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ENSO sentinels in the Americas' humid tropics: We need combined hydrometric and isotopic monitoring for improved El Niño and La Niña impact prediction

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Abstract

This Scientific Briefing presents results from a nearly 10-year hydrometric and isotope monitoring network across north-central Costa Rica, a region known as a headwater-dependent system. This monitoring system has recorded different El Niño and La Niña events and the direct/indirect effects of several hurricane and tropical storm passages. Our results show that El Niño-Southern Oscillation (ENSO) exerts a significant but predictable impact on rainfall amount anomalies, groundwater level and spring discharge, as evidenced by second-order water isotope parameters (e.g., line conditioned-excess or line-conditioned (LC)-excess). Sea surface temperature anomaly (El Niño Region 3) is correlated with a reduction in mean annual and cold front rainfall across the headwaters of north-central Costa Rica. During El Niño conditions, rainfall is substantially reduced (up to 69.2%) during the critical cold fronts period, limiting groundwater recharge and promoting an early onset of minimum baseflow conditions (up to 5 months). In contrast, La Niña is associated with increased rainfall and groundwater recharge (up to 94.7% during active cold front periods). During La Niña, the long-term mean spring discharge (39 Ls^{-1}) is exceeded 63–80% of the time, whereas, during El Niño, the exceedance time ranges between 26% and 44%. The regional hydroclimatic variability is also imprinted on the hydrogen and oxygen isotopic compositions of meteoric waters. Drier conditions favoured lower LC-excess in rainfall (−17.3‰) and spring water (−6.5‰), whereas wetter conditions resulted in greater values (rainfall = +17.5‰; spring water = +10.7‰). The lower and higher LC-excess values in rainfall corresponded to the very strong 2014–2016 El Niño and 2018 La Niña, respectively. During the recent triple-dip 2021–23 La Niña, LC-excess exhibited a significant and consistently increasing trend. These findings highlight the importance of combining hydrometric, synoptic and isotopic monitoring as ENSO sentinels to advance our current understanding of ENSO impacts on hydrological systems across the humid Tropics. Such information is critical to constraining the 21st century projections of future water stress across this fragile region.

KEYWORDS
ENSO, headwater-dependent systems, humid tropics, hydrometric and isotopic monitoring, stable isotopes, water resources management

1 | THE ENSO IMPACT CONUNDRUM: FROM A GLOBAL TO A REGIONAL PERSPECTIVE

El Niño-Southern Oscillation (ENSO) phenomena is an interannual climate variability with oceanic and atmospheric climate variation originating in the tropical Pacific region. ENSO is one of the most influential modes of variability largely due to its global teleconnections, which affect temperature and precipitation patterns worldwide (Bjerknes, 1966; Capotondi et al., 2015; Dijkstra, 2006; McPhaden et al., 2006; Posada-Marín et al., 2023; Wang et al., 2017). ENSO cycles are characterized by complex air–sea feedback processes, resulting in substantial droughts and flooding events (Fasullo et al., 2018; Kirtman, 2019; Latif et al., 1994; L'Heureux et al., 2020; Stevenson et al., 2012; Timmermann et al., 2018; Yun et al., 2021). The intricate nature of event-specific temperature and precipitation responses is rooted in the large spectrum of ENSO 'flavours' (An & Jin, 2004; Hoerling et al., 1997; Trenberth & Stepaniak, 2001), which depend on (a) the spatial distribution of sea surface temperatures (SST), (b) the prevailing hydrometeorological state of a particular region and (c) interaction with other climate conditions and variability modes (i.e., regional atmospheric noise, watershed storage conditions, Pacific Decadal and Atlantic Multidecadal Oscillations, Madden-Julian Oscillation) (Hendon et al., 2007; Kug et al., 2008; Larkin & Harrison, 2005; Levine et al., 2017; Soden, 2000; van Oldenborgh & Burgers, 2005; Wang et al., 2014; Wang & Hendon, 2007; Watanabe & Wittenberg, 2012; Weng et al., 2007). For example, the strong intensity of the 1997 El Niño event was associated with near-average rainfall across eastern Australia, but this region experienced record drought during the modest 2002 El Niño (Chung & Power, 2017; Wang & Hendon, 2007). Similarly, the very strong 2014–2016 El Niño was associated with a strong water deficit in northwestern Costa Rica and moderate deficits in the central portion of the country, whereas the weak 2018–2020 El Niño resulted in large water shortages in the Central Valley of Costa Rica (Morataya-Montenegro & Bautista-Solís, 2020; Sánchez-Murillo et al., 2017). Thus, ENSO's strength, pattern diversity and development evolution lead to uncertainties in individual event expression and enigmatic features of this recurrent climate pattern (Cai et al., 2020; Thual & Dewitte, 2023).

The main impacts of ENSO in Mesoamerica are the alterations of the onset and duration of the rainy season, where anomalous displacement of moisture convergence causes variations in rainfall amount, intensity and spatial distribution. In an area extending from central Mexico south through Central America, ENSO cold (La Niña) and warm (El Niño) phases translate into significant hydroclimatic anomalies and associated socio-economic impacts (Giannini et al., 2000; Hund et al., 2021; Magaña et al., 2003). During El Niño, the intensification of the easterly flow from the Caribbean Sea modulates the transport of moisture and moves the centres of moist convection to the Pacific Ocean (Figure 1). The latter results in warmer and drier conditions in the region, causing a net decrease in agricultural productivity as well as an increased risk of wildfires, water conflicts and vector-borne diseases due to the impact of water scarcity on sanitation (Bouma et al., 1997; Depsky & Pons, 2020; Esquivel-Hernández et al., 2018; Ewbank et al., 2019; Sardo et al., 2023).

