

Stable water isotope patterns in a micro-basin in the Panama Isthmus

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Abstract

This study was conducted in the narrowest section of the Isthmus of Panama, between the Pacific Ocean and the Caribbean Sea, near the country's geographic center. Although groundwater plays an increasingly important role in economic development and water security, the application of isotope techniques to improve hydrological understanding in tropical regions has been quite a bit meager. Due to the close proximity of two immense oceans, the low latitude, the brisk dynamism of its atmospheric processes, and the limited baseline data, the isotope hydrology of the Isthmus of Panama opens a large room for further investigation. Accordingly, this study marks an initial investigation related to the isotopic composition of precipitation and groundwater in La Zanguenga, a micro-basin located in Panamá Oeste province inside the Panama Canal basin. Groundwater samples were collected during six monitoring campaigns in 2022, while precipitation was sampled in October and November 2024. All samples were analyzed for $\delta^2\text{H}$, $\delta^{18}\text{O}$, and deuterium excess to establish a local isotopic baseline. The results from seventeen wells distributed along the southern sector of the basin showed highly similar isotopic compositions, suggesting a relatively homogeneous groundwater signature. In addition, the results suggest the dominant influence of the amount effect on the isotopic composition of precipitation, as well as the possible contribution of moisture sources from both the Pacific Ocean and the Caribbean Sea.

Keywords: La Zanguenga, tropical hydrology, groundwater, precipitation, isotopic hydrology.

Padrão de isótopos estáveis da água em uma microbacia no Istmo do Panamá

Resumo

Este estudo foi conduzido na porção mais estreita do Istmo do Panamá, entre o Oceano Pacífico e o Mar do Caribe, próximo ao centro geográfico do país. Embora as águas subterrâneas desempenhem um papel cada vez mais importante no desenvolvimento econômico e na segurança hídrica, a aplicação de técnicas isotópicas para aprimorar a compreensão hidrológica em regiões tropicais ainda é bastante limitada. Devido à proximidade de dois imensos oceanos, da baixa latitude, da intensa dinâmica dos processos atmosféricos e da escassez de dados de referência, a hidrologia isotópica do Istmo do Panamá oferece amplo potencial para novas investigações. Nesse contexto, este estudo constitui uma investigação inicial sobre a composição isotópica da precipitação e das águas subterrâneas na microbacia La Zanguenga, localizada na província de Panamá Oeste, dentro da bacia hidrográfica do Canal do Panamá. Amostras de água subterrânea foram coletadas durante seis campanhas de monitoramento em 2022, enquanto amostras de precipitação foram coletadas em outubro e novembro de 2024. Todas as amostras foram analisadas quanto a $\delta^2\text{H}$, $\delta^{18}\text{O}$ e excesso de deutério, com o objetivo de estabelecer uma linha de base isotópica local. Os resultados de dezessete poços distribuídos ao longo do setor sul da bacia mostraram composições isotópicas muito semelhantes, sugerindo uma assinatura relativamente homogênea das águas

subterrâneas. Além disso, os resultados sugerem a influência predominante do efeito quantidade sobre a composição isotópica da precipitação, bem como a possível contribuição de fontes de umidade provenientes tanto do Oceano Pacífico quanto do Mar do Caribe.

Palavras-chave: Zanguenga, hidrologia tropical, águas subterrâneas, precipitação, hidrologia isotópica.

1. Introduction

Isotope hydrology employs stable and radioactive isotopes as natural tracers to investigate water origin, quantify mixing processes, and evaluate evaporation effects, offering critical insights into the hydrological cycle. The stable isotopes (^2H - deuterium and ^{18}O) concentration in water molecules is particularly valuable due to their conservative behavior and sensitivity to phase-change processes, such as evaporation, condensation, and infiltration. These properties make them especially useful for characterizing spatial and temporal patterns in precipitation, tracing surface water-groundwater interactions and identifying recharge mechanisms in aquifer systems (Clark; Fritz, 1997; Dansgaard, 1964; Gat, 1996; Rozanski et al., 1992).

Although stable isotopes are widely recognized as powerful tools in large-scale hydrological investigations (Bowen et al., 2019; Rozanski et al., 1992), their application in tropical regions, particularly Latin America and the Caribbean, where highly variable and complex climatic conditions predominate, remains limited by several challenges (Sánchez-Murillo et al., 2017, 2020; Soto et al., 2020). Lachniet & Patterson (2006) investigated the dependency of $\delta^{18}\text{O}$ on the climatic controls prevailing in Panama, in a pioneering study in support of paleoclimatic research two decades ago. Since then, the intensity of studies has drastically dropped (Caballero, 2009; González-González et al., 2023), particularly those addressing central Panama, despite its undeniable economic and political importance.

Warm and humid tropical regions exhibit climate characteristics that are quite distinct from those in mid and high latitudes. In the extratropical continental stations, the $\delta^{18}\text{O}$ and the temperature are positively correlated (Fricke; O'Neil, 1999), whereas in tropical latitudes, the amount effect becomes an important control of δ values (Lachniet et al., 2007), being that the δ values substantially decrease during rainfall (Fricke; O'Neil, 1999).

The central region of Panama holds aquifer systems that are critical for the population's water supply and for sustaining sensitive ecosystems. Nonetheless, substantial knowledge gaps remain as related to isotopic fractionation patterns and surface-groundwater interactions in this region (Soto et al., 2020). Humid and hot environments are prone to promoting evapotranspiration, and stable isotope data could help explore the possibility and intensity of this process. Panama is right in the path of the northern Intertropical Convergence Zone (ITCZ); events associated with the El Niño-Southern Oscillation (ENSO) introduce additional complexities in the interpretation of isotopic data, as well as tools to analyze, as emphasized by Lachniet & Patterson (2006) and Sánchez-Murillo et al. (2017, 2020). Such questions reinforce the need for region-specific approaches tailored to tropical climates, considering that both humidity and temperature are very high in Central Panama.

In central-western Panama, Gatún Lake stands as the largest freshwater source and an artificial reservoir constructed to sustain the Panama Canal's operations and to supply the capital's population. Beyond its area of influence, groundwater plays an increasingly critical role in the country's economic development, particularly in peri-urban areas and secondary economic regions, serving as a primary source of water for agriculture and public health. Often referred to as "the most unknown component of the water cycle" (IAEA, 2019), understanding its origin, dynamics, and quality requires isotopic techniques to trace recharge sources, flow paths, and interactions with surface waters.

In Panama, however, hydrogeological and isotopic information remains limited. The most comprehensive datasets are concentrated in the Arco Seco region, which includes the provinces of Herrera, Los Santos, and parts of Coclé and Veraguas, where well inventory, pumping tests, and flow measurements have been conducted (Jaén, 2020). The Panamá Oeste province, though less studied than the Arco Seco region, also contains aquifer systems that support significant water supply infrastructure. In 2019, the Instituto de Acueductos y Alcantarillados Nacionales (IDAAN) reported 61 operational wells in the region (IDAAN, 2020), highlighting the importance of improving the understanding of groundwater conditions in this region.

Within the Panama Canal basin, the Los Hules-Tinajones-Caño Quebrado sub-basins are undergoing rapid land-use change due to agricultural expansion, livestock production and population growth. This trend has led to increased water demand and intensified groundwater extraction, particularly in the La Zanguenga micro-basin, where surface water resources are often insufficient in quantity and quality to meet local needs.

Close to La Zanguenga to the east there are plenty of thickset tropical forests in the Canal Zone. Further east,

nearly half of the Isthmus is covered by thickset tropical forests and even impervious rainy forests inside the Darien province. All these geographic and environmental characteristics are somehow and somewhat leveraging the hydrologic patterns at La Zanguenga.

In this context, the present study seeks to lay the groundwork for the construction of an isotopic baseline within the boundaries of the Panama Canal Watershed, using the La Zanguenga creek micro-basin as a starting point. The study focuses on the precipitation and groundwater aspects of the micro-basin's isotopic hydrology and is justified by its importance on a smaller geographic scale, as well as by its role within the Lake Gatún watershed. Furthermore, it constitutes a representative area for economic activities, particularly agriculture and livestock, as well as for the state of water supply in the countryside.

2. Study Area

The study was conducted in the La Zanguenga micro-basin, located in the upper-middle section of the Caño Quebrado River sub-basin, within the larger Panama Canal basin. Geographically, it is situated within the district of La Chorrera, Panamá Oeste province, between 8°57' - 8°59'N Latitude and 79°50' - 79°53' W Longitude (Figure 1) and covers an approximate surface area of 16.10 km² (Gómez et al., 2023). The land use within the micro-basin is predominantly agricultural, with approximately 91.07% of the area dedicated to pineapple cultivation and cattle pasture (MiAmbiente, 2012).

