Received: 2 December 2019 | Accepted: 24 March 2020

DOI: 10.1002/hyp.13758

RESEARCH ARTICLE

WILEY

Tracer hydrology of the data-scarce and heterogeneous Central American Isthmus

Ricardo Sánchez-Murillo[1] | Germain Esquivel-Hernández[1] | José L. Corrales-Salazar[1] | Laura Castro-Chacón[2] | Ana M. Durán-Quesada[3] | Manuel Guerrero-Hernández[4] | Valeria Delgado[5] | Javier Barberena[5] | Katia Montenegro-Rayo[5] | Heyddy Calderón[6] | Carlos Chevez[7] | Tania Peña-Paz[8] | Saúl García-Santos[8] | Pedro Ortiz-Roque[9] | Yaneth Alvarado-Callejas[10] | Laura Benegas[10] | Antonio Hernández-Antonio[11] | Marcela Matamoros-Ortega[12] | Lucia Ortega[13] | Stefan Terzer-Wassmuth[13]

[1]Stable Isotope Research Group, UNA-SIL, Universidad Nacional, Heredia, Costa Rica

[2]Empresa de Servicios Públicos de Heredia, ESPH S.A., Heredia, Costa Rica

[3]Atmospheric, Planetary and Oceanic Physics Department, School of Physics and Center of Geophysical Research, University of Costa Rica, San José, Costa Rica

[4]Foundation for the Development of the Volcanic Central Cordillera, FUNDECOR, San José, Costa Rica

[5]Centro para la Investigación en Recursos Acuáticos de Nicaragua, CIRA/UNAN-Managua, Universidad Nacional Autónoma de Nicaragua, Managua, Nicaragua

[6]Institute of Geology and Geophysics, IGG-CIGEO, Universidad Nacional Autonoma de Nicaragua, Managua, Nicaragua

[7]Water Resources Department,, Nicaraguan Institute of Territorial Studies, Managua, Nicaragua

[8]Instituto Hondureño de Ciencias de la Tierra, IHCIT, Universidad Nacional Autónoma de Honduras, Tegucigalpa, Honduras

[9]Servicio Autónomo Nacional de Acueductos y Alcantarillados, Gobierno de la República de Honduras, Tegucigalpa, Honduras

[10]Centro Agronómico Tropical de Investigación y Enseñanza, CATIE, Turrialba, Costa Rica

[11]Servicios de Investigación Científica y Técnica SC, Mexico, Mexico

[12]Escuela de Biología, Universidad Nacional Autónoma de Honduras, Tegucigalpa, Honduras

[13]International Atomic Energy Agency, Isotope Hydrology Section, Vienna International Center, Vienna, Austria

Correspondence
Ricardo Sánchez-Murillo, Stable Isotope Research Group, UNA-SIL; Universidad Nacional, Campus Omar Dengo, Heredia 86-3000, Costa Rica.
Email: ricardo.sanchez.murillo@una.cr

Funding information
European Union, Grant/Award Number: DCI-ENV 2014/350-470; International Atomic Energy Agency, Grant/Award Numbers: COS/7/005, NIC/5/009, RC-19747, RLA/7/024; Nature Conservancy, Grant/Award Number: Coca Cola FEMSA-TNC; Universidad Nacional, Costa Rica, Grant/Award Numbers: SIA-0101-14, SIA-0236-16, SIA-0482-13, SIA-411-17, SIA-414-17; University of Costa Rica Research Council; Empresa de Servicios Públicos de Heredia; National University, Grant/Award Number: SIA-0378-14

Abstract

Numerous socio-economic activities depend on the seasonal rainfall and groundwater recharge cycle across the Central American Isthmus. Population growth and unregulated land use changes resulted in extensive surface water pollution and a large dependency on groundwater resources. This work combines stable isotope variations in rainfall, surface water, and groundwater of Costa Rica, Nicaragua, El Salvador, and Honduras to develop a regionalized rainfall isoscape, isotopic lapse rates, spatial–temporal isotopic variations, and air mass back trajectories determining potential mean recharge elevations, moisture circulation patterns, and surface water–groundwater interactions. Intra-seasonal rainfall modes resulted in two isotopically depleted incursions (W-shaped isotopic pattern) during the wet season and two enriched pulses during the mid-summer drought and the months of the strongest trade winds. Notable isotopic sub-cloud fractionation and near-surface secondary evaporation were identified as common denominators within the Central American Dry Corridor. Groundwater and surface water isotope ratios depicted the strong orographic separation into the Caribbean and Pacific domains, mainly induced by the governing moisture transport from the Caribbean Sea, complex rainfall producing systems across the N-S mountain range, and the subsequent mixing with local evapotranspiration, and, to a lesser degree, the eastern Pacific Ocean fluxes. Groundwater recharge was characterized by (a) depleted recharge in highland areas (72.3%), (b) rapid recharge via preferential flow paths (13.1%), and enriched recharge due to near-surface secondary fractionation (14.6%). Median recharge elevation ranged from 1,104 to 1,979 m a.s.l. These results are intended to enhance forest conservation practices, inform water protection regulations, and facilitate water security and sustainability planning in the Central American Isthmus.

KEYWORDS

Central American Isthmus, Dry Corridor, ENSO, groundwater recharge processes, water resources management, water stable isotopes

1 | INTRODUCTION

Central America (522,760 km^2) is home to ~50 million inhabitants and highly depends on groundwater extraction (1.9×10^4 m^3 year^{-1}) as a primary water resource, as a result of the decline in quality and quantity of surface water resources (Ballestero, Reyes, & Astorga, 2007; Hoekstra et al., 2018; Hund, Allen, Morillas, & Johnson, 2018). During the last 100 years, the average surface temperature has increased by 0.5–1.0°C and the number of warm days (% of days when maximum daily temperature >90th percentile) rose by about 2.5% each decade since the 1970s (Aguilar et al., 2005; Knutson et al., 2006), turning the region into a prominent tropical hot-spot under future climate change scenarios (Giorgi, 2006). Temperature increase in the region has been widely documented in independent studies (González, Georgescu, Lemos, Hosannah, & Niyogi, 2017; Hidalgo & Alfaro, 2015; Imbach et al., 2018; Lyra et al., 2017). The increasing trend of long-term droughts (>5 months; Sheffield & Wood, 2008) poses a challenge for truly integrated water resources management in this region (Foster & MacDonald, 2014), particularly in light of a lack of national water balances.

Regional climate projections suggest relevant changes by 2050, including: (a) a rainfall decrease (10–25%) during the wet season, (b) spatial extension of the area affected by the mid-summer drought (MSD; Magaña, Amador, & Medina, 1999; Maldonado, Alfaro, Fallas-López, & Alvarado, 2013; Maurer, Roby, Stewart-Frey, & Bacon, 2017), and (c) positive trends in temperature and dry extreme events, resulting in a net decrease of water availability (Imbach et al., 2018). In particular, the Central America Dry Corridor (CADC) has received large attention in recent years due to its ecohydrological vulnerability (Bouroncle et al., 2017). The CADC is defined as a tropical dry forest region (dry season: mid-November to mid-May) on the Pacific domain that extends from Chiapas (Mexico) to the western part of Costa Rica and western provinces of Panama, also known as the Dry Arch of Panama (FAO, 2017; Sánchez-Murillo & Birkel, 2016; van der Zee Arias et al., 2012). The experience of recent warm El Niño-Southern Oscillation (ENSO) events and resulting water scarcity has promoted unified adaptation strategies regarding groundwater extraction for agriculture (FAO, 2015). The dependence on seasonal rainfall and groundwater recharge for agriculture, tourism and hydropower has further amplified the use of groundwater resources.

Approximately 3.5 million people experienced food insecurity after suffering major crop losses due to the prolonged warm ENSO-induced drought from 2014 to the beginning of 2016 (FAO, 2016; Herrera & Ault, 2017). Therefore, a better understanding of the factors that control rainfall patterns and the linkage to groundwater recharge and surface discharge is an imperative task for Central American countries. Robust and up-to-date hydrological information is required for stakeholders and governmental agencies to prioritize efforts, resources, and regulations in watersheds or regions, whereby potential droughts or extreme rainfall events could drastically disrupt ecohydrological assemblages. However, in the absence of well-established and long-term hydrometric networks in Central America, water stable isotopes are a reliable, fast, and relatively low-cost technique to study the interaction between rainfall inputs and surface/groundwater connectivity in complex tropical landscapes (Sánchez-Murillo & Durán-Quesada, 2018).

This work combines recent (2013–2018) and archive (sampling efforts since 1970s to early 2000s) stable isotope measurements in rainfall, surface water, and groundwater of Costa Rica, Nicaragua, El Salvador, and Honduras. Historically, most of the sampling efforts have been concentrated on the Pacific slope of Central America. However, isotopic distributions within the Caribbean slope of Costa Rica are also included to emphasize the relevance of the Caribbean Sea as a key moisture source.

A regionalized rainfall isoscape and isotopic lapse rate, air mass back trajectories, and spatial–temporal isotopic variations were combined to determine potential mean recharge elevations, moisture circulation patterns, and surface water-groundwater connectivity, with the following specific research questions:

1 Do water stable isotopes reflect the distinct atmospheric moisture regimes of the Central American Isthmus?
2 Do water stable isotopes reveal characteristics of groundwater recharge processes in a highly tropical dynamic setting?
3 What are the implications of calculated recharge elevations for groundwater resources sustainability in a changing climate within the Dry Corridor of Central America?

The results are intended to inform governmental institutions in Central America and raise awareness regarding protection and conservation (e.g., reforestation) of critical recharge zones. The present work also may contribute to the understanding of groundwater recharge mechanisms in other tropical regions where isotopically informed geospatial models are becoming robust and more widely applied tools to improve water resources planning (Dehaspe et al., 2018; Jasechko & Taylor, 2015; Munksgaard et al., 2019; Sánchez-Murillo & Birkel, 2016; Taylor et al., 2013; Villegas, Paredes, Betancur, Taupin, & Toro, 2018).

1.1 | Climatic features of Central America

The regional climate can be analysed in terms of the seasonal influence of four main large-scale circulation patterns: (a) NE trade winds, (b) the latitudinal migration of the intertropical convergence zone (ITCZ), (c) cold continental surges, and (d) direct and indirect influence of tropical cyclones (Sáenz & Durán-Quesada, 2015; Waylen, Caviedes, & Quesada, 1996). Those circulation patterns result from complex interactions among structures the North Atlantic Subtropical High (NASH), the Western Hemisphere Warm Pool (WHWP; Wang & Enfield, 2001) dynamics, the seasonal migration of the ITCZ (Adam, Bischoff, & Schneider, 2016) and the Caribbean Low-Level Jet (CLLJ; Amador, 1998, 2008). Figure 1 shows the seasonal patterns that characterize the above mentioned structures, with the upper panel showing the evolution of the sea surface temperature (SST) and the enhancement of the WHWP during the spring over the eastern tropical Pacific Ocean (Figure 1a) followed by the incursion of the WHWP in the Gulf of Mexico during the summer months (Figure 1b) and the further intensity decrease and dislocation to the inner Caribbean after September (Figure 1c). In a similar way, the months for which the CLLJ exhibits its characteristic maximum and minimum peaks are shown in Figure 1. A secondary peak is observed in February (Figure 1d) with a distinguished zonal flow which supports the development of the Papagayo jet to the Pacific due to wind funnelling across the northern Costa Rica plains and the Papagayo gap. The CLLJ primary peak develops during summer (Figure 2d) with a prominent northward branch that transports moist air to northern Central America and the Gulf of Mexico. In contrast, a marked minimum features the CLLJ by October (Figure 3d), period in which a southwestern low-level wind flow develops in the Pacific (known as the Choco Jet, Poveda & Mesa, 2000).

