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REPORT

The use of water stable isotopes for a better understanding of hydrogeological processes in Haiti: overview of existing $\delta^{18}O$ and $\delta^{2}H$ data

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Abstract

Isotope hydrological studies carried out since 1987 in Haiti have proven to be effective in improving conceptual models of the principal aquifers in this Caribbean island nation. However, many of these studies have been limited and are mostly unpublished. It is, therefore, important to share the available datasets with scientists and water managers to support further studies and guide decision-making. Eleven datasets were compiled in a unique database for continued advancement and application. This dataset now contains 248 $\delta^{18}O$ and $\delta^{2}H$ results from water samples collected at 190 locations throughout the country. $\delta^{18}O$ and $\delta^{2}H$ values range, respectively, from –3.8 to –8.95‰ and –67.4 to –16.8‰ for precipitation ($n = 5$), 0.9 to 2.76‰ and 8.8 to 18.4‰ for lakes ($n = 4$), –2.61 to 4.98‰ and –26.63 to 28.2‰ for rivers ($n = 11$), –5.11 to –2.6‰ and –29.8 to –6.9‰ for springs ($n = 82$) excluding hot springs, and –5.1 to –1.37‰ and –29.4 to –2.9‰ for boreholes ($n = 142$). The overall presentation of the available data is complemented with an overview of the studies in which stable isotope data acquisition was performed. The global dataset is presented under three primary contexts: (1) elaboration of a local isotope meteoric water line of equation $\delta^{2}H = 7.2\delta^{18}O + 8.8$ supported with data predominately from the Ouest jurisdictional department, (2) spatial variability analysis of the dataset, and (3) definition of the altitude gradient (per 100 m) using freshwater springs of the Plaine du Cul-de-Sac/Massif de la Selle area of –6.67‰ for $\delta^{2}H$ and –0.09‰ for $\delta^{18}O$.

Keywords Stable isotopes · Groundwater flow · Conceptual models · Haiti · Island hydrology

Introduction

For more than 50 years, the quantification of water stable isotopes has proven to be a useful technique to improve hydrogeological knowledge and provide valuable insights for water management and protection. Data on $\delta^{18}O$ and $\delta^{2}H$ in surface water and groundwater have been applied to determine recharge areas and mechanisms (Prada et al. 2016; Séraphin et al. 2016; Priestley et al. 2019), saline intrusion (Zhang et al. 2015; Telahigue et al. 2020; Wu et al. 2020), surface-water/groundwater interactions (Binet et al. 2017; Petelet-Giraud et al. 2018; Zhao et al. 2018; Mahlangu et al. 2020), groundwater flows and exchanges among aquifers (Mandal et al. 2011).

Stable isotopes in waters of the island of Hispaniola (comprising the nations of Haiti and the Dominican Republic) have been studied since the 1980s. Gonfiantini and Simonot (1987) studied the Plaine du Cul-de-Sac (PCS) in Haiti to determine the groundwater origin and delineate flow patterns in the multilayer alluvial aquifer and its relationship with the mountain block karst system of the Massif de la Selle (Gonfiantini and Simonot 1987). The study reported in this report supports the investigation of the origin of salinity in the northern part of the plain and Port-au-Prince. Febrillet et al. (1987) studied the area around Enriquillo Lake in the Dominican Republic and established groundwater recharge areas and interrelations between aquifers. New studies on Haiti include previously unpublished stable isotope data

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for the Plaine de Gonaives, Plaine du Cul-de-Sac, Plaine de Leogane, and two large springs from the Massif de la Selle (Adamson et al. 2022a, this issue; Adamson et al. 2022b, this issue; Miner et al. 2022, this issue), and these studies are described in other articles that are part of the topical collection published in this issue of *Hydrogeology Journal*.

Stable isotope techniques have also been applied in a variety of hydrogeological settings in the Caribbean region in proximity to Haiti. They encompass the carbonated rock aquifers in Cuba (Molerio-Leon et al. 2002; Peralta Vital et al. 2007; Boschetti et al. 2015), Puerto Rico (Jones et al. 2000; Jones and Banner 2003; Scholl and Murphy 2014; Scholl et al. 2015), Belize (Marfia et al. 2004), and Jamaica (Ellins 1992), as well as the volcanic islands of the Caribbean (Scholl et al. 2009; Windhorst et al. 2013; Hemmings et al. 2015; Gourcy et al. 2020).

The regional studies described in the preceding emphasize the value, efficiency, and importance of isotope techniques in improving conceptual hydrological models. In this context, the authors have recognized the importance of compiling and synthesizing isotope data that are otherwise unknown and/or unavailable. Stable isotope data collected from 11 separate water-related projects in Haiti were made available based on this effort.

The compilation of all data and metadata, such as data origin, laboratory information, and hydrogeological context, was followed by a thorough review of potential errors and confirmation of sampling locations. Some uncertainties remain, specifically related to exact locations and elevations, sampling techniques, and sampling depths in wells. Additional complementary field and analytical results such as tritium and major ions were also compiled for this work; however, this report focused on stable water isotopes data. The consolidated dataset, available as electronic supplementary material (ESM), was used for a global assessment of the isotope variability, confirming then the importance of making this dataset available and findable. A local meteoric water line (LMWL) for the Port-au-Prince area (Fig. 1) is proposed and comparisons are made to isotope data from other areas of Haiti and surrounding regions. Stable isotope data present important insights and results, thus demonstrating the importance of the isotopic analysis in advancing hydrogeological knowledge in Haiti.