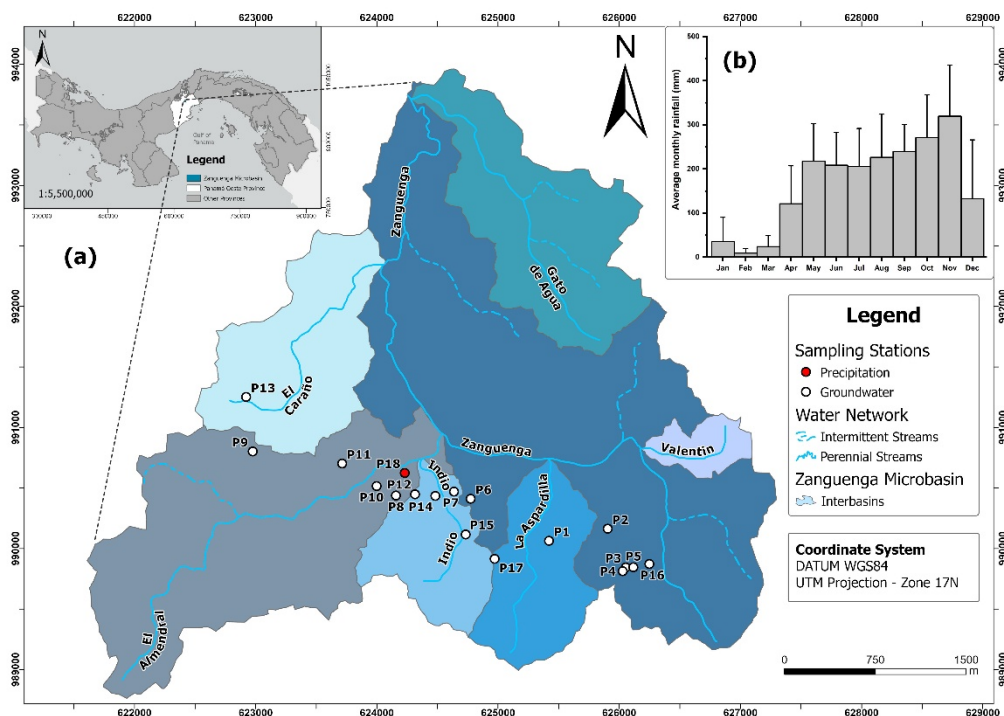


Figure 1. (a) Location map of the La Zanguenga micro-basin and sampling stations (P1 to P18). (b) Monthly precipitation rainfall for the La Zanguenga micro-basin based on 20 years of historical rainfall records (2005-2024). Bars indicate mean monthly totals, and error bars represent the standard deviation. Source: Authors, 2026.

The local climate is classified as humid tropical according to the Köppen system, with two well-defined seasons: a dry season from December to April and a rainy season from May to November (Flasz et al., 2010; IMHPA, n.d.). Annual precipitation in the micro-basin ranges from 1,482 to 2,831 mm, while average annual temperatures vary between 26.1 and 26.5 °C, according to the Environmental Atlas of the Republic of Panama (Flasz et al., 2010). The seasonal variation of rainfall at the micro-basin is shown in Figure 1 (b). Annual evapotranspiration is estimated to be between 1,251 and 1,325 mm, and the average relative humidity reaches 94.8% (IMHPA, n.d.).

The graph in Figure 1 (b) shows that the rainfall seasonal variation is large; in the three initial months of the year, it is low, but starting in April, it rapidly increases and remains intense for the rest of the year until November. This

profile resembles the temporal distribution of rainfall in the Isthmus, even that of the closest country, Costa Rica (Sánchez-Murillo et al., 2020). Besides, the vehemently humid characteristic of the rainfall graph indicates another remarkable feature: a high relative variability (size of the error bars), including in the less humid period.

Regarding the wind patterns in the region, which are important for the interpretation of isotopic signals in precipitation (IAEA, 2019), wind rose diagrams are presented in Figure 2. As observed at the La Zanguenga station, winds predominantly come from the NW. At nearby stations, the relative frequency of winds from secondary directions is higher compared to the local site.

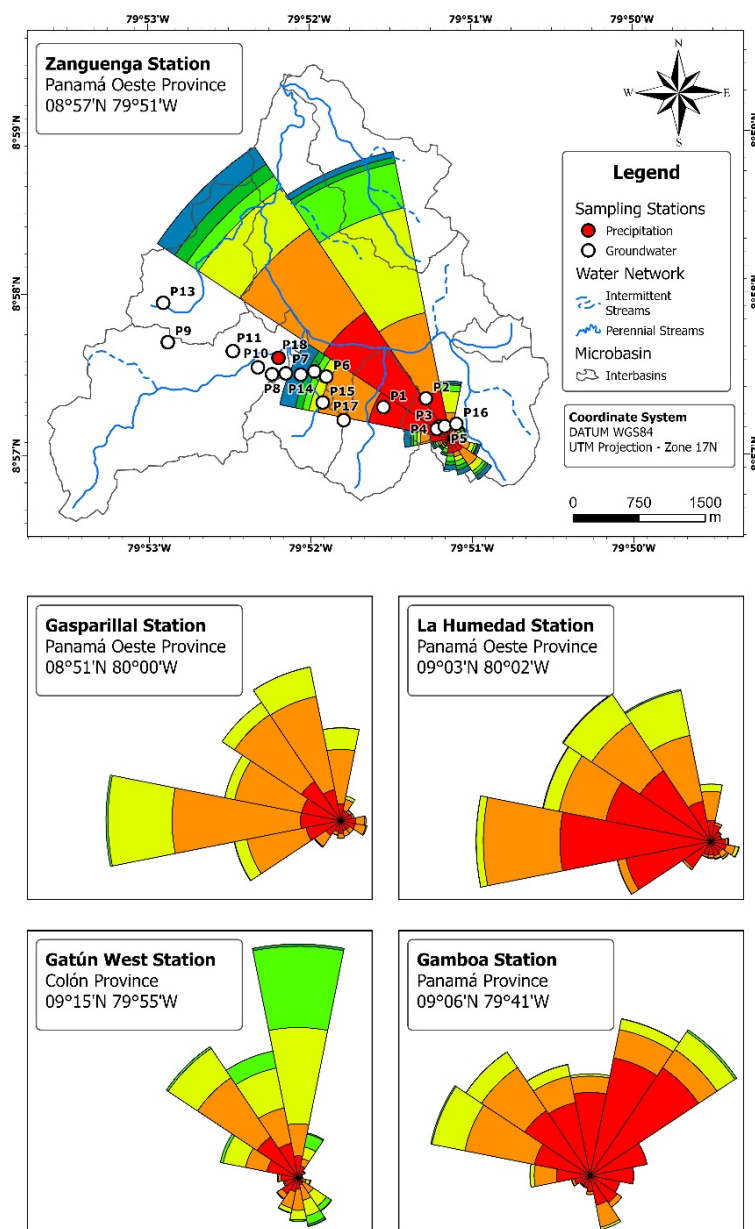


Figure 2. Wind rose diagrams for the La Zanguenga meteorological station and selected nearby stations, showing wind direction frequency and velocity. Wind speed in m/s: red (0.50 – 2.10), orange (2.10 – 3.60), yellow (3.60 – 5.70), lime green (5.70 – 8.80), forest green (8.80 – 11.10), blue (≥ 11.10). Source: Authors, 2026.

Geologically, the La Zanguenga micro-basin lies within the Tucué Volcanic Formation (TM-CATu), which consists of extrusive igneous rocks, including basalts, andesites, ignimbrites and volcanic breccias (Figure 3) (Candanedo; Fábrega, 1999; Flasz et al., 2010). Beneath the TM-CATu Formation, the TO-CAI Sedimentary Formation (Oligocene) is also present in the region; this formation belongs to the Caimito Group and consists mainly of

marine sandstones and shales (H. S. C. S.A., 2004b; MICI, 1991).