Rainfall in the region is defined by the intersection of large-scale circulation patterns and local processes in which topography and vegetation cover play a relevant role. Two rainfall maxima are predominant between May–June and September–October. The rainfall maxima are interrupted by a relative minimum in July–August known as the MSD which coincides with the CLLJ primary maximum. This rainfall decrease is mainly characteristic of the Pacific slope of Central

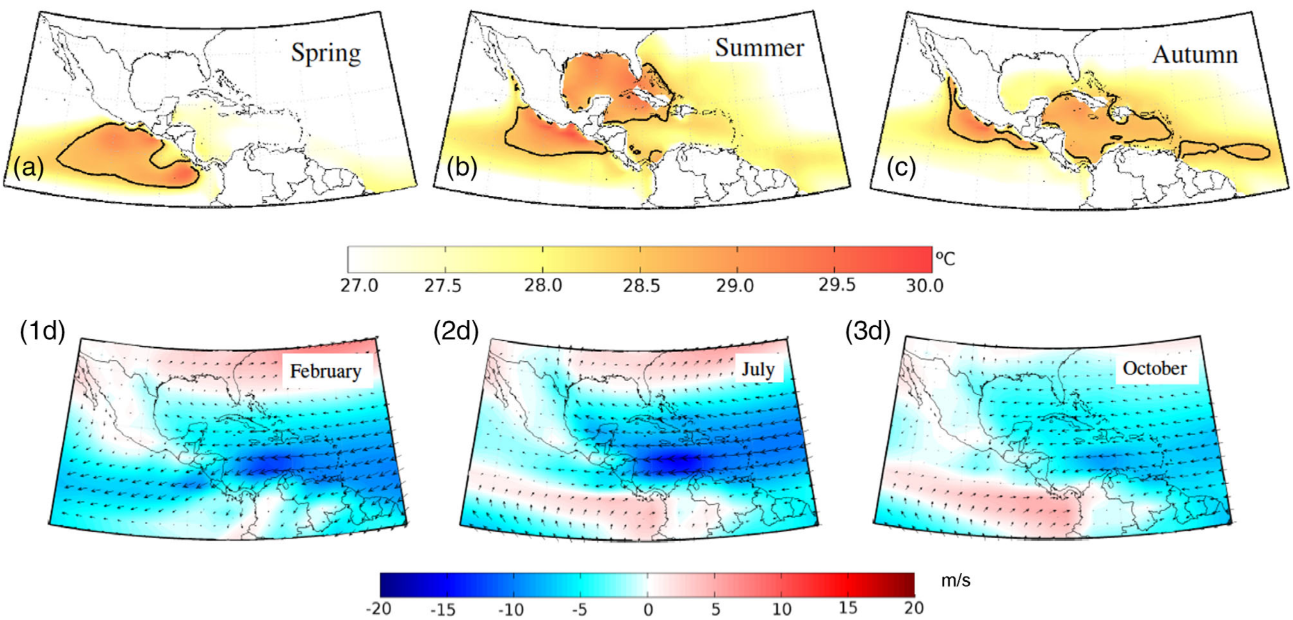

FIGURE 1 Seasonal variations of key regional climate features: WHWP shown as the area enclose by the SST > 28.5 isotherm based on Optimum Interpolation Sea Surface Temperature (Reynolds et al., 2007) for (a) Spring, (b) Summer, (c) Autumn and (d) CLLJ wind speed shaded contour and wind vector at 925 hPa (1d) February, (2d) July and (.d) October from ERA Interim (Dee et al., 2011) long-term averages (1998–2017). CLLJ, Caribbean Low-Level Jet; SST, sea surface temperature; WHWP, Western Hemisphere Warm Pool

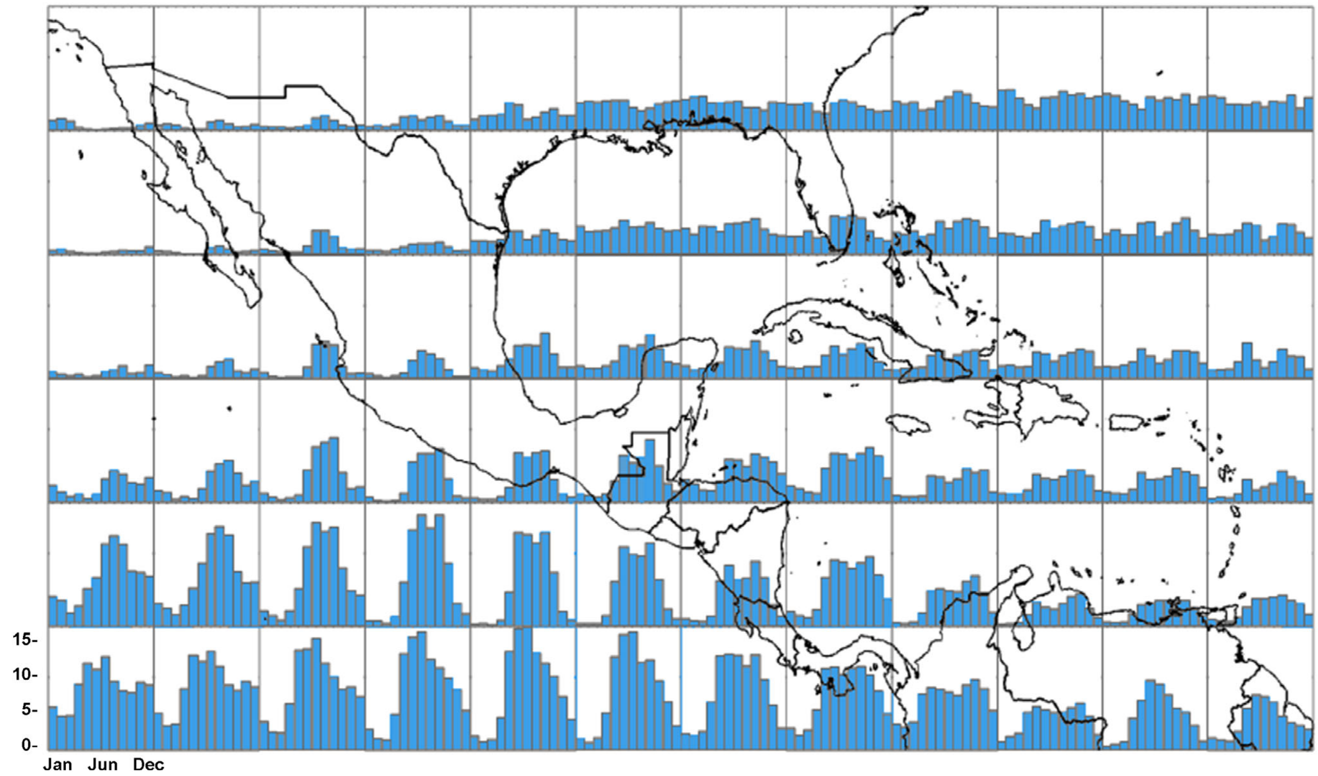

FIGURE 2 Spatial and temporal distribution of rainfall across the Central American Isthmus. Climatology distribution of monthly mean precipitation (in mm/day) for contiguous 5° × 5° area boxes for the 1998–2017 period, estimated using the rainfall product 3B43-7 (Huffman et al., 2015)

America as noticed from the average annual cycle of rainfall shown in Figure 2. Moreover, rainfall over the Pacific (as shown in Figure 2) also depicts a larger amount of rainfall when compared to the Caribbean slope, which features as a spatially explicit broader rainfall belt clearly identified as the ITCZ. It is also noteworthy that rainfall in the Caribbean has a smoother annual cycle that features similar amounts of rainfall throughout the year. Adding to the complexity of the precipitation system, the region also features the development of mesoscale convective systems (MCS), large-scale deep convective systems known for their diurnal cycling over land and over ocean (Houze Jr, 2004; Machado, Rossow, Guedes, & Walker, 1998; Mapes, Warner, Xu, & Negri, 2003). MCS development peaks in the region during late summer and early autumn months with a maximum occurrence over the Panama Bight resulting from positive SST anomalies (Zuidema, Mapes, Lin, Fairall, & Wick, 2006). These MCSs have a variable life cycle that ranges from short lived (few hours) to long lived (20–24 hr) systems and they are not only relevant for the accumulated rainfall but also form heavy rainfall events. Fuchs, Sessions, and Raymond (2014) linked the formation of MCS with the ITCZ and with Kelvin waves and travelling waves that led to heavy rainfall events. It is important to highlight that the nature of rainfall amount, intensity and associated rain producing systems that affect the region during the first and second legs of the rainy season are different. As Durán-Quesada, Gimeno, and Amador (2017) point out, the first leg of the rainy season is more likely to have a larger influence of local surface interaction processes while the second leg of the rainy season is more affected by large-scale dynamics.

Regional rainfall patterns are governed by the seasonal cyclicity of the SST distribution. It is evident that the magnitude of ENSO and associated SST variations are responsible for major changes in rainfall patterns with the shifting of the ITCZ being a fundamental driver of drier conditions during warm ENSO events. During El Niño, the more pronounced differences in warming between the northern and southern hemisphere induce anomalous northward movement of the ITCZ. The shifting is more prominent during boreal winter and is noticed as a southward shift of the ITCZ that can reach 5°S during strong El Niño events (Schneider, Bischoff, & Haug, 2014). The latitudinal shifting along with the longitudinal variation of the ITCZ results in a decrease of deep convective activity and negative precipitation anomalies along the Pacific slope of Central America. The latter is a recurring pattern, particularly, in the CADC (Cid-Serrano, Ramírez, Alfaro, & Enfield, 2015). Amador (2008) found that during warm ENSO phases, the CLLJ core is stronger, resulting in an increase of zonal easterly trade winds. Easterlies intensification increases the transport of moisture from the Caribbean and northern South America (Durán-Quesada, 2012) and in turn decreases the moisture transport from the eastern Pacific Ocean. Contrary to the Pacific side, the Caribbean domain of Central America is wetter during the warm phase and drier during the cold phase (Cid-Serrano et al., 2015). Hence, during warm ENSO events the dry-wet contrast of Central American Pacific and