Materials and methods

This research was focused on stable water isotopes (δ^2H, $\delta^{18}O$). For all of the data documented, analyses of δ^2H and $\delta^{18}O$ isotopes in water were carried out using isotope ratio mass spectrometers with an automated H_2–H_2O and CO_2–H_2O equilibrator. The precisions are typically ±0.1 and

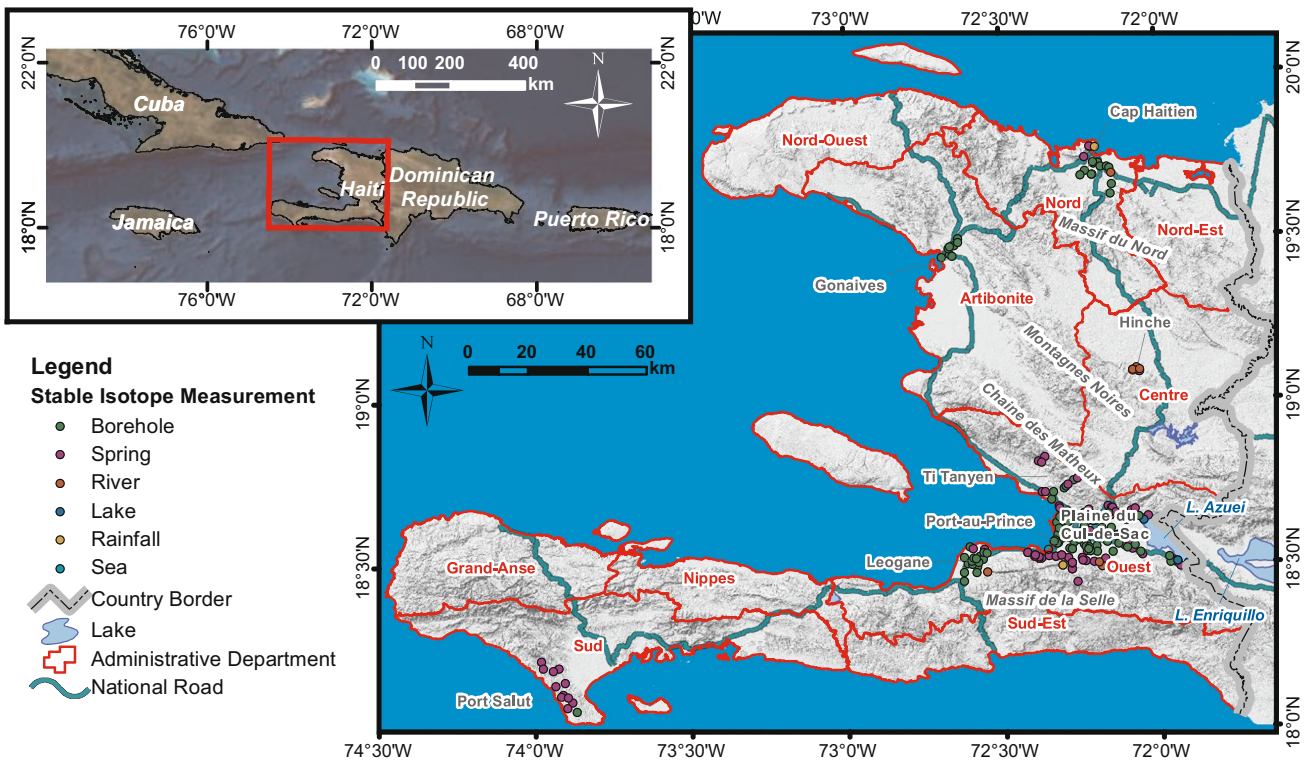


Fig 1 Stable isotope measurement locations in the context of the Haitian political and physical geography

±0.8‰ for $\delta^{18}O$ and $\delta^{2}H$, respectively. Depending on the dataset, some other techniques and precisions are reported (see ESM).

The results are reported in ‰ versus the VSMOW (Vienna Standard Mean Oceanic Water) standard using the conventional δ notation (in ‰): $\delta\text{sample}(‰) = (R\text{sample}/R\text{standard} - 1) \times 1000$.

The deuterium excess values relative to the Global Meteoric Water Line (GMWL; Craig 1961), calculated by the equation $d\text{-excess} = \delta^{2}H - 8 \times \delta^{18}O$, were also used in the data treatment.

A total of 248 stable isotope samples from 190 locations within five of Haiti's 10 administrative departments were assessed (Fig. 1; ESM). The samples encompass the five major hydrogeological environments in Haiti (Adamson et al. 2016), including unconsolidated alluvial deposits, reef carbonates, semiconsolidated sedimentary units, interior carbonates, and igneous and volcano-sedimentary environments.

Data source

Table 1 includes a summary of previously published and unpublished isotopic data sources available for Haiti that are summarized in this work. Background information is presented on each study area from which there is isotope data, and the hydrogeological context is provided.

Presentation of the studies for which data are available

The different data sets listed in Table 1 are briefly presented in the following paragraphs in order to specify the locations, the hydrogeological and geological context, and the objectives of the studies. Some important output obtained using isotope techniques at the study sites are presented, while a country-wide data treatment process is proposed in section 'Discussion on the compiled dataset'.

