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

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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; water stable isotopes; groundwater recharge processes; water resources management.

1. Introduction

Central America (522,760 km²) is home to ~50 million inhabitants and highly depends on groundwater extraction ($1.9x10^4$ $m^3 yr^{-1}$) as a primary water resource, as a result of the decline in quality and quantity of surface water resources (Ballestero et al., 2007; Hoekstra, 2018; Hund et al., 2018). During the last 100 years, the average surface temperature has increased by 0.5 to 1.0ºC 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 (Hidalgo and Alfaro, 2015; González et al., 2017; Lyra et al., 2017; Imbach et al., 2018). The increasing trend of long-term droughts (> 5 months; Sheffield and 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: 1) a rainfall decrease (10-25%) during the wet season, 2) spatial extension of the area affected by the Mid-Summer Drought (MSD; Magaña et al., 1999; Maldonado et al., 2013; Maurer et al., 2017), and 3) 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 extents from Chiapas (Mexico) to the western part of Costa Rica and western provinces of Panama, also known as the Dry Arch of Panama (van der Zee et al., 2012; Sánchez-Murillo and Birkel, 2016; FAO, 2017). 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 and 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 relative low-cost technique to study the interaction between rainfall inputs and surface/groundwater connectivity in complex tropical landscapes (Sánchez-Murillo and 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. The results are intended to inform governmental institutions in Central America and rise awareness regarding protection and conservation 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 (Taylor et al., 2013; Jasechko and Taylor, 2015; Sánchez-Murillo and Birkel, 2016; Dehaspe et al., 2018; Villegas et al., 2018; Munksgaard et al., 2019).

2.1. Climatic features of Central America

The regional climate can be analyzed in terms of the seasonal influence of four main large-scale circulation patterns: 1) NE trade winds, 2) the latitudinal migration of the Intertropical Convergence Zone (ITCZ), 3) cold continental surges, and 4) direct and indirect influence of tropical cyclones (Waylen et al., 1996, Sáenz and Durán-Quesada, 2015). Those circulation patterns result from complex interactions among structures the North Atlantic Subtropical High (NASH), the Western Hemisphere Warm Pool (WHWP, Wang and Enfield 2001) dynamics, the seasonal migration of the ITCZ (Adam et al., 2016) and the Caribbean Low-Level Jet (CLLJ, Amador 1998; Amador 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 (Fig. 1A) followed by the incursion of the WHWP in the Gulf of Mexico during the summer months (Fig. 1B) and the further intensity decrease and dislocation to the inner Caribbean after September (Fig. 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 (Fig. 1D) with a distinguished zonal flow which supports the development of the Papagayo jet to the Pacific due to wind funneling across the northern Costa Rica plains and the Papagayo gap. The CLLJ primary peak develops during summer (Fig. 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 (Fig. 3D), period in which a southwestern low-level wind flow develops in the Pacific (known as the Choco Jet, Poveda and Mesa, 2000).

Rainfall in the region is defined by the intersection of large-scale circulation patterns and local features and processes in which topography and vegetation cover play a relevant role, resulting in two predominant rainfall maxima, one in May-June and one in 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 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 (Machado et al., 1998; Mapes et al., 2003; Houze, 2004). 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 et al., 2006). These MCSs have a variable life cycle that ranges from short lived (few hours) to long lived (20-24 hours) systems and they are not only relevant for the accumulated rainfall but also form heavy rainfall events. Fuchs et al. (2014) linked the formation of MCS with the ITCZ and with Kelvin waves and traveling 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 et al (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 et al., 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 et al., 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 Caribbean slopes becomes more marked, leading to severe drought in the CADC and heavy rainfall extremes in the Caribbean.

2.2. Geological generalities 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 et al., 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 and 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). The maximum elevation of volcanoes 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, volcanoes 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 et al., 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 et al., 2017), challenges existing models of subsurface water flow paths and storage (Delcamp et al., 2016) in such systems across the isthmus.

3. Methods and Materials

3.1. 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 and 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 controlled by similar mechanisms, which enforce the idea of using regionalized isotope approaches to elucidate dominant hydrological processes to augment effective water resources management.

3.2. Stable isotope datasets

The rainfall stable isotope datasets 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 (Fig. 3A).

The rainfall stable isotope dataset 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) (Fig. 3A).

Similarly, the groundwater and surface water stable isotope datasets 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) (Fig. 3B and 3C). Recent sampling campaigns targeted base flow conditions with the aim of obtaining representative mean annual isotopic values at a high spatial resolution (Sánchez-Murillo and 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 minutes 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.

3.3. Stable isotope analysis

Stable isotope archives from IAEA data sources comprise multiple laboratories, whereby samples were analyzed by Isotope Ratio Mass Spectrometry (IRMS) 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 (CRDS) water isotope analyzer L2120-*i* (Picarro, USA) and a LWIA-45-EP water isotope analyzer (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 analyzer (Los Gatos, USA), and c) at the Water Center for Latin America and the Caribbean (Monterrey, México) using a DLT-100 water isotope analyzer (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 $d\text{-excess}=\delta^{2}H-8\cdot\delta^{18}O$ (Dansgaard, 1954).