More specifically, across the Central American Dry Corridor (i.e., a region embedded into the Mesoamerican Pacific slope domain from Chiapas, Mexico to central Panama) (Hidalgo et al., 2019; Muñoz-Jiménez et al., 2019), El Niño has led to widespread food insecurity (i.e., food shortages), economic hardship (i.e., increased prices) for local communities and massive climate-induced migrations to North America (Balsari et al., 2020; Simon & Riosmena, 2022). ENSO-induced droughts and floods, coupled with crop failures (e.g., beans and corn), are often a primary driver for the multi-country exodus, particularly among rural and indigenous communities (Baez et al., 2017). Briones (2022) estimated that the economic impact of hydroclimatic events linked to ENSO in Central America from 1972 to 2010 was $4015 billion. For a region with a total gross domestic product close to $1370 billion (2015), this three-fold economic disproportionality poses a true challenge to climate change resilience and adaptive capacity (Bouroncle et al., 2017). In a global tropical context, by combining ENSO intensity variations (1986–2018) with data on children's height and weight from 186 surveys conducted in 51 countries with ENSO-teleconnection (i.e., 48% of the world's under-5 population), Anttila-Hughes et al. (2021) estimated the association of ENSO with child nutrition. Their findings indicate that in most of the developing world, warmer El Niño conditions are strongly associated with child malnutrition.

In contrast, La Niña events often bring cooler and wetter conditions, leading to increased flooding and landslides linked to more active cyclogenesis over the Atlantic, resulting in extensive infrastructure damage, displacement of communities and loss of life (Dominguez & Magaña, 2018; Klotzbach, 2011; Poveda et al., 2006). Previous work also suggests that extreme rainfall events during La Niña are one of the dominant groundwater recharge sources (Dores et al., 2020) across the Pacific slope of Mesoamerica. However, this recharge mechanism has received less attention than the effects of dry spells on the region. La Niña events can negatively impact agriculture, as heavy rains can damage crops and cause soil erosion, as well as reduction to the available habitat volume or increase sediment and contaminant transport, respectively (Whitfield et al., 2016; Wolfe & Ralph, 2009). Broadly speaking, ENSO strongly affects the availability of water resources in the region, particularly for hydroelectric power generation and municipal water supply (Gonzalez-Salazar & Poganietz, 2021; Hund et al., 2021) across headwater-dependent

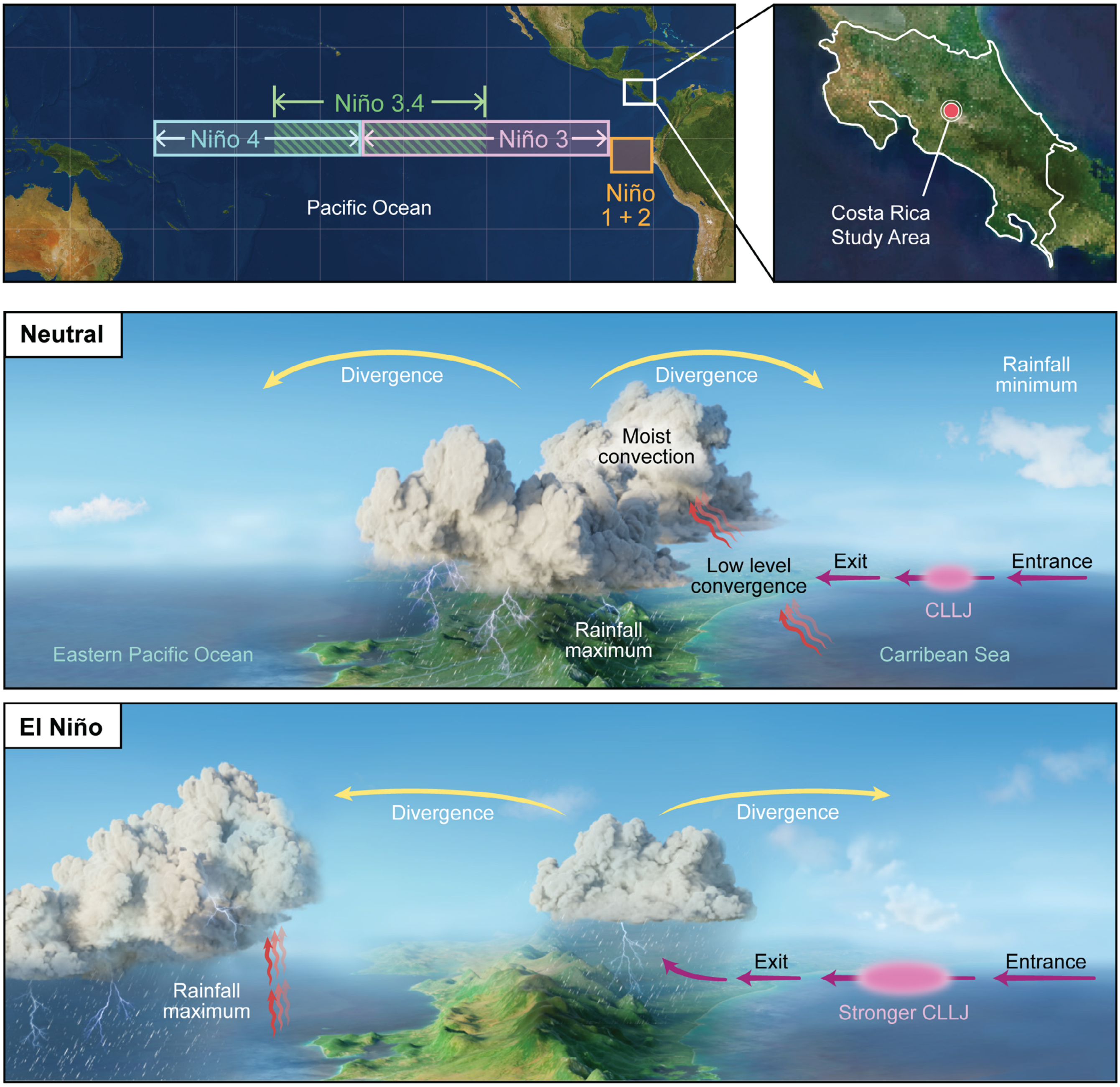

FIGURE 1 The upper panel shows the location of the study area within north-central Costa Rica and SST monitoring regions adapted from https://www.noaa.gov/jetstream/tropical/enso. The numbers of the El Niño 1, 2, 3 and 4 regions correspond to the labels assigned to historical ship tracks that crossed these regions. Data from these tracks enabled the historic records of El Niño to be reconstructed back in time to 1949 (https://climatedataguide.ucar.edu/climate-data/nino-sst-indices-nino-12-3-34-4-oni-and-tni) (Rasmusson & Carpenter, 1982). The middle and bottom panels show conceptual diagrams, including moisture transport and rainfall generation processes within the Central America Cordillera during El Niño-Southern Oscillation neutral and warm phases, respectively.

