O\ (ppm) = \left(\frac{\delta^{18}O}{1000} + 1\right) \times 0.0020052 \times 10^6$$

where $\delta^{18}O$ is the value of the sample relative to the Vienna Standard Mean Ocean Water ($^{18}O/^{16}O$ = 0.0020052). Concentrations, rather than δ-values, were used to avoid negative ratios. We only used ^{18}O given the strong linear correlation between $\delta^{18}O$ and $\delta^{2}H$ values. We calculated the precipitation to groundwater (P/GW) ratio using the rainfall amount-weighted mean in Sacramento, where values < 1 and > 1 indicate recharge biased to light or intense rainfall, respectively ((Jasechko & Taylor, 2015; Sánchez-Murillo & Birkel, 2016). We also calculated the surface water to groundwater ratio ($^{18}O_{SW}/^{18}O_{GW}$). Moreover, to investigate groundwater inputs with the adjacent surface water system, we calculated the surface water to groundwater ^{222}Rn activity ratio ($^{222}Rn_{SW}/^{222}Rn_{GW}$). Under the assumption that the ^{222}Rn activity in the surface water interacting with the aquifer will reach a secular equilibrium after about 5 half-lives (i.e., after 15 days), ^{222}Rn activity variations in the streams should reflect the background ^{222}Rn of the groundwater input (Schubert et al., 2006; Sukanya et al., 2022). In the study area, the groundwater head in the springs is continuously above the spring geomorphic outcrop. Therefore, we expect that the adjacent surface water system mostly acts as a 'gaining' system with seasonal increases in volume due to spring seepage, fracture flow, and macropore discharge (Irvine et al., 2024; Jasechko, 2019).

2.5 Water source contributions

To estimate the relative groundwater contribution to streamflow, we first applied a mass balance approach following:

$$\%_{GW} = \frac{X_{SW} - X_P}{X_{GW} - X_P} \times 100$$

where X_{SW} , X_P, X_{GW} are the tracer values in surface water, precipitation, and groundwater, respectively (Laudon & Slaymaker, 1997). We calculated the percentage contribution using monthly mean values of $\delta^{18}O$, ^{222}Rn activity, and EC. We also calculated the mean contribution for each tracer over the entire study period. A full ^{222}Rn mass balance was not applied due to limited site accessibility for longitudinal sampling of ^{222}Rn activity and measurements of hydraulic parameters (river depth, width, and flow), which are required to assess spatial variability and quantify all ^{222}Rn sources and sinks. However, our simplified mass balance can be used to semi-quantitatively assess whether the stream was gaining groundwater during each sampling campaign. Furthermore, we applied a Bayesian endmember mixing model using $\delta^{18}O$, ^{222}Rn activity, and EC as variables in the estimation of water sources (i.e., rainfall and groundwater) to streamflow (i.e., mixtures). We used the *Simmr* package (Govan & Parnell, 2019) with uninformative priors and 10,000 Markov Chain Monte-Carlo iterations (5,000 burn-in) to calculate the contribution of the endmembers. The Gelman-Rubin diagnostic (Gelman & Rubin, 1992) was performed to test model convergence. It evaluates Markov Chain Monte-Carlo convergence by analysing the difference between multiple Markov chains. All selected runs exhibited

good model convergences (Gelman-Rubin value equal 1 at $p < 0.05$). We measured the ^{222}Rn activity in rainfall samples collected after selected events that allowed sampling > 250 mL. EC values in precipitation were previously reported by Villalobos-Forbes et al. (2021).

2.6 Data analysis

To assess differences in isotopic and EC values, we carried out a Fisher-Pitman permutation test using the *coin* package in R (Hothorn et al., 2006). Association between parameters was tested using Spearman rank's correlation. All statistical analysis were carried out in R version 4.4.1 (R Development Core Team, 2024).