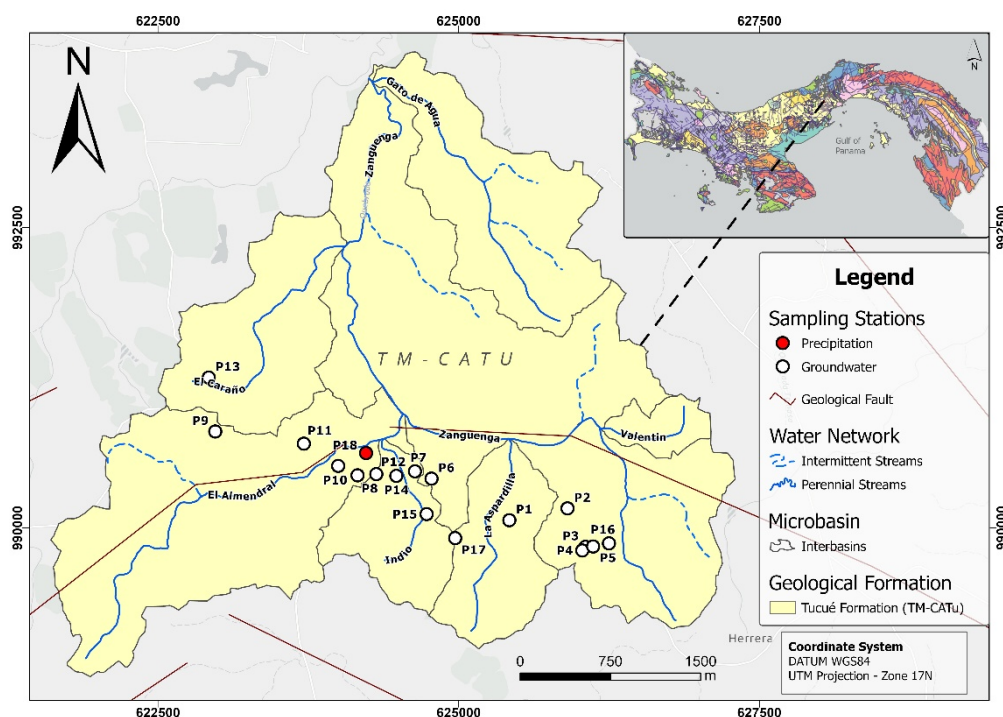


Figure 3. Geological map of the La Zanguenga micro-basin, located in the Eastern Caribbean water region. The geological formation, faults and the sampling stations are shown. Map elaborated from MICI (1991).

The river network at the micro-basin extends approximately 20.6 km and displays a dendritic drainage pattern. It consists of seven watercourses, with La Zanguenga Creek serving as the main channel, after which the study area is named. Its principal tributaries include Gato de Agua, El Almendral, Caraño, Aspadilla, Indio, and El Valentín creeks.

According to the National Hydrogeological Map, the La Zanguenga micro-basin is predominantly underlain by fissured (discontinuous) aquifers, classified as confined to semi-confined, with a delayed yield. These aquifers contain water with electrical conductivity ranging from 43 to 4000 $\mu\text{S cm}^{-1}$, variable permeability, and a moderate productivity, restricted mainly to fractured zones, which typically ranges from 3 to 10 $\text{m}^3 \text{h}^{-1}$ (Candanedo; Fábrega, 1999; MiAmbiente, 2025). However, a hydrogeological assessment of the Los Hules–Tinajones–Caño Quebrado (LH–T–Q) sub-basins, based on two wells located within the study area, indicated significantly lower permeability, classified as low to very low (9×10^{-3} - $7 \times 10^{-4} \text{ cm s}^{-1}$), and a yield ranging from poor to very poor (1 – 3 $\text{m}^3 \text{h}^{-1}$) (Candanedo; Fábrega, 1999; H. S. C. S.A., 2004b). This same study reported average transmissivity values of 48.45 and 66.79 $\text{m}^3 \text{day}^{-1} \text{m}^{-1}$ and hydraulic conductivity (filtration coefficients) of 1.53 and 2.30 m day^{-1} for the evaluated wells (H. S. C. S.A., 2004a).

3. Materials and Methods

3.1 Methodology

Prior to the monitoring campaigns, preliminary field visits were conducted to engage property owners, including residents, communal well managers, and owners of poultry, pineapple and cattle farms. These interactions were essential for establishing the groundwater and surface water sampling network. As a result, a total of 18 sampling stations were selected across the micro-basin, comprising 17 wells (P1-P17) and 1 precipitation station (P18) (Figure 1). All sampled wells were mechanically drilled and properly cased for protection. The depth of each well is presented in Table 2. For sample collection, the pumps installed in each well were used, and water was allowed to flow for approximately 2 to 3 minutes to ensure that the collected samples were representative of the aquifer and not residual water remaining within the extraction piping.

As part of the study design, six isotopic monitoring campaigns were carried out between February and April 2022,

and again from June to August 2022, for the collection of water samples for $\delta^2\text{H}$ and $\delta^{18}\text{O}$ analysis. Samples were collected in 50 mL narrow-necked polyethylene bottles, sealed with plastic caps. Each bottle was carefully labeled with the corresponding well code and number, along with the sampling date, prior to shipment and analysis by the Laboratorio de Manejo del Recurso Hídrico (LAMRHI). In addition, 31 precipitation samples were collected during October and November 2024 to complement the isotopic characterization of local rainfall. Each sample corresponds to different precipitation events occurring within a single day, based on the criterion that the minimum time interval between each event must be three hours.

Sample analysis was conducted at Stable Isotope Research Group facilities (National University of Costa Rica) using a Cavity Ring-Down Spectroscopy (CRDS) water isotope analyzer L2140-i (Picarro, USA) and a LWIA-45-EP analyzer (Los Gatos, USA). Analytical uncertainty was $\pm 0.6\text{‰}$ for $\delta^2\text{H}$ and $\pm 0.1\text{‰}$ for $\delta^{18}\text{O}$. Isotopic values are reported in delta notation (‰) relative to the VSMOW–SLAP reference standard. Deuterium excess (d-excess) was calculated as: $\text{d-excess} = \delta^2\text{H} - 8 \times \delta^{18}\text{O}$ (Dansgaard, 1964).

3.2 Data analysis

All data processing, statistical analyses, and graphical outputs were performed using R version 4.5.1 (R Core Team 2025, n.d.). To characterize the isotopic behavior in the La Zanguenga micro-basin, three regression methods were applied and compared: the Ordinary Least Squares Regression (OLSR), as recommended by the IAEA (1992), the Reduced Major Axis (RMA), and the Major Axis (MA) methods (Hughes; Crawford, 2012; Crawford et al., 2014). The resulting Water Lines were then compared to the Global Meteoric Water Line (GMWL), as defined by Craig (1961).

To support the interpretation of isotopic signatures in the La Zanguenga micro-basin, data from two Global Network of Isotopes in Precipitation (GNIP) stations were incorporated: Howard Air Force Base (AFB) (data from 1968 to 1997) and the University of Panama (data from 2002 to 2006). These datasets were obtained from the WISER platform, IAEA/WMO (2025). Following raw data processing, only records containing both $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values were retained. These were used to construct Local Meteoric Water Lines (LMWLs) for both stations through linear regression.

4. Results

The isotopic composition of water samples in the La Zanguenga micro-basin indicates a restricted variability among the rain and groundwater sources. The overall isotopic ranges and distributions are summarized in (Table 1).

Table 1. Summary statistics (minimum, maximum, mean, and standard deviation) of stable isotopes ($\delta^{18}\text{O}$, $\delta^2\text{H}$) and deuterium excess (d-excess) for precipitation and groundwater in the La Zanguenga micro-basin. Values are expressed in ‰ relative to VSMOW.

	$\delta^{18}\text{O}$ (‰)				$\delta^2\text{H}$ (‰)				d-excess (‰)			
	Min	Max	Avg	Sd	Min	Max	Avg	Sd	Min	Max	Avg	Sd
Precipitation	-9.29	-1.9	-5.48	2.38	-72.27	-4.22	-33.40	19.84	-4.98	18.5	10.42	5.18
Groundwater	-6.60	-3.87	-5.46	0.54	-42.71	-21.64	-32.99	4.21	8.77	13.88	10.72	0.88

Source: Authors, 2026.

Spatial variability in groundwater isotopic composition was assessed by mapping the mean $\delta^{18}\text{O}$ values for each sampling station (Figure 4). The most depleted isotopic composition occurs at point P15 (mean $\delta^{18}\text{O} = -6.46 \pm 0.15\text{‰}$), located in the southern sector of the micro-basin. Conversely, the least depleted composition is observed at point P2 (mean $\delta^{18}\text{O} = -4.64 \pm 0.47\text{‰}$) situated in the southeastern sector.