systems (HDS). These HDS are ecosystems that rely on water flowing from mountainous or upland areas (Scott et al., 2019), including rivers, lakes, wetlands and other freshwater habitats, which are critical for supporting biodiversity, providing multiple environmental services and sustaining human livelihoods.

Hydrometric and isotopic monitoring across mountainous tropical biomes is crucial but severely limited. However, it is recognized that observations and data from long-term experimental settings provide novel insights into the hydrological cycle by recording trends and natural cycles under baseline or disturbed conditions and can operate as a sentinel for future patterns (Tetzlaff et al., 2017). While remote sensing and satellite products are emerging as complementary techniques in the tropics to improve regional modelling of data-scarce regions (Arciniega-Esparza et al., 2022), in situ observations are needed to validate such efforts and to provide different lines of surface hydrology evidence, as in the case of ENSO-induced water resource variability. Furthermore, the spatial and temporal resolution of satellite products is not fit to inform water resources impacts at local scales (<10^3 km^2), which hinders the advancement of early warning systems and management.

To address these shortcomings, the continuous monitoring of stable oxygen and hydrogen isotopic compositions of water has shown potential to be used as a climatic sentinel in Mesoamerica. During an El Niño event, the trade winds weaken, reducing coastal upwelling, rise in SST, and increasing atmospheric instability over the eastern tropical Pacific Ocean, and the Choco low-level jet becomes stronger during its seasonal peak (Figure 1; Builes-Jaramillo et al., 2023), which allows warm water vapour from the western Pacific Ocean to flow eastward towards the Americas. Since warmer SST tends to favour kinetic fractionation, the water vapour in the atmosphere over the eastern Pacific Ocean should tend towards isotopically lighter (depleted) values during an El Niño event. Similarly, changes in convection patterns and reduced rainfall in the context of a drier atmosphere likely led to isotopically heavier (enriched) precipitation events over the eastern Pacific Ocean and in the surrounding land areas of Mesoamerica. This Scientific Briefing aims to (a) analyse the effects of ENSO phases in rainfall amount, groundwater levels and spring discharge anomalies in north-central Costa Rica (as a valid example of the wet tropics of Mesoamerica) and (b) evaluate line-conditioned (LC)-excess as a potential sentinel (predictor) of water deficit or surplus in ENSO-affected tropical regions. Overall, isotopic changes can potentially be used as an early regional warning signal of an impending El Niño event, providing a complimentary diagnosis tool for ENSO-induced changes in the regional hydrological cycle. The latter is particularly pressing due to the current increasing SST trend in the tropical Pacific Ocean, which favours the potential development of a strong El Niño event during the boreal autumn, with a probability ranging from 70% to 80% (ENSO Blog Team, 2023; WMO, 2023). Very strong El Niño events have produced catastrophic impacts across Mesoamerica in the last 40 years (1982–1983, 1997–1998 and 2015–2016) (Briones, 2022; Martínez et al., 2017).

2 | STUDY AREA

Figure 1 shows the location of the study area within north-central Costa Rica (in a transect between 1100 and 2400 m asl) (see Sánchez-Murillo et al., 2022 for a detailed hydrogeological and meteorological description), SST monitoring regions (i.e., 4, 3.4, 3 and 1 + 2) (see Rasmusson & Carpenter, 1982), and conceptual diagrams of moisture transport and rainfall generation during ENSO neutral and warm phases (Figure 1, middle and bottom panels), including ocean–atmosphere processes and their interaction with the Central America Cordillera. During El Niño, a net increase in the intensity of the Caribbean Low-Level Jet (known as CLLJ; Amador, 2008) generates an increase in vertical wind shear, causing inhibition of convection along the Pacific slope of Mesoamerica (Figure 1, bottom panel). This increase in the CCLJ intensity displaces the region of convergence of humid and warm air at low levels to the westwards, resulting in less Pacific slope rainfall and more precipitation over the eastern Pacific Ocean.

This region (Figure 2) comprises the most important recharge area for the lowland urban centres of the country (e.g., San José, Heredia, Alajuela). Annual precipitation ranges from nearly 2500–4000 mm in

