Water stable isotopes reveal groundwater vulnerability to land use fragmentation and climate variability in central Honduras

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Abstract

The inter-mountainous region of central Honduras has been experiencing abrupt urban water shortages during the last decade. Land use fragmentation to increase pasture, crop, and peri-urban areas has rapidly reduced surface water quantity and quality. Here we present a 3-yr (2018-2020) tracer study within the headwaters of the Choluteca River basin (2,949 km^2). We sampled rainfall (weekly N=156; daily N=270), drilled wells (N=166; up to 300 m depth), boreholes (N =70; 4-12 m depth), and springs (N=128) to assess the spatio-temporal connectivity between rainfall and groundwater recharge elevations (MREs). Rainfall isotopic seasonality from the dry to the wet season is characterized by a clear W-shaped pattern. HYSPLIT trajectory analysis reveals three main moisture sources: 73% (east, Caribbean Sea), 17% (southwest, Pacific Ocean), and 10% (north; Gulf of Mexico). Groundwater sources exhibit a strong meteoric origin with a slight evidence of secondary evaporation. MREs range between 813 to 2,130 m asl with a mean value of ~1,600 m asl. Seasonal isotopic variability along with the influence of rapid infiltration limited the MRE method performance as follows: springs (60%), borehole (77%), and drilled wells (93%). Isotope-informed MREs coincide in large degree with coniferous forest, pasture, and crop areas. These results are intended to guide the mapping and delineation of critical recharge areas in central Honduras to enhance water quality and quantity during dry periods.

Keywords: Honduras; water stable isotopes; rainfall; groundwater connectivity; critical recharge zones.

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1. Introduction

Honduras has some of the highest poverty rates in the Latin America and Caribbean region (Mateo, 2021). Out of a total population of 9,523,621 inhabitants (INE, 2021), an estimated 48.3% and 22.9% lived below the national poverty and extreme poverty lines in 2018, respectively (World Bank Group, 2020). It is expected that COVID-19 pandemic and the direct impacts of hurricanes ETA and IOTA may exacerbated the social inequality in a near future (World Bank Group, 2020; Zúñiga-Moya et al., 2020; Durón et al., 2021; Zambrano et al., 2021).

Water availability (in quality and quantity) is one of the most challenging public services in Honduras. Although nearly two thirds of Honduras have access to drinking water, 90% of systems provide only intermittent services (e.g., few hours weekly or biweekly) (Balthasar and Zairis, 2011; Grillos et al., 2021). As a common denominator people have reported being forced to purchase expensive bottled or trucked water during the prolonged dry season (5-7 months, from November to May) (Grillos et al., 2021; Rodríguez-Cruz et al., 2021).

The central region of Tegucigalpa (i.e., Francisco Morazán Department) hosts nearly 18% of the country´s population with a relatively high population density (198.4 inhabitants /km^2) (INE, 2021). This region is characterized by a highly urbanized intra-mountain valley including recent urban settlements across high elevation peri-urban areas. In the past decades, pine bark beetle has triggered the major loss of coniferous forests in central Honduras, decreasing thousands of hectares of pine trees and mixed forests (Valdez et al., 2017). The latter has concatenated a rapid change in land use with an increase in pasture and crops areas which in turn has rapidly reduced surface water quantity and quality (Lee, 2000; Vignola et al., 2015; Blair et al., 2019; Gotlieb et al., 2021). In addition, prolonged El Niño-induced droughts in Central America have reduced the availability of water-in particular for the western inter-mountainous region of the Dry Corridor of Honduras (Vignola et al., 2015a; Quesada-Hernández et al., 2019; Depsky et al., 2020; Olivera et al., 2021; Rodríguez-Cruz et al., 2021). Rainfall deficits are recurrently affecting the volume of the main surface water reservoirs in central Honduras.

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The combination of these factors is increasing illegal groundwater exploitation without a proper scientific baseline regarding the timing, magnitude, and identification of critical recharge areas in central Honduras. Therefore, the main goal of this study was to a) determine the spatio-temporal water isotopes variability (in rainfall, surface, and groundwater) and dominant atmospheric moisture sources and to b) understand the governing recharge mechanisms and mean recharge elevations (MREs) in the headwaters of the Choluteca River basin (in central Honduras). We hypothesized that groundwater recharge is governed by infiltration within the high elevations of the basin and in less degree by urban recharge. Our results highlight basin regions where water infiltration is affected by land use fragmentation as well as critical headwater recharge areas for water protection and conservation under a changing climate.

2. Study Area

The study area comprises the headwaters of the Choluteca River basin, located in the south-central region of Honduras with a total area of 2,949 km^2 (Fig. 1). The basin can be divided into four main sub-basins: Choluteca Alta (1,255 km^2), Guacerique-Grande (723 km^2), Río del Hombre (450 km^2), and Yegüare (524 km^2). The elevation gradient ranges from 541 up to 2,335 m asl.

2.1. Climate generalities

Precipitation in Honduras is mainly influenced by the trade winds (E-W prevailing direction), the Intertropical Convergence Zone (ITCZ), easterly tropical waves, cold front outbreaks, troughs (i.e., low pressure systems), indirect and direct effect of tropical cyclones, and El Niño Southern Oscillation (ENSO) (Westerberg et al., 2009; Alfaro et al., 2018). However, a robust moisture source-sink analysis is still lacking. Figure 2 shows a representative long-term seasonal pattern between the highlands (La Brea station; 1,610 m asl) and the Tegucigalpa valley (UNAH station; 1,063 m asl) within the headwaters of the Choluteca River basin (Fig. 1). The rainfall regime exhibits a common bimodal pattern for the Central America region (Durán-Quesada et al., 2017; Gouirand et al., 2020). Monthly mean rainfall oscillates from 4.6 and 167.4 mm at the urban lowlands (UNAH station) and from 9.0 and 285.0 mm at the highlands (Fig. 2).