3 Results

3.1 Hydro-meteorological conditions

Over the study period (September 2023 to December 2024), the monitoring site at Barva was characterised by a cumulative rainfall of 6122 mm, a mean temperature of 12.1 °C, and a mean relative humidity of 94.4 % (Figure 2a, Figure S1). This site showed a maximum rainfall of 132 mm d^{-1} (03-12-2024). In Sacramento, rainfall amount in composite bi-weekly samples ranged from 4 to 375 mm, with a cumulative value of 4259 mm (Figure 2a). The site in Heredia presented a maximum rainfall of 110 mm d^{-1} (19-10-2023), a cumulative rainfall of 4668 mm, a mean temperature of 22.3 °C, and mean relative humidity of 80.4 % (Figure 2b, Figure S1). Water discharge in Sacramento spring ranged from 23 to 66 L s^{-1} (Figure 2c). Low and nearly constant discharge (~23 L s^{-1}) was observed during the dry season (December – April). Discharge data at Segundo River were not available for the complete sampling period. However, discharge ranged from 1.4 to 109 L s^{-1}, with peak values (109 L s^{-1} and 85 L s^{-1}) during the wet seasons.

Figure 2. Temporal trends of rainfall and discharge at the study sites. a) daily rainfall in Barva (left) and cumulative bi-weekly rainfall in Sacramento (right, circles). b) daily rainfall in Heredia. c) discharge in Sacramento spring (orange) and Segundo river (blue). Shaded areas indicate dry seasons.

3.2 $\delta^{18}O$ and $\delta^{2}H$ in rainfall

We observed differences in the $\delta^{18}O$ and $\delta^{2}H$ values in rainfall between Sacramento and Heredia (Figure 3). In Sacramento, bi-weekly composite samples showed $\delta^{18}O$ and $\delta^{2}H$ values between -14.58 and -1.51 ‰ and from -105.76 to 1.31 ‰, respectively. Rainfall amount-weighted means were -10.16 for $\delta^{18}O$, -68.90 ‰ for $\delta^{2}H$, and 12.37 ‰ for *d-excess*. In Heredia, daily samples showed $\delta^{18}O$ and $\delta^{2}H$ values ranging from -17.35 to 1.71 ‰ and from -128.44 to 17.30 ‰, respectively. At this site, rainfall amount-weighted means were -9.18 ‰ for $\delta^{18}O$, -60.42 ‰ for $\delta^{2}H$, and 13.03 ‰ for *d-excess*. The regression line in Sacramento presented higher slope and intercept values compared to Heredia (Figure 3). Temporal trends in $\delta^{18}O$ in rainfall exhibited higher values during the periods of low rainfall (i.e., the dry season and the Mid-Summer Drought) (Figure 4a). In contrast, there was a tendency towards lower

$\delta^{18}O$ values during the wet season, when the Intertropical Convergence Zone and eastern tropical waves reach or pass across Costa Rica.

Figure 3. Dual plot showing the relationship between $\delta^{2}H$ and $\delta^{18}O$ in rainfall, springs, and streams. Rainfall amount-weighted regressions are shown for Heredia and Sacramento ($p < 0.001$).

Figure 4. Time series of environmental tracers. a) $\delta^{18}O$ values in rainfall in Sacramento and Heredia, b) $\delta^{18}O$ values in springs and streams. c) ^{222}Rn activity in springs and streams. d) electrical conductivity (EC) in springs and streams. Plots b – c show mean values ± 1σ. Shaded areas indicate the dry season.