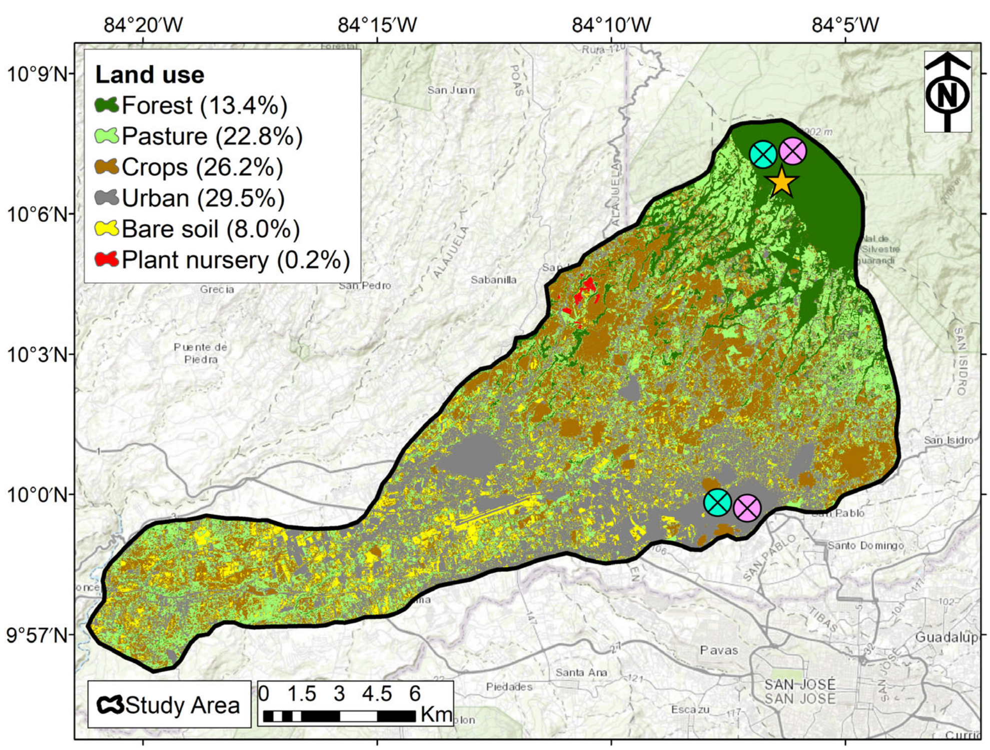

FIGURE 2 Location map of weather stations (pink crossed dots), spring (high elevation) and groundwater well (urban area; cyan crossed dots) and spring and rainfall isotope monitoring (orange star). The black polygon denotes the boundary of the unconfined aquifer unit. The land used was adapted after Sánchez-Murillo et al. (2022).

the urban centre and high-elevation recharge areas (Sánchez-Murillo et al., 2020), respectively, with roughly 20% of total recharge occurring above 1500 m asl (Sánchez-Murillo et al., 2022). In Costa Rica, a nation with a vast water capital of *c*. 2.8×10^4 m^3/person-year, over 700 water conflicts emerged during the last decade in response to the abrupt inter-annual climate variability and inefficient water use (Esquivel-Hernández et al., 2018; Stan et al., 2022; Vazquez & Muneepeerakul, 2013). Roughly 80% of the disputes have occurred due to inadequate water infrastructure or a lack of scientific knowledge ranging from spatial rainfall variability, groundwater recharge processes and tap water distribution (Esquivel-Hernández et al., 2018).

3 | METHODS

3.1 | Hydrometric and isotope measurements

Here, we present a representative case for the humid tropics of Mesoamerica, where a continuous hydrometric and isotopic monitoring network has been operating for nearly a decade across a natural-urban coupled system in north-central Costa Rica (from 1100 to *c*. 2400 m asl). This network has recorded different El Niño (2014–2016; 2018–2020) and La Niña (2016–2018; 2020–2022) events, neutral phases and the direct/indirect effects of several hurricane and tropical storm passages (2016-Otto, 2017-Nate, 2020-Eta and 2020-Iota), resulting in traceable hydrological variations. Records include (a) 30-min weather data (urban and a headwater system), (b) 15-min and hourly water levels in a high-elevation spring and a low-land observational well (urban area), respectively, and (c) 15-min spring discharge and weekly discharge measurements (i.e., volumetric method) (Figure 2). Hydrometric data were used to compute (i) spring rating curve and discharge duration curves, (ii) normalized precipitation and water level anomalies (i.e., a departure from the mean divided by the standard deviation) and (iii) cold front to annual rainfall ratio (i.e., cold front rainfall amount divided by the annual rainfall amount). Rainfall samples were collected weekly using a passive device (Palmex Ltd., Croatia). Spring samples were collected daily and weekly (using an automated sampler, Sigma 900MAX., HACH, Colorado, USA). All samples were transferred to 30 mL HDPE bottles and stored at 5°C until analysis. Samples were analysed at the Stable Isotopes Research Group laboratory at the Universidad Nacional (Heredia, Costa Rica) using an IWA-45EP water analyser (Los Gatos Research, Inc., California, USA) with a precision of ±0.5‰ for δ^2H and ± 0.1‰ for $\delta^{18}O$ (1σ; 8 injections). $^{18}O/^{16}O$ and $^2H/^1H$ ratios are presented in delta notation δ (‰), relative to the VSMOW-SLAP scale.

3.2 | ENSO relationship with annual/cold front rainfall amounts and LC-excess

Several ENSO indices are used to monitor and predict hydrological patterns worldwide (e.g., Southern Oscillation Index; Oceanic Niño Index: ONI; Multivariate ENSO Index: MEI V2; NOAA, 2023), but spatial and temporal variability obscures the accurate prediction of hydro-meteorological patterns at regional and local scales using ENSO indices alone. ENSO can affect different regions in different ways, and the timing and duration of these effects can vary yearly. Specifically, a large body of recent work demonstrates the importance of ENSO SST patterns on North American rainfall (e.g., Luo et al., 2022, 2023; Patricola et al., 2020). The centre of maximum warming in the tropical Pacific during individual El Niño events is variable and often shifts towards either the central or eastern Pacific (CP, EP events, called ENSO 'flavours') (Ashok et al., 2007; Capotondi et al., 2015; Kao & Yu, 2009; Kug et al., 2009; Luo et al., 2022; Takahashi et al., 2011). The impacts of these diverse SST patterns and ENSO 'flavours' on teleconnection rainfall requires a large sample size, but only *c*. 10 CP and EP events have occurred during the 20th century instrumental period, hindering our ability to robustly quantify how SST spatial variability in the eastern tropical Pacific should shift Mesoamerican rainfall (Liang et al., 2014; Ning & Bradley, 2015).