3.4. 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 modeled 48 hours 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 et al., 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.

3.5. Central America rainfall isoscape

A Central America rainfall isoscape (in the definition of Bowen et al. 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 $\delta^{2}H$ 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 was 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 and 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 et al. 2010 and Terzer et al. 2013 on the issue), which will require future re-assessments based on longer time series.

3.6. 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=0.32, p-value<0.001, ~ -1.0 ‰ $\delta^{18}O$ per km of elevation with 95% confidence intervals). Since most of Central America´s population (Fig. 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 calculated 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 and Birkel, 2016).

A Kruskal-Wallis non-parametric analysis of variance on ranks (Kruskal and Wallis, 1952) was applied to test if there was stochastically dominance of one group over another regarding $\delta^{18}O$ (‰), $\delta^{2}H$ (‰), *d*-excess (‰), and MRE values. A significant difference was determined (P<0.001) 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<0.05). 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).

4. Results and Discussion

4.1. Regional rainfall isotope variability and moisture transport

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

$$\delta^{18}O = 0.078 \cdot LAT - 0.0023 \cdot ALT - 5.447 \; (R^2 = 0.81, p - value < 0.01) \text{ (Eq. 1)}$$

$$\delta^{2}H = 0.585 \cdot LAT - 0.0174 \cdot ALT - 33.639 \; (R^2 = 0.79, p - value < 0.01) \text{ (Eq. 2)}$$

Mean annual $\delta^{18}O$ in rainfall ranged from -3.65‰ to -12.14‰ across the Central American Isthmus (Fig. 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 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 favored 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 $\delta^{18}O$, with an enriched composition over coastal areas as a result of rainfall forming at lower altitudes and a low-level convergence favored by higher temperatures. The northern portion of the CADC remarkably features more enriched values (as well as higher elevations), associated to water vapor 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 vapor budget during the wet season (Fig. 4B). Overall, as water vapor 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 (Sánchez-Murillo et al., 2016b; Ramírez-Leiva et al., 2017; Esquivel-Hernández et al., 2018).

Recent daily and weekly rainfall isotope measurements resulted in highly significant LMWLs (Fig. 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) (Fig. 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 (Kong and Pang, 2016; Salamalikis et al., 2016; Crawford et al., 2017; Graf et al., 2018), 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-Jimenez et al., 2018).

Figure 5B shows a time series of rainfall isotope during 2017-2018 in Costa Rica, Nicaragua, and Honduras. In general, climate seasonality from dry (Jan-Apr) to wet season (May-December) was characterized by a W-shaped isotopic pattern (Sánchez-Murillo et al., 2019). The latter is in consistency 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 (Fig. 5B). These trends were amplified within the CADC, whereas in the Caribbean domain the isotopic composition was less variable throughout the year. Differences found when comparing $\delta^{18}O$ 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

$\delta^{18}O$ 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.

4.2. 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 $\delta^{18}O$) (Fig. 6A). Similarly, *d*-excess variations indicated a mixture of enhanced moisture recycling (Caribbean Sea-derived moisture) and below cloud fractionation, particularly, in Nicaragua and El Salvador (Fig. 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‰) (Fig. 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 (Fig. 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 $\delta^{18}O$) (Fig. 6C).

4.3. 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 vapor 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=0.32; *p*-value<0.001) (Fig. 7A). Previous studies have reported similar isotopic lapse rates for particular countries in the region (Lachniet et al., 2007; Wassenaar et al., 2009; Sánchez-Murillo et al., 2013; Windhorst et al., 2013; Sánchez-Murillo and Birkel, 2016). 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 and 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 (Fig. 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 8A shows a rainfall to groundwater isotopic diagram to assess groundwater recharge bias (Jasechko and Taylor, 2015; Sánchez-Murillo and 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%) (Fig. 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 favored towards Costa Rica (Fig. 8B).

5. 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 i) sampling gradients to improve isotopic lapse rates, ii) surface water and groundwater sampling during baseflow regimes to characterize mean annual conditions, iii) an urgent groundwater assessment in the CADC, and iv) 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 a) improve the existing isoscape(s), triggering a positive feedback between prediction and observation efforts, b) enhance ongoing forest conservation and land use practices, c) enforce protection laws in critical recharge elevations, and d) guarantee water security and sustainability of ~50 million inhabitants through the incorporation of tracer hydrology insights in modelling assessments and decision making.