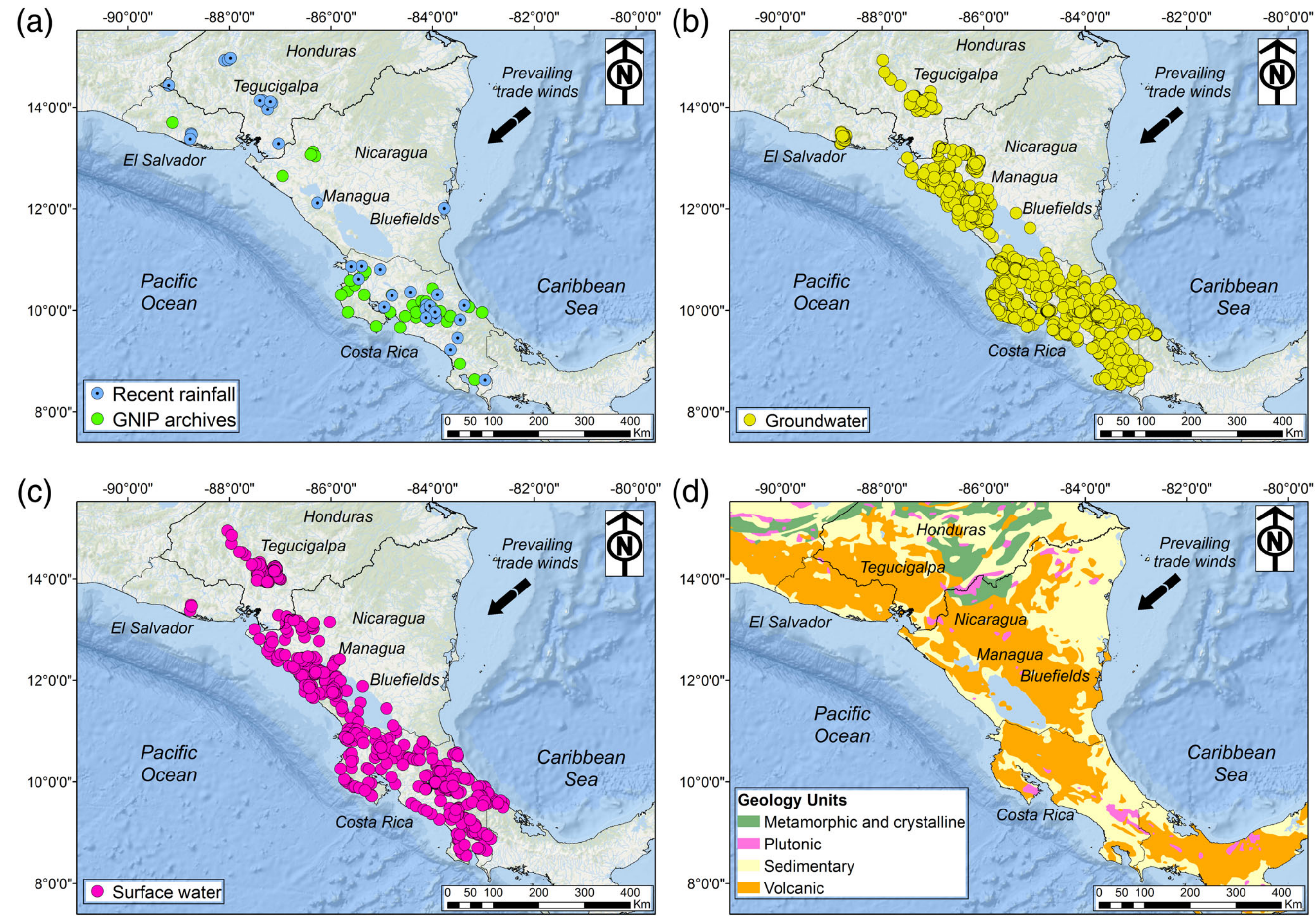

FIGURE 3 Spatial distribution of rainfall, groundwater, and surface water sampling sites across the Central American Isthmus. (a) Recent (2013–2018) rainfall monitoring sites (mostly daily and weekly sampling frequencies; blue circles and historical GNIP sites [green dots]. (b) Distribution of groundwater sampling sites (light green dots). (c) Distribution of surface water sampling sites (pink dots). (d) Main geological units across Central America. GNIP, Global Network of Isotopes in Precipitation

Caribbean slopes becomes more marked, leading to severe drought in the CADC and heavy rainfall extremes in the Caribbean.

1.2 | Geological and aquifer characteristics of Central America

The Central American subduction zone is a complex deformation region characterized by a rapid (70–90 mm/year) convergence rate of young (15–25 Ma) oceanic lithosphere responding to the interaction of four plates: Caribbean, Cocos, Nazca, and South American (Sak, Fisher, Gardner, Marshall, & LaFemina, 2009), whereby active tectonic deformation continues to shape the Central American landscape. Geologically, Central America is defined primarily by the northwest-trend of the Middle America trench and Central American volcanic front (Bundschuh & Alvarado, 2007). According to the overall tectonic setting, Central America is divided on the basis of crustal composition into two main blocks: Northern Central America, a continental block consisting of Guatemala, El Salvador, Honduras, and northern Nicaragua; and the southern Central America, an uplifted oceanic slice consisting of Southern Nicaragua, Costa Rica, and Panama (Dengo, 1973).

Volcano elevation along Central America decreases from Guatemala (Tajamulco volcano: 4,220 m a.s.l.) to Nicaragua (San Cristóbal volcano: 1,745 m a.s.l.) with a decrease in crustal thickness (50 km to <35 km) and variations in the basement geology from continental to oceanic dominated characteristics, whereas in Costa Rica, elevation increases (Irazú volcano: 3,432 m a.s.l.; ~45 km) near the amagmatic gap, then decreases (~25 km) beneath central Panamá (La Yeguada volcano: 1,297 m a.s.l.; Leeman, Carr, & Morris, 1994). Significant groundwater recharge takes place within fractured and sloping aquifers in dormant or active volcano complexes of Central America. However, the inherent complexity of volcanic-originated aquifers, particularly, in steep and highly fractured groundwater reservoirs, whereby lateral and vertical meteoric water mixing occurs (Madrigal-Solís, Fonseca-Sánchez, & Reynolds-Vargas, 2017), challenges existing models of subsurface water flow paths and storage (Delcamp, Roberti, & van Wyk de Vries, 2016) in such systems across the isthmus.

Overall, mountainous watersheds in Central America are comprised by fractured volcanic aquifers. At the lowlands, river basins are underlying aquifers of recent alluviums origin, whereas in the intramontane regions, aquifers are a mixture of volcanic materials, colluvial–alluvial and, of lesser importance, aquifers of sedimentary rocks (Losilla, 2001). These volcanic aquifers consist mainly of inter-stratifications of tuffs, gaps and quaternary as well as some tertiary lava, which present high permeability and fissure flows, which in turn make the aquifers highly vulnerable to anthropogenic pollution in highly populated urban areas and unregulated agricultural lands. The high heterogeneity of these aquifers, with differential horizontal and vertical flows, also makes them quite complicated to study and therefore to properly manage. Recharge has been mainly hypothesized as a net result of rainwater infiltration and to a lesser degree by a connection with surface water and excess of irrigation water application (Ballestero et al., 2007).

2 | METHODS AND MATERIALS

2.1 | Study area

The study area comprises four countries within the Central American Isthmus: Costa Rica (both Pacific and Caribbean slopes), Nicaragua (Pacific slope), Honduras (central and south Pacific slopes within the Choluteca river basin), and El Salvador (south Pacific slope within the Bajo Lempa river basin). Since Central America shares a common geomorphologic past (Coates & Obando, 1996), represented by the NW–SE mountain range that divides the region into the Caribbean and Pacific slopes with similar precipitation regimes (Alfaro, 2002) and soil characteristics, groundwater recharge and surface runoff processes may be analysed using regionalized isotope approaches to elucidate dominant hydrological processes to augment effective water resources management. However, it is important to highlight that abrupt land use changes across the region such as deforestation (Bebbington, Sauls, Rosa, Fash, & Bebbington, 2018; Tellman, 2019; Tobar-López, Bonin, Andrade, Pulido, & Ibrahim, 2019) should also be counted as a recent main driver of groundwater recharge and surface runoff changes in the region.

2.2 | Stable isotope data sets

The rainfall stable isotope data sets is composed of 1,873 recent samples (2013–2018) with weekly and daily collection frequencies, as part of concerted efforts between the Stable Isotope Research Group (National University, Costa Rica, the Earth Sciences Institute of Honduras (Autonomous National University, Honduras), the Research Center for Aquatic Resources of Nicaragua (National Autonomous University of Nicaragua, Managua), the Tropical Agricultural Research and Higher Education Center (CATIE, Costa Rica), and the Water Center for Latin America and the Caribbean (Monterrey, México), with the support of the Isotope Hydrology Section of the International Atomic Energy Agency (Vienna, Austria). Rainfall was collected using passive collectors (Palmex Ltd., Zagreb, Croatia; Gröning et al., 2012). Samples were collected in 15–50 ml HDPE-lined caps bottles, filled with no head space when permitted, and stored at 5°C until analysis. The ongoing isotope monitoring network in precipitation provides a better spatial distribution across different climatic zones, altitudes, and biomes of Central America (Figure 3a).

The rainfall stable isotope data set (see Supporting Information S1) is divided as follows: (a) Costa Rica Caribbean slope (*N* = 834; 2014–2018, ~30 km from the Caribbean coast); (b) Costa Rica Pacific slope (*N* = 472; 2013–2018, at the Central Valley of Costa Rica); (c) Nicaragua Caribbean slope (*N* = 48; 2017, near the Caribbean coast at Bluefields); (d) Nicaragua Pacific slope (*N* = 190; 2016–2018, at Managua); (e) Honduras (*N* = 232; 2018, within the Tegucigalpa Valley and southern Pacific slope); and (f) El Salvador (*N* = 94; 2016–2017, within the southern Pacific slope; Figure 3a).

Similarly, the groundwater and surface water stable isotope data sets (see Supporting Information S2 and S3) are composed of recent and archived measurements as follows: (a) El Salvador (*N* = 38; 2016–2017, within the southern Pacific slope), (b) Honduras (*N* = 391; 2018, within the Tegucigalpa Valley and north central region), (c) Nicaragua (*N* = 1,005; from 1970s to early 2000s and 2016, across the entire Pacific slope), (d) Costa Rica Caribbean slope (*N* = 354; 2014–2018), and (e) Costa Rica Pacific slope (*N* = 934; 2014–2018; Figure 3b,c). Recent sampling campaigns targeted base flow conditions with the aim of obtaining representative mean annual isotopic values at a high spatial resolution (Sánchez-Murillo & Birkel, 2016). Groundwater water samples were collected from automated and artisanal drinking water wells and perennial spring systems. Well valves were opened, and the water flowed for 10 min prior to sample collection to avoid stagnant water, in case the well was turned off for longer time periods according to local well operators. Surface waters were exclusively collected at the flowing sections of streams to avoid stagnant ponds with strong evaporative signals. Both groundwater and surface water samples were collected in 15–50 ml HDPE-lined caps bottles, filled with no head space, and stored at 5°C until analysis.

2.3 | Stable isotope analysis

Stable isotope archives from IAEA data sources comprise multiple laboratories, whereby samples were analysed by isotope ratio mass spectrometry before the advent of laser spectroscopy. Recent stable isotope analyses were conducted at (a) the Stable Isotope Research Group facilities of the National University (Heredia, Costa Rica) using a cavity ring down spectroscopy water isotope analyser L2120-*i* (Picarro, USA) and a LWIA-45-EP water isotope analyser (Los Gatos, USA), (b) the Research Center for Aquatic Resources of Nicaragua (National Autonomous University of Nicaragua, Managua) using a LWIA-45-EP water isotope analyser (Los Gatos, USA), and (c) at the Water Center for Latin America and the Caribbean (Monterrey, México) using a DLT-100 water isotope analyser (Los Gatos, USA). Calibrated secondary standards were used to normalize the results as well as to assess quality and drift control procedures. $^{18}O/^{16}O$ and $^{2}H/^{1}H$ ratios are presented in the established delta notation δ (‰), with reference to the VSMOW-SLAP scale. Deuterium excess was calculated as *d*-excess = $\delta^2H - 8 \cdot \delta^{18}O$ (Dansgaard, 1964).

2.4 | HYSPLIT air mass back trajectories

The influence of atmospheric trajectory and source meteorological conditions on the subsequent stable isotope composition of precipitation was studied using the HYSPLIT Lagrangian model (Stein et al., 2015) developed by the Air Resources Laboratory (ARL) of National Oceanic and Atmospheric Administration (NOAA, USA). The HYSPLIT model uses a three-dimensional Lagrangian air mass vertical velocity algorithm to determine the average position of the air mass which is reported at an hourly time-resolution over the trajectory (Soderberg et al., 2013). Air parcel trajectories were modelled 48 hr backwards in time based on the proximity of the Caribbean Sea and the Pacific Ocean. To compute a trajectory, the HYSPLIT model requires a starting time (13:00 p.m. UTC, which corresponds to the sample collection time of 7:00 a.m. in Costa Rica), location (−84.1091 W and 10.0004 N), and altitude (1,100 m a.s.l., Sánchez-Murillo et al., 2016a) as well as NOAA meteorological data files (e.g., GDAS, global data assimilation system: 2006–present; Su, Yuan, Fung, & Lau, 2015). In total, 476 air mass back trajectories were created and further divided into two main groups: the dry season (January–April) and the wet season (May–December) to compare the main moisture transport mechanisms across the Central American Isthmus.