Despite these challenges, ENSO indices remain valuable, particularly in regions such as Mesoamerica, where the relationship between ENSO and hydrological variables is well established. We primarily explored annual and seasonal rainfall amount relationships using the SST anomaly index across El Niño regions. This index is calculated by averaging SST anomalies in a defined region of the Pacific Ocean (Figure 1; upper panel) (Bamston et al., 1997). For example, the ONI index (Region 3.4) is calculated on a three-monthly basis and can be used to classify the ENSO into El Niño (positive), La Niña (negative), or neutral phase (Glantz & Ramirez, 2020; NOAA, 2023; Webb & Magi, 2022). Linear correlations between SST anomalies (within El Niño regions 4, 3.4, 3 and 1 + 2) were evaluated as predictors of mean annual and cold front rainfall amounts in the headwaters of north-central Costa Rica. In addition, since ENSO results in significant rainfall amount and intensity as well as temperature and moisture variability across the globe, it seems reasonable that stable isotope ratios in meteoric water will capture the influence of El Niño and La Niña events (Cobb et al., 2003; Lachniet et al., 2004; Moerman et al., 2013, 2014; Pasquini & Depetris, 2010; Sánchez-Murillo et al., 2017; Sutanto et al., 2013; Tindall et al., 2009; Vuille et al., 2003). SST annual anomaly (El Niño Region 3) was evaluated against the annual LC-excess variability in rainfall and spring water over the headwaters of central Costa Rica. The LC-excess (Landwehr & Coplen, 2006) was computed as LC-excess $= \delta^2H = a{\cdot}\delta^{18}O\text{-}b$; where a and b are the slope and intercept of the meteoric water line, respectively, using daily and weekly data ($N = 1120$) from rainfall and spring water.

4 | RESULTS AND DISCUSSION

4.1 | ENSO-induced long-term rainfall anomalies: A tropical urban perspective

Figure 3 shows the normalized monthly rainfall anomalies (2014–2022) compared to a 30-year averaging period (1982–2012) in the lowland urban area of north-central Costa Rica. During the very strong 2014–2016 El Niño, the net rainfall deficit varied from −25.1% (2014) to −13.1% (2016), with a maximum deficit in 2015 (−40.4%). During the weak 2018–2020 El Niño event, rainfall deficits varied from −22.6% (2018) to −16.1% (2020), with a maximum deficit in 2019 (−37.7%). In contrast, La Niña years have been characterized by rainfall surplus ranging from +2.4% (2017) to +28.7% (2022). The greatest rainfall deficits were reported during El Niño episodes (2015–2016 and 2019), whereas the wettest year (2022) occurred during the recent triple-dip La Niña event. Overall, these rainfall pattern changes may indicate a temporal shift in the typical bimodal rainfall mode of the Pacific slope of Mesoamerica as well as a potential intensification of the mid-summer drought (Corrales-Suastegui et al., 2020; Magaña et al., 1999; Rauscher et al., 2008). Aside from monthly or annual rainfall deficits, this region has also experienced increased extreme events, resulting in unprecedented and urban flash floods. A better understanding of changes in the intensity and duration of extreme rainfall events across the tropics under a warming climate is a matter of current global debate (Feng et al., 2013; Fowler et al., 2021; Li et al., 2020; Westra et al., 2014).

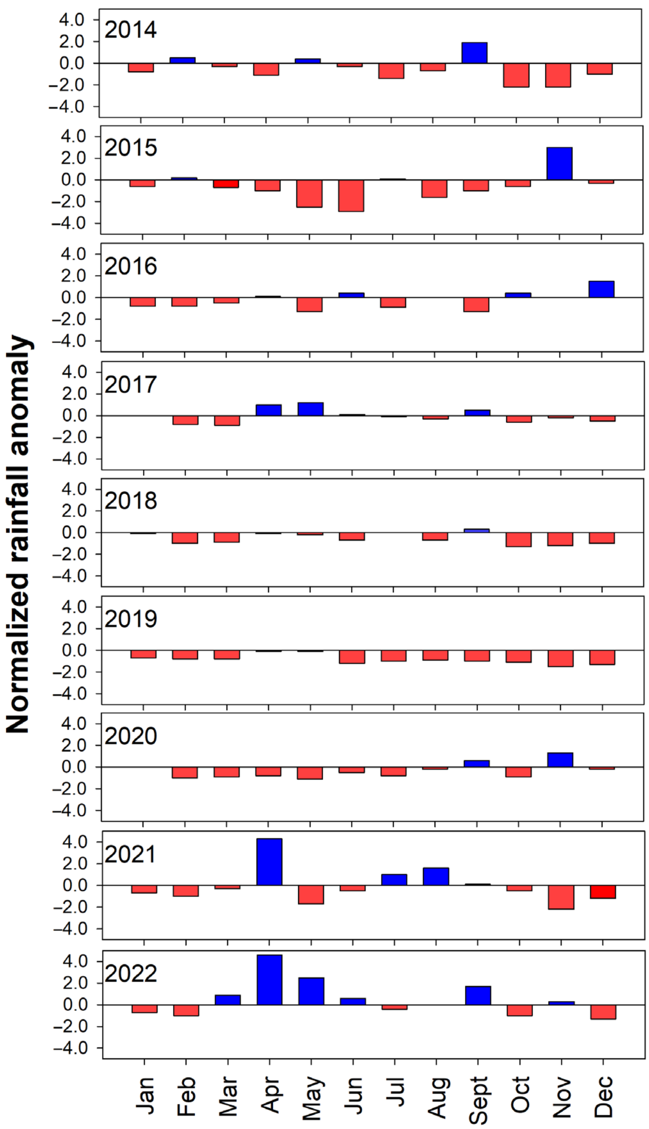

FIGURE 3 Normalized monthly rainfall anomaly (2014–2022) for a lowland urban centre in central Costa Rica, based on a normal period from 1982 to 2012. The 30-year mean annual rainfall is equal to 2452 ± 88 mm.