3.3 $\delta^{18}O$, ^{222}Rn and EC in streams and springs

Stream samples showed $\delta^{18}O$ and $\delta^{2}H$ values ranging from -10.22 to -3.78 ‰ (mean -8.57 ± 1.39 ‰) and from -67.72 to -14.05 ‰ (mean -53.88 ± 11.46 ‰), respectively. The mean *d-excess* was 14.66 ± 1.12 ‰. In the springs, the $\delta^{18}O$ and $\delta^{2}H$ values were between -10.17 and -7.78 ‰ (mean -8.71 ± 0.58 ‰) and between -64.25 and -46.73 ‰ (mean -54.95 ± 4.53 ‰), respectively. The mean *d-excess* in the springs was 14.72 ± 1.12 ‰. We did not find significant differences in mean $\delta^{18}O$ and $\delta^{2}H$ values between springs and streams (Z = -0.760, p = 0.447 for $\delta^{18}O$ and Z = -0.705, p = 0.481 for $\delta^{2}H$). Temporal trends of $\delta^{18}O$ in the streams showed two maxima that likely match those of rainfall in Sacramento (Figure 4a and 4b). Conversely, the springs exhibited more stable $\delta^{18}O$ values throughout the sampling period, clustering within a 2.42 ‰ range along the regression line of Sacramento (Figure 3). Despite these differences, $\delta^{18}O$ values in the springs and streams were positively correlated (ρ = 0.747, $p < 0.001$).

The ^{222}Rn activity in the streams ranged from 0.11 to 19.65 Bq L^{-1}, with a mean of 6.92 ± 5.65 Bq L^{-1}. In the springs, activities were between 0.22 and 74.87 Bq L^{-1} , with a mean of 18.91 ± 14.29 Bq L^{-1}. As expected, the mean ^{222}Rn activity in the springs was higher compared to that of the streams (Z = 3.6273, $p < 0.001$). The higher activities in the springs persisted during the sampling period (Figure 4c). Interestingly, we observed clear increases in the ^{222}Rn activity during the rainiest periods in October 2023 and June and September 2024 (Figure 4c). The similar temporal trends in ^{222}Rn activity between the springs and the streams was demonstrated by a significant positive correlation between both sample types (ρ = 0.707, $p < 0.001$).

Stream samples presented EC values ranging from 16 to 167 µS cm^{-1}, resulting in a mean of 70 ± 40 µS cm^{-1}. In the spring samples, EC ranged from 69 to 176 µS cm^{-1}, with a mean of 102 ± 29 µS cm^{-1}. Similar to the ^{222}Rn activity, mean EC values were significantly higher in the springs compared to the streams (Z = 4.870, $p < 0.001$). This trend prevailed throughout the study period (Figure 4d). We observed increases in EC shortly after the rainiest periods, followed by a gradual decline. In contrast to the isotopic tracers, EC showed decoupled temporal trends between the springs and the streams (ρ = 0.291, p = 0.089).

3.4 Isotopic ratios

The mean P/GW was 0.99852 ± 0.00032. We observed the lowest $^{18}O_{SW}/^{18}O_{GW}$ ratios during the

rainiest months (< 1), which coincided with the lowest $\delta^{18}O$ values found in rainfall (Figure 5a). In contrast, $^{18}O_{SW}/^{18}O_{GW}$ ratios > 1 were characteristic during the dry season (December – April) and the Mid-Summer Drought period. The underlying hydrological interaction between groundwater and surface water was demonstrated by the temporal variations in the $^{222}Rn_{SW}/^{222}Rn_{GW}$ ratio (Figure 5b). As expected ratios were constantly lower than 1. We observed, however, higher $^{222}Rn_{SW}/^{222}Rn_{GW}$ ratios with increasing spring discharge. The $^{18}O_{SW}/^{18}O_{GW}$ and the $^{222}Rn_{SW}/^{222}Rn_{GW}$ ratios did not show a significant correlation ($\rho = 0.208$, $p = 0.176$).

Figure 5. Time series of mean isotopic ratios. a) the $^{18}O_{SW}/^{18}O_{GW}$ ratio, based on ^{18}O concentrations (ppm), as a function of daily rainfall in Barva. b) $^{222}Rn_{SW}/^{222}Rn_{GW}$ ratio as a function of spring water discharge in Sacramento. Shaded areas indicate dry seasons.