The rainy season spans from May to November. Between May and June, rainfall is mainly caused by the entry of Pacific winds which are enhanced by a) the thermal

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gradient between the Pacific Ocean and the continental area of Central American territory and the confluence with the trade winds and b) the migration of the first tropical waves of the year from the Caribbean Sea. In general, a rainfall decrease between July and August is observed as a result of the Mid-summer drought (MSD) (Magaña et al., 1999; Small et al., 2007). The ITCZ influence and the indirect/direct effect of tropical cyclones results in a notable rainfall increase during September and November.

During ENSO´s warm phase a decrease in precipitation is observed during most of the year. Extreme dry spells in the region results in a net rainfall reduction of up to 31%, which is equivalent to about 368 mm of the mean annual precipitation, while during extreme rainy events, annual precipitation can increase by 35% (corresponding to approximately 434 mm). Mean monthly temperature ranges from 17.9°C to 25.8°C, for the rainy and dry seasons, respectively. The mean annual temperature is 22°C, reaching maximum values between March and May. Mean minimum temperature are observed between December and February, ranging from 17.9°C and 18.4°C.

2.2. Lithological outlines

The basin is defined by three groups known as Honduras Group, Valle de Ángeles Group and Padre Miguel Group, including three formations: Río Chiquito, Villanueva and Matagalpa. In the study area, the main outcrops correspond to Valle de Ángeles Group and Padre Miguel Group (Fig. 3). Valle de Ángeles Group (Rogers and O'Conner, 1993; Rogers et al., 2007) comprises the Río Chiquito Formation, which mainly consist of red layers of fine texture; being strata containing shales, limonites, sandstones and some layers of conglomerate of quartz; with a thickness ranging from 400 to 800 meters. On this unit of sedimentary rocks lie some thin layers of volcanic rocks known as the Matagalpa Formation (Williams & McBirney, 1969), which can be described as calc-alkaline lava flows with andesitic and basaltic compositions and minor pyroclastic layers (Barberi et al., 2013).

The Padre Miguel Group covers an area of approximately 70,000 km^2 in Honduras and is well exposed in the headwaters of the Choluteca River basin (Fig. 3) (Garza et al., 2012). This group is described as a silicic volcanic sequence (ca. ~2,000 m thickness) that forms part of the Central American Miocene volcanic arc built on the Chortis continental fragment (McBirney & Williams, 1969; Garza et al., 2012; Barberi et

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al., 2013). The rocks consist of white, red, pink and green rhyolitic, dacitic and andesitic tuffs with quartz, feldspars, sanidine, biotite and lithic crystals of pumice and clasts from the Valle de Ángeles Group and Matagalpa Formation. They also include some sedimentary rocks of volcanic clasts and well stratified ashlar type tuffs. After the deposition of the main ignimbrite rocks, there was a time of relative calm where the environmental conditions allowed the rocks to be altered and weakened, which originated the so-called Lahars. The outcrops of laharic conglomerate materials that are widely distributed in the Tegucigalpa quadrangle consist of highly angular, subangular and rounded clasts of coarse gravel from runoffs, tuffs and clasts from the Valle de Ángeles Group. The deposit is not well sorted and appears chaotically deposited in a paleo-valley in the Valle de Ángeles Group (McBirney & Williams, 1969; Garza et al., 2012; Barberi et al., 2013; Braun et al., 2019).

3. Methods and Materials

3.1. Rainfall collection

We monitored rainfall for stable isotopes analysis using two passive Palmex collectors (weekly collection at Cerro de Hula and El Picacho; N=156) and one in-house passive collector (daily collection at UNAH; N=270) with collection funnels from 13.5 cm to 18.0 cm and high-density polyethylene (HDPE) containers of 2.3 to 3 L, respectively (Gröning et al., 2012) (Fig. 1). Rainfall collectors were installed considering the elevation gradient, rainfall moisture sources, and access for maintenance and protection of the collectors throughout the hydrological year (Supplementary Table S1; García-Santos et al., 2021). It is important to highlight that site accessibility and security conditions within the headwaters of Choluteca River basin impeded rainfall collection at higher elevations (i.e., >1,700 m asl).

3.2. Springs, drilled wells, and boreholes sample collection

We collected samples from groundwater sources during three dry seasons (2018, 2019, and 2020) and during the MSD of 2018. Samples were collected targeting baseflow periods to better represent mean annual recharge and discharge isotopic values (Sánchez-Murillo et al., 2016; Sánchez-Murillo et al., 2020 a,b). Samples were classified as drilled wells (N=166) with depths up to 300 m, boreholes (N =70) with depths between 4 and 12 m and springs (N=128). In total, we sampled 364 water

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sources with a re-sampling rate per source of 29% for springs, 36% for boreholes, and 52% for drilled wells (two or three samples per site). All the samples were collected in HDPE bottles (15 to 30 mL) and stored at 4°C to avoid fractionation (Supplementary Table S2; García-Santos et al., 2021).