4.2 | ENSO-induced synoptic rainfall patterns: A tropical headwater perspective

As El Niño develops, the region experiences a significant reduction of (a) synoptic scale systems that cause rainfall during the second semester of the year (e.g., cyclones) and (b) the passage of cold fronts (an important contribution to annual rainfall), which can be affected by the drier conditions. Figure 4 explores the relationship between ONI and cold fronts and annual rainfall variability (2016–2023) in the headwaters (*c.* 3000 m asl) of north-central Costa Rica. During the monitoring period, warm ENSO events (2015–2016, 2018–2020) resulted in a notable disruption of cold front occurrences and, consequently, in a net rainfall decrease (Figure 4a,b). During cold front events, groundwater recharge is critical to maintaining the dry season low flow regime, which typically lasts until the end of May or the beginning of June. In contrast, cold ENSO events (2016–2018 and 2021–2023) were characterized by a net increase in cold front rainfall totals, with values up to 2068 mm (2017–2018) (Figure 4b).

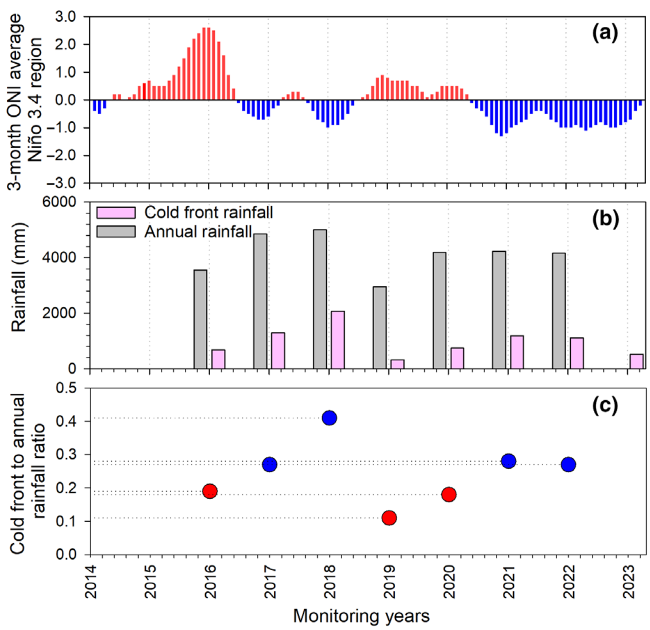

FIGURE 4 (a) Oceanic Niño Index (ONI) rolling 3-month average SST anomaly between 2014 and 2023 in the Niño 3.4 region (as a reference). Red and blue bars denote El Niño and La Niña years, respectively. (b) Annual (grey bars) and cold front rainfall (pink bars) (in mm) in the northern headwaters of central Costa Rica. (c) Cold front to annual rainfall ratio between 2016 and 2022. Red and blue dots denote El Niño and La Niña years, respectively.

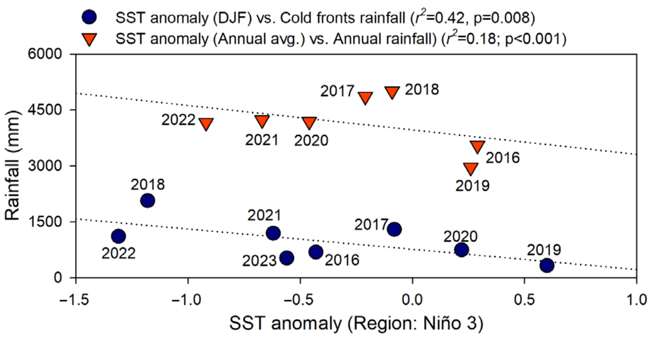

FIGURE 5 Linear regressions between sea surface temperatures (SST) anomaly values (Region: Niño 3) and annual and cold front rainfall amounts.

Overall, El Niño years are characterized by lower cold fronts (e.g., fronts originated from North America) to annual rainfall ratios (<0.20). In contrast, during La Niña years, cold front rainfall contributes from 27% up to 41% to the annual rainfall budget (Figure 4c). In 2023, the transition from a triple-dip La Niña (Graham, 2022; McPhaden et al., 2023) towards a most likely strong El Niño, with a very short transition period, resulted in the second lowest cold front rainfall amount recorded (528 mm) (Figure 4a,b). The lowest annual rainfall values coincided with two El Niño events, 2016 (3552 mm) and 2019 (2958 mm) (Figure 4b). In contrast, in La Niña years (or years partially dominated by a cold phase), total rainfall between 4100 and 5000 mm were recorded (Figure 4b). During El Niño events, the warmer SSTs can cause changes in atmospheric circulation that can weaken or delay the arrival of cold fronts in Central America. This leads to drier conditions and reduced precipitation, particularly across HDS, that rely on such rains to sustain greater baseflows. Interestingly, the weak 2019 El Niño resulted in the greatest cold front rainfall deficit (69.2%) compared to the very strong 2016 El Niño deficit (35.2%). The weak 2018 La Niña recorded the greatest cold front surplus (94.7%).

In general, correlations between SST anomaly values from El Niño Region 3 exhibited the strongest correlations with the rainfall anomalies observed in north-central Costa Rica (Figure 5). Other El Niño SST anomalies did not exhibit significant correlations. Annually averaged SST anomaly values show a weak correlation ($r^2 = 0.18$, $p < 0.001$) with annual rainfall amounts. However, SST anomaly values during the boreal winter (December–February) are strongly correlated with the decrease in cold front rainfall amounts ($r^2 = 0.42$, $p = 0.008$) (Figure 5). The latter suggests that ENSO's evolution, as reflected in SST anomalies (El Niño Region 3) during the boreal winter months, could be explored as a potential predictor of a cold front rainfall deficit and surplus, and highlights the strong teleconnection between ENSO phases and rainfall generation in the Pacific slope of Mesoamerica.

Several additional metrics have been developed to capture the diversity of ENSO events that occur year to year. While we here employ only SST anomalies (e.g., Region: Niño 3), extension work could monitor climate observations in Mesoamerica alongside the Niño 4, 3.4 and 1 + 2 regions, as well as CP and EP event classifications such as the ENSO longitudinal index (Williams & Patricola, 2018). Recent work extending the instrumental record and employing paleoclimate data assimilation and annual proxy reconstructions suggests that Central America is dry on average during both CP and EP events, while southern Mexico is relatively wet (Luo et al., 2022, 2023). Combined with a wide array of SST-based ENSO indices, the incorporation of high-resolution paleoclimate data (e.g., Cobb et al., 2013) and the use of the full SST pattern along with climate models (e.g., Brown et al., 2020) could bolster predictions of ENSO event-based rainfall anomalies in the region. Machine learning techniques such as self-organizing maps are increasingly used to develop predictive models linking tropical SST patterns to rainfall anomalies in North America; such techniques may also prove useful for rainfall prediction and monitoring in the Americas (e.g., Luo et al., 2023; Steiger et al., 2019).