3.5 Groundwater contribution to streamflow

Mass balance calculations based on ^{222}Rn activity and EC yielded monthly groundwater contributions to streamflow ranging from 5.9 to 63.1 % (mean 35.7 ± 16.1 %) and from 37.2 to 84.0 % (mean 65.3 ± 15.0 %), respectively (Figure 6a). The contributions based on $\delta^{18}O$ showed values outside the 0 – 100 range in 46 % of observations. We observed negative values in December 2023 and May 2024, and values > 100 % in September 2023 and August and September 2024. These estimates were not included for further calculations. ^{222}Rn activity presented the peak percentage contributions in March and September 2024 (> 55 %). In contrast, the highest percentage contributions based on EC were observed in April and May 2024 (> 80 %). Although stream discharge data were not available for the complete sampling period (Figure 2c), we estimated groundwater fluxes into local streamflow from 1.8 to 13.9 L s^{-1} based on ^{222}Rn activity and from 2.2 to 27.9 L s^{-1} based on EC.

The Bayesian endmember mixing analysis yielded total groundwater contributions to streamflow ranging from 51.1 to 89.2 %, depending on tracers' selection (Figure 6b). Several stream samples fell outside the expected ranges of the rainfall and groundwater endmembers, particularly in models that included EC (Figure 7a and 7c). Despite this, we found that the models based on EC – ^{222}Rn and $\delta^{18}O$ – ^{222}Rn produced similar groundwater contributions to streamflow. The EC – ^{222}Rn pair yielded 56.2 ± 12.7 %, while the $\delta^{18}O$ – ^{222}Rn pair yielded 51.1 ± 11.6 %. These results are similar to those of the mass balance approach (Figure 6b). In contrast, the Bayesian endmember mixing model based on the $\delta^{18}O$ – EC pair showed a substantially higher groundwater contribution of 89.2 ± 5.2 %.

Figure 6. Percentage contributions of groundwater to streamflow. a) time series based on tracer's mass balance as a function of spring discharge in Sacramento. b) mean total contributions from the tracer's mass balance and Bayesian endmember mixing models (error bars show ± 1σ). Shaded areas indicate dry seasons.

Figure 7. Dual plots showing the distribution of the stream samples according to those of the endmembers (rainfall and springs). a) electrical conductivity (EC) vs ^{222}Rn activity. b) $\delta^{18}O$ vs ^{222}Rn

activity. c) $\delta^{18}O$ vs electrical conductivity (EC). Error bars show ± 1σ.

4 Discussion

In the northern mountainous region of Central Valley, Costa Rica, previous work has primarily focused on quantifying groundwater recharge (e.g., Reynolds-Vargas & Fraile, 2009 and Sánchez-Murillo et al., 2022). Recent estimates indicate that recharge accounts for ~20 % of mean annual rainfall (Sánchez-Murillo et al., 2022). However, the proportion of groundwater that contributes to streamflow has remained poorly constrained. In this study, we addressed this gap by combining temporal trends in stable isotopes ($\delta^{18}O$ and $\delta^{2}H$), ^{222}Rn activity, and EC.

Our initial assessment of $\delta^{18}O$ and $\delta^{2}H$ in rainfall showed distinctive isotopic signatures along the elevation range of the Barva aquifer (Figure 3). These findings extend those of Sanchez-Murillo et al. (2017), confirming a stronger influence of moisture recycling processes in the headwaters of north-central Costa Rica. Seasonal variations in $\delta^{18}O$, $\delta^{2}H$, and rainfall amount can be explained by the interaction of two main atmospheric systems: i) an intensified easterly flow from the Caribbean Sea during the dry season, resulting in higher isotopic values, and ii) the migration of the Intertropical Convergence Zone together with eastern tropical waves during the wet season (Sánchez-Murillo et al., 2020; Sanchez-Murillo et al., 2017; Sánchez-Murillo et al., 2023). Our sampling period coincided with a warm phase of the El Niño 3.4 region (sea surface temperature anomaly > 0.5 °C) from September 2023 to April 2024, followed by a transition to weak La Niña conditions from May to December 2024. As such, the hydrological responses during the first two months of our study reflect a reduced cold front activity and an extended baseflow period.