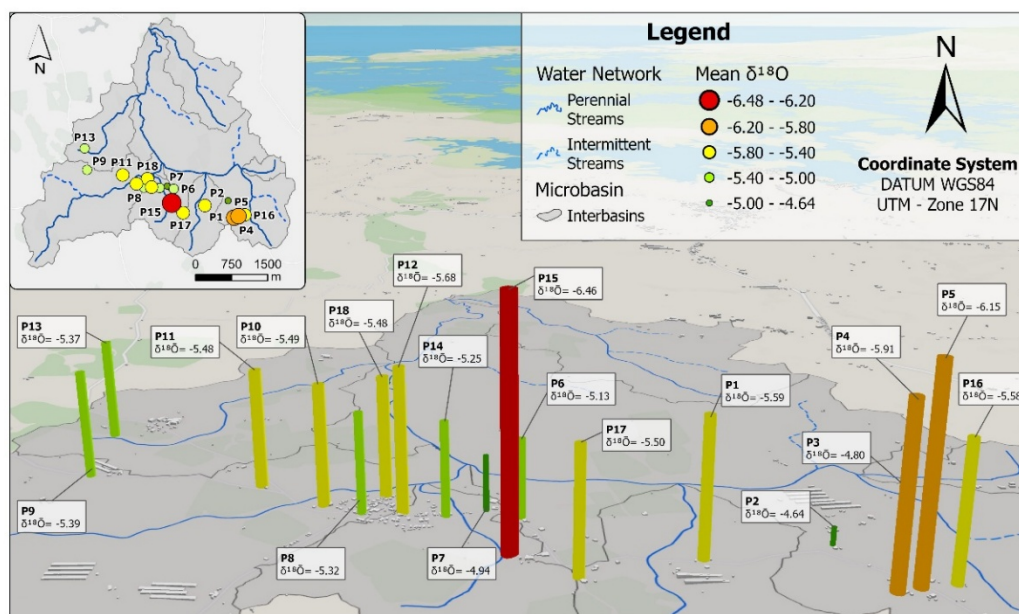


Figure 4. Map showing the mean values of $\delta^{18}\text{O}$ (‰) at the sampling stations. Note the slight spatial variation of mean $\delta^{18}\text{O}$ values highlighted along the W-E approximately oriented transect of groundwater wells. Source: Authors, 2026.

A baseline for the La Zanguenga micro-basin was derived from $n = 31$ precipitation samples collected during October and November 2024, and the groundwater regression line was derived from $n = 94$ groundwater samples collected from 17 wells in 2022 (Figure 5). The analyses were further complemented by long-term isotopic records from the GNIP-IAEA stations at Howard AFB and the University of Panama (Figure 6). The resulting regression equations are presented in Table 2, and the complete isotopic dataset is provided in (Table 3).

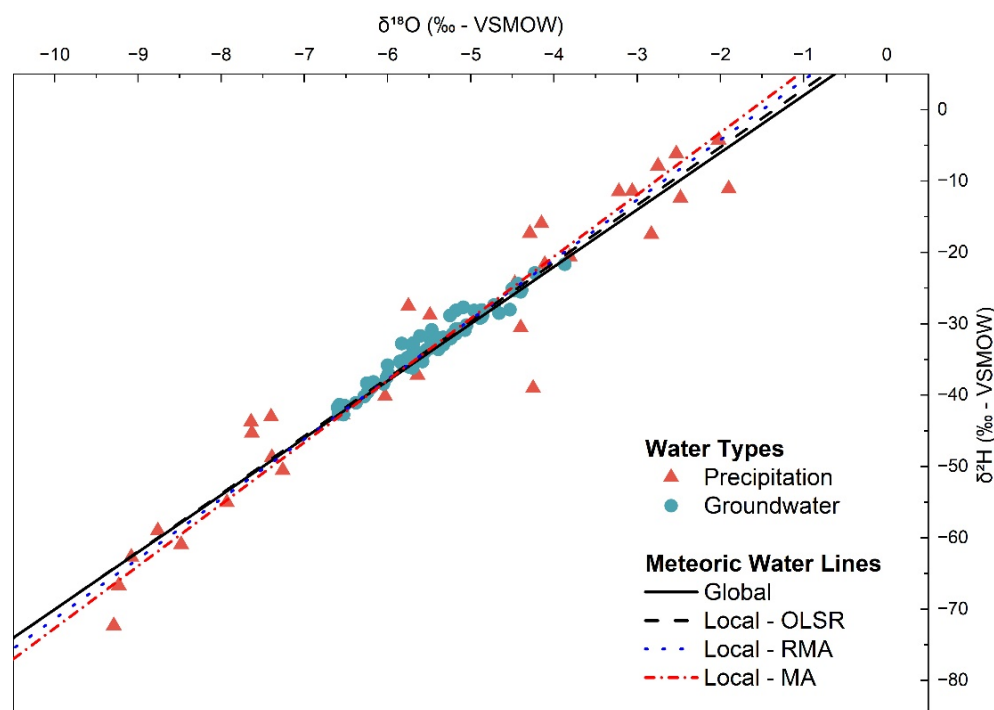


Figure 5. Water Lines for precipitation and groundwater obtained for the La Zanguenga micro-basin compared to the GMWL (Craig, 1961; Crawford et al., 2014; Hughes; Crawford, 2012). Source: Authors, 2026.

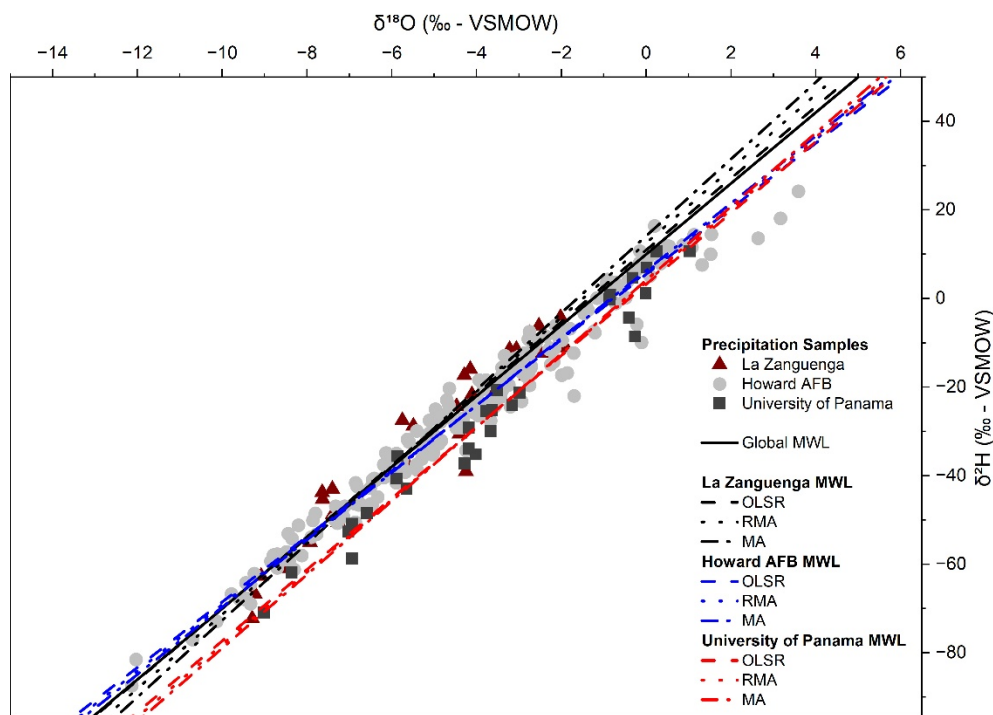


Figure 6. Water Lines obtained for the La Zanguenga micro-basin compared to the Howard AFB and University of Panama stations. Source: Authors, 2026.

Table 2. Fits for OLSR, RMA, and MA regression methods for precipitation and groundwater in La Zanguenga micro-basin, as well as for the Howard AFB and University of Panama GNIP-IAEA stations. The slopes and intercepts are presented with their standard deviation.