2.5 | Central America rainfall isoscape

A Central America rainfall isoscape (in the definition of Bowen, 2010) was generated using data originating from the Global Network of Isotopes in Precipitation (GNIP; IAEA/WMO, 2018), using the methods presented by Terzer et al. (2013; RCWIP—regionalized cluster-based water isotope prediction). This approach is based on a combined approach of regressing the mean $\delta^{18}O$ and δ^2H at a GNIP station against geographical and climatic regressors and applying the resulting function onto gridded climate data. The station-based residuals were then interpolated onto the resulting regression grid to account for local anomalies not accounted for by the regression. However, as the geographical domain was constrained, and given the rather coarse spatial resolution of this isoscape grids (10 arc-minutes), two major modifications were applied: (a) given the relative climatic homogeneity of the region, the input data were constrained to an area between 0° and 30°N and 70° and 110°W rather than applying any clustering, and (b) WorldClim2 gridded climate data (Fick & Hijmans, 2017) at 30 arc-seconds resolution were used, although the best-fit regression was determined on geographical regressors (latitude = LAT and altitude = ALT) alone. One of the particular caveats of the prediction technique was however, that the records used to derive the station-based mean isotopic values were spatially and temporally inhomogeneous as a result of data scarcity (cf. also Bowen, 2010 and Terzer et al., 2013 on the issue), which will require future re-assessments based on longer time series.

2.6 | Potential mean recharge elevation and rainfall–groundwater connectivity

Mean $\delta^{18}O$ annual values of 57 historical GNIP and recent stations (elevation range from 100 to 3,400 m a.s.l.) were used to construct a regionalized isotopic lapse rate for the Pacific slope of Central America (Adj. r^2 = .32, *p*-value <.001, ~−1.0‰ $\delta^{18}O$ per km of elevation with 95% confidence intervals). Since most of Central America's population (Figure 3d) and water scarcity issues are located on the Pacific slope, this analysis does not include the Caribbean domain information. The isotopic lapse rate was used to calculate potential mean recharge elevations (in m a.s.l.) under the assumption that groundwater isotope ratios are representative of mean annual recharge conditions. Furthermore, a rainfall to groundwater isotopic diagram was constructed following Jasechko and Taylor (2015) to estimate the isotopic recharge bias across the Central American Isthmus. Mean $\delta^{18}O$ annual values in rainfall were extracted from the regionalized isoscape and rainfall to groundwater isotope ratios (P/GW [−]) were calculated to evaluate groundwater recharge mechanisms. A P/GW > 1 indicates sites where infiltrated water is susceptible to near-surface secondary evaporation, while a P/GW ratio < 1 points towards recharge originating from more intense and more depleted rainfalls at high altitudes. A P/GW ~ 1 indicates a rapid recharge via preferential flow paths (Sánchez-Murillo & Birkel, 2016).

A Kruskal-Wallis non-parametric analysis of variance on ranks (Kruskal & Wallis, 1952) was applied to test if there was stochastic dominance of one group over another regarding $\delta^{18}O$ (‰), δ^2H (‰), *d*-excess (‰), and MRE values. A significant difference was determined ($p < .001$) when median values among the groups (countries) were greater than expected by chance. In addition, for all groups having a significant difference, an all pairwise multiple comparison procedure was applied using Dunn's method (Dunn, 1961) to test if there is evidence of stochastic dominance between the samples ($p < .05$). Dunn's method approximates exact rank-sum test statistics by using the median rankings of the results in each group from the previous Kruskal–Wallis non-parametric test and provides an inference in median ranks in each group. Statistical and graphical analysis was performed using the open source statistical R language and packages (R Development Core Team, 2014). All maps were developed in ArcGIS 10.5 (ESRI, USA).

3 | RESULTS AND DISCUSSION

3.1 | Regional rainfall isotope variability and moisture transport

The regression equations used as suitable predictions for the annual mean $\delta^{18}O$ and δ^2H in the Central America region (RMSE on $\delta^{18}O$ = 0.77 and δ^2H = 6.4) are:

$$\delta^{18}O = 0.078 \cdot LAT - 0.0023 \cdot ALT - 5.447 \left(R^2 = .81, p-\text{value} < .01\right) \quad (1)$$

$$\delta^{2}H = 0.585 \cdot LAT - 0.0174 \cdot ALT - 33.639 \left(R^2 = .79, p-\text{value} < .01\right) \quad (2)$$

Mean annual $\delta^{18}O$ in rainfall ranged from −3.65‰ to −12.14‰ across the Central American Isthmus (Figure 4a). Enriched rainfall was commonly observed in the Caribbean lowlands, whereas depleted rainfall was observed across the Pacific slope of the main mountain ranges from Guatemala (i.e., Sierra Madre) to the Costa Rica/Panama border (i.e., Talamanca range). Figure 4b shows a representative analysis of air mass back trajectories in the Central American Isthmus using a daily sampling station in central Costa Rica (2013–2017). During the 2013–2017 period, conditions featured weak as well as strong El Niño situations, with a very strong El Niño developing in 2015–2016. The

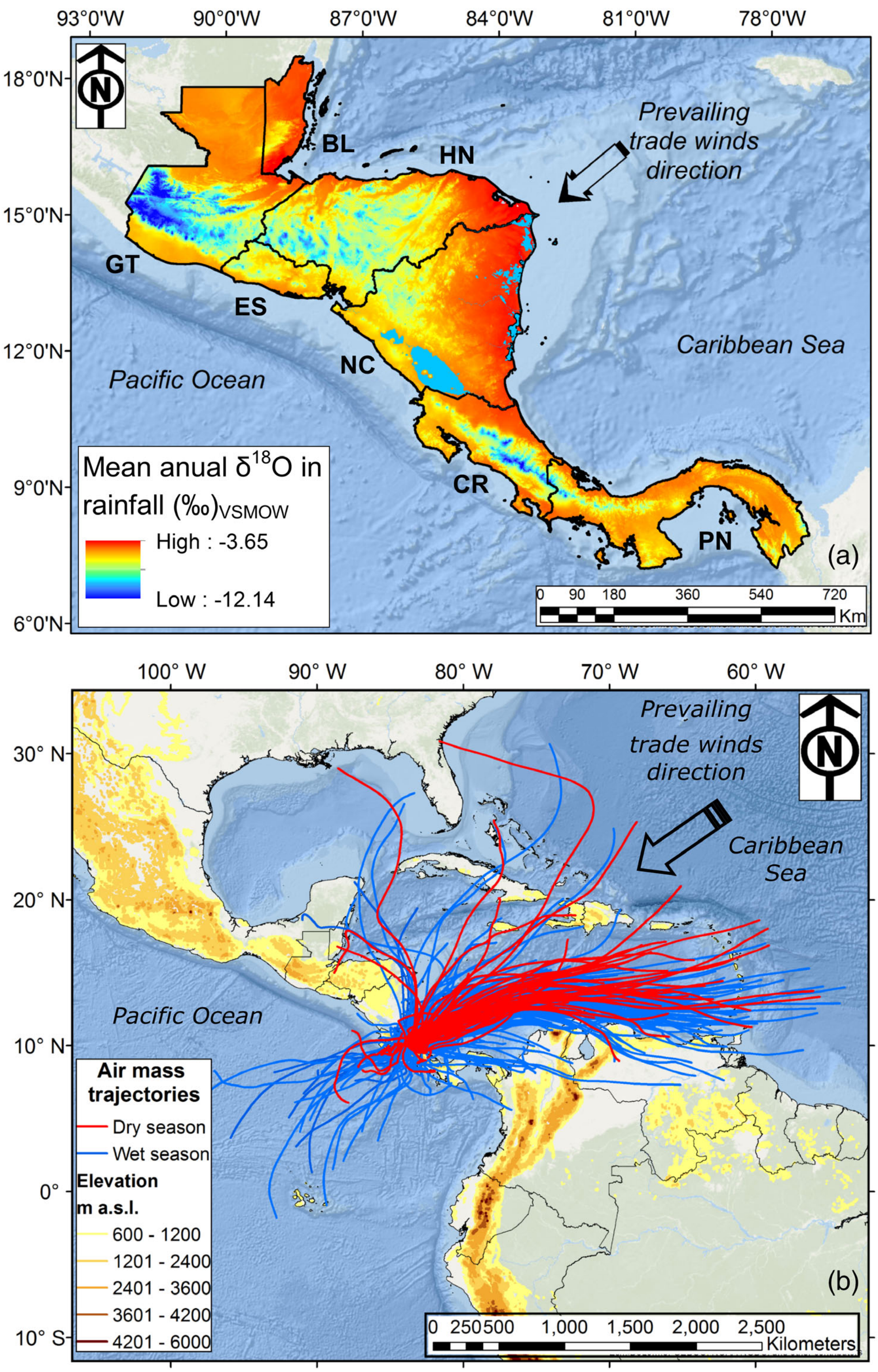

FIGURE 4 Study area characteristics. (a) Regionalized rainfall isoscape within the Central American Isthmus. Mean annual $\delta^{18}O$ (‰) is colour coded. (b) Representative (N = 476) dry (red) and wet (blue) seasons 48-hr air mass back trajectories over Costa Rica (2013–2017) using the HYSPLIT Lagrangian model (Stein et al., 2015). Trade winds cross Central America with a NE → SW prevailing direction, resulting in notable orographic distillation and complex isotopic spatial variations. BL, Belize; CR, Costa Rica; ES, El Salvador; GT, Guatemala; HN, Honduras; NC, Nicaragua; PN, Panama

dominance of El Niño in that period was associated with an anomalous migration of the ITCZ and a weaker CLLJ during winter time. Warmer waters favoured evaporation in the Pacific and the intensification of the southwesterly flow, which, given weaker easterlies, allowed for increased moisture transport from the tropical Pacific to the isthmus. The latter is in good agreement with previous results from Durán-Quesada (2012) which showed a positive, non-lagged correlation of 0.79 between the eastern tropical Pacific Ocean moisture transport to Central America and El Niño 3.4 index during February. The intensification of moisture transport to the isthmus under El Niño is consistent across the region with a larger transport to the northernmost part of the region (Durán-Quesada et al., 2017). The isoscape in Figure 4a, shows a remarkable spatial variability of δ^{18}O, with an enriched composition over coastal areas as a result of rainfall forming at lower altitudes and a low-level convergence favoured by higher temperatures. The northern portion of the CADC remarkably features more enriched values (as well as higher elevations), associated to water vapour coming from an environment of larger evaporation as observed during warm ENSO events in the area. Local evapotranspiration and Pacific moisture transport played a significant role in the vapour budget during the wet season (Figure 4b). Overall, as water vapour encounters the main mountain range, orographic distillation and convergence increased, resulting in depleted rainfall across the Pacific domain. Orographic depressions enhanced the incursion of enriched-type rainfall across the highlands of the Pacific slope, with subsequent mixing of depleted and enriched percolation into the mountainous aquifers (Esquivel-Hernández et al., 2018; Ramírez-Leiva et al., 2017; Sánchez-Murillo et al., 2016b).

Recent daily and weekly rainfall isotope measurements resulted in highly significant LMWLs (Figure 5a). Caribbean LMWLs (Nicaragua and Costa Rica) exhibited similar conditions relative to the global meteoric water line (GMWL; Craig, 1961), whereas stations located on the Pacific slope, consistently, exhibited lower slopes (7.42–7.88) and intercepts (4.99–8.42; Figure 5a). Sánchez-Murillo et al. (2016a) reported that sub-cloud evaporation is a key driver controlling rainfall isotope composition within the Pacific slope of Central America. Non-equilibrium processes under an unsaturated condition below the cloud base, enhance the net transfer of water molecules from the falling drops to the surrounding air (Crawford, Hollins, Meredith, & Hughes, 2017; Graf, Wernli, & Sodemann, 2018; Kong & Pang, 2016; Salamalikis, Argiriou, & Dotsika, 2016), resulting in enriched surface rainfall. The latter process is a potential common feature within the CADC, whereby recent warm ENSO-induced droughts decreased rainfall amounts and intensities as well as promoting more intense warming and unsaturated atmosphere conditions during rainfall events (Jimenez et al., 2018; Muñoz-Jiménez et al., 2019).