4.3 | ENSO rainfall and tropical groundwater connectivity

The subsurface hydrological response also depicts the impact of ENSO on the seasonal rainfall patterns (deficit and surplus) (Figure 6a). For example, the lowest groundwater levels reported in an unconfined volcanic aquifer (well depth: 153 m; located in the lowland urban centre) and spring discharge (*c.* 2400 m asl) (Figures 2 and 6), consistently have coincided with El Niño years (2014–2016 and 2018–2020), whereas the highest water levels and spring peak discharge have corresponded with the influence of La Niña years (2016–2018 and 2021–2023) (Figure 6a). La Niña events were also characterized by direct and indirect impacts of hurricanes and tropical storm passages (e.g., Otto, Nate, Eta and Iota). This unconfined aquifer is part of a multi-aquifer volcanic system, where the upper unconfined formation exhibits young water ages and a strong hydrogeological conductivity with the headwater recharge areas (Sánchez-Murillo et al., 2022) (Figure 2). Figure 6c shows the continuous (15 min) spring discharge response in the headwaters (Salas-Navarro et al., 2018). In this system, prolonged baseflow periods are systematically linked with El Niño years and weak cold front periods, whereas peak discharge is related to La Niña events. Baseflow recession time decreases during La Niña years, resulting in relatively high discharge during the dry season. During ENSO cold phases, the percentage of time equal to or above the long-term discharge value (*c.* 39 L/s) is greater than 63–80% (Figure 6d). However, during El Niño years, the percentage of exceedance ranges between 26% and 44% (Figure 6d). These significant water availability changes pose a challenge for drinking water operators and result in notable water shortages across the region. Predicting potential rainfall deficits (6 months to 1 year before the event) and, consequently, water deficits due to prolonged low flow regimes will allow water managers to improve infrastructure and drinking water allocation as well as to raise community awareness for efficient water use and water conservation during warm ENSO phases (Hund et al., 2021; Stan et al., 2022; Veldkamp et al., 2015; Vignola et al., 2018).

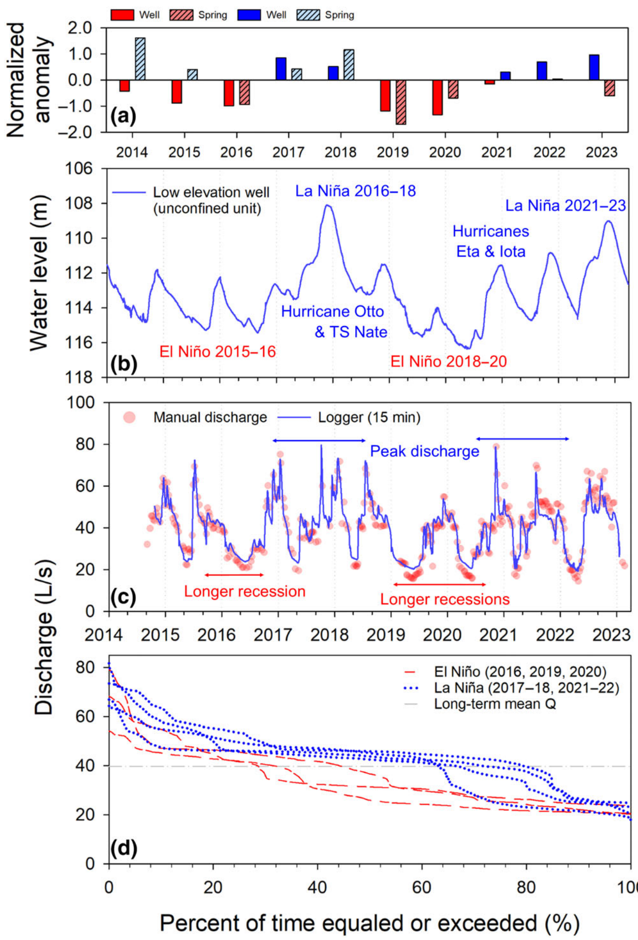

FIGURE 6 (a) Normalized water table and spring discharge anomaly. (b) Water level (in m) in a lowland well (153 m depth; 1147 m asl). (c) Automated (blue line) (15 min resolution) and manual discharge (red dots) (in L/s) in a high-elevation large spring system. (d) Annual duration curves for a high-elevation large spring system. El Niño and La Niña years are colour-coded. The grey dashed line depicts the long-term mean annual discharge, Q (in L/s).

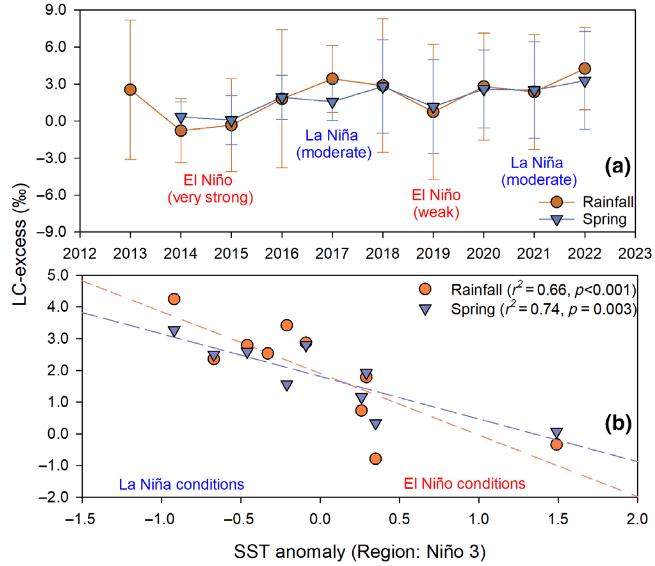

FIGURE 7 (a) Annual LC-excess (‰) variability (±1 σ) during El Niño and La Niña years in rainfall and spring water across the headwaters of central Costa Rica. (b) Linear regressions between SST annual averaged anomaly values (Region: Niño 3) and annual LC-excess (‰) in rainfall and spring water.