Data availability statement

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

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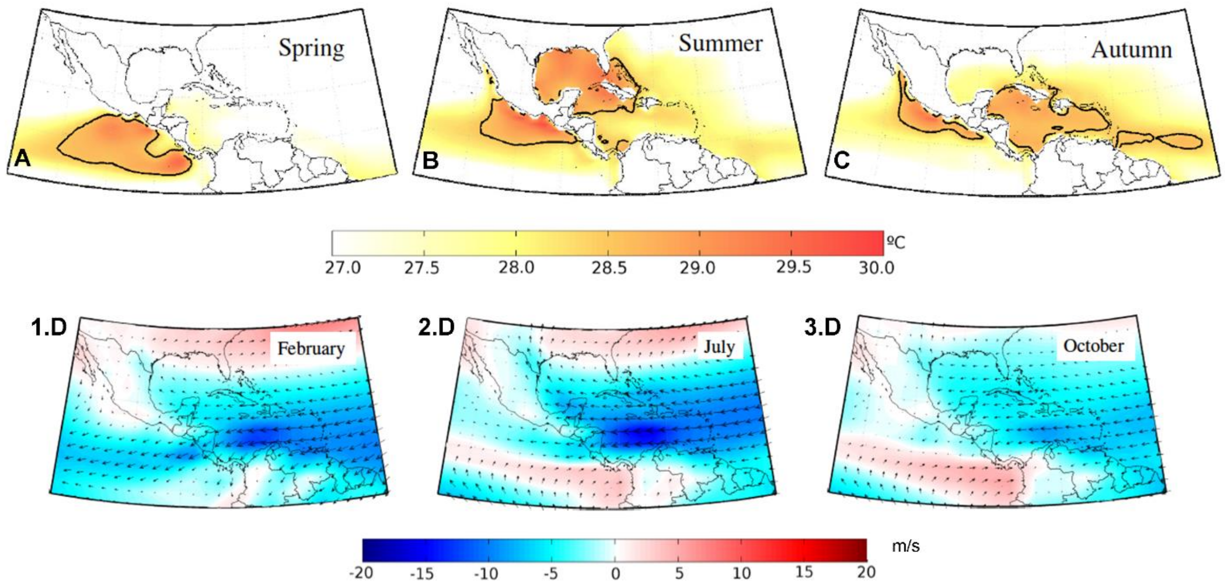

Figure 1: Seasonal variations of key regional climate features: WHWP shown as the area enclose by the SST > 28.5 isotherm based on Optimum Interpolation Sea Surface Temperature (Reynolds et al., 2007) for A) Spring, B) Summer, C) Autumn and D) CLLJ wind speed shaded contour and wind vector at 925hPa 1.D) February, 2.D) July and 3.D) October from ERA Interim (Dee et al., 2011) long term averages (1998-2017).

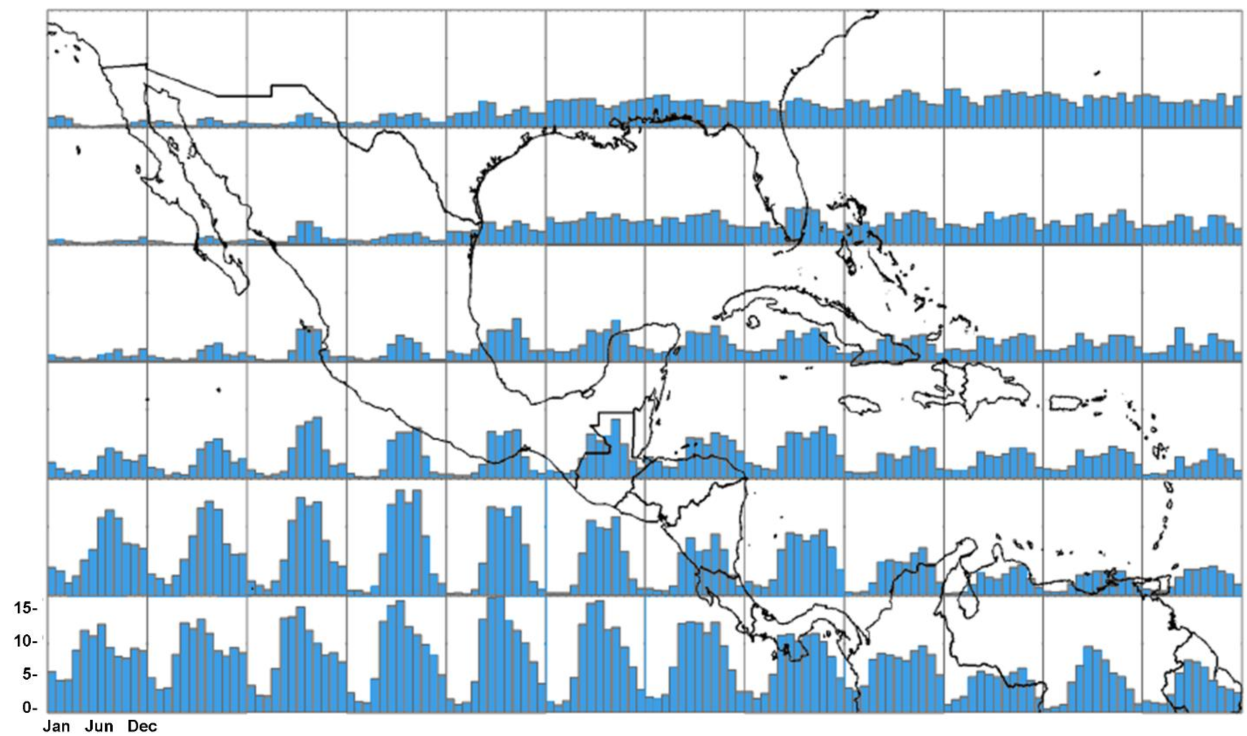

Figure 2: Spatial and temporal distribution of rainfall across the Central American Isthmus. Climatology distribution of monthly mean precipitation (in mm/day) for contiguous 5x5° area boxes for the 1998-2017 period, estimated using the rainfall product 3B43-7 (Huffman et al., 2014)**.**