Figure 5b shows a time series of rainfall isotope during 2017–2018 in Costa Rica, Nicaragua, and Honduras. In general, climate seasonality from dry (January–April) to wet season (May–December) was characterized by a W-shaped isotopic pattern (Sánchez-Murillo et al., 2019). The latter is consistent with the pronounced intra-seasonal rainfall variations that results in two depleted incursions during the wet season and enriched pulses during the MSD and the peak of the CLLJ (Figure 5b). These trends were amplified within the CADC,

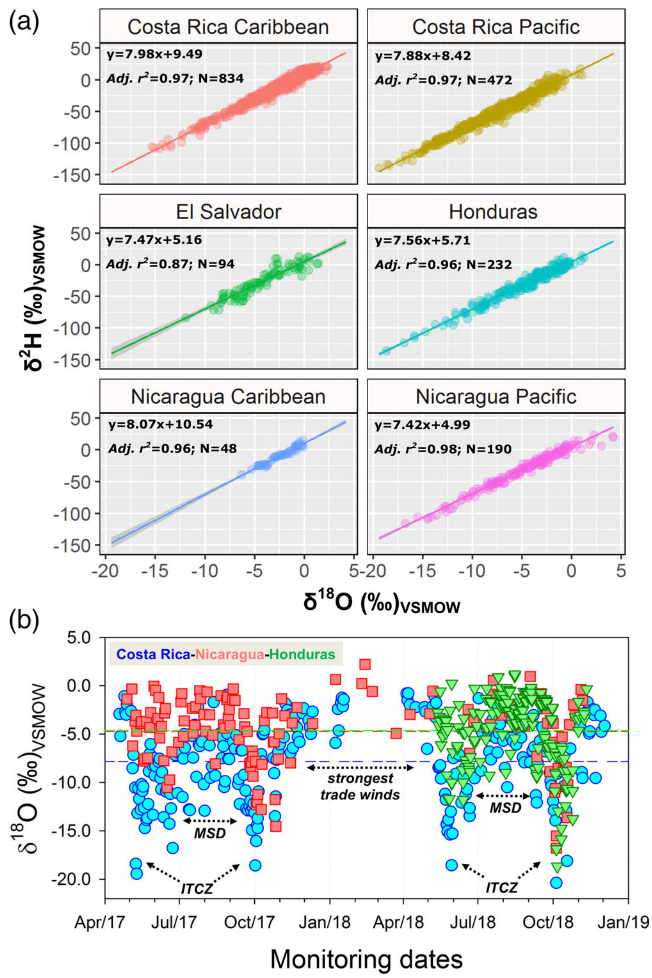

FIGURE 5 Stable isotope variations of rainfall in Central America. (a) Local meteoric water lines (LMWLs) by country and governing rainfall domain (Caribbean vs. Pacific). All regressions are significant with a *p*-value <.001. LMWLs include only recent (2013–2018) isotope measurements (mostly daily and weekly sampling frequencies) for comparison purposes. (b) δ^{18}O time series (2016–2018) in Costa Rica, Nicaragua, and Honduras. Horizontal dashed-lines represent the median value of each country. Three main climatic features are related with the isotopic variability in Central America: (1) the movement of the ITCZ, (2) the MSD, and (c) cold fronts during the strongest period of NE trade winds. ITCZ, intertropical convergence zone; MSD, mid-summer drought

whereas in the Caribbean domain the isotopic composition was less variable throughout the year. Differences found when comparing δ^{18}O values for the three countries reflected the larger influence of the ITCZ for Costa Rica as well as the relevance of rainfall events derived from highly energetic systems and a wetter environment that results from a supersaturated atmosphere. Meanwhile, seasonality of δ^{18}O for Nicaragua is described by drier conditions in comparison to Costa Rica. Honduras showed a rather special case as the influence of the ITCZ up north is lower compared to Costa Rica and the depleted values observed with a depleted composition in October show the influence of cyclonic activity and the activity of transients, which despite a similar isotopic composition as identified from the ITCZ passage denote the influence of a different process that also generates deep convection.

3.2 | Rainfall and surface/groundwater connectivity

Figure 6 shows a series of scattered and box plots in rainfall, groundwater, and surface water. Orographic isotope separation between the Caribbean and Pacific slopes was clearly depicted in Costa Rica, whereby rainfall medians differed by 5.3‰ in $\delta^{18}O$. Rainfall from the Caribbean lowlands of Nicaragua and Costa Rica exhibited a similar enrichment trend. Notably, the rainfall median values in the northern portion of the CADC (Nicaragua, El Salvador, and Honduras) were significantly greater than the Pacific slope of Costa Rica (median values ranging from −3.9 to −4.5‰ in $\delta^{18}O$; Figure 6a). Similarly, *d*-excess variations indicated a mixture of enhanced moisture recycling (Caribbean Sea-derived moisture) and

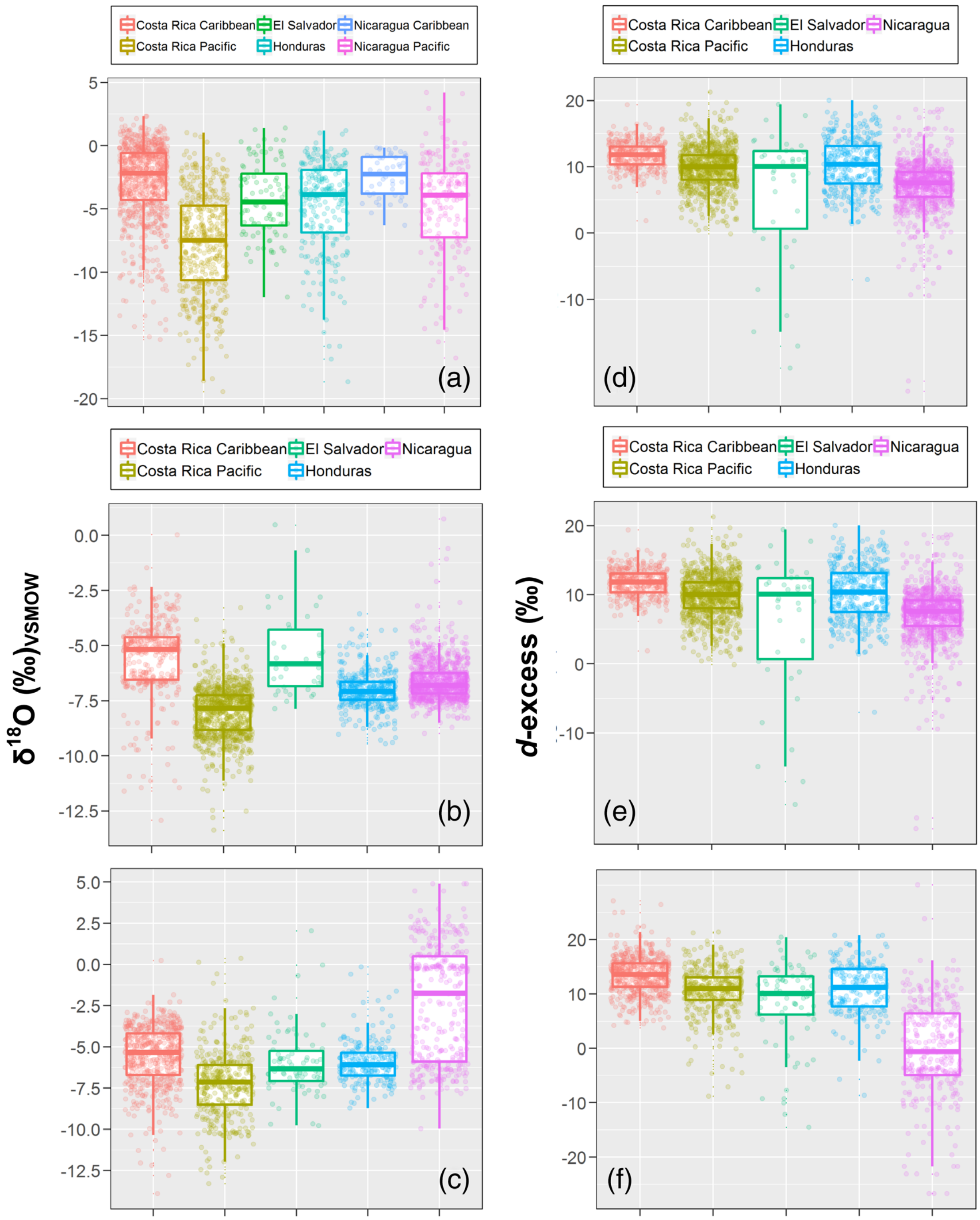

FIGURE 6 Scattered and box plots showing variations across the Central American Isthmus (ordered by country and governing rainfall domain) of (a–c) $\delta^{18}O$ in rainfall, groundwater, and surface water; and (d–f) *d*-excess in rainfall, groundwater, and surface water, respectively. Box plots include 25th, 75th, median, and outliers for each group

below cloud fractionation, particularly, in Nicaragua and El Salvador (Figure 6d).

The most $\delta^{18}O$ depleted groundwater was reported in the Pacific slope of Costa Rica (median = −7.9‰), while groundwater isotope values of Honduras (median = −7.1‰) and Nicaragua (median = −6.8‰) presented similar median values. The most enriched groundwater was reported in the south Pacific slope of El Salvador (median = −6.0‰; Figure 6b). The significantly low *d*-excess values in groundwater of Nicaragua evidenced the strong connectivity between lakes and groundwater reservoirs as well as potential surface secondary evaporation during recharge processes (Figure 6e).

Overall, surface waters across the isthmus exhibited a clear enrichment trend, reflected in the low *d*-excess median values. In Nicaragua, the large presence of sampled lakes, biased the median value towards −1.74‰ in $\delta^{18}O$ with a broad spectrum of isotope values (from +5 to −10‰). In Costa Rica, El Salvador, and Honduras surface water isotope values revealed a close relationship with the median values of groundwater (median values ranging from −6.1 to −7.1‰ in $\delta^{18}O$; Figure 6c).

3.3 | Regional groundwater recharge assessment

The complex topography of Central America and the existence of two large water pools nearby (i.e., Caribbean Sea and Pacific Ocean) provide a unique scenario to test the water vapour distillation/elevation effect on groundwater isotopic composition. A compilation of 57 historical and recent monitoring rainfall stations (>100 m a.s.l.) resulted in a significant regionalized isotopic lapse rate of ~1.0‰ in $\delta^{18}O$ per 1 km of elevation (Adj. r^2 = .32; p-value <.001; Figure 7a). Previous studies have reported similar isotopic lapse rates for particular countries in the region (Lachniet et al., 2007; Sánchez-Murillo & Birkel, 2016; Sánchez-Murillo et al., 2013; Wassenaar et al., 2009; Windhorst, Waltz, Timbe, Frede, & Breuer, 2013). The rain-out effect over the Caribbean slope was a result of the direct influence of the trade winds and nearby moisture transport from the Caribbean Sea (isotopic lapse rate not included; see Sánchez-Murillo & Birkel, 2016), whereas in the Pacific slope the combination of the rain shadow effect, more complex orography and biomes, and deep convective activity throughout the wet season, resulted in a weaker elevation trend (Figure 7a).