Plaine du Cul-de-Sac (PCS), Ouest Department

The PCS houses a multilayer aquifer of ~500 km^2, composed of sand/gravel/silt permeable layers and clay/silt semipermeable layers (Adamson et al. 2016). The plain is surrounded by karstic mountainous ranges, Chaine des Matheux in the north and Massif de la Selle in the south from where Rivière Grise and Rivière Blanche are born. The sea and brackish lakes (Lac Azuei and Trou Caïman) form the western and eastern boundaries of the plain. The drinking water supply for the Port-au-Prince municipal area comes from springs that originate from the Massif de la Selle. The drinking water supply of Port-au-Prince area is further complemented by various productive boreholes in the multilayer aquifer. Many private water trucks also distribute water extracted from many wells drilled in the upper part of the alluvial aquifer.

The growing urbanization of the Port-au Prince Metropolitan area has increased water demand, which is now about 400,000 m^3 day^{-1}, with about 300,000 m^3 day^{-1} available from the Cul-de-Sac wells and surrounding springs (A. Joseph, Head of the Water Resources Directorate, personal communication, 2019). The urban development has resulted in groundwater and surface-water impacts, particularly increasing salinity (Evans et al. 2004), heavy metals (Evans et al. 2009), and other contaminants (Fifi et al. 2013).

Hydraulic connections between the aquifer layers exist but are inadequately characterized. Deep groundwater circulation in the aquifer has been hypothesized by use of radioactive isotopes (Gonfiantini and Simonot 1987) and later observed by downhole geophysical logging which indicated upwelling from deep screened intervals into shallower screened intervals during rehabilitation of CTE-RMPP municipal wells (V3 Companies 2012).

The various studies undertaken in this area aimed at determining the hydrogeological conceptual model of the multilayer aquifer including connections with the Azuei/Enriquillo lakes at the Haiti-Dominican Republic border, and possible recharge from the Massif de la Selle.

The isotope data permitted solving important management questions: (1) despite the enriched stable isotope content of some of the more saline waters, the origin of salinity is not direct seawater intrusion, (2) the recharge of the alluvial aquifer is composed of direct rainfall and infiltration of the two major rivers and the Massif de la Selle springs (discussed in the following section) and (3) there is a minimal groundwater flow to the Rivière Grise (river). Conversely, the isotopic signature of the aquifer around the Riviere Grise indicates that this river is likely a primary source of recharge to the aquifer. Similar but less pronounced patterns are visible from the Riviere Blanche.

Massif de la Selle Springs, Ouest Department

The Tunnel Diquini is a horizontal tunnel reportedly 1.5 km in length, primarily excavated through limestone of the Massif de la Selle, with the majority of flow originating from a normal fault and numerous seeps along the length of the tunnel. Source Mariani is located at a lower elevation than the tunnel, forming the largest naturally flowing spring that supplies Port-au-Prince. Source Mariani seeps from a topographic intersection of the karst limestone aquifer and lower permeability semiconsolidated marls. Limited flow records exist for both water points; however, average flows for the tunnel and spring are 341 and 225 L s^{-1}, respectively (Miner et al. 2022). Due to the limited flow records for both points, concerns were raised by the municipality that flow at both springs has been decreasing over the last several decades and

Table 1 Summary of available stable isotope datasets in Haiti

Data source (funding agency and project number/name)	Number of isotope data points			Elevation range (m asl)	Administrative department	Hydrogeology	Sampling period	Reference
	Boreholes	Springs	Rivers					
IAEA/HAI/8/002, Plaine Cul-de-Sac	64	39	1	3-1,409	Ouest	Alluvial and karst limestone	1982–1985	Gonfiantini and Simonot 1987; IAEA 2009
IAEA/HAI/8/005, Plaine Cul-de-Sac	11	14	2	7–908	Ouest	Alluvial and karst limestone	Nov./Dec. 2007	Unpublished[a]
Northwater International, Plaine Cul-de-Sac	12	2	0	7–136	Ouest	Alluvial	Oct. 2016	Adamson et al. 2022b
IAEA/RLA/7/017 Plaine Cul-de-Sac	9	4	2	34–128	Ouest	Alluvial	Nov. 2012	Unpublished[b]
Northwater International, Titanyen-Cabaret	5	7	0	26–620	Ouest	Alluvial, semiconsolidated sedimentary and carbonate	Oct.2015 and Feb–March 2016	Unpublished[c]
Northwater International, Plaine de Leogane	4	2	1	6.4–86	Ouest	Alluvial	April 2019	Adamson et al. 2022b
Northwater International, Tunnel Diquini and Source Mariani (Massif de la Selle)	0	2	0	24–136	Ouest	Karst limestone	April 2018 and April 2019	Miner et al. 2022
Northwater International, Plaine de Gonaïves	8	0	0	1–44.6	Artibonite	Alluvial	Oct. 2018	Adamson et al. 2022a and 2022b
BRGM Cap Haitien	15	3	1	1.5–203	Nord	Alluvial and karst limestone	Oct. 2010	Unpublished[d]
Northwater International, Port Salut	1	11	0	26.5–206.5	Sud	Alluvial, semiconsolidated sedimentary, carbonate and igneous	June and Aug. 2016	Unpublished[e]
Northwater International, Hinche	0	2	5	313–418	Center	Karst limestone	March/April 2019	Unpublished[f]

[a]IAEA, Assessment of groundwater resources of Cul-de-Sac aquifer, IAEA project, IAEA/HAI/8/005, unpublished report, 2008