		Station			
		Precipitation	Groundwater	Howard AFB	University of Panama
		La Zanguenga	La Zanguenga		
OLSR	$a \pm \sigma_a$	8.09 ± 0.41	7.68 ± 0.17	7.40 ± 0.09	8.05 ± 0.29
	$b \pm \sigma_b$	10.94 ± 2.42	8.96 ± 0.93	5.50 ± 0.44	3.22 ± 1.30
	Water	$\delta^2\text{H} = 8.09 \delta^{18}\text{O} +$	$\delta^2\text{H} = 7.68 \delta^{18}\text{O} +$	$\delta^2\text{H} = 7.40 \delta^{18}\text{O} +$	$\delta^2\text{H} = 8.05 \delta^{18}\text{O} +$
	Line	10.94 (a1)	8.96 (b1)	5.50 (c1)	3.22 (d1)
RMA	r^2	0.932	0.957	0.973	0.968
	$a \pm \sigma_a$	8.39 ± 0.29	7.85 ± 0.12	7.50 ± 0.06	8.18 ± 0.20
	$b \pm \sigma_b$	12.53 ± 1.72	9.88 ± 0.66	5.91 ± 0.31	3.69 ± 0.93
	Water	$\delta^2\text{H} = 8.39 \delta^{18}\text{O} +$	$\delta^2\text{H} = 7.85 \delta^{18}\text{O} +$	$\delta^2\text{H} = 7.50 \delta^{18}\text{O} +$	$\delta^2\text{H} = 8.18 \delta^{18}\text{O} +$
MA	Line	12.53 (a2)	9.88 (b2)	5.91 (c2)	3.69 (d2)
	r^2	0.931	0.957	0.973	0.968
	$a \pm \sigma_a$	8.68 ± 0.05	8.01 ± 0.02	7.60 ± 0.01	8.31 ± 0.03
	$b \pm \sigma_b$	14.14 ± 0.29	10.79 ± 0.12	6.31 ± 0.06	4.15 ± 0.16
MA	Water	$\delta^2\text{H} = 8.68 \delta^{18}\text{O} +$	$\delta^2\text{H} = 8.01 \delta^{18}\text{O} +$	$\delta^2\text{H} = 7.60 \delta^{18}\text{O} +$	$\delta^2\text{H} = 8.31 \delta^{18}\text{O} +$
	Line	14.14 (a3)	10.79 (b3)	6.31 (c3)	4.15 (d3)
	r^2	0.927	0.956	0.973	0.967

Source: Authors, 2026.

Table 3. Stable isotopes ($\delta^{18}\text{O}$, $\delta^2\text{H}$) and deuterium excess (d-excess) for groundwater (P1-P17) and precipitation (weather station - P18) in the La Zanguenga micro-basin.

Site	Coordinates (WGS84 - Zone 17 North)		Depth (meters)	Date	Sample	$\delta^{18}\text{O}$	$\delta^{18}\text{O}$	$\delta^2\text{H}$	$\delta^2\text{H}$	d -excess	d -excess	Local Meteoric Water Line	R^2
	Latitude	Longitude				(‰)	Mean (‰)	(‰)	Mean (‰)	(‰)	Mean (‰)		
P1 - Peralta	8°57'17.8"N	79°51'32.8"W	27.43	02/22/2022	PZ01-01	-5.33		-32.35		10.33		$\delta^2\text{H} = 5.72 \delta^{18}\text{O} - 2.26$	0.7922
				03/30/2022	PZ01-02	-5.58		-35.27		9.37			
				04/27/2022	PZ01-03	-5.72	-5.59	-34.93	-34.24	10.81	10.47		
				06/24/2022	PZ01-04	-5.85		-35.25		11.51			
				07/29/2022	PZ01-05	-5.65		-34.60		10.57			
				08/26/2022	PZ01-06	-5.41		-33.01		10.25			
P2 - Brocal Pollines	8°57'20.9"N	79°51'17.0"W	15.24	02/22/2022	PZ02-01	-4.43		-24.39		11.06		$\delta^2\text{H} = 7.97 \delta^{18}\text{O} + 10.4$	0.9875
				03/30/2022	PZ02-02	-5.60		-34.27		10.53			
				04/27/2022	PZ02-03	-4.50	-4.64	-25.06	-26.58	10.92	10.55		
				06/24/2022	PZ02-04	-4.39		-25.25		9.90			
				07/29/2022	PZ02-05	-4.45		-25.17		10.45			
				08/26/2022	PZ02-06	-4.47		-25.33		10.44			
P3 - M. Sánchez	8°57'10.5"N	79°51'12.2"W	45.72	02/22/2022	PZ03-01	-4.87		-28.05		10.87		$\delta^2\text{H} = 9.07 \delta^{18}\text{O} + 15.5$	0.9863
				03/30/2022	PZ03-02	-5.24		-32.02		9.90			
				04/27/2022	PZ03-03	-4.23	-4.80	-22.87	-28.09	10.98	10.33		
				06/24/2022	PZ03-04	-4.72		-27.36		10.36			
				07/29/2022	PZ03-05	-4.89		-29.19		9.91			
				08/26/2022	PZ03-06	-4.87		-29.02		9.96			
P4 - Héctor Ábrego	8°57'09.5"N	79°51'13.0"W	24.38	02/22/2022	PZ04-01	-6.00		-35.78		12.22		$\delta^2\text{H} = 8.01 \delta^{18}\text{O} + 10.7$	0.9533
				03/30/2022	PZ04-02	-5.36		-32.45		10.43			
				04/27/2022	PZ04-03	-6.59	-5.91	-42.60	-36.62	10.14	10.64		
				06/24/2022	PZ04-04	-6.24		-39.56		10.38			
				07/29/2022	PZ04-05	-5.63		-35.03		9.99			
				08/26/2022	PZ04-06	-5.62		-34.32		10.67			
	8°57'10.6"N	79°51'10.1"W	42.67	02/22/2022	PZ05-01	-5.99		-36.99		10.93		$\delta^2\text{H} = 9.7 \delta^{18}\text{O} + 21.2$	0.9422
				03/30/2022	PZ05-02	-6.38		-41.06		9.98			
				04/27/2022	PZ05-03	-6.17	-6.15	-38.14	-38.53	11.24	10.70		

Site	Coordinates (WGS84 - Zone 17 North)		Depth (meters)	Date	Sample	$\delta^{18}\text{O}$ (‰)	$\delta^{18}\text{O}$ Mean (‰)	$\delta^2\text{H}$ (‰)	$\delta^2\text{H}$ Mean (‰)	d -excess (‰)	d -excess Mean (‰)	Local Meteoric Water Line	R^2
	Latitude	Longitude											
P5 - Negro Sánchez				06/24/2022	PZ05-04	-6.19		-38.86		10.63			
				07/29/2022	PZ05-05	-6.01		-37.51		10.59			
				08/26/2022	PZ05-06	-6.18		-38.62		10.84			
P6 - R. Delgado	8°57'29.1"N	79°51'54.0"W	-	02/22/2022	PZ06-01	-4.96		-28.12		11.56			
				03/30/2022	PZ06-02	-5.33		-32.91		9.73			
				04/27/2022	PZ06-03	-5.42	-5.13	-32.41	-30.53	10.91	10.53	$\delta^2\text{H} = 8.22 \delta^{18}\text{O} + 11.7$	0.8774
				06/24/2022	PZ06-04	-5.05		-30.17		10.25			
				07/29/2022	PZ06-05	-4.86		-28.83		10.07			
				08/26/2022	PZ06-06	-5.18		-30.74		10.66			
P7 - D. Díaz	8°57'31.1"N	79°51'58.5"W	54.86	02/22/2022	PZ07-01	-4.66		-28.49		8.77			
				03/30/2022	PZ07-02	-3.87		-21.64		9.32			
				04/27/2022	PZ07-03	-5.36	-4.94	-32.04	-29.52	10.84	9.96	$\delta^2\text{H} = 6.99 \delta^{18}\text{O} + 5.00$	0.9859
				06/24/2022	PZ07-04	-5.31		-32.09		10.39			
				07/29/2022	PZ07-05	-5.07		-30.52		10.05			
				08/26/2022	PZ07-06	-5.34		-32.33		10.41			
P8 - J. Carrasco	8°57'30.1"N	79°52'14.2"W	45.72	02/22/2022	PZ08-01	-5.18		-31.04		10.42			
				04/27/2022	PZ08-02	-5.45		-32.54		11.08			
				06/24/2022	PZ08-03	-5.40	-5.32	-32.61	-31.94	10.56	10.62	$\delta^2\text{H} = 5.83 \delta^{18}\text{O} - 0.954$	0.9586
				07/29/2022	PZ08-04	-5.22		-31.43		10.32			
				08/26/2022	PZ08-05	-5.35		-32.10		10.73			
P9 – Carlos Herrera	8°57'42.1"N	79°52'52.9"W	30.48	02/22/2022	PZ09-01	-5.47		-30.85		12.93			
				03/30/2022	PZ09-02	-5.39		-33.57		9.55			
				04/27/2022	PZ09-03	-5.43	-5.39	-32.45	-32.10	11.01	11.01	$\delta^2\text{H} = 2.00 \delta^{18}\text{O} - 21.3$	0.0455
				06/24/2022	PZ09-04	-5.48		-32.49		11.34			
				07/29/2022	PZ09-05	-5.20		-31.30		10.31			
				08/26/2022	PZ09-06	-5.36		-31.93		10.94			
P10 - H.	8°57'32.6"N	79°52'19.4"W	54.86	02/22/2022	PZ10-01	-5.70	-5.49	-33.23	-33.20	12.4	10.74	$\delta^2\text{H} = 4.88 \delta^{18}\text{O} - 6.38$	0.7924
				03/30/2022	PZ10-02	-5.07		-30.88		9.68			