Figure 7b shows the probabilistic density distribution of the isotope-derived MRE across the Pacific slope of the isthmus. Median MRE were not significantly different between Nicaragua (1,024 ± 15 m a.s.l.), Honduras (1,289 ± 27 m a.s.l.), and El Salvador (1,104 ± 119 m a.s.l.). Costa Rica exhibited a positive skewed distribution with a median MRE of 1,979 ± 30 m a.s.l. The bimodal distribution of Costa Rica in the MRE determination is affected by the strong influence of enriched-type rainfall across high elevation topographic depressions (i.e., a NE moisture pass) resulting in inverse altitude effects (Sánchez-Murillo et al., 2016b). Overall, MRE across the northern portion of the CADC indicated infiltration below 2,000 m a.s.l., while higher elevations were found in the central and southern Pacific domain of Costa Rica.

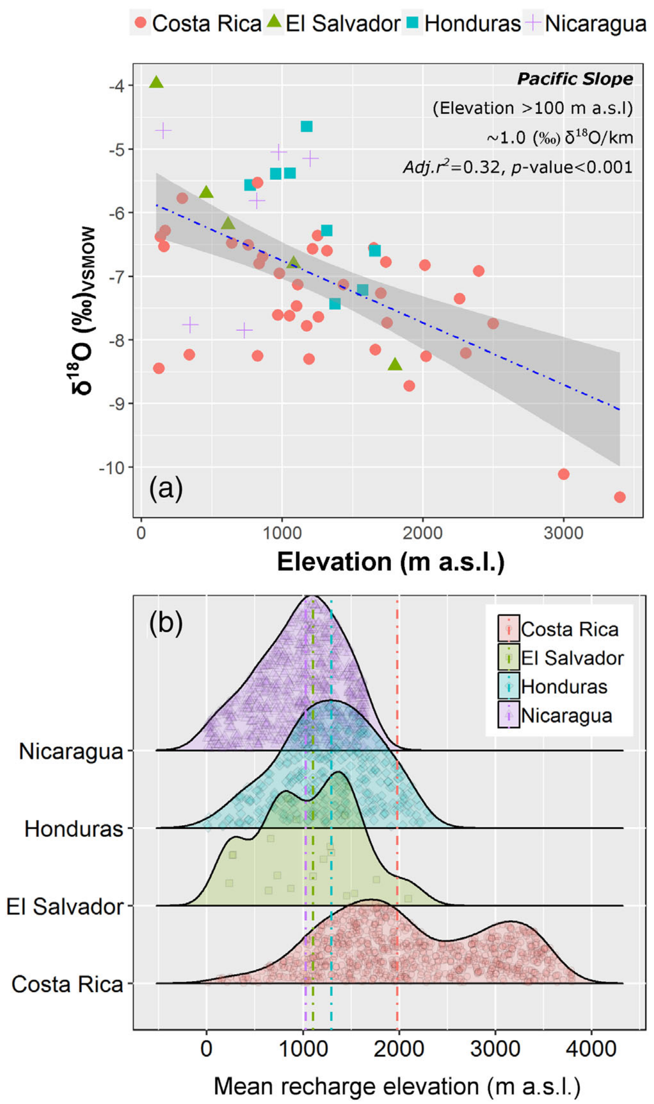

FIGURE 7 Isotopic lapse rates and potential mean recharge elevations (MRE). (a) Regionalized isotopic lapse rate within the Central American Isthmus using monitoring stations above 100 m a.s.l. Blue dashed-line represents the best linear fit resulting in ~−1‰ $\delta^{18}O$ per kilometre of elevation gradient with 95% confidence intervals (dark grey area). (b) Density distribution of MRE (m a.s.l.) by country. Dashed coloured-lines denote the median value of each country

Figure 8a shows a rainfall to groundwater isotopic diagram to assess groundwater recharge bias (Jasechko & Taylor, 2015; Sánchez-Murillo & Birkel, 2016). In general, groundwater recharge was characterized by three distinct mechanisms: (a) depleted recharge at the highland areas (72.3%), (b) rapid recharge via preferential flow paths (13.1%), and enriched recharge due to secondary fractionation in the rainfall generation and near-surface enrichment by soil matrix attenuation, small recharge rates, and interaction with large-scale lake systems (14.6%; Figure 8c). Latitudinally, P/GW isotopic ratios indicated preferential recharge may occur along the isthmus in highly fractured volcanic aquifers, whereas enriched recharge tends to increase from 8° to 14°N and depleted high elevation recharge was favoured towards Costa Rica (Figure 8b).

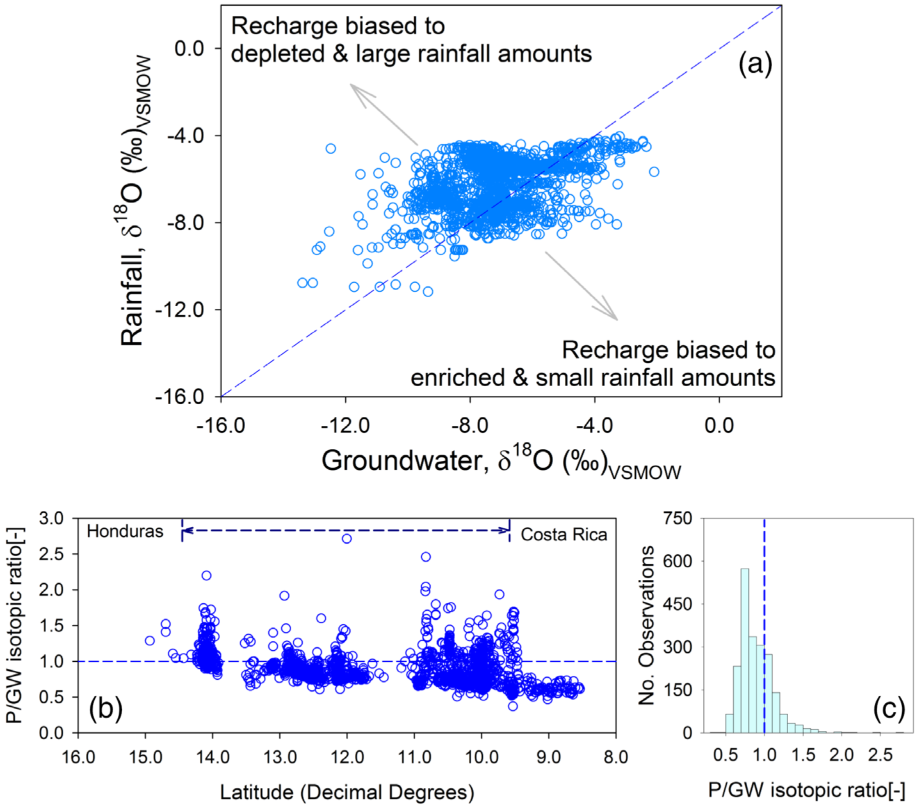

FIGURE 8 Rainfall and groundwater recharge bias across the Central American Isthmus. (a) Rainfall and groundwater recharge bias 1:1 diagram following Jasechko and Taylor (2015). (b) Latitudinal variation of P/GW isotopic ratios [–] from Costa Rica to Honduras. (c) Histogram of P/GW isotopic ratios [–]. In (b) and (c), the blue dashed-line represents a P/GW = 1

4 | CONCLUSIONS

This work presented the first regional synthesis of the spatio-temporal isotopic variability in four tropical countries: Costa Rica, Nicaragua, El Salvador, and Honduras, whereby decades of collaboration between IAEA and Member States established the foundation of tracer Hydrology studies in the Central American Isthmus. Recent sampling campaigns across the isthmus provided novel evidence of isotopic trends in the hydrological cycle. In this region, considered a climate change 'hot spot', complex rainfall and groundwater recharge mechanisms recurrently affected by ENSO events, challenge water resources management. Due to limited hydrometric networks, particularly, in monitoring groundwater levels and surface water discharge, rapid and robust isotopic assessments may shed light on the understanding of hydrogeological and meteorological processes.

Our results revealed a regionalized temporal pattern in the isotopic composition of rainfall, with a remarkable enrichment towards the northern portion of the CADC. Moisture transport was mainly governed by the semi-closed basin of the Caribbean Sea, and to a lesser degree, inputs from the central Pacific Ocean and local evapotranspiration fluxes were also attributed in the air mass back trajectory analysis. Groundwater recharge was characterized by three main governing mechanisms: (a) depleted recharge at the highland areas, (b) rapid recharge via preferential flow paths, and enriched recharge due to near-surface secondary fractionation. Consistent low *d*-excess values suggested a clear connection between surface water (i.e., rivers and large-scale lakes) and groundwater reservoirs.

Significant temporal and spatial gaps invoke more systematic efforts that accounts for better:

1 Sampling gradients to improve isotopic lapse rates.
2 Surface water and groundwater sampling during baseflow regimes to characterize mean annual conditions.
3 An urgent groundwater assessment (e.g., hydraulic properties and mass balances) in the CADC.
4 Characterization of the poorly sampled Caribbean lowland domain.

Furthermore, the climatic and hydrogeological similarities of the Central American isthmus should facilitate the selection of sites for effective mid- to long-term monitoring efforts of isotopes in various components of the water cycle, with resulting data that can be used to:

1 Improve the existing isoscape(s), triggering a positive feedback between prediction and observation efforts.
2 Enhance ongoing forest conservation and land use practices.
3 Enforce protection laws in critical recharge elevations.
4 Guarantee water security and sustainability of ~50 million inhabitants through the incorporation of tracer hydrology insights in modelling assessments and decision making.

ACKNOWLEDGEMENTS

This study was supported by International Atomic Energy Agency grants COS/7/005, RC-19747, and RLA/7/024. A Joint Research

Agreement (SIA-0378-14) by the National University (Heredia, Costa Rica) and Empresa de Servicios Públicos de Heredia (ESPH S. A.) was also fundamental. Funding from the Research Office of the National University (Heredia, Costa Rica) through grants SIA-0482-13, SIA-0101-14, SIA-0236-16, SIA-411-17, and SIA-414-17 was crucial for conducting sampling campaigns across the isthmus. Support from the Isotope Network for Tropical Ecosystem Studies (ISONet) funded by the University of Costa Rica Research Council is recognized. The Research Center for Aquatic Resources of Nicaragua (National Autonomous University of Nicaragua, Managua) thanks the support from the IAEA Technical Cooperation project NIC/5/009. Acknowledgement to the European Union through the Project WATERCLIMA LAC No. DCI-ENV 2014/350-470 executed by the Tropical Agricultural Research and Higher Education Center (CATIE), coastal zones management in El Salvador, as well as a sincere thanks to Alejandro Felix and Walter Chacon for coordinating field work and to Jurgen Mahlknecht and Antonio Torres of the Water Center for Latin America and the Caribbean for their valuable assistance in the analysis of samples. FUNDECOR recognizes the funding from Water for the Future within the Replenishment Project (Coca Cola FEMSA-TNC). The authors thank various anonymous helping hands that contributed to rainfall, surface water, and groundwater sampling in Central America.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article.

ORCID

Ricardo Sánchez-Murillo https://orcid.org/0000-0001-8721-8093
Germain Esquivel-Hernández https://orcid.org/0000-0002-6890-6509
Heyddy Calderón https://orcid.org/0000-0002-4405-8971
Lucia Ortega https://orcid.org/0000-0002-5181-9054

REFERENCES

Adam, O., Bischoff, T., & Schneider, T. (2016). Seasonal and interannual variations of the energy flux equator and ITCZ. Part II: Zonally varying shifts of the ITCZ. *Journal of Climate*, *29*(20), 7281–7293. https://doi.org/10.1175/JCLI-D-15-0710.1

Aguilar, E., Peterson, T. C., Ramírez-Obando, P., Frutos, R., Retana, J. A., Solera, M., … Mayorga, R. (2005). Changes in precipitation and temperature extremes in Central America and northern South America, 1961–2003. *Geophysical Research*, *110*, D23107. https://doi.org/10.1029/2005JD006119

Alfaro, E. (2002). Some characteristics of the annual precipitation cycle in Central America and their relationships with its surroundings tropical oceans. *Tropical Meteorology and Oceanography*, *9*(2), 88–103.