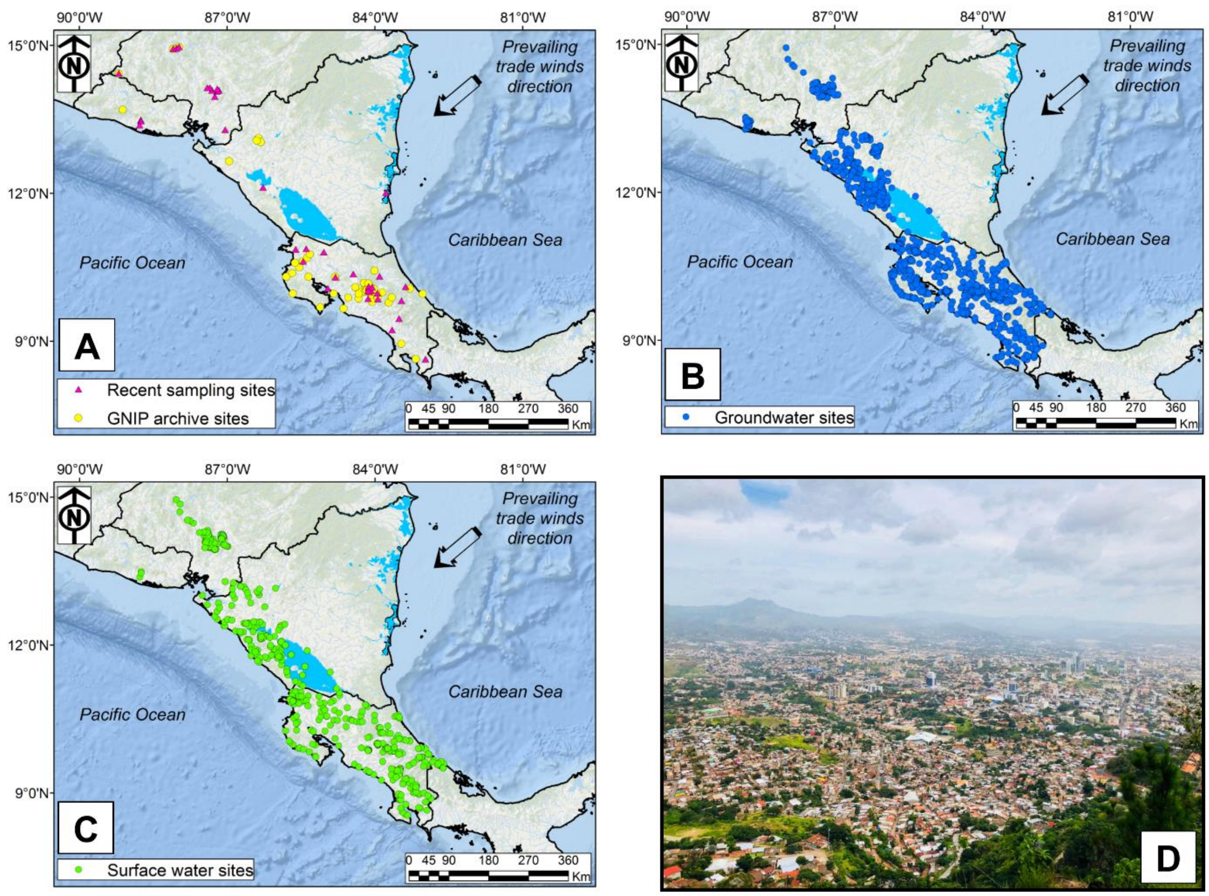

Figure 3: Spatial distribution of rainfall, groundwater, and surface water sampling sites across the Central American Isthmus. A) Recent (2013-2018) rainfall monitoring sites (mostly daily and weekly sampling frequencies; pink triangles) and historical GNIP sites (yellow dots). **B)** Distribution of groundwater sampling sites (blue dots). **C)** Distribution of surface water sampling sites (green dots). **D)** Photograph of the highly populated inter-mountainous city of Tegucigalpa, Honduras (Courtesy of RSM). Most cities within the Pacific slope of Central America share a rapid demographic growth coupled with unregulated urbanization within critical recharge elevations.