3.3. Stable isotopes analysis

Stable isotopes analyses were conducted at the Stable Isotopes Research Group facilities of Universidad Nacional (Heredia, Costa Rica) using a LWIA-45-EP 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 delta notation δ (‰), with reference to the VSMOW-SLAP scale. The long-term analytical uncertainty was ± 0.5 ‰ for $\delta^{2}H$ and ± 0.1 ‰ for $\delta^{18}O$. 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

In Central America, moisture transport often acts as an 'atmospheric bridge' that connects the semi-closed Caribbean Sea basin and the eastern Pacific warm pool (Sánchez-Murillo et al., 2020a,b). Inter-basin moisture transport is largely modulated by the ITCZ, easterly tropical waves, sea surface temperature (SST) variation, and the indirect/direct effect of tropical cyclones. Such interactions exert a large control on rainfall seasonality and distribution (Pan et al., 2018) with variability influenced by ENSO at interannual scales (Yun et al., 2021). In this context, moisture transport was evaluated using the HYSPLIT Lagrangian model (Stein et al., 2015; Rolph et al., 2017). This 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 (start time 12:00 p.m. UTC) were modeled 48 hours backwards in time based on the proximity of the Caribbean Sea and the Pacific Ocean. In total, 270 trajectories (UNAH daily station, Fig.1 and Table S1) were created and further divided by a) seasons (dry: December to April; wet: May to November), b) $\delta^{18}O$ compositions and c) *d*-excess variability.

3.6. Mean recharge elevations (MREs) and rainfall-groundwater connectivity

Critical recharge areas within the headwaters of the Choluteca River basin were evaluated using an isotopic lapse rate under the assumption that groundwater isotope

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ratios under baseflow conditions are representative of mean annual recharge conditions during the wet season (Yamanaka and Tamada, 2017; Sánchez-Murillo et al., 2020a,b). The latter is supported by the amount of rainfall generated in the wet season with respect to the annual volume (UNAH=98%, Cerro de Hula=97%). Mean annual $\delta^{18}O$ compositions were calculated in four stations within the study area: UNAH (-5.50‰), El Picacho (-5.41‰), Cerro de Hula (-7.13‰), and Rincón de Dolores (archive IAEA data; longitude=-87.3997, latitude=14.1401) (-7.42‰), resulting in a significant (r^2=0.82, $p<0.01$) linear regression between 1,063 and 1,643 m asl. A Kruskal-Wallis non-parametric (Kruskal and Wallis, 1952) one way analysis of variance on ranks was conducted to diagnose significant differences among the four sites. The differences in the median values among the sites are greater than would be expected by chance; thus, there is a statistically significant difference ($p<0.001$).

To contextualize the relevance for water resources management of the isotope-inferred MREs within the headwaters of the Choluteca River basin, the most recent land use map (2019) (resolution 10x10 m based on satellite images from the Copernicus Sentinel-2 mission) (https://sentinel.esa.int/web/sentinel/missions/sentinel-2) was obtained from the National Institute of Conservation and Forestry Development (http://www.geoportal.icf.gob.hn/geoportal/main). Land use includes 19 classifications which denote the high degree of land fragmentation within the basin. Statistical and graphical analysis was performed using the open source statistical R language and packages (R Development Core Team, 2021). All maps were developed in ArcGIS 10.5 (ESRI, USA).

4. Results

4.1. Rainfall isotopic variability

At the urban lowlands (UNAH station) $\delta^{18}O$ ranged from -18.67 to +2.13‰, with a mean of -5.11‰; while $\delta^{2}H$ varied from -136.2 to +19.8‰, with a mean of -32.5‰. At El Picacho station $\delta^{18}O$ ranged from -14.91 to +0.39‰ and $\delta^{2}H$ varied from -109.1 to +14.6‰; while at El Cerro de Hula station $\delta^{18}O$ ranged from -20.32 to -0.13‰ and $\delta^{2}H$ values varied from -148.0 to +15.8‰ (Fig. 4A). Climate seasonality from the dry (December-April) to the wet season (May-November) is characterized by a W-shaped isotopic pattern in rainfall (Fig. 4A). The latter is consistent with the intra-seasonal variability of Central America rainfall, that typically result in two or three depleted excursions during the wet season and two enriched pulses during the strongest trade winds period and the MSD. A similar pattern has been reported in Costa Rica, Nicaragua, Veracruz (México), and Guatemala (Wassenaar et al., 2009; Lachniet et al., 2009; Pérez-Quezadas et al., 2015; Sánchez-Murillo and Birkel, 2016; Sánchez-Murillo et al., 2019; Sánchez-Murillo et al., 2020 a,b).

Figure 4B shows the temporal *d*-excess variation in rainfall across the headwaters of Choluteca River basin. Relative high *d*-excess values (>20‰), at El Cerro de Hula and El Picacho stations during dry season months (December to April), indicate moisture recycling and the influence of cold front events from the Gulf of Mexico. After the onset of the rainy season in mid-May, mean *d*-excess varied between 10-15‰ in both high elevation stations (Fig. 4B). However, at the urban lowland *d*-excess values were consistently below 10‰ mainly due to the combination of strong sub-cloud evaporation and high ambient temperatures. Isotope ratios resulted in a highly significant meteoric water line (CBMWL): $\delta^2H=7.77\cdot\delta^{18}O+9.14$ ($Adj.r^2=0.97$; $p<0.001$; N=426) (Fig. 5), in agreement with MWLs within the Pacific slope of Central America (Sánchez-Murillo et al., 2020a).