[b]IAEA, Evaluating the dynamics of groundwater flow between the aquifers and the Enriquillo and Azuei lakes within the context of integrated and sustainable bi-national water and land management, IAEA project HAI/RLA/7/017, unpublished report, 2012

[c]Northwater International and Hasbrouck Geophysics, Groundwater assessment of the Titanyen - Cabaret Corridor, Republic of Haiti: Northwater international report 15-201, unpublished report, 2016

[d]BRGM, Etude de faisabilité pour la réhabilitation et l'extension du système d'alimentation en eau potable et la realization du système d'assainissement des rejets liquides de Cap Haitien ainsi que la supervision de l'ensemble des travaux N°26-02/10 (Feasibility study for the rehabilitation and extension of the drinking water supply system and the construction of the Cap Haitien liquid waste sanitation system as well as the supervision of all works No. 26-02/10), unpublished report, 2011

[e]V3 Companies and Northwater International. Étude sur la disponibilité et la qualité de l'eau à Port-Salut. Programme Tourisme Cotier Durable 3383/GR-HA-I (Study of the availability and quality of the water in Port-Salut. Program Tourism Cotier Durable 3383/GR-HA-I). Inter-American Development Bank, unpublished report, 2016

[f]Northwater International and Rezodlo. Caractérisation hydrogéologique des Sources Saltadére. Etudes hydrologiques du captage de Hinche. DINEPA and Cooperación Española (Hydrogeological characterization of the Saltadére Springs. Hydrological studies of the Hinche catchment. DINEPA and Cooperation Española). Contrat SCF-GG No. 110-03/18, unpublished report, 2019

especially since the 12 January 2010 earthquake. Both water points discharge from the Massif de la Selle karst carbonate aquifer.

This isotopic variability demonstrates the importance of the karstic limestones of the Massif de la Selle providing baseflow to the rivers. The observed altitude effect also

provides an estimate of the minimum and average recharge elevation of water discharging from the spring and tunnel which contributed to the understanding of the recharge amount and area.

The stable isotope results for Tunnel Diquini and source Mariani remained almost unchanged between the 1980s and the 2018/2019 sampling campaigns, suggesting a well-mixed aquifer with limited changes in hydrological regime over the past 40 years. Both the spring and tunnel data reveal very similar values to other major karst springs along the Massif de la Selle and near the LMWL, indicating low exposure to evaporation prior to recharge and likely high recharge rates, as is expected in karst limestone terrain.

Ti Tanyen–Cabaret Corridor, Ouest Department

The Ti Tanyen to Cabaret regional corridor traverses a 15-km stretch across the coastal plain, piedmont and mountain ridge from the northwestern end of the PCS to the Cabaret fan. The area has seen rapid periurbanization and economic development in the last decade, with an accompanying increase in water needs.

An aquifer is present within the carbonate bedrock, which is recharged at higher elevations and flows coastward in karst and fracture networks, often beneath less permeable strata. The Source Matelas spring complex emanates from Oligocene calcareous sandstone outcrops near the coastal center of the corridor, with estimated total flows over 300 L s^{-1}.

Groundwater for local use primarily originates from springs in the sedimentary bedrock away from the coast and from shallow wells in alluvial deposits near the coast. Given the significant aquifer housed within the carbonates as evidenced by the import flow of the source Matelas, the stable isotope sampling strategy focused on the major carbonate springs and select wells which were interpreted to intersect the main carbonate and alluvial aquifers. The objective of the study was to evaluate regional groundwater potential in the study area.

In Ti Tanyen, the data for many of the springs and wells show isotopic depletion and fall near or below the LMWL, indicating a combination of water exposure to evaporation and direct recharge. The carbonate formation springs and some wells appear to have distal recharge origins in the mountains, whereas the wells in the alluvium and semiconsolidated units exhibit local recharge. An increase in the heavy isotope content is accompanied by increased dissolved solids at some of the coastal and piedmont wells, suggesting that groundwater in some areas is mixing with older, more brackish groundwater. Stable isotope values suggest also that the source Matelas waters are recharged in the inland upper elevation karst limestones. To support this hypothesis, water from source Gran Remise was tested for tritium with the results indicating that the water was submodern (<0.8 TU), revealing distal recharge in the Chaine des Matheux and upwelling along the thrust faults.

Plaine de Leogane, Ouest Department

The Plaine de Leogane is a deltaic alluvial fan of approximately 120-km^2 spatial extent situated 25 km west of Port-au-Prince. Its alluvial aquifer supports the city of Leogane and many communities, and the agricultural sector has been hypothesized to receive a large portion of recharge from streamflow infiltration (Adamson et al. 2022a). The aquifer has historically been evaluated to serve as a supplemental water supply for the Port-au-Prince Metropolitan area.

A reconnaissance operation was performed in this area in 2018 (Adamson et al. 2022a, b). Three wells on the west side of the plain have a local recharge with high evaporation before infiltration. River infiltration recharge is an important mechanism for most of the wells near the Riviere Momance.

Plaine de Gonaïves aquifer, Artibonite Department

The Plaine de Gonaives supports a coastal alluvial aquifer of ~115 km^2 in spatial extent located in a semiarid area of the Artibonite Department. The aquifer system exceeds 100 m thickness, supports pumping yields as high as 532 m^3 h^{-1}, and its resources are a critical supply of water for the city of Gonaives and the agricultural sector (Adamson et al. 2022b).