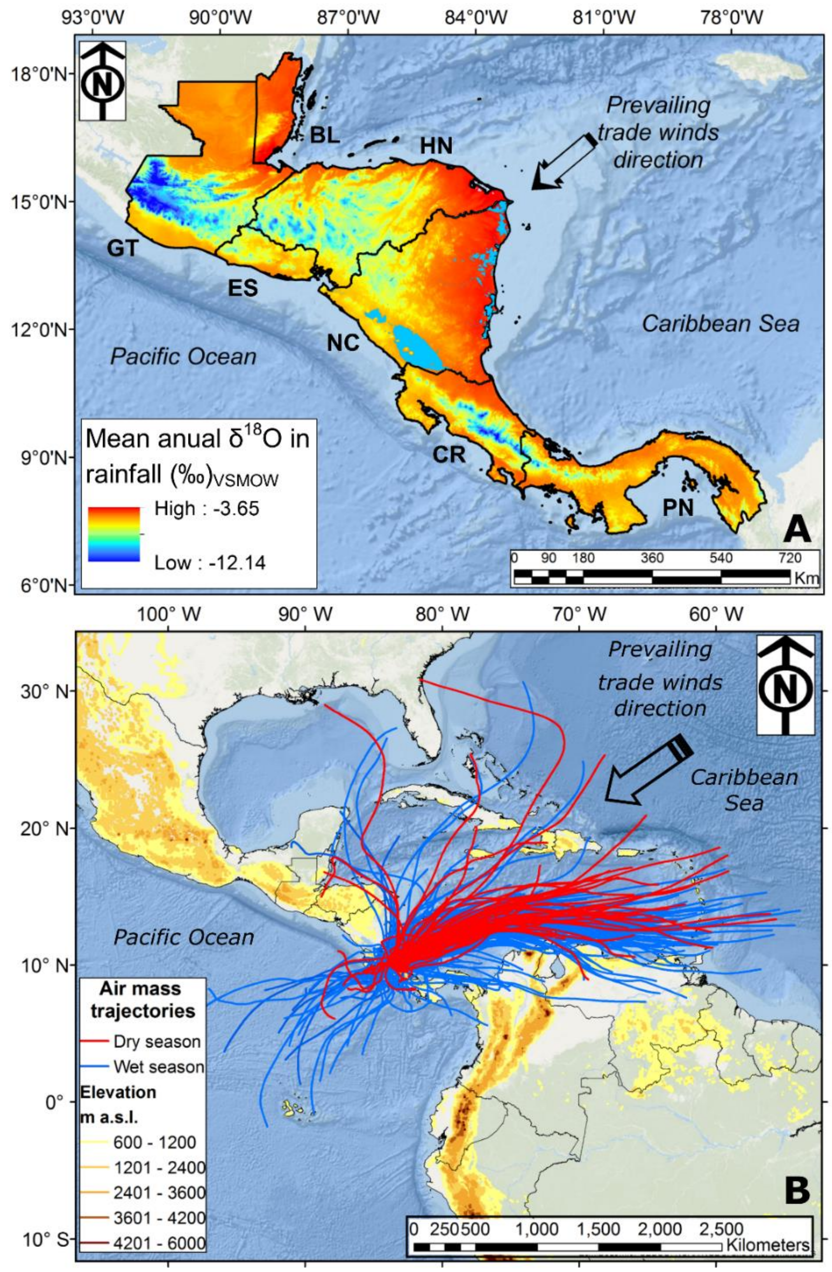

Figure 4: Study area characteristics. A) Regionalized rainfall isoscape within the Central American Isthmus. Mean annual $\delta^{18}O$ (‰) is color coded. **B)** Representative (N=476) dry (red) and wet (blue) seasons 48-hr air mass back trajectories over Costa Rica (2013-2017) using the HYSPLIT Lagrangian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