4.2. Springs, drilled wells, and boreholes isotopic variability

Figure 5 shows a combination of dual-isotope diagrams for springs, drilled wells and boreholes. Overall, all sources exhibited a strong meteoric origin with slight evidences of secondary evaporation. It is important to remark that mean $\delta^{18}O$ for all water sources is within the mean annual rainfall $\delta^{18}O$ compositions: UNAH (-5.50‰), El Picacho (-5.41‰), Cerro de Hula (-7.13‰). In the drilled wells, $\delta^{18}O$ ranged from -9.18 to -3.40‰, with a mean of -7.05±0.69‰ (1σ) (Fig. 5A). At the boreholes, $\delta^{18}O$ values fluctuated between -8.71 and -3.76‰, with a mean value of -6.52±1.02‰ (1σ) (Fig. 5B). Across the spring sites, $\delta^{18}O$ ranged from -9.11‰ to -1.14‰, with a mean of -7.08±1.02‰ (1σ) (Fig. 5C).

4.3. HYSPLIT air mass back trajectories

From 270 air parcel trajectories, 93% (N=250) and 7% (N=20) corresponded to the wet and dry seasons, respectively. Based on the main trajectory direction (quadrangle centered on Tegucigalpa), moisture transport origin can be divided as

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follows: 73% (east; Caribbean Sea), 17% (southwest; Pacific Ocean), and 10% (north; Gulf of Mexico). In the case of δ^{18}O, enriched events between -2.13 and -6.26‰ originated mostly from the Caribbean Sea with some early season events coming from the eastern Pacific Ocean (mainly in April). Depleted events (up to -18.67‰ in δ^{18}O) occurred mainly during the second leg of the rainy season and were originated from the southwest and in less degree from the Caribbean basin during the activation of the cyclonic activity (Fig. 6A). Cold front events from the Gulf of Mexico often result in enriched isotopic light rainfalls (Sánchez-Murillo et al., 2019; Welsh and Sánchez-Murillo, 2020).

Similarly, high *d*-excess rainfall events (>12.64‰) occurred mainly from the northeastern and southwest regions of the Caribbean Sea and Pacific Ocean, respectively. Rainfall events near the mean global *d*-excess value (10‰) were originated mainly from the Caribbean Sea and in less degree from the Pacific Ocean (Fonseca Gulf). Small rainfall events with relative low *d*-excess were indistinctive generated from both oceanic basins (Fig. 6B) and are related to sub-cloud evaporation in the Tegucigalpa valley (Managave et al., 2016; Salamalikis et al., 2016; Xia and Winnick, 2021).

4.4. Mean recharge elevations and rainfall-groundwater connectivity

The isotopic lapse rate resulted in a significant (r^2 = 0.82; p<0.01) slope of -3.6‰ per km of elevation between 1,063 and 1,643 m asl within the headwaters of the Choluteca River basin. Recently Sánchez-Murillo et al. (2020b) reported a pantropical spectrum of isotopic lapse rate ranging from -3.5 to -0.5‰/km, with a pantropical mean of -2.2‰/km. Similarly, Poage and Chamberlain (2001) reported a global isotopic lapse rate of -2.8‰/km. In the study area, MREs ranged between 813 to 2,130 m asl (Fig. 7A) with a mean value near 1,600 m asl (Fig. 7B). The seasonal isotopic variability, and consequently, the impact of near surface infiltration from recent rainfall events limited the inverse recharge elevation calculation. The latter is more evidence in springs 40% (51 sources of 128) and boreholes 23% (16 sources of 70); while the method exhibited a lower rate of invalid calculations in drilled wells with only 7% (12 sources of 166) (Fig. 7A). This result is also consistent with the pattern of water sources along the CBMWL with a greater dispersion in the springs and boreholes than drilled wells (Fig. 5). Drilled-

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wells exhibited a greater damping effect than shallow springs and boreholes (Berman et al., 2009; Dehaspe et al., 2018; Hu et al., 2020).

5. Discussion

5.1. Land use, groundwater recharge processes and critical recharge elevations

Isotope-inferred MREs were divided in five classes within the headwaters of the Choluteca River basin, as follows: (a) 541 to 1,090 m asl, (b) 1,091 to 1,470 m asl, (c) 1,471 to 1,678 m asl, (d) 1,679 to 1,854 m asl, and (e) 1,855 to 2,335 m asl. These classes cover 42%, 38%, 13%, 5%, and 3% of the study area, respectively. Class (a) represents a region with a large prevalence of anthropogenic activities and soil degradation such as pastures and crops (21%), technified agriculture (8%), and urban areas (6%). This class (a) involves one of the most human-altered regions of central Honduras (Vignola et al., 2015); however, MREs indicate a recharge bias towards higher recharge elevations and more depleted events in the basin (Jasechko and Taylor, 2015). The latter is consistent with a previous study across the Pacific slope of the Dry Corridor of Central America (including Honduras), where groundwater recharge was primordially reported in highland areas (72.3%) versus rapid (13.1%) and localized (14.5) recharge (Sánchez-Murillo et al., 2020a).

Class (b) comprises mainly pastures and crops (15.95%) and coniferous forests affected by the pine bark beetle plague (15.22%) (Valdez et al., 2017). In contrast to class (a), this class showed a high incidence of local recharge. Although most of the drilled wells are located in the lowlands (classes and b), the most prominent isotope-inferred MREs were found between 1,471 and 1,854 m asl, corresponding to classes (c) and (d). This highlights the large disproportionality existing between MREs and headwaters dependent systems in tropical regions (Yamanaka and Tamada, 2017; Immerzeel et al., 2020; Sánchez-Murillo et al., 2020 a,b). Class (c) is mainly covered by pine forests affected by the bark beetle plague (19%), pastures and crops (12%), whereas in class (d) the land use is mainly characterized by pastures and crops (13%) and coniferous forest (9%). The isotope-inferred indication of groundwater recharge across the altered coniferous forests may be explained by the devastation produced by the bark beetle plague (~381x10^3 ha in central Honduras; Blair et al., 2019), which may result in less evapotranspiration rates and in a net recharge and runoff increase.