Stable isotope data from wells in the Plaine de Gonaives are presented by Adamson et al. (2022b). Groundwater has been exposed to evaporation during recharge, a recharge that may partially be due to streamflow infiltration.

Plaine du Nord/Massacre aquifer, Nord Department

The groundwater resource currently used in the Cap Haitian region primarily for drinking water mainly originates from the ~1,140-km^2 alluvial aquifer located in the Plaine du Nord. This aquifer contains an alternation of various lithological strata of different permeability, such as silt, sand and gravels, leading to spatial and vertical aquifer heterogeneity. The infiltration area of the Massif du Nord reaches a max elevation of 1,200 m with an average of 400–500 m asl. The massif is composed of volcanic, intrusive, and metamorphic rocks, hosting various springs.

The isotope sampling strategy is set to confirm the hydrogeological conceptual model of the area, i.e. delineating the recharge processes, evaluating surface-water/groundwater exchange, and confirming possible sea-water intrusion.

Stable isotope results reveal a great contrast between the water origin in the alluvium (Plaine du Nord) and in the springs discharging from the mountain bedrock. The deuterium excess is higher for the karstic water, indicating a different origin of the precipitation than what recharges the

alluvial aquifer. In addition to the δ^2H and $\delta^{18}O$, chlorofluorocarbons (CFC-11, CFC-12, CFC-113) and sulfur hexafluoride (SF_6) were analyzed in the F8 municipal well, indicating transfer time from soil to aquifer of more than 60 years. This sampling point corresponds to a deep borehole with reducing conditions with stable isotope values similar to the other alluvial aquifer samples. No significant isotope variability with depth was observed in the Plaine du Nord aquifer based on a limited dataset.

Hinche, Centre Department

The city of Hinche is the capital of the Centre Department and relies entirely upon springs known as Saltadere 1 and 2 for its water supply. The springs flow from a karst limestone aquifer of the Montagnes Noires mountain range, which is also the origin of two nearby rivers that receive baseflow from the aquifer. The study was carried out to support water supply planning for the city of Hinche.

Stable isotope values suggest that source Saltadere 1 and source Tablon may be recharged from higher elevation precipitation from a more regional aquifer, while source Saltadere 2 may be more locally recharged, as evidenced by the larger annual fluctuations in flow and water quality at source Saltadere 2. CFCs and SF_6 sampling at source Saltadere 2 indicated an average groundwater age of 18–34 years.

Port Salut Peninsula, Sud Department

The Port-Salut area of Haiti's southern peninsula is an important tourist region. The study area is geologically complex which has made it historically challenging to secure groundwater supplies to support the region. The peninsula was formed by thrust faulting and uplift, resulting in a series of high SE trending ridges that slope SW across the piedmont and coastal alcoves. All of the hydrogeological environments of Haiti are represented in a relatively small area, from recent alluvial and coralliferous limestone to Cretaceous igneous rocks. The mountain karst carbonate aquifer and local alluvial aquifers have been identified as potential groundwater resources, and a study was commissioned to better understand the groundwater systems to support water sourcing for domestic and tourism water demands.

Stable isotope values of all samples taken near Port Salut indicate that springs are locally recharged along drainage lines and are not, or not significantly, influenced by a regional groundwater system. The sampled springs show an altitude effect, with a majority of recharge to springs appearing to occur between 200 and 500 masl. The single well sampled indicates minimal exposure to evaporation, suggesting direct recharge in the local aquifer composed of high-permeability reef limestone.

Discussion on the compiled dataset

Spatial distribution of stable isotopes

The surface water (rivers and lakes) data plot along the GMWL, except for points located in Plaine du Cul-de-Sac close to the Trou Caïman (saltwater lake) and with high salinity (Fig. 2). There are too few data considering the high temporal variability of stable isotopes in surface water to elaborate more conclusions on surface-water data.

The $\delta^{18}O$ values of springs (except thermal hot springs) and boreholes are presented for each study in Fig. 3. The studies are arranged on the X-axis based on location from south to north. A wide range of values for the Plaine du Cul-de-Sac and the HAI/8/002 is due to the greatest number of samples taken in a large area including different aquifers. In the same plain, the RLA/7/017 site, with only 12 samples, shows a large range of $\delta^{18}O$ covering a large area including strong influence of the Lac Azuei water. Cap Haitien, Gonaives, Hinche, and Ti Tanyen, aquifers show the least depleted isotope values. These three departments are located in the northern part of Haiti. Port Salut in the south and Plaine du Cul-de-Sac presented more depleted values. The diverse datasets are limited in their ability to support bulk country-level analysis, conclusions, and application. The available data however do support important local-scale insights, and advances discussion regarding the LWML and altitude effect.