4.4 | Water isotopes as ENSO sentinels: Observations, potential indicators and current challenges

Figure 7 shows, to the best of our knowledge, one of the longest and continuous isotope records (in the humid tropics of Mesoamerica) from the headwaters of north-central Costa Rica. Drier conditions favoured significantly lower LC-excess in rainfall and spring water. In contrast, wetter conditions resulted in greater LC-excess (Figure 7a). Interestingly, during the triple-dip La Niña episode (the first isotopically recorded in Mesoamerica), LC-excess exhibited a consistent increasing trend as La Niña evolved from 2021 to 2023 (Figure 7a). The seasonal response between meteoric and spring water provided strong evidence of how isotope rainfall inputs are translated to surface water and relatively shallow groundwater reservoirs in the humid tropics. Greater LC-excess values during La Niña years could be explained by the overall increase in moisture availability, cloud cover and rainfall surplus throughout the year, including stronger cold front incursions. During El Niño, warmer oceans and land surface temperatures coupled with a notable rainfall decrease favour stronger sub-cloud (e.g., re-evaporation) and surface fractionation (e.g., infiltration). These mechanisms are represented by strong linear correlations between LC-excess and SST annual averaged anomaly values (Region: Niño 3) in rainfall ($r^2 = 0.66$, $p < 0.001$) and spring water in rainfall ($r^2 = 0.74$, $p = 0.003$). The peak of the strong 2014–2016 El Niño resulted in the lowest annual LC-excess, whereas the most recent triple-dip 2021–2023 La Niña exhibited the greatest annual LC-excess. These significant relationships, representing fractionation changes across the humid tropics in rainfall and subsurface water reservoirs, could serve as an early impact predictor for regional ENSO teleconnections. In addition, ENSO-isotope association can also serve as a valuable proxy for paleoclimatic reconstructions and interpretations in the Mesoamerica region, where clearly defined causes and timing of climate-induced past civilization collapses are still subject to contradictory paleoclimate interpretations (Evans et al., 2018; Lachniet et al., 2012; Haug et al., 2010; Medina-Elizalde et al., 2016; Messenger, 2002; Therrell et al., 2010).

Despite the potential of stable isotopes to predict annual and seasonal ENSO teleconnections in rainfall and shallow groundwater in the Pacific slope of Mesoamerica, several challenges must be addressed before this approach can be widely used for operational forecasting. One of the main challenges is disentangling the complexity of the processes and factors that control the isotopic composition of precipitation in the humid tropics, including humidity, oceanic and terrestrial moisture sources, precipitation type and intensity (Aggarwal et al., 2016; Munksgaard et al., 2019; Sánchez-Murillo et al., 2016, 2019; Scholl et al., 2009; Scholl & Murphy, 2014). Employing water isotope-enabled general circulation models with moisture tagging capabilities would facilitate a more targeted investigation of moisture source and isotopic composition changes accompanying ENSO phases and climatic shifts (e.g., Dee et al., 2023 and references therein). Another challenge is the lack of long-term observational data for stable isotopes in the tropics (Sánchez-Murillo & Durán-Quesada, 2019; Terzer-Wassmuth et al., 2021). While there have been significant advances in the measurement and analysis of stable isotopes in recent years (Terzer-Wassmuth et al., 2020; Wassenaar et al., 2018), the available data is still limited in terms of its spatial and temporal coverage (Bowen & Good, 2015). The latter is required to constrain the development of robust statistical models that accurately predict ENSO patterns based on stable isotopes. In addition, the relationship between stable isotopes and ENSO can be affected by other factors that are not directly related to the climate variation, such as changes in land use and vegetation cover (Jasechko et al., 2013; Singh et al., 2023). These factors can introduce noise and uncertainty into the isotopic data, making it more difficult to identify the underlying ENSO signal.

5 | CONCLUSIONS

Although ENSO-based predictions of rainfall deficits and drought conditions have improved in recent years (Cai et al., 2021; Chattopadhyay et al., 2019; Wohl et al., 2012), there are still challenges across the humid tropics to sustaining long-term hydrometric records and accurately predicting the timing and magnitude of these events. This study demonstrates the strong teleconnection between ENSO phases, rainfall deficit/surplus and hydrological responses across an HDS in the humid tropics of Mesoamerica. We show that by combining hydrometric, synoptic and isotopic information, temporal variations can be identified in advance, allowing managers and policymakers to develop strategies to diagnose and mitigate the impacts of extreme weather events and promote ecosystem resilience across HDS. The case presented here constitutes an example of advances towards developing science-based solutions to inform water resources management that can be explored in other humid tropical regions.

Other factors, such as local weather patterns and land use change (e.g., deforestation or urbanization), can also exacerbate rainfall deficits and drought conditions. Therefore, there is a need to use high-resolution Earth system models with water isotope physics, forecasting tools, paleoclimate reconstructions, and, importantly, a robust observational hydrometric and isotopic record network. Local knowledge and expertise are also critical to developing citizen awareness and generating accurate and reliable predictions of Mesoamerican rainfall patterns and water availability. Combining hydrometeorological observations, modelling and water isotope ratios has the potential to become a more reliable forecasting ENSO indicator. Such developments are particularly timely given current warming conditions, under which the intensification of ENSO events has been projected (Cai et al., 2020). Addressing current challenges and incorporating isotopic information in operational forecasts will require continued investment in observational data, open science data, models representing local scale processes and interdisciplinary collaboration between climate scientists, hydrologists, isotope geochemists and policymakers.

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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