Nevertheless, detailed water balance estimations are still needed to clearly underpin the ecohydrological effects of this forest degradation and the expansion of crop lands across high elevations in the basin. Groundwater recharge over 1,855 m asl (class e) covers only 3% of the study area. This area comprises only a 7% of pastures and crops and is mostly linked to local recharge of springs and boreholes.

6. Conclusions

In Honduras complex interactions of socioeconomic and environmental factors have given rise to a dynamic mosaic of patches of reforestation, deforestation, urban and agricultural expansion (Kammerbauer and Ardon, 1999; Southworth et al., 2004; Munroe et al., 2007; Vignola et al., 2015b). Understanding of groundwater vulnerability to land use changes (i.e., recharge areas and potential contaminant transport) and climate variability (i.e., rainfall deficits and recharge amount) is critical in Central Honduras for the upcoming decades.

Our results indicated a large dependency of Caribbean-type moisture in rainfall events in central Honduras, a moisture transport mechanism often disrupted during the warm ENSO events. The latter results in extreme rainfall deficits, and consequently, in low levels of drinking water reservoirs and groundwater recharge.

Water stable isotope compositions in rainfall, drilled wells, boreholes, and springs (within the headwaters of the Choluteca River basin) revealed a strong connectivity between modern precipitation and groundwater reservoirs. Groundwater isotopic values (during baseflow periods) are within the range of annual mean $\delta^{18}O$ rainfall values in the valley. While groundwater apparent ages are still needed in this basin, these findings suggest a high potential of contaminants, pathogens, and solutes transport from agricultural and urban areas to shallow groundwater reservoirs.

Isotope-inferred mean recharge elevations range between 813 to 2,130 m asl with a mean value of ~1,600 m asl and corresponded with coniferous forests, crop lands, and urban areas. It is important to highlight that the influence of rapid infiltration of isotopic pulses prior and after baseflow periods (i.e., large rainfall events during the two peaks of the rainy season) limited the performance of inverse elevation calculations as follows: springs (60%), borehole (77%), and drilled wells (93%). Drilled wells (up to 300 m depth) denote well-mixed water and -in general- are more representative of the

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mean annual isotopic recharge composition. High elevation and shallow springs and boreholes are more susceptible to flashy recharge responses, which in turn may bias recharge elevation estimates based on annual isotopic lapse rates.

Our results are intended to enhance the delineation and mapping of critical recharge areas in the dense populated (198.4 inhabitants /km^2; INE, 2021) headwater basin of the Choluteca River. Conservation enforcement, municipal land use regulations, and groundwater extraction permits should be based on a strong scientific background that guarantees water quality and quantity within the large spectrum of climate events that Central Americas has been experiencing in the last decade.

Data availability statement

Our database is available at http://www.hydroshare.org/resource/99b6f970a56740be9b7d6204aeca0553 (García-Santos et al., 2021). CUAHSI´s hydrological repository Hydroshare (https://www.hydroshare.org/) is an online platform to share data, models, and code.

Credit author statement

SG-S, RS-M, and TP-P conceptualize the sampling strategies. SG-S, MC-E, and JH-O conducted all field sampling campaigns. Stable isotopes analysis was conducted by RS-M and SG-S. Isotope data was curated by RS-M. SG-S, RS-M, and JM-E initiated the manuscript. All co-authors contributed to the final manuscript version.

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References

1. Alfaro, E.J., Hidalgo, H.G. and Pérez-Briceño, P.M., 2018. Mapping Environmental and Socioeconomic impacts of hydrometeorological hazards across Central America. Study case: Honduras. Revista de Política Económica, 3(1): 20-43. https://doi.org/10.15359/peds.3-1.2
2. Balthasar, C.M. and Aida, Z., 2011. Insufficient water supply in an urban area-case study: Tegucigalpa, Honduras (Doctoral dissertation, KTH Royal Institute of Technology).
3. Barberi, F., Carapezza, M.L., Cioni, R., et al., 2013. New geochemical investigations in Platanares and Azacualpa geothermal sites (Honduras). Journal of volcanology and geothermal research, 257: 113-134. https://doi.org/10.1016/j.jvolgeores.2013.03.011
4. Berman, E.S., Gupta, M., Gabrielli, C., Garland, T. and McDonnell, J.J., 2009. High-frequency field-deployable isotope analyzer for hydrological applications. Water Resources Research, 45(10). https://doi.org/10.1029/2009WR008265
5. Braun A., Garcia Urquia E.L., Moncada Lopez R., Yamagishi H., 2019. Landslide Susceptibility Mapping in Tegucigalpa, Honduras, Using Data Mining Methods. In: Shakoor A., Cato K. (eds) IAEG/AEG Annual Meeting Proceedings, San Francisco, California, 2018 - Volume 1. Springer, Cham. https://doi.org/10.1007/978-3-319-93124-1_25
6. Blair, M.A., Ortiz, P., Argueta, M. and Romero, L., 2019. Water Quality in Honduras. Water Quality in the Americas, p.385.
7. David Ellison, Cindy E. Morris, Bruno Locatelli, et al., 2017. Trees, forests and water: cool insights for a hot world. Global Environmental Change, 43: 51-61. https://doi.org/10.1016/j.gloenvcha.2017.01.002
8. Dehaspe, J., Birkel, C., Tetzlaff, D., et al., 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
9. Depsky, N. and Pons, D., 2020. Meteorological droughts are projected to worsen in Central America's Dry Corridor throughout the 21st century. Environmental Research Letters, 16(1): 014001. https://doi.org/10.1088/1748-9326/abc5e2
10. Durán-Quesada, A.M., Gimeno, L. and 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
11. Durón, R.M., Sánchez, E., Choi, J.N., et al., 2021. Honduras: two hurricanes, COVID-19, dengue and the need for a new digital health surveillance system. Journal of Public Health, 43(2): e297-e298. https://doi.org/10.1093/pubmed/fdaa266
12. García-Santos, S., R. Sánchez-Murillo, T. Peña-Paz., 2021. Water stable isotopes database in Central Honduras, HydroShare, https://doi.org/10.4211/hs.99b6f970a56740be9b7d6204aeca0553
13. Garza, R.S.M., van Hinsbergen, D.J., Rogers, R.D., et al., 2012. The Padre Miguel Ignimbrite Suite, central Honduras: paleomagnetism, geochronology, and tectonic implications. Tectonophysics, 574: 144-157. https://doi.org/10.1016/j.tecto.2012.08.013