Temporal trends in $\delta^{18}O$, ^{222}Rn activity, and EC showed how the seasonal climate regulates groundwater-surface water connectivity. Although the $\delta^{18}O$ values in the streams closely followed rainfall variability (Figure 4a and 4b), the springs exhibited a weaker response (i.e., larger isotopic damping effect). The low variability observed in springs is likely attributed to the mixing of recent rainfall with pre-existing stored water in the aquifer (Salas-Navarro et al., 2019). Recharge processes in the Barva aquifer are slightly biased toward light rainfall, as demonstrated by the P/GW ratio < 1. The simultaneous spikes in ^{222}Rn activity in springs and streams during the rainiest periods also highlight the rapid recharge and the strong hydrological connectivity between the aquifer and surface water (Figure 4c). The higher $^{222}Rn_{SW}/^{222}Rn_{GW}$ ratios with increasing spring discharge suggest that this connectivity is potentially driven by higher phreatic levels (Figure 5b) (Unland et al., 2013; Zhou et al., 2024). The response of EC, however, lagged behind the peak of ^{222}Rn activity (Figure 4d). Given that EC variations in surface water are closely linked to rainfall intensity, changes in water flow pathways, and solute transport dynamics (Cartwright & Miller, 2021; Irvine et al., 2011; Zhou et al., 2024), the delayed increase in EC in the streams likely suggests the mobilisation of solutes from saturated soils or floodplains.

The combination of geochemical tracers showed different components of streamflow response. While ^{222}Rn activity primarily indicates the connectivity between groundwater and surface water, EC captures broader solute export dynamics, including the contribution from soils and floodplains (Kies et al., 2005). Consequently, the higher monthly groundwater contributions to streamflow calculated using

EC and the mass balance approach likely reflect the input of both groundwater and soil water (Figure 6a). This is supported by the wider range of EC values in the streams, which in some cases exceeded those of the springs, indicating additional water sources contributing to streamflow (Figure 7a and 7c). Despite these differences, mean groundwater contributions from both tracers likely fell within uncertainty and aligned with those of the Bayesian endmember mixing models based on the EC – ^{222}Rn and δ^{18}O – ^{222}Rn pairs (Figure 6b). Of these two Bayesian mixing models, the δ^{18}O – ^{222}Rn pair appears more reliable because most stream samples fell within the range values of the endmembers (Figure 7b). The models incorporating EC produced stream samples outside the endmember ranges, indicating incomplete endmember representation. The total groundwater contributions to streamflow are similar to those reported for other tropical and subtropical catchments, including humid forest (71 – 80 %, Birkel et al., 2021 and 53 – 80 %, Lim et al., 2022), cloud forest (35 – 95 %, Muñoz-Villers & McDonnell, 2012), and grassland catchments (71 – 78 %, Correa et al., 2017 and ~30 – 80 %, Bécher Quinodóz et al., 2024).

Our results indicate that streamflow response is controlled by rapid vertical groundwater recharge, with minor contributions of surficial processes during the rainiest months. The direct rapid recharge is in line with the hydrogeological characteristics of the aquifer: soils with high infiltration capacity and permeability (Madrigal-Solís et al., 2017; Reynolds-Vargas & Fraile, 2009), underlined by a shallow, volcanic, and fissured rock system (Salas-Navarro et al., 2019; Sánchez-Murillo et al., 2022). We suggest that although the shallow aquifer supplies most of the streamflow, surficial contributions (e.g., shallow subsurface flow) are higher during the wet season as soils become more saturated. In this regard, the spatial and temporal resolution of our sampling limits the ability to resolve between shallow groundwater and surficial contributions to streamflow, as well as changes in their relative contributions during individual rainfall events across seasons. Despite this, the consistent trends of three independent tracers allowed us to infer dominant pathways at a seasonal scale.