Amador, J. (2008). The intra-Americas seas low-level jet (IALLJ): Overview and future research. *Annals of the new York Academy of Sciences*, *1146*, 153–188. https://doi.org/10.1196/annals.1446.012

Amador, J. A. (1998). A climatic feature of the tropical Americas: The trade wind easterly jet. *Meteorological and Oceanographical Topics*, *5*(2), 91–102.

Ballestero, M., Reyes, V., & Astorga, Y. (2007). Groundwater in Central America: its importance, development and use, with reference to its role in irrigated agriculture. In M. Giordano & K. G. Villholth (Eds.), *The agricultural groundwater revolution. Opportunities and threads to development* (pp. 100–128). Colombo, Sri Lanka: International water Management Institute (IWMI).

Bebbington, A. J., Sauls, L. A., Rosa, H., Fash, B., & Bebbington, D. H. (2018). Conflicts over extractivist policy and the forest frontier in Central America. *European Review of Latin American and Caribbean Studies*, *106*, 03–132.

Bouroncle, C., Imbach, P., Rodríguez-Sánchez, B., Medellín, C., Martinez-Valle, A., & Läderach, P. (2017). Mapping climate change adaptive capacity and vulnerability of smallholder agricultural livelihoods in Central America: Ranking and descriptive approaches to support adaptation strategies. *Climatic Change*, *141*(1), 123–137. https://doi.org/10.1007/s10584-016-1792-0

Bowen, G. J. (2010). Statistical and geostatistical mapping of precipitation water isotope ratios. In J. B. West, G. J. Bowen, T. E. Dawson, & K. P. Tu (Eds.), *Isoscapes: Understanding movement, pattern, and process on earth through isotope mapping* (pp. 139–178). London: Springer. https://doi.org/10.1007/978-90-481-3354-3_7

Bundschuh, J., & Alvarado, G. E. (Eds.). (2007). *Central America: Geology, resources and hazards*. United Kingdom: CRC Press.

Cid-Serrano, L., Ramírez, S. M., Alfaro, E. J., & Enfield, D. B. (2015). Analysis of the Latin American west coast precipitation predictability using an ENSO index. *Atmosfera*, *28*(3), 191–203. https://doi.org/10.20937/ATM.2015.28.03.04

Coates, A. G., & Obando, J. A. (1996). The geologic evolution of the Central American Isthmus. In *Evolution and environment in tropical America* (pp. 21–56). Chicago, USA: University of Chicago Press.

Craig, H. (1961). Isotopic variations in meteoric waters. *Science*, *133* (3465), 1702–1703. https://doi.org/10.1126/science.133.3465.1702

Crawford, J., Hollins, S. E., Meredith, K. T., & Hughes, C. E. (2017). Precipitation stable isotope variability and subcloud evaporation processes in a semi-arid region. *Hydrological Processes*, *31*, 20–34. https://doi.org/10.1002/hyp.10885

Dansgaard, W. (1964). Stable isotopes in precipitation. *Tellus*, *16*, 436–468. https://doi.org/10.1111/j.2153-3490.1964.tb00181.x

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., … Vitart, F. (2011). The ERA-interim reanalysis: Configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, *137*(656), 553–597. https://doi.org/10.1002/qj.828

Dehaspe, J., Birkel, C., Tetzlaff, D., Sánchez-Murillo, R., Durán-Quesada, A. M., & Soulsby, C. (2018). Spatially distributed tracer-aided modelling to explore water and isotope transport, storage and mixing in a pristine, humid tropical catchment. *Hydrological Processes*, *32*(21), 3206–3224. https://doi.org/10.1002/hyp.13258

Delcamp, A., Roberti, G., & van Wyk de Vries, B. (2016). Water in volcanoes: Evolution, storage and rapid release during landslides. *Bulletin of Volcanology*, *78*(87), 87. https://doi.org/10.1007/s00445-016-1082-8

Dengo, G. (1973). *Structural geology, tectonic history, and morphology of Central America*. Boulder, Colorado, USA: Centro Regional de Ayuda Técnica, Agencia para el Desarrollo Internacional.

Dunn, O. J. (1961). Multiple comparisons among means. *Journal of the American Statistical Association*, *56*(293), 52–64. https://doi.org/10.2307/2282330

Durán-Quesada, A. M. (2012). Sources of moisture for Central America and transport based on a Lagrangian approach: variability, contributions to precipitation and transport mechanisms (PhD thesis). University of Vigo, Spain. 288 pp.

Durán-Quesada, A. M., Gimeno, L., & Amador, J. (2017). Role of moisture transport for Central American precipitation. *Earth System Dynamics*, *8* (1), 147–161. https://doi.org/10.5194/esd-8-147-2017

Esquivel-Hernández, G., Mosquera, G. M., Sánchez-Murillo, R., Quesada-Román, A., Birkel, C., Crespo, P., … Boll, J. (2018). Moisture transport and seasonal variations in the stable isotopic composition of rainfall in Central American and Andean Páramo during El Niño conditions (2015–2016). *Hydrological Processes*, *33*, 1802–1817. https://doi.org/10.1002/hyp.13438

Fick, S. E., & Hijmans, R. J. (2017). WorldClim 2: New 1-km spatial resolution climate surfaces for global land areas. *International Journal of Climatology*, *37*, 4302–4315. https://doi.org/10.1002/joc.5086

Food and Agriculture Organization of the United Nations. (2016). El Niño and La Niña: preparedness and response, situation report July 2016. Retrieved from http://www.fao.org/emergencies/resources/documents/resources-detail/en/c/423055/

Food and Agriculture Organization of the United Nations (FAO). (2015). Disaster risk programme to strengthen resilience in the Dry Corridor in Central America. Retrieved from http://www.fao.org/resilience/resources/resources-detail/en/c/330164/

Food and Agriculture Organization of the United Nations (FAO). (2017). Chronology of the Dry Corridor: The impetus for resilience in Central America. Retrieved from http://www.fao.org/in-action/agronoticias/detail/en/c/1024539/

Foster, S., & MacDonald, A. (2014). The 'water security' dialogue: Why it needs to be better informed about groundwater. *Hydrogeology Journal*, *22*(7), 1489–1492. https://doi.org/10.1007/s10040-014-1157-6

Fuchs, Ž., Sessions, S. L., & Raymond, D. J. (2014). Mechanisms controlling the onset of simulated convectively coupled Kelvin waves. *Tellus A: Dynamic Meteorology and Oceanography*, *66*(1), 22107. https://doi.org/10.3402/tellusa.v66.22107

Giorgi, F. (2006). Climate change hot-spots. *Geophysical Research Letters*, *33*, L08707. https://doi.org/10.1029/2006GL025734

González, J. E., Georgescu, M., Lemos, M. C., Hosannah, N., & Niyogi, D. (2017). Climate change's pulse is in Central America and the Caribbean. *Eos*, *98*, 1. https://doi.org/10.1029/2017EO071975

Graf, P., Wernli, H., Pfahl, S., & Sodemann, H. (2018). A new interpretative framework for below-cloud effects on stable water isotopes in vapour and rain. *Atmospheric chemistry and physics*, *19*(2), 747–765. https://doi.org/10.5194/acp-2018-482

Gröning, M., Lutz, H. O., Roller-Lutz, Z., Kralik, M., Gourcy, L., & Pöltenstein, L. (2012). A simple rain collector preventing water re-evaporation dedicated for $\delta^{18}O$ and $\delta^{2}H$ analysis of cumulative precipitation samples. *Journal of Hydrology*, *448*, 195–200. https://doi.org/10.1016/j.jhydrol.2012.04.041

Herrera, D., & Ault, T. (2017). Insights from a new high-resolution drought atlas for the Caribbean Spanning 1950–2016. *Journal of Climate*, *30* (19), 7801–7825. https://doi.org/10.1175/JCLI-D-16-0838.1

Hidalgo, H. G., & Alfaro, E. J. (2015). Skill of CMIP5 climate models in reproducing 20th century basic climate features in Central America. *International Journal of Climatology*, *35*(12), 3397–3421. https://doi.org/10.1002/joc.4216

Hoekstra, A. Y . (2018). Global food and trade dimensions of groundwater governance. In *Advances in groundwater governance* (pp. 353–366). United Kingdom: CRC Press.

Houze, R. A., Jr. (2004). Mesoscale convective systems. *Reviews of Geophysics*, *42*(4), RG4003. https://doi.org/10.1029/2004RG000150

Huffman, G., Bolvin, D., Braithwaite, D., Hsu, K., Joyce, R. & Xie, P. (2015). Integrated multi-satellite retrievals for GPM (IMERG), version 4.4. National Aeronautics and Space Administration (NASA), Washington, DC, USA, NASA's Precipitation Process Center.

Hund, S. V., Allen, D. M., Morillas, L., & Johnson, M. S. (2018). Groundwater recharge indicator as tool for decision makers to increase socio-hydrological resilience to seasonal drought. *Journal of Hydrology*, *563*, 1119–1134. https://doi.org/10.1016/j.jhydrol.2018.05.069

IAEA/WMO. (2018) Global network of isotopes in precipitation—the GNIP Database. Retrieved from https://nucleus.iaea.org/wiser

Imbach, P., Chou, S. C., Lyra, A., Rodrigues, D., Rodriguez, D., Latinovic, D., … Georgiou, S. (2018). Future climate change scenarios in Central America at high spatial resolution. *PLoS ONE*, *13*(4), e0193570. https://doi.org/10.1371/journal.pone.0193570

Jasechko, S., & Taylor, R. G. (2015). Intensive rainfall recharges tropical groundwaters. *Environmental Research Letters*, *10*(12), 124015. https://doi.org/10.1088/1748-9326/10/12/124015

Jimenez, J. C., Barichivich, J., Mattar, C., Takahashi, K., Santamaría-Artigas, A., Sobrino, J. A., & Malhi, Y. (2018). Spatio-temporal patterns of thermal anomalies and drought over tropical forests driven by recent extreme climatic anomalies. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *373*(1760), 20170300. https://doi.org/10.1098/rstb.2017.0300

Knutson, T. R., Delworth, T. L., Dixon, K. W., Held, I. M., Lu, J., Ramaswamy, V., … Stouffer, R. J. (2006). Assessment of twentieth–century regional surface temperature trends using the GFDL CM2 coupled models. *Climate*, *19*, 1624–1651. https://doi.org/10.1175/JCLI3709.1

Kong, Y., & Pang, Z. (2016). A positive altitude gradient of isotopes in the precipitation over the Tianshan Mountains: Effects of moisture recycling and sub-cloud evaporation. *Journal of Hydrology*, *542*, 222–230. https://doi.org/10.1016/j.jhydrol.2016.09.007

Kruskal, W. H., & Wallis, W. A. (1952). Use of ranks in one-criterion variance analysis. *Journal of the American Statistical Association*, *47*(260), 583–621. https://doi.org/10.2307/2280779

Lachniet, M. S., Patterson, W. P., Burns, S., Asmerom, Y. and Polyak, V., (2007). Caribbean and Pacific moisture sources on the Isthmus of Panama revealed from stalagmite and surface water δ18O gradients. *Geophysical Research Letters*, *34*(1).

Leeman, W. P., Carr, M. J., & Morris, J. D. (1994). Boron geochemistry of the Central American Volcanic Arc: Constraints on the genesis of subduction-related magmas. *Geochimica et Cosmochimica Acta*, *58*(1), 149–168. https://doi.org/10.1016/0016-7037(94)90453-7

Losilla, M. (2001). *Volcanic aquifers and sustainable development of Central America*. Costa Rica: Editorial Universidad de Costa Rica.