Electronic copy available at: https://ssrn.com/abstract=3994615

14. Gotlieb, Y. and Girón, J.D.G., 2020. The role of land use conversion in shaping the land cover of the Central American Dry Corridor. Land Use Policy, 94: 104351. https://doi.org/10.1016/j.landusepol.2019.104351
15. Gouirand, I., Moron, V. and Sing, B., 2020. Seasonal atmospheric transitions in the Caribbean basin and Central America. Climate Dynamics, 55(7): 1809-1828. https://doi.org/10.1007/s00382-020-05356-6
16. Gröning, M., Lutz, H.O., Roller-Lutz, Z., Kralik, M., Gourcy, L. and Pöltenstein, L., 2012. A simple rain collector preventing water re-evaporation dedicated for δ18O and δ^2H analysis of cumulative precipitation samples. Journal of Hydrology, 448: 195-200. https://doi.org/10.1016/j.jhydrol.2012.04.041
17. Grillos, T., Zarychta, A. and Nuñez, J.N., 2021. Water scarcity & procedural justice in Honduras: Community-based management meets market-based policy. World Development, 142: 105451. https://doi.org/10.1016/j.worlddev.2021.105451
18. Harvey, W.J., Petrokofsky, G., Stansell, N., et al., 2021. Forests, water, and land use change across the Central American Isthmus: mapping the evidence base for terrestrial Holocene paleo-environmental proxies. Forests 12 (8): 1057. https://doi.org/10.3390/f12081057
19. Hu, Y., Liu, Z., Ford, D., et al., 2020. Conservation of oxygen and hydrogen seasonal isotopic signals in meteoric precipitation in groundwater: an experimental tank study of the effects of land cover in a summer monsoon climate. Geochimica et Cosmochimica Acta, 284: 254-272. https://doi.org/10.1016/j.gca.2020.06.032
20. INE. Instituto Nacional de Estadística. [National Statistics Institute]. 2021. https://www.ine.gob.hn/V3/. Accessed on December 18, 2021.
21. Jasechko, S. and 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
22. Kammerbauer, J. and Ardon, C., 1999. Land use dynamics and landscape change pattern in a typical watershed in the hillside region of central Honduras. Agriculture, ecosystems & environment, 75(1-2): 93-100. https://doi.org/10.1016/S0167-8809(99)00071-7
23. Kruskal, W.H. and Wallis, W.A., 1952. Use of ranks in one-criterion variance analysis. Journal of the American statistical Association, 47(260): 583-621.
24. Lachniet, M.S. and Patterson, W.P., 2009. Oxygen isotope values of precipitation and surface waters in northern Central America (Belize and Guatemala) are dominated by temperature and amount effects. Earth and Planetary Science Letters, 284(3-4): 435-446. https://doi.org/10.1016/j.epsl.2009.05.010
25. Lee, M.D., 2000. Watershed protection challenges in rapidly urbanizing regions: The case of Tegucigalpa, Honduras. Water International, 25(2): 214-221. https://doi.org/10.1080/02508060008686821
26. Magaña, V., Amador, J. A., & Medina, S., 1999. The midsummer drought over Mexico and Central America. Journal of Climate, 12(6), 1577-1588. https://doi.org/10.1175/1520-0442(1999)012<1577:TMDOMA>2.0.CO;2
27. Managave, S.R., Jani, R.A., Rao, T.N., et al., 2016. Intra-event isotope and raindrop size data of tropical rain reveal effects concealed by event averaged

Electronic copy available at: https://ssrn.com/abstract=3994615

data. Climate Dynamics, 47(3): 981-987. https://doi.org/10.1007/s00382-015-2884-7

28. Mateo, Joanna. Chapter 4. Street Gangs of Honduras. Maras: Gang Violence and Security in Central America, New York, USA: University of Texas Press, 2021, pp. 87-104. https://doi.org/10.7560/728608-006.

29. McBirney, A. R., & Williams, H., 1969. Geology and petrology of the Galapagos Islands (Vol. 118). Geological Society of America.