Site	Coordinates (WGS84 - Zone 17 North)		Depth (meters)	Date	Sample	$\delta^{18}\text{O}$ (‰)	$\delta^{18}\text{O}$ Mean (‰)	$\delta^2\text{H}$ (‰)	$\delta^2\text{H}$ Mean (‰)	d -excess (‰)	d -excess Mean (‰)	Local Meteoric Water Line	R^2
	Latitude	Longitude											
Sánchez F.				04/27/2022	PZ10-03	-5.49		-33.22		10.68			
				06/24/2022	PZ10-04	-5.62		-34.30		10.64			
				07/29/2022	PZ10-05	-5.55		-33.93		10.45			
				08/26/2022	PZ10-06	-5.53		-33.61		10.61			
P11 - V. Carrasco	8°57'38.7"N	79°52'28.7"W	45.72	02/22/2022	PZ11-01	-5.61		-31.68		13.17			
				03/30/2022	PZ11-02	-4.89		-28.89		10.23			
				04/27/2022	PZ11-03	-5.48	-5.48	-33.19	-32.71	10.63	11.14	$\delta^2\text{H} = 6.25 \delta^{18}\text{O} + 1.56$	0.8122
				06/24/2022	PZ11-04	-5.76		-34.72		11.33			
				07/29/2022	PZ11-05	-5.48		-33.39		10.47			
				08/26/2022	PZ11-06	-5.68		-34.40		11.03			
P12 - C. Zanguenga	8°57'30.4"N	79°52'09.0"W	73.15	02/22/2022	PZ12-01	-5.69		-32.68		12.83			
				03/30/2022	PZ12-02	-5.74		-36.04		9.88			
				04/27/2022	PZ12-03	-5.68	-5.68	-34.40	-34.38	11.02	11.06	$\delta^2\text{H} = 6.19 \delta^{18}\text{O} + 0.8$	0.3439
				06/24/2022	PZ12-04	-5.79		-35.03		11.31			
				07/29/2022	PZ12-05	-5.46		-33.31		10.35			
				08/26/2022	PZ12-06	-5.73		-34.85		10.98			
P13 - Alex Díaz	8°57'56.7"N	79°52'54.6"W	45.72	02/22/2022	PZ13-01	-5.18		-28.12		13.3			
				03/30/2022	PZ13-02	-5.70		-36.16		9.44			
				04/27/2022	PZ13-03	-5.18	-5.37	-30.77	-32.18	10.67	10.80	$\delta^2\text{H} = 10.8 \delta^{18}\text{O} + 25.7$	0.8427
				06/24/2022	PZ13-04	-5.62		-34.12		10.84			
				07/29/2022	PZ13-05	-5.42		-33.19		10.15			
				08/26/2022	PZ13-06	-5.14		-30.73		10.42			
P14 - E. Ortega	8°57'29.9"N	79°52'03.6"W	-	02/24/2022	PZ14-01	-5.25	-5.25	-28.82	-28.82	13.17	13.17	-	-
P15 - Junier Díaz	8°57'19.5"N	79°51'55.4"W	45.72	02/24/2022	PZ15-01	-6.25		-38.31		11.67			
				03/30/2022	PZ15-02	-6.53		-42.71		9.53			
				04/27/2022	PZ15-03	-6.58		-41.32		11.34			
				06/24/2022	PZ15-04	-6.60	-6.46	-41.70	-40.94	11.09	10.74	$\delta^2\text{H} = 8.37 \delta^{18}\text{O} + 13.1$	0.7186
				07/29/2022	PZ15-05	-6.28		-40.17		10.10			

Site	Coordinates (WGS84 - Zone 17 North)		Depth (meters)	Date	Sample	$\delta^{18}\text{O}$ (‰)	$\delta^{18}\text{O}$ Mean (‰)	$\delta^2\text{H}$ (‰)	$\delta^2\text{H}$ Mean (‰)	d -excess (‰)	d -excess Mean (‰)	Local Meteoric Water Line	R^2
	Latitude	Longitude											
P16 - Jaime Sánchez	8°57'11.4"N	79°51'05.8"W	45.72	08/26/2022	PZ15-06	-6.52		-41.43		10.71		$\delta^2\text{H} = 4.25 \delta^{18}\text{O} - 9.68$	0.5609
				02/24/2022	PZ16-01	-5.83		-32.76		13.88			
				03/30/2022	PZ16-02	-5.18		-31.39		10.05			
				04/27/2022	PZ16-03	-5.66	-5.58	-34.11	-33.38	11.15	11.24		
				06/24/2022	PZ16-04	-5.83		-35.52		11.12			
				07/29/2022	PZ16-05	-5.57		-33.97		10.61			
				08/26/2022	PZ16-06	-5.39		-32.52		10.62			
P17 - Criadero La Valentina	8°57'13.0"N	79°51'47.6"W	-	03/30/2022	PZ17-01	-6.05		-38.41		9.99		$\delta^2\text{H} = 8.41 \delta^{18}\text{O} + 12.7$	0.9867
				04/27/2022	PZ17-02	-5.48	-5.50	-33.03	-33.54	10.77	10.41		
				07/29/2022	PZ17-03	-5.12		-30.82		10.10			
				08/26/2022	PZ17-04	-5.33		-31.88		10.78			
P18 – I. Flores (Colecta de agua lluvia)	8°57'36.1"N	79°52'11.8"W	-	10/10/2024	Rainfall-01	-7.63		-45.29		15.73		$\delta^2\text{H} = 8.09 \delta^{18}\text{O} + 10.9$	0.9319
				10/13/2024	Rainfall-02	-1.90		-11.06		4.12			
				10/13/2024	Rainfall-03	-2.53		-6.14		14.12			
				10/15/2024	Rainfall-04	-2.83		-17.44		5.23			
				10/15/2024	Rainfall-05	-7.40		-43.01		16.21			
				10/16/2024	Rainfall-06	-6.54		-42.77		9.52			
				10/16/2024	Rainfall-07	-7.26		-50.51		7.58			
				10/17/2024	Rainfall-08	-4.40		-30.53		4.65			
				10/19/2024	Rainfall-09	-4.47		-24.33		11.42			
				10/20/2024	Rainfall-10	-5.49		-28.77		15.17			
				10/26/2024	Rainfall-11	-2.48	-5.48	-12.35	-33.39	7.47	10.42		
				10/27/2024	Rainfall-12	-4.11		-21.65		11.25			
				10/28/2024	Rainfall-13	-3.81		-20.58		9.88			
				10/31/2024	Rainfall-14	-6.03		-40.14		8.09			
				11/01/2024	Rainfall-15	-8.76		-58.98		11.1			
				11/03/2024	Rainfall-16	-4.25		-39.01		-4.98			
				11/04/2024	Rainfall-17	-7.93		-55.02		8.44			
				11/08/2024	Rainfall-18	-9.08		-62.65		9.96			

Site	Coordinates		Depth (meters)	Date	Sample	$\delta^{18}\text{O}$ (‰)	$\delta^{18}\text{O}$ Mean (‰)	$\delta^2\text{H}$ (‰)	$\delta^2\text{H}$ Mean (‰)	$d\text{-excess}$ (‰)	$d\text{-excess}$ Mean (‰)	Local Meteoric Water Line	R^2
	(WGS84 - Zone 17 North)												
	Latitude	Longitude											
			11/08/2024	Rainfall-19	-9.23		-66.66		7.20				
			11/09/2024	Rainfall-20	-8.48		-60.91		6.92				
			11/10/2024	Rainfall-21	-9.29		-72.27		2.07				
			11/11/2024	Rainfall-22	-5.64		-37.18		7.91				
			11/11/2024	Rainfall-23	-7.39		-48.70		10.4				
			11/18/2024	Rainfall-24	-5.75		-27.50		18.52				
			11/18/2024	Rainfall-25	-4.15		-15.94		17.26				
			11/19/2024	Rainfall-26	-2.75		-7.85		14.17				
			11/20/2024	Rainfall-27	-3.22		-11.45		14.29				
			11/21/2024	Rainfall-28	-3.06		-11.42		13.04				
			11/22/2024	Rainfall-29	-4.29		-17.31		17.03				
			11/23/2024	Rainfall-30	-7.64		-43.73		17.41				
			11/25/2024	Rainfall-31	-2.02		-4.22		11.92				

Source: Authors, 2026.