Lyra, A., Imbach, P., Rodriguez, D., Chou, S. C., Georgiou, S., & Garofolo, L. (2017). Projections of climate change impacts on Central America tropical rainforest. *Climatic Change*, *141*(1), 93–105. https://doi.org/10.1007/s10584-016-1790-2

Machado, L. A. T., Rossow, W. B., Guedes, R. L., & Walker, A. W. (1998). Life cycle variations of mesoscale convective systems over the Americas. *Monthly Weather Review*, *126*(6), 1630–1654. https://doi.org/10.1175/1520-0493(1998)126<1630:LCVOMC>2.0.CO;2

Madrigal-Solís, H., Fonseca-Sánchez, A., & Reynolds-Vargas, J. (2017). Hydrogeochemical characterization of Barva and Colima aquifers in the Central Valley of Costa Rica. *Water Technology and Sciences (in Spanish)*, *8*(1), 115–132.

Magaña, V., Amador, J. A., & Medina, S. (1999). The midsummer drought over Mexico and Central America. *Journal of Climate*, *12*(1967), 1577–1588. https://doi.org/10.1175/1520-0442(1999)012<1577:TMDOMA>2.0.CO;2

Maldonado, T., Alfaro, E., Fallas-López, B., & Alvarado, L. (2013). Seasonal prediction of extreme precipitation events and frequency of rainy days over Costa Rica, Central America, using canonical correlation analysis. *Advances in Geosciences*, *33*(33), 41–52. https://doi.org/10.5194/adgeo-33-41-2013

Mapes, B. E., Warner, T. T., Xu, M., & Negri, A. J. (2003). Diurnal patterns of rainfall in northwestern South America. Part I: Observations and context. *Monthly Weather Review*, *131*(5), 799–812. https://doi.org/

10.1175/1520-0493(2003)131<0799:DPORIN>2.0.CO;2

Maurer, E. P., Roby, N., Stewart-Frey, I. T., & Bacon, C. M. (2017). Projected twenty-first-century changes in the Central American mid-summer drought using statistically downscaled climate projections. *Regional Environmental Change*, *17*(8), 2421–2432. https://doi.org/10.1007/s10113-017-1177-6

Munksgaard, N. C., Kurita, N., Sánchez-Murillo, R., Ahmed, N., Araguas, L., Balachew, D. L., … Zwart, C. (2019). Data Descriptor: Daily observations of stable isotope ratios of rainfall in the tropics. *Scientific Reports*, *9*, 14419. https://doi.org/10.1038/s41598-019-50973-9

Muñoz-Jiménez, R., Giraldo-Osorio, J. D., Brenes-Torres, A., Avendaño-Flores, I., Nauditt, A., Hidalgo-Leén, H. G. & Birkel, C. (2019). Spatial and temporal patterns, trends and teleconnection of cumulative rainfall deficits across Central America. *International Journal of Climatology*, *39*(4): 1940–1953. https://doi.org/10.1002/joc.5925

Poveda, G., & Mesa, O. J. (2000). On the existence of Lloró (the rainiest locality on Earth): Enhanced Ocean-land-atmosphere interaction by a low-level jet. *Geophysical Research Letters*, *27*(11), 1675–1678. https://doi.org/10.1029/1999GL006091

R Core Team. (2014). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing.

Ramírez-Leiva, A., Sánchez-Murillo, R., Martínez-Cruz, M., Calderón, H., Esquivel-Hernández, G., Delgado, V., … Soulsby, C. (2017). Stable isotopes evidence of recycled subduction fluids in the hydrothermal/volcanic activity across Nicaragua and Costa Rica. *Journal of Volcanology and Geothermal Research*, *345*, 172–183. https://doi.org/10.1016/j.jvolgeores.2017.08.013

Reynolds, R. W., Smith, T. M., Liu, C., Chelton, D. B., Casey, K. S., & Schlax, M. G. (2007). Daily high-resolution-blended analyses for sea surface temperature. *Journal of Climate*, *20*(22), 5473–5496. https://doi.org/10.1175/2007JCLI1824.1

Sáenz, F., & Durán-Quesada, A. M. (2015). A climatology of low-level wind regimes over Central America using weather type classification approach. *Frontiers in Earth Science*, *3*(15), 1–18. https://doi.org/10.3389/feart.2015.00015

Sak, P. B., Fisher, D. M., Gardner, T. W., Marshall, J. S., & LaFemina, P. C. (2009). Rough crust subduction, forearc kinematics, and Quaternary uplift rates, Costa Rican segment of the Middle American Trench. *Geological Society of America Bulletin*, *121*(7–8), 992–1012. https://doi.org/10.1130/B26237.1

Salamalikis, V., Argiriou, A. A., & Dotsika, E. (2016). Isotopic modeling of the sub-cloud evaporation effect in precipitation. *Science of the Total Environment*, *544*, 1059–1072. https://doi.org/10.1016/j.scitotenv.2015.11.072

Sánchez-Murillo, R., & Birkel, C. (2016). Groundwater recharge mechanisms inferred from isoscapes in a complex tropical mountainous region. *Geophysical Research Letters*, *43*(10), 5060–5069. https://doi.org/10.1002/2016GL068888

Sánchez-Murillo, R., & Durán-Quesada, A. M. (2018). Preface to stable isotopes in hydrological studies in the tropics: Ecohydrological perspectives in a changing climate. *Hydrological Processes*, *33*, 2160–2165. https://doi.org/10.1002/hyp.13305

Sánchez-Murillo, R., Durán-Quesada, A. M., Esquivel-Hernández, G., Rojas-Cantillano, D., Birkel, C., Welsh, K., … Cobb, K. M. (2019). Deciphering key processes controlling rainfall isotopic variability during extreme tropical cyclones. *Nature Communications*, *10*, 4321. https://doi.org/10.1038/s41467-019-12062-3, https://doi.org/10.1038/s41467-019-12062-3

Sánchez-Murillo, R., Esquivel-Hernández, G., Welsh, K., Brooks, E. S., Boll, J., Alfaro-Solís, R., & Valdés-González, J. (2013). Spatial and temporal variation of stable isotopes in precipitation across Costa Rica: An analysis of historic GNIP records. *Open Journal of Modern Hydrology*, *3*(4), 226–240. https://doi.org/10.4236/ojmh.2013.34027

Sánchez-Murillo, R., Birkel, C., Welsh, K., Esquivel-Hernández, G., Corrales-Salazar, J., Boll, J., … Arce-Mesén, R. (2016a). Key drivers controlling stable isotope variations in daily precipitation of Costa Rica: Caribbean Sea versus Eastern Pacific Ocean moisture sources. *Quaternary Science Reviews*, *131*(Part B), 250–261. https://doi.org/10.1016/j.quascirev.2015.08.028

Sánchez-Murillo, R., Esquivel-Hernández, G., Sáenz-Rosales, O., Piedra-Marín, G., Fonseca-Sánchez, A., Madrigal-Solís, H., … Vargas-Víquez, J. A. (2016b). Isotopic composition in precipitation and groundwater in the northern mountainous region of the Central Valley of Costa Rica. *Isotopes in Environmental and Health Studies*, *53*(1), 1–17. https://doi.org/10.1080/10256016.2016.1193503

Schneider, T., Bischoff, T., & Haug, G. H. (2014). Migrations and dynamics of the intertropical convergence zone. *Nature*, *513*(7516), 45–53. https://doi.org/10.1038/nature13636

Sheffield, J., & Wood, E. F. (2008). Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations. *Climate Dynamics*, *31*(1), 79–105. https://doi.org/10.1007/s00382-007-0340-z

Soderberg, K., Good, S. P., O'Connor, M., Wang, L., Ryan, K., Caylor, K. K. (2013). Using atmospheric trajectories to model the isotopic composition of precipitation in central Kenya. *Ecosphere*. *4*(3). http://dx.doi.org/10.1890/ES12-00160.1.

Stein, A. F., Draxler, R. R., Rolph, G. D., Stunder, B. J. B., Cohen, M. D., & Ngan, F. (2015). NOAA's HYSPLIT atmospheric transport and dispersion modeling system. *Bulletin of the American Meteorological Society*, *96*, 2059–2077. https://doi.org/10.1175/BAMS-D-14-00110.1, https://doi.org/10.1175/BAMS-D-14-00110.1

Su, L., Yuan, Z., Fung, J. C. H., & Lau, A. K. H. (2015). A comparison of HYSPLIT backward trajectories generated from two GDAS datasets. *Science of the Total Environment*, *506-507*, 527–537. https://doi.org/10.1016/j.scitotenv.2014.11.072

Taylor, R. G., Scanlon, B., Döll, P., Rodell, M., van Beek, R., Wada, Y., … Treidel, H. (2013). Groundwater and climate change. *Nature Climate Change*, *3*(4), 322–329. https://doi.org/10.1038/nclimate1744

Tellman, E. (2019). Mapping and modeling illicit and clandestine drivers of land use change: Urban expansion in Mexico City and deforestation in Central America (Doctoral dissertation). Arizona State University. Retrieved from https://search.proquest.com/docview/2228222051?pq-origsite=gscholar

Terzer, S., Wassenaar, L. I., Araguás-Araguás, L. J. & Aggarwal, P. K. (2013). Global isoscapes for $\delta^{18}O$ and $\delta^{2}H$ in precipitation: Improved prediction using regionalized climatic regression models. *Hydrology and Earth System Sciences*, *17*, 4713–4728. https://doi.org/10.5194/hess-17-4713-2013,2013

Tobar-López, D., Bonin, M., Andrade, H. J., Pulido, A., & Ibrahim, M. (2019). Deforestation processes in the livestock territory of La Vía Láctea. *Matagalpa*, *Nicaragua*, *Journal of Land Use Science*, *14*(3), 225–241. https://doi.org/10.1080/1747423X.2019.1671907

Van der Zee Arias, A., Van der Zee, J., Meyrat, A., Poveda, C. & Picado, L. (2012). *Estudio de caracterización del Corredor Seco Centroamericano (Países CA-4): Tomo I*. Roma, Italia: FAO.

Villegas, P., Paredes, V., Betancur, T., Taupin, J. D., & Toro, L. E. (2018). Groundwater evolution and mean water age inferred from hydrochemical and isotopic tracers in a tropical confined aquifer. *Hydrological Processes*, *32*, 2158–2175. https://doi.org/10.1002/hyp.13160

Wang, C., & Enfield, D. B. (2001). The tropical Western Hemisphere warm pool. *Geophysical Research Letters*, *28*(8), 1635–1638. https://doi.org/10.1029/2000GL011763

Wassenaar, L. I., Van Wilgenburg, S. L.,Larson, K. and Hobson, K.A. (2009). A groundwater isoscape (δD, δ18O) forMexico. *Journal of GeochemicalExploration*. *102*(3): 123–136.

Waylen, P. R., Caviedes, C. N., & Quesada, M. E. (1996). Interannual variability of monthly precipitation in Costa Rica. *Journal of Climate*, *9*, 2606–2613. https://doi.org/10.1175/1520-0442(1996)009<2606:IVOMPI>2.0.CO;2

Windhorst, D., Waltz, T., Timbe, E., Frede, H. G., & Breuer, L. (2013). Impact of elevation and weather patterns on the isotopic composition of precipitation in a tropical montane rainforest. *Hydrology and Earth System Sciences*, *17*(1), 409–419. https://doi.org/10.5194/hess-17-409-2013

Zuidema, P., Mapes, B., Lin, J., Fairall, C., & Wick, G. (2006). The interaction of clouds and dry air in the eastern tropical Pacific. *Journal of Climate*, *19*(18), 4531–4544. https://doi.org/10.1175/JCLI3836.1

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

How to cite this article: Sánchez-Murillo R, Esquivel-Hernández G, Corrales-Salazar JL, et al. Tracer hydrology of the data-scarce and heterogeneous Central American Isthmus. *Hydrological Processes*. 2020;1–16. https://doi.org/10.1002/hyp.13758