Local meteoric water line

Due to the absence of a regular collection of rainfall for stable isotopes analyses in Haiti, a proposed LMWL was deduced from nearby stations belonging to the Global

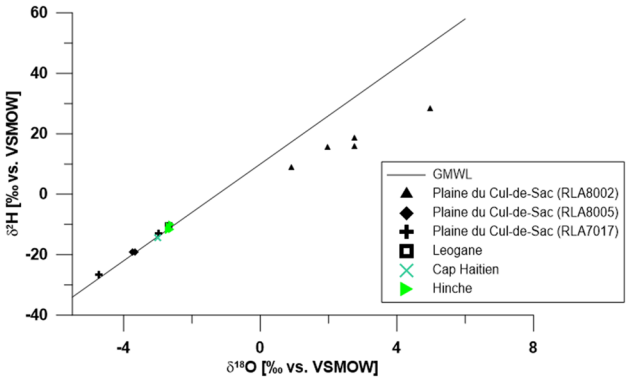


Fig. 2 Stable water isotopes for surface water (lakes and rivers) available in the compiled dataset. The black symbols are from the Ouest department, the green for the Centre department and the blue for the Nord department

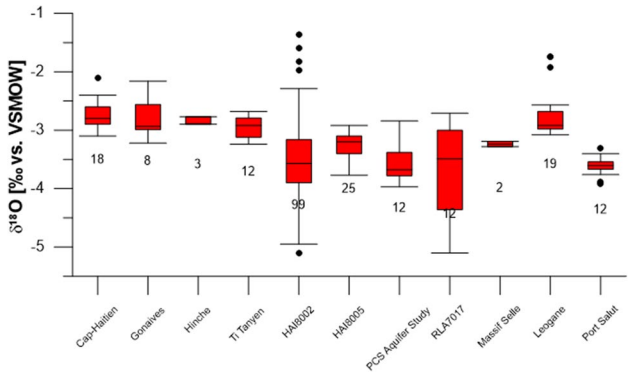


Fig. 3 Box-Whisker plot of $\delta^{18}O$ of groundwater (boreholes and springs) in the 11 studies where data were collected (number below the plot refers to the number of samples considered)

Network of Isotopes in Precipitation (GNIP; IAEA/WMO 2020), from meteoric lines defined in neighboring countries and from the compiled dataset.

The GNIP stations located closest to Haiti with recent data (less than 10 years) are Santo Domingo and Santana (Dominican Republic, 1994–2018), Havana CPHR (Cuba, 2002–2018), and Mayaguez and La Parguera (Puerto Rico, 2013–2016). In Haiti, samples from four individual rainfall events were collected in October 2016 during Hurricane Matthew in Laboule and Clercine, and one event was sampled in Cap Haitien in October 2010. GNIP stations and various LMWLs from west Cuba (Boschetti et al. 2015), southwest Dominican Republic (Febrillet et al. 1987) and east Puerto Rico (Scholl and Murphy 2014) were also compared to the Haiti samples. Figure 4 also depicts the mean annual $\delta^{18}O$ and $\delta^{2}H$ values calculated for Port-au-Prince using the Online Isotopes in Precipitation Calculator OIPC (Bowen and Revenaugh 2003) and the average annual values obtained for Santana/Santo Domingo by mean, multiple regression and kriging (IAEA 2009).

The three LMWLs established using GNIP data (Havana $\delta^{2}H = 7.27\ \delta^{18}O + 7.36$, Santana/Santo Domingo $\delta^{2}H = 8.54\ \delta^{18}O + 12.61$ and Puerto Rico $\delta^{2}H = 7.85\ \delta^{18}O + 10.11$) and the meteoric water line (MWL) established by Febrillet et al. (1987) for southwest Dominican Republic ($\delta^{2}H = 8\ \delta^{18}O + 14.2$), the Cuban MWL established by Boschetti et al. (2015) ($\delta^{2}H = 7.33\ \delta^{18}O + 9.13$) and the MWL in Puerto Rico ($\delta^{2}H = 8.2\ \delta^{18}O + 14$) proposed by Scholl and Murphy (2014) are quite different. The Santana/Santo Domingo GNIP has the higher slope but fits best with the more depleted precipitation values from the Laboule Station in Haiti. However, the most depleted samples corresponding to Laboule Station were collected at a high altitude (837 m) and during Hurricane Matthew in 2016. It has been demonstrated that the stable isotope signal of precipitation during extreme events such as hurricanes, might differ from the stable isotope composition of commonly occurring precipitation (Sánchez-Murillo et al. 2019; Welsh and Sanchez-Murillo 2020).

Lacking representative isotope data from precipitation in Haiti and according to other studies in the Caribbean (Hemmings et al. 2015), a LMWL for Haiti was constructed by use of isotopic content in freshwater springs and precipitation data not related to hurricane events which are considered more representative of average precipitation. It is hypothesized that springs with water lower in electrical conductivity (EC) indicate shortest residence times and negligible influence of evaporation, deep groundwater, and seawater intrusion. The EC of springs in the dataset ranges between 7 and 1,250 µS cm^{-1} with a median value of 470 µS cm^{-1}. Springs in calcareous formations were quite rapidly enriched in dissolved salts and it was decided to include springs with EC less than or equal to 500 µS cm^{-1} (50 in total) to determine the correlation line between $\delta^{18}O$ and $\delta^{2}H$. This line of equation $\delta^{2}H = 7.2\ \delta^{18}O + 8.8$ is reported as LMWL in Fig. 5. In all, 22 of 50 values used in this LMWL were already included in the LMWL $\delta^{2}H = 7.75\ \delta^{18}O + 11.02$ proposed by Gonfiantini and Simonot (1987) for springs and shallow freshwater wells in the PCS aquifer. Only 11 springs were collected outside the Ouest department. The LMWL mainly represents, therefore, the central area of Haiti.