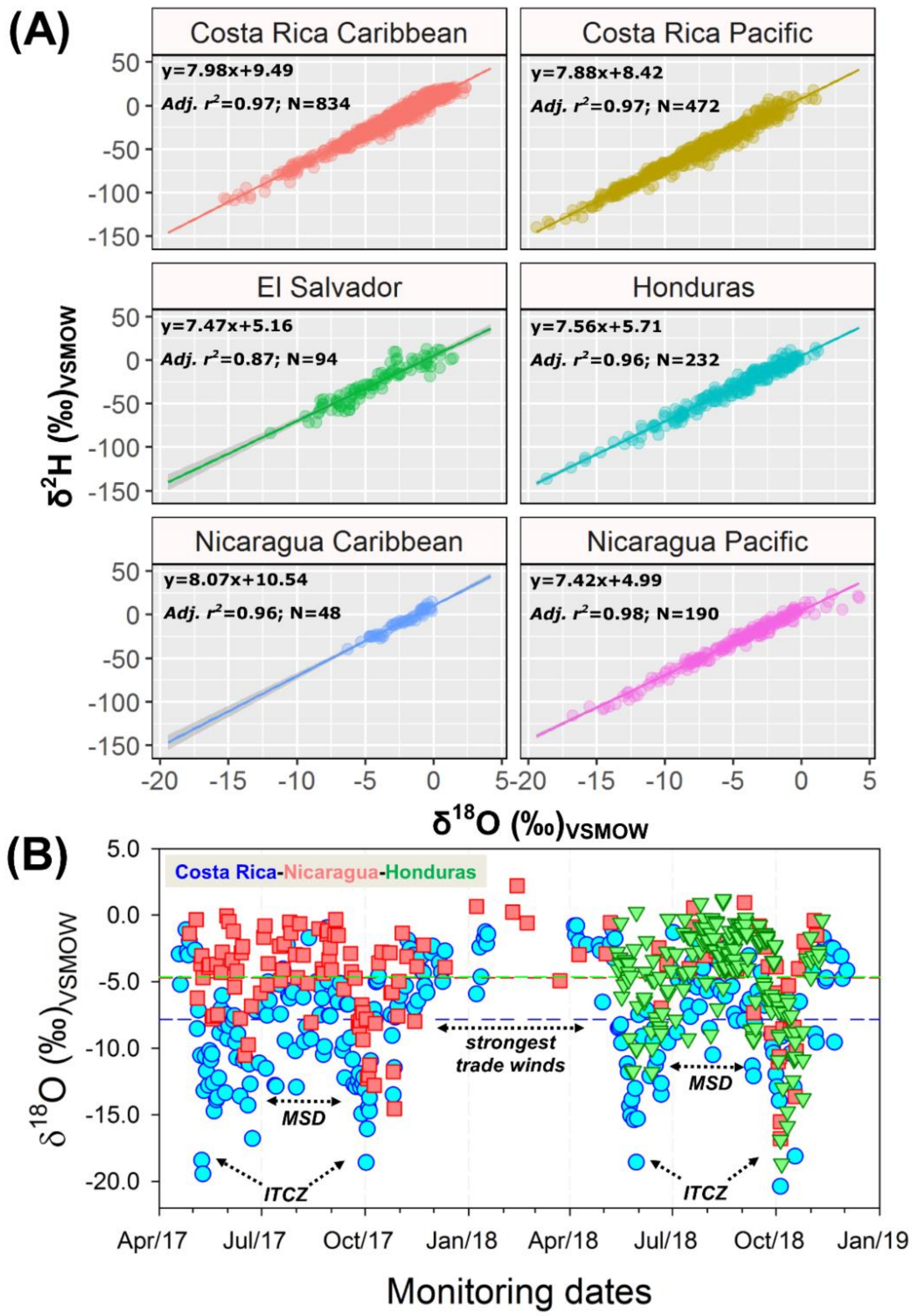

Figure 5: Stable isotope variations of rainfall in Central America. A) Local meteoric water lines (LMWLs) by country and governing rainfall domain (Caribbean versus Pacific). All regressions are significant with a *p*-value <0.001. LMWLs include only recent (2013-2018) isotope measurements (mostly daily and weekly sampling frequencies) for comparison purposes. **B)** $\delta^{18}O$ 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: a) the movement of the ITCZ, b) the MSD, and c) cold fronts during the strongest period of NE trade winds.