30. Munroe, D.K., Nagendra, H. and Southworth, J., 2007. Monitoring landscape fragmentation in an inaccessible mountain area: Celaque National Park, Western Honduras. Landscape and urban planning, 83(2-3): 154-167. https://doi.org/10.1016/j.landurbplan.2007.04.001

31. Olivera, S., Fuerte-Celis, MDP., Bolaños, B., 2021. Drought: the silent harm of migration from Central America during the period 1990 to 2019. Preprints 2021, 2021060612. doi: 10.20944/preprints202106.0612.v1.

32. Pan, Y., Zeng, N., Mariotti, A., Wang, H., et al., 2018. Covariability of Central America/Mexico winter precipitation and tropical sea surface temperatures. Climate Dynamics. 50(11-12): 4335-4346.https://doi.org/10.1007/s00382-017-3878-4

33. Pérez Quezadas, J., Cortés Silva, A., Inguaggiato, S., et al., 2015. Meteoric isotopic gradient on the windward side of the Sierra Madre Oriental area, Veracruz-Mexico. Geofísica internacional, 54(3): 267-276. https://doi.org/10.1016/j.gi.2015.04.021

34. Poage, M.A. and Chamberlain, C.P., 2001. Empirical relationships between elevation and the stable isotope composition of precipitation and surface waters: considerations for studies of paleoelevation change. American Journal of Science, 301(1): 1-15. https://doi.org/10.2475/ajs.301.1.1

35. Quesada-Hernández, L.E., Calvo-Solano, O.D., Hidalgo, H.G., et al., 2019. Dynamical delimitation of the Central American Dry Corridor (CADC) using drought indices and aridity values. Progress in Physical Geography: Earth and Environment, 43(5): 627-642. https://doi.org/10.1177/0309133319860224

36. Rodríguez Cruz, G.O., 2021. Escasez de agua en Tegucigalpa, Honduras: ¿Está siendo afectada la subcuenca Guacerique por la variabilidad climática y el arrastre de sedimentos? [Water shortages in Tegucigalpa, Honduras: Is the Guacerique sub-basin being affected by climatic variability and sedimentation? Revista de Ciencias Ambientales, 55(1): 118-136. http://dx.doi.org/10.15359/rca.55-1.6

37. Rolph, G., Stein, A., Stunder, B., 2017. Real-time environmental applications and display system: READY. Environmental Modelling & Software, 95, 210-228. https://doi.org/10.1016/j.envsoft.2017.06.025

38. Rogers, R.D. and E.A. O'Conner., 1993. Mapa Geológico de Honduras: Hoja de Tegucigalpa (segunda edición). [Geological Map of Honduras]. Instituto Geográfico Nacional, Tegucigalpa, Honduras. 1:50,000

39. Rogers, R.D., P. Mann, P. Emmet, M. Venable., 2007. Colon fold-thrust belt of Honduras: Evidence for late Cretaceous collision between the continental Chortis block in P. Mann (ed) GSA Special Paper 428: Geologic and Tectonic

Development of the Caribbean Plate in Northern Central America, Geological Society of America Special Paper 428, p. 129-150.

40. Salamalikis, V., Argiriou, A.A. and 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

41. Sánchez-Murillo, R. and 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

42. Sánchez-Murillo, R., Durán-Quesada, A.M., Esquivel-Hernández, G. et al., 2019. Deciphering key processes controlling rainfall isotopic variability during extreme tropical cyclones. Nat. Commun. 10: 4321. https://doi.org/10.1038/s41467-019-12062-3

43. Sánchez-Murillo, R, Esquivel-Hernández, G, Corrales-Salazar, JL, et al., 2020a. Tracer hydrology of the data-scarce and heterogeneous Central American Isthmus. Hydrological Processes. 34: 2660–2675. https://doi.org/10.1002/hyp.13758

44. Sánchez-Murillo, R., Esquivel-Hernández, G., Birkel, C., et al., 2020b. Tracing water sources and fluxes in a dynamic tropical environment: from observations to modeling. Frontiers in Earth Science, 8:571477. https://doi.org/10.3389/feart.2020.571477

45. Small, R.J., De Szoeke, S.P., Xie, S.P., 2007. The Central American midsummer drought: regional aspects and large-scale forcing. Journal of Climate. (19):4853-73. https://doi.org/10.1175/JCLI4261.1

46. Soderberg, K., Good, S. P., O'Connor, M., et al., 2013. Using atmospheric trajectories to model the isotopic composition of rainfall in central Kenya. Ecosphere, 4(3), 1-18. https://doi.org/10.1890/ES12-00160.1

47. Southworth, J., Munroe, D., Nagendra, H., 2004. Land cover change and landscape fragmentation—comparing the utility of continuous and discrete analyses for a western Honduras region. Agriculture, ecosystems & environment, 101(2-3): 185-205. https://doi.org/10.1016/j.agee.2003.09.011

48. Stein, A. F., Draxler, R. R., Rolph, G. D., et al., 2015. NOAA's HYSPLIT atmospheric transport and dispersion modeling system. Bulletin of the American Meteorological Society, 96(12), 2059-2077. https://doi.org/10.1175/BAMS-D-14-00110.1

49. Valdez, M.C., Chang, K.T., Chen, C.F., Chiang, S.H. and Santos, J.L., 2017. Modelling the spatial variability of wildfire susceptibility in Honduras using remote sensing and geographical information systems. Geomatics, Natural Hazards and Risk, 8(2): 876-892. https://doi.org/10.1080/19475705.2016.1278404

50. Vignola, R., Proctor, A., McDaniels, T., et al., 2015a. Honduras: Changing Land Use Today for a More Resilient Tomorrow. Accessed on December 18, 2021

51. Vignola, R., Finegan, B., Díaz Briones, A.A., et al., 2015b. Honduras: The case of drinking water supply in Tegucigalpa. Accessed on December 18, 2021