Figure 5 reveals a noticeable variability of the spring and river samples collected within this study, mainly related to

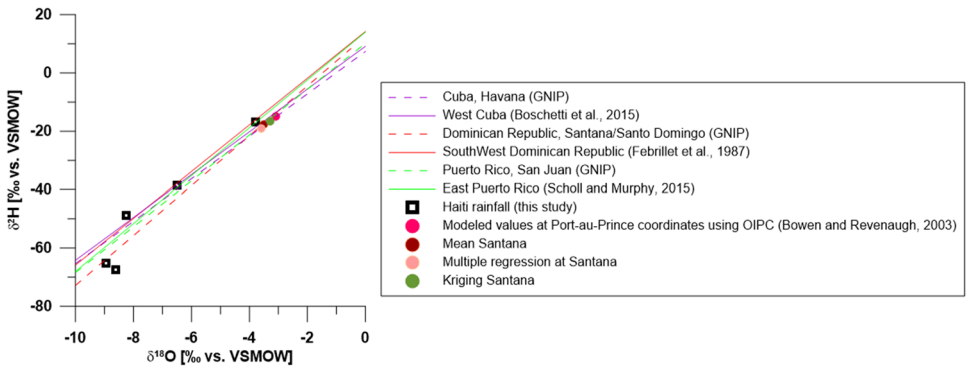


Fig. 4 $\delta^{18}O$ and $\delta^{2}H$ composition of individual rainfall events collected in Haiti ("Haiti rainfall") and meteoric water lines for some active or recently active GNIP stations, published LMWLs, and modeled values at Port-au-Prince coordinates using average OIPC (Bowen and Revenaugh 2003)

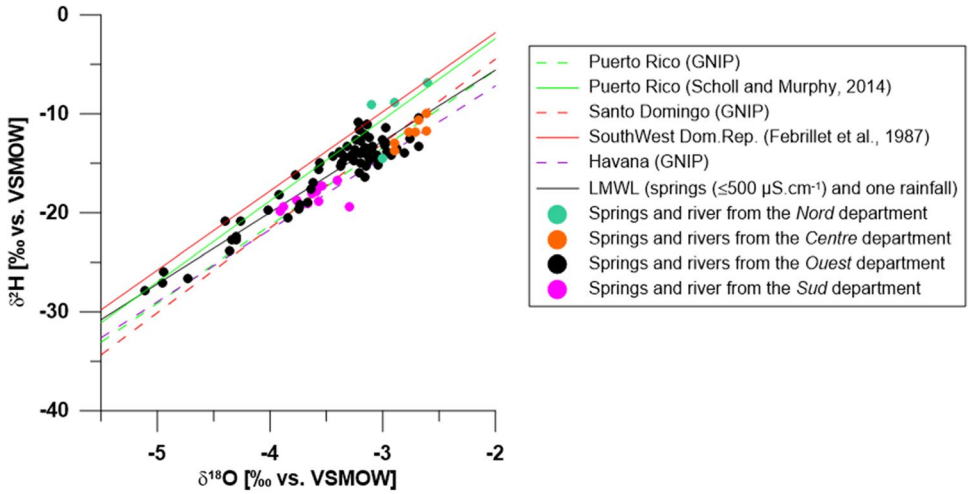


Fig. 5 Stable isotope composition of freshwater from springs and rivers collected in Haiti and meteoric water lines for some active or recently active GNIP stations, published MWLs in the Caribbean region and estimated LMWL using freshwater springs collected in Haiti

precipitation variability. The samples from the Nord Department better fit the Puerto Rico (Scholl and Murphy 2014) and SW Dominican Republic (Febrillet et al. 1987) MWLs, while the data from Centre and Sud departments follow the MWLs established using Santana/Santo Domingo, Havana and Puerto Rico GNIP data. Data from the Ouest Department were distributed between the two extreme LMWLs, indicating a variability in *d*-excess from 8.14 to 14.96‰.

The differences of the proposed LMWLs can be explained by seasonal variations of rainfall amount and intensity, such as during hurricanes, thus reflecting different origins of air masses and climate features. This hypothesis was underpinned by investigations of a clear seasonal evolution of *d*-excess in precipitation in tropical islands (Mandal et al. 2011; Permana et al. 2016; Gourcy et al. 2020).

Determining recharge areas and processes

Due to the contrasting orography in Haiti and high probability of contrasting recharge area elevations, the isotope composition of Haitian natural waters revealed a consistency with the isotope altitude effect.

The altitude effect depends mainly on temperature and pressure changes leading to a theoretical calculated decrease of –0.2 and –1.5‰ for $\delta^{18}O$ and $\delta^{2}H$ (Siegenthaler and Oeschger 1980); however, other parameters such as the origin of the atmospheric air masses and weather patterns (Scholl et al. 1996; Windhorst et al. 2013) or amount effect (Rozanski et al. 1993; Araguas et al. 1998) influence this relationship. Although a specific altitude gradient should be estimated for each area of interest, the use of a predefined isotope altitude gradient is useful in areas lacking data. A compilation of data collected from mountainous areas of the Caribbean are presented in Table 2.

The resulting range of altitude gradients is –0.09 to –0.24‰ per 100 m in $\delta^{18}O$. The range of altitude gradient is –0.59 to –1.53‰ per 100 m in $\delta^{2}H$ and is based on a smaller quantity and higher variability of $\delta^{2}H$ values as compared to $\delta^{18}O$.