There were limitations in estimating water source contributions to streamflow depending on the methodological approach and tracers selection. First, the mass balance using δ^{18}O yielded unsatisfactory results for almost half the study period. It was not possible to calculate water source contributions during the transition months due to i) similar δ^{18}O values between the springs and rainfall, and ii) higher δ^{18}O values in the streams compared to those of rainfall. Variations in δ^{18}O values can be problematic for constraining the mass balance (Jasechko, 2019; Klaus & McDonnell, 2013). Limitations in mass balance calculations with δ^{18}O have been also previously reported (Dusek & Vogel, 2018; Fischer et al., 2017). Second, our groundwater contributions from the ^{222}Rn mass balance should be interpreted as approximate estimates. Further studies are needed to fully constrain a ^{222}Rn mass balance in this area that includes all possible sinks and sources (e.g., gas exchange, radioactive decay, and hyporheic exchange) (Adyasari et al., 2023; Cook, 2012). Third, the Bayesian endmember mixing model based on EC – δ^{18}O likely overestimated the total groundwater contributions to streamflow (Figure 6b). The use of ^{222}Rn activity with either EC or δ^{18}O helped constrain the magnitude of groundwater contributions. However, we emphasise the importance of selecting tracers and endmembers that adequately capture the full range of stream samples (i.e., mixtures) (Barthold et al., 2011; Ramón et al., 2021). Overall, our findings highlight the value of using multiple tracers and

complementary approaches for estimating water source contributions to streamflow.

5 Conclusions

Our findings highlight the strong hydrological connectivity between groundwater and surface water within the northern mountainous region of Central Valley, Costa Rica. Using three independent tracers ($\delta^{18}O$, ^{222}Rn, and EC), we demonstrated a rapid hydrological response to local rainfall events on monthly and seasonal timescales. Mass balance and Bayesian endmember mixing models allowed us to quantify the relative groundwater contribution to streamflow, ranging from 35.7 to 89.2 %. Despite variation in mass balance derived contributions between tracers, the consistent seasonal patterns observed in both EC and ^{222}Rn mass balances demonstrate their applicability in characterising groundwater-surface water connectivity. The Bayesian endmember model based on $\delta^{18}O$ – ^{222}Rn was well constrained, with all stream samples falling within the mixing area. Overall, our results indicate that groundwater inputs from the shallow Barva aquifer are important in sustaining streamflow in these catchments. However, the aquifer storage capacity may be limited during extended dry periods. Future research is needed to better quantify groundwater-surface water connectivity during such periods, requiring high frequency sampling and the incorporation of additional water source endmembers (e.g., soil water) are necessary. Nevertheless, our approach provides a means of estimating both seasonal and annual hydrological balances, making it potentially useful to other mountainous catchments in tropical regions. We emphasise the importance of long-term monitoring to investigate inter-annual variations in water source contributions, particularly in areas of high groundwater recharge.

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Data availability statement

Data supporting the findings of this study are available at Zenodo, DOI: https://doi.org/10.5281/zenodo.18938508 (Mena-Rivera et al., 2026)

Declaration of competing interest

Authors declared no competing interests.

Authors contribution

LM-R: conceptualization; formal analysis; funding acquisition; methodology; visualisation; writing – original draft. GE-H: conceptualization; data curation; formal analysis; funding acquisition; methodology; writing – original draft. MV-L: investigation; formal analysis; writing – original draft. RS-G: investigation; formal analysis. R.S-M: writing – review & editing. LC-C: writing – review & editing. LR-J: writing –

review & editing. AH: writing – review & editing.

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