52. Wassenaar, L.I., Van Wilgenburg, S.L., Larson, K. and Hobson, K.A., 2009. A groundwater isoscape (δD, $\delta^{18}O$) for Mexico. Journal of Geochemical Exploration, 102(3): 123-136. https://doi.org/10.1016/j.gexplo.2009.01.001

Electronic copy available at: https://ssrn.com/abstract=3994615

53. Welsh, K. and Sánchez-Murillo, R., 2020. Rainfall, groundwater, and surface water isotope data from extreme tropical cyclones (2016-2019) within the Caribbean Sea and Atlantic Ocean basins. Data in Brief, 30, 105633. https://doi.org/10.1016/j.dib.2020.105633

54. World Bank Group., 2020. Latin America and the Caribbean. www.povertydata.worldbank.org Accessed on December 18, 2021

55. Xia, Z. and Winnick, M.J., 2021. The competing effects of terrestrial evapotranspiration and raindrop re-evaporation on the deuterium excess of continental precipitation. Earth and Planetary Science Letters, 572: 117120. https://doi.org/10.1016/j.epsl.2021.117120

56. Yaping L, Yamanaka T., 2012.Tracing groundwater recharge sources in a mountain–plain transitional area using stable isotopes and hydrochemistry, Journal of Hydrology. 464–465: 116-126- https://doi.org/10.1016/j.jhydrol.2012.06.053.

57. Yamanaka, T. and Yamada, Y., 2017. Regional Assessment of Recharge Elevation of Tap Water Sources Using the Isoscape Approach. Mountain research and development. 37(2): 198-205. https://doi.org/10.1659/MRD-JOURNAL-D-16-00066.1

58. Yun, K.S., Lee, J.Y., Timmermann, A., et al., 2021. Increasing ENSO–rainfall variability due to changes in future tropical temperature–rainfall relationship. Communications Earth & Environment, 2(1): 1-7. https://doi.org/10.1038/s43247-021-00108-8

59. Zambrano, L.I., Fuentes-Barahona, I.C., Henriquez-Marquez, K.I. et al., 2021. COVID-19 and Hurricanes: the impact of natural disasters during a pandemic in Honduras, Central America. Prehospital and Disaster Medicine, 36(2): 246-248. https://doi.org/10.1017/S1049023X21000182

60. Zúñiga-Moya, J.C., Norwood, D.A., Romero Reyes, L.E. et al., 2020. Epidemiology, outcomes and associated factors of COVID-19 RT-PCR confirmed cases in the San Pedro Sula Metropolitan Area, Honduras. Clinical Infectious Diseases. 72 (10): e476–e483, https://doi.org/10.1093/cid/ciaa1188

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Figure 1: Study area within the upper basin (headwaters) of the Choluteca River (dark green polygon). Elevation gradient is color-coded in a gray-scale (from 541 to 2,335 m asl). Sampled water sources for stable isotopes analysis are color and symbol-coded: springs (cyan triangles), boreholes (orange squares), drilled wells (red circles), and rainfall (purple crosses). La Brea (upper basin; orange cross) and UNAH (lower basin; purple cross) meteorological stations are included for reference. Main streams are represented by blue lines. The inset shows the location of the Choluteca River basin in Honduras and the Central America Isthmus.

Figure 2: Monthly rainfall seasonality between the upper (La Brea station; 1,610 m asl; blue bars) and lower (UNAH station; 1,063 m asl; pink bars) basin areas. Long-term (La Brea: 1976-2012; UNAH: 1979-2019) standard deviations are denoted by crossed bars.

Figure 3: Major lithological features within the headwaters of the Choluteca River

Figure 4: Monthly $\delta^{18}O$ (‰) (A) and deuterium excess (‰) (B) variability at three rainfall monitoring stations (Cerro de Hula, El Picacho, and UNAH) across the headwaters of the Choluteca River basin from 2018 to 2020 (daily, N=270 and weekly, N=156). Black arrows represent five main climatic features: E-W trade winds, easterly waves, MSD, tropical cyclones season and ITCZ activation.

Figure 5: Dual isotope diagrams including: drilled wells (A), boreholes (B), and springs (C). Rainfall mean values at UNAH (daily), El Picacho and El Cerro de Hula (weekly) are denoted by color-coded circles and bi-directional error bars. Grey crosses represent the rainfall isotopic variability within the Choluteca River basin (CBMWL; gray line). The GMWL (pink line) is included as reference.

Figure 6: HYSPLIT air mass back trajectories (48 hours backwards) coded by $\delta^{18}O$ (‰) (A) and *d*-excess (‰) in daily rainfall at Tegucigalpa, Honduras (black star) (2018-2020; N=270).

Figure 7: (A) Map of potential recharge elevations within the headwaters of the Choluteca River basin. The background shows a color-coded digital elevation map from 541 to 2,335 m asl. Color-coded circles denote groundwater samples (springs, N=128; drilled wells, N=166; and boreholes, N=70) with resolved elevations from a basin-wide isotopic lapse rate. Grey circles represent sites where large seasonal variability limited the inverse recharge elevation calculation. (B) Mean recharge elevation histogram.

Figure 8: Land use types within the headwaters of the Choluteca River basin in 2019. The Institute of Conservation and Forestry Development (Tegucigalpa, Honduras) defined 19 classifications which denote the high degree of land fragmentation. The most prominent recharge areas cover elevations from 813 to 2,130 m asl with a mean value near 1,600 m asl.

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662

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