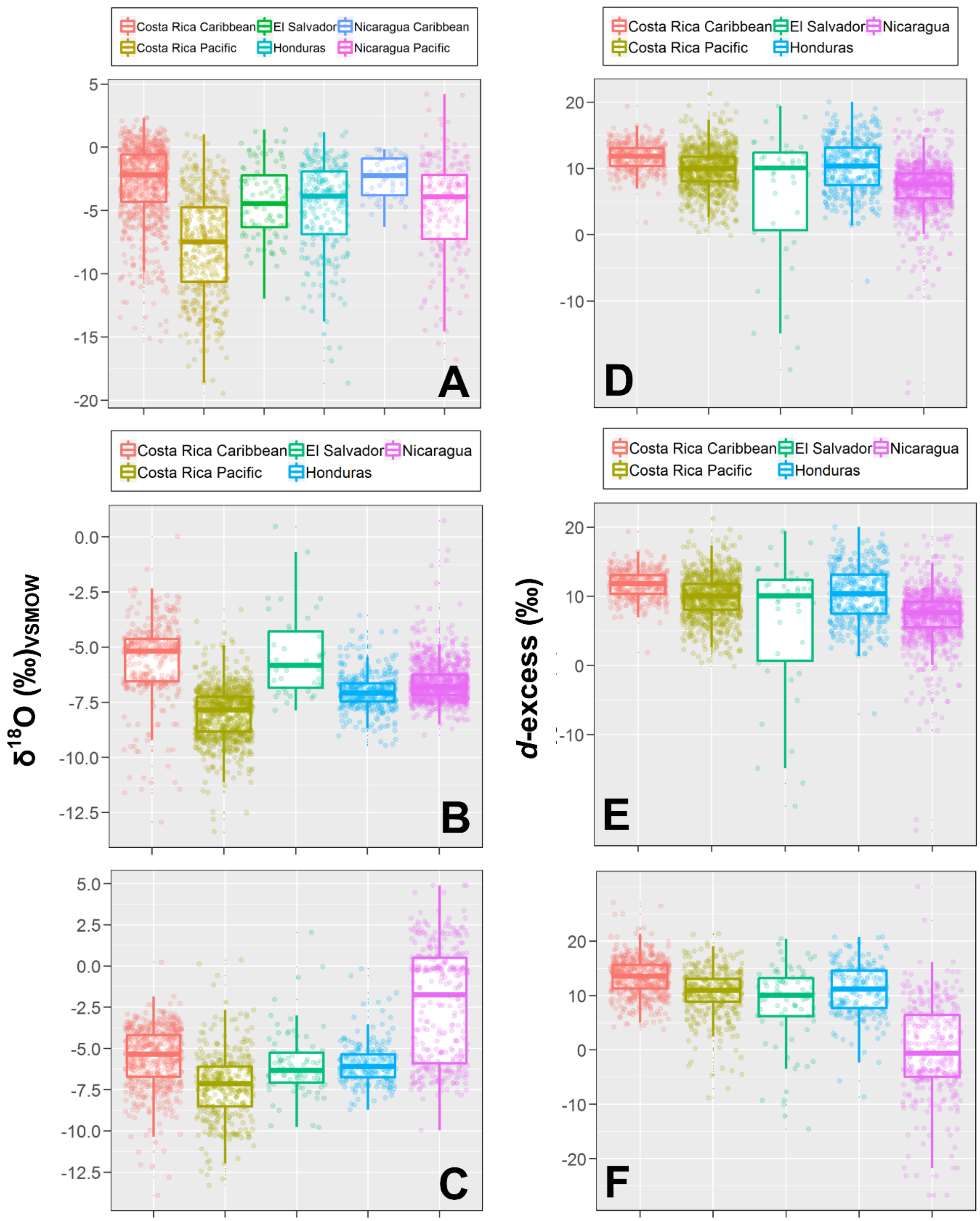

Figure 6: Scattered and box plots showing variations across the Central American Isthmus (ordered by country and governing rainfall domain) of (A-C) $\delta^{18}O$ in rainfall, groundwater, and surface water; and **(D-F)** *d*-excess in rainfall, groundwater, and surface water, respectively. Box plots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