The application of the isotope gradient concept in the Massif de la Selle carbonate mountains using data from the same sampling period (1983–1984) reveals an altitude gradient of –0.67‰ per 100 m for $\delta^{18}O$ and –0.09‰/100 m for $\delta^{2}H$, which is very similar to the one proposed in Haiti

Table 2 Isotope gradient for an altitude increase of 100 m compiled from published data (estimated using spring data for Haiti and precipitation for other countries)

Country	Area	$\delta^{2}H$ ‰	$\delta^{18}O$ ‰	Reference
Haiti	Cul-de-Sac	–0.59	–0.09	Gonfiantini and Simonot 1987
Haiti	Cul-de-Sac, Massif de la Selle	–0.67	–0.09	This work
Dominican Rep.	South-west	-	–0.24	Febrillet et al. 1987
Puerto Rico	West	–0.63	–0.12	Scholl and Murphy 2014
Bolivia	Tropical rains	-	–0.239	Gonfiantini et al. 2001
Panama	Country	-	–0.16 up to –0.24	Lachniet and Patterson 2006
Jamaica	Country	–0.9 up to –2.2	-	Ellins 1992
Mexico	Caribbean coast	–1.53	–0.21	Perez-Quezadas et al. 2015

by Gonfiantini and Simonot (1987) and in Puerto Rico by Scholl and Murphy (2014) (Table 2). This gradient is estimated considering the altitude of the springs and not the altitude of the precipitation; however, assuming that each spring represents a small catchment area and therefore spring altitude is proximate to the mean altitude of precipitation, these values can be considered as a first estimate. Groundwaters depleted in ^{18}O and ^{2}H demonstrate that part of the PCS alluvial aquifer was recharged at a higher altitude (Fig. 6). Fifty-five percent of the freshwater wells of the western part of PCS have an isotope composition higher than –3.6‰ $\delta^{18}O$ and are at an average recharge altitude higher than 500 m.

Conclusions

The presented dataset is the first compilation of stable isotope hydrological data in Haiti. Efforts were made to consolidate this dataset by evaluating and analyzing the original analytical results from various sources and studies. The quality of other chemical and tritium data made available was not evaluated, although these complementary data are included in the ESM. The water stable isotopes data demonstrate spatial distribution in various hydrogeological settings across the island and provide input for future hydrogeological studies and direction for groundwater management. Stable isotope data have been applied discretely in several studies throughout the country producing valuable data and informative results that improve local knowledge about important aquifers in Haiti. An in-depth analysis of precipitation and spring water enabled the proposition of a LMWL for general application in Haiti, specifically in the Ouest department and the central region of Haiti. Data from other areas should be collected in order to increase the knowledge of the spatial variability of the precipitation isotope signal that can be predicted by the variability of *d*-excess values noticed from springs collected in the Nord department. The analysis of stable isotope data across the country illustrates spatial variability of the groundwater and the importance of the altitude effect.

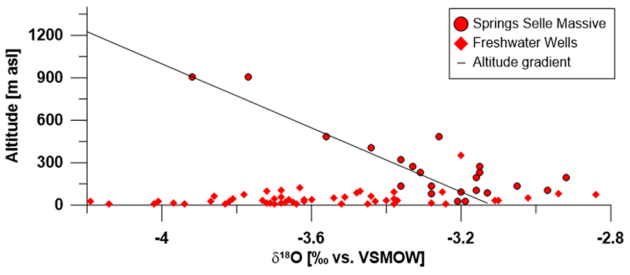


Fig. 6 Altitude of the sampling points vs $\delta^{18}O$ for the samples collected in the Plaine du Cul-de-Sac and the Massive de la Selle carbonate aquifer system

IAEA training programs in Haiti have occurred over 40 years; thus, there is a potential for establishing long-term consortia of trained professionals, international experts, and Haitian universities, and this can be considered as a possible step forward for advancing isotope hydrology science and application in Haiti. This process may take advantage of reinterpretation of various older datasets and revitalization of monitoring programmes that were mostly interrupted due to natural disasters and political challenges in the more recent past. For example, it has been shown here that the absence of a well-defined LMWL limits the interpretation of isotopic results, thus causing gaps in the conceptual models of the aquifers. It is of utmost importance to set up a WMO/IAEA GNIP monitoring station that would support studies of the spatial distribution of precipitation to better define the stable isotope distribution patterns across the island. Unlike many inland and continental landmasses, interpolation of values from other Caribbean stations to Haiti is limited.

In addition to stable isotope data ($\delta^{2}H$ and $\delta^{18}O$) presented in this study, collection of other relevant isotopic and hydrochemical tracer data is of great importance to identify old to very old groundwater in the deeper aquifer compartments such as the Cul-de-Sac aquifer. Except for a few sparse $\delta^{13}C$, ^{14}C, CFC and SF6 data, there is no information on the residence and travel times in Haiti's principal aquifers. This information is critical to guide sustainable use of the deeper and older groundwater resources, which are hypothesized to provide a more sustainable resource due to a high vulnerability of the shallow aquifers to overexploitation, contamination, and salinization. For the same reason, reliable hydrochemical data (Ca, Mg, Na, K, HCO_3+CO_3, SO_4, Cl, NO_3, SiO_2) are recommended to complement all field data (static water level, discharge rate, conductivity, temperature, pH, screened interval, etc.) obtained in the principal aquifers. This first database of stable isotopes in natural water in Haiti is expected to enhance the motivation of scientists and managers to maintain this initiative and enrich the database in the future.

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Declarations

Conflicts of interest No potential conflict of interest was reported by the authors

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