5. Discussion

The results denote that the isotopic composition of precipitation in the La Zanguenga micro-basin manifests some characteristics of the Global Meteoric Water Line (GMWL) (Table 2 as well as Figure 5). The similarity between the two lines suggests that only slight fractionation occurs along the trajectory of the air masses before condensation, which is to be expected given that the distances from their sources, the Caribbean Sea and Pacific Ocean close at hand.

The close correspondence between the GMWL, the Local Meteoric Water Line (LMWL), and the groundwater regression line (Table 2) suggests that the isotopic composition of precipitation was largely preserved during groundwater recharge, implying a limited post-precipitation fractionation. According to Gonfiantini (1986), the isotopic depletion of the evaporating liquid residue decreases as the air humidity at the site increases, and both the evaporated and the rainwater lines plot close together. This circumstance is likely to occur in the Panama Isthmus due to its high humidity levels.

The small offset observed between the LMWL and the groundwater line is therefore consistent with the predominance of direct recharge under conditions of limited evaporation. However, minor deviations from the LMWL may reflect local processes operating within the soil that modify the isotopic composition. The limited evaporation or re-evaporation before infiltration, together with mixing between recent recharge and older groundwater that has already been isotopically altered, may contribute to this shift. This is consistent with the hypothesis that, in La Zanguenga, both evaporative/re-evaporative and recharge-mixing processes were limited; however, the available dataset does not allow these two mechanisms to be distinguished from one another, and this remains an open question for future work.

An additional aspect deserving attention is that some precipitation samples plot slightly above both the LMWL and the GMWL (Figure 5). Although this behavior is uncommon in humid tropical regions, it may reflect more than one process. One possibility is limited re-evaporation, even though some existing literature rejects this process because the humidity in the region is too high to permit it (Schär et al., 1999). Alternatively, partial recycling of atmospheric moisture through regional evapotranspiration may have contributed to the observed enrichment, as reported for other humid tropical regions, including the Amazonia, where comparable climatic conditions prevail. However, this remains an open question that merits further study.

The spatial distribution of the wells inside the micro-basin is noteworthy: a belt stretched from approximately W-E over a length of about 3.5 km in the southern portion of the triangular-shaped basin inside a gentle topographic landscape. Along this alignment, there are three townlets, some small and medium-sized cultivation plots (mainly pineapple), as well as pastureland. The peculiarity of this spatial distribution, both in shape and scale, would induce an expectation of smooth differences between isotope compositions in the 17 analyzed wells (at distances less than 50 m from each other in most cases). However, this expectation was not fully confirmed. The significance of the data reported in Table 1 or on the map in Figure 4, where the length bars are proportional to $\delta^{18}\text{O}$, is unmistakable. It is hardly noticeable that there is a faint trend of decrease in $\delta^{18}\text{O}$ levels in wells along a line from WNW to ESE. However, the trend is not smooth; two of the less depleted wells are close to some of the more depleted ones, near the source of the La Zanguenga creek.

Notwithstanding, the weather peculiarities in the region (Trade Winds, El Niño/La Niña) have a major leverage on water isotopic composition, which is unveiled by the seasonal variation of the isotopic groundwater values. Comparing Figures 1(b) and 7, it is possible to observe a decrease in the median $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values between February and August 2022, the last time La Zanguenga was sampled. Rozanski et al. (1992) noticed that in tropical climates, the isotopic composition of precipitation ($\delta^{18}\text{O}_{\text{pt}}$) is just the opposite of that in temperate latitudes. In the tropics, the main agent controlling isotope composition in precipitation is the amount effect, due to which the rainfall $\delta^{18}\text{O}_{\text{pt}}$ decreases with increasing rainwater amount. Fricke & O'Neil (1999) correlated $\delta^{18}\text{O}_{\text{pt}}$ with temperature and explained that this relationship leads to air saturation below the cloud base during precipitation, which provides an additional physical explanation for the observed seasonal trend.

As some other authors (Hu et al. 2018) have noticed, d-excess (a dual isotope system) results are more stable than $\delta^{18}\text{O}$ or $\delta^2\text{H}$ values (a single isotope system). As a result, d-excess provides a complementary and often more robust tracer for interpreting processes than $\delta^{18}\text{O}$ or $\delta^2\text{H}$ individually. It can be seen in Figure 8, that $\delta^{18}\text{O}$ is mainly distributed over the range -5.7‰ to -5.2‰, accounting for 49% of the measured period, while d-excess was evidently more concentrated; 51% over the 10.1‰ to 10.8‰ of the same period. These are very common values in groundwater.

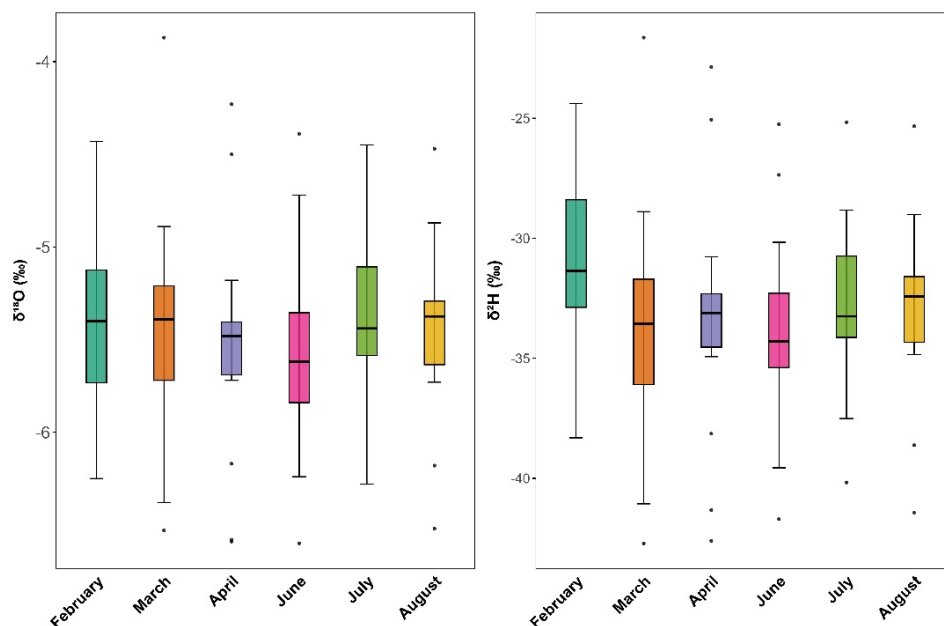


Figure 7. Monthly boxplots of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values in groundwater samples from the La Zanguenga micro-basin, based on six monitoring campaigns conducted in 2022. Source: Authors, 2026.

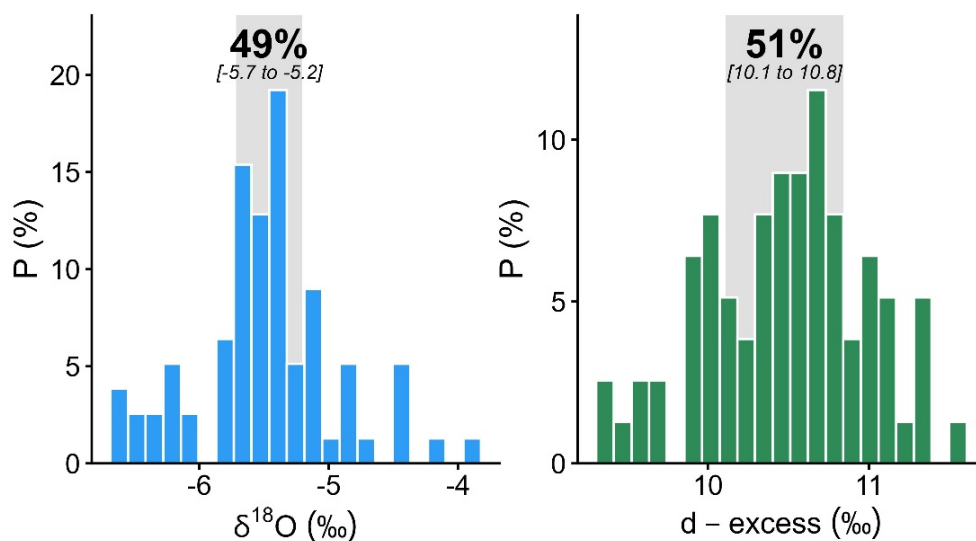


Figure 8. Probability distribution of $\delta^{18}\text{O}$ and d-excess values in groundwater samples during the 2022 period. Source: Authors, 2026.