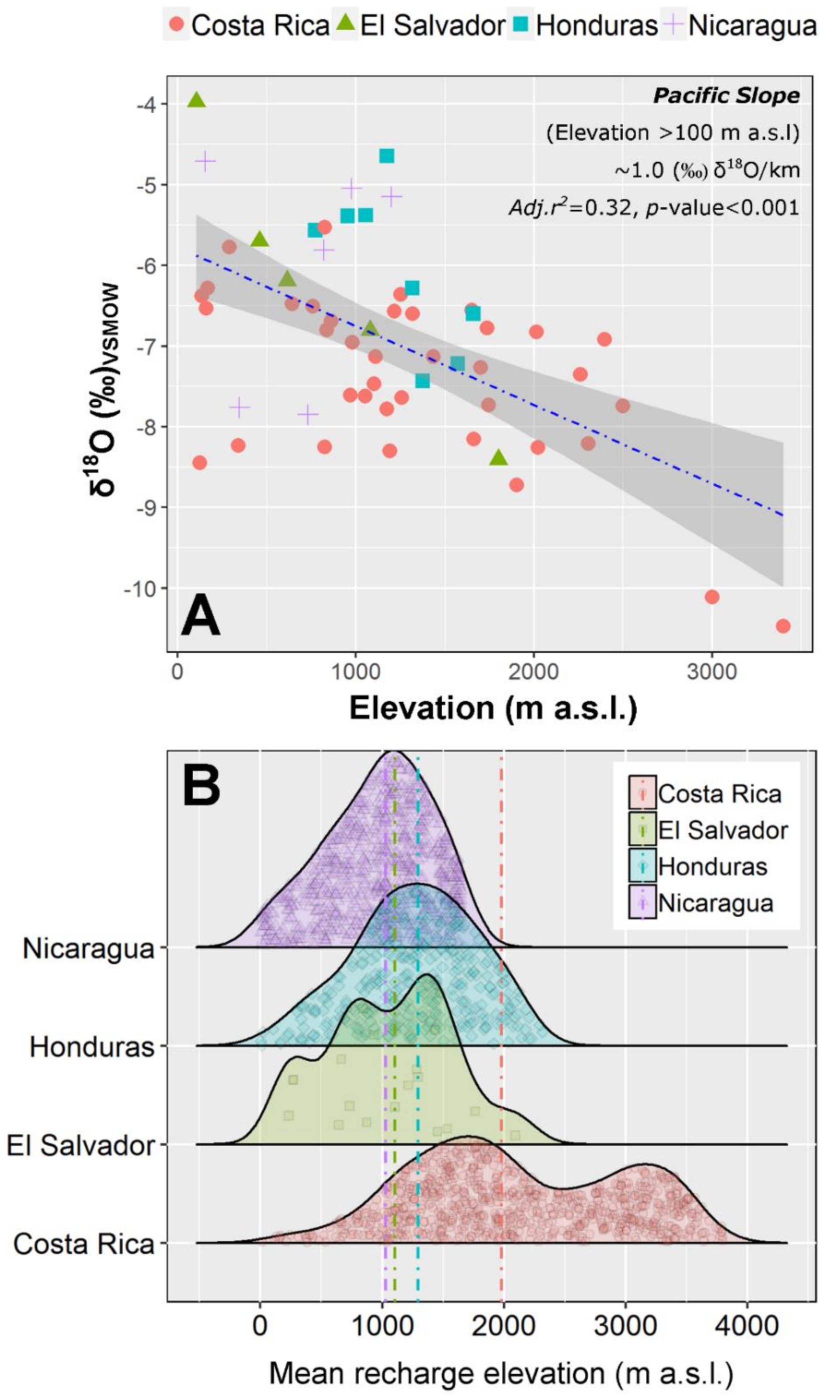

Figure 7: Isotopic lapse rates and potential mean recharge elevations (MRE). A) Regionalized isotopic lapse rate within the Central American Isthmus using monitoring stations above 100 m a.s.l. Blue dashed-line represents the best linear fit resulting in ~ -1‰ $\delta^{18}O$ per km of elevation gradient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

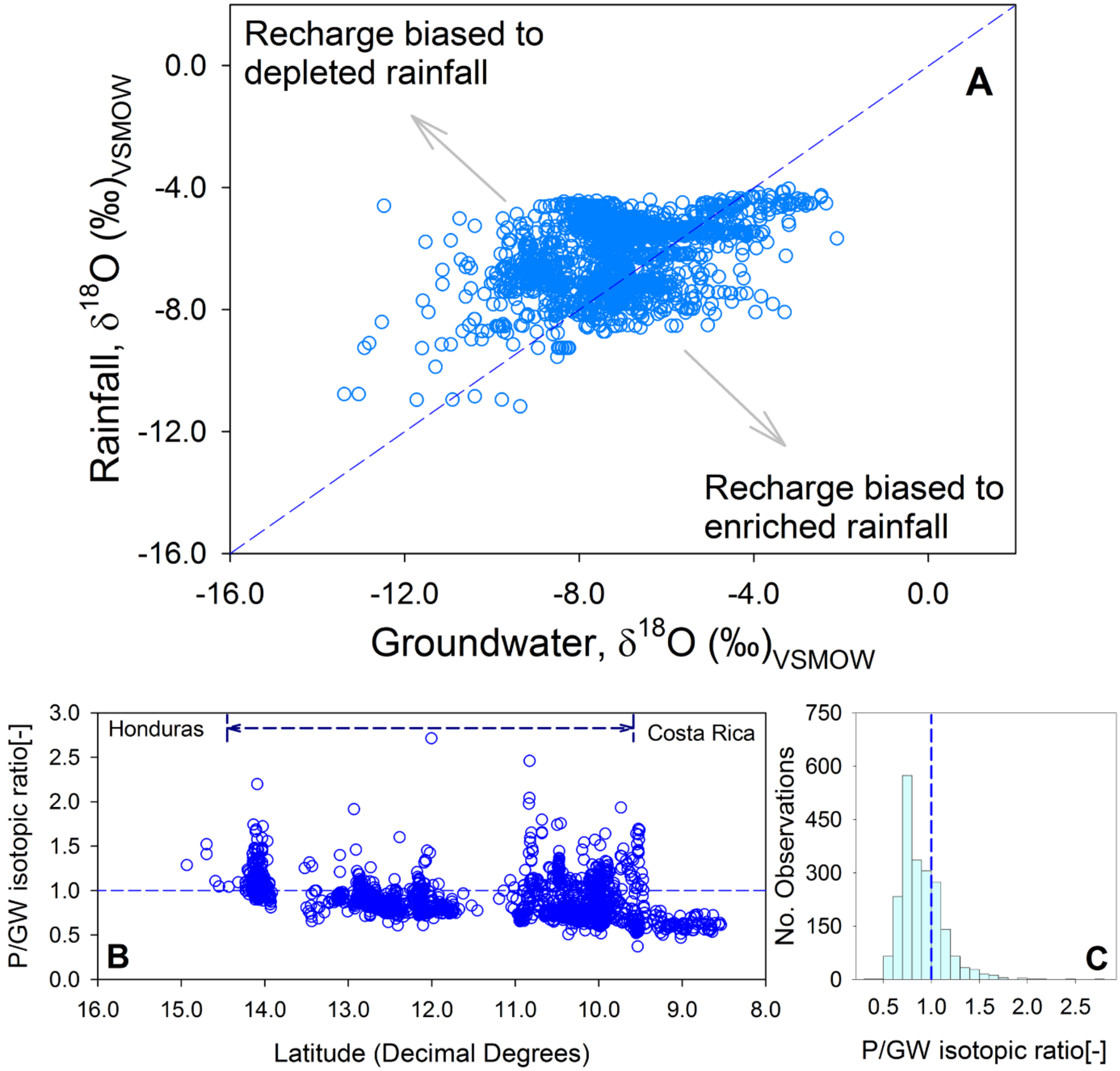

Figure 8: Rainfall and groundwater recharge bias across the Central American Isthmus. A) Rainfall and groundwater recharge bias 1:1 diagram following Jasechko and Taylor (2015). **B)** Latitudinal variation of P/GW isotopic ratios [-] from Costa Rica to Honduras. C) Histogram of P/GW isotopic ratios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