The geographical position of the La Zanguenga micro-basin, approximately 45 km from the Caribbean Sea and 25 km from the Pacific Ocean, raises an important question about which of the two oceans has more influence on the isotope composition of precipitation and on surface and groundwater in the region. Because the Isthmus of Panama is narrow and lacks a pronounced orographic barrier in the study area, atmospheric moisture from both oceans can potentially contribute to local precipitation, producing a more complex isotopic signal than would be expected in continental settings.

Lachniet et al., back in 2007, addressed this question based on a large amount of data on rain and surface water from Costa Rica and Panama. The large and wide scattered number of values with which these authors worked

was based on dispersed information extrapolating the Panama territory. The authors observed that $\delta^{18}\text{O}$ tended to decrease linearly with increasing distance from the Caribbean coast, reflecting progressive rainout during atmospheric transport, whereas beyond approximately 100 km from the Caribbean the isotopic trend becomes increasingly influenced by Pacific-derived moisture. This conceptual framework has become an important reference for interpreting spatial isotope gradients across the Central American Isthmus.

Figure 9 compares the groundwater $\delta^{18}\text{O}$ values obtained in this study with the regional relationship proposed by Lachniet et al. (2007), whose reported range is represented by the colored stripe. The inversion of slope at approximately 35 km from the Caribbean corresponds to the approximate distance at which the observations of these authors mark the transition from predominantly Caribbean to an increasing influence of Pacific-sourced. In contrast, the width of the Isthmus at the La Zanguenga micro-basin is about 60 km, without any significant orographic divide.

Consequently, the scenario that was foreseen by Lachniet et al. (2007), with quite larger widths, does not flawlessly apply to the La Zanguenga context. Despite these differences, it seems that the trial did not completely fail. The plotted values effectively point to a decrease of $\delta^{18}\text{O}$ as distances from the oceans increase, and that there is a definite influence of the Pacific Ocean on the La Zanguenga groundwater isotopic constitution. A higher amount of data in larger, diverse regions would be needed to better evaluate this behavior.

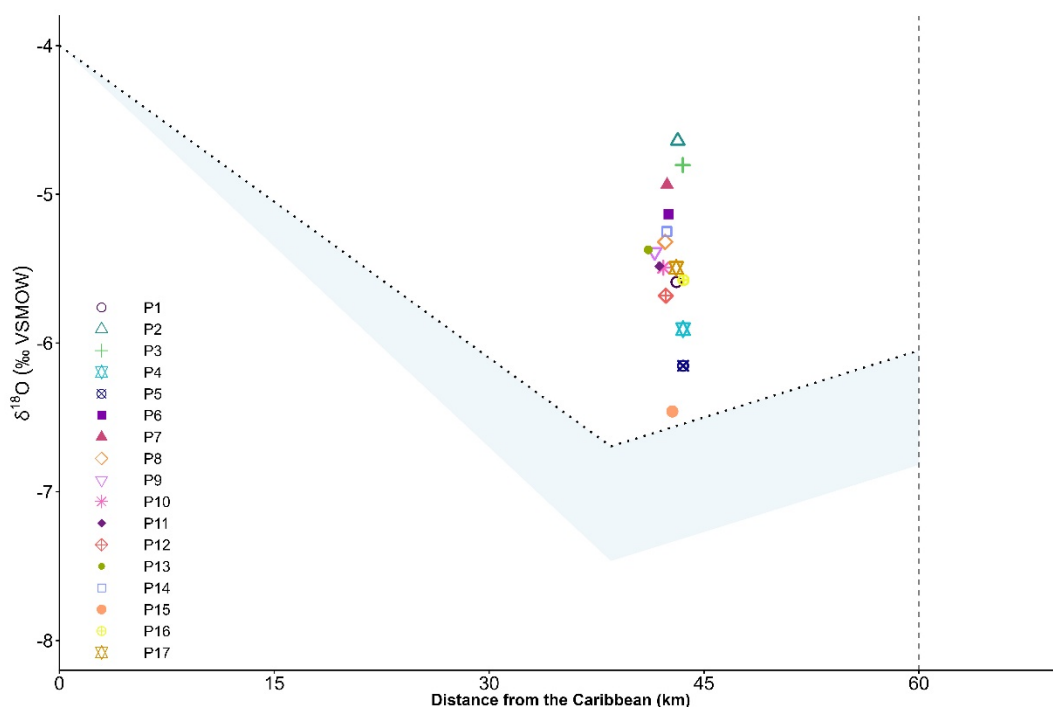


Figure 9. $\delta^{18}\text{O}$ (‰) values obtained in this study as a function of their distance to the Caribbean Sea, compared with the values obtained by Lachniet et al. (2007), are shown dispersed within the colored stripe. Source: Authors, 2026.

6. Conclusions

This study establishes the first isotopic baseline for precipitation and groundwater in the La Zanguenga micro-basin. Beyond characterizing the local isotopic composition of water, the study demonstrates the value of stable isotopes for investigating groundwater recharge processes in central Panama, where isotope-hydrology studies have remained limited since the pioneering work of Lachniet and Patterson (2006). The results provide a conceptual basis for future investigations and permit us to reach the following preliminary conclusions:

- Groundwater ($\delta^{18}\text{O} = -5.46 \pm 0.54\text{‰}$; $\delta^2\text{H} = -32.99 \pm 4.21\text{‰}$; d-excess = $10.72 \pm 0.88\text{‰}$) and precipitation ($\delta^{18}\text{O} = -5.48 \pm 2.38\text{‰}$; $\delta^2\text{H} = -33.40 \pm 19.84\text{‰}$; d-excess = $10.42 \pm 5.18\text{‰}$) display

similar isotopic compositions in the La Zanguenga micro-basin, as shown by their respective $\delta^{18}\text{O}$ vs. $\delta^2\text{H}$ diagrams. This suggests low evaporation caused by highly humid weather at the place.

- The close agreement between the GMWL ($\delta^2\text{H} = 8.0 \delta^{18}\text{O} + 10$), the LMWL ($\delta^2\text{H} = 8.09 \delta^{18}\text{O} + 10.94$), and the groundwater regression line ($\delta^2\text{H} = 7.68 \delta^{18}\text{O} + 8.96$) indicates that the meteoric isotopic signal is largely preserved. Measurement of the groundwater age would help to address this issue and its significance in agriculture and in population water consumption.
- A correlation of $\delta^{18}\text{O}$ with the distance from the ocean does exist at the isthmus. However, it still needs to be better substantiated. In any case, the study supports the interpretation that the Pacific Ocean contributes to the isotopic composition of the water environment in the region of the study.

Although these findings provide a consistent conceptual interpretation about groundwater in the La Zanguenga micro-basin, some limitations should be considered. Groundwater and precipitation were sampled in different years (2022 and 2024), requiring the assumption that the isotopic composition of local precipitation remained broadly stable over this period. This assumption is indirectly supported by the close agreement between the 2024 LMWL and long-term GNIP records from central Panama. Likewise, the LMWL was derived from precipitation collected over two months and should therefore be regarded as a preliminary characterization of local meteoric conditions.

Future investigations should prioritize continuous precipitation monitoring over at least one complete hydrological year, together with comprehensive hydrochemical characterization to refine the conceptual understanding of groundwater recharge developed in this study.

7. Acknowledgements

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8. Authors' Contributions

Shantale Gómez-Aparicio: resources, investigation, data curation, software, writing - original draft. *Rubens Martins Moreira*: formal analysis, supervision, methodology, writing – review & editing, validation. *Leila Rodrigues de Araújo*: resources, investigation, methodology, software. *Cláudio José Chagas*: investigation, resources. *Alexander Esquivel-López*: writing – review & editing, conceptualization, project administration and funding acquisition.

9. Conflicts of Interest

The authors declare that they have no conflict of interest.

10. Ethics Approval

Not applicable.

11. Artificial Intelligence Statement: Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

The authors declare that no generative artificial intelligence (AI) or AI-assisted tools were used in the preparation of this manuscript. No AI technologies were employed for writing, language editing, data analysis, interpretation of results, preparation of figures, images, schemes, tables, or the Graphical Abstract. All content presented in this manuscript was created exclusively by the authors, who assume full responsibility for its accuracy, originality, and scientific integrity. AI tools are not authors and do not assume any responsibility for the content of this manuscript.

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